The Optimal Pitch Distance for Maximizing the Power Ratio for Savonius Turbine on Inline Configuration

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Received: 13.03.2021 Accepted:21.04.2021

Abstract- Vertical Axis Wind Turbine (VAWT) array received less attention from researchers due to the low efficiency of VAWT and the challenge to obtain the optimal arrangement of the turbine array. The inline array of the wind turbine is less desirable due to the low power ratio of the array; however, the inline array uses a smaller area to be maximized on limited land. This study focuses on the inline array of the Savonius turbine with four variations based on the pitch (distance between each turbine) by using turbine diameter (D) as reference. The variation for pitch between the first and second row turbines is ranging from 1D – 4D. Through experimental test, each layout is studied. It shows a significant change concerning the turbulence intensity in the midpoint. Turbulence changes also affect the power ratio of the turbine array. The highest power ratio value is obtained by using pitch 3D. This important finding can be used as a special reference for determining the distance between Savonius turbines in inline arrays.

Keywords Windfarm, Inline array, Savonius turbine, VAWT, Power ratio

1. Introduction

Vertical Axis Wind Turbine (VAWT) has the opportunity to be used in special areas with low wind potential. This technology can also be applied for exceptional areas, such as toll roads, railways, parks, and roofs of houses with special purposes as mini power grids for household applications like water pumping, street lighting, and other utilities [1]-[3]. The aim can be maximized by installing several turbines in a specific cluster called a wind farm. The use of windfarm specifically intended to maximize energy production in a particular area, improving the produced energy density to reduce operational and production costs [4].

VAWT itself is less attractive to be developed because due to many technical barriers for the turbine design [5], low power coefficient [6], and uneconomically [7]. Thus, there are limited research can be found which discusses the windfarm for VAWT. A. Vergaerde et al. [8] elaborate clearly on the challenges of the VAWT about turbine design. Even though, there is still an opportunity for the application of VAWT by maximizing the windfarm configuration. For example, A. Barnes and B. Hughes [9] propose the opportunity to develop a windfarm for VAWT to meet the wind energy market. A. Goude and F. Bülow offer the optimization for VAWT windfarms by installing an advanced control system for the produced electricity [10]. S. Sahebzadeh et al. recommend the staggered arrangement for the VAWT windfarm to maximize the windfarm's power density [11].

Windfarm is classified into two different arrangements, namely staggered and inline. The staggered array is more developed considering a more predictable wake effect and a better energy density [12]. The inline model is a parallel turbine array and less developed due to low energy density [13]. Although it has shortcomings, in principle, inline arrays can be maximized if intended for a particular application. Moreover, an optimized VAWT windfarm can be applied to maximize the power generation of wind energy [14]. Besides, the inline array requires less area than staggered, which means limited space can be used to install the inline array of the VAWT. Our study looks at this unique opportunity for the VAWT windfarm, namely, implementing VAWT with an inline array.

This study is specifically aimed at obtaining the optimal layout for the inline array of the VAWT windfarm. Seeing these opportunities, the authors realized that the wind turbine array for VAWT could be further developed to maximize wind potential as renewable energy [15]. Moreover, with a small wind potential, development can be seen from an industrial perspective and can be seen in the spirit of minimizing the use of fossil fuels in urban applications through the micro windfarm model [16]. Considering this, the study conducted specifically examined the application of the inline array for the VAWT type Savonius. Using a better layout for the VAWT windfarm, the energy density of the windfarm can be maximized, particularly for the micro windfarm [17]. To achieve the goal, the designed VAWT is also proposed, including a specific measurement to ensure the replicability of the result and provide an accurate reference for the other researchers to develop and apply the findings in this study.

2. Method

The first important thing to do is determine the design of the Savonius rotor. Among several types of Savonius rotor, Bach-type was chosen as the best model to be developed by considering that it is easy to manufacture and has a superior performance compared to the other type. Next is the layout of the array based on a specific reference by using the diameter (D) of the rotor set at several different distances or pitch. The predefined turbine types and layout are made then installed in the wind tunnel to determine which layout has the best performance. All of these steps are expected to provide clear information that other researchers can apply to provide relevant results related to the use of the VAWT micro wind farm.

