International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9 Issue-1, November 2019

Renewable Energy: Dynamic Modelling of a Wind Turbine

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***Abstract*: Recently, much attention has shifted to a renewable source of energy, as depletion of existing source hovers significantly. The wind turbine has become one of the preferred alternatives of power generation as it poses less risk as well as its economic and environmental benefits, which has prompted renewed effort in designing the optimum system.**

This work details the operation of a horizontal axis wind turbine along with the complexities of various parts, for example, streamlined transformation, drive train, and generator representation. Additionally, the conditions portraying its dynamic conduct were successfully simulated using MATLAB/SIMULINK, which is necessary to understand its behaviour over specific regions of operations, which differs significantly. The result of this modelling helps in the development of a comprehensive controlling algorithm to aid the performance of the system. This project, therefore, entails the design of a suitable wind energy conversion framework used as an independent, stand-alone energy generator for remote communities in Nigeria. The result of this modelling will be useful in designing better-performing turbines at a reduced cost to ensure economic viability.

Keywords: MATLAB, Renewable Energy, Simulation, Wind turbine.

I. INTRODUCTION

With increasing prices of fossil fuel together with the abatement in their stores, it is fundamental that elective techniques for energy production be explored and acquainted on a worldwide scale with keep up our standard of life. Power generation and demand have become more challenging along with the environmental impact of fossil fuel utilisation which includes increasing carbon footprint with increasing demand, rapid depletion of resources, etc. For over four decades, the Nigerian government has not been able to provide an uninterrupted power supply [1] successfully. The implementation of independent, renewable energy to meet this need is essential. Wind energy can satisfy need necessities, and a few inquiries have been conducted on improving the efficiency of this source of energy [2]. This research has resulted in about a 90% decline in the cost of wind-generated energy over the years.

Revised Manuscript Received on November 30, 2019.
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Several other alternatives to fossil fuel were discovered, such as geothermal, wave, tide, biomass, etc., however, wind energy remains the method of choice due to its eco-friendly attributes. Wind turbine produces energy by conversion of dynamic energy from the wind, which is utilised in the rotation of the shaft to generate Electromagnetic force which yields electrical energy desired. Wind energy has also been used in the past for mechanical power, ship sailing, etc.
The utilisation of wind energy is expected to increase significantly due to the new sustainable development initiative pioneered by the United Nations General Assembly in 2015 [3]. Although recent technology allows for utilisation of other renewable forms, wind energy is anticipated to assume a critical role in achieving this initiative. According to [4], it is theoretically possible to generate 1000TWh of annual energy form wind.

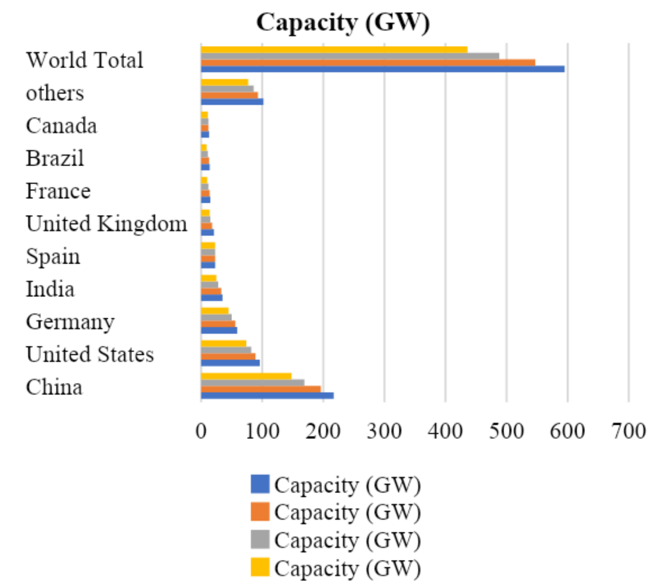

Fig. 1.Distribution of wind power capacity [5]
Fig. 2.

