Energy Reports 4 (2018) 619–623

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Design, modeling and economic performance of a vertical axis wind turbine

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HIGHLIGHTS

- Vertical axis wind turbine was designed, simulated, and analyzed.
- Four Savonius rotors blades rotational performances were compared.
- MATLAB simulation was used to develop an algorithm.
- The new turbine has the capability of producing an annual energy output of 7838 kWh.
- The annual electricity cost/saving in Ontario has been estimated to be $846.51.

ARTICLE INFO

Article history:
Received 4 May 2018
Received in revised form 21 September 2018
Accepted 23 September 2018
Available online xxxx

Keywords:
Vertical axis wind turbine
Blade design
Power coefficient
Simulation
Annual energy output

ABSTRACT

Vertical Axis Wind Turbine (VAWT) is relatively simple to implement in urban areas on ground or/and building-roofs, the development of appropriate design of VAWT will open new opportunities for the large-scale acceptance of these machines. The primary objective of this research was to design and modeling of a small-scale VAWT, which can be used to meet the power for low demand applications. Two new shapes of Savonius rotor blades were examined in terms of their rotational performances against the conventional straight and the curved blades. MATLAB simulation was utilized to develop a mathematical model, which comprised of wind power coefficient, tip speed ratio, mechanical and electrical subcomponents. The measured results of developed turbine were used for the validation of the model. The aims were to analyze the turbine blade shapes, develop a mathematical algorithm, and to establish the techno-economic performance of the new curved shape design. It was modeled that the proposed turbine is capable of producing an annual energy output of 7838 kWh and the annual electricity cost/saving in Ontario turned out to be $846.51 (the price of electricity was taken $0.108/kWh).

1. Introduction

Wind power has become one of the fastest emerging renewable energy technologies for electricity generation, and the total installed capacity has reached 487 GW (about 4% of the global electricity) by the end of 2016 (Kumar et al., 2018). The development of an effective wind turbine (WT) design, especially for an urban area, is critically needed to increase the penetration of wind power technology in cities and semi-urban areas. Substantial wind is blown in urban areas with a potential of power, viz. highway, railway track, and between/around the high-rise buildings. The wind is blowing continuously with varying intensity in all these areas, and an effective turbine design must include all the site-specific changes in the wind speed, direction, and turbulence.

Two main types of WTs: horizontal axis and vertical axis. Horizontal axis WTs (HAWTs) are widely used in large wind farm applications in remote and offshore areas where the clean and an undisturbed wind is available. Wind patterns in urban areas are more chaotic, less predictable, and full of turbulence, which makes HAWTs relatively ineffective (Walker, 2011; Keith et al., 2013; Toja-Silva et al., 2013; Allen et al., 2008). The Vertical Axis Wind Turbines (VAWTs) might be an effective option in all these areas due to their low cut-in wind speed, no yawing requirement, less structural support, and no noise concerns (Tjiu et al., 2015). Numerous small-scale wind turbine designs have been suggested, tested and implemented in many urbanized areas where the wind is gustier and inconsistent. The efforts have also been undertaken in several countries on VAWT to make them a viable technology. The research and development activities were focused on the design, modeling, integration, sitting, and environmental aspects (Burlando et al., 2015; Danao et al., 2014; Sunderland et al., 2013; Marini et al., 1992). Aerodynamic and economic performances of

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https://doi.org/10.1016/j.egyr.2018.09.007

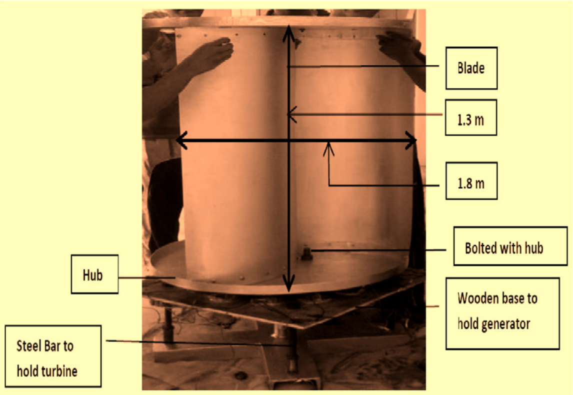

Fig. 1a. A side view of designed and assembled blade configuration of VAWT.

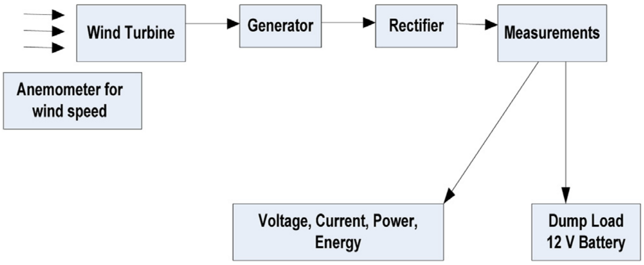

Fig. 1b. A block diagram of experimental measurement setup.

