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Modelling and Control of a Small Domestic Wind Turbine

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ABSTRACT

A wind turbine is a machine that converts the kinetic energy of wind into mechanical energy like wind turbines. This mechanical wind power has been used through the ages to pump water or grind grain. Current machines are used to produce wind-type electricity which is consumed locally (isolated sites), or injected into the electricity network (wind turbines connected to the network). In this work, we are only interested in the modelling of a three-bladed horizontal axis wind turbine. All the models were developed by the Matlab/Simulink software, which makes it possible to set up fairly quickly models as well as the associated. The results revealed that the wind profile ranges between 6-7 (m/s), the power coefficient C_p for a pitch angle of =2 has an average value of 0.54 with a relative speed λ value of 6.40, and when the origin of electrical losses is ignored, the electrical power equals the electromagnetic power, and the mechanical speed is stable between (70-80 rd/s).

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1. INTRODUCTION

Wind energy is one of the clean renewable energies. It is the movement of air from one place to another caused by differences in atmospheric pressure over the earth. Wind can be classified into two types, global and local. However, global wind corresponds to large air movements and local wind corresponds to small movements in a specific part of the earth (Wang *et al.*, 2019). A wide range of devices can convert ambient energy (solar rays, heat, wind, water flow, geothermal energy, etc.) into a form more useful for human beings (Khechekhouche *et al.*, 2019; Ghodbane *et al.*, 2020; Khechekhouche *et al.*, 2021; Hadjadj *et al.*, 2020). Wind turbines are among the best known and most accessible devices for converting ambient energy into electricity (Yang *et al.*, 2018). However, wind power, like most other renewable energy sources, has high investment costs, but over the past few years, this trend has changed significantly. Investigations show that the cost of wind generation has fallen (Martinez et al., 2022). This progression has enabled the construction of wind power plants in several developing countries (Pavlowsky et al., 2021).

Many scientists have focused their work on defining the shape and structure of wind turbines and their effects on aerodynamics (Yeter *et al.*, 2022; Albert *et al.*, 2019). Others have tried to improve the performance of turbines from a mechanical and electrical point of view by optimizing the placement and height of the hub (Taghinezhad *et al.*, 2021; Zhou *et al.*, 2022). Despite these efforts, wind speed remains the main factor of this device and this factor is uncontrollable and this makes the production of wind energy difficult for certain places (Asadi *et al.*, 2021). To overcome this problem, researchers have worked on simulation and several studies have been published using more or less sophisticated software (Sung-ho Hur, 2018; Leisten *et al.*, 2018; Saidi *et al.*, 2018). The objective of our work is the reinforcement of experimental studies and especially the construction of small prototypes (either domestic or educational or other) by modelling using the Matlab / Simulink software.

2. METHODS

2.1. Modelling of the Horizontal Axis Wind Turbine

The modelling of the turbine consists in expressing the extractable power according to the incident speed of the wind and the operating conditions, its speed of rotation in particular. This will make it possible to know the wind torque applied to the shaft of the wind turbine. Finally, we can obtain a global model composed of three subsystems, the turbine, the multiplier, and the shaft as shown in **Figure 1**.

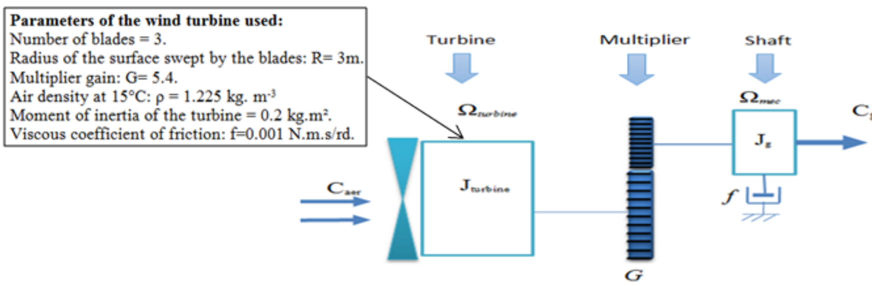

Figure 1. Simplified mechanical model of the turbine.

