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Performance Analysis and Simulation of a 1.5 MW Wind Turbine under Specific Wind Conditions

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Abstract
In this research, the performance of a 1.5 MW horizontal-axis wind turbine (HAWT) was studied. The primary objective was to simulate the mechanical to electrical energy conversion process in a small wind turbine system and analyze the turbine output under different wind speeds and blade radii. A mathematical model was developed based on basic aerodynamic principles, including kinetic energy extraction, power coefficient (Cp), and tip speed ratio (λ). The simulation was performed using MATLAB/Simulink, incorporating real wind speed data from selected cities in Nigeria. Key parameters such as output power, mechanical torque, and electrical torque were monitored and analyzed. The results demonstrate the turbine's characteristic power curve and its dynamic response to wind speed changes, achieving a power output close to its rated capacity. The results provide insights into the optimal setup for wind power generation under similar climatic conditions and contribute to feasibility studies for wind farm projects.

Keywords: Horizontal-Axis Wind Turbine (HAWT) ,Wind Energy Conversion ,MATLAB/Simulink Simulation ,wind turbine, Renewable Energy Systems ,Turbine Performance Analysis ,Wind Turbine Modeling.

1. Introduction

The global shift to renewable energy sources has become an urgent necessity, given the pressing environmental challenges and dwindling fossil fuel reserves. Although fossil fuels still dominate global energy consumption today, the limited availability of these reserves and the large greenhouse gas emissions resulting from their combustion pose a serious threat to the planet's environment [1]. Wind energy is emerging as a viable option among renewable energy sources, as it harnesses the kinetic energy of wind to generate electricity without any environmentally polluting effects. Wind energy is characterized as an inexhaustible resource due to its availability over wide areas. Compared to traditional fossil fuel sources, wind energy has clear development potential and advantages, making it a promising alternative . In the context of the contemporary green energy industry, wind energy technology is considered the most mature and widespread among renewable energy sources to date [2].

Wind turbines can be utilized as a direct source of mechanical energy or as an indirect source, converting the kinetic energy of the wind into rotational energy within the turbines, and subsequently into electrical energy . A wind turbine farm typically comprises a potentially large cluster of wind turbines spanning hundreds of square miles . Key components of a wind power system include turbines, capacitor banks, main transformers, transmission lines, and bus bars . The integration of renewable energy sources (solar and wind) with energy storage systems promotes energy diversity and significantly reduces greenhouse gas emissions [3]. Despite the high initial construction costs, many countries increasingly rely on wind energy. For instance, Denmark generated 8% of its power from wind in 2008 [4]. The generation of electricity by wind turbines has recently become both popular and economically viable . There is a strong aspiration to further increase energy production through prominent renewable sources like solar and wind, a goal that is actively being pursued .The wind turbine industry is continuously seeking to reduce both production and maintenance costs [5]. Horizontal Axis Wind Turbines (HAWTs) are the oldest type, offering high torque,

