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Design parameters and mechanical efficiency of jet wind turbine under high wind speed conditions

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Abstract: Turbines are one of the most important means of producing clean energy, as they do not cause any negative emissions affecting the environment. Recently, the need to design turbines capable of facing strong winds has appeared because the currently designed turbines must be cut off in such circumstances. This study aims to find the best design parameters and investigate the efficiency of the jet turbine at high wind speed conditions. SolidWorks and MatLab are used to design and analyze small jet wind turbines. The design parameters were chosen to obtain the best efficiency. The turbine diameter is 0.5 m, and the short blade length helps withstand the generated stresses due to strong wind, especially fatigue stress, and resists bending. Blade pitch angle beta starts from 2° from the vertical axis at the hub and changes harmonically along the length to end at an angle of 88° at the blade's tip to allow air to pass through and not form a wall. The blade number has chosen 15 blades, corresponding to the Betz limit, to obtain the maximum power coefficient. As a result, the assigned power was obtained at a wind speed of 28 m/s. At a lower wind speed, it will work with acceptable efficiency and more efficiently at higher speeds. Therefore, this turbine is suitable to use in such cases.

Keywords: renewable energy, mechanical power, jet wind turbine parameters, jet wind turbine efficiency

Nomenclatures

C_P	power coefficient (performance coefficient) for the turbine
S	swept area (m^2)
V	wind speed (m/s).
D	diameter of the wind turbine (m)
P_{avail}	wind energy converted into mechanical work (watt)
P_v	total energy of wind flow (watt)

Greek symbols

β	pitch angle of the blade (deg.)
τ_b	number of wind turbine blades
b_c	section chord at the end of the blade (m)

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Abbreviations

ICE	internal combustion engine
WT	wind turbine

1 Introduction

The energy generated from wind turbines (WTs) constitutes 5% of global energy resources, according to a report by The World Wind Energy Association; Denmark alone can cover 43% of its energy consumption with these sources [1].

Clean energy resources require improving generated power, typically in distant areas where it is considered economically unfeasible to extend power supply lines (Amir and Khan 2021) [2].

Clean natural resources and wind energy have a predictable increase average (2014–2040) of 4.8% [18].

Generally, most designers prefer large turbines and design for normal weather conditions. The large rotor diameters allow the WT to sweep more area, capture more wind, and produce more power [3].

Due to climate changes, some areas will be exposed to storms and high wind speeds most of the time. In these cases, the turbines must stop working to insure they are not damaged (Figure 1).

When the wind speed reaches about 24.587 m/s (88.5 km/h) (cut-out speed changes depending on turbine design), the WT is designed to shut off automatically.

Currently, there is little information about designing storm-flexible systems due to the limited number of deployments. In modern turbines, when wind speeds exceed the estimated wind speed, the blades rotate about their axis to reduce the air resistance and/or reduce their surface area. Consequently, the resulting power decreases and may reach zero [4].

In some models, even though not widespread, the blades can be locked down to come through sharp storms. When the storming finishes and the sensors register the wind speed as less than the turbine cut-out speed, the blades return to their shape and restart the usual running. This operation is called feathering the blades.

The blade's pitch angle beta adjustment is the common active trend to control output power by changing aerodynamic force on the rotor blades at high wind speed conditions.

Yaw control ensures the entire turbine's rotation around its vertical axis to face the wind and extract the maximum power. Otherwise, the system will face power-out losses [5].

Small WTs are designed regardless of the optimal wind conditions that have been taken into account in the design of large turbines [6].

Therefore, it is used at a low airspeed and a small turbine size, leading to poor efficiency and low energy production [7]. As for its use in urban areas, it led to higher fatigue stresses because of wind speed variation and high rotational speed [8,9].

Nowadays, finding an optimal design for small turbines is necessary to ensure shorter blades with better power generation [10].

Therefore, small turbines built to withstand those conditions would be a good alternative to withstand environmental conditions. In addition, they will be easy to install and maintain, economical, and environmentally friendly. They could be selected as independent power generation systems in rural areas and far from city centers (Singh and Gill) [11].

On the other hand, these turbine types can be used on vehicles with high speed to generate power rather than depending on internal combustion engines, which require fuel and cause negative emissions.

