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Performance of Intelligent Wind Turbine Pitch Control through PI, PID, and LQR and Hybrid of PI and LQR Controllers

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Abstract-This work focuses on the development and evaluation of wind pitch control techniques for a wind turbine equipped use a PMSG, or permanent magnet synchronizing generator. Optimizing the power is the goal. capture and enhance system stability while minimizing harmonic distortion in the generated electrical power. Four different control strategies are investigated: PMSG-LQR, PMSG-LQR-PID, PMSG-PID, and PMSG-PI. The PMSG-LQR control strategy utilizes the Linear Quadratic Regulator (LQR) to optimize depending on the system, adjust the pitch angle dynamics and control objectives. The PMSG-LQR-PID approach combines LQR utilizing a PID (Proportional-Integral-Derivative) controller to speed up reaction and regulate output. The PMSG-PID technique employs a PID controller as the sole control strategy, while the PMSG-PI approach utilizes an integral-proportional (PI) controller. Simulations are conducted to utilizing a PID controlling (proportional-integral-derivative) to speed up reaction and regulate output, and harmonic distortion. The results show that the PMSG-LQR-PID technique achieves the lowest Total Harmonic Distortion (THD), indicating a cleaner and more stable power output. The PMSG-LQR technique also performs well in terms of THD, while the PMSG-PI technique exhibits a moderate level of distortion. However, the PMSG-PID technique shows a significantly higher THD value, suggesting poorer power quality.

Keywords- *PMSG-LQR,PID, PI ,Wind, Total Harmonic Distortion (THD*

1. Introduction

The fundamental building block of the wind business is the wind turbine, which may use the kinetic energy of the wind to generate power. Wind turbines with a horizontal axis (HAWTs) The two fundamental types of wind turbines are horizontal-axis and vertical-axis turbines. (VAWTs). Typically, HAWTs are bigger than VAWTs and have a greater ability to produce power. they also control the wind energy sector. Modern wind turbines are being erected higher and larger to capture more energy because of the rise in power consumption and the expectations of efficiency from the commercial sector. An illustration, The Nordic N131/ 3300 tower, which was built in Germany, is 164 has a rotor diameter of meters tall. 131 m [1-2]. Due to the wind's capacity to produce design loads that are dominant and significant vibrations, a wind turbine of size is susceptible to damage and failure. In addition to these challenges, the production rate and maintenance costs have a big impact on how the wind energy industry develops. Although onshore and offshore wind turbines use comparable technology, each has a unique benefit, disadvantages, and specialization. A key factor in guaranteeing the efficiency and dependability of wind energy systems is the effectiveness of wind turbine pitch control. The pitch control system alters the angle of the turbine blades for best power collection, turbine safety, and grid stability. As wind energy is being incorporated into the electrical power grid, its effects on frequency and voltage stability are becoming more significant.

The type of control approach used, the properties of the wind turbine rotor, and the variance in wind speeds throughout the rotor blades all have an impact on how well wind turbine pitch control works. By reducing aerodynamic, gravitational, and centrifugal stresses on the rotor blades, effective pitch control can reduce wear, vibration, and deterioration. Additionally, it let the wind to produce as much energy as possible while controlling the production to meet grid requirements. [3-4].

The investigation of and recommendation of various pitch control techniques has enhanced wind turbine performance. These include time-tested model-based control strategies like the linear quadratic regulator (LQR), the proportional-integral-derivative (PID) control approach, and hybrid control strategies that combine the advantages of several control systems.

This study's goal is to assess and contrast the effectiveness of various wind turbine pitch control methods. The analysis of the control techniques and their effects on crucial performance characteristics, such as frequency and voltage stability, power output, efficiency, and the reduction of stresses on the rotor blades, is centered on a mathematical modeling and simulation methodology. This study intends to contribute to the development of more effective and dependable wind

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energy systems by providing information on the performance of various pitch control approaches. The findings can guide the selection of the best control method for certain wind turbine layouts and operational circumstances, improving power production, lowering maintenance costs, and better integrating wind energy into the grid [5].

The control techniques investigated in this study include:

PMSG-LQR: Utilizing the Linear Quadratic Regulator (LQR) control strategy, which optimizes the pitch angle control based on system dynamics and control objectives.

PMSG-LQR-PID: A hybrid approach combining the LQR control strategy in conjunction with a Proportional-Integral-Derivative (PID) controller, aiming to improve response time and overall control performance.

PMSG-PID: Using a PID controller as the sole method of controlling pitch angle.

PMSG-PI: Employing Pitch angle control using a Proportional-Integral (PI) controller, providing steady-state accuracy and robustness.

Wind turbines are necessary for converting wind power into electrical energy, and wind energy is a sustainable energy source that is growing swiftly. As Effective control techniques are more crucial as wind turbines grow more common in the electrical power system. The pitch control system, which modifies the angle of the turbine blades to maximize power extraction and reduce loads, is a crucial component of wind turbine management.[9]

Problem Scope:

This study's objective is to develop and evaluate wind turbines using a Permanent Magnet Synchronous Motor wind pitch control technologies. Generator. (PMSG). The specific problem is to determine the most effective control strategy that maximizes power output, ensures system stability, and minimizes harmonic distortion in the generated electrical power.

Motivation:

There are several motivations for conducting this research. Firstly, optimizing the pitch control system is essential for maximizing power capture from the wind and improving the overall efficiency of wind turbines. Secondly, maintaining grid stability is crucial when wind energy becomes more integrated into the electricity system. The power output may be controlled and wind-related fluctuations can be lessened with good pitch control. Thirdly, it's crucial to lessen harmonic distortion in electrical power generation to maintain good power quality and lessen the impact on the grid and linked loads.

This research intends to develop wind pitch control methods and their use in PMSG-based wind turbines by overcoming these difficulties. The results may be used to enhance system stability, power capture efficiency, control strategy optimization, and high-quality power generation. In the end, this study aids in the creation of wind energy systems that are more dependable, effective, and sustainable.

2. Literature Review

Recall that altering the generator's speed and the pitch of its blades are the greatest ways to alter output strength. To modify turbine performance along the power curve, the following control strategies use pitch and generator speed control: Fixed speed, variable speed, fixed speed variations, and fixed speed are the four types of pitch. The power curves for each of the control techniques displayed in Figure 9 are provided below. Considering a variable-speed, variable-pitch power curve is ideal, or VS-VP [10]

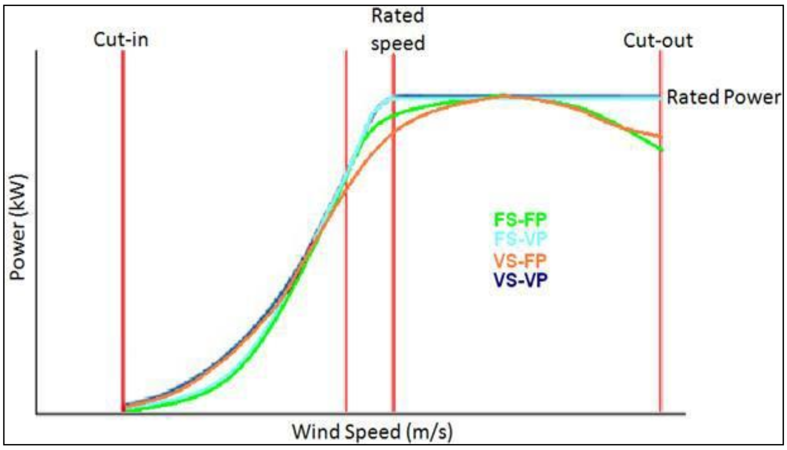

Fig 1 shows the power curves for several control strategies. The optimal curve is VS-VP, or variable-speed variable-pitch.

Fixed-speed Fixed-pitch (FS-FP), when active control is ineffective in enhancing performance. In this configuration, the generator of the turbine is directly connected to the electrical grid, locking its speed to the frequency of the power line. These turbines are managed using passive stall approaches at high wind speeds. It does this because it ensures that the rated power is not exceeded when the real power and the ideal power are clearly different, indicating a slower rate of energy buildup, the gearbox ratio for this passive control must be carefully tuned. Please be aware that the turbine only operates at peak efficiency in the low-speed sector at one wind speed. Only one wind speed is required for the turbine to produce its rated output. The forbidden actions reveal a lack of effective power control.

Variable-speed fixed-pitch (VS-FP) Using electronic power The design continually adjusts the rotor speed to match the wind speed in order to regulate the generator's synchronous speed. This sort of control shows how linked to the grid the generator is by enabling the rotor and powertrain to revolve freely without the grid frequency interfering. The fixed-pitch's reliance on passive stalling to reduce power is significantly influenced by the blade's design. [11-12].

Table 1 characteristics of non-linear control methods

Strategy	Advantage	Disadvantage
regulating the sliding mode	providing a steady dynamic strength in the event that the turbine's performance is unclear characteristics - ensuring appropriate consistency between efficiency changes and torque variations	Need for wind data; Dependence on mathematical model of wind turbine When governing parameters are suddenly changed, the turbine is under high pressure, which has a high chattering impact.
Integrated Control Approach	An appropriate output power level that maintains Rotor speed that is constant	providing a steady dynamic strength in the event that the turbine's performance is unclear
Control with a linear quadratic Gaussian equation	Unknown non-linear systems: Control using linear feedback Gain margin and phase margin are improved for rotor speed estimation.	Limited controller performance as a result of nonlinear features on the wind turbine's top a poor track record as an automated optimizer
Recognizing the Uncertainties	Without the use of wind, air density, and Cp level data, the maximum active power may be set and obtained.	Mechanical parameter modeling is challenging.
Fuzzy	Lack of reliance on parameter adjustments when noisy signals are present High simplicity and efficiency - Earn more power because the blade angle isn't as important	difficulty in modifying the membership functions and weighting coefficients with the proper system controls An online optimizer is required in windy regions for setting the settings in their terms.