As seen in figure 1 above, the utilisation of wind energy increases over the years, with China being the dominant country implementing this technology. Wind turbines arrive in an assortment of structures with changing yields and efficiencies; however, all convert the kinetic energy contained in an airstream into mechanical work. The most widely recognized kind of wind turbine is the Horizontal pivot wind turbine, which generally is limited to between one to three blades. Shu et al. [6] and Weis [7] research showed that the three-axis HAWT configuration was best adaptable to standard wind conditions aside from their being appealing in comparison with other configurations of wind turbines.

Different variety of VAWT is also being utilised in electricity generation. Nevertheless, they cannot attain a high level of power coefficients as their horizontal-axis counterparts [8], as they were initially designed for drag type rotors.

II. TURBINE MODELLING

The doubly-fed induction generator is widely utilised of all the configurations of wind turbines due to its economical solution and power quality, which surpasses the fully rated converter turbines. Several considerations in designing turbines are energy extraction, aerodynamics, mechanical, and electrical components. The engineering of wind turbine construction also entails designing and manufacturing of rotor blades whose aerofoil properties authorise smooth propulsion of the rotor by low wind speed. It also demands the design and fabrication of a smooth moving rotor shaft in the requisite size of bearing to withstand the weight and achieve a frictionless motion [8]. It calls for a tower design to endure extreme wind conditions, as well as form a formidable framework for the rotor bearing housings, gearboxes (as the case may be), and the machine or alternator.

Models used steady-state analysis are relatively straight forward. However, dynamic modelling which takes other factors like stability, control mechanism, optimisation, etc., it necessary. According to [9], the modelling is comparatively simple due to the use of standardised models and process controller as well as readily available data. But in modelling wind turbines, there is not enough data or structures control system leading neglect of control systems in manufacturing design, which significantly impacts the reliability of analytical results

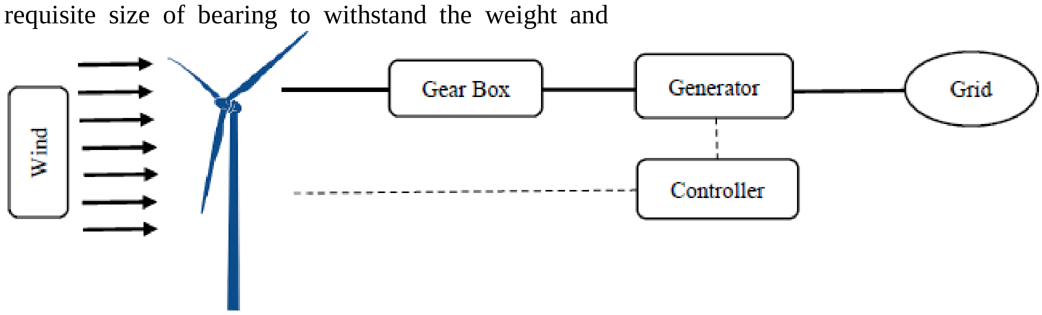

Fig. 3.Figure of wind turbine

The utilisation of wind energy requires a suitable model that is efficient for the prevailing environmental properties of its installation location. Despite advances analysis tools, numerical algorithms of large mathematical models still require simplification of individual components. Although this is preventable by the utilisation of advanced supercomputers, it is not an economical option. Several research efforts in reducing computational effort and simulation time have been carried out [10] [11]. The model studied by [12] showed clustered wind turbines in a wind farm with similar wind speed. In [13], the summation of torques of each turbine which was fed to an equivalent generator. A transfer function represented the Variable speed turbines shown in [14].

