A Dynamic Linear PID Pitch Controller based on Gain-Scheduling under Wind Turbulence and Fatigue Loads

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ABSTRACT:

Wind turbines operate in dynamic environments characterized by wind turbulence, which can cause notable alterations in aerodynamic loads. The output of the wind generator is disrupted and fluctuates under extreme wind turbulence and fatigue loads. It also causes fatigue loads and damage to the wind turbine. Turbines can resist the load once or twice, but when the same load is applied repeatedly, they may not survive it. Variable pitch control system changes pitch angle of vanes of turbine in real time in such conditions. This performance ensures optimal power generation, reduces mechanical stresses, and prolongs the lifespan of critical components. A dynamic linear PID pitch controller, enhanced with gain-scheduling, is a robust approach to managing wind turbulence and fatigue loads. Gain-scheduling dynamically adjusts PID gains under wind turbulence and fatigue loads. It estimates the irregular kinetics of wind machine to guarantee precise tip-speed-ratio under wind turbulence. Simulink results show the proposed controller adjusts the pitch angles when the speed of the wind changes. These changes result in power regulation. Furthermore, they lead to improved pitch performance. Hence, the proposed model will be beneficial to maintain a constant peak value even with high wind speed, providing a reliable solution for wind turbine control systems.

KEYWORDS: Wind Turbine; Variable Speed Variable Pitch; Wind Turbulence; Starting Torque; Simulink

INTRODUCTION

Wind energy is green energy that comes from air masses that flow over the earth's exterior. The kinetic energy of winds is captured and converted to mechanical rotational energy by the blades of wind turbines. Electrical generators, which are integrated with wind turbines, transform this mechanical energy into electrical energy. Drag and lift force on vanes of wind turbines cause the rotor to rotate like a propeller. Fig. 1 shows an aerofoil with an air stream flowing over the leading edge. It illustrates the aerodynamic lift and drag forces, as well as their resultant. Gradient that is created betwixt the chord line and the incoming air stream is known angle of attack (α).

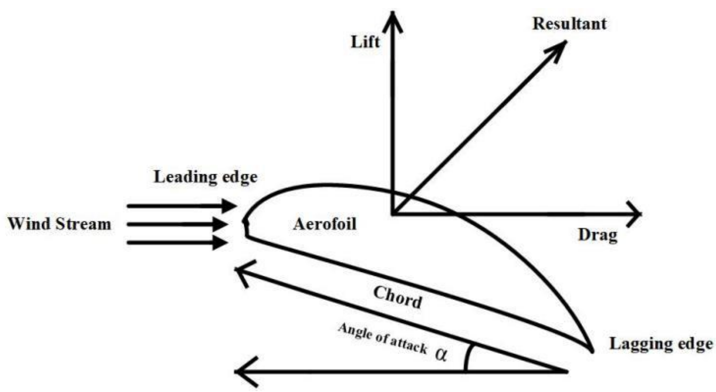


Fig. 1. Forces(Lift and drag) on the propeller of a wind machine

The propeller of a wind machine uses a pitch control mechanism to vary the pitch angle in events of wind turbulence. This alteration of pitch angle increases or decreases the drag force on the blades of the turbine, and hence, the RPM is controlled.

Wind turbines are continuously exposed to different loads due to varying wind speeds. Hence, during the design of wind turbines, fatigue analysis is given importance, and its durability is checked for various cycles of loads. To keep rotor speed within operating limits during wind turbulence and fatigue loads, almost all large contemporary horizontal and vertical-axis wind turbines employ pitch-controlled mechanisms. Blades of wind turbines are generally feathered to reduce the risk of unstable rotational speed of the turbines during events of high wind speeds. (Adarmola et al., 2011).