3. Proposed Work

The mechanism that regulates the generators with permanent magnets pitch angle (PMSG) is suggested. For the purpose of maximizing power output and optimizing pitch angle, a mix of linear quadratic regulator (LQR) and PI controllers will be employed. In order to evaluate how well PI, PID, and LQR controllers regulate the pitch angle, their performance will also be compared.

The primary goal of the pitch the rotor blade angles are adjusted by the angle control system. to increase power production in accordance with the present wind speed. The gadget may maximize the quantity of power that can be produced from the wind by adjusting the pitch angle. The hybrid controller combines the LQR and PI techniques to fully utilize the advantages of each approach when used alone. In order to determine the best possible control signal that minimizes a specified cost function, the LQR controller employs optimization techniques. It takes system dynamics, control objectives, and restrictions into account. The LQR controller is extremely helpful for linear systems. On the other side, the PI controller provides dependability and steady-state accuracy. By combining the two controllers, steady-state performance, and transient response, the hybrid approach aims to provide the optimum transient response and disturbance rejection.

Numerous metrics will be monitored and analyzed in order to assess the efficacy Pitch Angle Control System. Real power, efficiency, voltage, and current are some of these factors. Similarly, reactive power Voltage and current measurements show the system's electrical characteristics, while efficiency assesses how successfully the system converts wind energy into electrical power. Measuring the real and reactive powers makes it simpler to quantify the real and Interaction between the grid and reactive power. In the recommended system, the wind speed may be manually changed. This makes it possible to assess the control approaches' ability to adapt to and maximize power production under diverse wind conditions.

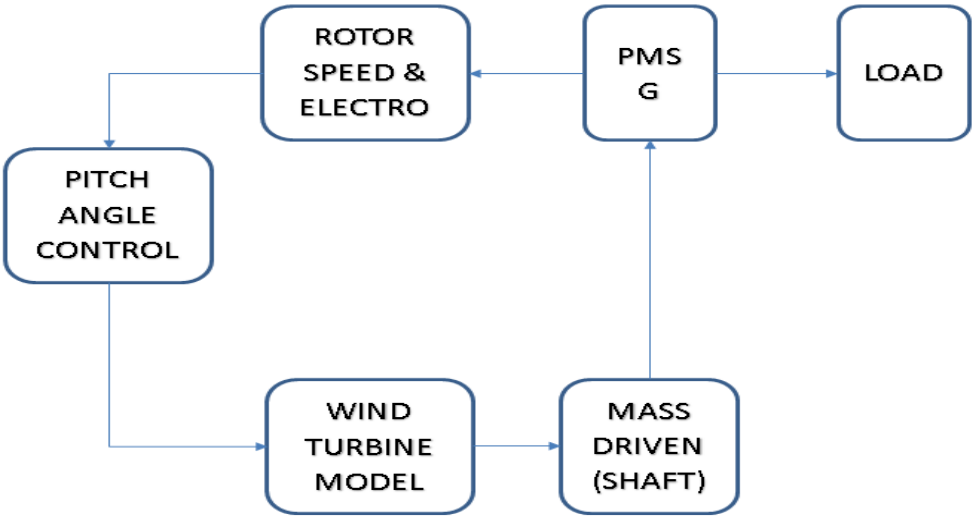

Fig.2 Proposed Block Diagram

PMSG-LQR-PID: A proportional-integral-derivative approach is used in this technique. (PID) controller with the LQR control technique. The derivative term that the PID controller adds to the control signal accounts for the error's rate of change. Through this combination, the reaction time, oscillation damping, and overall control performance are all intended to be improved.

PMSG-PI: For pitch angle control, this method employs a proportional-integral (PI) controller. The PI controller generates the control signal by integrating the error over time and adjusting the pitch angle in response to the error. It offers resilience and steady-state precision for adjusting pitch angle.

A-PMSG –LQR Modeling

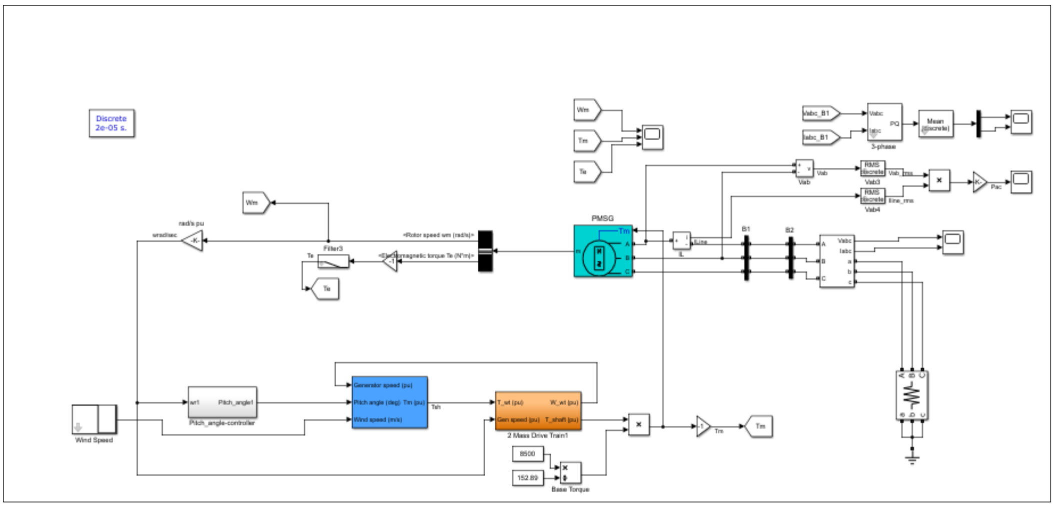

Fig.3 Wind Pitch Control Techniques Based On PMSG –LQR

Permanent Magnet Synchronous Machine

Resistance in each phase of the PMSG is represented by the stator phase resistance, or Rs. The value in this instance is 0.425 ohms. The PMSG's direct and quadrature axis inductances are represented by the inductances Ld and Lq. The values are reported as 0.0082 Henry for both inductances. The flux linkage is a representation of the PMSG's magnetic flux connection. The value in this instance is stated as 0.433. The mechanical characteristics of the wind turbine system are described by the parameters inertia, viscous damping, pole pairs, and static friction (J, F, p, Tf).Inertia (J): Its value is 0.01197 kg.m2, and it denotes the moment of inertia of the wind turbine rotor.

Viscous damping (F): A graph illustrating the viscous damping coefficient as 0.001189 N.m.s.[13-14]

PMSG Model Equations:

The electrical and mechanical equations below can be used to simulate the PMSG:

Electrical Equations:

Stator Voltage Equations:

$Vsd = Rs * Isd - \omega r * Lq * Isq + \omega r * \lambda d$

$Vsq = Rs * Isq + \omega r * Ld * Isd + \omega r * \lambda q$

Mechanical Equations:

Mechanical Torque Equation:

$Te = 3/2 * p * (\lambda d * Isq - \lambda q * Isd)$

$Tm = J * d\omega r/dt + B * \omega r + Tf$

Linear Quadratic Regulator (LQR) Control:

The LQR control technique uses a state feedback control law to regulate the pitch angle based on system dynamics. The control law is designed to minimize a quadratic cost function that captures control objectives and performance requirements. The state feedback control law is given by:

u(t) = -K * x(t) Eq.1

State Space Model:

By combining the PMSG model equations and the LQR control law, a state space model can be derived. The state space model is represented as:

dx(t)/dt = Ax(t) + Bu(t) Eq.2

y(t) = Cx(t) Eq.3

A, B, and C are matrices that represent the system dynamics. The specific form of the A, B, and C matrices will depend on the chosen PMSG model and the control objectives. By formulating the PMSG-LQR control system using these mathematical modeling equations, it is possible to analyze and design the control strategy, tune the LQR gain matrix, and simulate the behavior of the wind pitch control system.[15] This enables the evaluation and optimization of the system's performance in terms of pitch angle regulation, power extraction, and response to different operating conditions.

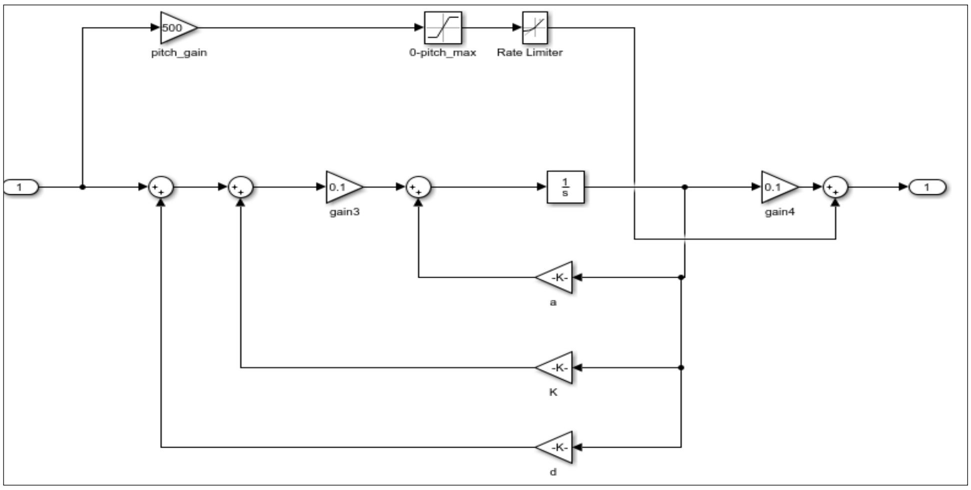

Fig.4 LQR subsystem

The LQR (Linear Quadratic Regulator) subsystem is a key component of the wind pitch control system based on PMSG-LQR. It is responsible for generating the control signal (pitch angle command) based on the system states and desired control objectives. Here, I'll explain the components and equations involved in the LQR subsystem.