Many industrial facilities contribute directly to increased pollution. Transport accounts for a quarter of greenhouse gas emissions and a fifth of the energy used in the world. A shift

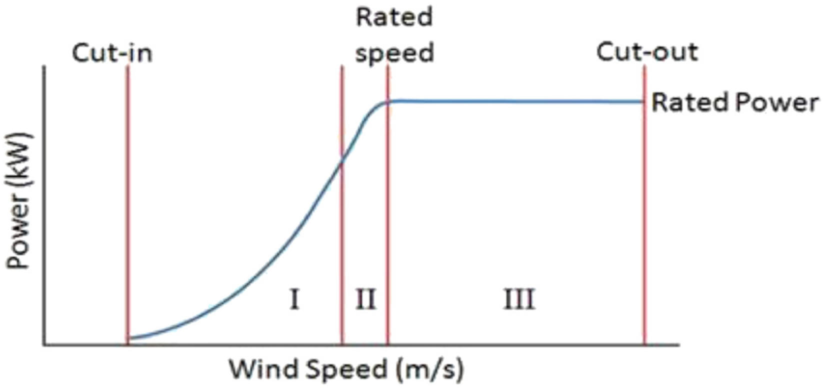


Figure 1: Turbine power curve.

to environmentally friendly, low-carbon transport by mid-century would save governments, companies, and individuals a great deal of money. There are more than a billion passenger cars worldwide, and by 2040, there will be at least two billion. This means that we need to find ways to reduce transport emissions [12].

Many undesirable loads in the vehicles require replacing their driveway and using new ways to reduce fuel consumption, for example, the A/C compressor.

A modern compressor operation allows the engine to work with fewer loads than the turbo system performs (Figure 2). The momentum and compression of the polluted gases have already been used to drive the turbo propeller blades, as a result driving the air conditioner compressor via a magnetic gear (Kumar et al.) [13]. The main feature of this procedure is that low-power engines can apply without effort and can guarantee a rising ability. This process ensures the effective use of waste gas and can decrease fuel squandering.

That research supports using gas turbines as an energy supply for AC press pistons via computational fluid dynamics.

An important study also used an electric compressor for an A/C system with some features that were small, lightweight, and good performance compared to the conventional compressor [14,15]. The disadvantage of this study was that it takes 42 V electric AC system for specially designed vehicles [16]. In addition, it still produces unacceptable levels of emissions.

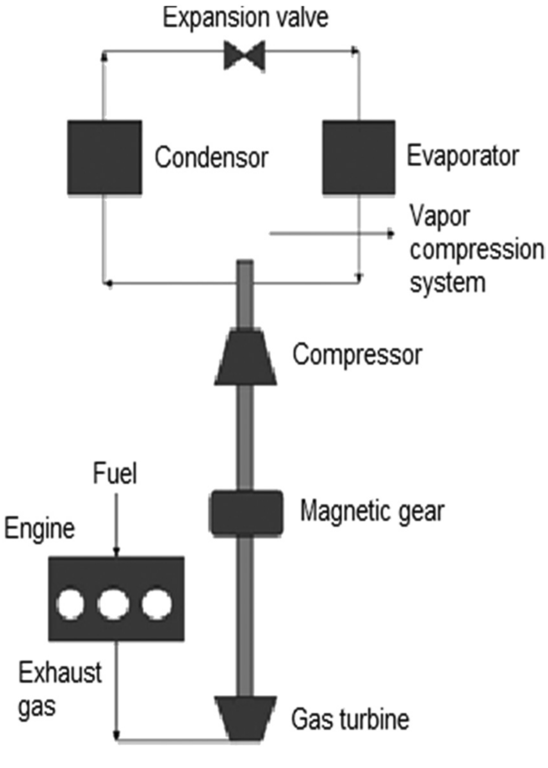


Figure 2: Air compressor turbo.

Jet WT has chosen to deal with this challenge, and some important parameters must be defined. In addition, one of the most important parameters is the blade number, which gives the maximum power coefficient. Also, the blade length to resist stresses, blade angle beta to extract energy from the wind, and its design should be appropriate so that the turbine does not turn into the wall and prevents wind from passing through. Then, represent them in SolidWorks to find the total design and its important properties such as mass, volume, moment of inertia, and center of gravity; at last, represent the equations related to MatLab to find the efficiency of the designed turbine.

This study aims to find the optimal design for the jet WT and its efficiency in generating a mechanical power of about 1.4 kW (2H) under high wind speeds.

2 Mathematical modeling

2.1 Jet turbine power coefficient

The power produced by the WT primarily does not depend on the design, where the outer part of the blades is the effective part [17,21].

Therefore, this study designed the blade angle to start with 2° from the vertical axis at the hub. Then, it gradually changes to be at the end of the blade 88° at the tip, as shown in Figure 3. The power distribution relies on the distorted blade shape and reaches the maximum value when the angle at the tip is parallel to the horizontal axis [18,22].