The problem with a fixed-speed turbine is that it is prone to high wind speed and fatigue loads. A fast pitch mechanism can be used in such turbines, but the power is not regulated, and neither is the optimum speed accurately achieved. Turbines with changing speed and pitch control operate at a steady tip-speed ratio (TSR) by adjusting rotational speed of rotor in proportion to velocity of wind. Electric power of generator is controlled by its torque to an optimum value, while a variable pitch mechanism, when optimum power is achieved, controls rotor rotation. The rotation of rotor may increase significantly to an unstable level in events of wind gusts, but generator output is still kept at the optimum level. During high winds, pitch is varied to reduce aerodynamic torque, and rotor speed is brought back to its rated value. Similarly, in the events of calm winds, pitch is assorted again to maintain constant output of the generator. Thus, the pitch mechanism of wind turbines with variable speed has a slower pitch mechanism but continuous output power compared to constant-speed wind turbines. (Hansen et al., 2010).

Power coefficient is an important aspect of wind turbine. It is an estimate of the ability with which a wind turbine transforms energy in air into electrical energy. The fraction of electrical energy and all available energy in wind at the same speed is the power coefficient(C_p) of wind turbine. When wind strike the blades of turbine its kinetic energy is converted to mechanical rotational energy. For greater efficiency of turbine all wind energy should be transferred to rotor blades and hence to mechanical rotational energy. The tip speed ratio (TSR) plays an important role in the design of wind turbines. Most of the wind passes in between the gap of blades if the rotor of the wind turbine spins too slowly; conversely, the blades will act as a solid wall if the rotor rotates too quickly. The wake of the wind turbine reduces speed of air and increases wind turbulence. Efficient power extraction is not possible if the next blade of the turbine reaches this turbulent, windy area. But, if rotation of rotor is slow, it means less turbulent air is hitting the blades of the turbine. To avoid passing of excessive stormy wind, tip speed ratio (TSR) is selected meticulously. Therefore, during design of wind turbines, best ratio for tip speed is considered for maximum power extraction from wind. (Tang et al., 2017).

Different studies have tried to highlight or study issues to optimize the efficiency of Wind turbines. Wang et al. (2020) developed an autonomous scheme for pitch control that used FAST and MATLAB/Simulink for vigorous modelling, simulation, and in-depth analysis. The control scheme is customized for a limited type or model of wind turbine. Ullah et al. (2019) suggested that the speed of rotor and energy generation is managed by linear active disturbance rejection control. This design could not have encountered the turbulence of wind speeds. Zhang et al. (2021) combined the optimization method with the PID controller to control the output power and test control response for wind machines yet, the accuracy of the system was not achieved. Yue et al. (2021) introduced a Fuzzy controller to the segmented PID control. This study was limited to low-power wind machines. Rehman et al. (2020) proposed an optimum torque control method for the pitch control of wind turbines. However, it could not adjust to the real-time alteration of the system. Qian et al. (2012) worked on a prediction-corrected pitch control blueprint. This scheme first comes up with the moving mean methodology to utilize speed of air and then with pitch angle curve fitting for wind speed to acquire an expected pitch angle value. This control strategy banks on ideal operating conditions and may not hold true to practical turbines.

This paper focuses on the design of a precise pitched-control system to control the speed of the turbine during high-speed winds and repeated loads. A systematic changeable pitch controller is designed for pitch angle contingent on gain scheduling which considers maximum power, maximum torque, gusty winds, and cyclic loads. Gain scheduling allows PID controllers to adapt to changes in system dynamics or operating conditions, making them effective in environments where these parameters vary significantly. Different wind bands are categorized for the controller. For a particular band, a specific controller will work. The design of the controller is such that it takes into account all the different wind bands possible.

PROPOSED DESIGN

Whole system used to transform wind energy into electrical energy is called a wind energy conversion system (WECS). This system is employed accurately to simulate and analyze efficiency of wind energy conversion structures. It ensures efficient and reliable energy production from wind resources. The primary equation governing a wind energy conversion system relates to power drawn from wind by the wind turbine that is given:

P_m=1/2C_p(λ, β) ρAV^3 (1)

Where:

P_m= Mechanically produced power (w)

R = Radius of blade (m)

A = area of blades exposed to wind (m^2).

