Estimating an Optimal Multiple Savonius Wind Turbines Layout by CFD Velocity Pattern Analysis

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Abstract. Proper arrangement of multiple VAWT turbines has been known to have increased the overall power efficiency. The challenge is how to optimally place each turbine within a given location such that the overall performance is improved. This paper presents a methodology by which the placement of individual turbine is determined by the location of vortices created by the upstream turbine. This analysis is carried out by using commercial CFD solver via sliding mesh approach. To clearly observe the creation of wake and vortices by an isolated Savonius turbine, the extra fine mesh was defined outside the rotating zone of the computational domain. The resulted velocity pattern generated shows an area of the high vortex created at the tip of advancing blade at a certain rotor angle. However, the returning blade generates a weaker vortex. The placement of consecutive Savonius wind turbine is, therefore, should be at an angle ranges between 20º to 90º with respect to the advancing blade of the upstream turbine. The analyses on two-turbine, three-turbines and nine turbines in V formation have shown an improvement up to 11% in the overall power efficiency.

1. Introduction
The performance of a wind turbine is measured by its power coefficient or \( C_p \) which is the ratio of actual power generated (\( P_{act} \)) to the theoretically available power, \( P_{th} \), i.e.

\[ C_p = \frac{P_{act}}{P_{th}} \]  
\[ P_{act} = T \cdot \omega \]  
\[ P_{th} = 0.5 \rho AV^3 \]  

Where \( T \) is the torque generated by the turbine, \( \omega \) is turbine rotational speed (rad/sec), \( \rho \) is density of air (1.225 kg/m³) and \( V \) is the wind speed (m/s).

A quest for a higher performance wind turbine is ongoing research. For horizontal axis wind turbine (HAWT), the incorporation of a variable pitch blade is the most popular approach. However, for vertical axis wind turbine (VAWT) which applications mainly in low wind density areas, the use of multiple turbines arrangement sounds very promising proposition. Many approaches are inspired by the biological behavior of the animal kingdom. For instance, Whittlesey et al [1], proposed the placement of VAWTs within the shed vortices in the wake of fish schooling. On a similar manner, Zhang et al [2], investigated the idea of arranging the turbine layout according to V and I formation of flying geese. In general, wind farm power efficiency has increased to more than 30%. On the other hand, Numerical
analysis conducted by Shaheen et al. [3] has resulted in several configurations of turbine clusters. They suggested three turbine cluster configuration gives the best overall performance.

The objective of the present study is to numerically estimate an optimal configuration of multiple Savonius wind turbines such that overall power efficiency is improved. Velocity pattern of an isolated turbine is first studied. Next turbines in the downstream are placed in the areas of vortices outside the wake of the upstream turbine. To ensure an acceptable level of accuracy, a mesh sensitivity analysis was carried out. This paper presents the initial results obtained from this ongoing study.

2. Savonius model
The 90° twisted helical Savonius rotor as shown in Figure 1, with diameter, D of 0.27 m and height, H of 0.5 m is used as a case study. The additional of 1.1D endplate at both rotor end and overlap ratio, e/d = 0.242 used in present Savonius design parameter.

![Figure 1. Parameter annotation for Savonius rotor model](image)

3. Computation domain & Boundary condition
The rectangular computational domain with a dimension of 30D x 16D x 16D used in this study where D is wind turbine diameter [4]. The fixed domain in the shape of rectangular represents the surrounding environment and a cylinder rotating domain acts as a rotating environment around the wind turbine. The sliding mesh approach is used in order to reduce the computational time. The specified rotational velocity, ω is set to the rotating domain based on tip speed ratio, TSR relationship is given by equation 4.

\[
\text{TSR} = \frac{\omega R}{V}
\]

(4)

The transient analysis is related to the numerical iteration that requires an appropriate time step size. 10-degree time step size used in the study and the turbine is set to rotate for 5 revolutions [5]. The turbulence model of Spalart Allmaras used as it suitable for low TSR condition [6].

4. Mesh generation
The accuracy of CFD results is greatly influenced by the computational grid or mesh. Good quality of meshing can also improve solution convergence but requires a longer computational time. Coarse meshing with low-quality grid leads to error solution and unacceptable result [7]. The optimum grid resolution can be determined by running a few sets of mesh sizing until the result was significant regardless of changing the grid size. Zone mesh is created around the Savonius turbine with fine mesh to clearly capture flow around the rotor as shown in Figure 2.
5. Result and discussions

5.1. Analysis of a single turbine
A 2D velocity contour of an isolated rotor is shown in Figure 3. The flow separation on the advancing blade and the returning blade can clearly be seen in the refinement zone (figure 3-c) where a drop in wind velocity is shown in blue. Vortices created by the rotor outside the wake are also observed. However, a region of the highest velocity is found at the tip of the advancing blade shown in red. This velocity pattern is similar to the flow around a Savonius rotor as observed particle image velocimetry (PIV) study [8]. Logical placement of a downstream rotor is therefore in the area of increased wind velocity i.e. within $\theta_1 = 20^\circ$ and $\theta_2 = 90^\circ$. Good to indicate velocity index and direction of rotation/wind direction. At this stage, a gap between the first and the proposed second turbine is yet to be determined.