The available power that obtains from the WT can be defined in the following equation:

$$P = \frac{1}{2} \times \rho \times S \times V^3. \tag{1}$$

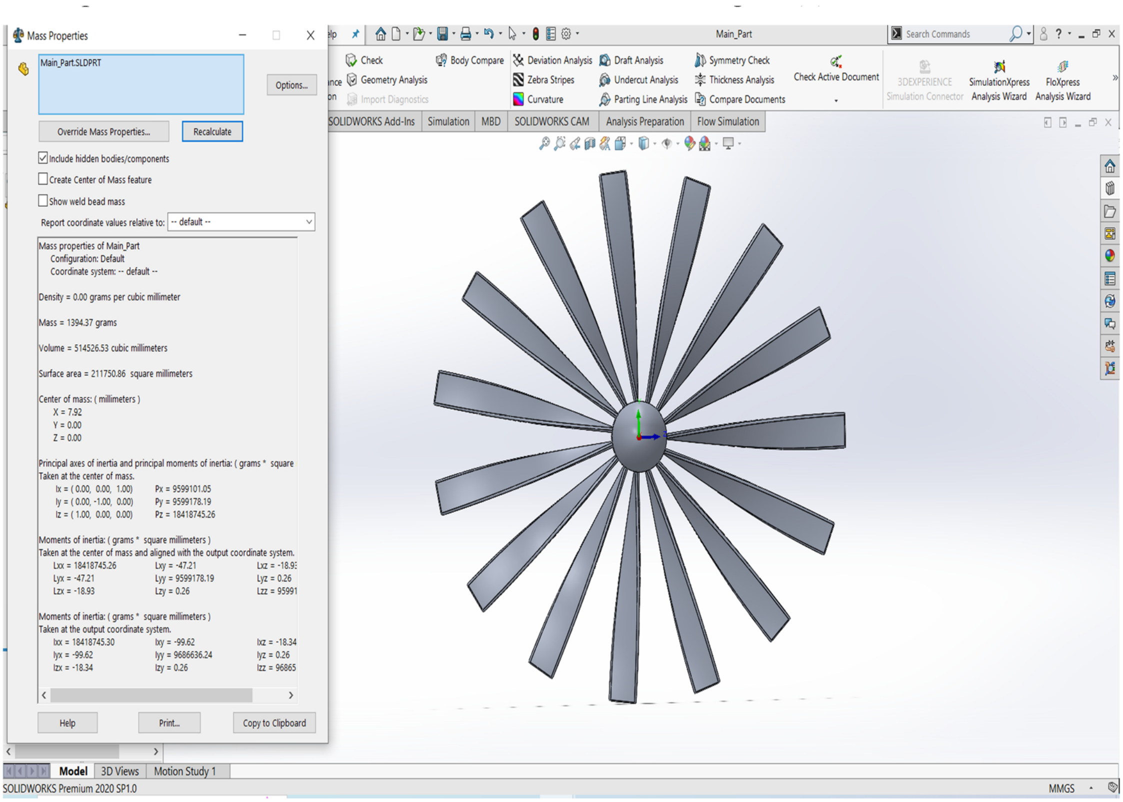
The power generated from the turbine is linked to a special relationship with wind power, as proved by the German scientist Betz in 1919:

$$P_{\mathrm{avail}} = P_{\mathrm{v}} \times C_{\mathrm{p}}. \tag{2}$$

From the aforementioned equation, the important factor in turbines is the turbine power coefficient C_{p}, which is expressed as:

$$C_{\mathrm{p}} = \frac{P_{\mathrm{avail}}}{P_{\mathrm{v}}}. \tag{3}$$

Albert Betz has confirmed that the amount of energy that can be converted into mechanical energy is limited to a particular amount, which is $\frac{16}{27}$ (59.3%) of the wind kinetic



☑ Include hidden bodies/components

☐ Create Center of Mass feature

☐ Show weld bead mass

Report coordinate values relative to: -- default --

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Mass properties of Main_Part
     Configuration: Default
     Coordinate system: -- default --

Density = 0.00 grams per cubic millimeter

Mass = 1394.37 grams

Volume = 514526.53 cubic millimeters

Surface area = 211750.86  square millimeters

Center of mass: ( millimeters )
      X = 7.92
      Y = 0.00
      Z = 0.00

Principal axes of inertia and principal moments of inertia: ( grams *  square
Taken at the center of mass.
       Ix = ( 0.00,  0.00,  1.00)         Px = 9599101.05
       Iy = ( 0.00, -1.00,  0.00)         Py = 9599178.19
       Iz = ( 1.00,  0.00,  0.00)         Pz = 18418745.26

