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by Kylie Hirth

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Optimization of staggered array configurations to enhance the aerodynamic performance of Darrieus wind turbines

Yosua Heru Irawan[a*], Aditya Sukma Nugraha[b], Po Ting Lin[c]
[a]Department of Mechanical Engineering, Institut Teknologi Nasional Yogyakarta
Yogyakarta, Indonesia
[b]Research Centre for Smart Mechatronics, National Research and Innovation Agency
Bandung, Indonesia
[c]Department of Mechanical Engineering, National Taiwan University of Science and Technology
Taipei, Taiwan
*e-mail: yhirawan@itny.ac.id

Abstract

This research focuses on optimizing the arrangement of Darrieus wind turbines through an adjustable R array, which represents the spacing between the turbine rotors. This study aims to optimize the staggered array configuration of Darrieus Wind Turbines to enhance their aerodynamic performance. Using computational fluid dynamics (CFD) simulations and optimization techniques in MATLAB, various array configurations were evaluated. The ANSYS Fluent solver, employing the k-epsilon turbulent model and sliding mesh technique, was utilized to predict turbine performance. Additionally, a grid independence test was conducted to validate the solver's effectiveness. The optimization of the R array was achieved using the conjugate gradient method. Simulation results indicate that a blade grid size of 1 mm results in an error under 1%. A smaller R array yields a lower average coefficient of power ($Cp_{average}$) due to the wake interactions between the rotors. The optimal spacing for each turbine to achieve a $Cp_{average}$ value of 0.4088 is determined to be 1.772 meters. The optimal radius was found to significantly improve the average coefficient of performance (Cpaverage), demonstrating reduced wake interactions and enhanced efficiency. These findings provide a framework for designing more efficient wind farms with VAWTs, contributing to the advancement of renewable energy technologies. The optimized configurations are applicable in urban and offshore wind farms where space and efficiency are critical.

***Keywords**: conjugate gradient; Darrieus wind turbine; optimization*

1. INTRODUCTION

Amid concerns about global warming and increasing global energy demands, there is a significant shift in the development of electricity supply towards renewable energy sources. Wind energy, recognized for its cleanliness, has received substantial support from policymakers and major energy companies. In urban settings where wind conditions are highly dynamic, small-scale Vertical Axis Wind Turbines (VAWTs) are noted for their superior efficiency compared to Horizontal Axis Wind Turbines (HAWTs). VAWTs have several advantages over HAWTs, especially in urban and offshore settings. They are less sensitive to wind direction, allowing them to capture wind from any direction without needing to reorient. This makes them particularly effective in turbulent and varying wind conditions typical in urban environments. Additionally, VAWTs have a simpler design and fewer moving parts, resulting in lower maintenance costs. Their lower height and compact structure also make them more suitable for integration into urban landscapes and offshore platforms where space and stability are crucial (1). This efficiency is due to their ability to operate effectively in various wind directions, their adaptability to turbulent or distorted winds, and their lower noise levels. For offshore settings, VAWTs are favored over HAWTs due to their lower center of gravity, simpler construction, reduced deployment and maintenance costs, and greater scalability to larger sizes (2-4).

Despite the growing interest in VAWTs, their power coefficient remains relatively low compared to HAWTs, which poses a significant limitation on their widespread adoption. The primary limitation of VAWTs is their generally lower power coefficient compared to HAWTs, which means they are less efficient in converting wind energy into electrical energy (5). Additionally, VAWTs often experience higher structural loads and fatigue due to their design, which can lead to shorter lifespans and increased maintenance requirements. Moreover, VAWTs can suffer from issues related to self-starting and require external mechanisms to initiate rotation under low wind conditions. Efforts to enhance the design of modern VAWTs have included (a) modifying spatial or operational parameters to improve aerodynamics, and (b) developing new airfoil designs (6-8). Optimizing the design of VAWTs is crucial to improving their power coefficient, which directly affects their efficiency and viability as a renewable energy source. By enhancing the aerodynamic performance and structural integrity, optimized VAWTs can generate more power from the same wind resources, making them more competitive with HAWTs (9). Optimized designs also help in reducing operational and maintenance costs, further enhancing their economic feasibility. A common approach involves analyzing the fluid-dynamic behavior around the airfoil using a two-dimensional cascade, essentially an infinite array of airfoils on a two-dimensional (x,y) plane. Numerous studies have aimed to optimize the performance of VAWTs by minimizing airfoil losses based on criteria such as airfoil lift and blade chord. In airfoil research, some studies have successfully employed genetic algorithms with Bézier control points to derive optimal airfoil shapes (6).

