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Experimental and theoretical investigation of micro wind turbine for low wind speed regions

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ABSTRACT

Micro wind turbine blades for low average wind speed regions like the Arabian Peninsula, Jordan Desert and United Arab Emirates are designed and implemented. Wind profiles for two locations in UAE are investigated and utilized in the design and the economic analysis. Airfoils BW3, A18 and SG6043 are selected and utilized as candidates for designing micro turbine blades. Blade element momentum theory is used to design the blade 3D geometry. A methodology to optimize the blade geometry for average wind speed 5 m/s based on operational Reynolds number is developed and utilized. To account for the aerodynamic behavior over the 3D blade geometry, the power coefficient for the blades of each airfoil is obtained using the simulation software QBlade. Blades developed using airfoil BW3 showed the highest performance. A prototype is built using 3D printer and tested in open air environment (natural environment) to validate the simulation results. Comparison with existing commercial wind turbines according to cost and output power is carried out based on the concept of replacing wind turbines swept area with the equivalent array of micro wind turbines. The results show that the new design is more cost-effective and more wind energy is harnessed using equivalent swept area.

1. Introduction

Wind energy represents one of the most promising sector of renewable energy. Harvesting energy from low average wind speed profile regions such as the Arabian Peninsula is a challenge. Due to the low average of wind speeds in Arabian Peninsula, use of large and medium size conventional wind turbines is not economically feasible. These conventional turbines are designed for high rated wind speeds in range of 10 m/s to 15 m/s. However the average wind speed in the Arabian Peninsula is in range of 4 m/s to 7 m/s. The intent of this study is to design a micro wind turbine that fits the low average wind speed regions. United Arab Emirates (UAE) located in the Gulf Region of south-eastern part of the Arabian Peninsula is chosen as sample site for experimental and theoretical investigation of micro wind turbine for low wind speed regions. The average wind speed in UAE is in range of 5 m/s to 6 m/s [1].

The key part in designing wind turbines is the blade. Generally, the main goal in designing a wind turbine blade is maximizing the power coefficient. In case of micro wind turbine, the starting time (cut-in speed) and economic feasibility are very important in optimizing the final design of micro wind turbine blade. The starting time optimization carried out by Pourrajabian et al. have shown that the starting time of micro wind turbine can be reduced by increasing the number of blades which would also increase the power coefficient, C_p [2]. Increasing the number of blades increases the overall energy of the system, but it increases the overall cost of the system.

Centimeter-scaled micro wind turbines (2–12 cm diameter) are very economical to produce, however they have shown low C_p which ranges between 5 and 10%. They usually have 3–12 blades [3–5]. Larger micro wind turbines with 120–420 cm diameter have shown greater C_p values of about 40% [6]. The reason for the difference in C_p goes back to the fact that the larger blades employ aerodynamic airfoil blade configuration whereas the small ones have fan type blade configuration [4].

Micro wind turbine performance evaluation and optimizing can be done using computational fluid dynamics (CFD) as well as Blade Element Momentum (BEM) theory codes [6–10]. BEM theory codes have an advantage of having much less computational time over CFD. Recent studies have shown that there is a good agreement between BEM theory codes results and experimental results of micro wind turbine [6].

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The main objective of the current study is to design an efficient micro wind turbine blade using BEM theory codes by employing low Reynolds number airfoils, i.e. low wind speed airfoil. It is proven by Refs. [11] and [12] that Reynolds number has considerable effect on turbine blades performance that employ such airfoils. The wind profiles of two cities in UAE, Abu Dhabi and Al Ain, are considered as case studies in examining the performance of the new blades design. QBlade software is used in evaluating the performance of the micro wind turbine blade since it has been successfully validated by researchers against the BEM theory codes and wind tunnel test data of full scale wind turbines [13].

A 3D printer is used to prototype the blade final geometry. 3D printed wind turbine blades are utilized by other researchers and they have shown to have good performance [14]. In this study, the blades have been built and tested in real life environment to validate the theoretical predictions.

2. Wind data analysis

The wind data of Abu Dhabi and Al Ain is obtained from Iowa Environmental Mesonet (IEM) that collects environmental data using the Automated Surface Observing System (ASOS) which is located at airports. Table 1 shows summary of the data.

Weibull distribution is widely used by many researches for wind data analysis, but since the sites have low wind speeds, it has some limitations for the low wind speed probabilities [15]. For this reason, Rayleigh distribution is also used. Graphs for Weibull and Rayleigh probability density function (PDF) for Abu Dhabi and Al Ain are shown in Figs. 1 and 2 respectively.