State Vector:

The state vector represents the system states that are used for feedback control. The specific states included in the vector will depend on the chosen PMSG model and the control objectives. Common states in a PMSG-LQR system may include rotor speed, flux linkages, and current components.

x(t) = [x1(t), x2(t), ..., xn(t)]^T Eq.4

Control Input: The control input is the desired output of the LQR subsystem, which is the pitch angle command. It determines the angle at which the wind turbine blades should be positioned to achieve the desired control objectives.

$u(t)$ = pitch angle command

State Feedback Control Law:

The LQR control law employs state feedback to generate the control input. The control law is designed to minimize a quadratic cost function that captures control objectives and performance requirements. The state feedback control law is given by:

$u(t) = -K * x(t)$ Eq.5

Here, K is the system model's state feedback gain matrix, which is computed based on the intended control goals. Because it makes a connection between the system states and the control input, the gain matrix is crucial for managing the pitch angle.

Quadratic Cost Function:

The control technique minimizes a quadratic cost function to get the LQR Optimal control performance. Typically, the cost function requires the following form:

$J = \int [x(t)^T * Q * x(t) + u(t)^T * R * u(t)]\, dt$ Eq.6

Here, Q is the control input weighting matrix, while R is the state weighting matrix. These matrices are chosen to assign the states and control input the appropriate weights based on their respective importance to the control objectives.. The LQR method enhances the control law by altering the state feedback gain matrix (K) to minimize the cost function. The ideal gain matrix for the stated system model and cost function weights is created by solving the algebraic Rickety problem.[17]

Simulation Result PMSG –LQR

A numerical simulation or software tool created especially for wind turbine modeling and control can be used to acquire simulation results for the PMSG-LQR wind pitch control system. These tools make it possible to simulate the PMSG model and use the LQR control method a number of inputs and parameters, including wind speed, beginning circumstances, control Before the simulation may start, gains and desired control objectives must be defined. The simulation tool will then calculate the system response, which will also result in some interesting output variables.

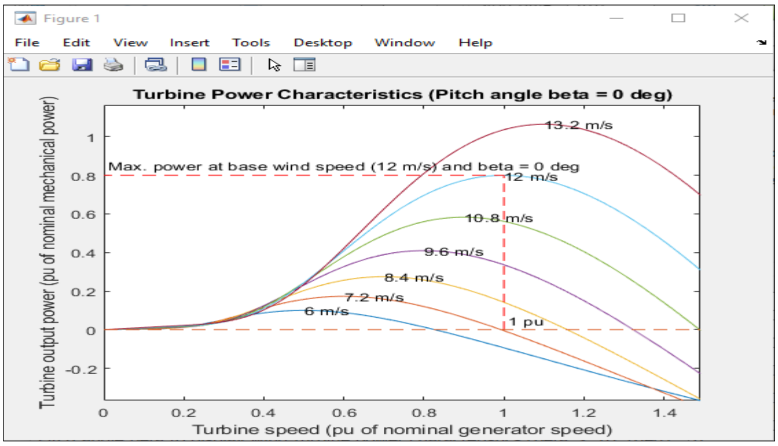

Fig.5 turbine power characteristics

At its quickest, the pitch angle may shift by three to ten degrees every second. The speed of the rotor may be increased somewhat from its default speed thanks to the pitch angle controller. The wind turbine's construction is unaffected in any way by this. The amount of power the rotor receives from the wind may be directly controlled via pitch actuators at the tips of the blades. The pitch angle will be close to 45 degrees when the wind speed is very low and the rotor rotates very slowly or not at all. This will provide the rotor with the greatest starting moment, enabling it to accelerate more quickly as the wind speed increases. The controller will then rotate the blades such that they point in the direction that is opposed to the direction of the wind. To come closer to the nominal speed, the rotor and generator will accelerate, and the controller will use speed control to try to maintain stability. The generator will be disconnected from the grid and the controller will take over speed management when the wind speed drops below a certain threshold and the quantity of electricity generated turns negative.

