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Effect of air density on the performance of a small wind turbine blade: A case study in Iran

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ABSTRACT

The influence of the air density variation with altitude on the performance of a small horizontal axis wind turbine blade was studied for four regions of good wind resources in Iran and altitudes up to 3000 m. In order to improve the performance of the turbine at low wind speed, starting time was combined with output power in an objective function and a three-bladed, 2 m diameter rotor was designed and optimized for those regions using a purpose-built genetic algorithm. The Blade-Element Momentum (BEM) theory was employed to calculate the output power and a modified version was used to determine the starting time in the presence of a small, but significant resistive torque. The optimization procedure maximized a combination of the output power in terms of the power coefficient and the starting time. Results show that the performance of a blade optimized for sea level degrades for other locations and that degradation is more important for the starting performance than the power coefficient. In order to improve the performance of the blade at the different altitudes, the optimization process was performed in two steps. First, the geometry of the blade was optimized for the air density at the appropriate altitude that increased both the power coefficient and the starting time. Much more power was achieved using the second step in which the tip speed ratio was optimized along with the geometry of the blade in the optimization procedure. The results highlight the importance of the drive train and generator resistive torque which delays the starting of the wind turbine especially at very high altitudes as the aerodynamic torque is reduced.

1. Introduction

Small Wind Turbines (SWTs) have an effective role to supply the increasing demand for the production of electricity especially for remote applications which are often in mountains. According to International Electrotechnical Commission (IEC) Standard 61400-2, IEC (2006), which only considers horizontal-axis turbines, a SWT has a swept area of less than 200 m^2, which corresponds to a power output of about 50 kW. SWTs must be installed close to the load they supply even if the wind resource is poor. There is usually no pitch adjustment on the blades of SWTs because it is too expensive. The absence of pitch adjustment requires advanced blade design to generate lift at high angles of attack during the starting to overcome the resistive torque of the drive train and generator. SWTs blades should also have a high aerodynamic efficiency during the operation to harness the wind energy as much as possible. So, design and optimization of the blades for SWTs is a challenging task and it has a vital role in the overall system design and optimization of the SWTs.

After selection of an airfoil profile, blade optimization has traditionally aimed to find the distributions of the chord and twist to maximize the output power. In the absence of drag and tip losses, the ideal distribution of the chord (c) and twist (θ_p) was determined by Burton et al. (2011) for a chosen airfoil profile with lift coefficient C_l, Tip Speed Ratio (TSR) λ, and number of blades N, as

$$cC_l = \frac{16\pi}{9N\lambda\sqrt{4/9+[\lambda_r+(2/(9\lambda_r))]^2}} \tag{1.1}$$

$$\theta_p = \phi-\alpha, \quad \tan\phi = \frac{2}{3\lambda_r+(2/\lambda_r)} \tag{1.2}$$

where θ_p is the blade pitch (twist) angle (between the chord line and the plane of rotation), α is the angle of attack and the inflow angle (ϕ) can be determined by knowing the local speed ratio, $\lambda_r = (r/R)\lambda$, where R is the tip radius. These ideal equations neglect tip losses which typically affect the optimum values only in the tip region, Clifton-Smith (2009).

Generally, the main goal of design and optimization of a wind turbine blade is to maximize the output power. However, other goals

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must sometimes be considered during the optimization procedure. Mass minimization of the blade to reduce cost, and reduction of noise are other important goals which may be included in the objective function, particularly for large turbines. Starting time is another parameter which must be minimized to improve low wind speed performance of SWTs. Even though the influence of the starting time is unimportant for large wind turbines, it is critical for the low wind speed performance of SWT blades with no pitch adjustment (Ebert and Wood, 1997; Mayer et al., 2001; Wood and Robotham, 1999; Wright and Wood, 2004).

An experiment on a two-bladed 5 kW turbine by Ebert and Wood (1997) revealed two main phases in the starting sequence, namely the initial period of idling followed by one of the rapid acceleration. During the former, the turbine blades rotate with low acceleration and the angle of attack gradually decreases until the blade can generate a high lift to drag ratio. After that, the turbine accelerates rapidly to the point at which useful power can be extracted. Since the rapid acceleration period is comparatively short, it can be neglected in designing a small turbine for improved starting performance. The starting of a three-bladed, 2 m diameter small HAWT was investigated by Wright and Wood (2004). Their results showed that the torque generated near the hub is large during starting while the torque near the tip dominates during power production. They also showed that a simple modification of the blade element theory provided a surprisingly accurate description of starting. The modifications comprised of neglecting axial and circumferential induction, and the use of generic equations for lift and drag at high angles of incidence. Mayer et al. (2001) investigated the effect of collective blade pitch angle on the idling period. They found that increasing the collective pitch caused more rapid starting and the idling period was shortened due to the lower angles of attack. Moreover, they suggested that the collective pitch angle that gives the best starting behavior was 20°.

