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Simple Vertical Axis Wind Turbine for Low Wind Speed

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Abstract

Wind energy is one of the potential renewable energy in Indonesia, however low wind speed turbine needs to be designed to adjust for available wind characteristic in the area. Vertical axis wind turbine with Savonius type is suitable for low wind speed application and in this paper turbine design has been optimized aerodynamically using computational fluid dynamics and following raw material size constraint. One-level savonius wind turbine has been designed and compared to previous work of two-lavel wind turbine. Based on CFD simulations, one-level turbine has better performance than the other one. Both wind turbines have large torque at zero RPM which indicates that they are suitable for low wind speed application.

CCS CONCEPTS

•Hardware~Power and energy~Energy distribution~Power conversion

Keywords

CFD, OpenFOAM, VAWT, wind turbine, low speed wind, vertical axis wind turbine

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1. Introduction

Wind turbine to harvest wind energy has been developed all over the world as one of the potential renewable energy resources. The wind turbine converts the wind's kinetic energy into electrical energy. There are two type of wind turbines, Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). Large three-bladed horizontal-axis wind turbines (HAWT) are the overwhelming majority of wind turbine in the world now. These turbines have its main horizontal axis and electrical generator on the top of a tower as seen in Fig.1. Most of them will have a gearbox to increase slow blade rotation into faster rotation to suit electrical generator. Turbines are used in wind farms for commercial production. The blades are usually painted white for aircraft visibility reason. The size and height of the wind turbines increase every year. Currently, offshore wind turbines are designed for up to 8 MW and have a blade length up to 80 meters. Usual wind turbines will have tubular steel towers with its height of 70 to 120 meters. Wind turbines are designed to produce electric power in a range of wind speeds and the example is a General Electric turbine which has peak electric generated power of 2.5 MW. Its cut-in speed is 3 m/s, cut-out at 25 m/s and rated wind speed of 12 m/s [1], see Fig.1. This wind turbine costs around US$ 4.5 million installed.

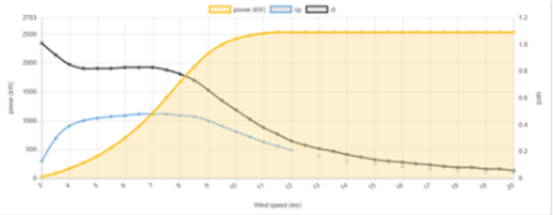

Figure 1: Horizontal axis wind turbine (HAWT) farm and Power curve of General Electric 2.5 MW wind turbine [1].

Vertical axis wind turbine company in Italy named Enessere [2] has a VAWT product with maximum power of 3.5 kW, cut-in wind speed around 4 m/s, rated wind speed 25 m/s, and maximum rotation speed 200 RPM. The product is designed to survive up to the wind speed of 39 m/s. Dimension of the turbine is total height of 8.85 m, tower height 6 m, rotor width 2.67 m, wing height 3.76 m as shown in Fig. 2 along with its power curve. Typical price of this wind turbine is around €60,000.

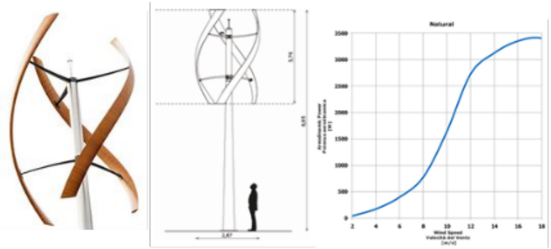

Figure 2: Vertical axis wind turbine (VAWT) product from Italian company Enessere with its power curve [2].

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ESP3 Danida, Denmark embassy Indonesia, Ministry of ESDM Indonesia [3] have published a wind energy potential map in Indonesia as shown in Fig.3. The map shows that the most wind energy potential in Indonesia are Nusa Tenggara Timur, south Papua, south Sulawesi and south coastal region of Java. Wind energy in Indonesia is estimated to reach around 150 MW.