which makes them well-suited for applications such as water pumps. Their blades are relatively uncomplicated and were historically made of wood. Vertical Axis Wind Turbines (VAWTs), on the other hand, are more appropriate for marine and urban environments due to their lower noise levels, enhanced durability, reduced costs compared to HAWTs, and their scalability. However, their aerodynamic performance is generally weaker than that of horizontal axis wind turbines [6].
The most of important uses of wind energy is to pay sailing shrinks and grinding grain by air rows that were converted to mechanical energy for rotating rows , and wind pumps that were used for pumping water too . electricity from the wind is generated using the turbines, the first time the wind power was transferred to electrical power in Scotland in 1887 . the air turbines are placed in areas where high wind are available , with different forms and sizes based on the purpose , and are generated by electricity generators when the frequency of the turbines fans move electricity. Despite the many studies on wind energy, each researcher has approached it according to his own field of interest and vision. Since the seminal works of Betz (1920) and Joukowsky (1920)[7], substantial research efforts have been made in the field of wind-turbine aerodynamics, and particularly in the optimization of horizontal-axis wind turbine (HAWT) rotors. Glauert (1935) achieved a major breakthrough when he formulated the blade-element momentum (BEM) theory. In the 19th century, some individuals supported the advancement of this technology. Notable among them were Charles F. Brush, who had researched wind turbines by 1888 . Poul La Cour in 1897 built the first wind turbine in Demark. In 1941, Smith–Putnam developed the first mega sized wind turbine, but the design failed initially, as a turbine blade fell off the system due to poor selection of its material [8]. In particular ,Dabiri (2011) hypothesized that Vertical Axis Wind Turbines (VAWTs) operate with better efficiency when in close proximity compared to isolated conditions, making them more suitable for areas with limited land resources where devices need to be installed closer together. This hypothesis has been confirmed by several more recent works (see, for instance, Brownstein et al., 2016, 2019; Ahmadi-Baloutaki et al., 2016; De Tavernier et al., 2018; Zanforlin, 2018; Alexander and Santhanakrishnan, 2019; and Barnes and Hughes, 2019). To assess the interaction between VAWTs, especially those aligned with the main flow direction, understanding their wake signature and the process of momentum recovery is critical, as it affects the choice of mutual distance in wind farm configurations. Such recovery is a function of both the rotational speed of the turbines and their geometric solidity, depending on their rotor diameter and number of blades [9]. Currently, studies are being conducted in the wind turbine industry to improve their performance.

2. Theoretical Framework and Methodology

Fundamental Formulation The kinetic energy of a moving air can be expressed as:

$$K.E = \frac{1}{2} m V_1^2 \dots\dots\dots\dots\dots (1)$$

The air mass flow rate with the air density (ρ) passes through a certain cross-sectional area (A) at velocity (V_1), is

$$m^\circ = \rho A V1 \dots\dots\dots\dots\dots\dots\dots\dots\dots . (2)$$

The power available in the wind represents the rate of kinetic energy and that leads to following Eq.

$$Pw = \langle \frac{1}{2} * \rho A V_1^3 \rangle \dots\dots\dots\dots\dots . (3)$$

The angular velocities (ω) of the rotor blades can be estimate from the rotor rotational speed (N) and can be written as:

$$\omega = (2\pi N / 60) \dots\dots\dots\dots\dots\dots . \dots (4)$$

The tip rotor blade velocities (v) , at the blade tip (R) are estimate from the angular velocity multiplied by the rotor blade outer radius and can be written as:

$$v = (R \omega) \dots\dots\dots\dots\dots\dots\dots\dots (5)$$

The tip speed ratio represents the ratio between rotor blade velocities to the upstream wind velocities, which can be written as

$$\lambda = T S R = (R \omega / V 1) = (v / V 1) \dots\dots . . (6)$$

Power Coefficient The ratio of extracted mechanical power by the rotor to the power available in the wind is called the power coefficient, ($C P$) and can be expressed as follows:

CP=[pex/pw]...................(7) Dimensionless parameter

$\boldsymbol{P e x}$ = Power extracted by the rotor.
$\boldsymbol{P w}$ = Power available in the wind

The ratio between the thrust force transfer to the shaft of wind turbine rotor, to the thrust force exerted by the wind on the rotor is called thrust coefficient, (C_{FT}) and can be formulated as follows:-

$$CFT = [F/ 0.5 \times \rho \times V_1^2 \times R] \;.... (8) \; Dimensionless\ parameter$$

The ratio between the torque transfer to the shaft of wind turbine rotor, to the torque exerted by the wind on the rotor is called torque coefficient, (CT) and can be formulated as follows

$$\mathrm{CT} = [\mathrm{T}/ 0.5 \times \rho \times \mathrm{V}_1^2 \times \mathrm{A} \times \mathrm{R}] \ldots\ldots \ (9) \text{ Dimensionless parameter}$$

