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New Technique For Suppressing Wind Gust–Induced Turbine Blade Vibrations

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Abstract
This work presents the effectiveness of a Lorentz torque-based feedback controller in mitigating wind gust–induced vibrations in wind turbine blades. A mathematical model of performance evaluation of Lorentz torque controller for vibration suppression was developed and implemented in the MATLAB/ Simulink environment, incorporating turbine generator and blade dynamics, wind torque under both calm and turbulent conditions, wind speed sensors, a Lorentz torque controller, and a closed-loop feedback system. Simulation tests combined these wind torque inputs and activated the controller when wind speeds exceeded 25 m/s. The results demonstrated that the controller significantly reduced blade vibrations, producing both stable and unstable system responses depending on the wind conditions, and validated its potential to enhance turbine performance. This novel approach supports the development of lightweight, fast-acting, and energy-efficient wind turbines, benefiting the renewable energy sector and its stakeholders. Additionally, it provides a solid foundation for future research into advanced turbine control technologies.

Keywords: *Wind turbine vibration, Lorentz torque, MATLAB/Simulink, blade dynamics, wind gust, active damping, control systems*

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I. Introduction

Renewable energy is becoming increasingly essential in reducing reliance on fossil fuels and addressing climate change (Ma et al., 2015). As global energy demand surges and environmental concerns grow, transitioning from traditional energy sources to sustainable alternatives is imperative (Gao et al., 2020). Renewable energy technologies provide long-term solutions with reduced environmental impacts, making them central to this shift (Kocabiyikoğlu, 2020). Among the various renewable energy sources, wind energy stands out as a prominent contributor (Machado & Dutkiewicz, 2024a).

Wind energy's rapid technological advancements, minimal carbon emissions, and adaptability for both small- and large-scale applications make it a key player in the energy transition (Huang et al., 2021). Wind farms, both onshore and offshore, are increasingly integrated into national energy grids, highlighting their significance in the current energy landscape (Bin et al., 2018). However, despite its potential, wind energy systems encounter technical and structural challenges, particularly concerning blade vibrations (Okokpujie et al., 2021).

Wind turbine blades are vulnerable to gusts and turbulence, which generate structural vibrations (Zhu & Li, 2018). These aerodynamic disturbances lead to periodic and random forces acting on the rotating blades, resulting in unwanted oscillations that compromise the turbine's steady-state operation (Fitzgerald et al., 2013). To address these blade vibrations, various vibration mitigation strategies have been implemented

These methods include passive dampers, tuned mass dampers (TMDs), and aerodynamic modifications (Chong et al., 2021). However, they often come with inherent limitations. Passive systems typically lack adaptability, respond slowly to rapid changes in wind conditions, and can inadvertently increase the turbine's mass and complexity, potentially deteriorating dynamic performance during extreme conditions (Fitzgerald et al., 2013). To overcome these challenges, a new approach is needed

The objective of this study is proposed and evaluate the performance of a new Lorentz torque-based controller that will be activated by a wind speed sensor that sensed a turbulence. This sensor is integrated into a feedback loop of a given wind turbine system. When activated, the component generate a retarding force from the feedback current through a secondary coil of the turbine. This will slow down the turbine whereby the ensuing blade vibrations due to the turbulence dies.

II. Mathematical Modeling

Blade dynamics are typically modeled by a second-order differential equation incorporating inertia, damping, and stiffness to capture the vibrational response to aerodynamic loads, while the generator dynamics were represented by a similar second-order differential equation that captured the effects of rotational inertia and electromagnetic damping on rotor motion (Elhaji, 2018). It was essential for analyzing system stability and designing control strategies in power systems. Wind torque was modeled as a sinusoidal input derived from wind speed, air density, and rotor characteristics, representing the turbine's primary driving force under steady conditions (Sumair et al., 2021). Wind gusts were introduced as a Gaussian-distributed stochastic component added to the nominal torque (Ismaiel, 2023). This approach captured the transient, random disturbances affecting turbine performance and structural integrity. To suppress gust-induced blade vibrations, a Lorentz torque-based control system was employed, which applied a state feedback control law that utilized real-time measurements of blade displacement and velocity to compute corrective electromagnetic torques (Machado & Dutkiewicz, 2024b). The Lorentz torque arose from the vector cross-product of current and magnetic flux density, enabling precise, contactless actuation to mitigate blade vibrations (Beskhyroun et al., 2011). The complete system model, which included blade and generator dynamics as well as a Lorentz-based controller, was represented in the Laplace domain using transfer functions, with wind torque and gust torque considered as external inputs. This framework supported real-time simulation, control design, and performance evaluation, thereby improving turbine efficiency, reliability, and operational lifespan under variable wind conditions (Zhang et al., 2024).