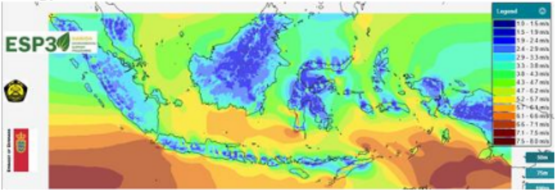


Figure 3: Wind energy potential map in Indonesia by ESP3 Danida, Denmark embassy and Ministry of ESDM [3].

Based on the map, it shows that maximum wind speed in Indonesia is only around 8 m/s. This is less than most rated wind speed for existing HAWT and VAWT products.

Badan Pengkajian dan Penerapan Teknologi (BPPT, Agency For The Assessment And Application Of Technology) has identified wind energy potential area in 10 java regions [4] as shown in Fig.4. In the report, the highest average wind speed is only 6.6 m/s which are in Ciemas Sukabumi and in Cikelet Garut and their potential wind power is 50 MW and 68 MW.

Figure 4: Wind energy potential in several areas in Java, Indonesia [4]

Most of existing wind turbine products are designed for wind speed of 12 m/s or more. In Indonesia, particularly in Java area, the highest average wind speed is only 6.6 m/s. Existing wind turbine products will not work well in Java area. New wind turbines designed for low wind speed, such as 4 m/s, is needed for Indonesia area. The turbine should have low cut-in wind speed such as 1 m/s to utilize low speed wind. Cut-out wind speed can be as low as 10 m/s so the foundation does not need to be very strong which lead to cheaper foundation.

Wind turbine design can be optimized using computer simulation. OpenFoam is a Computational Fluid Dynamics (CFD) software which is an open source software that can be used for this purpose [5]. This software has been applied to optimize wind turbine design by analyzing the air flow in a horizontal axist wind turbine, e.g. in [6]. The basic difference between wind turbine designs for high and low wind speed is in the area of the blades. Low speed wind turbine will require larger blade area to capture low air momentum to be converted to rotational motion of the turbine.

In this paper, a Vertical Axis Wind Turbine (VAWT) will be developed which is a continuation work from two level VAWT [7]. To further reduce the manufacturing price, two level VAWT will be converted into single level. OpenFOAM will be used to further optimize turbine blades with wind speed of 4 m/s.

2. Literature Review

There are two different type of vertical axis wind turbines, Darrieus and Savonius types. The Darrieus type of turbine consists of a number of curved aerofoil blades mounted on a rotating shaft. When the Darrieus turbine blades are rotating, the aerofoils are moving forward on the air in circular path creating lift force which gives a positive torque to the shaft in the direction it is travelling.

Savonius type of wind turbine works to convert the momentum of wind into torque on a rotating shaft. It consists of several scoop-shape of blades and when the scoop front side is facing the wind, it creates more drag than the back side facing scoop. This drag difference is creating positive torque for rotating the shaft.

2.1. Darrieus Type of VAWT

Development of Darrieus type of VAWT started after its invention by Georges Jean Marie Darrieus, a French aeronautical engineer, in 1926. Lately, computational fluid dynamic analysis and wind tunnel test has been done by Howell et. al. [8] in the development of Darrieus type of turbine. The paper showed that 3D CFD analysis agreed well with the wind tunnel test result while 2D analysis tended to over predict the Performance Coefficient Cp value at high TSR value. The wind tunnel results showed that maximum Cp value for two-bladed Darrieus wind turbine was at TSR value around 2.5 while for three-bladed one at TSR value of 2.0.

Twist angle of blade in the Darrieus type has been studied by Ismail et. al. [9]. This report explained different performance between 0 degree twist angle versus 30 degree twist angle wind turbine. The 0 degree wind turbine had higher maximum torque while 30 degree one had higher maximum power due to higher maximum RPM.

