Vertical axis wind turbine analysis using MATLAB

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Abstract. Wind Turbines have become one of the feasible power plants to replaced fossil fuels. Because this plant is affordable cost and did not produce pollutants as an output. Vertical Axis Wind Turbine can be placed at points with high wind intensity such as; toll roads, ships, railroads, airports. The energy produced can be distributed for the civilian house light, the street lights, the fishing boats light, others. The hope is that wind turbines can generate 100 watts of power, so that charging time can be at least 6 hours. But, the average velocity data in the field is worth under 2.85 m/s (minimum wind speed to get 100 watt). Resulting in a turbine charging time more than 6 hours. In this case, The Turbine needed more than one accu as a place to store the energy even the accu take more than 6 hours to be charged.

1. Introduction
Energy is a basic human need that must be fulfilled, it continues to increase as time passes, it is directly proportional to human life. Fuel oil holds a very dominant position in meeting national energy needs. The current composition of energy consumption is fuel oil: 52.50%; Gas: 19.04%; Coal: 21.52%; Water: 3.73%; Geothermal: 3.01%; and Renewable Energy: 0.2%. [1]

Indonesia is a tropical country located on the equator, as an archipelago with varied geological contours, has more than 100 mountains, and also beaches. One of the energies that can be utilized is wind. The movement of wind from the mountains which has high air pressure towards the coast with low air pressure can be utilized in the implementation of wind turbines, which convert mechanical energy into electrical energy. At an affordable cost, didn’t produced pollutants as an output, Wind Turbines have become one of the feasible power plants to replace fossil fuels.

Generally, there are two types of Wind Power Plants; Horizontal Axis Wind Turbines, and Vertical Axis Wind Turbines. The Horizontal Axis Wind Turbine is a type of porous turbine parallel to the wind direction like a typical aircraft propeller, so it requires its own mechanism to adjust the blade to be able to follow the direction of the wind turbine rotating, with the generator placed behind the turbine. Meanwhile, the Vertical Axis Wind Turbine is a type of turbine with a axis perpendicular to the wind direction, easy for each blade to catch wind even though the direction changes, and the position of the generator is at the base of the turbine so that this will facilitate maintenance of the turbine. [3]

Later, this Vertical Axis Wind Turbine can be placed at points with high wind intensity such as; toll roads, ships, railroads, airports, and so on. The energy produced can be distributed to lighting the civil house, lighting the street lights, lights on the fishing boats, and others.

There are various types of Vertical Axis Wind Turbines, and what is currently being analyzed is the Savonius type, although it generally moves more slowly than the Horizontal Axis Wind Turbine, but the torque produced is larger.
Figure 1 shows the design of the Savonius Type Vertical Axis Wind Turbine and its size. The length of the blade is 150 cm, the radius is 30 cm, and the blade is 120 degrees. This 4 kg wind turbine is made of lightweight stainless-steel material which is expected to be easy to rotate, and the design of the 3 blade that forms the letter S can catch the wind even though it blows from various directions. With this size, it is also expected to produce a power output of 100 watts if the intensity of the wind in the field fulfill the expected calculations.

2. Literature Review

2.1. Beltz Limit

Beltz Limit, in theory is the maximum efficiency value for a wind turbine, put forward by German Physicist Albert Beltz in 1919. The value of Beltz Limit is 16/27 or 59.3%, that is only 59.3% of the kinetic energy of the wind can drive the turbine. In fact, the turbine cannot reach Beltz Limit. And generally, the efficiency value of a turbine is between 35% and 45%. [5]

Figure 2. The Coefficient power, Cp functions as a factor b

Table 1. Performance coefficient, Cp as a factor b

| b  | 0   | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8  | 0.9 | 1   |
|----|-----|-----|-----|-----|-----|-----|-----|-----|------|-----|-----|
| Cp | 0.5 | 0.5445 | 0.576 | 0.5915 | 0.588 | 0.5625 | 0.512 | 0.4335 | 0.324 | 0.1805 | 0   |
2.2. **Turbine Power**

Wind turbines work by converting the kinetic energy in the wind first into rotational kinetic energy in the turbine and then electrical energy that can be supplied. [6]

\[
E_k = \frac{1}{2}mV^2
\]  