It can be seen from Figs. 1 and 2 that wind speeds close to 5 m/s have the highest probability. It is obvious that the average wind speeds of both sites are close to 5 m/s. Therefore, this speed is chosen to be the design rated wind speed for the micro wind turbine blades.

The wind rose for both cities Abu Dhabi and Al Ain are presented in Fig. 3. These graphs illustrate that the wind dominant direction is North-West. The wind turbine is equipped with guide vane to allow self-adjustment with the wind direction.

3. Theoretical modeling

Theoretical analysis is conducted for selected airfoils of high performance at low wind speeds (low Reynolds number), i.e. Airfoils that have high lift coefficient. The blade geometry is optimized for wind speed of 5 m/s. It is well known that the lift and drag coefficients are function of angle of attack and Reynolds Number [11,12]. To reach highest performance, Reynolds number is considered as an optimization parameters' along with the other parameters' considered by the BEM theory. Fig. 3 illustrates the developed methodology that considers Reynolds number in designing the blades. This method is developed to reach the optimum geometry of the blades.

The basic assumptions used in the design are mainly the assumptions of the BEM theory. The assumptions and conditions that are implemented in the design process are as the following:

Table 1
Descriptive statistics for Abu Dhabi and Al Ain.

Abu Dhabi		Al Ain	
Average (m/s)	5.36	Mean (m/s)	6.39
Median (m/s)	5.02	Median (m/s)	5.90
Mode (m/s)	4.21	Mode (m/s)	5.01
Standard Deviation	3.71	Standard Deviation	3.48

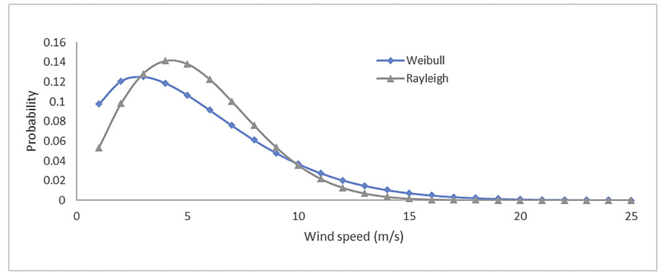

Fig. 1. Rayleigh and Weibull PDFs for Abu Dhabi.

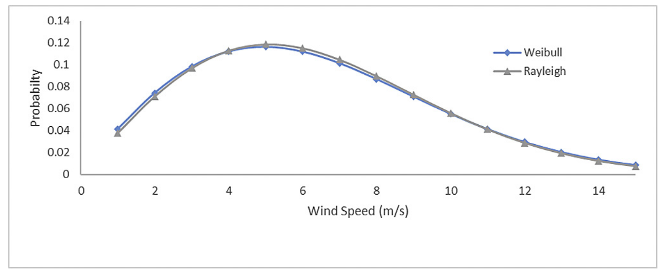

Fig. 2. Rayleigh and Weibull PDFs for Al Ain.

1. Each blade is divided into set of elements.
2. There is no aerodynamic interaction between elements (thus, no radial flow).
3. The forces on the blades are determined by the lift and drag characteristics of the airfoil shape of the blades where these are function of Reynolds number.
4. The design is optimized for wind speed of 5 m/s. Two main variables are impeded in Reynolds number, the chord length and the wind speed. The design wind speed is fixed at 5 m/s whereas the chord length is varied to reach the optimum geometry for the blades that maximizes the power coefficient.
5. BEM theory for ideal rotor with wake is used in designing the blade shape.
6. The performance analysis of the optimum geometry, which is obtained from BEM, is performed using Qblade software Package. Qblade carries the performance analysis by considering the aerodynamic effects of the neighboring elements that is ignored by the BEM theory. This provides performance analysis that is very close to the real life performance.

3.1. Airfoils

The airfoils for the micro wind turbine blades are chosen from ‘Summary of Low-Speed Airfoil Data’ [11,12]. Three airfoils are considered for designing the micro wind turbine blades. Simulation is performed to choose the airfoils with highest C_p. Airfoils BW3, SG6043 and A18 have been chosen because they are designed to operate at low Reynolds number i.e. to operate at low wind speed. These airfoils are presented in Fig. 4. Careful analysis is done on these airfoils to investigate their performance at low values of Reynolds number that reflects the operational condition in UAE.

3.1.1. A18

The A18 airfoil was not designed for wind turbines initially but for free flight airplanes by Randy Archer. This airfoil was named after his model that he used in 1993 World championship contest. It has smooth surface finish, maximum thickness of 7.26% of the