Relation Between $\boldsymbol{CP}$ & $\boldsymbol{CT}$

$$\frac{\mathrm{CP}}{\mathrm{CT}} = \frac{\mathrm{Pex}}{0.5\, \rho\, \mathrm{A\, V13}} \times \frac{0.5 \times \rho \times \mathrm{V}_1^2 \times \mathrm{A} \times \mathrm{R}}{\mathrm{T}}$$

$$\frac{\mathrm{CP}}{\mathrm{CT}} = \frac{\mathrm{Pex} \times \mathrm{R}}{\mathrm{T} \times \mathrm{V1}}$$

$$\frac{\mathrm{CP}}{\mathrm{CT}} = \omega \times \frac{\mathrm{R}}{\mathrm{V}_1} \to \frac{\mathrm{CP}}{\mathrm{CT}} = \lambda \qquad \ldots\ldots\ldots \ (10) \text{ Dimensionless parameter}$$

Wind Speed Variation with Height (Wind Shear)

$$V_z/ V_h = (z/h)^m$$

$\boldsymbol{h\ o}$ = Reference height ,

$\boldsymbol{m}$ =exponent that depends on the roughness height

$$\frac{Vz}{Vh} = \frac{ln(\frac{z}{zo})}{ln(\frac{h}{zo})} \quad \ldots\ldots\ldots\ldots (11)$$

$\boldsymbol{z\ o}$ = Roughness height

also the Capacity factor is ratio of the energy actually produced by the system to the energy that could have been produced by it, if the machine would have operated as its rated power throughout the time period.

$$C_F = \frac{E_T}{T\, P_R} \qquad \ldots\ldots\ldots\ldots (12)$$

while Efficiency is:

$$power\ in = \frac{1}{2} * \rho A_t U_t U_u^2$$

$$power\ out = 1/4 * \rho A_t\, U_t\, U_u^3\, (1 - U_d^2/U_u^d)(1 + U_d/U_u)$$

$$\eta = \frac{power\ out}{power\ in}$$

Simulation model of a 1.5 MW wind turbine was developed in Simulink, an approach validated for such studies. The input parameters for the simulation are listed in Table[1]. The model was tested using recorded wind speed data from Nigerian sites ,and the blade radius was varied to observe its impact on the output, a key parameter in turbine design and scaling .

Rated power	1.5MW
Frequency	60HZ
Stator voltage	575V
DVR capacity	1.5MVA
Phase(deg.)	0
Nominal power	$4*10^6$
Capacitive reactive power	$400*10^3$ Var
Resistance	66 Ohms
Base power	$10*10^6$ VA
Rated wind speed	12 m/s
R (Pu)	0.025/30
L (Pu)	0.025
Lm(pu)	Inf

Table [1], Simulation Input Parameters.

3. Results and Discussion

Figure [1] presents the MATLAB/Simulink simulation model developed to analyze the performance of a grid-connected wind power system. This model incorporates essential components such as a three-phase programmable voltage source representing the electrical grid, a three-phase transformer, a three-phase RLC load, along with the pivotal component: the Wind Turbine Induction Generator (Phasor Type). Through this model, we were able to monitor and measure a range of vital parameters for the system's performance, which are clearly displayed in the 'Displays' blocks and 'Scopes' on the right side of the model.