Typical Darrieus wind turbine have difficulties in protecting from extreme wind conditions and in making it self-starting. It is a challenge to design strong Darrieus turbine blades to survive high wind load due to its curvy shape. Also, the turbine produces small torque at 0 RPM because of small lift force generated at 0 RPM. This leads to higher cut-in wind speed.

2.2. Savonius Type of VAWT

Savonius type of wind turbine was invented by Sigurd Johannes Savonius in 1922. Recently, work on optimizing the shape of Savonius blade was done by Chan et. al. [10]. A genetic algorithm was incorporated into computational fluid dynamics simulations coupling with blade geometry definition and mesh generation in an iterative process to find optimal blade shape. Regular circular shape of blade, the maximum performance coefficient was around 20% at TSR value of 0.7. With genetic algorithm, the optimized blade shape turbine maximum performance was around 23% at TSR value of 0.9.

Twist angle of savonius blade has been studied by Lee et. al. [11] using computational fluid dynamic simulations and wind tunnel tests. From their works, it showed that changing blade twist angle would change its maximum performance coefficient and corresponding TSR value. For 0 degree twist angle blade, the maximum Cp is around 12.5% at TSR value around 0.65. For 45 degree twist angle blade, maximum Cp is around 14% at TSR of 0.6. For 90 degree twist angle blade, maximum Cp is around 10.5% at TSR of 0.5 and for 135 degree, maximum Cp is 11% at TSR 0.6. Based on this result, optimal blade twist angle is 45 degree.

2.3. Previous Work of VAWT design

This paper is based on previous work [7] to optimize Savonius type wind turbine as shown in Fig.5. The choise of Savonius type is because it has higher torque value at 0 RPM resulting lower cut-in wind speed and it will be more suitable for low wind speed area. The turbine has 2 levels, with identical blades, 2 pieces at each level. The total height of the turbine is 2.4 m and the total outer diameter is 2.4 m. The width of the turbine is chosen to maximize the utilization of plate material in the market, 1.2m. Gap size between two blades is around 0.5 m. Blade chord length is 2.12 meter.

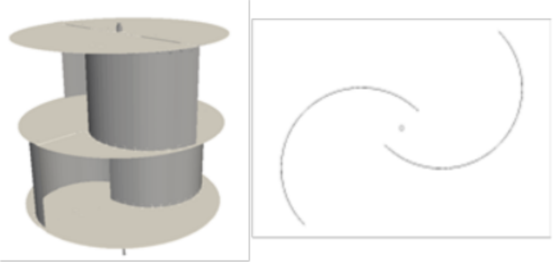


Figure 5: Two-level Savonius VAWT from previous work from different view angle and cut-section on the blade.

3. New One-Level VAWT Turbine Design

Further development of Savonius type of VAWT is done for low wind speed area with higher performance coefficient and maximal material utilization. Computational fluid dynamic analysis is used to optimize the blade aerodynamics.

Baseline design is based on maximal material utilization, which is a material plate of 1.2m x 2.4m. One level turbine design will save 1 circular material so the base design is as shown in Fig.6. The turbine has 4 identical blade with its height of 2.4m and chord length of 1.2m. Top and bottom identical plates has diameter of 2.4m, with structural strengthening. The arrangement of 4 blades is that each edge of the blade is 5 cm from the edge of base plate and each blade are 90 degree apart to each other.

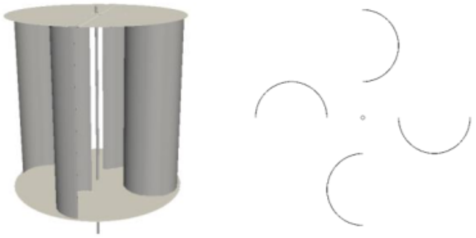


Figure 6: Baseline design for one-level Savonius wind turbine and cut-section of the blades.

3.1. Methodology - Computational Fluid Dynamics

Computer simulation analysis is performed using RANS turbulence method by the software OpenFOAM. OpenFOAM user guide [5] can be referred for more detail information. This open source software has been undergoing a lot of tests and validations by the CFD community in the world and good results have been reported everywhere.