Blade Dynamics

Blade dynamics were modeled using a second-order differential equation that included inertia, damping, and stiffness to capture the blade's vibrational response to wind loads (Gao et al., 2020). This formulation enabled analysis of blade behavior under both steady and transient aerodynamic forces. The model served as a foundation for designing vibration suppression strategies (Ma et al., 2015). The modeled equation representing the blade vibration i given by

$$J_b\ddot{\theta} + c_b\dot{\theta} + k_b\theta = T_{wind} + T_{gust} - T_{control} \qquad (1)$$

where $J_b$is moment of inertia of the blade, c_b is the damping coefficient and k_b is stiffness coefficient ,T_{wind} is the wind torque, T_{gust} is the disturbance torque from wind gust, $T_{control}$ is a Lorentz torque applied, $\ddot{\theta}$ is angular acceleration, $\dot{\theta}$ is angular velocity, θ is angular displacement.

Blade Transfer Function

The blade dynamics were modeled by a second-order transfer function in the Laplace domain that characterized the blade's vibrational response to aerodynamic forces (Machado & Dutkiewicz, 2024a). This function incorporated key physical parameters such as inertia, damping, and stiffness to describe how the blade displacement evolved under dynamic wind loading(Huang et al., 2021). The Laplace domain representation of the turbine blade transfer function is given by

$$\frac{\theta(s)}{T_{wind} + T_{gust} - T_{control}} = \frac{1}{J_b s^2 + c_b s + k_b} \qquad (2)$$

where s is the root of quadratic equation, θ(s) is the angular output displacement of the blade

Generator Dynamics

Generator dynamics were expressed through differential equations and were integrated with the overall system model, ensuring accurate interaction between mechanical and electrical subsystems by incorporating rotational inertia and the electromagnetic domain for damping (Bin et al., 2018). The modeled equation representing the generator dynamics is given by.

$$J\ddot{\theta} = T_m - T_e - B\dot{\theta} \qquad (3)$$

where J is moment of inertia of the generator and B damping coefficient, T_m and T_e are mechanical and electrical torques respectively

Generator Transfer Function

The blade dynamics were modeled by a second-order transfer function in the Laplace domain that characterized the blade's vibrational response to aerodynamic forces(Okokpujie et al., 2021). This function incorporated key physical parameters such as inertia, damping, and stiffness to describe how the blade displacement evolved under dynamic wind loading(Chong et al., 2021). The Laplace domain representation of the turbine blade transfer function is given by

$$\frac{\theta(s)}{T_m - T_e} = \frac{1}{Js^2 + Bs} \qquad (4)$$

Wind Gust Torque Model

This model captured the impact of short-term, random wind fluctuations on turbine torque. Wind gusts were introduced as Gaussian-distributed stochastic disturbances added to the nominal torque, simulating the unpredictable nature of atmospheric turbulence(Ma et al., 2015). It was essential for analyzing turbine structural loads, control robustness, and fatigue under real-world conditions. The modeled equation of wind gust is represented by

$$T_{gust} = A \sin \omega t + rand \tag{5}$$

where A is the amplitude of the torque , ω is the angular frequency, rand to account for stochastic wind around the blade

Wind Torque model

This model represented the steady-state aerodynamic torque produced by wind interacting with turbine blades(Zhu & Li, 2018). It was derived from wind speed, air density, rotor characteristics, and blade pitch, typically modeled as a deterministic or sinusoidal input(Panagiotis, 2024). This formed the baseline torque for turbine operation and control system design. The modeled equation of wind torque is represented by

$$T_{wind} = A \sin \omega t \tag{6}$$

State feedback control law

State feedback control used real-time sensor data such as blade position and velocity to calculate corrective actions that maintained stability and suppressed vibrations (Elhaji, 2018). This method enabled precise, adaptive regulation of turbine dynamics in response to wind disturbances (Hussain et al., 2021). It was key to improving turbine efficiency, structural integrity, and energy output. The equation of the current control law of this Lorentz torque is given by

$$I(t) = -K_1\theta - K_2\dot{\theta} \tag{7}$$

where K_1 and K_2 are gains of the state feedback controller, I(t) is the current control, θ and $\dot{\theta}$ are angular displacement and angular velocity respectively.