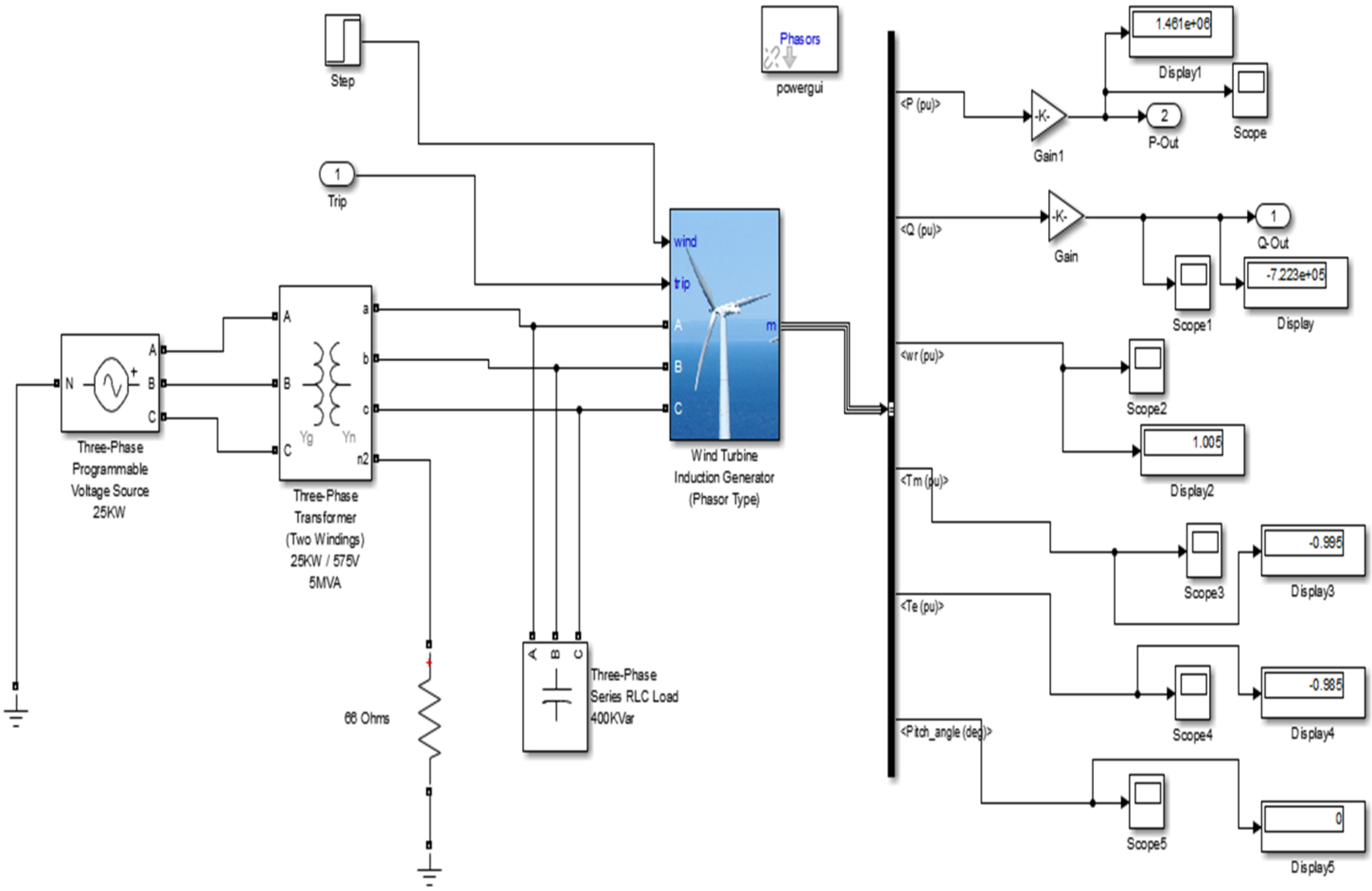


Figure [1], Modeling and simulation of 1.5 MW Wind Turbine

For instance, the active power (P-Out) and reactive power (Q-Out) generated by the turbine were measured. These measurements provide direct insights into the energy conversion efficiency and the dynamic response of the generator. Furthermore, the mechanical torque (Tm) and the electrical torque (Te), along with the pitch angle, were observed, all of which are crucial factors in understanding the turbine's control behavior and its response to variations in wind speed. Upon running the simulation under steady-state conditions, the key results were obtained shown in Table[2]:

P(pu)	1.461e+06
Q(pu)	-7223e+05
Wt(pu)	1.005
Tm(pu)	-0.995
Te(pu)	-0.985
P(toh)_angle(deg.)	0

Table 2: Simulation output Parameters.