Approaches to enhancing the efficiency of modern VAWTs include advanced aerodynamic modeling, material improvements, and innovative structural designs. Computational fluid dynamics (CFD) is extensively used to analyze and optimize blade shapes and turbine configurations. Researchers also experiment with different materials to improve durability and reduce weight (10). Additionally, optimizing the layout of VAWT arrays, such as using staggered configurations, can minimize wake effects and improve overall energy capture.

Furthermore, it is crucial to predict the performance of the optimized design under realistic conditions before proceeding with prototyping. The three-dimensional computational fluid dynamics (CFD) approach, utilizing the finite volume method, serves as an effective tool for predicting the performance of Vertical Axis Wind Turbines (VAWTs). CFD plays a vital role in predicting the performance of VAWTs by simulating airflow and assessing the aerodynamic forces acting on the turbine blades (11). Specific parameters determined through CFD include the pressure distribution, velocity fields, and turbulence characteristics around the turbine. CFD helps in optimizing blade design, improving energy capture efficiency, and reducing aerodynamic losses. It also aids in identifying the optimal arrangement of turbines in an array to minimize wake interactions and enhance overall performance. This method facilitates the prediction of specific flow parameters in complex flow scenarios, which are challenging to measure experimentally. For instance, it allows for the determination of velocity and pressure contours at any point within the computational domain (12).

Research on optimizing the array configurations of VAWTs is necessary to maximize energy extraction from wind farms. Properly arranged VAWTs can significantly reduce the negative impact of wake effects, where the downstream turbines receive less wind energy due to the turbulence created by upstream turbines (13). This optimization aims to address challenges such as uneven energy production, increased mechanical stress, and reduced overall efficiency. By finding the optimal spacing and arrangement, researchers can enhance the collective performance of VAWT arrays, making them more viable for large-scale applications.

Numerous studies have been conducted on the performance of single-array Vertical Axis Wind Turbines (VAWTs), yet research on optimizing their array configurations remains scarce. Consequently, this research focuses on studying and enhancing the efficiency of VAWTs when deployed in arrays. The structure of this article is designed to facilitate understanding of the objectives and findings of this study. Section 1 outlines the purpose of the current work. Section 2 describes the numerical model used for the study and its validation process. The results and analysis of the empirical investigation are presented in Section 3. The article concludes with a summary of the findings and implications of the research.

2. THE SCOPE AND METHODOLOGY OF WORKS

2.1 The aim of the present work

Optimizing the layout of Vertical Axis Wind Turbines (VAWTs) is an intriguing research area, particularly because of the potential to maximize wind energy extraction from a given land area. Previous studies have primarily explored configurations involving three side-by-side clusters or pairs of generators. It has been observed that the interactions among turbines positioned side by side are less intense than those among turbines arranged in rows over expansive VAWT farm areas (14-15). Consequently, there is a need for further investigation into the interplay within a cluster of turbines and among adjacent and subsequent clusters in large-scale VAWT farms. While earlier research focused on optimizing arrangements of two or three closely spaced turbines side-by-side, the present study aims to extend this exploration to larger wind farm configurations.

In the wind farm, the staggered layout is preferred from the the point of view of power generation. The staggered deployment, each row of turbines, is positioned to face the wind between the gaps in the previous row as seen in Figure 1.