Moments of inertia: ( grams *  square millimeters )
Taken at the center of mass and aligned with the output coordinate system.
      Lxx = 18418745.26           Lxy = -47.21            Lxz = -18.9
      Lyx = -47.21                Lyy = 9599178.19        Lyz = 0.26
      Lzx = -18.93                Lzy = 0.26              Lzz = 95991

Moments of inertia: ( grams *  square millimeters )
Taken at the output coordinate system.
      Ixx = 18418745.30           Ixy = -99.62            Ixz = -18.34
      Iyx = -99.62                Iyy = 9686636.24        Iyz = 0.26
      Izx = -18.34                Izy = 0.26              Izz = 96865
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Figure 3: SolidWorks design and parameters of the jet turbine.

energy required to rotate the rotor. On this basis, that ratio was named after him, Betz limit or Betz law. The power coefficient is any WT design's theoretical maximum power efficiency that cannot exceed 0.59. Moreover, it is defined as:

$$C_{\text{pmax}} = 0.59 = \frac{P_{\text{avail}}}{P_{\text{v}}} = \frac{\left(\left(1+\frac{v1}{v1}\right)\left(1-\frac{v1}{v1}\right)^{2}\right)}{2}. \tag{4}$$

The maximum value of the C_{p} can be reached through the jet turbine, which is 1.45 times more efficient than an ordinary WT for a single-rotor jet WT [19].

The following equation is to find the maximum C_{p} by neglecting friction:

$$C_{\text{pmax}} = (-0.109\delta_{\text{c}}^{2} + 0.18514\delta_{\text{c}}^{2} + 0.4283)\cdot 0.825. \tag{5}$$

The jet WT equations depend on the number of the WT blades, the section chord at the end of the blade, and the diameter of the WT.

$$\delta_{\text{c}} = \frac{2\tau_{\text{b}}b_{\text{c}}}{D}, \tag{6}$$

where τ_{b} is the number of WT blades; b_{c} is the section chord at the end of the blade, *m*; and *D* is the diameter of the WT, *m* [20].

2.2 Initial parameters of the jet WT

In the SolidWorks package, where the model is built of aluminium, the mass characteristics were employed by WT to compute the jet turbine's moment of inertia. The research used 15 blades. The angle of each blade starts from 2° from the vertical axis at the hub and then changes harmonically along the length to end at an angle of 88° at the tip. The diameter of the turbine is 0.5 m, the length of each blade is 0.22 m, and the thickness is 0.04 m. The initial parameters of the WT are shown in Figure 3.

Density = 2710 kg/m^3; mass = 1394.37 g (1.39437 kg); volume = 514526.53 mm^3 (0.00051452653 m^3); surface area = 211750.86 mm^2 (0.21175 m^2); center of mass: (mm) $X = 7.92$ (0.00792 m); $Y = 0.00$; $Z = 0.00$.

Ixx = 18418745.30 (0.0184187453 kg/m^2), Iyy = 9686636.24 (0.00968663624 kg/m^2), Izz = 9686559.14 (0.00968655914 kg/m^2).

2.3 Assumptions to modeling the jet turbine

There is some assumption to start modeling the turbine in ideal conditions:

1. Consider that the blades are similar and homogenous and have the same moment of inertia and the same parameters;
2. The friction coefficient for the air is zero;
3. Wind speed is homogenous when it hits the turbine blade area.

3 Results and discussion

Using renewable energy to reduce the negative effect of fossil fuel and its exhausted gases is important to save the planet; WT is one of the most common forms of energy to replace fuel. Therefore, this research used a jet type of WT to obtain the maximum efficiency power from the wind. The SolidWorks design relied on the beta angle gradient, which starts from 2° with the vertical axis near the axis of rotation and increases with the increase in the blade length to reach 88° at the blade tip. This design allows air to pass through the blades during high-speed operation, and the turbine does not turn into a wall in front of the wind. Although the angle of 2° will give less efficiency, it will make the turbine rotate continuously for the availability of pressure difference and channels for air movements. At the same time, the degree 88° is perfect for obtaining the maximum power efficiency applied at the blade's tip.

The diameter of the turbines is about 50 cm, and the length of the blades is short, not exceeding 22 cm for each blade, so that it can resist the force of the wind attacks and bear the internal stresses as a result of the wind, especially the fatigue stress, and also resist bending stress.

According to the limits of Betz, the percentage of benefit from wind energy does not exceed 59% when neglecting energy losses due to friction and others. On this basis, the number of blades that fulfill this condition was chosen by applying equations (5) and (6) so that the optimal number of blades is chosen 15 blades, as shown in Figure 5.