ρ= Density of wind ($^{kg}/_{m^3}$)

V= velocity of wind (m/s)

C_p= Coefficient of power (Constant)

λ = Tip and speed ratio for blades of turbine machine (Constant)

β = Angle of pitch (degrees)

$\Omega =$ Rotor angular speed (rad/sec)

Coefficient of power (C_p) is measured in terms of tip speed ratio (TSR) λ, and pitch angle (β) as;

$$C_p\,(\lambda,\beta) = K_1({}^{K_2}/_{\lambda_i} - K_3\,\beta - K_4).\,e^{(-K_5/\lambda i)} + K_6\,\lambda$$

With:

$$1/\lambda_i = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \qquad (4)$$

Where $K_1 \sim K_6$ are experimentally determined coefficients?

$K_1 = 0.5176$; $K_2 = 116$; $K_3 = 0.4$; $K_4 = 5$; $K_5 = 21$; $K_6 = 0.0068$

$$\lambda = \frac{R.\Omega}{V} \qquad (4)$$

The following formula calculates the torque of the turbine:

$$T_m = \frac{P}{\Omega} \qquad (5)$$

The mechanical power and rotational torque of the wind turbine is shown in Fig. 2. With all variable and constants (Power coefficient, wind speed, pitch angle, tip speed ratio, angular speed, etc.).

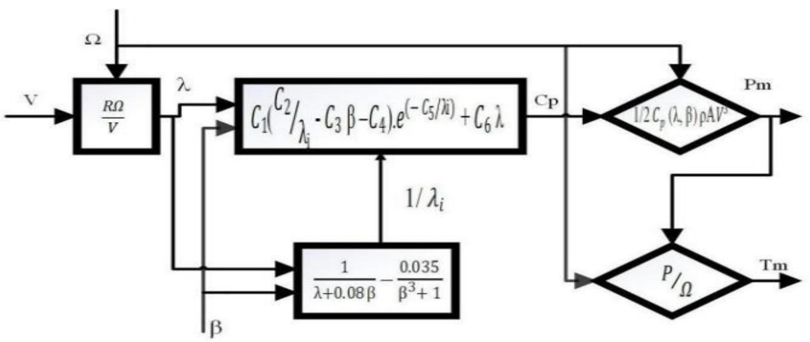


Fig. 2. Block Diagram of power (*Pm*) and torque (*Tm*) in terms of $(V, \lambda, \beta, Cp, \Omega)$

In Fig.3, a model of a variable speed pitch control wind turbine, which comprises two PID controllers (based on gain scheduling) cross-coupled to each other, is shown. When wind speed is below rated, the speed controller continuously changes the speed of the rotor to keep tip speed ratio fixed for production of maximum power from turbine. This increases Turbine performance.

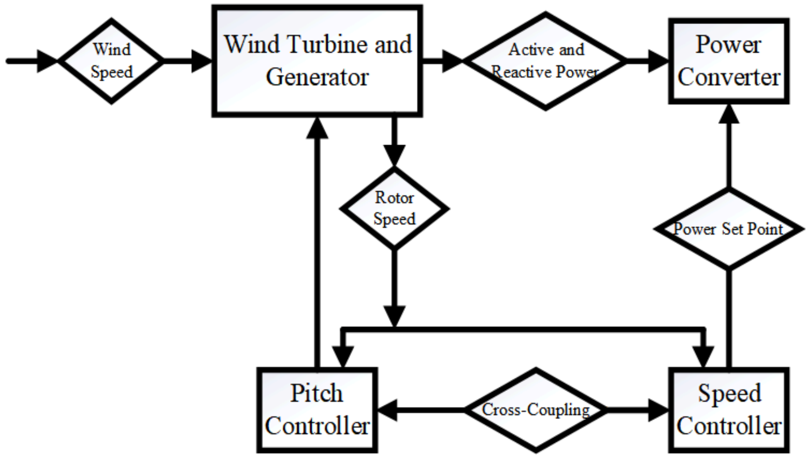


Fig. 3. The proposed model of variable-speed wind turbine

For all probable tip speed ratios (TSR), performance of rotor is crucially examined. Aerodynamic conditions need to be found for each section of blade at every tip speed ratio. In this way, the efficiency of the rotor is increased. The result is normally shown in a graph of coefficient of power C_p vs tip speed ratio λ. this is shown in Fig. 4.