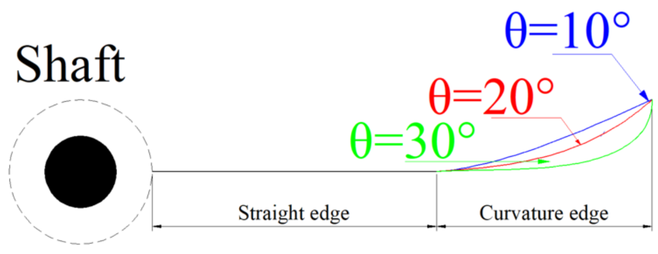

Fig. 1. The effect of θ for the curvature edge.

The prototype of Savonius rotor is developed based on the Bach–type rotor. Bach-type is well known as a superior model for harvesting wind energy. The challenge is the curvature edge for the Bach-type rotor is difficult to adapt since it has no specific variable control for the curvature blade. A modified Bach-type is developed to encounter this issue by using the Myring equation for controlling the curvature of the AUV [18]. The arch of the fore and after body AUV can be referred to determine the curvature edge of Bach-type blade. The θ in the Myring equation is taken as a parameter control to adjust the curvature edge of the blade. Figure 1 presents the effect of θ as a control parameter to the curvature edge of the blade.

Three different turbines were assembled by using three different curvature edge (θ = 10°, 20° and 30°) and tested in the wind tunnel to evaluate which model has the best performance. The result shows that a turbine with curvature edge by using θ = 10° shows the highest performance. This model is used for the experimental evaluation to evaluate the ideal arrangement of the turbines. The detailed rotor dimension is shown in Figure 2, where b is the straight edge, c is the curvature edge blade and e is the overlap. The height of the turbine is 300 mm, with a diameter of 150 mm. The turbine has three blades and made by using an aluminum sheet (δ = 1.05 mm).

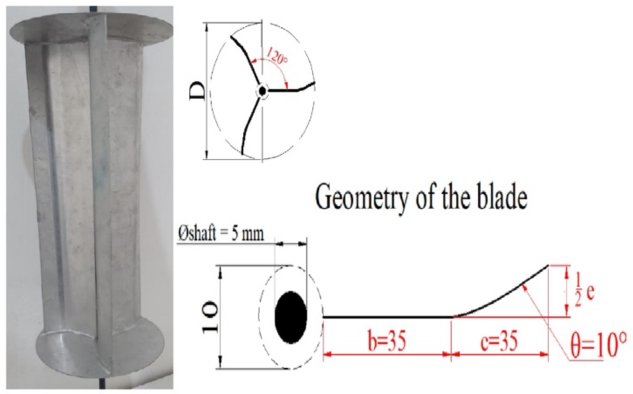

Fig. 2. Detail geometry for the modified turbine prototype

The variation of the inline array is determined based on the distance between the turbine in the first and second row, which is determined based on the pitch (p). Figure 3 shows the basic adjustments for the orientation of the important parts of the test chamber area. A clear orientation can help other researchers replicate or create accurate models to minimize variations in test results between researchers and make it easy for adaptations to actual application plans.

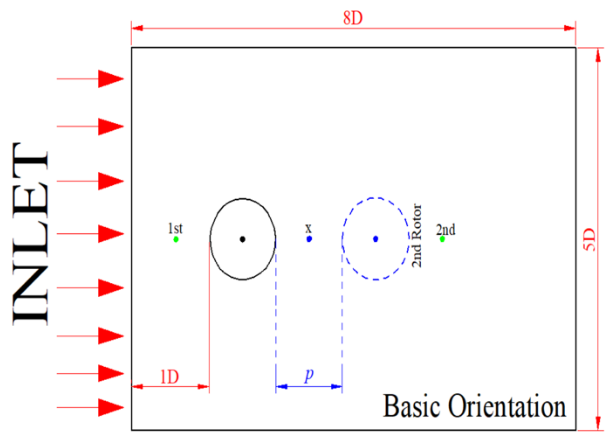

Fig. 3. Basic orientation for rotor and measurement position

The green dots in Figure 3 show the points for measuring wind speed before rotor 1 and after rotor 2 with a fixed distance of ½ D. The pitch (p) shows the distance from the outside diameter of the turbine in each row. Pitch values are made in 1D–4D as variations. To obtain the same measurement result, the measurement point in the wake area (x) is made based on ½ p.