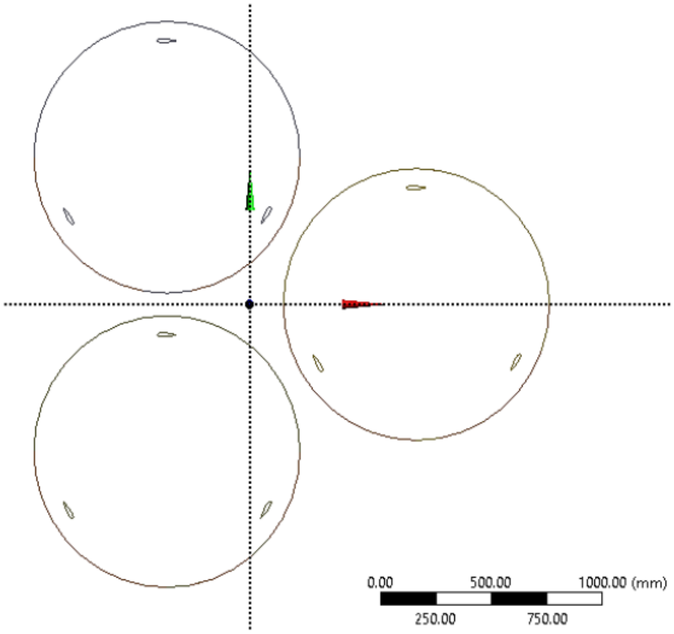

Figure 1. The arrangement of Darrius wind turbine

The objective of the current research is to optimize the spacing between small Vertical Axis Wind Turbines (VAWTs) in large-scale clustered wind farms. This optimization relies on constant values for the turbine tip speed ratio, velocity, and a single blade model. The aim is to maximize the coefficient of performance per unit area within the VAWT farm. To achieve this, the study identifies an optimal spacing that reduces aerodynamic interference among the turbines in staggered wind farm configurations. The key geometric features of the model are detailed in the table provided below.

Table 1. The main geometry features of VAWT

Rotor diameter (*D*)	1.03 m
Rotor high	1 m (2D case)
Number of blades (*N*)	3
Blade profile	NACA 0021
Chord length (*c*)	0.0858 m
Solidity (*Nc/R*)	0.5

2.2 Numerical Simulation

The ANSYS Fluent solver is employed to simulate the airflow around the wind turbine rotor. The *k-epsilon* model is utilized to capture the turbulent flow dynamics. A sliding mesh method, which requires the use of a transient solver, models the rotation of the wind turbine rotor. In this approach, the rotor's rotation speed and the coordinates of the rotor center are essential inputs for calculating the rotor's torque. Both spatial and time discretization are implemented using second-order upwind and second-order implicit methods, respectively. The boundary conditions are set with uniform velocity at the inlet, constant pressure at the outlet, and symmetry conditions along both lateral boundaries. The size of the computational domain is specified as 45*D* x 30*D*, where *D* represents the rotor's diameter, with further details available in Figure 2.

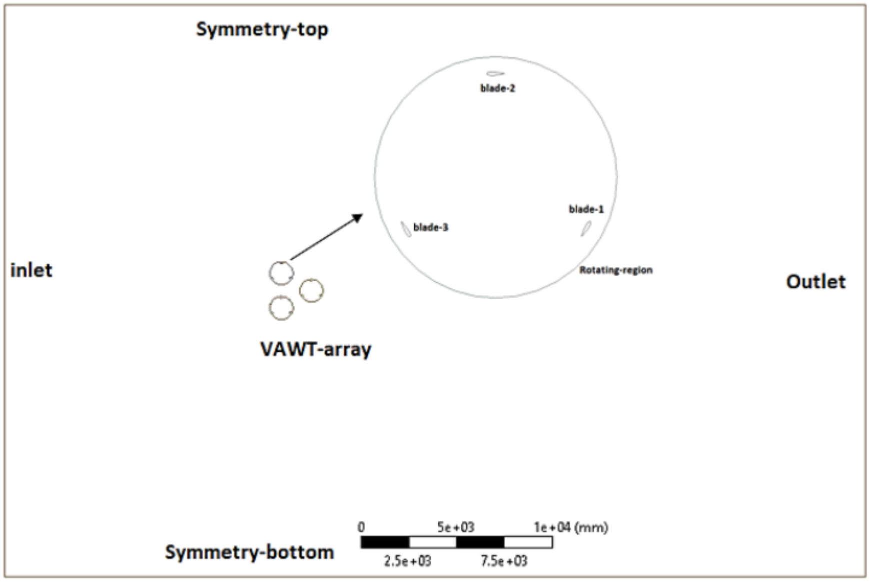

Figure 2. The computational domain

The output of this simulation is torque, then this torque is used to calculate the coefficient of performance (*Cp*) using equation (1). In equation (1) ω is the rotational speed of the rotor input, ρ is the density of air, A is the area of the rotor sweep and U is the velocity of air, for this case we use $U = 9$ m / s.

$$Cp = \frac{T\omega}{0.5\rho A U^3} \tag{1}$$

For the calculation of the average *Cp* of the VAWT array, the equation below is used, where Cp_1, Cp_2 and Cp_3 are *Cp* for each turbine simulated in the array.

$$Cp_{average} = \frac{Cp_1+Cp_2+Cp_3}{3} \quad (2)$$

2.3 Grid Independence Test

A grid independence test was conducted by varying the grid size on each blade, with grid sizes ranging from 1 to 2 mm. The outcomes of this test are compared with previously published results to validate the solver employed. Additionally, the optimal grid size identified through this test will serve as the reference for the grid sizes in all subsequent model simulations. Further details on the setup of the grid independence test are provided in the accompanying illustration below.

