A

Project Report

on

"WIND ENERGY CONVERSION SYSTEM BASED ON PMSG"

Submitted

In partial fulfillment for the award of degree of Bachelor of Electrical Engineering

By

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(2021-2022)

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CERTIFICATE

This is to certify that,

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have satisfactorily completed the project work entitled "**WIND ENERGY CONVERSION SYSTEM BASED ON PERMENENT MAGNET SYNCHRONOUS GENERATOR**". This work is being submitted in the partial fulfillment for the award of degree of **"Bachelor of Technology" in "Electrical Engineering"** of Shivaji University, Kolhapur. This bonafide work is carried out and completed under my guidance and supervision during the academic year 2021-22.

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ACKNOWLEDGEMENT

Engineers normally do not express themselves adequately, we are not exception. Even then, we wish to express my feeling, because the absence of this always makes to feel something to be missing in this report. We have great pleasure in presenting the project report on **"WECS Bases on PMSG".**

It is our proud privilege to express a deep sense of gratitude and respect to our project guide **Mr. Satyajeet S. Pore** for allowing me to pursue a topic of my choice and valuable guidance at every stage provided a constant source of inspiration and encouragement to us for intensive studies in this dissertation work. Without her guidance, it would not have been possible to complete the dissertation work within the limit time frame.

We would like to offer special thanks to head of the electrical engineering department **Prof. (Dr.) PM Joshi**. We are also thankful to Principal **Dr. A. T. Pise** for permitting us for this course and providing the entire infrastructure needed. We also wish to thank all those who directly or indirectly helped us in completing this dissertation work.

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LIST OF ABBREVIATIONS

PMSG – Permanent Magnet Synchronous Generator

WECS – Wind Energy Conversion Systems

BESS – Battery Energy Storage System

SG – Synchronous Generator

PM – Permanent Magnet

WT – Wind Turbine

HAWT – Horizontal Axis Wind Turbine

VAWT – Vertical Axis Wind Turbine

GSC – Grid Side Converter

MSC – Machine Side Converter

CSC – Current Source Inverter

MPPT – Maximum Power Point Tracking

RAPS – Remote Area Power Supply

PLL – Phase Locked Loop

PCC – Point of Common Coupling

FLC – Fuzzy Logic Controller

AFLC – Adaptive Fuzzy Logic Controller

ANN – Artificial Neural Network

DTC – Direct Torque Control

PSO – Particle Swarm Optimization

GA – Genetic Algorithm

BFO – Bacterial-Foraging-Optimization

ABSTRACT

Wind energy is one of the world's fastest-growing energy technologies. There are many loads (such as remote villages, islands, ships, etc.) that are away from the main grid. They require a stand-alone generator system (which can provide constant nominal voltage and frequency) to provide for their local electrification. This requirement has led to widespread research on the development of new technologies for stand-alone generators.

So, this project discusses about the recent research on Wind Energy Conversion System, the advancement of wind energy conversion system is a permanent magnet synchronous generator-based wind energy conversion system. PMSG-based WECS has higher efficiency than other generator-based wind energy conversion system. In this system, there are no requirements for the gearbox.

This project presents the dynamic model of a Permanent Magnet Synchronous Generator (PMSG) based on a Wind Energy Conversion System (WECS). The models of WECS consist of a wind turbine, pitch angle control, drive train, PMSG, and power converter. The performance analysis of PMSG can be enhanced by adopting several control mechanisms with the benefit of advanced optimization techniques. A wind turbine model with a controller for generator protection at high wind speed is also presented in this project. The PMSG and converter model are established in the d-q model. The presented model, dynamic simulation, and simulation results are tested in MATLAB/SIMULINK.

CHAPTER 1
INTRODUCTION

Since the dawn of generating electricity people have been continuously utilizing various resources such as coal, oil, gas, and other natural sources. Due to the constant consumption of the sources, the reduction of storage of these sources now has begun. Also, these phenomena have risen the impact of global warming on a large scale. So, the new era of the world is focusing more on renewable energy sources and wind is one of the most effective one. Wind energy is the purest form of renewable energy. The power of wind is now being the subject of research and it has the capability of replacing the conventional energy sources for power production. It will also help to reduce the effect of global warming. Among the several renewable sources, the wind is one of the considerable sources of electricity generation. By using the potential of wind effectively, it can reduce the power crisis problem. The wind power system exists are of various types. Some of them are connected to the power grid and some are independent of the grid system. This nature depends on the purpose of the use of wind power. Wind energy is converted into electrical energy which is commonly known as Wind Energy Conversion System (WECS). WECS consists of a Wind turbine, Control Method, Generate or Power converter. There are several types of generators used in the conversion process such as Induction Generator (IG), Double-Fed Induction Generator (DFIG), and Permanent Magnet Synchronous Generator (PMSG). The PMSG is vastly used in WECS because of its high efficiency and controllability. Nowadays permanent magnet materials with high coercive field strength, temperature resistance, and economical nature make them highly desirable for wind power generation. The proposed model of PMSG-based WECS includes a wind turbine, drive train, PMSG, and control mechanism.

The control strategy used in this project for maximizing the performance and efficiency of a PMSG-based WECS is categorized into two parts. Firstly, the blade pitch angle control of the wind turbine. It will enable the turbine to operate at a wind speed that is higher than the rated wind speed. Without pitch angle control this would have not been possible. Secondly, there is a method for turbine operation control in such a range of wind speed that whenever the wind speed exceeds a certain upper limit the turbine will shut down. Otherwise, the generator will lose control of its rotor speed and hence will create several damages to the entire system.

A simulation-based study is always necessary for a better understanding of a topic before implementing it practically. This project uses MATLAB/SIMULINK Software for designing the simulation model and also analyzing the overall performance of the proposed approach.

CHAPTER 2

LITERATURE REVIEW

Michael Negnevitsky, Senior Member, IEEE (2009)

This paper presents a novel control strategy for the operation of a direct-drive permanent-magnet synchronous-generator-based stand-alone variable-speed wind turbine. The control strategy for the generator-side converter with maximum power extraction is presented. The stand-alone control is featured with output voltage and frequency controller that is capable of handling variable load. The potential excess of power is dissipated in the dump-load resistor with the chopper control, and the dc-link voltage is maintained. Dynamic representation of dc bus and small-signal analysis are presented. Simulation results show that the controllers can extract maximum power and regulate the voltage and frequency under varying wind and load conditions. The controller shows very good dynamic and steady-state performance.

R. Bharanikumar (2012)

In his paper performance analysis of a three phase Permanent Magnet Synchronous Generator (PMSG) connected to a Vertical Axis Wind Turbine (VAWT). Low speed wind condition (less than 5 m/s) is taken in consideration and the entire simulation is carried in MATLAB/Simulink environment. The rated power for the generator is fixed at 1.5 KW and number of poles at 20. It is observed under low wind speed of 6 m/s, a turbine having approximately 1 m of radius and 2.6 m of height develops 150 Nm mechanical torque that can generate power up to 1.5 KW.

Sina Lotfi and Mahyar Sajedi (2011)

In his paper, maximum power control of wind turbine and permanent magnet synchronous generator connected with two back-to-back voltage source converters to grid are studied. Machine currents are controlled by indirect vector control method. In this method, generator side converter controls the maximum excitation (airgap flux) by machine's d-axis current and controls generator torque by machine's q-axis current. Permanent magnet synchronous generator (PMSG) speed is controlled by tip speed ratio upon the wind speed variations to generate the maximum output power. Grid side converter regulates the DC link voltage and injective active power by d-axis current and regulates the injective reactive power by q-axis current using simple control method P-Q. Simulation results depict that the proposed method.

Siegfried Heier (1998)

This popular reference describes the integration of wind-generated power into electrical power systems and, with the use of advanced control systems, illustrates how wind farms can be made to operate like conventional power plants. Fully revised, the third edition provides up-to-date coverage on new generator developments for wind turbines, recent technical developments in electrical power conversion systems, control design and essential operating conditions. With expanded coverage of offshore technologies, this edition looks at the characteristics and static and dynamic behavior of offshore wind farms and their connection to the mainland grid.