(1)

Where, \(\frac{dm}{dt} = \rho AV\) \(\rightarrow\) mass of flow air through disc of area-A

The power in the wind is given by the rate of change of energy:

\[
P = \frac{dE}{dt} = \frac{1}{2} \frac{dm}{dt} V^2
\]  

(2)

\[
P = \frac{1}{2} \rho AV^3
\]  

(3)

Where:

- \(P\) = turbine power, watt
- \(\rho\) = Air density = 1.225 kg.m\(^{-3}\)
- \(A\) = swept surface area = \(\pi r^2 = 3.14 \times (1.5)^2 = 7\) m\(^2\)
- \(V\) = wind speed (m/s)

If, \(P_{out} = 100\) watt

Then,

\[
V^3 = \frac{2P}{\rho A} = \frac{2 \times 100}{1.225 \times 7} = \frac{200}{857.5} = 23.32
\]

\[
V = \sqrt[3]{23.32} = 2.85\ m/s
\]  

(4)

To get \(P_{out} = 100\) watt, the turbine needs 2.85 m/s of wind speed at least

2.3. **Wind Speed Sample**

In reality, the average wind speed based on the sample data taken below is:

| Time            | Wind Sample Average (m/s) on 1 - 3 July 2019 | Wind Sample Average (m/s) |
|-----------------|---------------------------------------------|---------------------------|
|                 | 1   | 2   | 3   |                             |                           |
| Morning         | 1.21| 1.41| 1.45| 1.36                        |
| Evening         | 1.89| 2.78| 1.64| 2.10                        |
| Night           | 2.74| 4   | 2.71| 3.15                        |

In table 2, it can be seen that in the morning and evening, the average wind speed does not reach 2.85 m/s. So at that time the battery takes longer to fill. Whereas at night from the range of 8 PM - 9:30 PM, the average wind speed is above 2.85 m/s, it is possible to fill the battery faster and produce output power of more than 100 watts. For the calculation of battery usage and charging can be seen in the next sub-chapter.
2.4. Wind Torque

The wind torque and load torque can be expressed as follows equation 5 and 4 [6].

\[
M_{\text{wind}} = \frac{\rho \times R \times L \times \eta \times V^3}{2 \times \omega}
\]  

(5)

Where:
- \(M_{\text{wind}}\) = wind turbine torque, Nm
- \(V\) = wind speed (m/s) = 2.8 m/s
- \(L\) = length of the blades, m = 1.5 m
- \(R\) = wind turbine rotor radius = 0.3 m
- \(\rho\) = air density = 1.225 kg.m\(^{-3}\)
- \(\eta\) = wind turbine efficiency, 0.275
- \(\omega\) = angular speed = 6

Then, substitute the value to the equation 5,

\[
M_{\text{wind}} = \frac{1.225 \times 0.3 \times 1.5 \times 0.275 \times 2.8^3}{2 \times 6} = 0.27 \text{ Nm}
\]

And,

\[
M_{\text{load}} = \frac{\pi \times \rho \times R^5 \times \eta \times \omega^2}{2 \times \lambda^3}
\]

(6)

Where:
- \(\pi = 3.14\)
- \(\lambda = \frac{\omega R}{V} = \frac{6 \times 0.3}{2.8} = 0.64 = \text{tip speed ratio}\)

Substitute the value to the equation 6,

\[
M_{\text{load}} = \frac{3.14 \times 1.225 \times 0.3^5 \times 0.275}{2 \times 0.64^3} \times 6^2 = 0.17 \text{ Nm}
\]

2.5. Battery Charging Time

\[
P = V \times I
\]

(7)

Where:
- \(P\) = Power (Watt) = 100 watt (expected power output)
- \(V\) = Accu voltage (Volt) = 12 Volt
- \(I\) = Current (Ampere)

Substitute the value to the equation 5 to find the current,

\[
P_{\text{out}} = V \times I
\]

100 Watt = 12 Volt x I

\[
I = \frac{100}{12} = 8.3 \text{ Ampere}
\]

Accu specification: 12V/50Ah
Charging Time = \( T = \frac{Q}{i} = \frac{50 \text{ Ah}}{8.3\: \text{A}} \) = 6 Hour

Where :

\( Q = \) Charging Q, (Ampere Hour)

With the Equation 3, we can find the real charging time using the wind speed average.