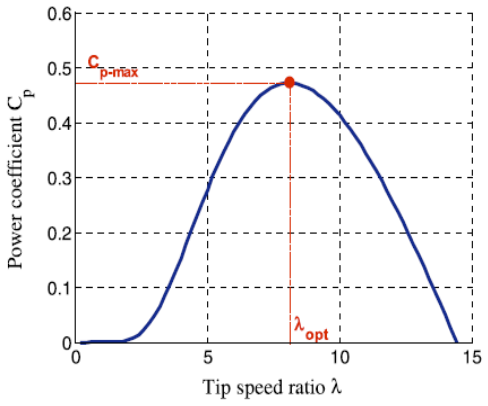


Fig. 4. A coefficient of power (C_p) vs tip-speed ratio (λ)

- At zero tip speed ratio ($\lambda = 0$), power is not drawn from wind rotor as it does not rotate.

- At substantial tip speed ratio (e.g. $\lambda = 12$), the blade rotor rotates very quickly and acts as a complete rotational solid disk for the coming wind. So there is no passage of air through the rotor and hence no extraction of mechanical rotational power from wind. For maximum power extraction, the ideal value of λ is 7.

The RPM of the rotor must be maintained at around optimum value irrespective of wind turbulence. The speed of the rotor increases significantly at very high wind speeds. Think about a wind turbine whose stable RPM is 102 rad/s for a fixed wind speed of 12 m/s and a fixed pitch angle of 0 degrees (ideal operating conditions for a wind turbine). The design of the controller in this paper maintains the speed of the rotor at around 102 rad/s for all possible wind variations during wind turbulence by adjusting the pitch angle.

RESULTS AND DISCUSSION

A variable pitched-control scheme for a wind turbine simulated in Simulink is depicted in Fig. 5. It uses wind speed and pitch angle inputs to interact with the system. The pitch control mechanism changes the pitch of the blade in relation to wind and rotor speed to enhance performance and protect the turbine against overloads. Rotor speed and generator output loops monitor the electro-mechanical health of the machine, providing data needed for continuous, stable, and efficient operation.

Fig. 5. Implemented Simulink Model with PMSG

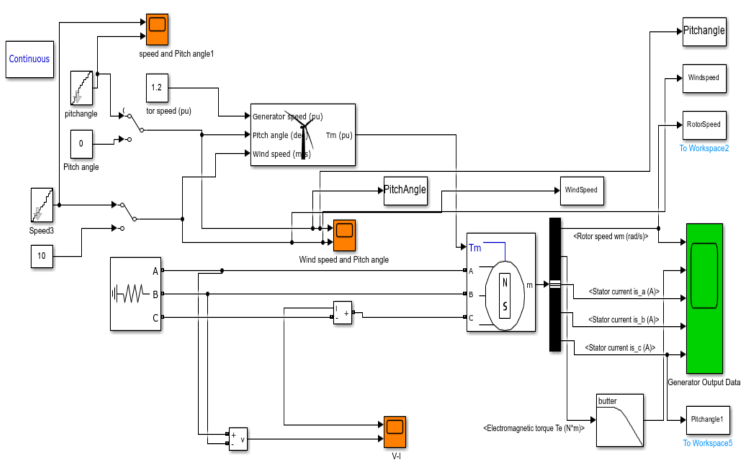


Table 1 shows that rotor speed is considerably increased with the speed of wind varied.