Rolan A., Alvaro L., Gerardo V., and Daniel A. (2009)

The aim of this work is to analyze a typical configuration of a wind turbine generator system (WTGS) equipped with a variable speed generator. Nowadays, doubly-fed induction generators are being widely used on WTGS, although synchronous generators are being extensively utilized too. There are different types of synchronous generators, but the multi-pole permanent magnet synchronous generator (PMSG) is chosen in order to obtain its model. It offers better performance due to higher efficiency and less maintenance since it does not have rotor current and can be used without a gearbox, which also implies a reduction of the weight of the nacelle and a reduction of costs. Apart from the generator, the analyzed WTGS consists of another three parts: wind speed, wind turbine and drive train. These elements have been modeled and the equations that explain their behavior have been introduced. What is more, the whole WTGS has been implemented in MATLAB/Simulink interface. Moreover, the concept of the maximum power point tracking (MPPT) has been presented in terms of the adjustment of the generator rotor speed according to instantaneous wind speed.

Ming Y., Gengyin L., Ming Z., and Chengyong Z. (2007)

The paper presents the dynamic model and control schemes of a variable speed pitch wind turbine with permanent magnet synchronous generator (PMSG). The model includes a PMSG model, a pitch-angled controlled wind turbine model and a drive train model. The drive train model uses one-mass model to represent the mechanical characteristics of the generator set. The generator model is established in the dq-synchronous rotating reference frame. The wind turbine model details the mechanism of variable speed operation of the turbine by a pitch control. The control schemes in the paper include a pitch angle control for the wind turbine and a speed control for the generator. The pitch angle control uses wind speeds and electric power output as the input signals to ensure normal operation in high wind speed. The speed control is realized through field orientation where the d-axis current is set to zero and the q-axis current is used to control the rotational speed of the generator according to the variation of wind speed. In order to verify the presented model and the control strategy, simulations with MATLAB/Simulink software have been conducted. Simulation results prove the validity of the model and the control scheme.

CHAPTER 3

MATHEMATICAL MODEL

The block diagram of the proposed model is shown in Fig 1. In this section, the mathematical model of these blocks has been discussed.

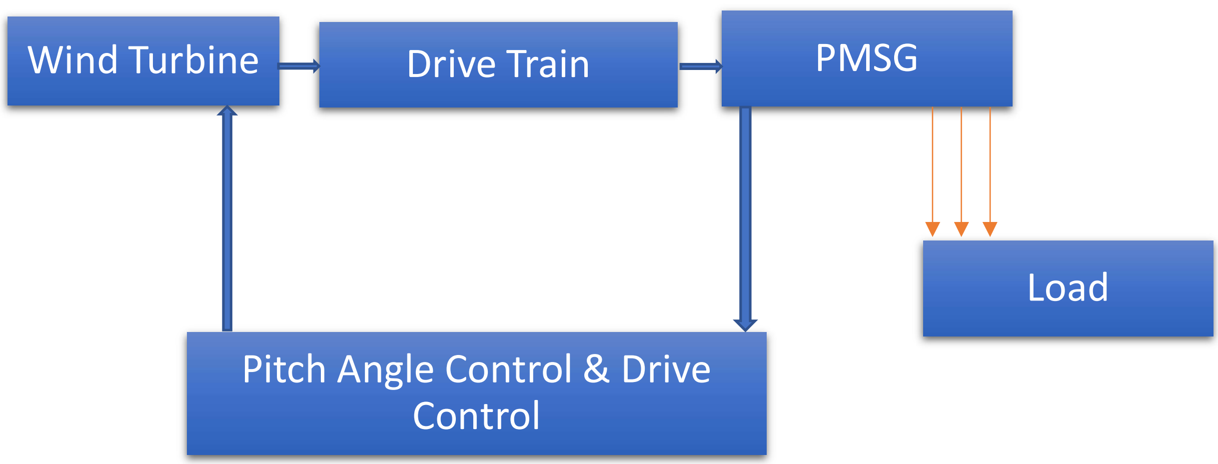


Figure 1. Block Diagram of PMSG-based WECS.

3.1) WIND TURBINE MODEL

The following equation represents the kinetic energy stored in the wind as follows:

Ec = 1/2 (mv^2) (1)

$m = \rho v S$ (2)

where,

m = air mass

v = wind speed

ρ = air density

S = surface area of the turbine

Thus, the wind power can be written as:

$Pw = Ec = 1/2\ mv^2 = 1/2\ \rho S v^3$ (3)

After that wind turbine is used to convert the wind energy into mechanical torque. It can be determined from mechanical power at the turbine extracted from wind power. The power coefficient of the turbine (Cp) is applied. It is defined as the ratio between mechanical power (Pm) and wind power (Pw). It is shown below:

$Cp = (Pm/Pw)$; $Cp < 1$ (4)

The power coefficient is the function of pitch angle (β) and tip speed (λ). Pitch angle is defined as the angle of the turbine blade and tip speed is the ratio of rotational speed and wind speed [6]. The maximum value of the power coefficient (Cp) is denoted as Betz's limit and is equal to 0.593 theoretically. Itmeans that the power extracted from the wind turbine can be no longer than 59.3%.

The power coefficient(Cp) can also be expressed in terms of pitch angle (β)and tip-speed (λ) as:

$$C_p\,(\lambda, \beta) = c1\,(c2/\lambda i - c3\beta - c4)\,e^{-c5\,/\lambda i} + c_6\lambda \qquad (5)$$

$$1/\lambda i = [(1/\lambda + 0.08\beta) - (0.035/\beta^3 + 1)] \qquad (6)$$

If we put the constant values as $c1 = 0.5716$, $c2 = 116$, $c3 = 0.4$, $c4 = 5$, $c5 = 21$ and $c6 = 0.0068$ then the characteristics of $Cp - \lambda$ curve is shown in Fig 2 for different values of β. The maximum value of Cp is attained for $\beta = 0$ and $\lambda = 8.1$.

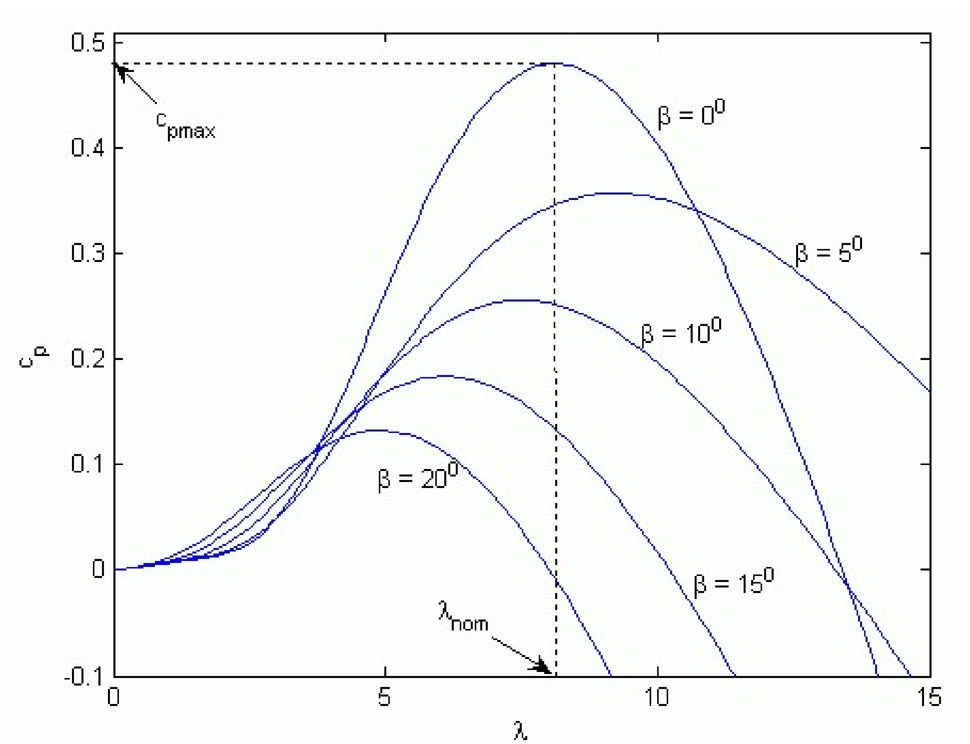


Figure 2. Cp - λ Curve

The following equations express the mechanical output power and mechanical torque as shown below:

