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A numerical analysis of unsteady inflow wind for site specific vertical axis wind turbine: A case study for Marsabit and Garissa in Kenya

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ABSTRACT

Most of the wind analysis studies have been conducted under steady wind conditions. The study of real unsteady wind environment, however, is still an open-ended research question. This is attributable to the existing aerodynamic complexities under such conditions. In this paper, therefore, a numerical approach to investigate wind energy potential under unsteady conditions was proposed. In carrying out the study, the wind characteristics for two rural-urban towns in Kenya, namely Marsabit (2°19′N, 37°58′E) and Garissa (0°28′S,39°38′E), were selected. A CFD analysis method was used to evaluate both unsteady wind inflow performance and the flow physics that affects the performance on a Vertical Axis Wind Turbine (VAWT). Using the validated CFD model, unsteady wind simulations were performed and the results obtained compared with empirical methods. Compared to the prevailing methods, the proposed numerical approach is not only computationally inexpensive, but also robust in both steady and unsteady wind conditions. The numerical method demonstrates that Garissa station is unsuitable for grid-connected power generation, while Marsabit station is suitable for both grid-connected and stand-alone power generation activities. The study results will hopefully be of importance to the wind industries that require designs for wind turbines reflecting real unsteady wind environment.

1. Introduction

Wind energy is the latest alternative energy source that is renewable, and that has become an extremely popular field of research interest [1,2]. The wind converters, commonly referred as wind turbines, are classified as Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs) based on the rotor axis configuration with respect to the wind direction. Compared to the horizontal axis wind turbines, the vertical-axis wind turbines can be effectively used in urban areas where wind has characteristics of unsteadiness with turbulence [3]. Though VAWTs have inherent advantages in severe wind climates, HAWTs are dominant commercially as little research is available on VAWT aerodynamics. Yet, it has never been shown that the HAWTs are fundamentally more aerodynamically efficient than the VAWTs [2,4].

The principal substantial advantages of the VAWTs are their ability to accept wind from any direction without yawing, typically quieter due to relatively lower rotational speed, ease maintenance and cheaper cost due to the location of the gearbox-generator system at the base of the turbine, as well as potentially better performance in unsteady and skewed wind conditions [2,5,6], and references therein]. The VAWT can be broadly divided into three basic types: Savonius type, Darrieus type, and Giromill type [4]. In the small-scale wind turbine market, the simple straight-bladed Darrieus VAWT is preferred due to its simple blade design.

The various methods used to investigate the performance of VAWTs can be categorized into numerical and experimental methods. The latter is limited by the huge capital cost requirements, an array of diverse technical skills, time constrains, operational know-how, and a number of physical and environmental parameters that can influence measurements [7]. Numerical methods can be classified into two types: The Computational

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Fluid Dynamics (CFD) methods that analyze directly the flow around the blade of a wind turbine; and the semi-empirical method of the Blade Element Momentum (BEM) theory that adopts the lift and drag coefficients of two-dimensional airfoils obtained by a wind tunnel test [8,9].

Although momentum theories have an advantage of a low computation effort, it is often difficult to investigate the complexity of aerodynamic phenomena involved in unsteady behavior of vertical axis turbines through theory of the blade elements [10,11]. The limitations by BEM theory can be overcome by CFD methods through the integration of the Navier Stokes equations in the neighborhood of the wind turbine blade profile [12].

Consul et al. [13], investigated solidity by use of a 2D CFD method to model a two-bladed and four-bladed VAWTs of NACA 0015 profile with corresponding solidities of $\sigma = 0.019$ and $\sigma = 0.038$. Various tip speed ratios from $\lambda = 3$ to $\lambda = 8$ were analyzed to determine the effects of varying solidity on VAWT aerodynamic performance at steady inflow. From the study, the entire performance curve of the higher solidity VAWT is shifted to the left hence attaining the maximum power coefficient at $\lambda = 4$, while the smaller solidity VAWT attained maximum power coefficient at $\lambda = 6$. The shifting of the power performance curve to the left at higher solidity was attributed to the decrease in streamwise velocity presented with lower angles of attack.

A similar investigation was carried out in Ref. [14] to compare NACA 0012 and NACA 0022 profiles each of solidities $\sigma = 0.2$, $\sigma = 0.6$ and $\sigma = 0.98$. From the study, NACA 0012 performed better than the NACA 0022 for all tip speed ratios >3.5, while the performance of the NACA 0022 solidities was better at lower tip speed ratios than those of NACA 0012. In addition, the lower solidity turbines have a wider power coefficient-tip speed ratio (CP-λ) which reduces as the solidity (chord length) increases for both profiles. However, as in the study by Consul et al. [13], the choice of inlet free stream velocity was based on the steady wind speed tunnel experimental data that had been performed in Ref. [15]. Consequently, the realistic unsteady inflow wind experienced by vertical axis wind turbines operating in unsteady wind conditions was not considered.