III. BLADE MODELLING

The design, shape, and turbine rotor blades centre on the size of the turbine and its rated energy yield. Expecting no wake and drag, the most extreme reachable power coefficient of the turbine will occur with a pivotal induction viewpoint of one-third [15]. Using this assumption, an idyllic blade shape can be modelled by utilising the blade element and momentum (BEM) equations to adequately analyse the parameters that are crucial in design through the determination of forces due to fluid motion along with the blade geometry. The result of the analysis will estimate the maximum power at the structured tip speed proportion of the actual turbine. Similarly, it is noticed that drag and lift act parallel and perpendicular, individually, to the effective or relative wind along the sections of the blades. The kinetic energy in the air is therefore given as

$$E = \frac{1}{2}mv^2 = W = Fs \tag{1}$$

But giving Newton's Law:

$$F = ma \tag{2}$$

Hence, with an initial velocity of the object being zero,

$$a = \frac{(v^2 - u^2)}{2s} = \frac{v^2}{2s} \tag{3}$$

The wind power is given as:

$$P = \frac{dE}{dT} = \frac{1}{2}v^2\frac{dm}{dt} \tag{4}$$

mass flow rate is given as:

$$\frac{dm}{dt} = \rho A\frac{dx}{dt} \tag{5}$$

while the rate of change of distance is:

$$\frac{dx}{dt} = v \tag{6}$$

Substituting $\frac{dx}{dt}$ into $\frac{dm}{dt}$, we get:

$$\frac{dm}{dt} = \rho Av \tag{7}$$

Hence, power can be defined as:

$$P = \frac{1}{2}\rho Av^3 \tag{8}$$

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DOI: 10.35940/ijitee.A4411.119119
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Hypothetically, the maximum power efficiency of wind turbines is 0.59 (which is approximately fifty-nine percent of wind energy). This is the Betz Limit, and it is defined as:

$$C_{pmax} = 0.590$$

Although turbines do not function at this maximum limit. The value of its coefficient of performance is unique to the turbine type and wind speed of its operating environment. The collectable wind power is:

$$P_{avail} = \frac{1}{2}\rho A v^3 C_p \qquad (9)$$

Where the turbine swept area is given as

$$A = \pi r^2 \qquad (10)$$

The rotor power coefficient is a function of blade tip speed ratio λ and pitch angle β, which is the angle between the rotational plane and cross-sectional chord. The tip speed ratio is given as

$$\lambda = \frac{\omega_m . R}{V} \qquad (11)$$

Rotor torque T_w is given by

$$T_w = \frac{\frac{1}{2}\pi.\rho R^2 v^3 \, C_p(\lambda,\beta)}{\omega_m} \qquad (12)$$

Where the power coefficient is given as

$$C_p(\lambda,\beta) = c_1(c_2\frac{1}{\gamma} - c_3.\beta - c_4.\beta^x - c_5)e^{-c_6\frac{1}{\gamma}} \qquad (13)$$

And γ is defined as

$$\frac{1}{\gamma} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{1+\beta^3} \qquad (14)$$

The thrust acting on the turbine is attained by the equation below:

$$F_A = 4a(1-\alpha)\frac{1}{2}\rho A_1 V_1^2 = C_F\frac{1}{2}\rho A_1 V_1^2 \qquad (15)$$

Where CF is the coefficient of axial force, which is given as 4a(1−α).

The most extreme torque happens when the greatest push is applied to the turbine rotors, the tips of which are at a span R from the centre point focus. The most extreme power or hub push happens when the impedance factor a=0.5, CF=1, and $F=\frac{1}{2}\rho A1V_1^2$. The maximum torque is expressed as:

$$T_{max}=12\rho A_1 V_1^2 R \qquad (16)$$

The actual torque created is less than the maximum torque and can be acquired by a product of the maximum torque and the torque coefficient, which reliant on the design and rotor system utilised.

$$T=CTT_{max} \qquad (17)$$

Where CT is the torque coefficient. The mechanical power is, therefore,

$$PT=T\omega \; PT=CTT_{max}\omega \qquad (18)$$

Where ω is the angular velocity in rad/s.

Both synchronous and DC motors can be utilised as the preferred generators. When the load is detached, the motor will still induce magnetizing current with a significant drop in output power. The application of mechanical power to the rotor shaft initiating further rotation leading to an expansion in speed to a point where it is spinning above synchronous speed, the previous induction motor starts to work as an induction generator, at which point the value of slip approaches a negative number. The rotor conductors are therefore moving at speed more prominent than the revolving flux, implying that the movement of the rotor conductors with respect to the motion will alter in course. This will result in the change of the course of the rotor current, and an inversion in the electromotive flux being produced in the stator winding. This subsequently prompts electric power streaming out of the stator windings as it is moving toward an electric generator.