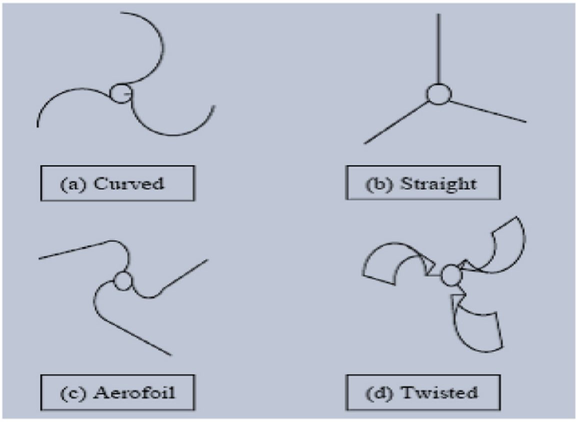

Fig. 2. A sectional view of tested blade designs.

VAWTs have been studied in Iran (Saeidi et al., 2013). The study has revealed that site-specific design considerations could result in improving the cost of energy (COE). Several design techniques of VAWTs were analyzed and discussed by Bhutta et al. (2012). They optimized the coefficient of power (C_p) with reference to the tip speed ratio (TSR). Wekesa et al. (2014) have examined the influence of blade design on power output, vibration, and turbine loads. Wenehenubun et al. (2015) have presented the experimental results of Savonius turbine, and the impact of blade numbers were determined on the tip speed ratio, torque, and power coefficient.

It was noted the absence of reliable performance prediction model of VAWTs is considered one of the key hindrances to the widespread acceptance of these machines (Buchner et al., 2015; Burlando et al., 2015; Lee and Lim, 2015). This paper is intended in that direction and involved both experimental and theoretical investigations on VAWT. Savonius turbine blades were redesigned and their rotational performances were analyzed. A comprehensive MATLAB/Simulink simulation model was developed, and the model was validated and applied for the performance evaluation of new design of VAWT.

2. Design of turbine

2.1. Description of turbine and performance

The design intended that the turbine should have low cut-in wind speed, lightweight, and can be easily moveable. The drag-based machine should be capable of harnessing energy from the non-directional wind at low cut-in speed, which makes it a better choice for many urban applications. Fig. 1 shows a view of the proposed turbine blades and support system. The blades were attached to the hub with the help of three steel bars, and each bar is welded to the center to provide stability to the design. The blade was fabricated from flattened trapezoidal profiled galvanized (GI) steel sheet of equal dimensions (width of each blade = 0.8 m; height of each blade = 1.3 m; the angle between the cross-arm = 120; total height = 1.5 m). A 12 gauge GI sheet has been chosen due to inherent material properties, viz. good tensile and compressive strength, rugged, high stiffness to weight ratio, good resistance to corrosion, and durability. The mild steel is used for the hub, which is connected to the main shaft. The main shaft is also made of a mild steel rod. The shaft is passed through the two bearings and connected to the shaft of the generator with the help of a coupling arrangement. The generator is rested on the wooden base, which is supported by the three steel bars on the ground.

The shaft is connected to an AC permanent magnet generator (PMG) to produce the electrical output. An electrical converter is used to convert low voltage AC into high-quality DC power for battery charging. The rectifier provides a constant voltage at the battery terminal. The other parts of the machine are a mechanical shaft, stator, two magnet rotors, and a rectifier. The electrical outputs were measured by transducers and subsequently fed to the dump load (12 V DC batteries). The current and voltage were recorded with high accuracy at the outlet of the rectifier, and an anemometer was used for the measurement of wind speed. The accuracy of measured power was estimated 0.5%, whereas the accuracy of anemometer was taken from the product specifications (3%).

2.2. Rotational performance of the tested blade configurations

The simplest design of VAWTs is the Savonius rotor, which works like a cup anemometer. The design has been accepted because it requires relatively low cut-in wind speeds. Savonius rotors are a drag-type machine, consisting of two or three blades. Savonius rotors with four shapes were tested, and their relative rotational performances have been analyzed. The experiments were conducted for the curved, straight, aerofoil, and twisted blade shapes (Shah, 2014; Kumar et al., 2018). A sectional view of tested blades is shown in Fig. 2.

The rotations per minute (RPM) for each blade types were recorded with respect to wind speed and illustrated in Fig. 3. The straight blade was found to have lowest RPM in all four shapes while the best RPM has been posted for the twisted blade. In respect to the wind speed, the straight blade has been seen to have less efficiency in comparison to other three blades shapes. The reason for this is there is a more drag force acting on the straight blades, separated by 120°, relative to the other three configurations. The same speed of wind produces the lesser amount of torque for straight blade shape. The rotational performance for the curved blade type was closer to the twisted type, whereas, the aerofoil blade has lower RPM than the twisted and curved blades. The subsequent theoretical and experimental studies were carried out only for the curved shape blade configuration.