Substitute the value of Wind Speed Average to the equation 3 to find the Real Output Power and charging time.

1. Power with Wind Speed Average on Morning

\[
P = \frac{1}{2} \rho AV^3
\]
\[
P = \frac{1}{2} * 1,225 * 7 * 1,36^3
\]
\[
P = 10.78 \text{ Watt}
\]

Then, the current output will be,

\[
P_{\text{out}} = V \times I
\]
\[
10.78 \text{ Watt} = 12 \text{ Volt} \times I
\]
\[
I = \frac{10.78}{12} = 0.89 \text{ Ampere}
\]

The Charging time,

\[
\text{Charging time} = \frac{50 \text{ Ah}}{0.89 \text{A}} = 56 \text{ Hour}
\]

2. Power with Wind Speed Average on Evening

\[
P = \frac{1}{2} \rho AV^3
\]
\[
P = \frac{1}{2} * 1,225 * 7 * 2,10^3
\]
\[
P = 39.7 \text{ Watt}
\]

Then, the current output will be,

\[
P_{\text{out}} = V \times I
\]
\[
39.7 \text{ Watt} = 12 \text{ Volt} \times I
\]
\[
I = \frac{39.7}{12} = 3.3 \text{ Ampere}
\]

The Charging time,

\[
\text{Charging Time} = \frac{50 \text{ Ah}}{3.3 \text{A}} = 15 \text{ Hour}
\]

3. Power with Wind Speed Average on Night

\[
P = \frac{1}{2} \rho AV^3
\]
\[
P = \frac{1}{2} * 1,225 * 7 * 3,15^3
\]
\[
P = 134 \text{ Watt}
\]

Then, the current output will be,

\[
P_{\text{out}} = V \times I
\]
134 Watt = 12 Volt x I
I = 134/12 = 11 Ampere

The Charging time,

\[
\text{Charging Time} = \frac{50 \text{ Ah}}{11 A} = 4.5 \text{ Hour}
\]

3. Methodology

**Figure 3.** Research Method VAWT Analysis Flowchart

In Figure 3 we briefly explain the methodology for analysing Vertical Axis Wind Turbines.

**Table 3.** Work Timeline for VAWT Analysis

| Step                | Explanation                                                                                                                                 |
|---------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Start               | Start                                                                                                                                       |
| Literature Review   | Literature Review is the preparation stage, journal searches and papers related to Vertical Axis Wind Turbines as a reference when making comparisons of valid sources, such as Beltz Law, Output Power, Battery charging (batteries) in Turbines, Analysis of wind speed relationships with output power. |
| Matlab Simulation   | Try Matlab Simulation in each of the papers that have been searched for in step 1.                                                           |
| Wind Speed Sampling | Looking for a comparison of the relationship between Wind Speed and Power                                                                   |
Wind Speed Sampling

Sampling of wind speed, as a reference in the process of calculation, Turbine Torque, Output Turbine Power, Time of Use (usage), Time of Charging on turbine batteries. The collection location is on the 7th Floor of Al-Azhar University in Indonesia.

Matlab Simulation

Simulated back in Matlab using data that has been obtained directly from the Field, or real data

Data Analysis

Analyze formulas to calculate power output, usage time, battery charging time, and turbine torque at each time; morning afternoon Evening

Conclusion

Conclusions can be obtained from the graph in matlab and calculation

End

4. Result and Discussion

4.1. MATLAB Code and The Result

4.1.1. MATLAB Code for Wind Torque Function

```
v = [3:0.25:6];     %wind speed m/s
L = 1.5;           %length of the blades, m
R = 0.3;           %wind turbine rotor radius, m
rho = 1.225;       %air density
windt = 0.275;     %wind turbine efficiency
omega = 6;         %angular speed
m1 = 15;           %mass turbine blades, kg
m2 = 1;            %mass wind turbine rotor, kg
l = 0.01;          %radius mass centre, m
J=(2*(m1*(m2/2))/(m1+(m2/2))*l^2); %time constant
lambda = (omega.*R)./v;    %tip speed ratio
Mw = (rho*R*L*windt*v.^3)./(2*omega);
Mlo = ((pi.*rho.*R.^5.*windt)./(2.*lambda.^3)).*omega.^2;
T=(J*omega)./(Mw-Mlo);  %time constant
plot (v,Mw,v,Mlo);
```