Table 1. Rotational speed of Rotor with changing wind speed and fixed pitch angle

Changing speed of wind (m/s)	**Rotational speed of Rotor** (rad/s)
13	128

14	150
15	173
16	193
17	208
18	222
19	235
20	241
21	247
22	250
23	251
24	254

According to Table 1, if the speed changes from 13 m/s to 24 m/s (cutoff speed), the speed of the rotor increases accordingly, which can cause mechanical stress and may lead to equipment casualties, reduced efficiency, and increased safety risks. If rotor speed is too high, it can also cause structural damage and regulatory non-compliance. Variable pitch can stabilize the rotor speed and bring it to optimum value by adjusting the blade's angles. Table 2 shows how angle for pitch is varied in relation to variable speed of wind to bring rotor speed to an optimum value.

Table 2. Rotor speed with variable wind speed and variable pitch angle

Variable wind speed (m/s)	**Variable pitch (degrees)**	**Rotor Speed** (rad/s)
13	2	101.5
14	6	101.8
15	10	102
16	14	101.9
17	16.3	101.8
18	19	101.7
19	21.1	102
20	23	102.2
21	24	102.4
22	26.3	101.25
23	27.7	101.2
24	28.9	102

As can be seen in Table 2 above, the pitch angle is varied as the wind speed changes, which results in an optimum rotor speed of 102 rad/s. This data is tested and verified in Matlab Simulink. As shown in Fig. 6. Rotor speed is best kept near 102 rad/s with variable wind, which is the required result of the control mechanism. This control scheme accurately avails optimum rotor speed even for a cutoff speed of 24 m/s, shown in Table III.

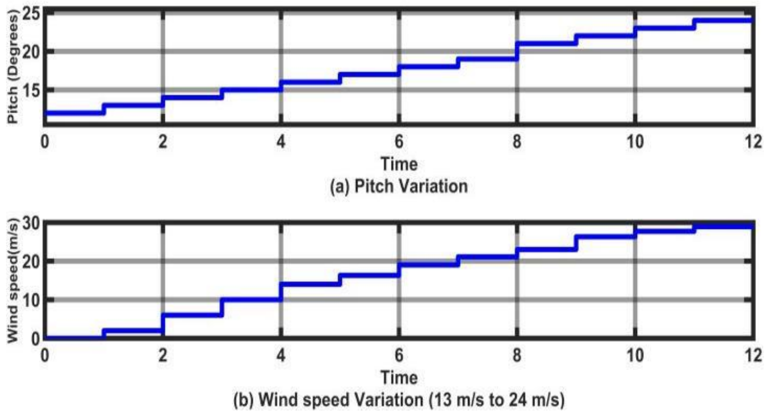


Fig. 6. Variable Wind Speed vs. Variable Pitch (a) Pitch variation (b) Wind speed Variation (13m/s to 24m/s)

The rotational movement of the rotor decreases with dropping wind speed below 12 m/s. For a cut-in speed of 8 m/s, the rotor speed decreases to 11.2 rad/s, as appear in Table III.

Table 3. Changing wind speed vs. constant pitch when wind speed is decreasing.

Changing wind speed (m/s)	**Rotor Speed** (rad/s)
11	76
10	52
9	30
8	11.2

When the pitch is assorted, the speed of the rotor increases a bit and so the cut-in speed of the wind machine is attained. Table IV shows the result.

Table 4. Variable wind speed vs. Variable Pitch with decreasing wind speed

Variable wind speed (m/s)	**Variable pitch (degrees)**	**Rotor Speed** (rad/s)

11	1	78
10	1	58
9	2	38
8	2	26

A difference plot is drawn for pitch variation and no pitch variation rotor speed. Fig. 7. Shows a graph between wind speed and Rotor speed. Rotor Speed increases very rapidly under wind turbulence. The blue line represents uncompensated rotor speed. The poly-fit rotor speed gives a smoothed and slightly idealized curve of how rotor speed should increase related to speed of wind. To bring rotation of rotor to the optimum value, pitch is varied. In this manner, uncompensated rotor speed is compensated, and the optimum speed for rotor is attained. Green line in the graph shows this compensated rotor speed.