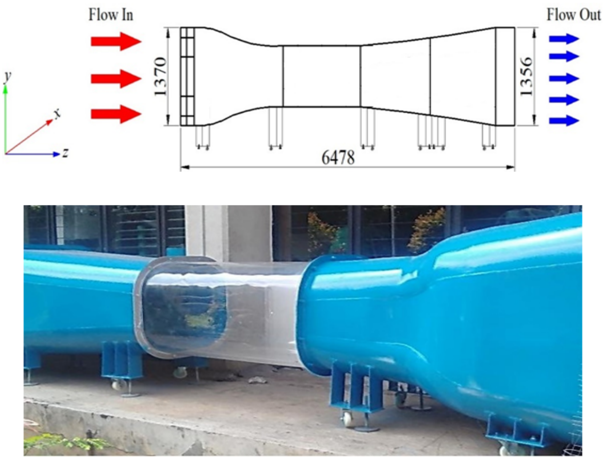

Fig. 4. The detail of the wind tunnel for the experiment

Four arrangements are evaluated based on the pitch ranging from 1D–4D. The value of wind speed varies from 1–5 m/s according to the average wind speed in Indonesia [19]. Each array is tested in the wind tunnel with a size of 1.370 x 6.478 x 1.356 mm (Fig. 4). The wind is provided by using an axial fan (three-phase AC, with power 5.5 kW and diameter of 1.225 m). A frequency regulator is used to control the fan's speed. Also, wind tunnel has a turbulence intensity of 0.8 % [20]. The area of the section test is 750 x 750 x 1,200 mm. A hotwire anemometer is used to measure the wind speed, where a digital tachometer measures the turbine's rotational speed. The overall deviation for the measurement is taken by 1.2%.

3. Result and Discussion

The turbulence phenomenon is the critical factor that affects the overall performance of the windfarm [21]. It causes the decrease of the wind speed and change in the flow direction after passing the turbine at the first row. The absorption of wind energy in the first row interrupts the flow of the wind, which results in a decrease in wind power that the turbine can absorb at the second row. Figure 5 shows the effect of pitch between turbines on the turbulence intensity. The turbulence intensity at the front area (1st measurement point) is relatively small, which is entirely caused by the wind tunnel's nature. The turbulence intensity at the middle area between the first and second turbine (x measurement point) increased sharply and then fell drastically at the rear area (2nd point measurement).

The wake phenomenon causes the turbulence intensity at the midpoint after the wind passes the turbine at the first row. The magnitude of turbulence intensity increases as the wind speed increases and occurs for all arrangements with different pitch. It can be observed clearly that the further distance between turbines, the higher turbulence intensity occurs due to pressure and speed change. The exceptional conditions are shown for pitch 3D and 4D, where the overall turbulence intensity for 4D is lower than 3D. The key finding is where the turbulence intensity will increase from pitch 1D to 3D and then decrease at 4D. It can be said that pitch 3D is the maximum distance that creates the highest turbulence intensity. This condition can be seen from five different wind speeds, the turbulence intensity between pitch 3D and 4D at all speeds decreases except for a speed of 3 m/s with a small increase (0.92%).

The effect of turbulence can be seen from the power ratio between the turbine in the first row and the second row. Power ratio is a ratio to describe the generated power at the first turbine to the second turbine. Figure 6 presents the average power ratio for each pitch at given wind velocity. The highest power ratio is obtained at a value of 54% for a speed of 3 m/s at pitch 1D and 2D. Referring to the turbulence intensity value in the wake area for the velocity and distance (Figure 6), the highest power ratio in 3D and 4D