Lorentz Torque Equation

The Lorentz torque equation defined the electromagnetic torque generated by actuators to suppress blade vibrations. This torque arose from the interaction between electric current and magnetic fields, producing real-time mechanical corrections. When integrated with state feedback control, it enhanced structural stability and ensured efficient turbine operation under varying wind conditions. The equation representing the Lorentz torque is given as.

$$T_{control} = rBLI(t) \tag{8}$$

where B is the Magnetic field strength I(t) is the Induced current, L is the Length of the coil in magnetic field, r is the Radius of the torque arm

Control Activation and Feedback Integration

The Lorentz torque controller is activated using a conditional logic block or switch in Simulink, which continuously compares the real-time wind speed V_w against a predefined critical threshold V_{crit} .When the wind speed exceeds this threshold, the controller is engaged to mitigate induced vibrations. The system's angular displacement serves as feedback, which is processed in real time to compute the appropriate control signal. This closed-loop configuration is consistently implemented in the Simulink-based simulation and ensuring accurate and responsive vibration suppression. The control activation and feedback integration representation is given by

$$T_{control} = \begin{cases} rBLI(t) & V_w \geq V_{crit} \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

where V_w is the wind speed below critical threshold , V_{crit} is the critical threshold wind speed.

III. Materials And Method

This simulation study was conducted using MATLAB R2023b, employing the Simulink platform for dynamic system modeling and implementation of the Lorentz torque control strategy. The system model included key components: turbine generator dynamics, blade dynamics, wind torque under both calm and turbulent conditions, a wind speed sensor, a Lorentz torque controller, and a feedback control loop. The simulation scenario involved applying a combination of wind torque inputs representing steady and gusty wind environments. The Lorentz torque controller was triggered when wind speeds exceeded 25 m/s, actively suppressing vibrations induced by turbulence. The MATLAB/Simulink model block for performance evaluation of lorentz torque control for vibration suppression in wind turbine blades is presented.

