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Computational and experimental optimization of the exhaust air energy recovery wind turbine generator

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ABSTRACT

This paper studies the optimization of an innovative exhaust air recovery wind turbine generator through computational fluid dynamic (CFD) simulations. The optimization strategy aims to optimize the overall system energy generation and simultaneously guarantee that it does not violate the cooling tower performance in terms of decreasing airflow intake and increasing fan motor power consumption. The wind turbine rotor position, modifying diffuser plates, and introducing separator plates to the design are considered as the variable factors for the optimization. The generated power coefficient is selected as optimization objective. Unlike most of previous optimizations in field of wind turbines, in this study, response surface methodology (RSM) as a method of analytical procedures optimization has been utilised by using multivariate statistic techniques. A comprehensive study on CFD parameters including the mesh resolution, the turbulence model and transient time step values is presented. The system is simulated using SST K-ω turbulence model and then both computational and optimization results are validated by experimental data obtained in laboratory. Results show that the optimization strategy can improve the wind turbine generated power by 48.6% compared to baseline design. Meanwhile, it is able to enhance the fan intake airflow rate and decrease fan motor power consumption. The obtained optimization equations are also validated by both CFD and experimental results and a negligible deviation in range of 6–8.5% is observed.

1. Introduction

Although wind energy is known as one the most promising renewable energy sources, there are several limitations in using wind turbines. For one, the main restriction of using conventional wind turbines is the insufficiency of "minimum wind velocity" to rotate wind turbine. Due to this issue, energy generation from wind is highly dependent to the location and is only applicable in regions owing the specific minimum wind velocity. Furthermore, in order to extract power from wind efficiently, large size wind turbines are needed which are only possible to be installed in remote areas. High initial cost is also another concern which has restricted the large scale marketing of such devices. These drawbacks are more outstanding in horizontal axis wind turbines (HAWT) and these problems result in vertical axis wind turbines (VAWT) are more appropriate than HAWT in the urban areas [1]. In addition, lower noise emission of the VAWT causes it is more attractive to employ in the urban areas. However, VAWT has not been widely employed yet due to the lower performance of the VAWT compared with HAWT. The low wind speed and complex topographies of the urban areas are also other main disadvantages induce lower VAWT performance in urban area.

Many researches have been done to overcome low wind velocity issue by either the wind turbine design augmentation or using man-made wind sources. Chong et al. [2] experimentally studied the effect of using a novel omni-directional guide vane on a five-blade vertical axis wind turbine (VAWT). They claimed to achieve up to 58% performance improvement at tip speed ratio of 2.5. The efficiency of diffuser augmented wind turbines (DAWT) was also investigated in several studies [3–5]. Sahizareh et al. [6,7] carried out an experimental and computational study on an omni-directional guide vane to find the most optimized design. They also reported a possible 58% increment in torque coefficient using the optimum parameters. To tackle the unavailability of sufficient wind speed, a novel on-site wind energy generation system using artificial wind resources has been designed [8]. The discharged air from an exhaust fan in cooling tower systems can be potentially

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used for energy generation purposes. The exhaust air energy recovery wind turbine generator is presented to be utilised for this purpose [9]. On the other hand, some innovative solutions have been proposed to increase the VAWT performance, as an interesting example, a novel VAWT was designed by Ying Wang et al. [10] that the turbine blades were deformed automatically into the desired geometry. In that study, a sequence of numerical simulations has been accomplished via the united computational fluid dynamics (CFD) code to improve the VAWT performance. The results show an appropriate increment in the VAWT performance.

In the current study, the authors have tried to achieve the optimum design for this wind turbine using combination of response surface methodology (RSM) and computational fluid dynamics (CFD) simulation. The objective of using RSM in design optimization is not only to minimise the cost of analysis methods such as finite element method and CFD analysis [11] but also to reduce their associated numerical noise [12]. Many researchers have used RSM to optimize wind turbine designs. Jafaryar et al. [13] carried out a study to numerically optimize symmetric blades shapes in a VAWT. Sun [14], Ahn et al. [15] and Li et al. [16] have used this method to optimize airfoils design. They all confirmed that the RSM is a time-effective and accurate method to achieve better aerodynamic performance for wind turbines. Madsen et al. [17] successfully applied RSM method to optimize a wind turbine diffuser shape. CFD model and experimentation were combined by RSM to optimize a horizontal axis micro wind turbine by Abrar et al. [18].