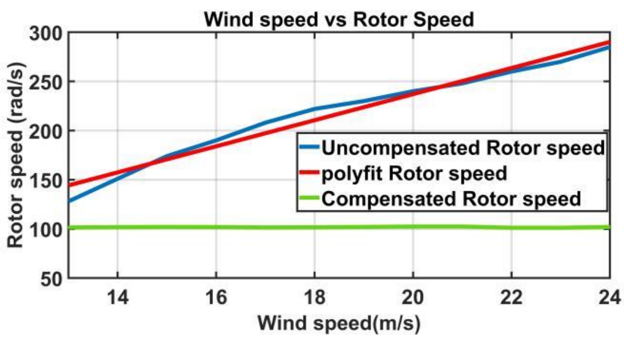


Fig. 7. Rotor speed vs. wind speed

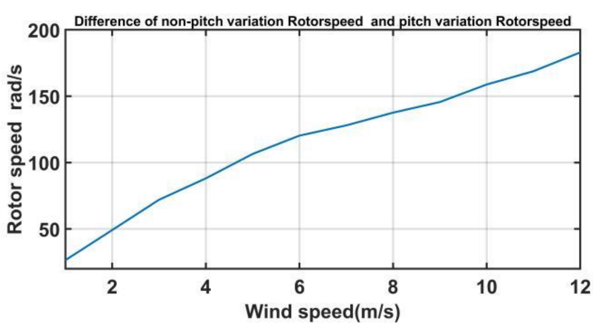


Fig. 8. Difference of non-pitch variation RPM VS pitch variation RPM

The difference between compensated rotor speed and non-compensated rotor speed is shown in Fig. 8. This graph illustrates difference between rotor speeds of non-pitch variation vs pitch variation scenarios. There is a significant rise in rotor speed difference, especially for high wind speed, which indicates the impact of the pitch control system on rotor speed. This graph shows that rotor speed can be effectively regulated and stabilized under wind turbulence and non-pitch variation scenarios.

Compensated rotor speed, uncompensated rotor speed, and their difference is shown individually in Fig. 9

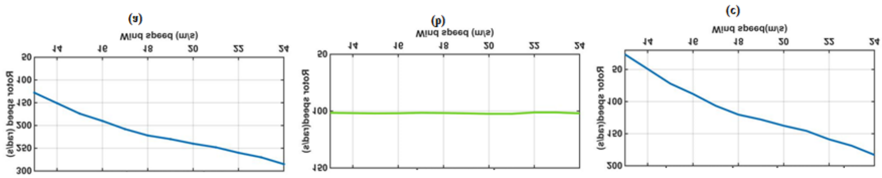


Fig. 9. Waveform of the different rotor speeds: (a) Uncompensated Rotor speed, (b) compensated Rotor speed, (c) difference between compensated rotor speed and uncompensated rotor speed

3-Φ Parallel RLC load is controlled using a Permanent Magnet Synchronous Generator (PMSG). Voltage and current curves for this system are shown in the following Simulink graphs Fig. 10. These are normal operating conditions of wind turbines. The voltage is set to 400 volts, and the current is 0.15 A.