$$Pm = Cp(\lambda,\beta)\ \rho S/2\ v^3_{\text{wind}} \tag{7}$$

$$Tm = Pm/w \tag{8}$$

where,

Pm = the mechanical output power

Tm = the mechanical torque

ρ = air density

S = surface area of the turbine

v_{wind} = velocity of the wind

λ = the tip speed ratio

β = the pitch angle

3.2) DRIVE TRAIN MODDEL

A Drive train is considered as a mechanical system of a wind turbine comprising the turbine, generator, and gearbox. The gearbox converts the low speed of the wind turbine into the desired speed of the generator turbine. Themathematical model of a two-mass drive train is expressed as follows:

$$2Ht(dwt/dt) = Tm - Ts \tag{9}$$

$$(1/webs)\ (d\theta sta/dt) = wt - wr \tag{10}$$

$$Ts = K_{ss}\ \theta_{sta} + Dt(d\theta_{ss}/dt) \tag{11}$$

where,

Ht = Inertia constant of the turbine

Θ_{ss} = Shaft twist angle

wt = Angular speed of the wind turbine

wr = Rotor speed of the generator

$webs$ = Electrical base speed

Ts = Shaft torque

Kss = Shaft stiffness

Dt = Damping Coefficient

3.3) GENERATOR MODEL

Permanent magnets are broadly used in synchronous machines with the advantages of simple rotor design without field windings, slip rings, and excitation systems. The PMSG is becoming very popular for its compact size, high power density, high reliability, and robustness. As our study is based on offshore wind power installation, the gearless PMSG generator becomes more suitable than geared double-fed induction generator or induction generator. The equivalent circuit of PMSG-based WECS is shown in Fig 3. This model is created in the *d-q* synchronous reference frame.

The voltage equations of PMSG can be written as:

$d/dt(\mathrm{id}) = (1/Ld)\ vd - (R/Ld)\ \mathrm{id} + (Lq/Ld)\ pwr\ \mathrm{i}q$ (12)

$d/dt(\mathrm{iq}) = (1/Ld)\ vd - (R/Ld)\ \mathrm{id} + (Lq/Ld)\ pw_r\ \mathrm{i_d} - (\lambda pwr/Lq)$ (13)

The electromagnetic torque is written by the following equation:

$Te=1.5\rho[\lambda \mathrm{i}q+(Ld-Lq)\ \mathrm{id\ iq}]$ (14)

Where,

Ld=d−axis inductance

Lq=q−axis inductance

R=resistance of the stator winding

λd=d−axis current

λq=q−axis current

vd=d−axis voltage

vq=q−axis voltage

wr=angular velocity of the rotor

λ=amplitude of flux induced

p=number of pole pairs

The dynamic equations are given by,

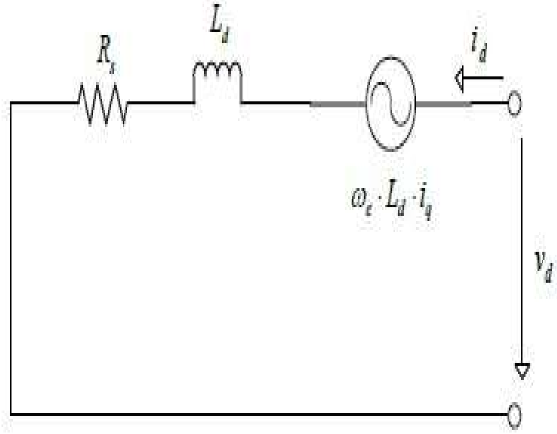
$$d/dt(wr) = (1/J)\,(Te - Fwr - Tm)\,(1)\; ddt = wr \tag{16}$$

Where,

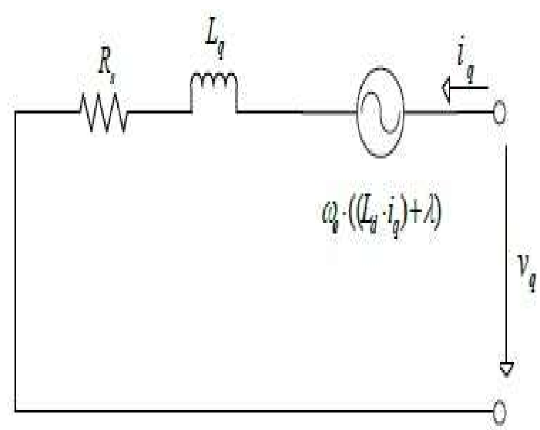
J =inertia of the rotor

F=friction of rotor, θ =rotor angular

This project discusses the turbine blade pitch angle control and turbine operation control for getting an efficient wind power system.



(a) *d-axis* equivalent circuit



(b) *q-axis* equivalent circuit

Fig 3. Equivalent Circuit of PMSG in the d-q reference frame

CHAPTER 4
CONTROL METHOD

4.1) Pitch Angle Control

This control strategy is applied to control the mechanical power input at the nominal value and also prevent the electrical power output from becoming so high. It is usually active in the condition of high wind speed. In those situations, the rotor speed cannot be controlled by increasing the generated power because this would make the overloading of the generator. That's why the blade pitch angle is modified for limiting the aerodynamic efficiency of the rotor which helps to control the rotor speed to become high. In this criterion, the turbine blades are turned away from the wind for minimum power extraction. Whenever there is an unbalance between power output and input wind energy the pitch angle control method must be implemented in order to keep the balance between mechanical input and electrical output. After the clearance of fault, the pitch angle again retains its optimum value for maximum power output. Then again, the turbine blades are turned with the wind for maximum power extraction.

As we discussed earlier, the power coefficient, $CCCC$ is a function of tip speed, λ, and blade pitch angle, β. So, modifying the β would also modify the $CCCC$ and therefore it will help to control the rotational speed as well as the generator output. We know that the maximum value of $CCCC$ is attained when blade pitch angle, β is zero which defines the condition when pitch angle control is not required which means the turbine is operating at the nominal wind speed. But when the wind speed exceeds the rated wind speed by some extent where the rotor speed exceeds its rated value then this control method must be applied.

Then the value of pitch angle β will be increased by some mechanism to decrease the value of C to maintain the balance between input and output power. In this project, Proportional-Integral (PI) control method has been discussed for pitch angle control.

This method of pitch angle control uses the different rotor speeds and a reference value of rotor speed to control the pitch angle. A reference value is set to compare the given input rotor speed. Whenever the rotor speed exceeds the reference value there is a difference in signals found which causes the controller to operate. This error signal is followed by the controller block, angle limit, and rate limiter block which is shown in Fig 4.

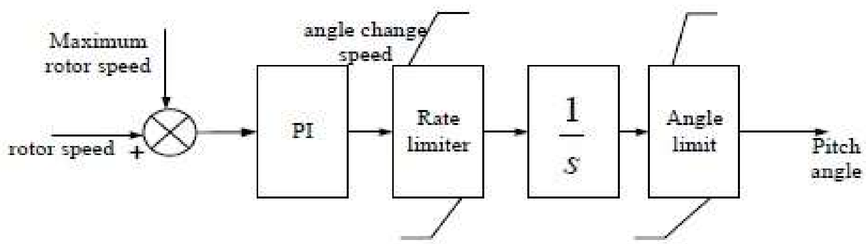


Fig 4. Pitch Angle Controller

If the rotor speed is lower than the referred value then the pitch angle controller will not work and it will give the value of β= 0 to the turbine for initiating maximum power output.

4.2) OPERATION CONTROL

Though we use a pitch angle controller to control the turbine in windy conditions, there must be a method for shutting down the complete operation in the case of an extension of cut-off speed. Then the turbine must not operate at all otherwise it will create a massive disaster for the whole system. We have taken the cut-in speed as 3 m/s i.e., the speed at which the turbine will start to generate reasonable electrical power. The running speed is defined in the range of (3-11) m/s. After the wind speed reaches 11 m/s the turbine must shut down its operation. So, 11 m/s is the cut-off speed defined in our proposed model. This control strategy is implemented in SIMULINK by using a User-defined MATLAB Function block where certain criteria are achieved. In this block, we defined the turbine to operate under (3-11) m/s. If the wind speed is lower than 3 m/s or greater than 11 m/s the turbine will not produce any mechanical torque i.e., Tm=0. Therefore, there will be no output power from the generator.