In addition, Response Surface Analysis (RSA) was employed based on fully automated optimization technique by Ismail [19] to maximize the average torque of a VAWT. He has also applied the CFD to produce the data set of the RSA optimization. In this study, the applied model in the CFD simulation was also validated against the experimental results. The output of that study enclosed a considerable improvement in aerodynamic of the VAWT in both of static and dynamic conditions. As another similar application of the CFD, a simulation has been applied by this tool to analyse aerodynamic physiognomies of Emergency Response Vehicles (e.g. Ambulance Van Conversion) [20]. The experimental data of this study were also applied in order to validate CFD simulation. The results depicted the strong agreement between the experimental and simulation. In detail, an optimization framework was combined with CFD simulation to minimise drag force of the emergency response vehicle in that study. In addition, an automatic optimization method was accomplished via RSA to maximize the effective (or average) torque generated by the VAWT blades result in the more power generation [21]. A CFD method has been employed in this stated study to produce the dataset for the mentioned optimization. Results show there is a significant improvement in average torque due to the aerodynamics optimization of the VAWT blade.

On the other hand, the wind turbine noise is always a major problem, particularly in the city area, that CFD simulation was applied to reduce this noise [22]. The VAWT is an appropriate turbine that can be established inside the densely populated urban area, so the noise of the VAWT should be diminished considerably. Additionally, result of a study was accomplished by Masoud Ghasemian and Amir Nejat [23] reveals that there is a direct relation between the strength of the noise and the wind speed. M.H. Mohamed [24] proposed a novel design of the lift VAWTs (vertical axis wind turbines) to decrease the noise radiations. In fact, the radiated noise of the blades was scrutinized via CFD simulation to identify the optimal acoustic aerodynamic design. This author has also studied the aerodynamic acoustics of the Darrius VAWT in another study [25]. A similar content was applied in this article and blades noise was investigated numerically and aerodynamically via the CFD simulation based on FW–H (Ffowcs Williams and Hawkings) equations and its integral solutions. Moreover, the aerodynamic noise features of Savonius VAWT were scrutinized using 3D CFD simulation by Sanghyeon Kim and Cheolung Cheong [26]. They employed hybrid computational aero-acoustics techniques to design low-noise VAWT based on the understanding of the noise generation mechanism. As well as [25], the aerodynamic noise emission from wind turbine was forecasted using FW–H (Ffowcs Williams and Hawkings) equations. Based on the results of that study, the noise pollution of this turbine has been decreased considerably by applying the mentioned aero-acoustics techniques. In a previous study, which was accomplished by Tabatabaeikia et al. [27], four guide vanes were successfully used to improve output power of this system. However, the vibration in guide vane plates was likely to cause considerable noise pollution. Therefore, in this study, it was tried to introduce a more rigid design to minimise the undesirable noises. This study discusses the application of RSM for optimization in a specific wind turbine design.

Traditionally, optimization in the field of wind turbines has been done by considering the effect of a single factor at a time on a specific factor. Therefore, only a single parameter is altered while the other factors are kept unchanged. This optimization method is known as one-variable-at-a-time [28]. One of the main drawbacks of this method is that it does not consider the possible interactions of studied variables on each other. Consequently, it does not express the influence of the parameters on the response effectively [29]. Another obstacle of the one-factor optimization is the high number of needed experiments, which causes a surge in time, costs and material consumption.

To address this issue, multivariate statistic techniques have been used to carry out the optimization of analytical procedures. In analytical optimization, among multivariate statistic techniques, response surface methodology (RSM) is known as one of the most relevant ones. RSM was developed by Box and collaborators in the 50 s [30,31]. This term refers to the graphical representation created after fitting the mathematical model. RSM includes mathematical and statistical techniques collection based on the fit of a polynomial equation to the obtained data, which depicts the behaviour of a data set in order to make statistical predictions. RSM is utilised when a single or a series of responses are affected by various variables. The ultimate goal of RSM application is to optimize these variables levels simultaneously to obtain the best system performance [32].

2. Methodology

2.1. Flow analysis

Computational fluid dynamics (CFD) is known as a competent way to solve and investigate fluid flow problems by applying numerical algorithms and methods. Thanks to the considerable development in computer science in last two decades, CFD method has been increasingly employed in aerospace and wind energy. Due to the high cost of large-scale models experimentation in a wind tunnel, CFD simulation has garnered more popularity. In addition to the cost, performing a wind tunnel experiment require a huge amount of time, which is much lesser in CFD investigations.

2.1.1. Governing equations

Three fundamental principles are used to govern the physical nature of fluid and heat flow. These foundations of the modern flow analysis are the conservation of mass, the conservation of momentum, and the conservation of energy. Since the conservation of energy is only applied in cases of considering heat transfer, it will be neglected in this investigation.