The plot result show below,

![Wind Speed Vs Wind Turbine Torque](image)

Figure 4. Wind Speed Vs Wind Turbine Torque

In Figure 4, it can be seen that the turbine torque when there is a load decreases, this occurs because there is a Beltz Limit, where only 59.3% of the kinetic energy of the wind can drive the turbine, which
causes a decrease in turbine torque. From 0.27 Nm to half which is 0.17 Nm. This of course will affect many things, such as the value of the output power decreases, charging the battery will require more time, as explained in sub-section 2. Except, if the wind speed that drives the turbine can reach 2.85 m/s or more, the output power will be as desired, which is 100 watts, so charging the battery only takes 6 hours.

4.1.2. MATLAB Code with Power Function

```
v = [0:0.25:5];           %wind speed, m/s
rho = 1;                  %air density, assumption 1 kg/m^3
R = 1.5;                  %Lenght of blades,m
A = pi.*R.^2;             %Swept surface area, m^2
P = (1/2)*rho.*A.*(v.^3); %Power, watt
plot (v,P);              %graph, wind speed vs power
```

The plot result show below,

According to the Power equation referred to equation 3, There are two things that can affect the value of output power. First is wind speed. The second is the cross-sectional area of the blade.

The relationship of Power to wind speed is, directly proportional to power 3, only at the speed of 2 m/s, the value of power will be 8. If the wind speed is 3 m/s, then the power value will be 27. The Power difference is very significant, even though the wind speed only increases by one number. And also, the greater the cross section, the more wind is captured, causing large torque, and the output power also increases.

5. Conclusions
As mentioned in the Chapter Introduction, that Vertical Axis Wind Turbine moves more slowly, but produces a large Torque. Which Turbine Torque Wind with a length of 1,5 m, and radius of 0,3 m, mass of will produce a torque of 0.27 Nm. Because the wind turbine has an efficiency value, commonly referred to as Beltz Limit, the torque value will decrease because the Turbine absorbed wind energy is only 59.3%, then the torque value when there is a load drops to 0.17 Nm. And even though the hope is that wind turbines can generate 100 watts of power, so that charging time at least 6 hours. The average velocity data in the field is worth under 2.85 m/s (minimum wind speed to get 100-watt output power), except the night time. Resulting in a turbine charging time is more than 6 hours. The solution of the Wind Turbine that is analysed is, the addition of batteries is needed, so that the capacity of the number of usages can be increased even the charging time take more than 6 hours.
References

[1] Kholiq, I. *Pemanfaatan Energi Alternatif Sebagai Energi*. 2015. Paper, Wijaya Putra University, Engineering, Surabaya.

[2] Aymane, E., Darhmaoui, D., & Sheikh, D. *Savonius Vertical Wind Turbine: Design, Simulation, And Physical*. 2017. Al-Akhwaryn University, School of Science and Engineering.

[3] DeCoste, J., & McKay, D. *Vertical Axis Wind Turbine*. 2005. Design Project, Dalhouse University, Department of Mechanical Engineering.

[4] Jess. *Wind Turbine Power Calculations*. 2003. The Royal Academy of Engineering. Mechanical and Electrical Engineering. North Hoyle: npower.

[5] Afework, B., Hanania, J., Stenhouse, K., & Donev, J. *Beltz Limit*. 2018.

[6] Komass, T., & Sniders, A. *Design And Verification Of Vertical Axis Wind Turbine Simulation Model*. 2014. Latvia University of Agriculture, Engineering.

