Performance Evaluation of Vertical Axis Wind Turbine on Highways

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Abstract. The consumption of electricity at highways is increasing over time, consequently, more fossil fuel is burned to generate more electrical energy. However, this expensive cost of burning fossil fuels can be saved by replacing them with renewable energy sources such as wind energy. Wind energy can be generated by using a wind turbine. Therefore, this study aims to develop a vertical axis wind turbine (VAWT) that can work effectively in highway wind speed conditions while evaluating its performance in terms of torque and power by using a simulation approach. The simulation involves the use of K-omega shear-stress transport (SST) as the turbulence viscosity model. The VAWT undergoes two types of tests during the simulation process. In Test 1, the wind turbine is tested with a various number of blades at constant wind speed to find which model has the best performance in terms of torque and power output. Then, the selected model with the better output proceeds to Test 2 where it is tested with different sizes of blade radius. The results have shown that a Savonius wind turbine with five blades produces more torque and power output compared to the other rotors with two, three and four blades reaching the maximum at 140 RPM. In terms of blade radius, the model with a 400 mm radius has a better performance and capable of producing higher torque and power output than the other blade sizes.

1. Introduction

Energy is the focal theme in the socio-economic development and economic growth of a nation. An estimation has been made that about 10 million MW of wind energy are continuously available on the earth. This is an environment friendly option and can be a replacement for fossil fuels as it threatens the long-term sustainability of the global economy [1]. Nowadays, most of the world's countries are relying heavily on natural gas, coal, and oil for their source of energy. However, fossil fuels are non-renewable and concentrated in a limited number of countries. Eventually, it becomes more limited and expensive day by day as they are highly demanded. Fossil fuel also causes environmental pollution. Therefore, various renewable energy sources such as wind and solar energies are continuously...
replenished on a human timescale. Renewable energies have many advantages, such as low maintenance of their facilities, compared to traditional generators, where their fuels are derived from natural and available resources. Moreover, renewable energy projects also provide economic benefits to many regional areas because most projects are located in large urban centres and suburbs of the cities [2], [3].

Wind energy is becoming cost-effective because the land-based utility-scale wind is one of the lowest-priced energy sources available today, which costs between two and six cents per kilowatt-hour. It depends on the wind resource and the particular project’s financing. Besides, wind energy is a clean fuel source, and it does not cause air pollution as the power plants rely on the combustion of fossil fuels [4], [5]. The device that is used to convert wind energy into electrical energy is called a wind turbine. Commonly, the small turbines are used for battery charging for auxiliary power for boats to power traffic warning signs. While large turbines are used for domestic power supply and sending back the unused power to the utility supplier. Wind turbines are divided into two types, which are the vertical axis and the horizontal axis. The vertical axis wind turbine (VAWT) has the main rotor shaft arranged vertically. This arrangement has its advantage where the turbine does not need to be pointed into the wind to be effective. It is very much used for a site that has a high variability of wind direction. Another advantage of this design is the accessibility for maintenance. The gearbox and generator can be placed at the ground due to direct drive from the rotor to the ground-based gearbox [6]. The VAWT itself has two types of designs, which are named Darrieus and Savonius. The Darrieus design has excellent efficiency, but it is poorly reliable due to broad torque ripple generation and cyclical stress on the tower. This design also requires some external power sources to start turning due to the very low starting torque. In contrast, the Savonius is a drag-type device that has the capability of self-starting if it has at least three scoops (blades). The Savonius with two scoops is usually used in anemometers, in some high-reliability and low-efficiency power turbines. They are commonly seen on the roofs of houses, bus or vans. In order to provide smooth torque, this design has been modified with long helical scoops and it is known as twisted Savonius rotor [7]-[9].

Depending on the primary power grid to supply electricity to the highway, the grid power is costly in terms of cost and implementation, and it is also not a long-term sustainable energy source. However, the wind energy restored in the wakes of moving vehicles on the road has its potential to be a source of energy that can be converted to electricity, but it is yet to be discovered [10]-[12]. Therefore, this study’s main objectives are to design an efficient vertical axis wind turbine with a Savonius-type while investigating the performance of VAWT in terms of torque and power on the highway.

2. Materials and methods
This study starts with selecting the Savonius-type blade for VAWT, which is used in this study. The proposed 3D model of the VAWT is designed and developed using the modelling SolidWorks software with specific parameters. The proposed VAWT is then imported into ANSYS to run the CFD simulations. The power and torque outputs are then extracted from the simulation results. Equations 1 to 3 are respectively the theoretical power, actual mechanical power and the maximum power extractable by a wind turbine.

\[ P_w = \frac{1}{2} \rho A V^3 \]  
\[ P_T = T_m \times \omega \]  
\[ P_{ex} = (0.593)T_m \times \omega \]
Meanwhile, the rotor thrust force equation and the rotor theoretical torque equation of wind turbine are respectively presented in Equation 4 and Equation 5.

\[ F = \frac{1}{2} \rho_a AV^2 \quad (4) \]
\[ T = \frac{1}{2} \rho_a AV^2 \quad (5) \]

2.1. Rotor design

The S-type design, which is known as the Savonius type, is selected for blades of the VAWT. In the first test, the S-type wind turbine is tested with a various number of blades. The blades are C-shape design with a radius of 300 mm. The original design has three combinations of C-shape, where each of them is cut into a 270 mm radius. Then, the number of C-shape combinations will depend on the number of blades of the wind turbine. In the second test, the chosen wind turbine in Test 1 is tested with different radius sizes of blades, which are 300 mm, 350 mm, and 350 mm. The blades with a radius of 350 mm are cut into 320 mm, and blades with a radius of 400 mm are cut into 370 mm. The height and thickness of the rotors of all models are maintained at 120 mm and 5 mm, respectively in both tests. The geometrical details of the models are shown in Figure 1.
2.2. Boundary conditions and simulation technique

The CAD model designed is imported into ANSYS, and a proper simulation domain is created. Given that a turbine is a rotating machine, the present model's domain is divided into two regions; rotating and non-rotating regions. The non-rotating region characterizes the simulation's general computation territory, and the rotating region has the rotor.

