



Assessment and optimization of the power performance of twin vertical axis wind turbines via numerical simulations

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ABSTRACT

The power performance of twin vertical axis wind turbines (VAWTs) is believed to surpass that of their individual counterparts. In this study, the power performance of twin VAWTs was investigated via computational fluid dynamics (CFD) simulations by changing their configuration parameters, including the airfoil section (NACA), solidity ratio (σ), pitch angle (β), rotational direction (φ), and turbine spacing (S/D). The CFD model was validated against wind tunnel test data from the literature. An L_{16} (4^3) orthogonal table was adopted to optimize the power performance using the Taguchi method. The rated power coefficient (C_p) and rated tip speed ratio (TSR) were calculated for the 16 cases in the table. The extent of impact of the five parameters on the rated TSR ranked as $\sigma > \beta > NACA > \varphi > S/D$. In comparison, the extent of impact of these parameters on C_p ranked as $\beta > S/D > \sigma > NACA > \varphi$. The optimal and worst configurations of the twin VAWTs were determined and their C_p values increased by 13% and 8%, respectively, from that of their standalone counterparts. Moreover, the rated TSRs of the twin VAWTs differed from those of their standalone counterparts.

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1. Introduction

With the large-scale exploitation of traditional fossil fuels, related problems, such as energy crises and environmental deterioration, have seriously affected human society. Therefore, shifting toward clean and renewable energy is imperative [1,2]. Wind energy is abundant on our planet and its market share has increased greatly in recent years [3]. Wind turbines are commonly used to harness wind energy. According to the orientation of the rotational axis, wind turbines can be classified as horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) [4]. HAWTs have strict requirements for the surrounding environment and lose significant power efficiency under turbulent conditions [5]. Moreover, the size of HAWTs tends to increase to allow for large power output [6], resulting in noise pollution and ecological problems. In contrast, VAWTs do not have these kinds of problems. Furthermore, interest in VAWTs among academic communities has resurged [7]. Dabiri found that VAWTs were likely to have higher power output per unit area of land [8]. In addition, some advantages of VAWTs include their small size, low noise level, low cost, easy installation,

and ability to capture wind energy without yawing [9]. More importantly, VAWTs demonstrate better power performance in turbulence than their HAWT counterparts [10]. This suggests that VAWTs have great potential for wind energy harnessing.

One of the major goals of studying VAWTs is to maximize their power performance by optimizing their configuration parameters. The main turbine parameters for a single VAWT are the solidity ratio, airfoil section, pitch angle, and tower diameter. Li and colleagues measured the power performance of VAWTs with different solidity ratios using a torque meter and a six-component force balance [11,12]. Their experimental results showed that the power coefficient decreased as the solidity ratio increased. In contrast, the torque coefficient increased as the solidity ratio increased. Subramanian and colleagues conducted computational fluid dynamics (CFD) simulations to examine the effect of the airfoil section on the power performance of VAWTs [13]. The NACA 0015 airfoil was found to have the highest power coefficient at the rated tip speed ratio (TSR). The NACA 0030 airfoil performed better at low TSRs, whereas the NACA 0012 airfoil performed better at high TSRs. This indicates that no airfoil can always achieve the best performance across the range of TSRs. Rezaeiha and colleagues carried out CFD simulations to study the power performance of VAWTs by varying pitch angles [14,15]. They observed that a 6.6% increase in the

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power coefficient could be obtained with a toe-out pitch angle (leading edge pitches outward) compared with a zero pitch angle. In contrast, a significant reduction of 66.5% in the power coefficient was noted with a toe-in pitch angle (leading edge pitches inward) compared with a zero pitch angle. Rezaeiha and colleagues analyzed the effect of tower on the power performance of a VAWT via CFD simulations [14,15]. They aimed to quantify the turbine power losses for various tower-to-turbine ratios and found that the former increased as the latter increased. However, few studies have examined the impacts of turbine parameters on the power performance of twin VAWTs.

The turbine parameters for multiple VAWTs include rotational direction, turbine spacing, flow direction, and blade rotational angle. Ahmadi-Baloutaki and colleagues studied the power performance of co- and counter-rotating VAWTs via wind tunnel testing [16]. The counter-rotating VAWTs demonstrated a slight improvement in power performance compared with a standalone VAWT, whereas the co-rotating VAWTs demonstrated a slight reduction. Lam and Peng conducted systematic measurements of the wake aerodynamics of twin VAWTs in a wind tunnel [17]. They observed that the counter-rotating twin configuration contributed to a fast wake recovery. This indicates that the counter-rotating twin configuration of VAWTs have a good potential for array configurations. In another study, twin counter-rotating VAWTs were studied via CFD simulations [18]. The aerodynamic performance of the twin VAWTs with various turbine spacing, TSRs, and flow directions was examined. The power performance of the twin VAWTs was augmented compared with that of a standalone VAWT. The power performance of the side-by-side VAWTs was better than that of the staggered VAWTs. Moreover, smaller turbine spacing improved power performance in the side-by-side configuration. Sun and colleagues made similar observations [19]. Chen and colleagues conducted CFD simulations to analyze the impact of different turbine parameters on the power performance of twin VAWTs [6]. They found that the TSR and flow direction played important roles in determining the power performance, whereas the blade rotational angle had little effect on power performance. However, few relevant studies have considered all the main turbine parameters to systematically assess their effects on the aerodynamic performance of twin VAWTs.