The total performance of the turbine can be described by the level of variation in the three key pointers, which are the power, torque, and thrust for a range of varying wind speeds. Generally, the turbine performance is expressed in non-dimensional charts from which any turbine's exhibition can be assessed, paying little respect to its operational circumstance, consistent pivot, variable rotor speed, etc. Most frequently, the coefficient of power, thrust, and torque are recorded as an element of the tip speed proportion λ. The tip speed ratio is the fraction of the rotor tip speed to the wind speed. wind speed fluctuates with stature and can be sensibly approximated in the accompanying relationship [16]

$$V = V_r In \frac{\frac{z}{z_0}}{\frac{z_r}{z_0}} \qquad (19)$$

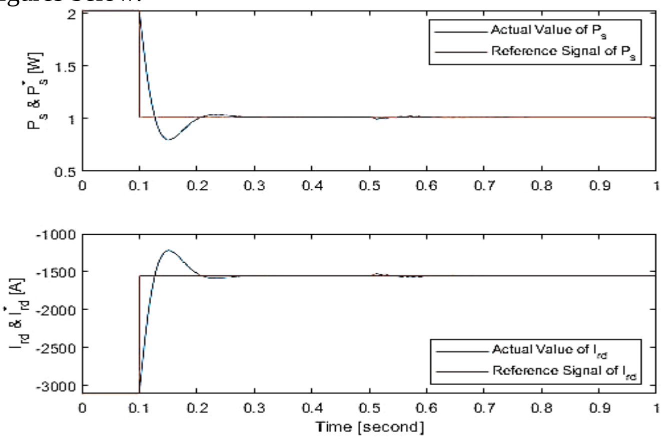
Where V is the horizontal velocity, Z is the height, Z_0 represents roughness length, Z_r is the reference height, and V_r is the wind speed at reference height.

$$\text{The velocity of the hub (U)} = U_{ref}\left[\frac{hub\ height}{H_{ref}}\right]^{1/7} \qquad (20)$$

IV. DISCUSSION

In simulating this wind turbine, the examination of the DFIG controller was implemented and simulated using MATLAB Simulink, which simulated features such as load flow, fluctuations, transient and output power, etc. The model also describes the effect of fluctuations in wind speed on power output. It is seen that output power is affected by blade swept area and condition of flow at the rotor.

Wind turbines usually function at wind speed between 5m/s to approximately 25m/s. An average wind velocity of 6m/s was selected based on average annual measured windspeed in Lagos, Nigeria. Additionally, A 4-pole generator was selected, and the results of the simulation are shown in the figures below.



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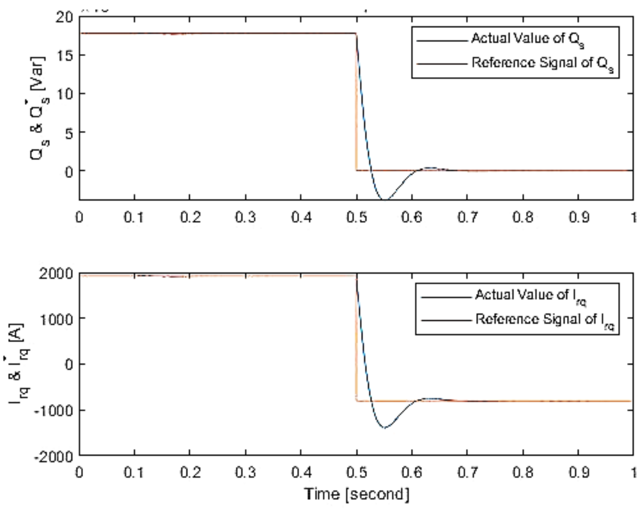
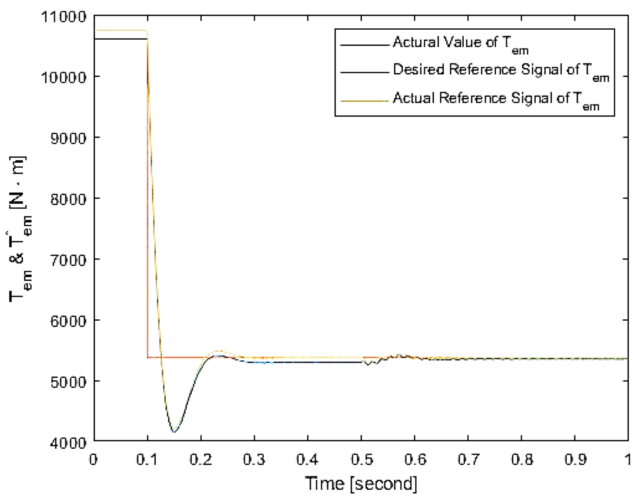