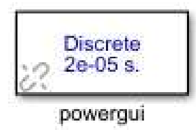
CHAPTER 5

SIMULATION MODEL

The mathematical model of all necessary equipment has been established so far. Now we need to implement it in a simulation-based study. For that MATLAB/SIMULINK software package is used where all the equipment re successfully modeled with respective parameters. After that, the performance of the proposed model was analyzed.

5.1) Various Blocks used in SIMULINK

5.1.1) Powergui



You need the power$_{GUI}$ block to simulate any Simulink model containing Simscape Electrical Specialized Power Systems blocks. It stores the equivalent Simulink circuit that represents the state-space equations of the model.

5.1.2) Constant

The Constant block generates a real or complex constant value signal. Use this block to provide a constant signal input. The block generates scalar, vector, or matrix output.

5.1.3) Gain

The Gain block multiplies the input by a constant value (gain). The input and the gain can each be a scalar, vector, or matrix.

5.1.4) IN port

Create an input port for subsystem or external input. IN port blocks link signals from outside a system into the system.

5.1.5) Outport

Create output port for subsystem or external output. Outport blocks link signals from a system to a destination outside of the system. They can connect signals flowing from a subsystem to other parts of the model. They can also supply external outputs at the top level of a model hierarchy.

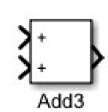
5.1.6) Saturation

Limit input signal to the upper and lower saturation values. The Saturation block produces an output signal that is the value of the input signal bounded to the upper and lower saturation values. The upper and lower limits are specified by the parameters Upper limit and Lower limit.

5.1.7) Rate Limiter

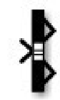
Limit rate of change of signal. The Rate Limiter block limits the first derivative of the signal passing through it. The output changes no faster than the specified limit.

5.1.8) Sum



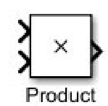
Add or subtract inputs. The Sum block performs addition or subtraction on its inputs. The Add, Subtract, Sum of Elements, and Sum blocks are identical blocks. This block can add or subtract scalar, vector, or matrix inputs. It can also collapse the elements of a signal and perform a summation.

5.1.9) <u>Bus Selector</u>



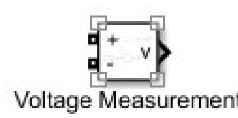
Select signals from the incoming bus. The Bus Selector block outputs a specified subset of the elements of the bus at its input. The block can output the specified elements as separate signals or as a new bus.

5.1.10) <u>Product</u>



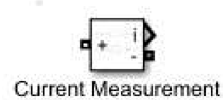
Multiply and divide scalars and non-scalars or multiply and invert matrices. The Product block outputs the result of multiplying two inputs: two scalars, a scalar and a non-scalar, or two non-scalars that have the same dimensions.

5.1.11) <u>Voltage Measurement</u>



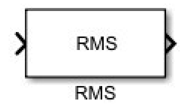
Measures voltage in the circuit. The Voltage Measurement block measures the instantaneous voltage between two electric nodes. The output provides a Simulink® signal that can be used by other Simulink blocks.

5.1.12) <u>Current Measurement</u>



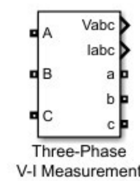
Measures current in the circuit. The Current Measurement block is used to measure the instantaneous current flowing in any electrical block or connection line. The Simulink output provides a Simulink signal that can be used by other Simulink blocks.

5.1.13) RMS



Compute the true root mean square (RMS) value of the signal. The RMS block computes the true root mean square (RMS) value of the input signal. The true RMS value of the input signal is calculated over a running average window of one cycle of the specified fundamental frequency.

5.1.14) Three Phase V-I measurement

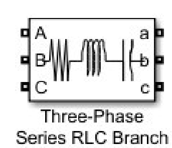


Measure three-phase currents and voltages in the circuit. The Three-Phase V-I Measurement block is used to measure instantaneous three-phase voltages and currents in a circuit. When connected in series with three-phase elements, it returns the three phase-to-ground or phase-to-phase peak voltages and currents.

The block can output the voltages and currents in per unit (PU) values or in volts and amperes.

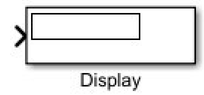
If you choose to measure phase-to-ground voltages in per unit, the block converts the measured voltages based on the peak value of the nominal phase-to-ground voltage

5.1.15) Three-phase phase series RLC Branch



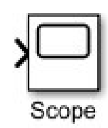
Implement a three-phase series RLC branch. The Three-Phase Series RLC Branch block implements three balanced branches consisting of a resistor, an inductor, a capacitor, or a series combination of these. Use the Branch type parameter to select elements you want to include in each branch. Negative values are allowed for resistance, inductance, and capacitance.

5.1.16) Display



Show the value of the input. The Display block shows the value of the input data. You can specify the frequency of the display. For numeric input data, you can also specify the format of the display. If the block input is an array, you can resize the block vertically or horizontally to show more than just the first element. If the block input is a vector, the block sequentially adds display fields from left to right and top to bottom. The block displays as many values as possible. A black triangle indicates that the block is not displaying all input array elements. The Display block shows the first 200 elements of a vector signal and the first 20 rows and 10 columns of a matrix signal.

4.1.16) Scope



Display signals generated during simulation. It displays the waveform in the time domain.

5.2) WIND TURBINE MODEL

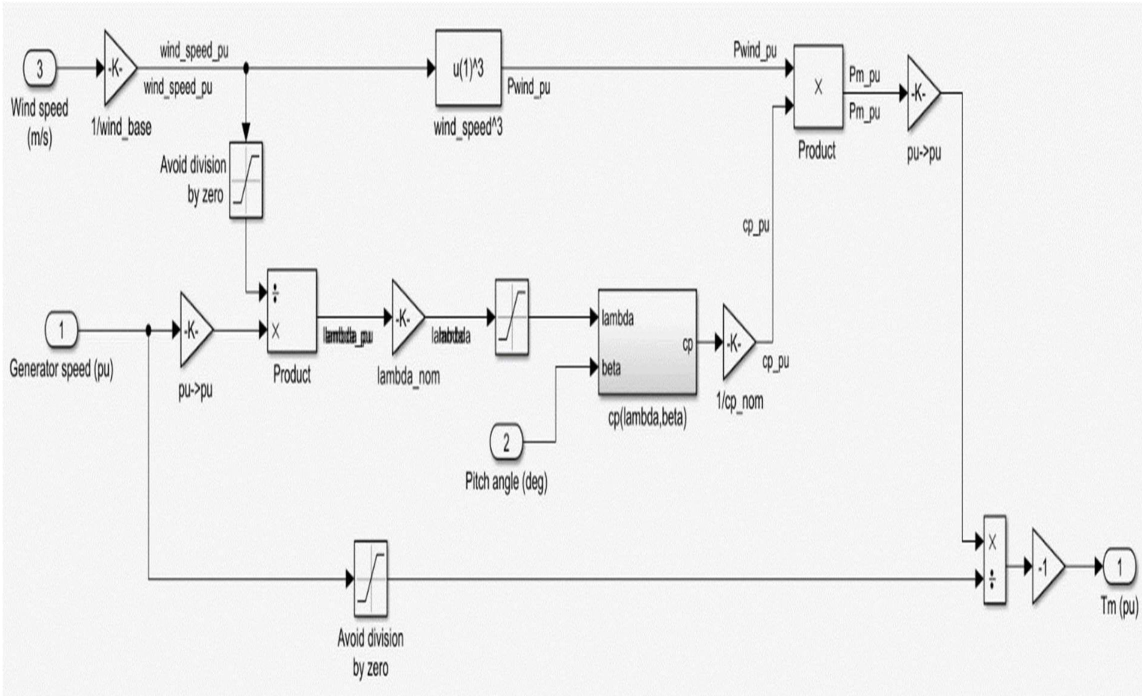


Fig 5. Simulink Model of Wind Turbine

The Specifications used for these models are listed in Table 1.