2.1.1. Modelling of the Turbine

The available power of the wind crossing a surface (*S*) is defined by Equation [1]:

$$P_v = \frac{1}{2}\rho S v^3 \tag{1}$$

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where ρ is the air density (approx. 1.22 kg.m³ at atmospheric pressure at 15°C), and S is the circular area swept by the turbine. The radius of the circle is determined by the length of the blade. In reality, the conversion device (the wind turbine) extracts an aerodynamic power (P_{aer}) that is lower than the available power (P_v), as shown in Equation [2]:

$$\mathrm{P_{aer}} = \mathrm{C_p}.\mathrm{P_v} = \mathrm{C_p}(\beta,\lambda).\frac{1}{2}\rho \mathrm{S v^3} \quad (2)$$

The power coefficient C_p represents the aerodynamic efficiency of the wind turbine ($\frac{P_{aer}}{P_v}$). It depends on the characteristic of the turbine. This coefficient varies with the angle of orientation of the blades (β) and the speed ratio (λ). The speed ratio is defined as the ratio between the linear speed of the blades and the wind speed (see Equation [3]):

$$\lambda = \frac{\mathrm{R}\Omega_{\mathrm{turbine}}}{\mathrm{v}} \quad (3)$$

where $\Omega_{turbine}$ is the speed of the turbine. Knowing the speed of the turbine, therefore the aerodynamic torque is directly determined by Equation [4]:

$$C_{aer} = \frac{P_{aer}}{\Omega_{turbine}} = C_p \frac{1}{2}\rho S v^3 \frac{1}{\Omega_{turbine}} \quad (4)$$

We assume the angle of orientation of β is constant so the coefficient C_p is given by the following Equation [5]:

$$C_p = 7.95633\lambda^5.10^{-5} - 17.375\lambda^4.10^{-4} + 9.86\lambda^3.10^{-3} - 9.4\lambda^2.10^{-3} + 6.38\lambda.10^{-2} + 0.001 \quad (5)$$

Thus, the maximum value of the coefficient C_p is 0.548 corresponding to λ = 6.4.

The multiplier adapts the (slow) speed of the turbine to the speed of the generator. This multiplier is mathematically modelled by the following Equations [6-7]:

$$C_g = \frac{C_{aer}}{G} \quad (6)$$

$$\Omega_{turbine} = \frac{\Omega_{mec}}{G} \quad (7)$$

The mechanical equation that manages this set is given by Equations [8-9]:

$$C_{mec} = C_g - C_{em} - C_{vis}$$

$$C_g - C_{em} = J.\frac{d\Omega_{mec}}{dt} + f.\Omega_{mec} \quad (8)$$

$$J = \frac{J_{turbine}}{G^2} + J_g \quad (9)$$

Using LAPLACE Transfer, we obtain the speed (see Equation [10]):

$$\Omega_{mec} = \frac{1}{Js+f}(C_g - C_{em}) \quad (10)$$

2.1.2. Shaft Dynamic Equation

The mass of the wind turbine is plotted on the turbine shaft as an inertia $J_{turbine}$ and includes the mass of the blades and the mass of the turbine rotor. The proposed mechanical model considers the total inertia J consisting of the inertia of the turbine transferred to the rotor of the generator and the inertia of the generator (see Equation [13]):

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$$J = \frac{J_{turbine}}{G^2} + J_g \quad (13)$$

It should be noted that the inertia of the generator rotor is very low compared to the inertia of the turbine reported by this axis. The fundamental equation of the dynamics makes it possible to determine the evolution of the mechanical speed from the total mechanical torque (C_{mec}) applied to the rotor (see Equation [14]):

$$J.\frac{d\Omega_{mec}}{dt} = C_{mec} \quad (14)$$

where J is the total inertia that appears on the generator rotor. This mechanical torque takes into account the electromagnetic torque C_{em} produced by the generator, the viscous friction torque C_{vis}, and the torque resulting from the multiplier C_g. The resistant torque due to friction is modelled by a viscous friction coefficient *f* (see Equation [15]):

$$C_{vis} = f.\Omega_{mec} \quad (15)$$

By taking into account the inertia and the friction of the bearings the wing can be presented as in **Figure 2**. The electrical equivalent of such an inertial system is shown in **Figure 3**.