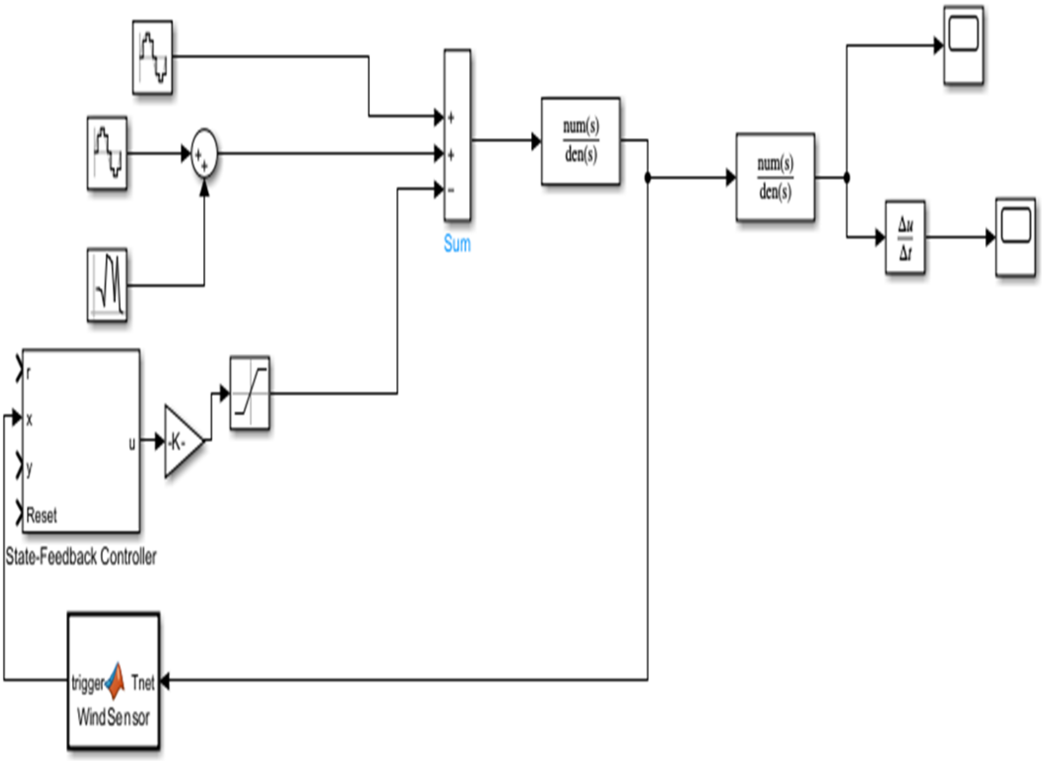
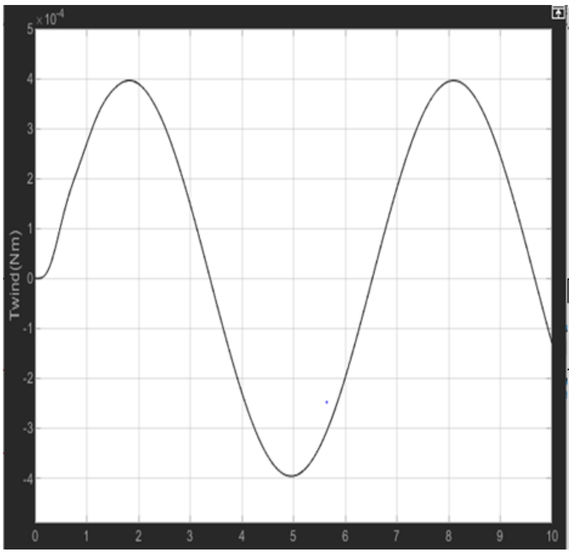


Figure 1. Simulink Implementation of the Lorentz Torque-Based Performance Evaluation System

IV. Results And Discussion

This section presents the simulation results that demonstrate the effectiveness of a Lorentz torque-based controller in suppressing vibrations in wind turbine blades caused by wind gusts and turbulence. The results of the wind turbine without turbulence, along with those that include wind torque with turbulence and the Lorentz torque used to mitigate vibration, are presented.

Figures 2(a) and 3(b) show the output of the turbine for wind torque that is calm and the wind torque under turbulent conditions.



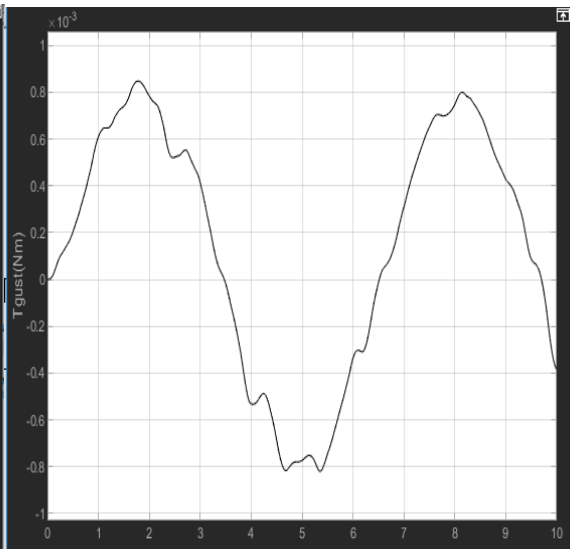
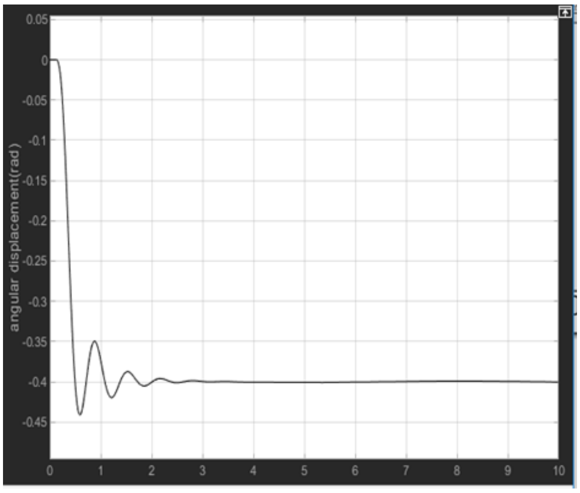