Parameter	Value
Mechanical Output Power	8.5 KW
Base Power of the electrical generator	8.5e3/0.9
Base Wind Speed	12 m/s
Maximum Power at base wind speed	0.8
Base Rotational Speed in pu	1

Table 1: Wind Turbine Parameters

5.3) DRIVE TRAIN MODEL

Fig 6 shows the two-mass drive train model implemented in MATLAB /SIMULINK.

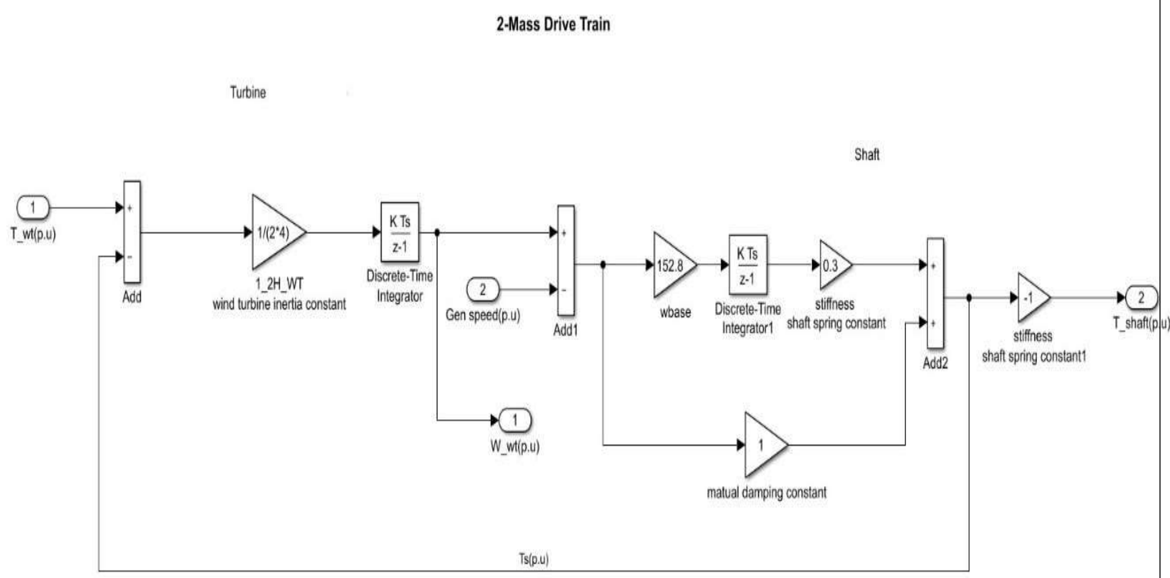


Fig 6. SIMULINK Model of the two-mass drive train

The Specifications used for this model are listed in Table 2.

Parameter	**Value**
Inertia at the turbine	8
Shaft Stiffness	0.3
Damping Coefficient	1

Table 2: Drive Train Parameters

5.4) PMSG SIMULINK MODEL

The Permanent Magnet Synchronous Generator (PMSG) block is found in the Simulink Library. The specifications used in this PMSG model are listed in Table 3.

Parameter	**Value**
Rating	8.5 KW
Base Rotor Speed	8.5e3/0.9
Stator phase resistance	0.425 ohms
Armature inductance	0.000395 H
Flux linkage	0.433
Number of Poles pair	5
Inertia	0.01197 J(kg.m^2)
Viscous Damping	0.001189 F (N.m.s)

Table 3: Generator Parameters

5.5) Pitch Angle Control SIMULINK Model

Fig 7 shows the simulation model of the proposed pitch angle controller. There is also a provision for manual control of pitch angle where we can manually input the value of β instead of the pitch angle controller.

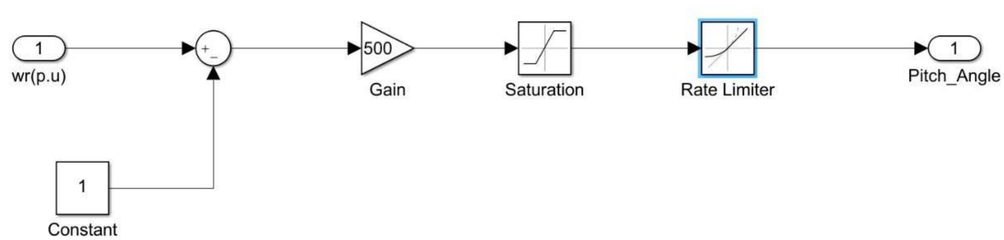


Fig 7. SIMULINK Model of Pitch Angle Controller

5.6) COMPLETE MODEL OF THE SYSTEM

Fig 8 shows a complete model diagram of our proposal implemented in the MATLAB/ SIMULINK interface.

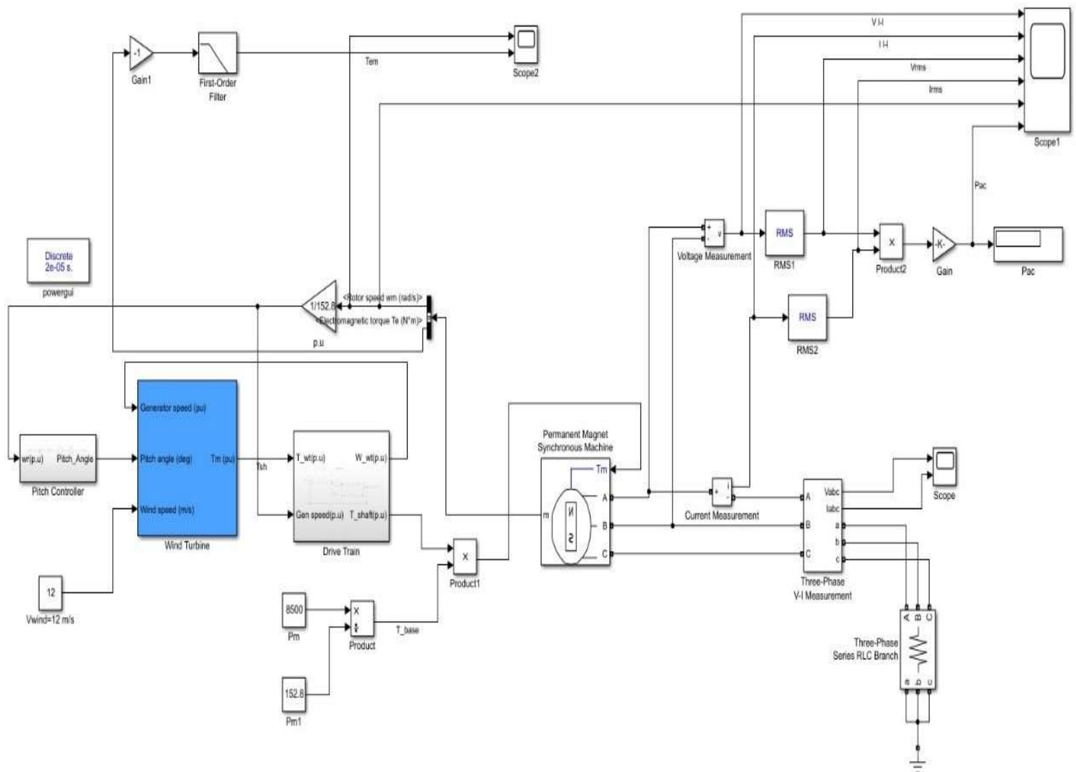


Fig 8. SIMULINK Model of PMSG based WECS

CHAPTER 6

SIMULATION RESULTS

The following curves found from Scope1 show the rotor speed of the generator both in pu value (Fig 9), actual value (Fig 10), the electromagnetic torque (Fig 11), and mechanical torque (Fig 12) for the base wind speed of 12 m/s. In Fig 9 and Fig 10, we see that the rotor speed initially fluctuates until it comes to a stable state after 0.15 sec. In Fig 11 and Fig 12, after some fluctuations both electromagnetic and mechanical torque become stable after 0.14 sec. As expected, the starting torque is higher than the running mechanical torque.