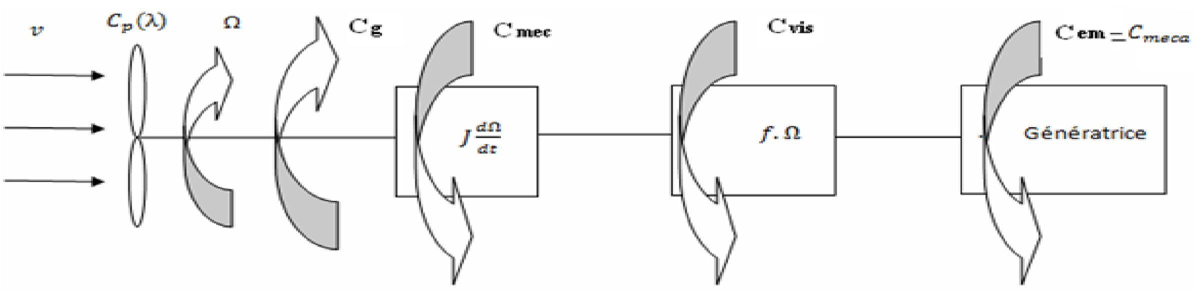

Figure 2. Model of a wind turbine.

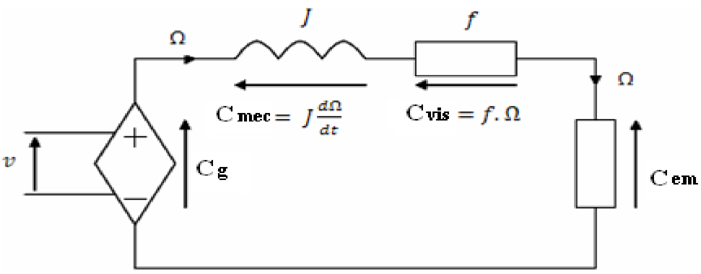

Figure 3. Equivalent electrical diagram of the turbine of a wind turbine.

The mechanical equation that manages such a set is given by Equation [16-17]:

$$C_{mec} = C_g - C_{em} - C_{vis} \quad (16)$$

$$C_g - C_{em} = J.\frac{d\Omega_{mec}}{dt} + f.\Omega_{mec} \quad (17)$$

From where in the transfer of LAPLACE one can obtain the speed (see Equation [18]):

$$\Omega_{mec} = \frac{1}{Js+f}(C_g - C_{em}) \quad (18)$$

2.1.3. Turbine Control Strategy

Figure 4 shows the Power - speed characteristic of a wind turbine. There are four main operating areas.

(i) Zone1: From a certain minimum speed necessary to drive the wind turbine, the wind turbine begins to rotate.
(ii) Zone2: From a certain threshold speed of the generator (corresponding to a slip of 30%), a control algorithm allowing the extraction of the maximum wind power (MPPT) is applied. The pitch angle is maintained at its minimum value which corresponds to the maximum of the power coefficient.
(iii) Zone3: Beyond, the wind turbine operates at a constant speed. In this zone, the power reaches up to 90% of its nominal value.
(iv) Zone 4: arrival at nominal power, the speed must be limited, this is the phase where speed limitation occurs by blade orientation (pitch angle), this is "Pitch Control" (Zhou *et al.*, 2018).

In the following, we are interested in zone 2 or the maximization of the electrical energy extracted, this operation is carried out by controlling the electromagnetic torque generated.