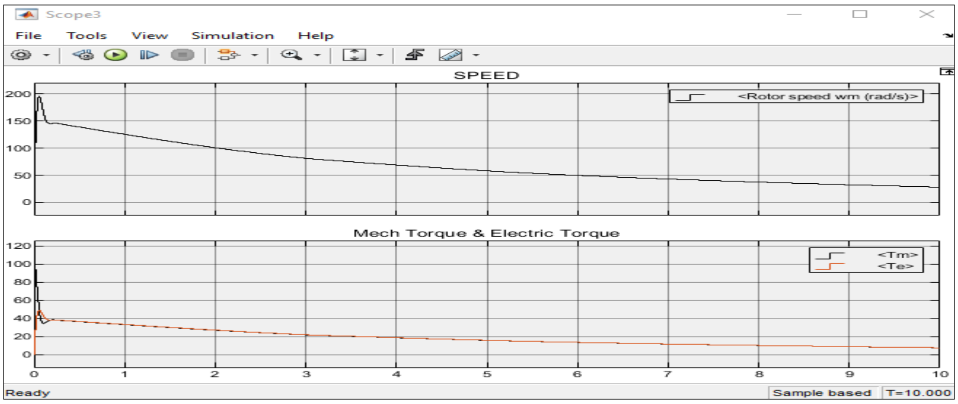

Fig.6 rotor speed and mechanical and electrical torque

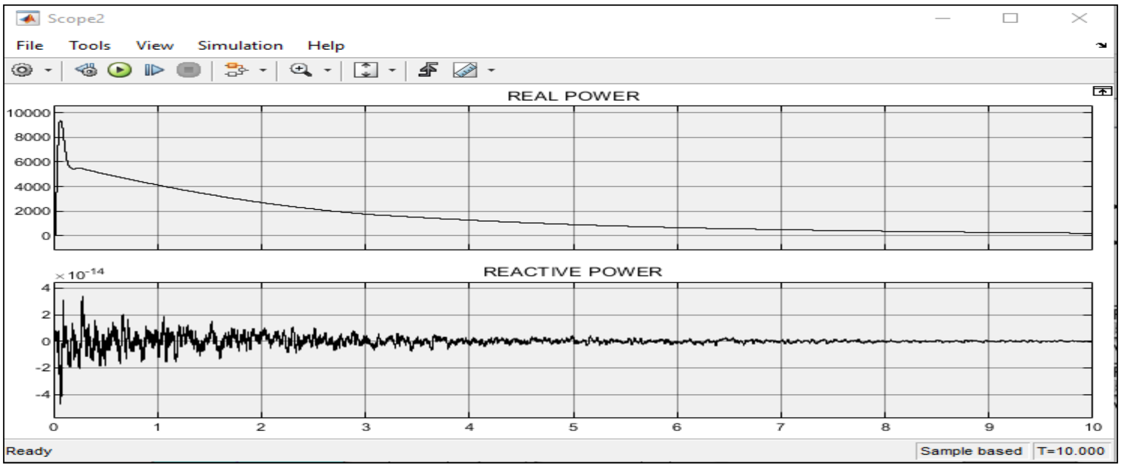

Fig.7 real and reactive power

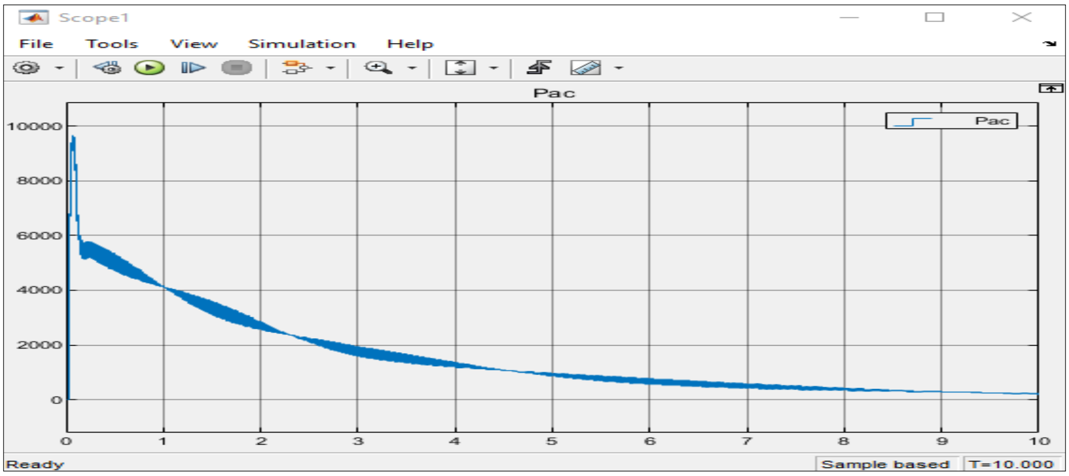

Fig.8 Pac RMS power

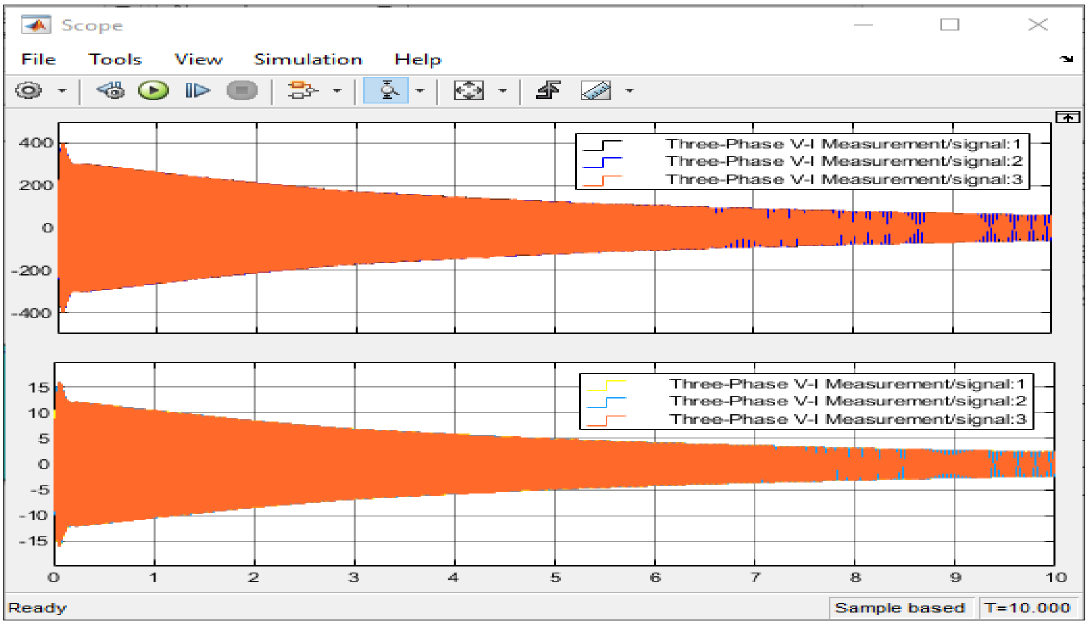

Fig.9 three phased voltage and current of P MSG generator

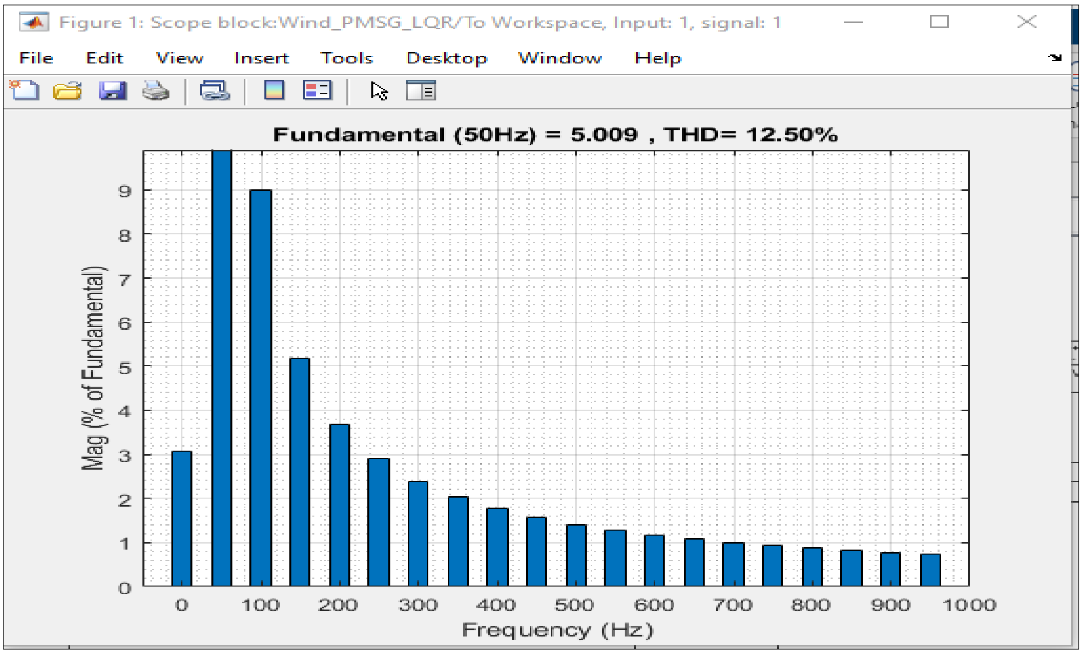

Fig. 10 THD performance of PMSG –LQR

B-PMSG –LQR-PID Modeling

The LQR controller and PID controller are integrated to provide a hybrid control technique in the PMSG-LQR-PID control system. In order to get the best pitch angle control performance, the LQR controller primarily controls quick dynamics. On the other hand, the PID controller concentrates on fine-tuning the control signal to increase the system's responsiveness and resilience.

LQR-PID hybrid control system - The LQR controller serves as the primary controller in a LQR-PID hybrid control system, while the PID controller serves as a secondary controller to offer extra control action. This hybrid technique attempts to improve the performance and resilience of the wind pitch control system. The particular implementation details, including the tuning of the LQR and PID parameters, will rely on the system dynamics, control objectives, and performance requirements. I'll give the mathematical formulation for the hybrid PMSG-LQR-PID control system here.

PMSG Model Equations: The electrical and mechanical dynamics of the PMSG are described by the equations for the PMSG model. These equations match those from the PMSG-LQR control system that were previously discussed.

LQR Control: The LQR A state feedback control law is provided by control component [18] to control the pitch angle in accordance with system states. The control input is determined as follows: $u_{LQR}(t) = -K * x(t)$ Eq.7

Here, K is the state feedback gain matrix, x(t) is the system state vector, and $u_{LQR}(t)$ is the control input from the LQR controller.

PID Control: Based on the discrepancy between the target pitch angle and the actual pitch angle, the PID control component is employed to further refine the control input. The PID controller receives its control input from: $u_{PID}(t) = Kp * e(t) + Ki * \int e(t)\, dt + Kd * de(t)/dt$ Eq.8

Here, $u_{PID}(t)$, The control input from the PID controller is the proportional, integral, and derivative gains, denoted by the letters Kp, Ki, and Kd, respectively. Pitch angle error is a measurement of the discrepancy between the desired and actual pitch angles, and it is quantified by the ratio. e(t)/dt.

Hybrid Control: The LQR and PID The hybrid control system combines the control inputs from the controllers. The final control input is obtained by linearly combining the LQR and PID control inputs. u(t): $u(t) = u_{LQR}(t) + u_{PID}(t)$ Eq.9

It is possible to alter the pitch angle of the wind turbine blades. using this hybrid control input. The PMSG-LQR-PID hybrid control system can produce improved control performance by merging the LQR and PID control components. The PID component enhances tracking of the intended pitch angle and corrects for any steady-state mistake, while the LQR component offers optimum control based on system states.

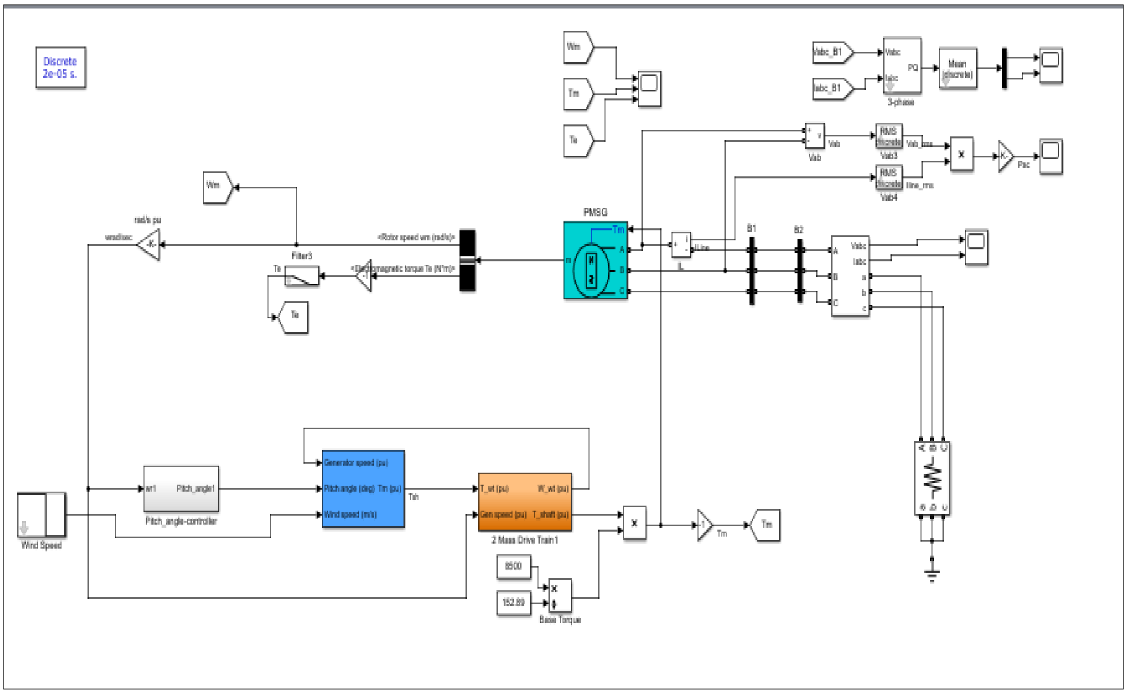

Fig.11 Wind Pitch Control Techniques Based On PMSG –LQR-PID

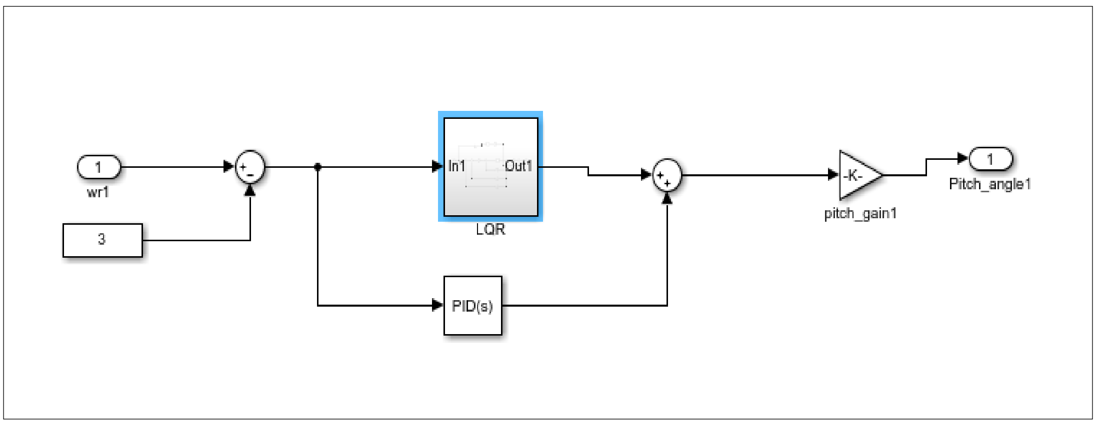

Fig.12 LQR and PID Subsystem

Figure 12 demonstrates the common PID used in the Simulink model of the wind turbine pitch control system. Figure 11 displays the PID controller's control parameters. We built a mathematical model of the wind turbine pitch control system and used MATLAB/Simulink and a PID controller to simulate it in order to get the best response.