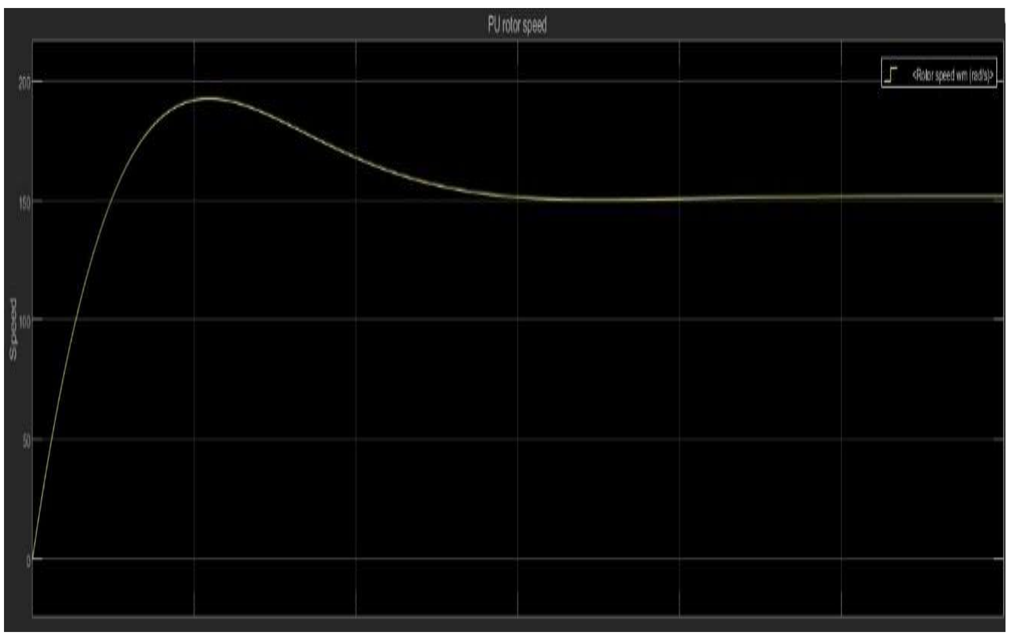


Fig 9. Rotor Speed in PU value

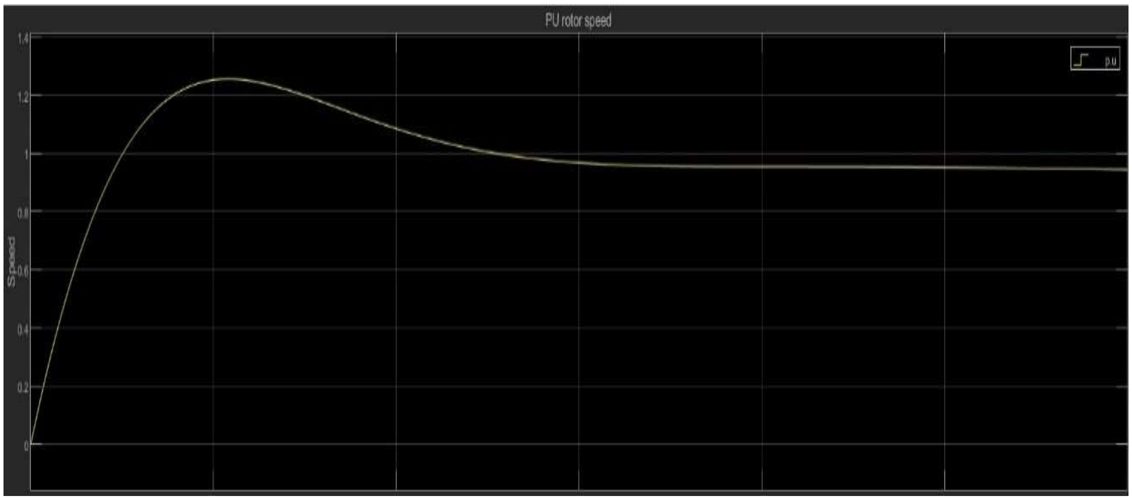


Fig 10. Rotor speed in actual

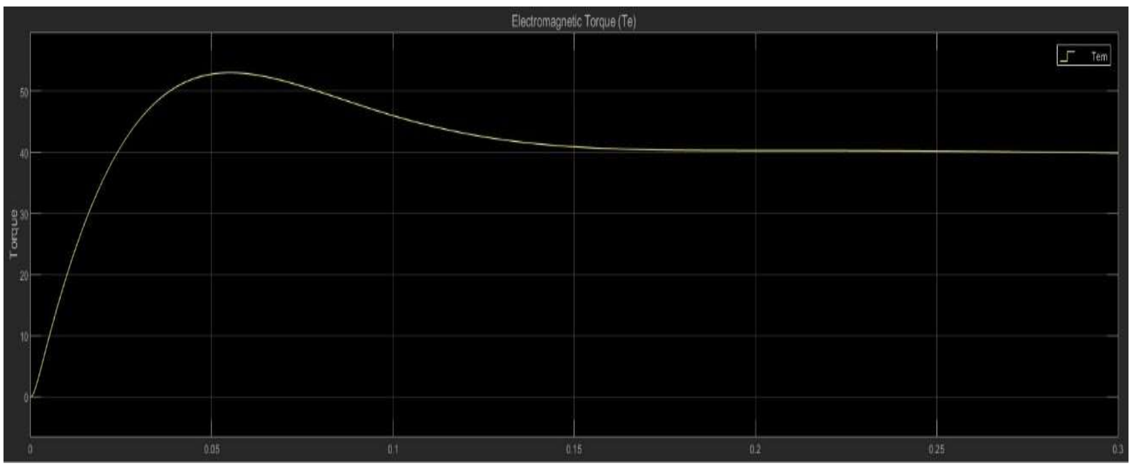


Fig 11. Electromagnetic Torque, Te

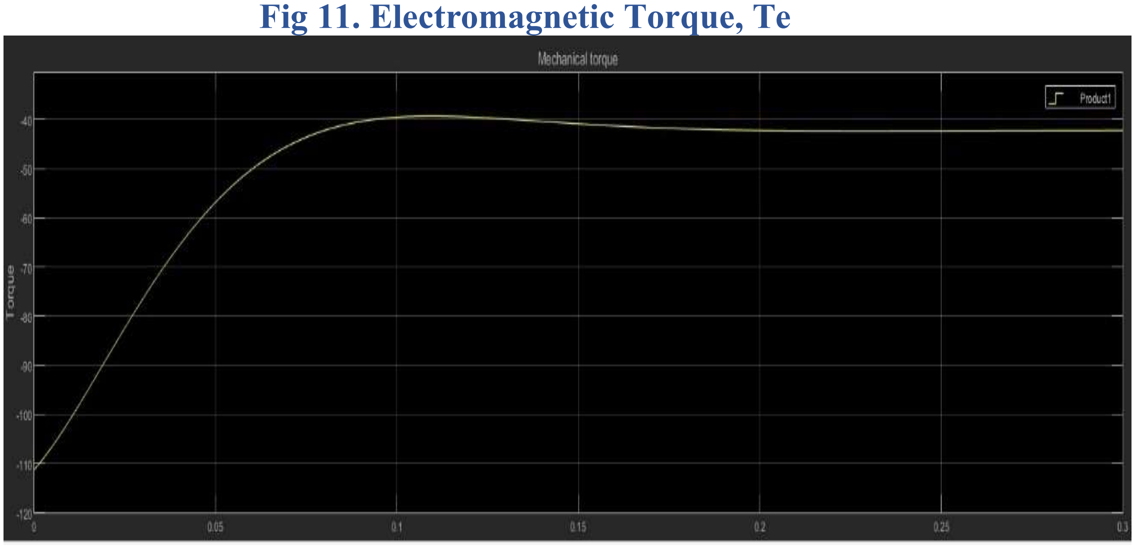


Fig 12. Mechanical Torque, Tm

The following waveforms found from Scope2 display the Phase Voltage

(Fig 13), Line Current (Fig 14), RMS Phase Voltage (Fig 15), RMS Line Current (Fig 16), AC power (Fig 17). From Fig 17, the time taken for starting the machine initially produces no power until 0.04 s. Then the power rises above the rated value and after 0.25 s it comes to the steady-state condition.