Fully-coupled numerical modeling of offshore wind turbines using fully nonlinear CFD models for simplified models of wind turbines was studied by Viré et al. [16]. The work provides a first step towards the fully coupled simulations of floating wind turbines. However, the details of dynamics and aerodynamic performance for more complex and realistic wind turbine models were not considered as the study focus was on simplified models.

Castelli et al. [12], presented a numerical model to evaluate energy performance and aerodynamic forces acting on a straight-bladed vertical-axis Darrieus wind turbine using 2-D simulations of a classical NACA 0021 three bladed rotor. In this study, the 2D rotor was analyzed at 8 different tip speed ratios with a constant wind speed of 9 m/s. The work proved that CFD method was able to visualize the basic physics behind a VAWT, and that it can be used as an alternative to wind tunnel tests. There was a constant discrepancy of factor 2 between the numerical and wind tunnel experiments. This was associated with the effect of finite blade length and spoke drag that were not considered in the numerical analysis.

To yield and predict a higher performance, Castelli et al. [12] study was extended by Rosario et al. [17] using both open and novel vertical axis Augmented Wind Turbine (AWT) rotors. From this study, introduction of an augmented device (stator) around the rotor blades improved the power output of the VAWT by about 30%. The CP-λ performance curve trend of the open rotor matched that by Castelli et al. [12], but with a higher CP of about 10%; a phenomenon which could be attributed to the difference in blade profiles [17]. Similar to studies proposed in Refs. [13,14], simulations in both research were carried out under the assumption that the turbine was operating in steady and uniform wind conditions. Consequently, unsteady blade performance by turbine operating in unsteady wind conditions remained a challenge for this approach.

A parametric study by Saeidi et al. [18] indicated the need to provide site-specific small vertical axis wind turbines to evaluate their performance and derive important aerodynamic characteristics. In their study, a three bladed H-rotor VAWT was designed for nominal power production of 1.5 kWh for Fadashk station located in south of Khorasan province in Iran. To enable effective energy extraction, the study used the weather station wind characteristics data for the built environment to compliment the data from controlled wind tunnel conditions. However, like in the previous studies, the designed VAWT model using the BEM and double multiple stream tube model was based on steady inflow.

The aerodynamic performance of an isolated turbine within a steady inflow is not a representative of the actual performance of an operational urban wind turbine due to the inherent fluctuating wind [5]. Moreover, turbine performance is dependent on the cube of wind speed, hence moderate fluctuations in wind speed would result in very large fluctuation in available power. Therefore, for effective analysis of VAWT performance for a potential site, the energy contained within the frequency components of a fluctuating wind should be accounted for.

In Refs. [12–14,17,18], numerical and experimental investigation have been conducted on the performance of vertical-axis wind turbines using a steady inflow. Little work has been done on unsteady blade aerodynamic performance induced by unsteady wind conditions in the real urban environment. This is because turbine aerodynamics under varying wind conditions are still less understood. This is attributable to the current limitations of available computing power. In Refs. [19,20], the aerodynamic performance and wake dynamics have been investigated using a 2D free vortex model, both in steady and unsteady wind conditions of VAWTs. The authors limited their studies on low fluctuation frequencies within frequency range ≤ 1 Hz following McIntosh et al. [19] study that found the range to be a major part (over 90%) of the energy content.

The steady and unsteady wind conditions investigation of the aerodynamic performance and wake dynamics using vorticity transport model has been carried out by Scheurich et al. [21]. The unsteady wind conditions with a fluctuating mean wind speed of 5.4 m/s and a fluctuating frequency of 1 Hz was used. Out of the three blade configurations, helical blades performed much better than straight and curved blades, with the unsteady CP tracing the steady performance curve quite well. The results revealed that there is no significant increase in energy extraction at higher frequencies. That implies, there is no practical reason to extract the energy content at higher fluctuation frequencies. Furthermore, the numerical model results reveal a drop in performance at higher fluctuation amplitudes.

To further understand VAWT performance in unsteady wind conditions, Danao et al. [5] carried out an experimental investigation at a mean wind speed of 7 m/s. The experimental results of the study are the first of their kind, and provide a big break through in turbine aerodynamics research under varying wind conditions. For the mean wind speed of 7 m/s, the instantaneous CP rose and approached the steady CP profile of a higher free stream wind speed as the wind speed increased. Contrary to the works in Refs. [19–21], the unsteady VAWT performance did not follow the steady curves. However, the extent of the unsteady CP profiles was much shorter than that of the reference case when the fluctuation amplitude U_{amp} was reduced from ±12% to ±7%. Nevertheless, similar to works in Refs. [19–21], the unsteady free stream caused a drop in performance of the tested wind tunnel VAWT scale.