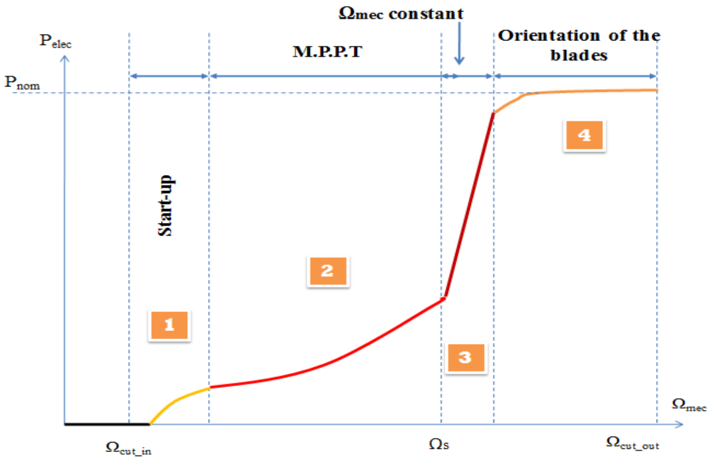

Figure 4. Power - speed characteristic of a wind turbine.

2.1.4. Maximization of Power Extracted

In practice, the rotation speed is controlled by the electromagnetic torque, to maximize the electrical power generated, this is the principle of MPPT. There are two command structures: Mechanical speed servo control and Control without mechanical speed control. It is difficult to accurately measure the wind speed which is by nature a very fluctuating quantity. An erroneous measurement of the speed, therefore, leads to a degradation of the power captured according to the MPPT technique. This is why most wind turbines are controlled without speed feedback (Zhou *et al.*, 2018).

3. RESULTS AND DISCUSSION

3.1. Characteristic of the Power Coefficient Evolution

Figure 5 represents the power coefficient characteristic as a function of the relative speed λ. Note that any increase in speed ratio will be tracked by the power coefficient C_p. Note that the maximum values are 6.401 for speed ratio λ and 0.5483 for the C_p.

3.2. Wind Profile

Our simulations are focused only on the mechanical part of the wind turbine. They are made in the MATLAB/SIMULINK environment and this allows us to develop control block diagrams and associate them with machine models. Note that we are not going to connect the propeller and the multiplier to a generator but simply observe the torque produced at the

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output of the multiplier according to the evolution of the wind. To do this, we need the value of the electromagnetic torque multiplier, torque which would be imposed by the generator according to the power it produces. We are therefore going to set ourselves a reference torque and use the wind profile to validate the model established previously. We will observe the shape of the mechanical speed and the reference power according to the evolution of the wind. **Figure 6** shows this wind profile that will be applied for the wind turbine, which varies between 6-7 (m/s).

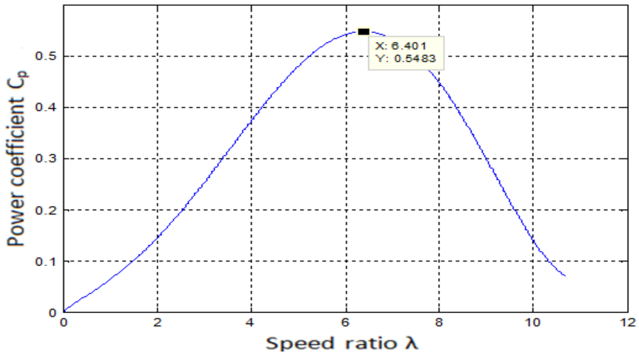

Figure 5. Characteristic of the power coefficient evolution.

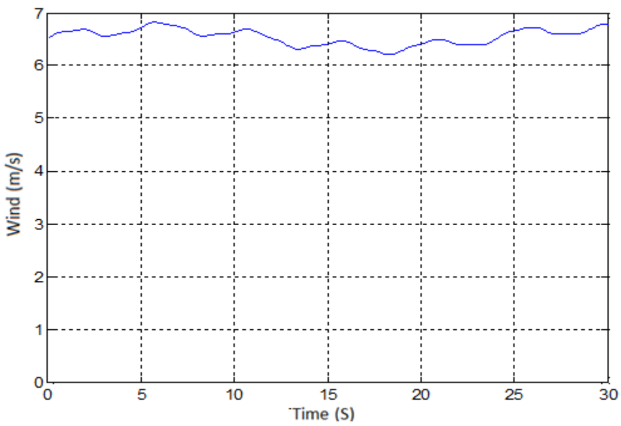

Figure 6. Wind profile evolution.