In this analysis, incompressible solver with Reynolds Averaged Navier-Stokes (RANS) and with k-ω turbulence model is used. The module name in OpenFOAM is simpleFoam and the simulation is run to get steady-state solution. Setup of the simulation is sketched in the following Fig.7. Turbine surface velocity is set according to the desired rotational speed.

Figure 7: Simulation boundary conditions for turbine CFD analysis.

3.2. Methodology Baseline Results

Computer simulation is done on the baseline with fixed rotation of 50 RPM. Because the wind turbine is in similar shape every 90 degree rotation, computer simulation is done for 0 and 45 degree turbine orientations. The CFD results are shown in Fig.8. Wind turbine geometry is colored by air pressure, where blue is low pressure and red is high pressure.

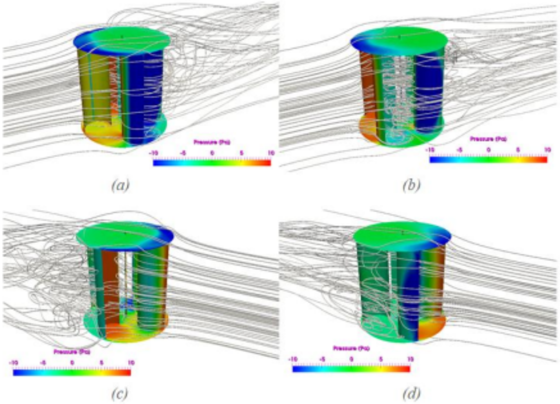


Figure 8: Wind turbine colored by air pressure with air streamlines (a) 0 degree orientation from right side view, (b) 45 degree orientation from right side view, (c) 0 degree orientation from left side view, (d) 45 degree orientation from left side view.

The results show that the convex surface of the blade has low pressure due to air flow acceleration on it while the concave surface of the blade has high pressure due to the air flow impingement on the surface. This condition is resulting a positive torque rotating the axis. Computer simulation calculates the total torque for 0 degree turbine orientation is close to twice of 45 degree orientation and its average torque will be used as a reference for other torque calculations.

3.3. Study of Different Number of Blade

Wind turbine with 5 blades has been investigated and the average power output for 50 RPM is around 12% less than 4 blade turbine. Simulation for 5 blade turbine is performed at 0 and 36 degree orientation and the result for 5 blade turbine is shown in Fig.9 along with normalized average power output comparison between 4-blade and 5-blade turbines.

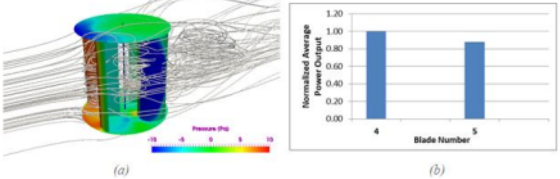


Figure 9: (a) 5-Bladed Turbine simulation result, (b) Normalized Average Power output comparison for 4-bladed and 5-bladed wind turbines.

The result shows that adding more blade to become 5-bladed wind turbine does not improve the performance of the turbine.This might due to having more blade create air flow blockage to other blades.

3.4. Study of Different Blade Radius

Next step is to optimize the radius of the blade with a constraint of chord length to be 1.2m. There are 3 radius are considered: 0.382m, 0.432m, 0.519m. Note that the baseline is using radius of 0.382m. The arrangement of blades with different radius is sketched as shown in Fig.10. The comparison is done with turbine orientation only 45 degree. The normalized power output of wind turbine with different blade radius is shown in Fig.10b. It shows that the larger the radius, the smaller the turbine power output.

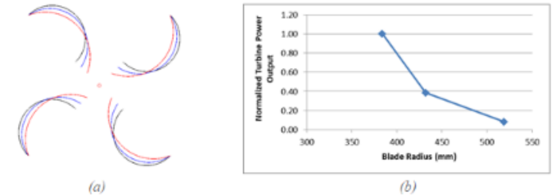


Figure 10: (a) Cross section of 3 turbine blades with different radius viewed from top, (b) Turbine power output for different blade radius.