The above mentioned experimental research led to the design of improved blades having good starting performance and suitable output power. Reducing the moment of inertia and using an evolutionary algorithm, Hampsey (2002) designed an improved turbine blade which could accelerate more quickly with good output power. Later studies by Wood (2004) and Clifton-Smith and Wood (2007) showed that new designs provide a good compromise between the starting torque and the power extraction. Their starting calculations assumed that the difference between the aerodynamic torque and the resistive torque in the drive train accelerated the rotor without extracting power. The resistive torque is dominated by the cogging torque if a permanent magnet generator and no gearbox is used. Alternatively, there will be a frictional torque in a gearbox in combination with an induction generator (Wood, 2011).

One valuable lesson of these multi-dimensional analyses is that the best power-extracting blades always have poor starting performance. However, a large decrease in the starting time could be achieved for a small reduction in output power. Clifton-Smith (2010) considered a sound power level as another parameter in the multi-dimensional analysis. Using Differential Evolution (DE) for optimization, he found a range of blades which limit noise and reduce starting time while retaining power producing performance. It must be emphasized that multi-dimensional optimization uses computationally cheap objective functions to limit as much as possible the parameter range of the final blade design. However, it is not the totality of the blade design. Candidate optimal blades must be analyzed structurally using finite element analysis and their aero-elastic and aerodynamic damping behavior analyzed thoroughly by more complex computational fluid dynamics methods before they are actually made. This combination of multi-objective optimization followed by more detailed design has worked satisfactorily for several previous blades that were manufactured and field tested. The closest example to the blade considered here is the 2.5 m long blade described in Wood (2011) which is currently under extensive field testing at the University of Newcastle, Australia. The experiments include an instrumented blade to determine the actual blade loadings for further study of the aero-elastic behavior of SWT blades. For convenience, the multi-objective optimization used here will be called “design” but the need for subsequent substantial assessment and possible modification is taken as understood.

The main aim of this paper is to investigate the impact of altitude on the performance of a SWT blade. Altitude should have a very predictable influence on power extraction through its effect on the density and kinematic viscosity and, hence, Reynolds number. However, altitude effects on starting are less obvious. We assume that the resistive torque is independent of altitude and so, the reduction in aerodynamic torque with density makes starting progressively more difficult as altitude increases. While the efficiency of power extraction of the SWT is the first objective of the present study, the starting improvement of the SWT is also addressed as another goal and priority. Four sites in Iran of altitudes up to 3000 m are selected as test cases, and a three-bladed, 2 m diameter small HAWT is designed and optimized for those regions. A combination of the starting time and the output power is included in the objective function and a genetic algorithm is used to design a blade for high output power and low starting time.

2. Wind resources in Iran

Situated in the south-western part of Asia, Iran (Persia) is bordered on the north by Armenia, Azerbaijan and Turkmenistan as well as the Caspian Sea, Turkey and Iraq to the west, the Persian Gulf and the Sea of Oman to the south, and Pakistan and Afghanistan to the east (Fig. 1). Persians were pioneers in designing and using windmills for both grinding grain and pumping water. Although the potential capacity of wind energy is high, there is only 91 MW installed capacity by 2012 (Mostafaeipour et al., 2014). Obviously, much more work is still needed to use the available wind power in Iran. Wind energy potential has been assessed for some locations in Iran such as Tehran (Keyhani et al., 2010), Manjil (Mostafaeipour and Abarghooei, 2008) and Shahrbabak (Mostafaeipour et al., 2011). Moreover, the feasibility of offshore wind turbines both in the Caspian Sea and the Persian Gulf has been assessed by Mostafaeipour (2010). There are some excellent regions such as Manjil and Binalud in which the two wind farms have been installed. In order to investigate the effect of altitude on the performance of SWTs, four locations with different altitude were selected, Table 1. The average wind speed of the locations was measured at a height of 30 m. The priority of Renewable Energy Organization of Iran[1] is to harness the wind energy in these, as well as other windy regions. Fig. 2 shows the chosen locations in the wind atlas of Iran. The properties of air on those regions were determined on the basis of International Standard Atmosphere (ISA) (U.S. Standard Atmosphere, 1962).

3. Aerodynamic modeling

The aerodynamic model used here is the Blade-Element Momentum (BEM) theory which is a combination of the momentum and blade element theory. In BEM, the blade is divided into several stations and at each station, the blade element theory is employed to calculate the thrust and torque over the blade element (airfoil) such that the momentum and angular

[1] http://www.suna.org.ir (accessed 02.05.13).