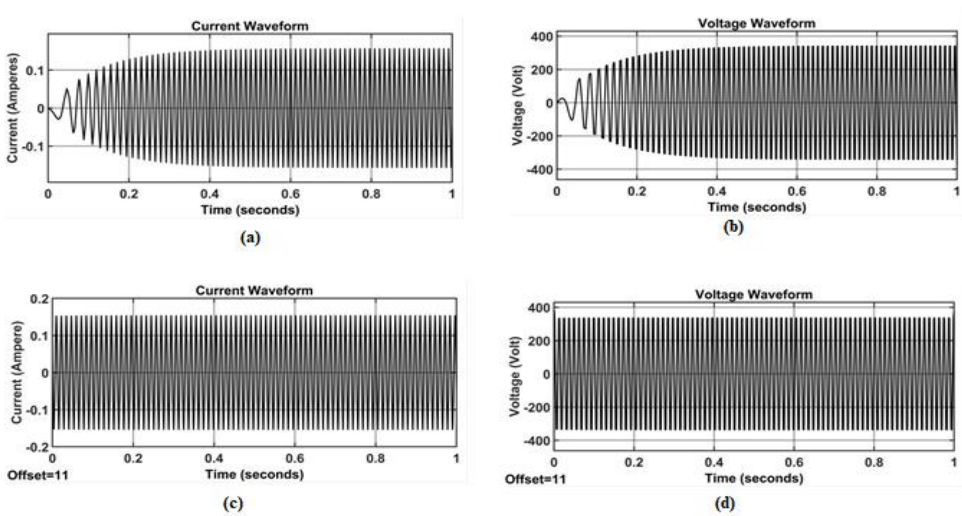
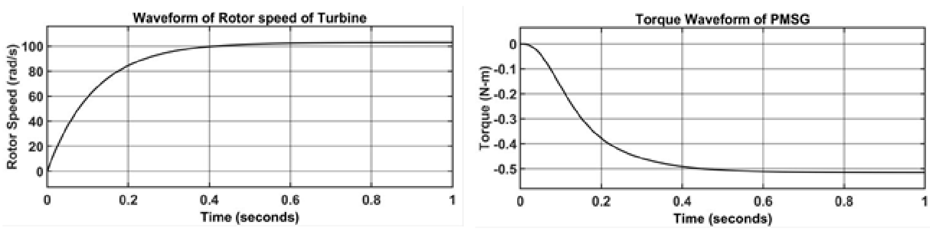
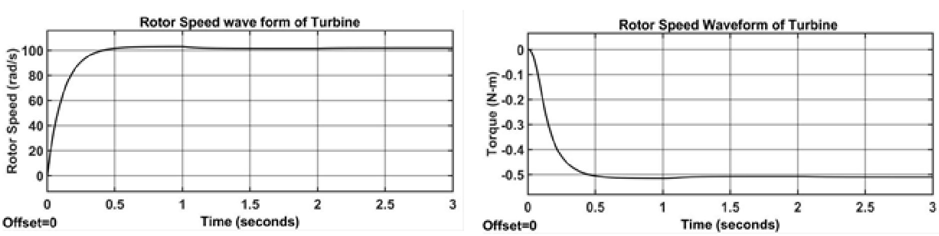


Fig.10. Simulink results of current and voltage waveforms for pitch angle and wind speed, (a) current waveform for fixed pitch angle (0 degrees) and wind speed (12 m/s), (b) Voltage waveform for fixed pitch angle (0 degrees) and wind speed (12 m/s), (c) current waveform for variable pitch angle and wind speed, (d) voltage waveform for variable pitch angle and wind speed

The current response remains relatively stable under constant conditions of a fixed pitch angle and steady wind speed. The voltage output corresponds to a steady energy extraction from the wind turbine, resulting in a relatively smooth and constant voltage waveform. Transients, if any, are minor and occur during the initialization of the system with little wind turbulence. The current is disturbed significantly because of pitch angle and wind speed variations. The waveform is characterized by periodic fluctuations, capturing the interplay between pitch angle adjustments and wind speed variations to maintain optimal power output. The voltage waveform dynamically responds to changing pitch angles and wind speeds. It includes transient peaks and dips as the system adapts to maintain efficiency under varying conditions. The waveform reflects the controller's effectiveness in stabilizing the system despite external disturbances.



(a) fixed wind speed and a pitch angle



(b) Variable wind speed and pitch angle

Fig. 11. Waveform of PMGS rotor speed and torque, (a) fixed wind speed & pitch angle, (b) variable wind speed & pitch angle

The simulation results for the Permanent Magnet Synchronous Generator (PMSG) are illustrated in Fig. 11. Fig 11(a) correspond to the working of wind turbine under a fixed wind speed (12 m/s) and a pitch angle (0 degrees). The rotor speed is maintained at a stable level (102 rad/s). The stability of the system ensures maximum extraction of energy from wind. The results further validate the effectiveness of the control strategy in maintaining optimal turbine performance within its designed operational range. The simulation results for the Permanent Magnet Synchronous Generator (PMSG) under a changing wind profile and an alternative variable pitch profile are presented in Fig 11(b). Wind speed variation (13 m/s to 24 m/s) is the operation of wind turbine is tested. The rotor speed remains consistently at 102 rad/s, demonstrating the effectiveness of the pitch control system in mitigating the effects of wind turbulence. The system maintains the rotor speed within the normal operating range in spite of significant variations in wind speed and continuous adjustments in the pitch angle. This stability of the system features the robust design of the gain-scheduled PID controller, which ensures optimal turbine performance even under dynamically challenging conditions.