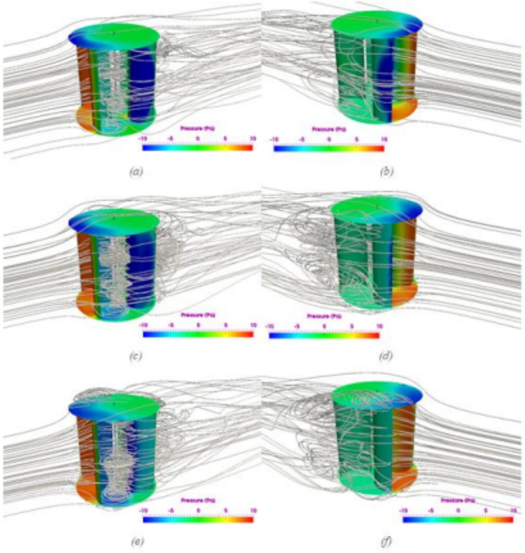


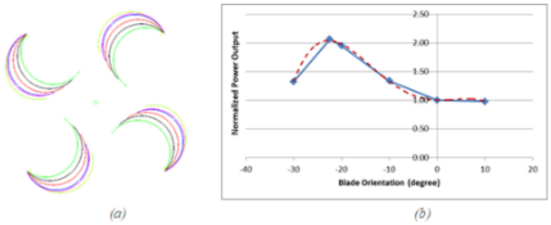
Fig Figure 11: Simulation results of wind turbine colored by air pressure with air streamlines, (a) case for blade radius 0.382m from right view and (b) from left view, (c) case for blade radius 0.432m from right view and (d) from left view, (e) case for blade radius 0.519m from right view and (f) from left view.

Simulation results for different blade radius are shown in Fig.11. Based on the images, the large changes when blade radius is larger is the convex face of the blade. When the radius is larger, convex face of the blade becomes having higher pressure which gives higher resistance to the rotation. The turbine will produce more power when the convex face of the blade has lower pressure and the concave face of the blade has higher pressure.

3.5. Study of Different Blade Orientation

Next optimization is on the blade orientations as shown in Fig.12a. In the test, rotational speed is 50 RPM. The outer edge of the blade is used to rotate blade orientation. The blade orientations considered are +10 degree (green curve in Fig.12a), 0 degree (black), -10 degree (red), -20 degree (blue), -22.5 degree (magenta), -30 degree (yellow). Note that blade orientation 0 degree is the baseline case. The orientation value of -22.5 degree is considered due to its special number, which is 90/4 degree. Simulation shows that from the baseline, increasing the blade orientation does not improve the power output. When the blade orientation is decreased, the power output is improving. Maximal power output which is twice of baseline power output, is obtained when blade orientation is -22.5 degree. Beyond -22.5 degree, the power output decreases.

Optimized wind turbine design from this study is using 4-blade, blade in half circle shape and blade orientation of -22.5 degree.



(a) (b)

Figure 12: (a) Cross section of turbine blades with different orientations, (b) Normalized wind turbine power output for different blade orientation.

3.6. Optimized Design Performance

The Normalized average power output as a function of turbine RPM and normalized average torque output as a function of turbine RPM are shown in Fig.13.