5.2. Multiple turbine analysis
Two turbines and three turbines are arranged in accordance with the finding in the previous section. At this presence study, the downstream turbines are placed at $\theta_1 = 60^\circ$ and 1D gap distance. This is an optimum location as suggested by [3]. Figure 4 shows the three turbine configuration.
Table 1 shows the power coefficient, \( C_p \) for the isolated turbine, two turbines, and three turbines configurations. The average power coefficient for the two turbines is improved by 5% while the three turbines configuration yields 11% overall efficiency improvement. The results for two turbines analysis shows a close agreement with the published data [3]. However, for the three turbine configuration, a similar trend as found by [2] is observed. The energy created by the upstream turbine is seen to have been reused by its consecutive downstream turbines.

| Turbine/Analysis | Isolated turbine | Oblique Two turbines | Cluster Three turbines |
|------------------|------------------|-----------------------|------------------------|
| 1                | 0.128            | 0.124                 | 0.130                  |
| 2                | -                | 0.146                 | 0.145                  |
| 3                | -                | -                     | 0.154                  |

5.3. Turbines in V-formation analysis

By using the rule established in section 5.1 in estimating the location the downstream turbine, two types of turbines in V-formation as shown in Figure 5 are analyzed. Basically, each configuration consists of nine Savonius rotors placed symmetrically on the horizontal axis with a gap distance of 1D and \( \theta \) of 60°. In the co-rotation configuration (figure 5-a), all rotors rotate in the counter-clockwise rotation. However in the case of the counter-rotating analysis (figure 5-b), all rotors on the returning blade of the upstream turbine (T1) are designed to rotate in a clockwise direction while others remain in a counter-clockwise direction.

Figure 5. Velocity contour of Savonius wind turbine in V-formation (a) co-rotation (b) counter-rotation.

Table 2 and Table 3 show the individual and the average power coefficient of the Savonius wind turbine in V-formation. The co-rotation configuration shows only a 9% improvement in the overall turbine performance. Whereas, an improvement of 11% of power efficiency obtained in the case of the counter-rotation turbine configuration. The following explains why this is happened.

| Turbine | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 | T9 | Average |
|---------|----|----|----|----|----|----|----|----|----|---------|
| \( C_p \) | 0.134 | 0.135 | 0.148 | 0.135 | 0.144 | 0.134 | 0.145 | 0.129 | 0.152 | 0.140   |
| Rotation | CCW | CCW | CCW | CCW | CCW | CCW | CCW | CCW | CCW | CCW     |
Table 3. Power efficiency for counter-rotation turbine analysis.

| Turbine | T1   | T2   | T3   | T4   | T5   | T6   | T7   | T8   | T9   | Average |
|---------|------|------|------|------|------|------|------|------|------|---------|
| $C_p$   | 0.109| 0.133| 0.139| 0.146| 0.142| 0.152| 0.146| 0.161| 0.153| 0.142   |
| Rotation| CCW  | CW   | CCW  | CW   | CCW  | CW   | CCW  | CW   | CCW  |         |

The reduced $C_p$ of the upstream turbine (T1) in the case of counter-rotation configuration (figure 6-b) is attributed to the high-pressure region created by turbine T2 thus inducing a reverse torque to turbine T1. Hence, reducing the performance of the T1 turbine. On the contrary, the situation is not present in the co-rotation case. The optimum gap distance between T1 turbine and T2 turbine requires further investigation in order to maximize the overall performance in counter-rotation condition.

Figure 6. Pressure contour around the upstream turbine (T1) (a) co-rotation condition (b) counter-rotation condition

6. Conclusion

The velocity pattern analysis conducted in this study has shown its potential is estimating an optimal location of the downstream turbine in multiple turbine configurations such as wind farm. In the case of a Savonius rotor, the wake generated by its rotation has created vortices that can clearly be identified via the velocity pattern. This is achieved by the zone mesh adaption strategy adopted in this analysis. Hence placing a turbine at within this location will certainly improve its power efficiency. The initial results show a line array of turbines in 60° with respect to the upstream turbine will provide power enhancement. This is an agreement with published data [3]. A properly arranged Savonius rotors in V formation increases the overall power efficiency up to 11%.

Current work is being undertaken to investigate other different configuration and validation by wind tunnel test.

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