These numerical results highlight the operating point of the system and its interaction with the grid and load. The positive value for active power (P) indicates power generation by the wind turbine, while the negative reactive power (Q) suggests that the generator is absorbing reactive power from the grid (or supplying it, depending on convention and power factor compensation). The close values of mechanical and electrical torques demonstrate the efficient power transfer. The wind turbine speed remaining close to 1 pu and a pitch angle of(0) degrees indicate stable operation under the simulated conditions.

This simulation serves as a fundamental tool for evaluating the system's stability and the wind generator's performance under various operating conditions, thereby allowing for an analysis of the impact of factors such as electrical load and voltage source variations on power generation efficiency and grid stability.
The figure [2] illustrates the power characteristics of a wind turbine at a fixed pitch angle, showing how output power varies with turbine speed and different wind velocities. We observe that for each wind speed, there is an optimal operating point to achieve maximum power. As wind speed increases, the maximum extractable power significantly rises.

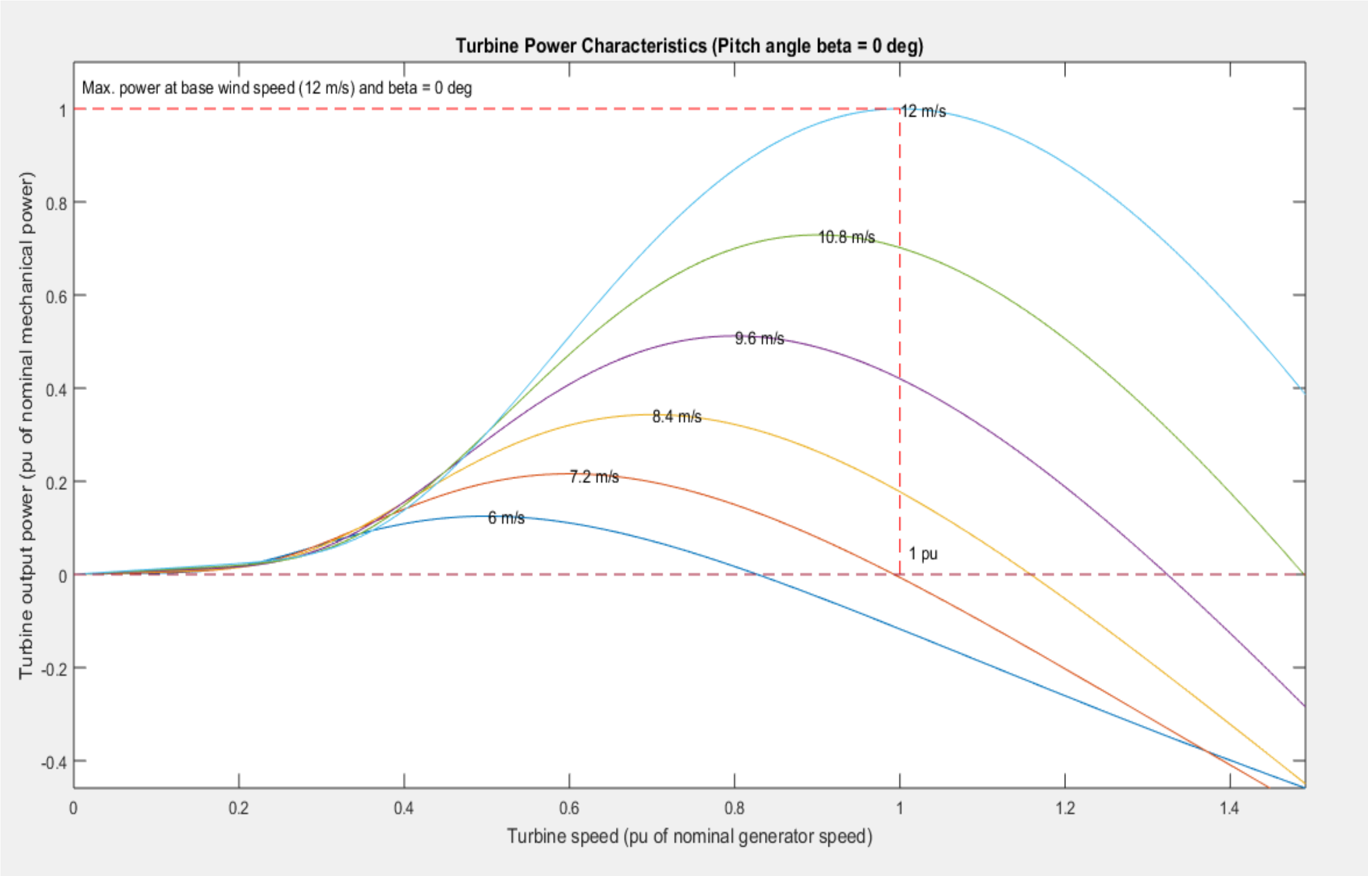
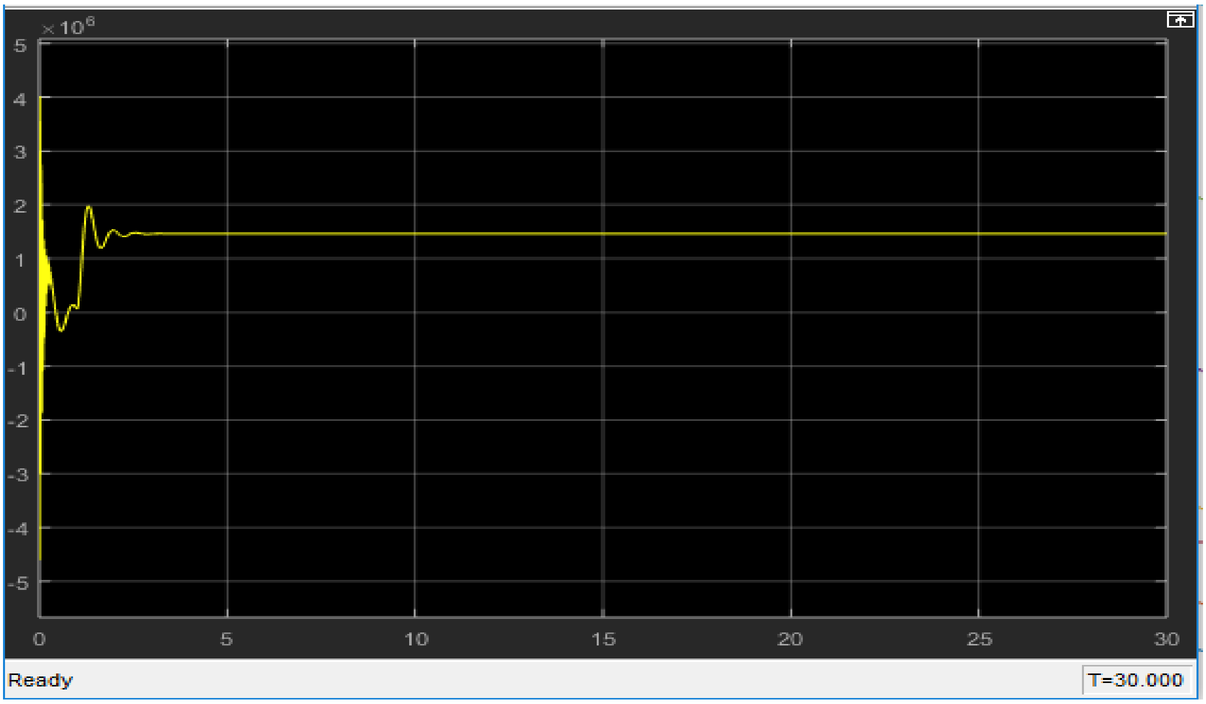


Figure [2], Wind speed(rad/s) VS wind speed 12 to 25

Output Power and Torque: The temporal variation of output power (Figure 3), mechanical torque (Figure 4), and electrical torque (Figure 5) were analyzed. After initial transient oscillations, the results indicate stable operation under the simulated conditions, with the mechanical torque (Tm) closely tracking the electrical torque (Te), as expected in a well-regulated system .