Aluminum was used for its good mechanical properties. In addition to its lightweight, its hardness is good compared to plastic. In addition, it is cheap compared to other materials.

To analyze data from the equations, the high-performance computing platform MatLab has been used, presenting all related equations in the program as shown in Figure 4.

The maximum value of the power coefficient C_{pmax} depends on the turbine diameter and the number of blades. In this case, $C_{\text{pmax}} = 0.56$ when the turbine diameter is fixed through time, as illustrated in Figure 5.

This is the right percentage of the power coefficient because it is still in the range of the Bitz limit. The next main factor that is important to find the turbine power is the wind speed that attacks the blades to extract energy from them. During wind speed change, the good value of the speed lies between 20 m/s (72 km/h) and 30 m/s (108 km/h) (Figure 6).

This study assumed that the air density is a constant value equal to $1.2\ \text{kg/m}^{3,}$ and the wind speed is homogenous when it hits the turbine blade area. The turbine power obtained from these wind speeds is around the required power to drive the required device, as shown in Figure 7.

The device efficiency assumed 1,460 watts as the ideal condition, which can be obtained when the wind speed is near 28 m/s (100 km/h) for the ideal operation, as shown in Figure 8.

These are the optimal turbine power and wind speed values for the designated device. However, the device can

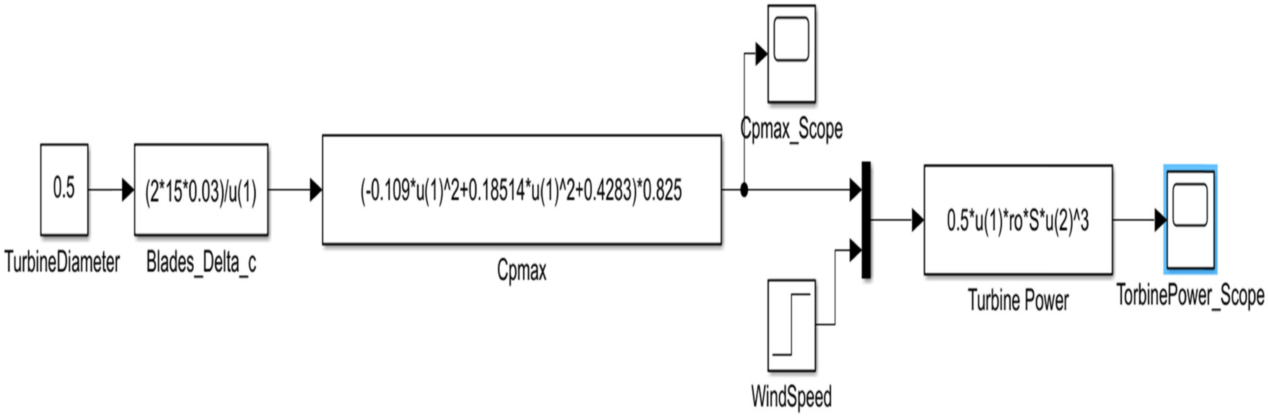

Figure 4: Representing and finding the power coefficient and turbine power by MatLab.