Figure 2 (a): Wind torque under calm conditions Figure **3 (b):** Wind torque under turbulent conditions

Figure2 (a) is showing a stable response under calm conditions and figure 3(b) is highlighting the fluctuations condition caused by gust-induced disturbances. The two conditions indicated that the system exhibited both stable and unstable responses under varying wind profiles, effectively validating the controller's ability to suppress gust-induced vibrations in wind turbine blades.

Figures 4(c) represent the successful suppression of blades vibration in wind turbine and Figure 5(d) indicating the response of the stable airflow condition depicting the effective performance of wind turbine devoid of external disturbance.



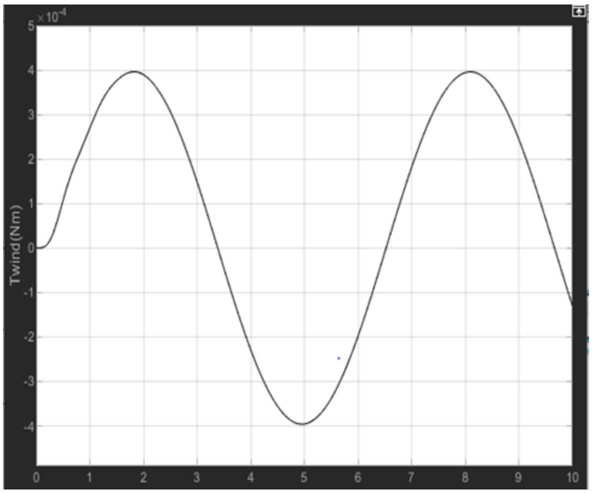


Fig 4 (c): Blade vibration suppressed. **Fig 5 (d):** Wind torque with blade vibration suppressed

Figure4 (c) demonstrates the success of control strategies that reduce vibrations in wind turbine blade. Figure 5(d) displays the torque response of a wind turbine blade under stable airflow conditions, highlighting optimal performance without external disturbances. This analysis emphasizes the importance of establishing reliable baselines for evaluating turbine efficiency and effectively responding to variable environmental factors.

V. Conclusion

This work demonstrated the effectiveness of using Lorentz torque-based controller for real-time suppression of blade vibrations caused by wind gusts. The use of a Lorentz torque controller effectively reduces blade vibrations, enhancing wind turbine efficiency, energy output, and lifespan while lowering maintenance costs. This work presents a novel, lightweight, and energy-efficient damping solution that outperforms traditional methods. Future work should focus on optimization, field testing, and collaboration with industry for real-world deployment.

References

[1] Beskhyroun, S., Wegner, L. D., & Sparling, B. F. (2011). Integral Resonant Control Scheme For Cancelling Human-Induced Vibrations In Light-Weight Pedestrian Structures. Structural Control And Health Monitoring, May 2011, N/A-N/A. Https://Doi.Org/10.1002/Stc

[2] Bin, G., Li, X., Shen, Y., & Wang, W. (2018). Development Of Whole-Machine High Speed Balance Approach For Turbomachinery Shaft System With N + 1 Supports. Measurement: Journal Of The International Measurement Confederation, 122(May 2016), 368–379. Https://Doi.Org/10.1016/J.Measurement.2018.02.035

[3] Chong, C. H., Rigit, A. R. H., & Ali, I. (2021). Wind Turbine Modelling And Simulation Using Matlab / SIMULINK. IOP Conference Series: Materials Science And Engineering, 1101(1), 012034. Https://Doi.Org/10.1088/1757-899x/1101/1/012034

[4] Elhaji, E. M. (2018). Modeling And Control Of Wind Turbine To Damp The Power Oscillation. Stability Control And Reliable Performance Of Wind Turbines. Https://Doi.Org/10.5772/Intechopen.74835

[5] Fitzgerald, B., Basu, B., & Nielsen, S. R. K. (2013). Active Tuned Mass Dampers For Control Of In-Plane Vibrations Of Wind Turbine Blades. January, 1377–1396. Https://Doi.Org/10.1002/Stc

