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Power generation of small wind turbine: Under high-speed operation

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ABSTRACT

Mechanical energy is produced through the rotation of wind turbine blades by air that converts mechanical energy into electrical energy. Wind turbines are usually designed for particular applications, and design characteristics may vary depending on the area of use. The variety of applications is reflected on the size of turbines and their infrastructures. Wind turbine performance may be enhanced by analyzing the small horizontal axis wind turbine (SHAWT) under high-wind-speed operation. This work analyzes the implementation of the SHAWT and investigates its performance in simulation and real life. The power performance of the SHAWT, which largely depends on the real structure of the rotor geometry and aerodynamic test, was simulated using ANSYS Fluent software at different wind speeds of up to 33.33 m/s (120 km/h) to numerically investigate actual turbine operation. Dynamic mesh and user-defined function (UDF) were used to revolve the rotor turbine via wind. Simulation results were further validated by experimental data, and good matching was achieved. A car alternator was formed and used as a small horizontal wind turbine to reduce energy production cost. Consequently, the alternator-based turbine system was found to be a low-cost solution for the exploitation of wind energy.

Introduction

Electrical energy from wind turbines is now classified as more efficient and worthier than other green energy resources. This remarkable development can be primarily attributed to the development of large wind turbine technology [1]. However, small wind turbines are still in their developmental stage. In the past decades, the installed power capacity of large wind turbines had an annual growth rate of approximately 30%, whereas that of small wind turbines was only 9% [2]. Hence, the huge potential of small wind turbines to be exploited in generating electricity at low cost needs to be explored immediately as the power generation sector has shown minimal interest and small wind turbines are costly [3].

The generator is the main component of small wind turbines and converts mechanical energy into electrical energy. Thus, reducing the cost of generators in such turbines would certainly lower their overall cost, thus making them cost competitive [4]. A major reason for the decreased utilization of big wind turbines is the use of expensive high-quality generators by current systems. Previous studies on energy have successfully yielded commercially available small wind turbines, thereby showing that electricity generated by small wind turbines is cost effective [5].

This work aimed to evaluate the power produced by small wind turbines using an automotive alternator, determine the feasibility of installing a small horizontal axis wind turbine (SHAWT) on top of automotive cars, and subsequently validate the results using computational fluid dynamics (CFD) software. The validation between the numerical simulation and experimental test was based on wind speed and aimed to achieve good matching between the numerical simulation and the experimental test, which are the main contributions of this paper.

A vehicle alternator can be used as a wind turbine generator in multifarious applications, including automobiles, tractors, and other industrial transportation systems with a wide operating speed range (400–8000 rpm) [6] that are available in many standard output voltages (12, 24, 32, or 48 V). According to Ani et al. [7], the efficiency of the alternator is generally low, and it achieves maximum efficiency (~54%) at low speeds (~1500 rpm). This feature is advantageous for various low-speed applications because efficiency is significantly reduced at high speeds (~2500 rpm). The typical output power of a vehicle alternator operating at 2500 rpm with a 14 V DC is ~600 W. A power output of 150 W is achieved at 1000 rpm, with a maximum efficiency of ~54% at 1300 rpm [2,7].

In this study, a 14 V DC alternator was used as a cheap alternative. The output voltage is usually maintained at 14 V DC by an internal regulator that samples the voltage and adjusts the field current accordingly. The regulator maintains the desired voltage by varying the duty cycle of the pulse-width modulated voltage applied to the field winding [8,9]. The output voltage drops by increasing the electrical

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Nomenclature

A	swept area of rotor (m^2)
P	power (W)
V	wind speed (m/s^2)
ω	angular velocity (rad/s)
r	rotor radius (m)
V	voltage (v)
I	current (Amp)
ρ	air density ($kg{\cdot}m^{-3}$)
C_p	power coefficient
C_q	torque coefficient

load in the vehicle and as more currents are drawn from the alternator. Whenever the electrical load drops, the regulator detects it and raises the voltage by enhancing the duty cycle to increase the field current, and vice versa [10]. The rotor speed was measured using a tachometer, whereas current output was measured after connecting load resistance to the alternator for evaluating the power output performance of the system [11]. In this research, wind speed started at 22.22 m/s (80 km/h) in the numerical simulation and experimental test because the alternator worked at least 400 rpm to start produce the power [6,7].