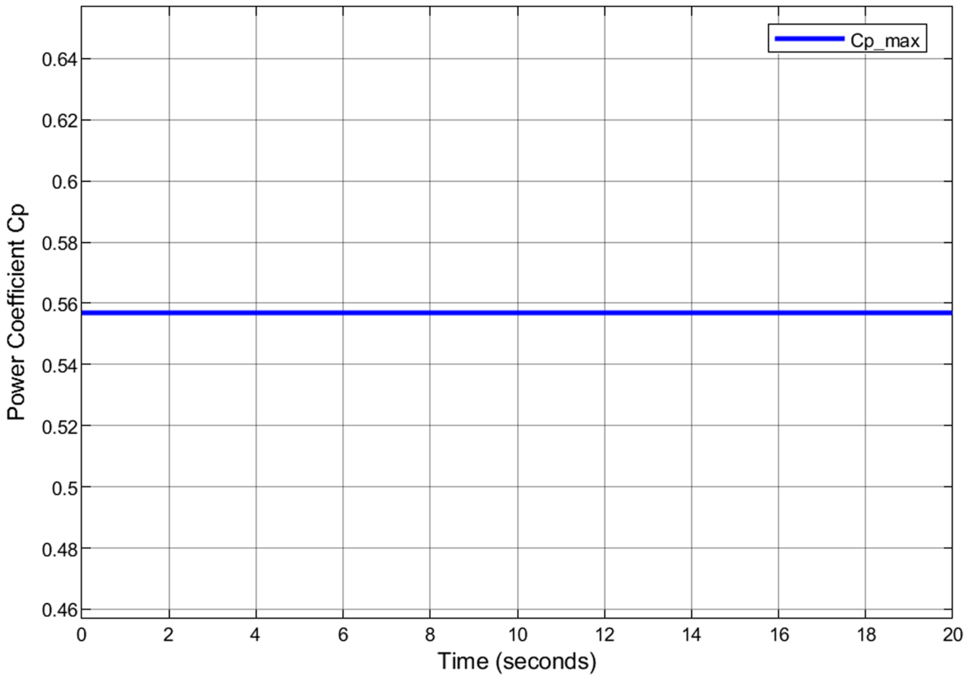

Figure 5: Maximum value of power coefficient for the turbine model.

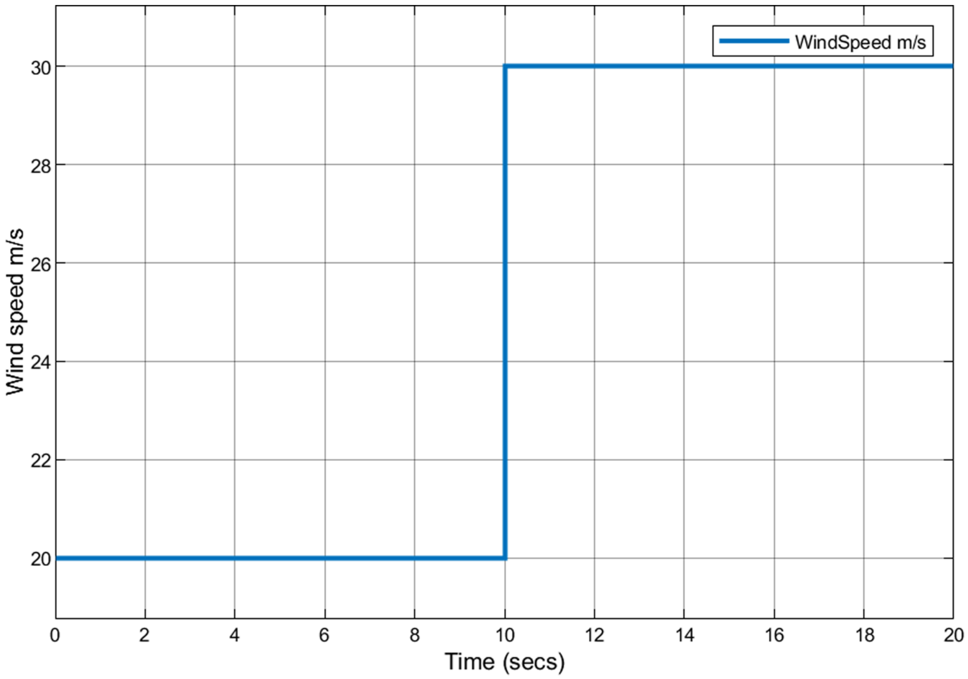

Figure 6: Second factor in finding turbine power is wind speed.

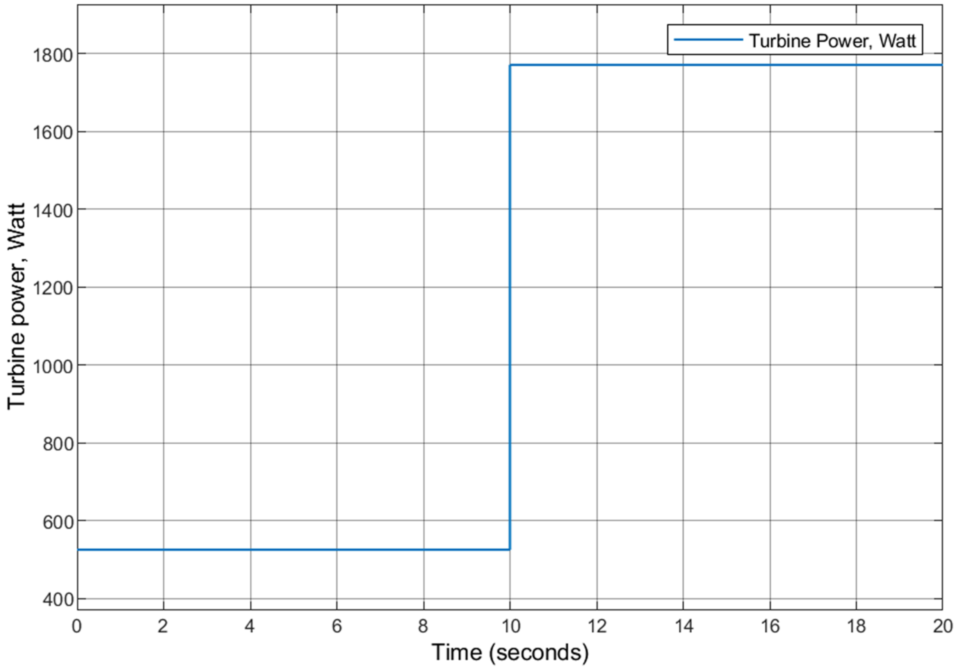

Figure 7: Mechanical power at wind speed between 20 and 30 m/s.