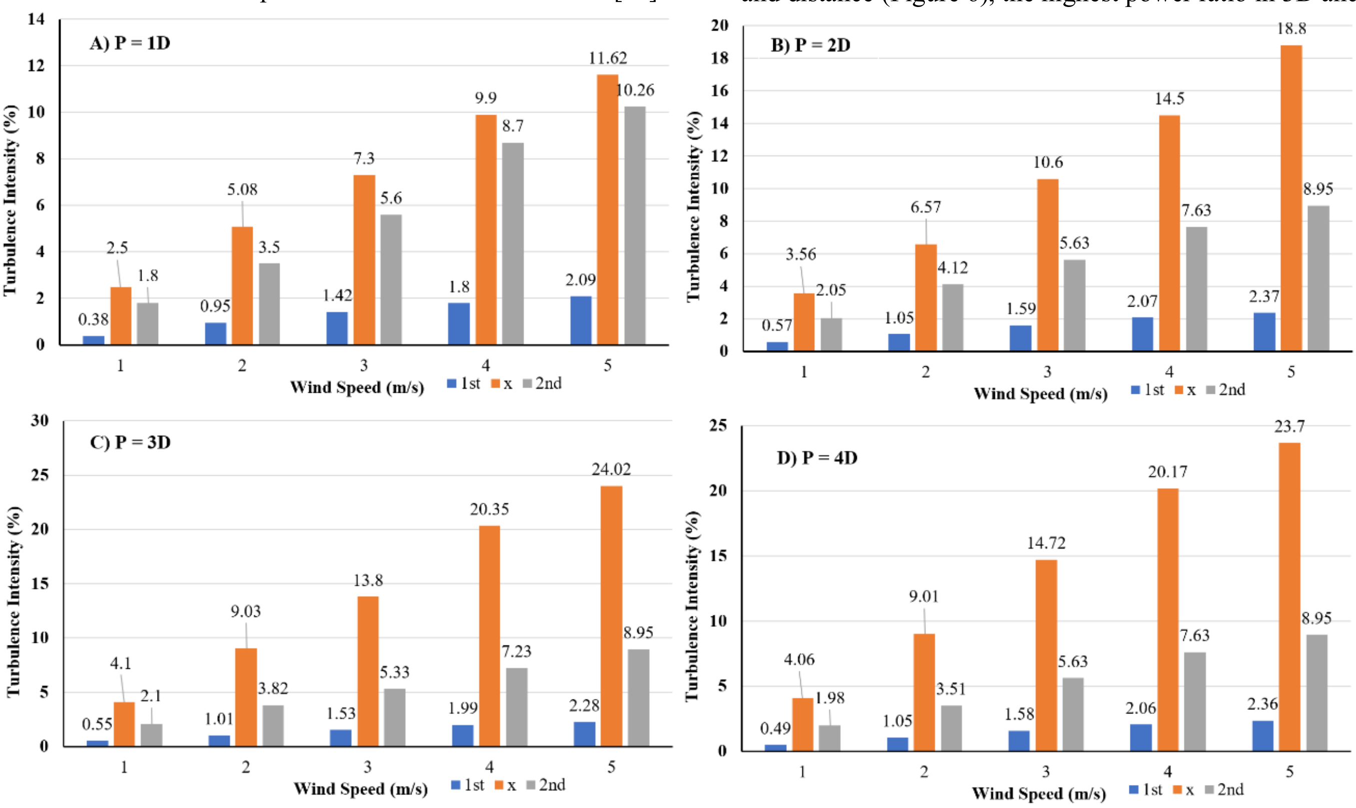

Fig. 5. The result of turbulence intensity under different pitch

pitch are achieved at a speed of 2 m/s with power ratio of 43% and 51%, respectively. It can be concluded that the acceptable value of turbulence intensity for obtaining a high-power ratio is below 10.6%. If the turbulence intensity is higher than 10.6%, the power ratio for the array will drop significantly.

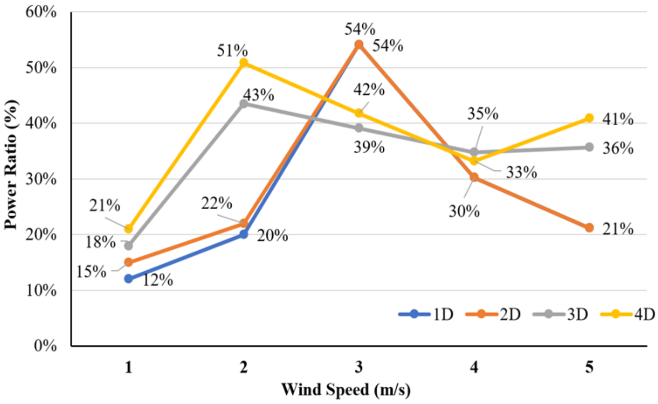

Fig. 6. Power ratio for each array at a different pitch

Figure 7 shows the relation between power ratio and turbulence intensity at the various pitch. The result indicates that the highest power ratio is obtained at pitch 4D by 38%, followed by pitch 3D, where the power ratio is 34%. The power ratio for pitch 2D and 1D is the lowest by 29% and 28%. It demonstrates the distance between turbines (pitch), the highest power ratio can be generated.