As turbulence modeling and computing techniques has advanced considerably in the past decade, CFD simulations have become very promising tools in the study of VAWTs [20–22]. By assuming that the rotor blades have infinite length in the span-wise direction, CFD simulations of VAWTs can be conducted in a two-dimensional (2D) manner [23]. As suggested by Simão Ferreira, the 2D CFD modeling is capable of dealing with the complexity of VAWTs' aerodynamics by reproducing the generation of shed vorticity and its interaction with blades in the downstream half-revolution during dynamic stall. Lam and Peng carried out two- and three-dimensional (3D) CFD simulations to study the power performance of a VAWT [24]. Though the 2D CFD model noticeably overestimated the power coefficients C_p , the essential feature of the characteristic C_p - λ curve (λ for tip speed ratio) was well captured, with the rated λ coinciding with that by the 3D model. This finding is also proved to be true by comparing numerical results and experimental data. Raciti Castelli and colleagues found that the two C_p - λ curves by 2D CFD simulations and experimental measurements were of similar shape with roughly a constant discrepancy gap [25]. The constant discrepancy is attributed to the combined effects of finite blade depth and support arms. The 2D CFD modeling is concluded to be valid in design and optimization of VAWTs by predicting the power performance and visualizing the flow physics [22,26–28]. Moreover, the 2D CFD modeling is cost-effective compared with the 3D modeling in terms of

computational demanding. Hence, the 2D CFD simulations serve the best interest of this paper for the optimization of twin turbine configurations.

A careful review of the literature reveals that most of the research has examined the effects of only a small proportion of configuration parameters on the power performance of twin VAWTs. In this study, comprehensive 2D CFD simulations are conducted to maximize the power performance of twin VAWTs by optimizing the important turbine parameters. The impacts of these parameters on the rated TSRs of twin VAWTs are assessed. Moreover, the effects of these turbine parameters on the power performance of twin VAWTs are analyzed using the Taguchi method. The power performance of twin VAWTs and their standalone counterparts at the optimal and worst configurations are evaluated and discussed.

2. Computational methodology

2.1. Geometry of VAWT prototype

The straight-bladed VAWT prototype under investigation was adopted from the literature [29]. The specific configuration parameters of the VAWT are shown in Fig. 1. The number of blades (N) was three. The blades were extruded straight from a NACA 0015 airfoil section. The pitch angle (β) was 0° (Fig. 2). The chord length (c) of the blade was 0.42 m. The offset (a) from the leading edge was 0.15 m. The upper blade was called blade 1. It had an azimuthal angle of $\theta = 0^\circ$ and rotated counterclockwise. The radius (R) of the VAWT was 1.4 m. The radius (r) of the tower was 0.05 m. As a result, the solidity ratio was $\sigma = Nc/2R = 0.45$ (> 0.4), which corresponds to a high-solidity VAWT.

2.2. CFD modeling of twin VAWTs

The main components of VAWTs are blades, towers, and support rods. Elkhoury and colleagues suggested that components such as support rods had less influence on the flow field [30]. Therefore, support rods were not modeled in this study. The schematic of the computational domain of side-by-side twin VAWTs is shown in Fig. 3. The size of the computational domain was $32D \times 24D$ (a specific independence study is conducted later), with D being the diameter of individual VAWTs. The configuration parameters of twin VAWTs, i.e., airfoil section, solidity ratio, pitch angle, turbine spacing and rotational direction, were considered in this study. Turbine spacing, S , was defined as the center-to-center distance of

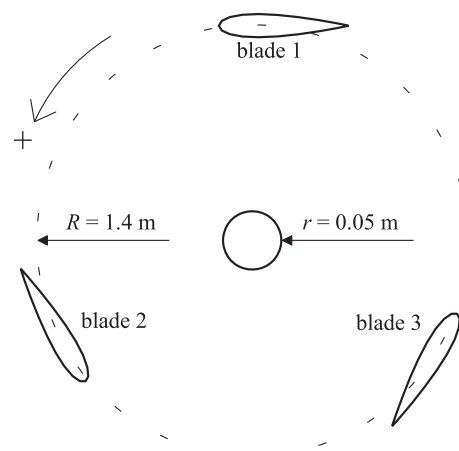


Fig. 1. Schematic of the VAWT (top view).

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