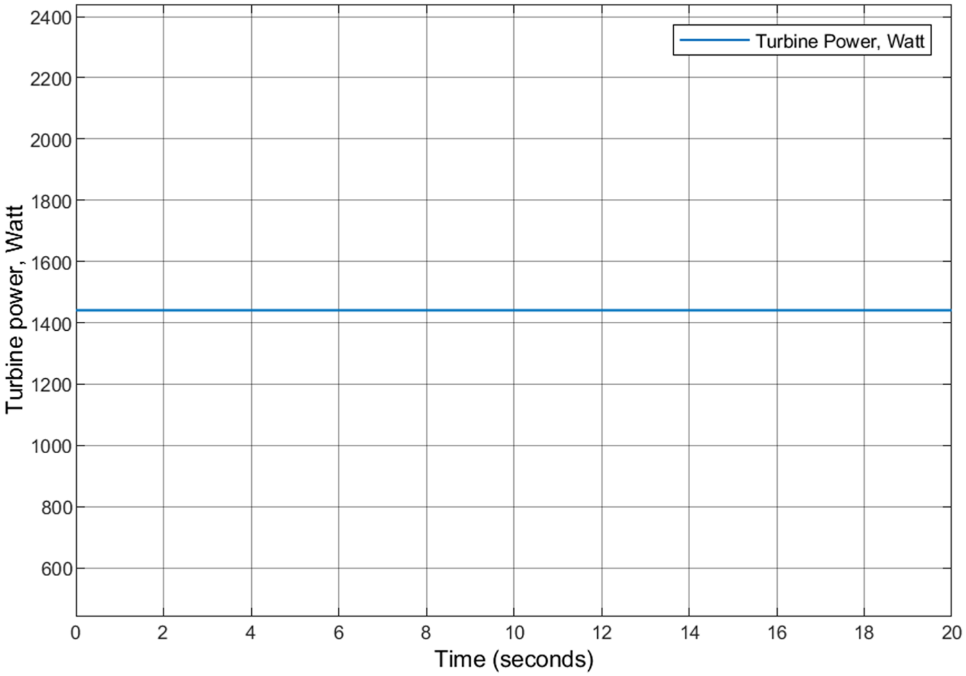

Figure 8: Finding optimal mechanical power at a wind speed of 28 m/s.

work efficiently at lower wind speeds and lower power from the turbine, while the higher wind speed will give higher turbine power and efficiency.

4 Conclusion

The jet WT is one of the most promising forms of renewable energy. Its importance lies for several reasons. First, it is usable at high wind speed conditions, where the effect of stresses on the blades will be less than that on large turbine blades. Second, the production, maintenance, or replacement cost will be lower than other types of turbines. The blade design plays a major role in obtaining the maximum power at high wind speed, where this study aims to find the best design parameters and efficiency. The optimal design for this type depends on the gradient with a pitch angle beta from 2 to 88° at the tip that allows air to pass through the turbines and does not lead to making the turbines like a wall facing the wind.

The design of the turbine is completely based on the Betz limit, so blade number 15 blades were chosen, allowing the turbine to extract 0.56 of the wind energy while neglecting other energy losses. Therefore, the maximum power coefficient C_{pmax} could be obtained in the right range.

As a result, when the wind speed is between 20 m/s (72 km/h) and 30 m/s (108 km/h), the jet turbine produces about 550–1,800 watts. The generated mechanical power is directly proportional to the wind speed that attacks the turbine blades; this power is enough to rotate the appointed device. The optimal power required for the device is 1,460 watts (2H), which the jet turbine can reach at a wind speed of 28 m/s (100 km/h) to obtain optimal system efficiency. The system could work with low performance at a lower wind speed that attacks the jet turbine (lower than 28 m/s). However, a wind speed higher than 28 m/s gives better jet turbine performance. So, using small-diameter jet WTs at high-speed wind conditions is suitable to meet specific requirements.

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Data availability statement: Most datasets generated and analyzed in this study are in this submitted manuscript. The other datasets are available on a reasonable request from the corresponding author with the attached information.