[7] Ragheb, M., & Ragheb, A. M. *Wind Turbines Theory - The Betz Equation and Optimal Rotor Tip Speed Ratio*. 2011. University of Illinois, Department of Nuclear, Plasma and Radiological Engineering. Urbana-Champaign, 216 Talbot Laboratory: InTech.

[8] Pagnini, Luisa., Piccardo, Giuseppe. *Full Scale Behaviour of a Small Size Vertical Axis Wind Turbine*. Renewable Energy. 2018. Vol.1: Pages 1.

[9] Hansen, L.H., Blaabjerg, F., Christensen, H.C. *Generators and Power Electronics Technology for Wind Turbines*. The 27th Annual Conference of the IEEE Industrial Electronics Society. 2001. Vol. 1: Pages 1.

[10] Hogberg, Lars. *Automated Electric Control Of A Vertical Axis Wind Turbine In Inland Operation*. Uppsalas University. 2009 : 2-3.

[11] Jamieson, Peter. *Innovation In Wind Turbine Design. Second Edition. UK. John Wiley & Sons, Inc*. 2018 : 42-45.

[12] Safe, A.A., Moniruzzaman, M., Islam, M.T. *Increasing Efficiency of a Twisted Blade Vertical Axis Wind Turbine (VAWT) by Changing Various Parameter*. International Conference on Mechanical Engineering and Renewable Energy. Chittagong, Bangladesh. 2015 : 1-2.

[13] Nagare, P., Shettigar, R., Nair, Arnav. *Vertical Axis Wind Turbine*. International Conference on Technologies for Sustainable Development. Mumbai, India. 2015 : 1-2.

[14] Shah, R., Kumar, Rakesh. Raahemifar, Kamran. *Design, Modeling and Economic Performance of a Vertical Axis Wind Turbine*. Energy Report. 2018 : 2-3.

[15] Rezaeiha, Abdolrahim., Kalkman, Ivo. *Effect of Pitch Angle on Power Performance and Aerodynamics of a Vertical Axis Wind Turbine*. Applied Energy. 2017 : 7.

[16] Wu, Zhenlong., Bangga, Galih., Cao, Yihua. *Effects of Lateral Wind Gusts on Vertical Axis Wind Turbines*. Energy. 2018 : 2-3.

[17] Liu, Kan., Zhu, Weidong. *Enhancing Wind Energy Harvesting Performance of Vertical Axis Wind Turbines With a New Hybrid Design: A Fluid-Structure Interaction Study*. Renewable Energy. 2018 : 1-3.

[18] Johari, K. Muhd., Jalil, A. M. Azim. *Comparison of Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT)*. International Journal of Engineering & Technology. 2018 : 2.

[19] H. Mahmoud, M. Gedalya. *Wind Turbine Power: The Betz Limit and Beyond*. IntechOpen Journal. 3-29

[20] F. M. Chw. Al, A. A. Al, I. Ahmad, P. A. D. Shalsa, W. Putri, S. Ary. *Charging and Discharging Battery System Automation in Simple Wind Power Plant*. Conference in Iconistech 2019, Bandung, Indonesia
[21] A. Natalia, C. David, H. Miguel, R. Gustavo. Impact analysis of wind turbine and battery energy storage connection in power systems. 978-1-5090-6678-0/17/$31.00 ©2017 IEEE

[22] A. Firman, M. I. Made, N. Made. Pengaruh Kecepatan Angin Dan Variasi Jumlah Sudut Terhadap Unjuk Kerja Turbin Angin Poros Horizontal. Dinamika Teknik Mesin Journal. 2013; 3(1): 50-59.

[23] Rines. Unjuk Kerja Model-Model Kincir Angin Savonius Dua Tingkat Dengan Kelengkungan Sudu Termodifikasi. MediaTeknika Jurnal Teknologi. 2016; 11(1): 29-39

[24] R. Sagita, S. B. Prijo. Rancang Bangun Generator Turbin Angin Putaran Rendah Sebagai Pembangkit Energi Listrik Alternatif Di Daerah Pesisir. Wahana Journal. 2018; 70(1): 25-34.

[25] P. J. Schuble, R. J. Chrossley. Wind Turbine Blade Design Review. Wind Engineering Journal. 2012; 36(4): 365-388