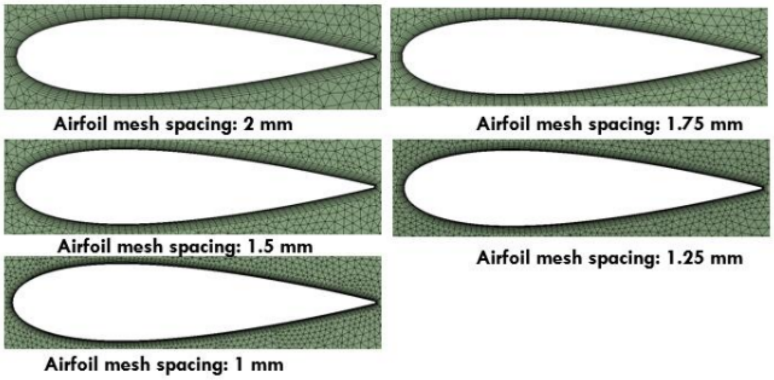

Figure 3. Grid independence test

2.4 Procedure of the optimization system

The optimization process for this study is centered around a Tip Speed Ratio (TSR) of 1.0 and encompasses the complete optimization cycle. The primary objective is to optimize the radius distance of the Vertical Axis Wind Turbine (VAWT) to enhance its aerodynamic efficiency. This process is executed through an iterative loop that includes simulation, meshing and estimation, data analysis, and the application of an optimization algorithm. In this study, optimization techniques are classified under Gradient Search Methods (GSMs), which have been employed to determine the optimal radius for achieving maximum coefficient efficiency.

The conjugate gradient method serves as an intermediary between the steepest descent method and the Newton method. Essentially, this method modifies the direction of the steepest descent by incorporating a positive multiple of the previously used direction. Enhancements such as restarting and preconditioning play crucial roles in optimizing the efficiency of the conjugate gradient method. The core strategy involves utilizing the coordinate axes as search directions. The initial step accurately determines the x_1 coordinate, setting the stage for subsequent steps. Typically, each step strategically selects the next point as follows:

$$x_{(i+1)} = x_i + \alpha_i d_i \quad (3)$$

Where $d_i = -\nabla f_i + \frac{\nabla f_i . \nabla f_i}{\nabla f_{i-1} . \nabla f_{i-1}} d_{i-1}$ (4)

The MATLAB software was utilized to develop the code for optimizing the radius array of Vertical Axis Wind Turbines (VAWTs). Figure 4 features a flow chart that outlines the methodology used to enhance the optimization of aerodynamic coefficient performance.

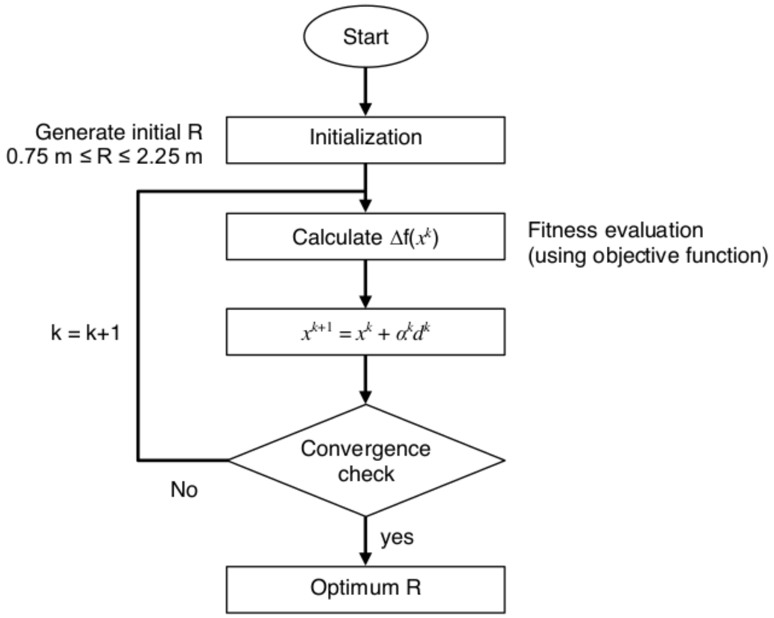

Figure 4. The optimization procedure

3. RESULT AND DISCUSSION

3.1 Grid independence test results

The outcomes of the grid independence test were benchmarked against findings from Raceti et al. (16) (*Cp* = 0.4286) to evaluate errors arising from varying grid sizes around the blade. The configuration with a 1 mm grid spacing resulted in an error below 1%. Based on these findings, a grid spacing of 1 mm on each blade will be adopted for all model simulations.