This block implements both continuous and discrete time PID control techniques and includes complex features like signal tracking, external reset, and anti-windup. The "Tune..." button on the PID allows gains to be automatically modified (Simulink Control Design is required). [20

Simulation Result PMSG –LQR-PID

The simulation will demonstrate how the pitch angle responds to variations in wind speed and the intended control goals. It will show how the PMSG-LQR-PID control system modifies the pitch angle to manage the power output and obtain the required performance.

Fig.13 rotor speed and mechanical and electrical torque

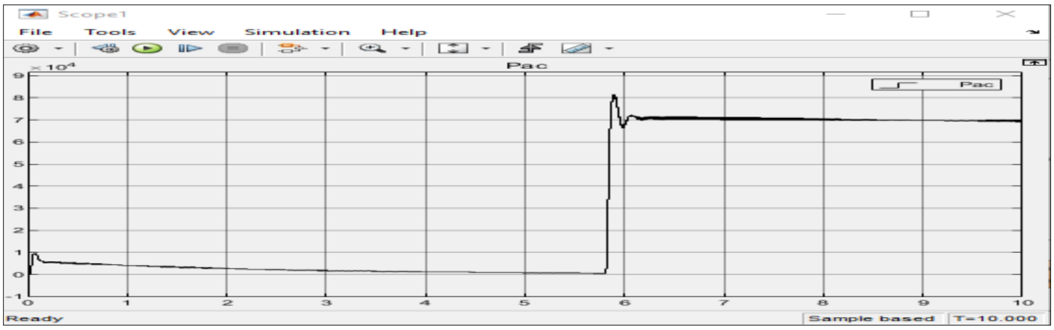

Fig.14 Pac RMS power

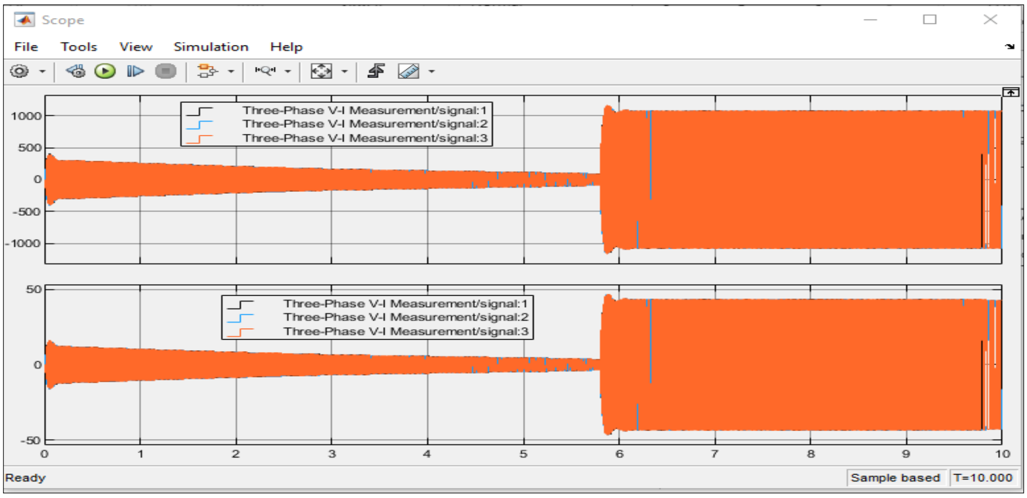

Fig.15 three phased voltage and current of PMSG generator

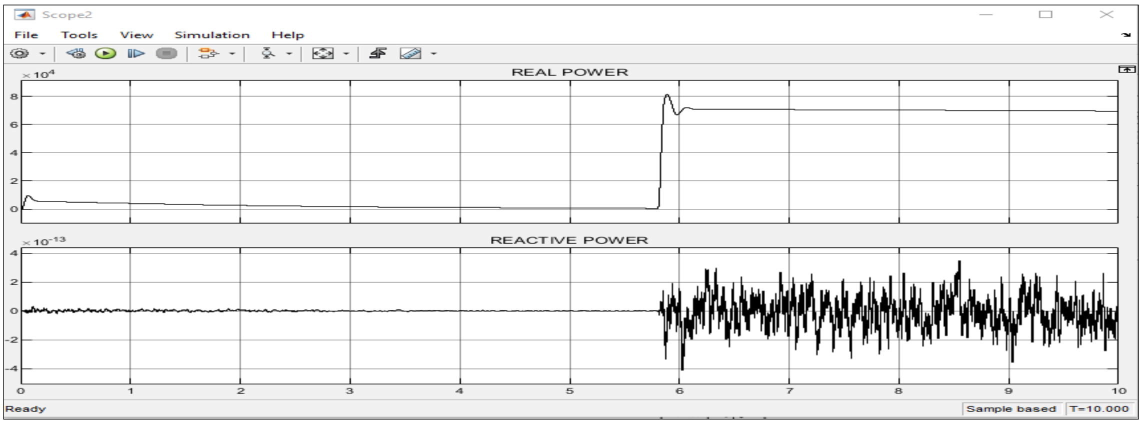

Fig.16 real and reactive power

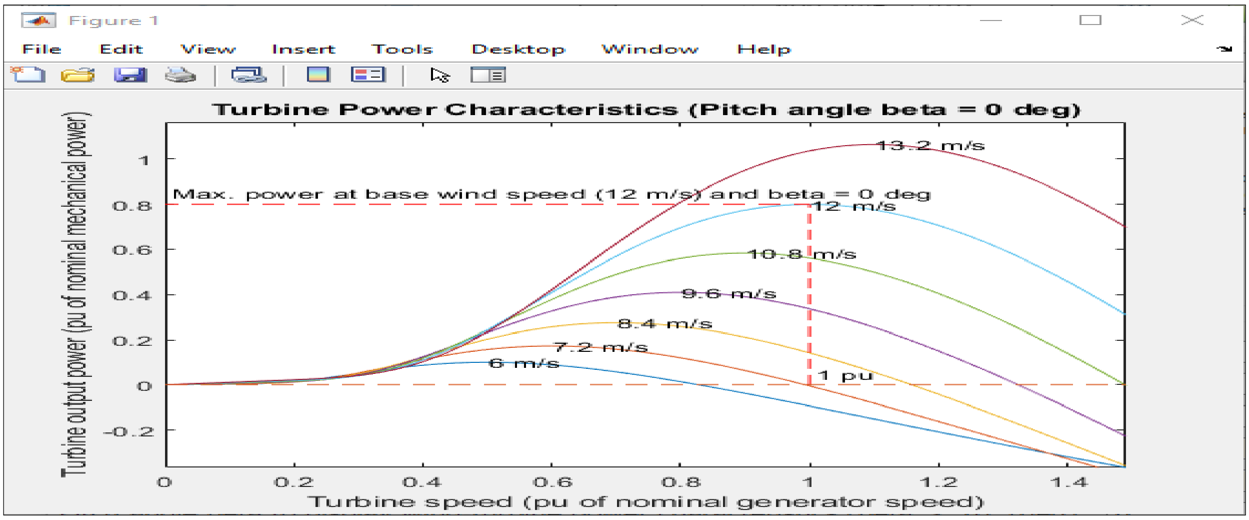

Fig.17 turbine power characteristics

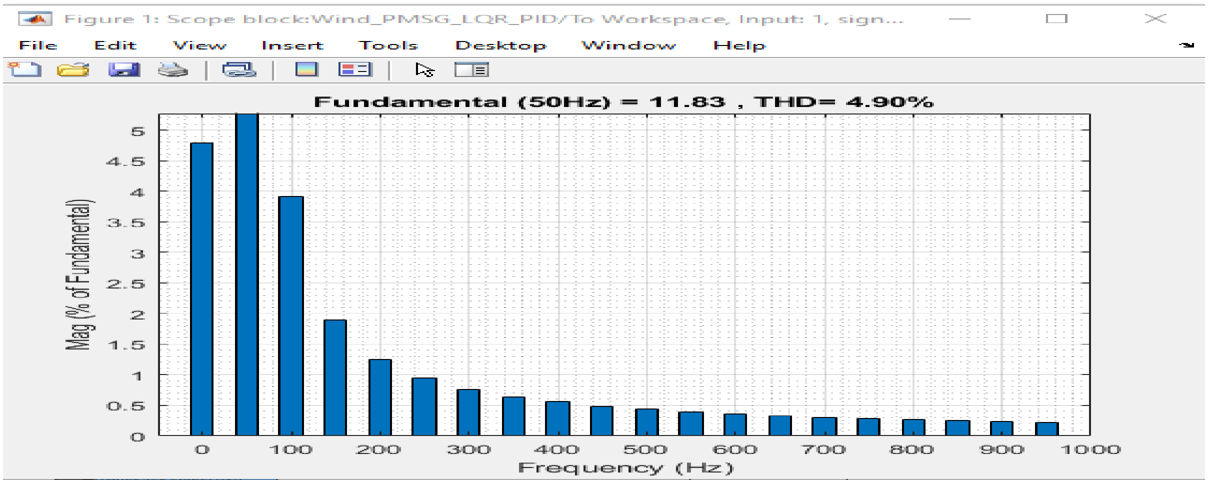

Fig. 18 THD performance of PMSG –LQR-PID

C-PMSG –PI Modeling

The PMSG-PI (Proportional-Integral) control system, which is based on a PMSG, regulates the pitch angle of a wind turbine using a PI controller. If the anticipated pitch angle and the actual pitch angle differ from one other, the PI controller adjusts the pitch angle accordingly. Here is a schematic of the mathematical model for the PMSG-PI control system.