(b)

Fig. 4.(a)Simulation of control effect with reference signal i_{rd} (b) i_{rq}



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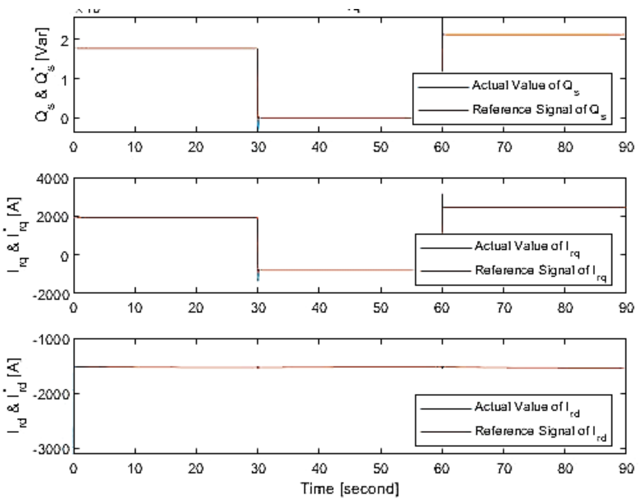
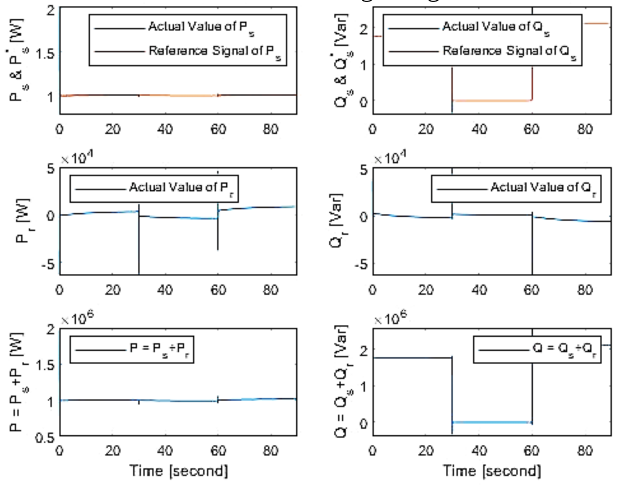


(b)

Fig. 5.(a)Simulation of electromagnetic torque T_{em} (b) Control effect of i_{rq}

Figure 4 above shows that actual reference signal is desired, and the space seen between the actual electromagnetic torque and desired outcome is as a result of losses due to truncation errors in calculation. The figure 4b also shows the graph of reference signals. It is seen that varying the values allows for more control and tracking of signals.