[6] Gao, L., Yang, S., Abraham, A., & Hong, J. (2020). Effects Of Inflow Turbulence On Structural Response Of Wind Turbine Blades. Journal Of Wind Engineering And Industrial Aerodynamics, 199(September 2021). Https://Doi.Org/10.1016/J.Jweia.2020.104137

[7] Huang, Z., Tan, J., & Lu, X. (2021). Phase Difference And Stability Of A Shaft Mounted A Dry Friction Damper: Effects Of Viscous Internal Damping And Gyroscopic Moment. Advances In Mechanical Engineering, 13(3), 1–17. Https://Doi.Org/10.1177/1687814021996919

[8] Hussain, T., Min Ullah, F. U., Muhammad, K., Rho, S., Ullah, A., Hwang, E., Moon, J., & Baik, S. W. (2021). Smart And Intelligent Energy Monitoring Systems: A Comprehensive Literature Survey And Future Research Guidelines. International Journal Of Energy Research, 45(3), 3590–3614. Https://Doi.Org/10.1002/Er.6093

[9] Ismaiel, A. (2023). Wind Turbine Blade Dynamics Simulation Under The Effect Of Atmospheric Turbulence. Emerging Science Journal, 7(1), 162–176. Https://Doi.Org/10.28991/ESJ-2023-07-01-012

[10] Kocabiyikoğlu, Z. U. (2020). Principles Of Electromechanical Energy Conversion. Electromechanical Energy Conversion, 103–136. Https://Doi.Org/10.1201/9780429317637-3

[11] Ma, H., Zhao, Q., Zhao, X., Han, Q., & Wen, B. (2015). Dynamic Characteristics Analysis Of A Rotor-Stator System Under Different Rubbing Forms. Applied Mathematical Modelling, 39(8), 2392–2408. Https://Doi.Org/10.1016/J.Apm.2014.11.009

[12] Machado, M. R., & Dutkiewicz, M. (2024a). Wind Turbine Vibration Management: An Integrated Analysis Of Existing Solutions,

Products, And Open-Source Developments. Energy Reports, 11(February), 3756–3791. Https://Doi.Org/10.1016/J.Egyr.2024.03.014
[13] Machado, M. R., & Dutkiewicz, M. (2024b). Wind Turbine Vibration Management: An Integrated Analysis Of Existing Solutions, Products, And Open-Source Developments. Energy Reports, 11(December 2023), 3756–3791. Https://Doi.Org/10.1016/J.Egyr.2024.03.014
[14] Okokpujie, I. P., Akinlabi, E. T., Udoye, N. E., & Okokpujie, K. (2021). Comprehensive Review Of The Effects Of Vibrations On Wind Turbine During Energy Generation Operation, Its Structural Challenges And Way Forward. Lecture Notes In Mechanical Engineering, January, 935–948. Https://Doi.Org/10.1007/978-981-15-4488-0_79
[15] Panagiotis, C. J. (2024). Vibrations And Damping Mechanisms In Wind Turbines : Challenges And Advances In Material Design And Control Systems. 11(11), 1–19. Https://Doi.Org/10.17148/IARJSET.2024.111101
[16] Sumair, M., Aized, T., Gardezi, S. A. R., Rehman, S. M. S., & Ur Rehman, S. U. (2021). Investigation Of Wind Shear Coefficients And Their Effect On Annual Energy Yields Along The Coastal Sites Of Pakistan. Energy Exploration And Exploitation, 39(6), 2169–2190. Https://Doi.Org/10.1177/0144598720930422
[17] Zhang, Z., Li, X., Larsen, T. G., Sun, T., & Yang, Q. (2024). Pole-Placement-Based Calibration Of An Electromagnetically Realizable Inerter-Based Vibration Absorber (IDVA) For Rotating Wind Turbine Blades. Structural Control And Health Monitoring, 2024. Https://Doi.Org/10.1155/2024/7255774
[18] Zhu, C., & Li, Y. (2018). Reliability Analysis Of Wind Turbines. Stability Control And Reliable Performance Of Wind Turbines. Https://Doi.Org/10.5772/Intechopen.74859