Pitch Angle Control:

The pitch angle control system adjusts the wind turbine blade angles to maximize power output and ensure steady operation. The aerodynamic forces acting on the blades are controlled by the pitch angle, which also affects how much power is produced by the turbine. The pitch angle is controlled by a PI controller in the PMSG-PI control system.

Error Calculation:

The difference between the expected pitch angle, or set point, and the actual pitch angle is how the control algorithm determines the error:

e(t) = desired pitch angle - actual pitch angle

PI Control Law:

The PI controller decides the control signal to use in accordance with the error signal. The input under control is the sum of the integral and proportional terms.. $u(t) = Kp * e(t) + Ki * \int e(t)\,dt$ Eq.10 In this case, Kp is the proportional gain, Ki is the integral gain, and u(t) is the control input (instruction to adjust the pitch angle). The proportional term, Kp * e(t), reacts promptly to the mistake, but the integral component, Ki * e(t) dt, eliminates steady-state error and provides long-term control.

Pitch Angle Adjustment: The PI controller's control input may be used to modify the pitch angle of the wind turbine blades. The control system continuously computes the control signal based on the error and adjusts the pitch angle as necessary to maintain the correct performance. in order to successfully achieve desired control goals, such power optimization and system stability, the PMSG-PI The wind turbine's pitch angle can be successfully controlled by the control system. The gains (Kp and Ki) of the PI controller must be precisely tuned while taking into consideration the special characteristics and control requirements of wind turbines in order to achieve optimal performance.[21-23]

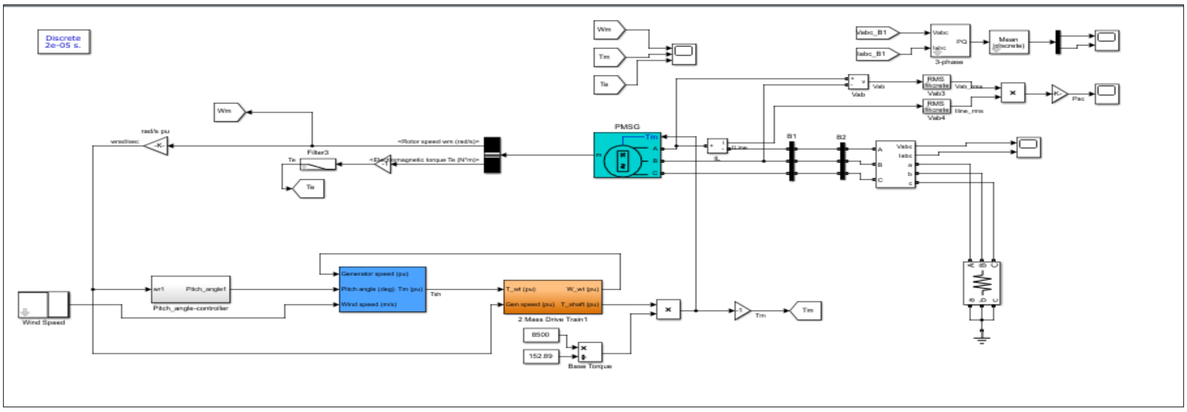

Fig.19 Wind Pitch Control Techniques Based On PMSG -PI

Proportional Integral (PI) Controller

Proportional In certain situations, Integral controllers are sometimes known as proportional plus integral (PI) controllers. This sort of controller is produced by fusing proportional control action and integral control action. As a result, we call it the PI controller. The proportional-integral controller makes use of both the integral controller's and proportional controller's control actions. The two distinct controllers together provide a superior controller without the drawbacks of the two individual controllers.

Simulation Results and Analysis of PMSG -PI

The simulation will demonstrate how the pitch angle responds to adjustments in the wind speed and control instructions. It will show how the PMSG-PI control system modifies the pitch angle in order to manage the power output and achieve the required performance. Both the pitch angle's transitory beginning behavior and its steady-state behavior will be included in the response.

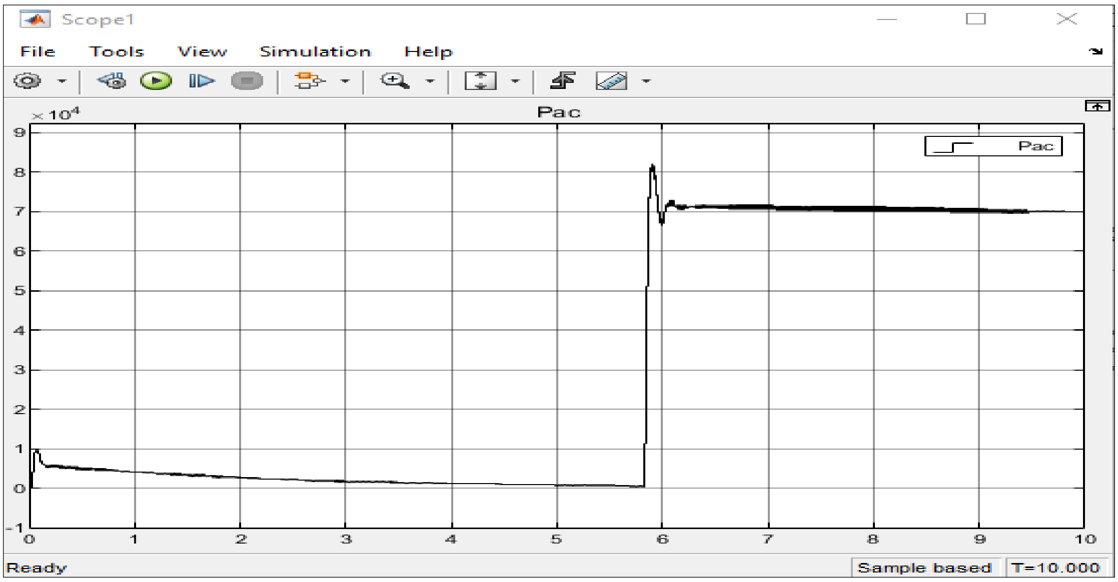

Fig.20 Pac RMS power

Obtain the instantaneous power values: Measure or calculate the instantaneous power generated by the wind turbine at each time step. This can be done by multiplying the wind turbine's voltage and current values

Mathematically, the calculation of RMS power (Pac) can be expressed as:

Pac = sqrt((1/N) * Σ(P^2)) Eq.11

Where:

Pac: RMS power (average power)