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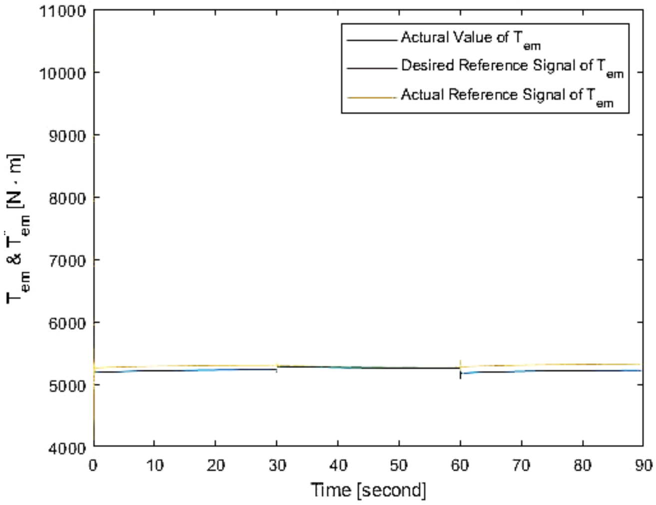

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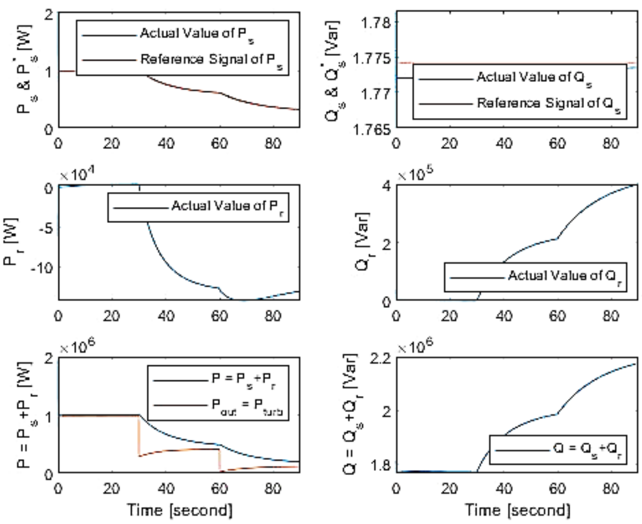
Fig. 6.(a)Power simulation (b) electromagnetic torque T_{em} and its reference signal



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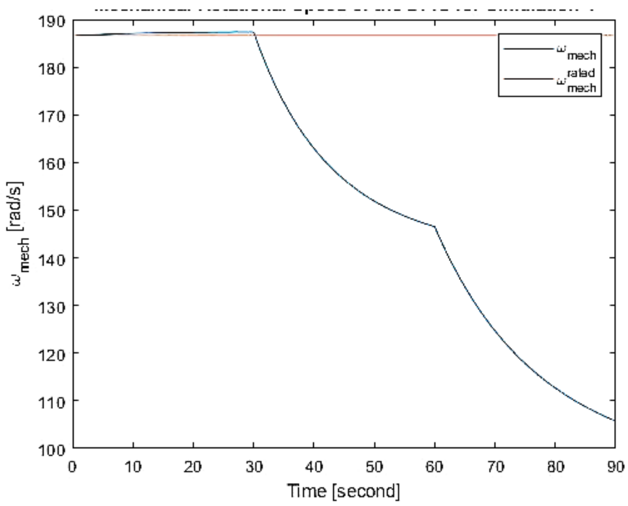
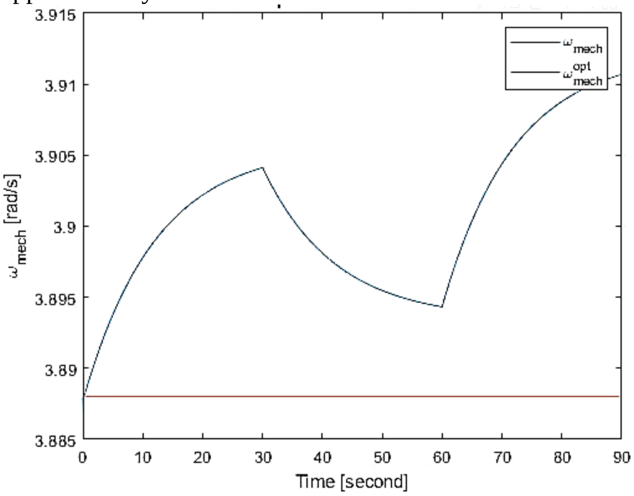


(b)

Fig. 7.(a) Real and Reactive Power of DFIG (b) rotational Speed of DFIG

By assuming constant wind velocity in the turbine, input power is constant; hence, the output power will remain unchanged given that variation in rotational speed is negligible. From the simulation result, the output power was approximately $2.01{\times}10^6$ W.