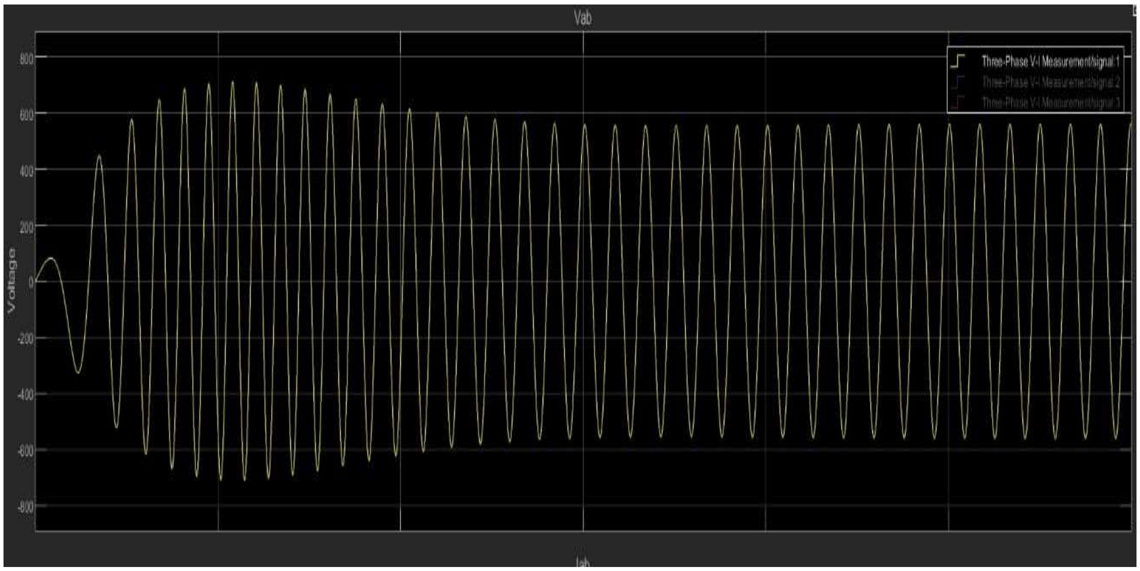


Fig 13. Phase Voltage

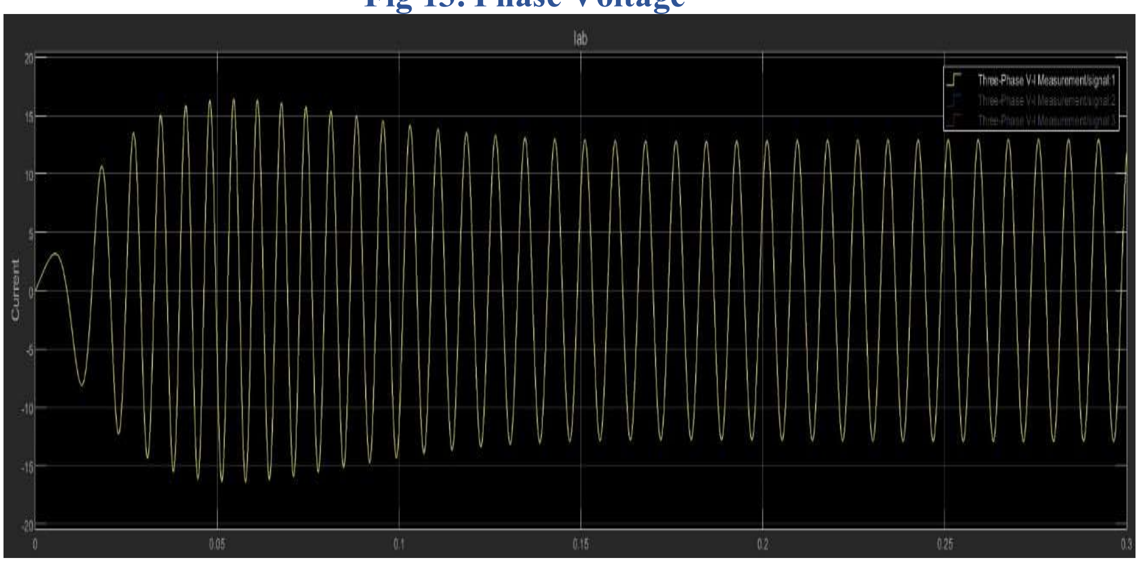


Fig 14. Phase Current

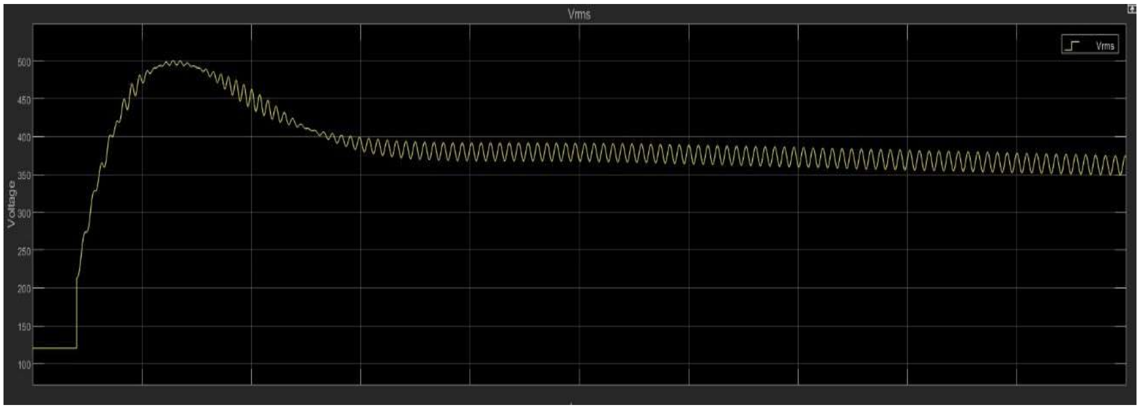


Fig 15. RMS Phase voltage

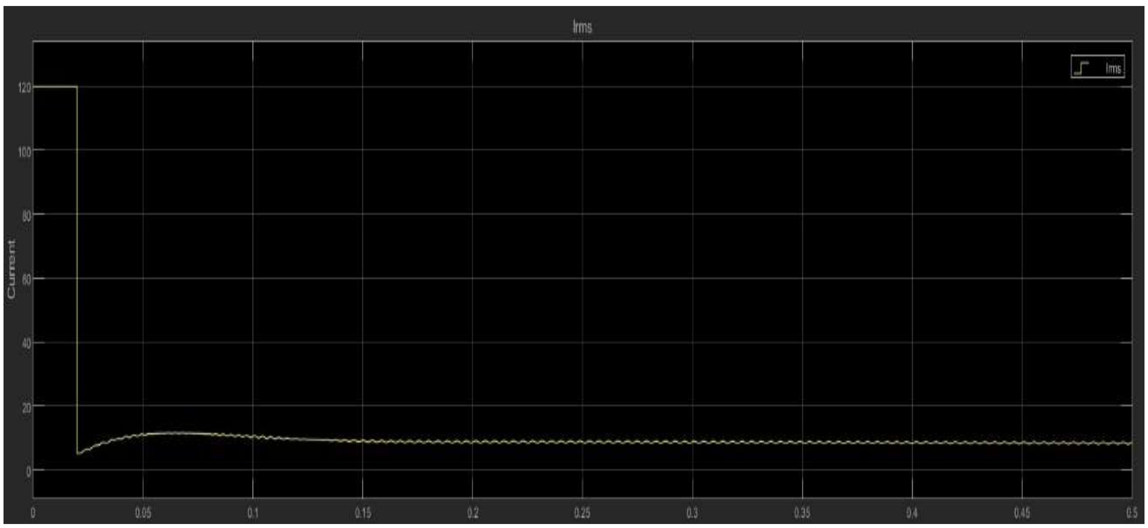


Fig 16. RMS phase current

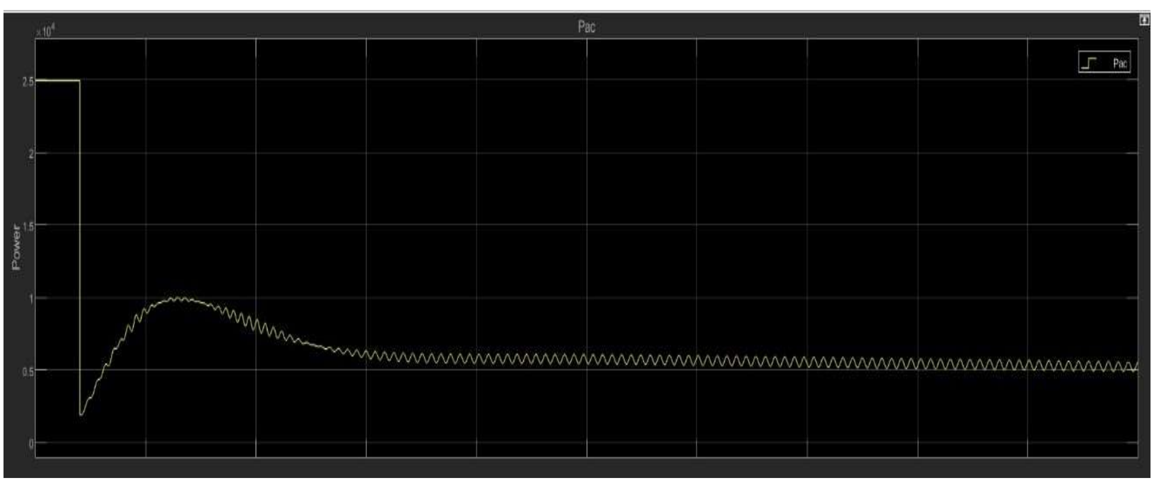


Fig 17. AC Power Output

Three-phase voltage, current, active power, and reactive power are shown in Fig 18, Fig 19, Fig 20, and Fig 21 respectively.

Fig 18. Three-phase Voltage

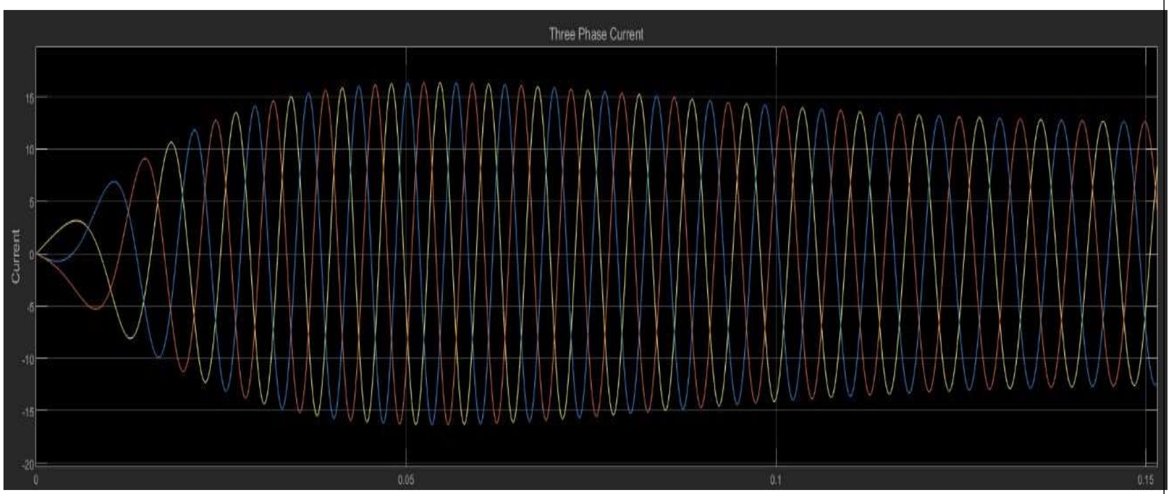


Fig 19. Three-phase Current

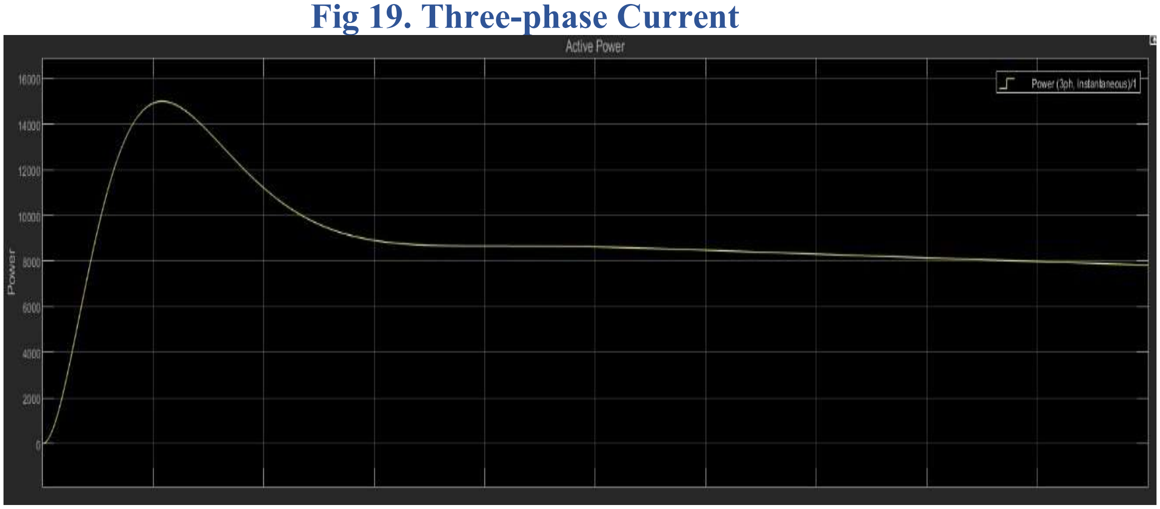


Fig 20. Three-phase Active Power

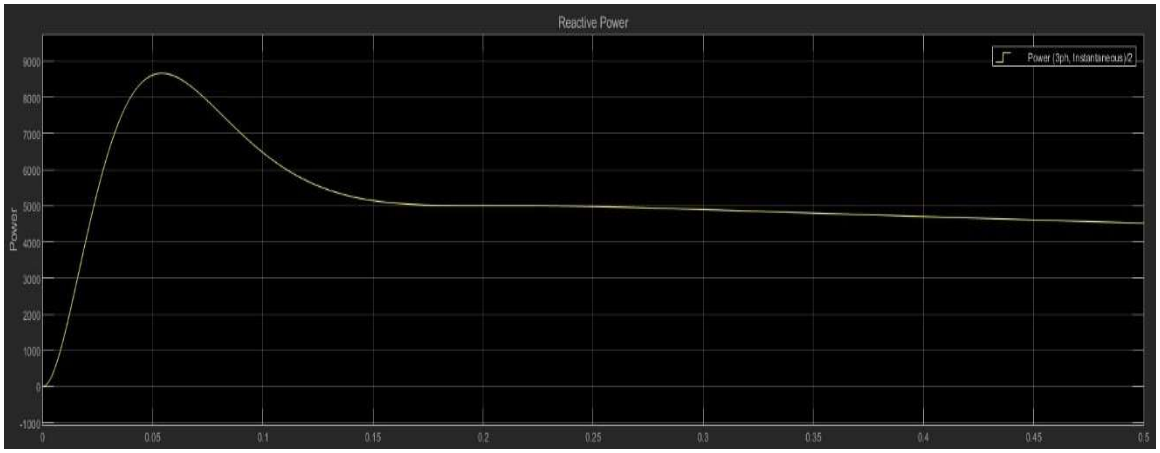


Fig 21. Three-phase Reactive Power

CONCLUSION

This project has established a complete model of PMSG based wind turbine. It consists of a wind turbine, drive train, PMSG, and pitch angle control model. There are two control strategies named pitch angle control and operation control of turbine explained here. The results show that by applying these control methods, system efficiency and reliability can be achieved to a good extent and show the efficiency of the proposed mathematical model to determine the predicted dynamic behaviors such as voltage, current, and power using MATLAB/Simulink environment.

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