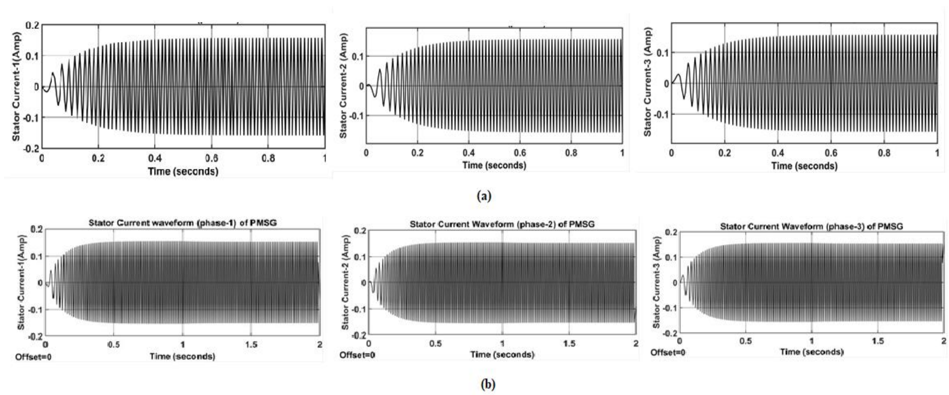


Fig. 12. Stator current waveform of PMSG (phase-1, phase-2 and phase-3); (a) fixed wind speed & pitch angle, (b) variable wind speed & pitch angle

The stator current waveforms for the PMSG under different operating conditions are analyzed as follows: In Figure 12(a), the current waveforms for phase-1, phase-2, and phase-3 are shown with a constant speed of wind (12 m/s) and a constant pitch angle (0 degrees). The current waveforms exhibit a sinusoidal pattern, which suggests that the system is functioning at optimal performance with minimal distortion. This steady current indicates efficient energy conversion and minimal electrical disturbances in the generator output. Fig. 12(b) shows the current waveforms for phase-1, phase-2, and phase-3 under a variable wind speed profile (13 m/s to 24 m/s), and an alternative variable pitch profile shows dynamic fluctuations. The waveforms adapt continuously to the wind turbulence, with changes in amplitude and a few transient effects because of variance in wind speed and pitch. The waveforms adapt continuously to the wind turbulence, with changes in amplitude and slight transient effects due to variations in wind speed and pitch. The waveforms remain essentially sinusoidal in spite of these fluctuations. This result illustrates the controller's effectiveness in maintaining operational stability under turbulent conditions.

CONCLUSION

This paper designs and simulates a dynamic model of variable-pitch, variable-speed wind turbines. Using input-output data, the control scheme enables optimal tip-speed ratio across varying wind speeds. During wind turbulence, i.e. wind speed varies from 13 m/s to 24 m/s, the controller maintains the rotor speed at 102 rad/s (optimum speed). This research paper aims to ensure the smooth output of wind turbines and less mechanical stress in diverse and turbulent conditions. The result is verified in Matlab Simulink. Variable pitch-controlled wind turbines demonstrate superior performance in handling wind turbulence and reducing fatigue loads. The integration of dynamic linear PID controllers with gain-scheduling further enhances their ability to stabilize power output and extend structural lifespan. Progressive improvements in control strategies and materials are expected to enhance their reliability and efficiency further. Simulation results show that the proposed design results in power regulation and enhanced pitch performance. Thus, the output maintains a constant peak value despite alteration in velocity of wind. This demonstrates effectiveness of the VSVP control system in optimizing wind turbine performance under dynamic wind conditions.

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