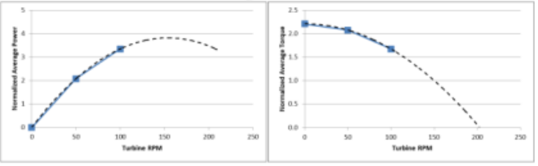
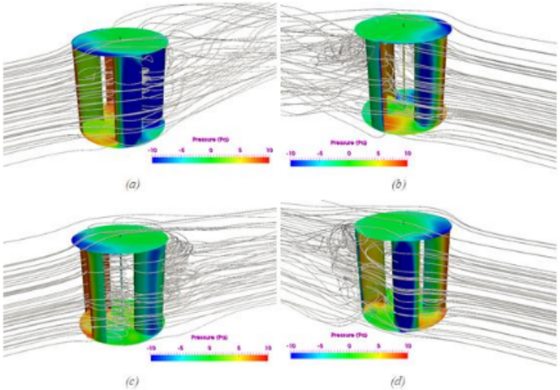


Figure 13: Normalized average turbine power output and normalized average torque as a function of turbine rotational speed.

Based on the Fig.13, the normalized average turbine power peak is at turbine rotational speed of 150 RPM. It seems to be in high value and it needs to be verified by experiment.

The simulation results for 50 rpm case with 0 and 45 degree orientation are shown in Fig.14. The images show that convex surface of the blade with blue color is significantly large at Fig.14a for 0 degree blade orientation while for 45 degree orientation convex surface with blue color moves to the other blade as shown in Fig.14d.



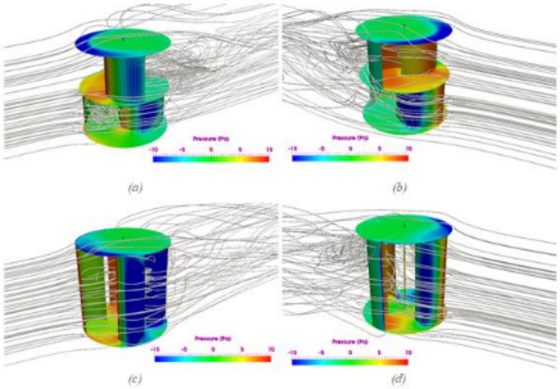
(a) (b)

(c) (d)

Figure 14: Wind turbine colored by air pressure for 50 RPM case, (a) 0-degree blade orientation, right side view, (b) 0 degree blade orientation, left side view, (c) 45 degree blade orientation, right side view, (d) 45 degree blade orientation, left side view.

3.7. Comparison to Previous Work

The optimized wind turbine design is compared with previous work and the comparion is shown in Fig.15. Both wind turbine have been optimized in term of its aerodynamics.



(a) (b)

(c) (d)

Figure 15: Wind turbine colored by air pressure, (a) Two-level wind turbine from previous work, right side view, (b) left side view, (c) One-level wind turbine, right side view, (d) left side view.

Their relative performance comparison is shown in Fig.16. Based on these graphs, One-level VAWT generate more power output and higher torques on wide range of turbine RPM. Based on CFD simulations, One-level VAWT is better than Two-level VAWT.

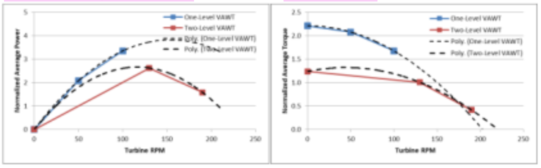


Figure 16: Wind turbine relative performance comparison between One-Level and Two-Level Turbines, (a) Normalized power output curve as a function of RPM, (b) Normalized torque output curve as a function of RPM.

4. Prototyping Process

Next step is to verify the performance of both wind turbines in the field. Prototype constructions for both turbines were done in a workshop at Pamulang, see Fig. 17. The plan is to put both wind turbines in Pelabuhan Ratu area which has a good wind energy potential. Our expectation is that both wind turbine will be performing well, and one-level turbine will perform slightly better than two-level turbine.


(a) (b)

Figure 17: Prototype constructions for both (a) Two-Level and (b) One-Level wind turbines.

5 Conclusion

One-level wind turbine has been designed to optimize its aerodynamic performance with material size constraint to be available in the market. Based on consistent CFD simulation procedure, One-level VAWT performs better than Two-level VAWT from previous work.

Verification of the wind turbines performance should be done in the field to confirm simulation results.

Acknowledgement

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