Figure[3],Output power response with time.

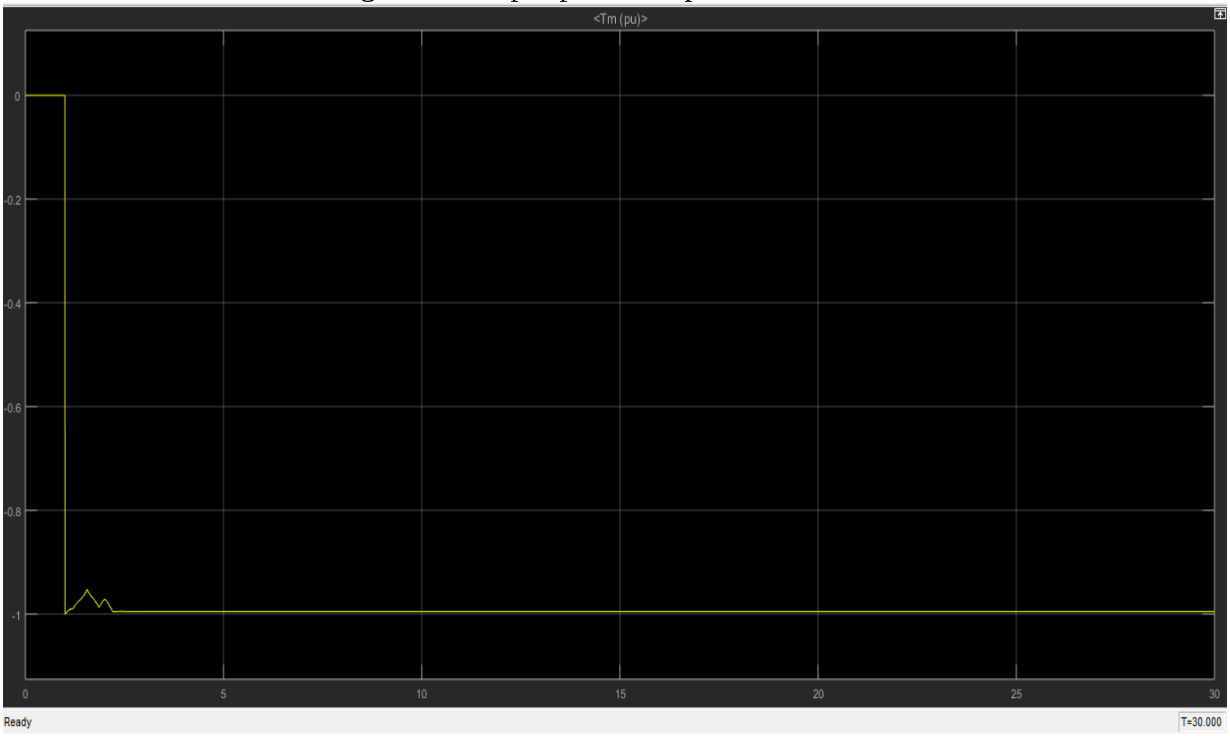


Figure [4] ,Turbine mechanical torque variation with time.