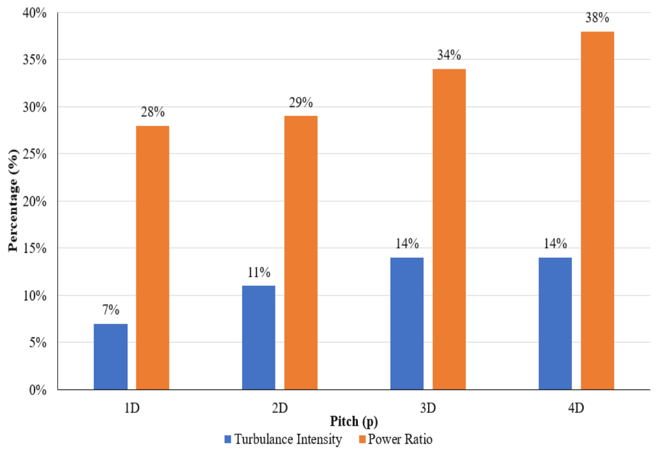

Fig. 7. Comparison for turbulence intensity and power ratio at different pitch (*p*)

For the turbulence intensity, pitch 3D and 4D has the same magnitude with turbulence intensity by 14%, where the turbulence intensity for pitch 2D and 1D are 11% and 7%. The overall magnitude of turbulence intensity between the all-proposed layout relatively varies with a small value. Thus, by considering the power ratio as the main parameter and the area of the windfarm, pitch 3D is the most suitable layout for an inline VAWT windfarm even it has a relatively smaller power ratio compared to pitch 4D, pitch 3D uses a smaller area which able to maximize the power density of the windfarm.

This condition can be used as an important reference for the inline array using the Savonius turbine, where the ideal distance value for the inline model is 3D as the optimal distance value between the first and second turbines in the inline array. These results can be used as a model for the inline array model with the best power ratio to maximize the area used for the turbine array so that the energy density value of the turbine array can be maximized.

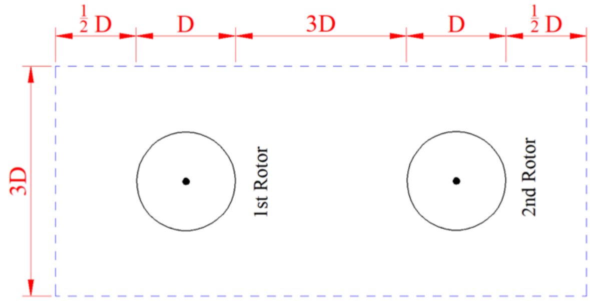

Figure 8. Optimal layout for Savonius turbine array in an inline configuration

Figure 8 shows the optimal layout for the Savonius inline array. This layout has a 6D x 3D area. Area reference with a power ratio of 34% provides a better energy density. This layout reference can be used as a reference in determining the Savonius inline layout model.

4. Conclusion

The experimental evaluation for the inline arrangement for the Savonius turbine presents a specific relation between the turbulence intensity and the power ratio to the pitch between the turbine. The closer position between the turbines causes an increase in turbulence intensity in the middle area of the array. Even though there is an increase in turbulence, the power ratio is an independent factor of the turbulence value. The various power ratio values at different distances and velocities indicate the unpredictable wind characteristics and wake phenomenon [22]. From the overall evaluation based on the power ratio and the area size, pitch 3D is recommended for inline VAWT windfarm. Pitch 3D has the power ratio of 34%, though it is smaller than pitch 4D, pitch 3D has the highest power density because it requires smaller area. The power ratio of pitch is 34% and requires area by 6D x 3D. It has the highest power ratio for a smaller unit area; thus, the density of the windfarm is high. This conclusion can be used as a reference in determining the Savonius turbine array model on limited land with low wind potential.

Acknowledgements

The authors were grateful to Universitas Pancasila as being the funder of research under internal grant funder No: 1845/LPPM/UP/VII/2020 and also to Ari Wisnu Nugroho and Anton Frasiscus for helping the research.

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