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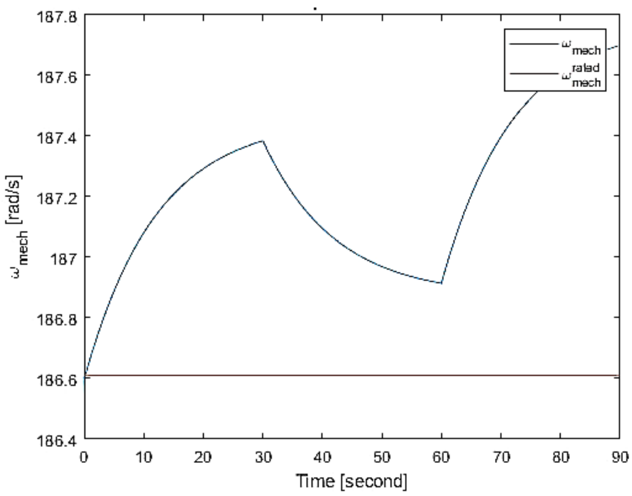
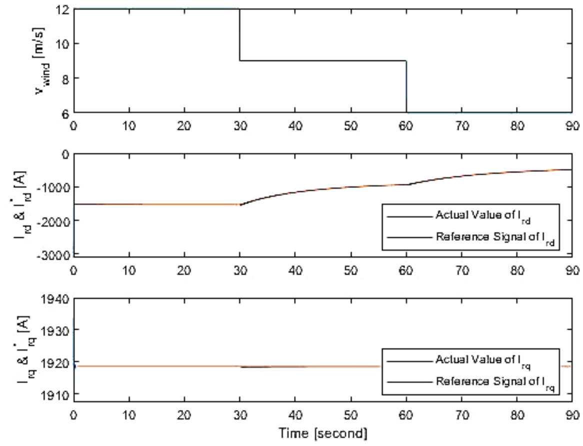


(b)

Fig. 8.(a) Turbine rotational speed (b) DFIG rotational speed

Figure 7 above indicated that the mechanical speed of the DFIG and turbines is not fixed at the ideal or optimum point. However, the variation is negligible, making the system reliable.



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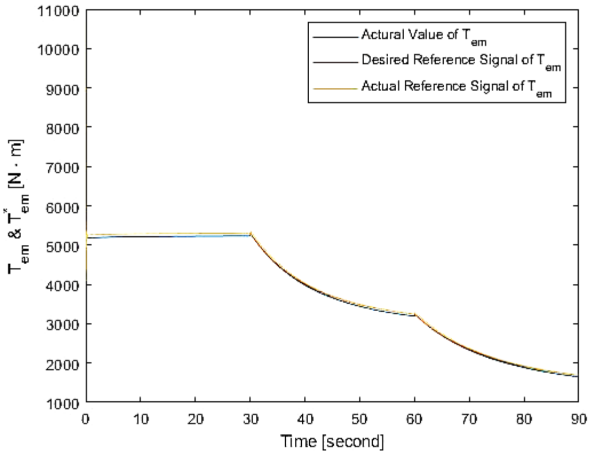

(b)

Fig. 9.Simulation of (a) control effect of i_{rd} (b) T_{em} and its reference signal

V. CONCLUSION

This paper presented the modelling and simulation of a wind turbine consisting of the blades, generator, and other parts. Power quality was studied and modelled using MATLAB to review control strategies and assess the performance of the model Likewise, simulation of turbine reaction to variations in wind speed and blade pitch revealed performance under the pre-set conditions. From the simulation, it is seen that the rotor output voltage can be varied using the design controllers.

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