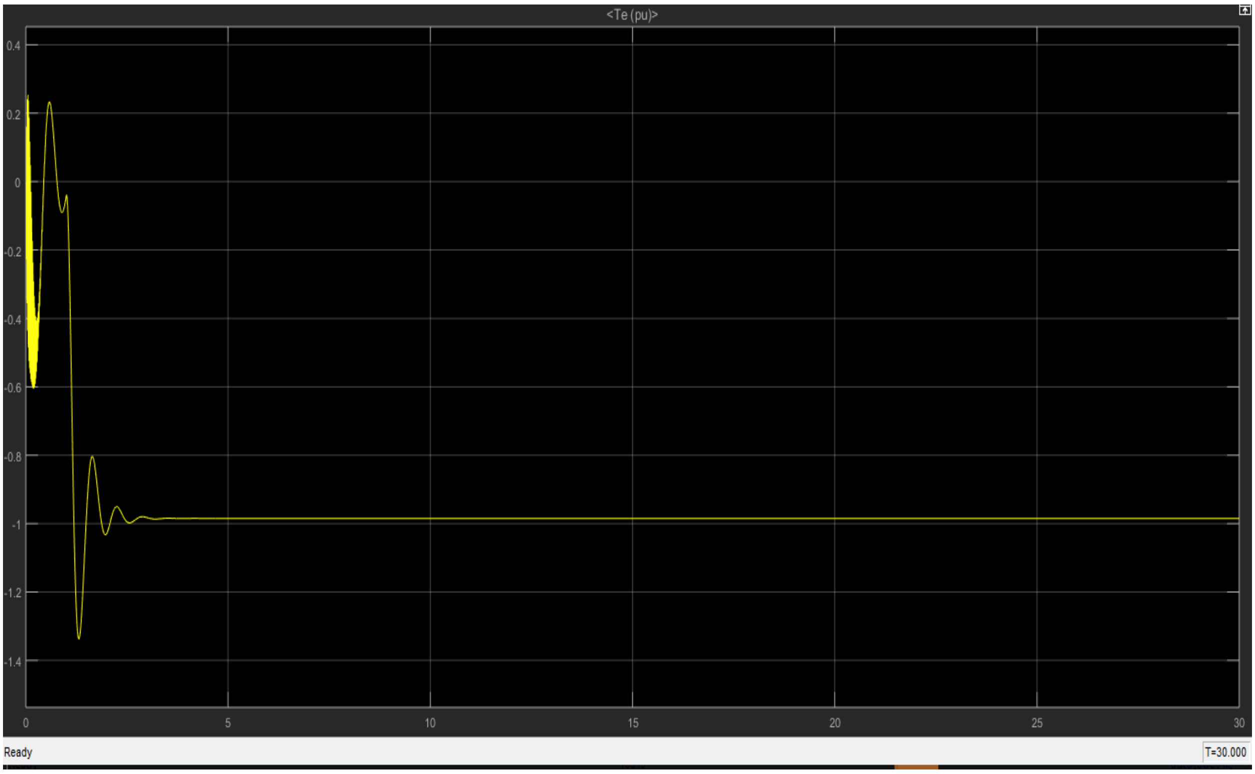


Figure [5] ,Turbine electrical torque variation with time.

The output power of approximately 1.46 MW (pu) achieved in the simulation is close to the rated capacity, indicating good model efficiency and aligning with performance expectations for modern HAWTs . The fluctuations in torque over time can be attributed to the simulated wind speed variations, a common challenge in wind turbine dynamics . The relationship between Cp and λ was crucial in achieving these results, consistent with foundational and contemporary theories . The findings are particularly relevant for the assessed regions in Nigeria, which show promising potential for wind energy deployment .

4. Conclusion

This study successfully modeled and simulated a 1.5 MW wind turbine using a MATLAB/Simulink environment. The results confirm the theoretical relationship between wind speed, blade geometry, and power output, consistent with established and recent research . The model effectively demonstrated the dynamic behavior of key parameters like power and torque. For future work, it is recommended to incorporate more complex wind models (e.g., with turbulence) and conduct a detailed techno-economic analysis for deployment in the target regions, especially given the declining costs of wind energy . This research serves as a foundational step for optimizing wind turbine performance in specific geographical locations and contributes to the broader understanding of wind system dynamics .

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