3.3. Power Coefficient

Figure 7 shows the power coefficient obtained by the wind profile. This power coefficient is obtained for a fixed pitch angle of (β=2˚), which gives us a relative speed λ. We note that the C_p reaches an average value of 0.54, it seeks to be kept as much as possible to maximize production and varies slightly according to the variation in wind speed.

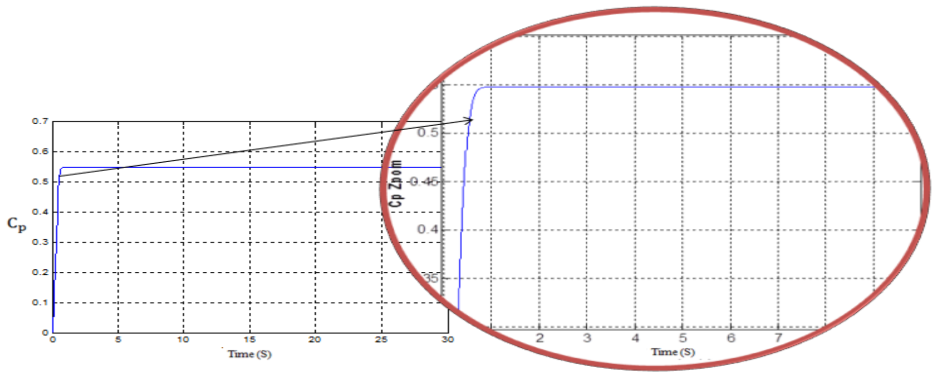

Figure 7. Power coefficient with zoom.

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3.4. Mechanical Speed

Neglecting the losses of electrical origin, then the electrical power will be equal to the electromagnetic power and respect the receiver convention of the whole. When these two powers are equal, the wind turbine rotates at a fairly stable speed as shown in **Figure 8**. The speed in our case is between (70-80 rd/s).

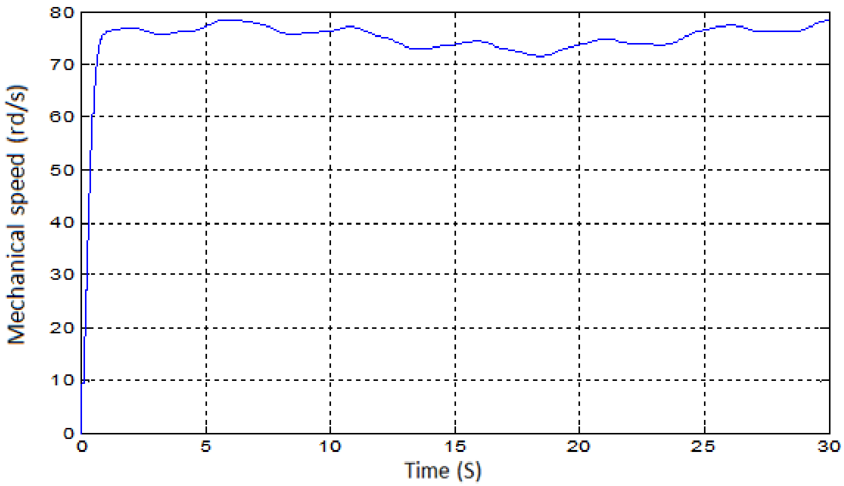

Figure 8. Mechanical speed (rd/s) evolution

4. CONCLUSION

In this work, we have detailed modelling of the different parts of the wind turbine taking into account the characteristics of the blade profile, its offset angle, and the wind profile used.

(i) We modelled the mechanical assembly including the multiplier, allowing the interconnection with a generator that will have the torque as input and the speed as output. This model makes it possible to obtain the shape of the couple.