N: Total number of data points or time steps

Σ: Summation symbol

P: Instantaneous power value at each time step

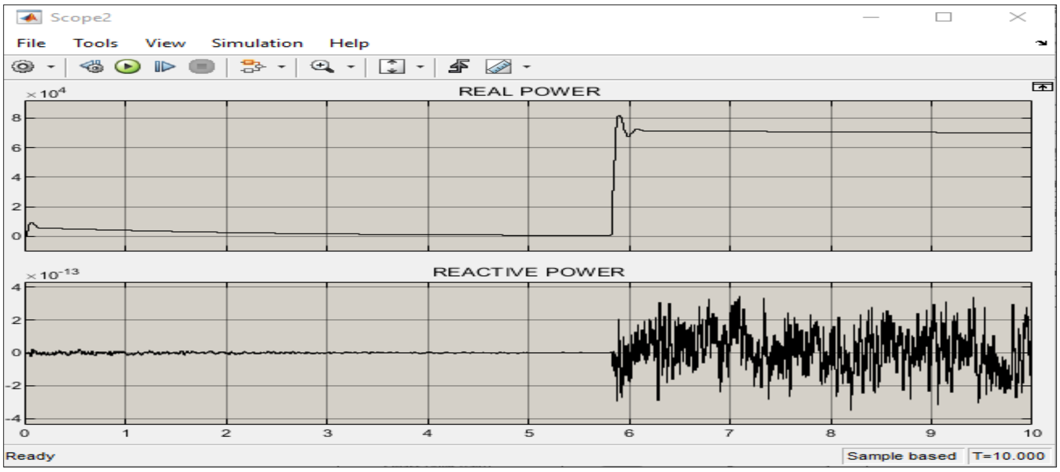

Fig.21 real and reactive power

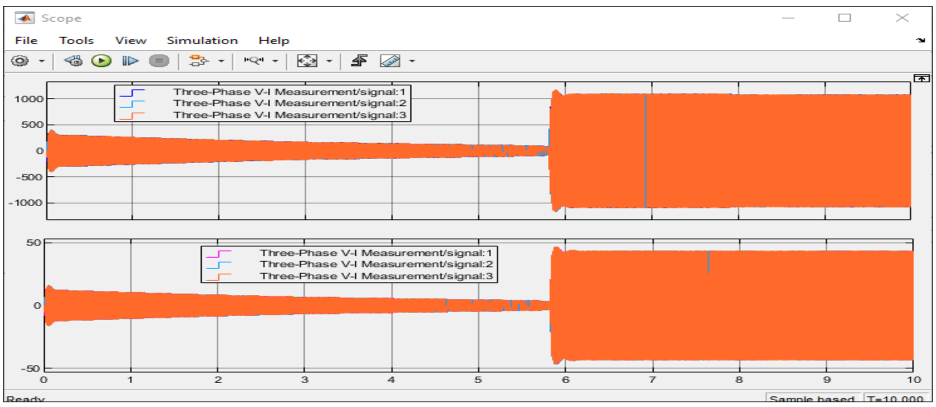

Fig.22 three phased voltage and current of PMSG generator

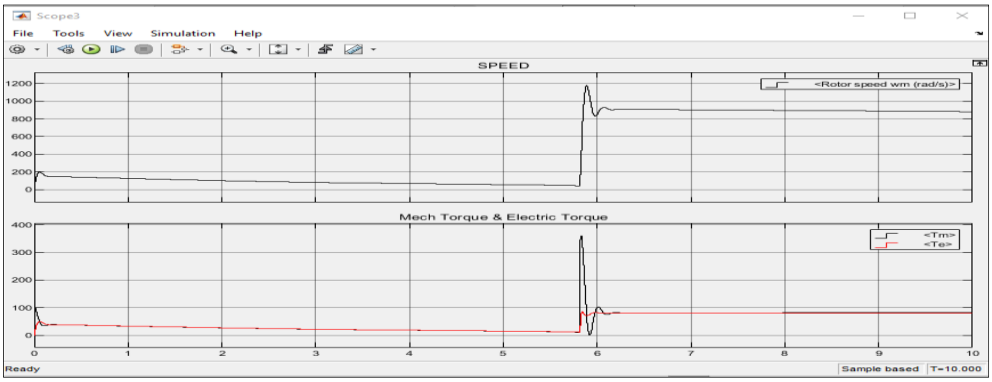

Fig.23 rotor speed and mechanical and electrical torque

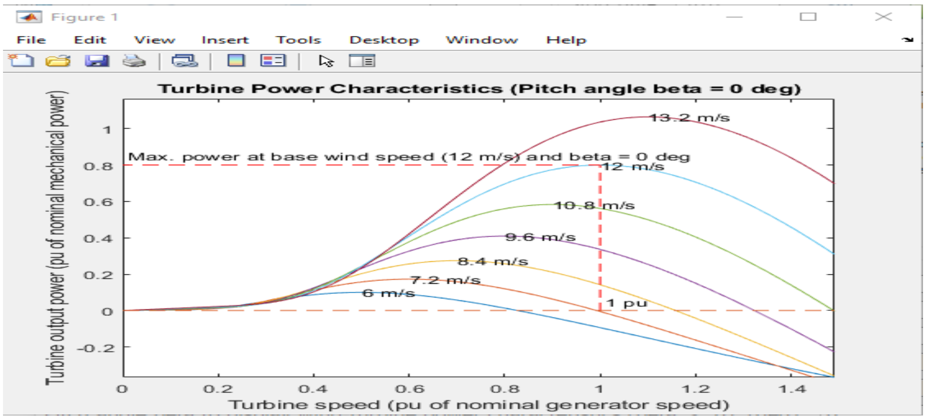

Fig.24 turbine power characteristics

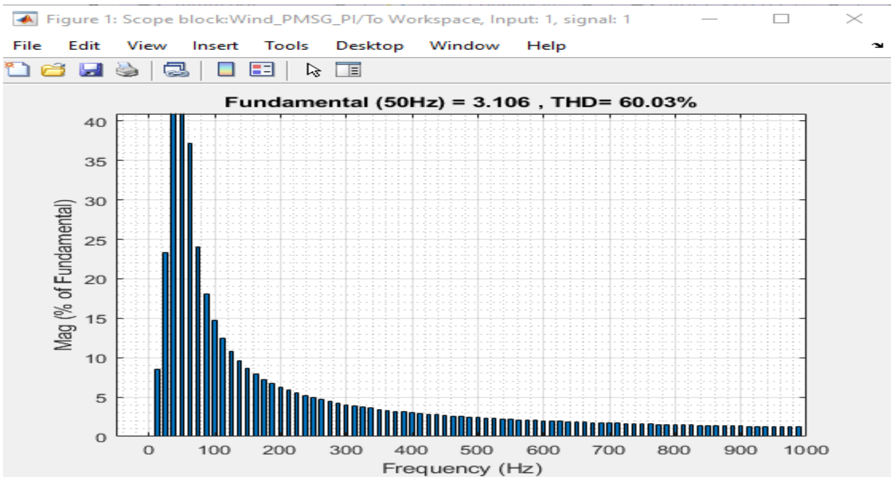

Fig. 25 THD performance of PMSG -PI

D-PMSG –PID Modeling

PID is utilized on the pitch angle controller to regulate the wind turbine's speed. The FA technique (PMSG) is used to adjust the control speed in wind turbines using permanent magnet synchronous generators. The speed control system must be able to maintain the ship's motion at the same speed when the wind speed is below average. Then it will exert all of its power, which will improve the efficiency of the turbine the pitch angle needs to be adjusted when the wind speed is higher than desired. Power output may be significantly impacted by even a little variation in pitch angle. When the wind speed is greater than the on speed, one approach to alter the aerodynamic thrust of a wind turbine is to alter the pitch angle.

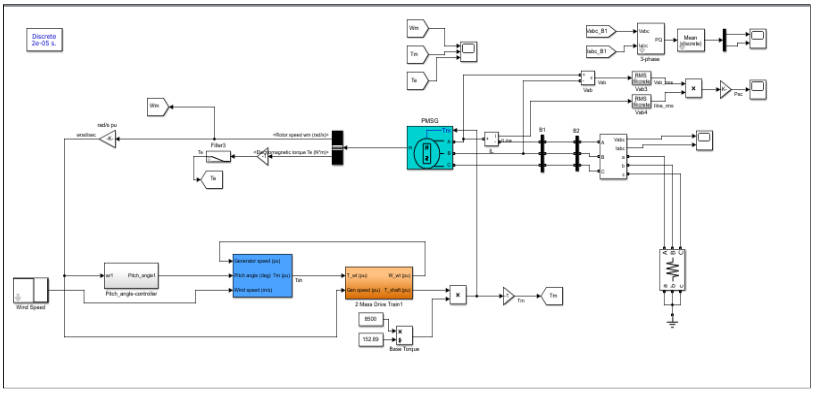

Fig.26 Wind Pitch Control Techniques Based On PMSG –LQR-PID

Simulation Results and Analysis of PMSG –PI

To obtain simulation results for the PMSG-PI wind pitch control system, a numerical simulation or software tool capable of modeling the system dynamics and implementing the PI control algorithm is required.