Table 2. The results from grid independence test

Mesh spacing	*Cp*	Error (%)
2 mm	0.2987	30.2860
1.75 mm	0.3526	17.7198
1.5 mm	0.3907	8.8390
1.25 mm	0.4119	3.8956
1 mm	0.4322	0.8536

3.2 Simulation and optimization result

Figure 5 shows the relationship between the average coefficient of performance ($Cp_{average}$) and the radius (*R*) of a staggered array of Darrieus Wind Turbine. The $Cp_{average}$ values are plotted against varying radius ranging from 0.5 meters to 2.5 meters. The $Cp_{average}$ increases sharply as the radius increases from 0.5 meters, reaching a peak around 1.5 meters, and then it begins to decrease slightly as the radius continues to increase towards 2.5 meters.

Figure 5 presents the average coefficient performance of Vertical Axis Wind Turbines (VAWTs) at a Tip Speed Ratio (TSR) of 2.33, derived from CFD simulations across a radius range of 0.7 to 2.25 meters. The illustration reveals that a smaller radius array results in a lower average coefficient of performance ($Cp_{average}$), primarily due to the wake interactions between the turbine rotors. As the radius array increases, the average *Cp* also rises. Beyond a certain point, the $Cp_{average}$ stabilizes and may even begin to decrease. The optimization process determined that the optimal radius array is 1.772 meters. Subsequent simulations using this optimal radius array with CFD achieved a maximum average *Cp* of 0.4088 for each turbine. The small R array gives a low average *Cp*, this is due to the wake interaction between the wind turbine rotors that influence each other, as shown in Fig. 6.

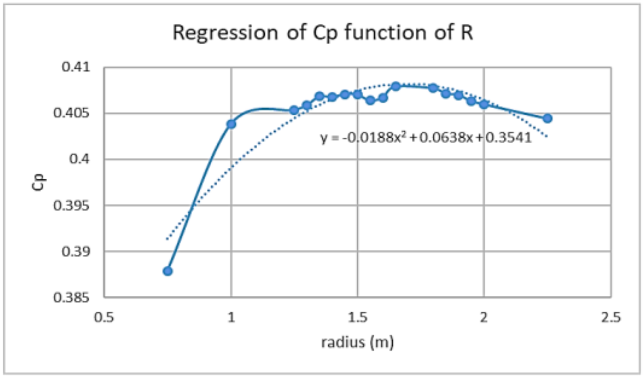

Figure 5. The initial objective function of array VAWTs

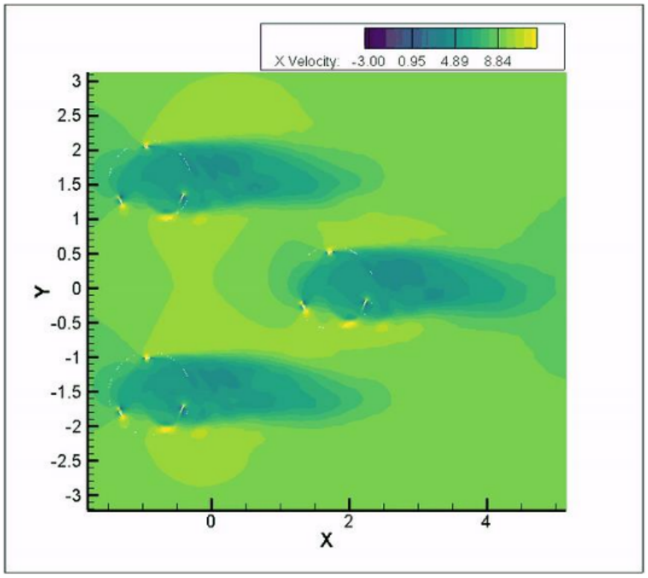

Figure 6. The velocity contour for optimal array

4. CONCLUSION

The optimization process for the wind turbine array has been successfully conducted using the conjugate gradient method to refine the radius of a Staggered Array of Darrieus Wind Turbines. A smaller radius array results in a lower average coefficient of performance ($Cp_{average}$), attributable to the wake interactions among the turbine rotors, which affect each other's efficiency. The optimal radius (*R)* for each turbine in the array has been established at 1.772 meters, corresponding to a $Cp_{average}$ value of 0.4088.

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