(ii) The mechanical part is a very essential element in wind turbine conversion. It has its control to maximize the power extracted from the wind by MPPT.

(iii) The results showed that the wind profile varies between 6-7 (m/s), the power coefficient C_p for a pitch angle of (β=2˚) has an average value of 0.54 with relative speed λ = 6.40, and finally, when the origin of electrical losses is neglected, the electrical power equal to the electromagnetic power, and the mechanical speed is stable between (70-80 rd/s).

6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

7. REFERENCES

Albert, M. Urban, and Raúl Guanche. (2019). Wind turbine aerodynamics scale-modeling for floating offshore wind platform testing. *Journal of Wind Engineering and Industrial Aerodynamics*, *186,* 49-57.

Asadi, M., and Pourhossein, K. (2021). Wind farm site selection considering turbulence intensity. *Energy*, *236*, 121480.

Ghodbane, M., Benmenine, D., Khechekhouche, A., and Boumeddane, B. (2020). Brief on solar concentrators: differences and applications, instrumentation. *Instumentation, Mesures, Métrologies*, *19*, 371-378.

Hadjadj, A., Benhaoua, B., Atia, A., Khechekhouche, A., Lebbihiat, N., and Rouag, A. (2020). Air velocity effect on geothermal helicoidally water-air heat exchanger under El Oued climate, Algeria. *Thermal Science and Engineering Progress*, *20*, 100548.

Hur, S. H (2018). Modelling and control of a wind turbine and farm. *Energy*, *156*, 360-370.

Khechekhouche, A., Elsharif, N., Kermerchou, I., and Sadoun, A. (2019). Construction and performance evaluation of a conventional solar distiller. *Heritage and Sustainable Development*, *1*(2), 72-77.

Khechekhouche, A., Ghodbane, M., Kemerchou, I., Hodza, A., and Sadoun, A. (2021). Reynolds horizontal and vertical test bench from an educational point of view. *Indonesian Journal of Educational Research and Technology*, *1*(2), 81-86.

Leisten C., Jassmann U., Balshüsemann J., and Abel, D. (2018). Model predictive speed control of a wind turbine system test bench. *IFAC-Papers Online*, *51*(32), 349-354.

Martinez, A., and Iglesias, G. (2022). Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic. *Renewable and Sustainable Energy Reviews*, *154*, 111889.

Pavlowsky, C. E., and Gliedt, T. (2021). Individual and local scale interactions and adaptations to wind energy development: A case study of Oklahoma, USA. *Geography and Sustainability*, *2*(3), 175-181.

Saidi Y, Mezoua A, Miloud Y., Benmahdjoub M. A., and Yahiaoui M. (2018). Modeling and comparative study of speed sensor and sensor-less based on TSR-MPPT method for PMSG-WT applications. *International Journal of Energetica*, *3*(2), 6-12.

Taghinezhad, J., Alimardani, R., Masdari, M., and Mahmoodi, E. (2021). Performance optimization of a dual-rotor ducted wind turbine by using response surface method. *Energy Conversion and Management: X*, *12*, 100120.

Wang, Q., Cheng, Y., Garg, A., and Zhu, Z. (2019). Characteristics of local wind pressure distribution and global aerodynamic forces on a vertical forest. *Ecological Engineering*, *138*, 61-70.

Yang, B., Yu, T., Shu, H, Dong, J., and Jiang, L. (2018). Robust sliding-mode control of wind energy conversion systems for optimal power extraction via nonlinear perturbation observers. *Applied Energy*, *210*, 711-723.

Yeter, B., and Garbatov, Y. (2022). Structural integrity assessment of fixed support structures for offshore wind turbines: A review. *Ocean Engineering*, *244*, 110271.

Zhou, F., and Liu J. (2018). Pitch controller design of wind turbine based on nonlinear PI/PD control. *Shock and Vibration*, *2018*, 1-14.

Zhou, T., Cao, H., Zhang, M., and Liao, C. (2022). Performance simulation of wind turbine with optimal designed trailing-edge serrations. *Energy*, *243*, 122998.

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