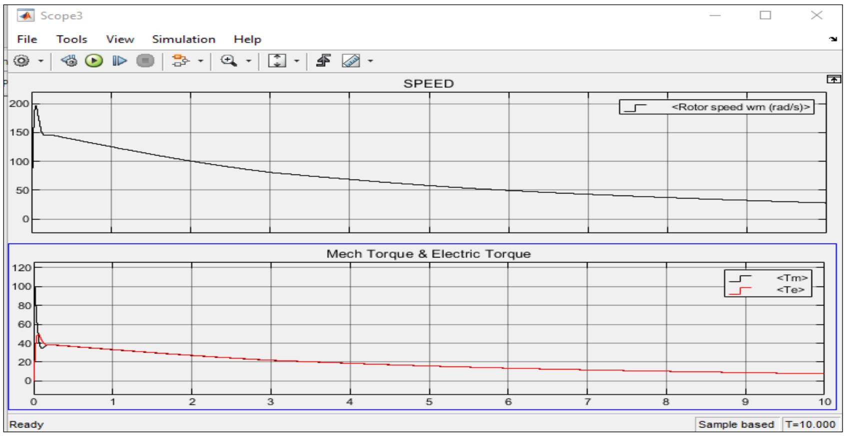

Fig.27 rotor speed and mechanical and electrical torque

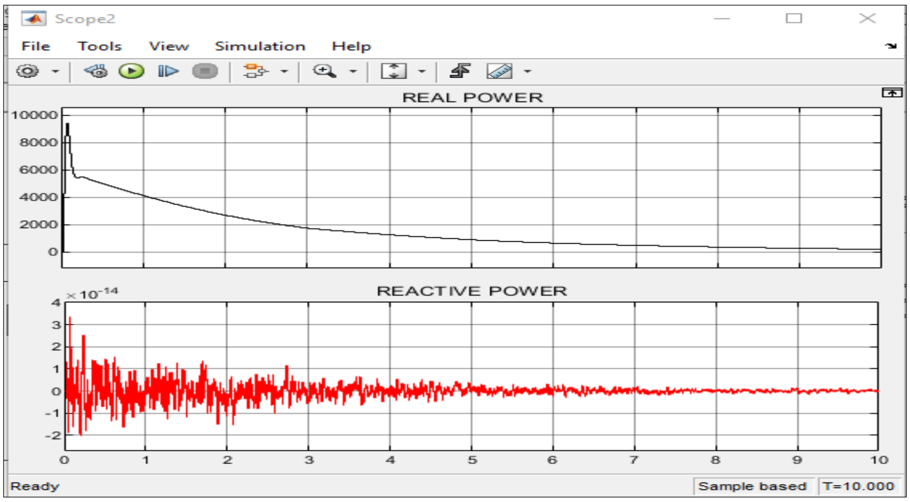

Fig.28 real and reactive power

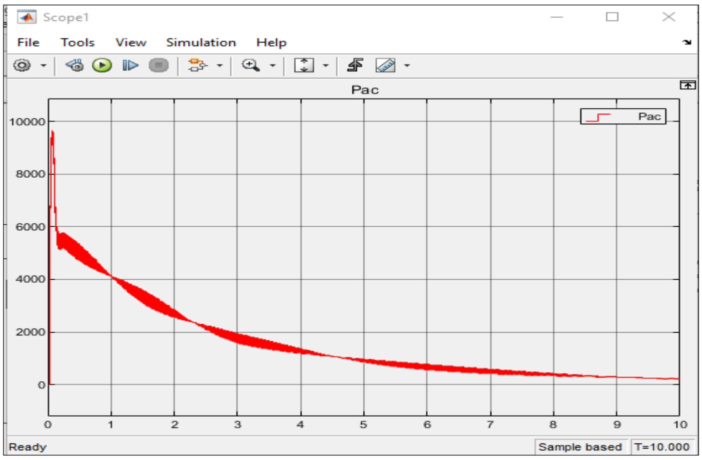

Fig.29 Pac RMS power

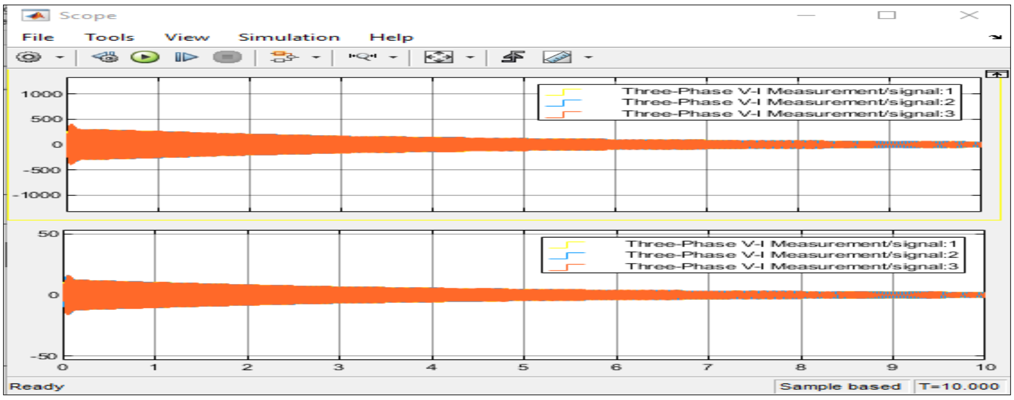

Fig.30 three phased voltage and current of PMSG generator

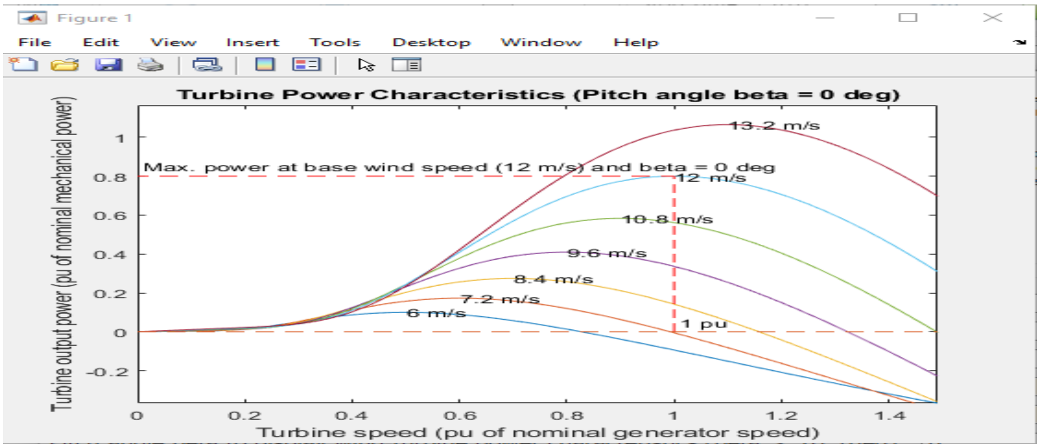

Fig.31 turbine power characteristics

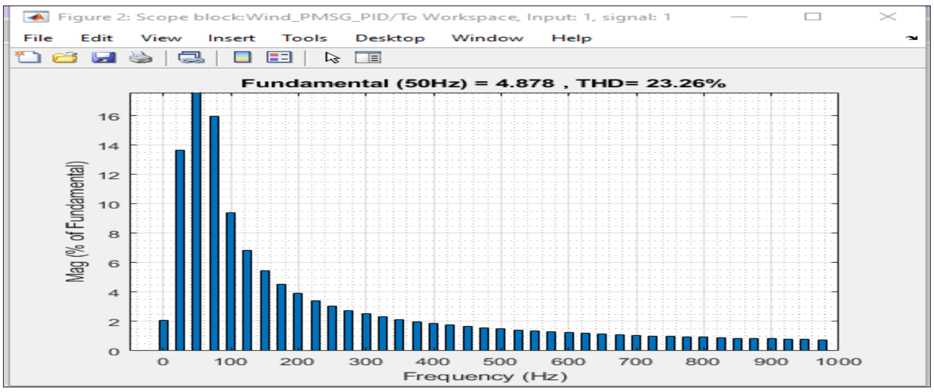

Fig. 32 THD performance of PMSG –PID

Table 1 Comparison Result with Different Pitch Control Technique

Techniques	THD (%)
PMSG –LQR	12.50
PMSG –LQR-PID	4.90
PMSG –PID	60.03
PMSG –PI	23.26

The Total Harmonic Distortion (THD) is a measure of the distortion in a signal compared to its fundamental frequency. In the context of wind turbine power control techniques, THD is used to evaluate the quality of the generated electrical power waveform. A lower THD value indicates a cleaner and more stable power output. Based on the provided THD values for different wind turbine control techniques, here is a comparison:

PMSG-LQR: The THD value for the PMSG-LQR control technique is 12.50%. This indicates that the generated electrical power waveform has a distortion level of 12.50% compared to the fundamental frequency.

PMSG-LQR-PID: The PMSG-LQR-PID control technique shows a lower THD value of 4.90%. This suggests that the power output with this hybrid control strategy has a lower distortion level compared to the PMSG-LQR technique.

PMSG-PID: The PMSG-PID control technique exhibits a higher THD value of 60.03%. This indicates a significantly higher distortion level in the generated electrical power waveform compared to the other control techniques.

PMSG-PI: The THD value for the PMSG-PI control technique is 23.26%. This suggests a moderate level of distortion in the generated electrical power waveform compared to the fundamental frequency.From the provided THD values, it can be observed that the PMSG-LQR-PID control technique offers the lowest distortion level among the listed techniques. This indicates that the hybrid approach combining LQR and PID control can help improve the power quality by reducing harmonic distortions. On the other hand, the PMSG-PID technique shows a considerably higher THD value, suggesting a higher level of distortion in the power waveform.

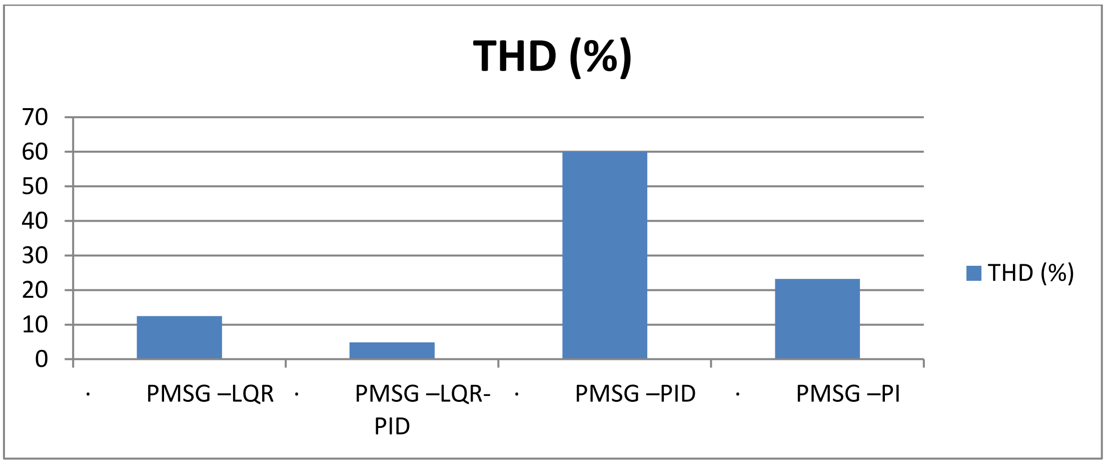

Fig.33 Comparison Result with Different Pitch Control Technique

4. Conclusion

In conclusion, the PMSG-LQR-PID control strategy emerges as the most promising wind pitch control technique among the evaluated options. It combines the advantages of LQR optimization, PID response characteristics, and integral control to achieve improved power quality, control efficiency, and robustness. However It is crucial to remember that choosing the best control method depends on a number of criteria, including the specific wind turbine system, desired control objectives, and system requirements. Further analysis, validation, and fine-tuning of the control to maximize the effectiveness of the chosen approach in real-world wind turbine applications, certain criteria are required

Performance Comparison: Among the evaluated techniques, the PMSG-LQR-PID control strategy demonstrates the best performance. It achieves a lower

Compared to the other methods, the Total Harmonic Distortion (THD) number shows a cleaner and more steady power output. In terms of THD, the PMSG-LQR approach likewise performs well, however the PMSG-PI technique exhibits a modest amount of distortion. However, the PMSG-PID technique exhibits a significantly higher THD value, suggesting poorer power quality.

Control Efficiency: The PMSG-LQR-PID control strategy combines the advantages of both LQR and PID controllers. It benefits from the optimization capabilities of the LQR controller and the improved response time and damping characteristics of the PID controller. This hybrid approach shows promising results in terms of control efficiency, achieving the desired pitch angle response with lower oscillations and faster settling time.

Control Robustness: The PMSG-LQR-PID and PMSG-PI control techniques offer better control robustness compared to the PMSG-PID technique. The inclusion of integral control in both strategies helps to mitigate steady-state errors and enhance disturbance rejection capabilities. The PMSG-LQR technique also benefits from the optimization properties of the LQR controller, allowing it to handle uncertainties and disturbances more effectively.

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