Most aerodynamics problems involving wind turbines are tackled by CFD using the Reynolds-averaged Navier–Stokes (RANS) method with different turbulence models [12]. Various numerical schemes have been developed to solve such problems, including SIMPLE, SIMPLEC, PISO, and COUPLED [13]. In this study, the SIMPLE scheme of the ANSYS Fluent software was used to solve the flow around the SHAWT.

The simulation was evaluated using the following expression of powers:

- Experimental power formulas

The actual power produced from wind turbine was calculated according to voltage and current as shown in the equation below:

$$Power\ Output = (I)*(V), \tag{1}$$

where V is the voltage (volts) and I is the current (ampere).

- Calculation power formulas:

The power produced by wind stream is proportional to the cube of the free-stream velocity [14]. The torque responsible for actual turbine power was extracted from the wind due to the interaction between the rotor and the wind [15]. The rotor power and torque are usually calculated to rate the overall performance of a wind turbine.

$$Tip\ Speed\ Ratio\ (\lambda) = angular\ velocity\ (\omega)*(r)/V_{in} \tag{2}$$

$$power\ coefficient\ C_p = \lambda*C_q \tag{3}$$

$$power\ output = 0.5*\rho*A*C_p*V^3, \tag{4}$$

where A is the swept area of the rotor, V is the wind speed, ρ is the air density, C_q is the torque coefficient, and C_q is the torque coefficient [16,17].

Experimental procedure

In the experiment, the fabricated SHAWT (rotor diameter of 0.36 m, rotor width of 0.04 m, blade span of 0.117 m, and blade chord of 0.035 m) was fixed on a car and positioned to face the incoming wind. Fig. 1 illustrates the final position of the entire mode on the car. The experimental data obtained from this experiment were then compared with the simulation results obtained from the CFD simulation.

CFD analysis

The aerodynamic behavior of a seven-blade SHAWT was observed through a simulation conducted using ANSYS Fluent. The wind speed at the computational domain entrance was kept constant. The rotational speed of the turbine (rotating zone) was measured to evaluate turbine performance.

3D RANS equations were used for viscous, incompressible, and continuous flow. In this flow pattern, the temperature variations over the flow field were kept nearly constant. Thus, the energy equation was eliminated [18].

The wind turbine model was developed by using SolidWorks and comprised a stationary domain (cylinder) for the surrounding air, where the distances from the rotor to the inlet, top, and outlet were 3, 3, and 7 times the diameter of the blade, respectively, (Fig. 2[b]), and a rotor turbine (Fig. 2[a]) [19,20].

In this study, a non-uniform, unstructured mesh was used with a medium mesh implemented in regions of high gradients. A tetrahedral element was selected as the mesh for the stationary and rotating domains.

Fig. 3 depicts the planar cross-sectional view of the mesh layout for the turbine and the cylindrical domain. The total numbers of tetrahedral elements and triangular interior faces were 354622 and 3979649, respectively.

Fig. 4 displays the boundary conditions applied to the computational domain. Three types of boundary conditions were used, namely, walls, velocity inlet, and pressure outlet [21]. Flow properties at sea level were applied to all regions. Table 1 lists the simulated features of flow field.

The SHAWT model was rotated using the dynamic mesh and user-defined function (UDF). The physical properties of the SHAWT, such as mass properties and rotation axis, were defined in the UDF written in C language.

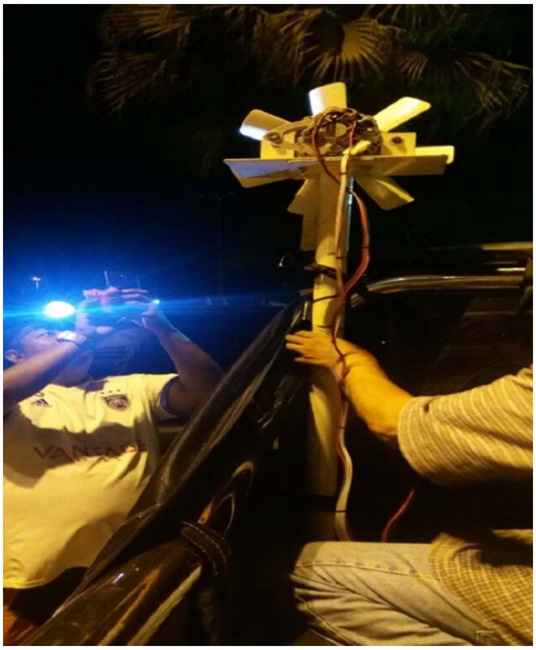

Fig. 1. Installation of wind turbine system on car body.