This study's specific boundary conditions are the velocity inlet boundary condition at the inlet position, pressure outlet at the outlet position, and non-slip wall boundary condition at the rotor surfaces and lateral walls non-conformal interface boundary condition is used between the rotating domain and non-rotating domain. The two-equation K-omega Shear-stress transport (SST) is used as the turbulent viscosity model. For the solution method, the pressure-based coupled algorithm is chosen as the pressure-velocity coupling scheme.

3. Results and discussion

The numerical simulation process starts with a verification process, grid independence test (GIT), and then proceeds with the validation process before presenting the results.

3.1. Grid independence Test and Model Validation

The grid independence test (GIT) was conducted to fix the study's grid sensitivity and determine the mesh's acceptable size so that the number of elements does not influence the solution results. It was observed that all different sizes of mesh have a small amount of relative error. However, the torque output becomes grid-independent when the size of the element is below 0.0125 m. Therefore, the 0.010m size element is selected as it is considered reliable and more accurate to be incorporated into the subsequent simulation processes. Moreover, Figure 2 shows the results of the validation of the present simulation results with the previous experimental results presented in [10]. The graph demonstrates that the current simulation results are close to the previous experimental results. The average percentage of relative error is 12.47%, and it is in the acceptable range. Therefore, the current simulation's reliability is proven to be genuine and valid to carry on the simulation process.
Figure 2. Current simulation and previous experimental torque output [10].

3.2. Evaluation of predicted torque with different number of blades and radius size
In this section, the torque of the various number of blades and radius size of the Savonius VAWT are predicted at highway wind speed at 5 m/s. The results are shown in Figure 3 and Figure 4 with respect to the torque output. Figure 3 shows that the Savonius rotor's torque with five blades increases significantly as the RPM increases compared to other blades and reach a maximum at 140 RPM with 0.17954 Nm. Simultaneously, the rotor with two blades has the smallest torque overall and reaches 0.12093 Nm at 140 RPM. This may be due to the increasing amount of wind force captured by the blades. Thus, when the number of blades increases, thus the torque produced will be higher. However, the three blades have slightly higher torque than the four blades. Moreover, Figure 4 shows that the torque of blades with a 400 mm radius increases significantly when the RPM increases compared to the other radiiuses and reaches a maximum at 140 RPM with 0.4143 Nm. While blades with a 300 mm radius have the smallest torque and only reaches a maximum of 0.1795 Nm. This is because the higher the radius, the higher the torque produced.
3.3. Evaluation of predicted power with different number of blades and radius size

This section shows the aerodynamic behavior of the Savonius VAWT in relation to power output by using a numerical simulation approach. Figure 5 shows the power output of wind turbines with a various number of blades. From Figure 5, it shows that Savonius with five blades produces the highest power output when the RPM increases, followed by 3, 4, and 2 blades and reach the maximum at 140 RPM with 2.6322 W. While Savonius with two blades has the smallest power output overall and reaches 1.7729 W at 140 RPM. However, the three blades Savonius has slightly higher power output than the four blades. Furthermore, Figure 6 shows that blades with a 400 mm radius produce the highest power output when
the RPM increases, followed by 350 mm and 300 mm and reaches the maximum at 140 RPM with 6.074 W. Meanwhile, blades with a 300 mm radius have the smallest power output and only reach a maximum value of 2.6322 W.

![Figure 5](image1.png)

**Figure 5.** Power against rotational speed per minute (with different number of blades).

![Figure 6](image2.png)

**Figure 6.** Power against rotational speed per minute (with different size of radius).

4. Conclusions
In this study, a Savonius-type vertical axis wind turbine (VAWT) performance on the induced wind on highways has been studied using the computational fluids dynamic (CFD) simulations approach. The main aim of this study to develop a vertical axis wind turbine (VAWT) that can work effectively in
highway wind speed conditions while evaluating its performance in terms of torque and power output. The simulation involves the use of K-omega shear-stress transport (SST) as the turbulence viscosity model. Two types of testing are performed while attaining the torque and power outputs of the turbine. The first test involves the use of a varying number of blades (two blades, three blades, four blades, and five blades), and the second test used the rotor with the better performance in the first test and tested it again using different sizes of blade radius (300 mm, 350 mm and 400 mm).

It is concluded that the five-blade rotor has produced the highest torque and power outputs at various RPM among all the number of blades tested. Hence, the five-blade rotor was tested with various sizes of the blade radius the maximum torque and power values of 0.17954 Nm and 2.6322 W, respectively. Then the five-blade rotor is tested with different sizes of blade radius starting from 300 mm, 350 mm and 400 mm. The 400 mm blade radius has shown better performance in both torque and power outputs with the corresponding maximum torque and power values of 0.4143 Nm and 6.074 W, respectively.

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