References

[1] World Wind Energy Association. Wind Power Capacity Reaches 539 GW, with 52.6 GW Added in 2017. https://wwindea.org/blog/2018/02/12/2017-statistics/ (accessed on 20 February 2018).
[2] Amir M, Khan SZ. Assessment of renewable energy: Status, challenges, COVID-19 impacts, opportunities, and sustainable energy solutions in Africa. Energy Built Env. 2021. doi: 10.1016/j.enbenv.2021.03.002 In Press.
[3] https://www.energy.gov/eere/office-energy-efficiency-renewable-energy.
[4] https://www.energy.gov/eere/articles/wind-turbines-extreme-weather-solutions-hurricane-resiliency.
[5] https://www.windsystemsmag.com/wind-turbine-control-methods/.
[6] Karthikeyan N, Murugavel KK, Kumar SA, Rajakumar S. Review of aerodynamic developments on small horizontal axis wind turbine blade. Renew Sustain Energy Rev. 2015;42:801–22.
[7] Singh RK, Ahmed MR. Blade design and performance testing of a small wind turbine rotor for low wind speed applications. Renew Energy. 2013;50:812–9.
[8] Song D, Fan X, Yang J, Liu A, Chen S, Joo YH. Power extraction efficiency optimization of horizontal-axis wind turbines through optimizing control parameters of yaw control systems using an intelligent method. Appl Energy. 2018;224:267–79.
[9] Kassenov AZh, Abishev KK, Yanyushkin AS, Iskakova DA, Absadykov BN. Research of the stress-strain state of holes with new broach designs. /News Natl Acad Sci Repub Kazakhstan, Ser Geol Tech Sci. 2022;2(452):89–103. doi: 10.32014/2022.2518-170X.162.
[10] Sarkar M, Julai S, Wen Tong C, Toha SF. Effectiveness of nature-inspired algorithms using ANFIS for blade design optimization and wind turbine efficiency. Symmetry. 2019;11:456.
[11] Singh B, Gill HS. Wind turbine blade design for low rotational inertia materials at variable speeds with different twisting angle Using Q-Blade. Mater Today: Proc. 2020;33(3):1666–70.
[12] American National Park Service. https://www.ekoenergy.org/ru/extras/background-information/climate-change/.
[13] Kumar SMK, Mathews B, Sagardas SOC, Vishnu K, Varun R, Vishnu CV. Analysis on turbo air-conditioner: an innovative concept. Int J Mech Prod Eng 2(3):38–41. http://www.iraj.in/journal/journal_file/journal_pdf/2-43-139583892738-41.pdf.
[14] Henry N, Yamani M, Sumeru K. Performance study of DC compressor for automotive air conditioning system. Adv Mater Res. 2013;614:674–7. Trans Tech Publ.
[15] Guyonvarch G, Aloup C, Petitjean C, De Savasse ADM. 42 V electric air conditioning systems (EA/CS) for low emissions, architecture, comfort and safety of next generation vehicles. SAE Technical Paper; 2001.
[16] Zulkifli AA, Dahlan AA, Zulkifli AH, Nasution H, Aziz AA, Perang MRM, et al. Impact of the electric compressor for automotive air conditioning system on fuel consumption and performance analysis. In: IOP Conference Series: Materials Science and Engineering. IOP Publishing; 2015, Nov; Vol. 100, No. 1. p. 012028.
[17] Haddad Z. The effective area on the rotor of wind turbine. J Sustain Energy Eng. 2018;6(1):3–10.
[18] Marzouk O. Proposed 2MW wind turbine for use in Thumrait, Dhofar, sultanate of Oman. J Sustain Energy Eng. 2019;6(4):252–70.

[19] Sheth DU, Khokhar AAS. Jet Wind Turbine. Int J Sci Eng Res. Sep-2015;6(9):1477 ISSN 2229-5518 IJSER ©. 2015 http://www.ijser.org.

[20] Pchelnikova-Grotova O. Improving the efficiency of autonomous wind turbines. E3S Web of Conferences. 2021;279, EDP Sciences.

[21] Lipian M, Karczewski M, Molinski J, Jozwik K. Numerical simulation methodologies for design and development of Diffuser-Augmented Wind Turbines – analysis and comparison. Open Eng. 2016;6(1):235–40. doi: 10.1515/eng-2016-0032.

[22] Yass MAR, Majeed Rasheed R, Hamad Muhiesen A. Contribution of lift-to-drag ratio on power coefficient of HAWT blade for different cross-sections. Open Eng. 2022;12(1):716–28. doi: 10.1515/eng-2022-0324.