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Research Article

Optimization of 300 Watt Vertical Axis Wind Turbine for Low Wind Speed Regions: A Case Study of Malaysia

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Abstract: This study demonstrates the overall performance and efficiency of a 300 Watt conventional vertical axis wind turbine manufactured by (i-wind) for a low wind speed regions. The study investigates the increasing of blade tangential velocity by adding a new blade attached to the main blade of the turbine. The new blades called secondary blades which will take the effect of increasing the tangential velocity and hence increasing the rated output power. The new contribution proposed in this study was taken into considerations the optimum position of the secondary blades. The position was taken to be in parallel location with the main blades under different configurations and distances (7, 10, 15 and 20 cm). A simulation analysis using ANSYS CFD was proposed in this study to evaluate the tangential velocity and the rotational speed of different cases for the modified vertical axis wind turbine. The range of wind velocities were 5 to 12 m/s in order to cover a reasonable range of wind speed. The variation of power and rotational speed was compared with the power and rotational speed calculated for the conventional wind turbine. The study illustrates the correlations of power and rotational speed of the modified vertical axis wind turbine. The increasing of tangential velocity and output power for the modified turbine under a minimum wind speed of 5 m/s were found to be 17% and 51% respectively.

Keywords: Secondary blade, simulation, vertical axis wind turbine, wind energy, wind turbine

INTRODUCTION

Wind power could be defined as the power that utilizing the air flow over or through a wind turbine to generate electricity. The electrical power generated from wind turbine is extracted by converting the mechanical energy into electrical energy (Malael *et al*., 2014). Wind turbines are the devices that convert the kinetic energy of wind flow stream into electrical energy. This kinetic energy is generated from the movement of air in the atmosphere enhanced several important applications (Eboibi, 2013). One of these applications is the wind turbine. The power generated from wind turbine is a resultant of rotating the rotor part of the turbine which is connected to a generator (Basak, 2012). The rotor part of the turbine is rotated by rotating the blades attached to it. The aerodynamic behavior of air free stream blow on these blades could generate aerodynamic forces that create some centrifugal forces to rotate the turbine (Vassberg *et al*., 2005). There are two main types of wind turbines classified according to the direction of rotational axis. Horizontal axis wind turbine and vertical axis wind turbine. Where the Horizontal Axis Wind Turbine (HAWT) is defined in which the rotational direction is perpendicular to the axis of rotation. While in Vertical Axis Wind Turbine (VAWT), the direction of rotation is parallel to the axis of rotation. There are some advantages in which vertical axis wind turbine comes over the horizontal type (Tummala *et al*., 2016). The ability of catching wind from any direction is considered as the most effective advantage, while in horizontal axis wind turbine, the wind direction should be perpendicular to the direction of rotation. Other advantages are noiseless, low elevation and low cost (Balduzzi *et al*., 2016).

There are some parameters that influence the performance of VAWT. One of the most important parameter is the blade of the wind turbine. The first indication about the blade design was conducted that it should be straight without any twisting with specific types of airfoils (Lee *et al*., 2016). Therefore, in order to increase the performance and efficiency of vertical axis wind turbine, a new design could be presented. The new design is proposed to have twisted blades to gain more wind power (Shahizare *et al*., 2016). Streedbart and Singbji designed the first model of wind turbine with twisting bladesin 1977(Salih *et al*., 2015). The

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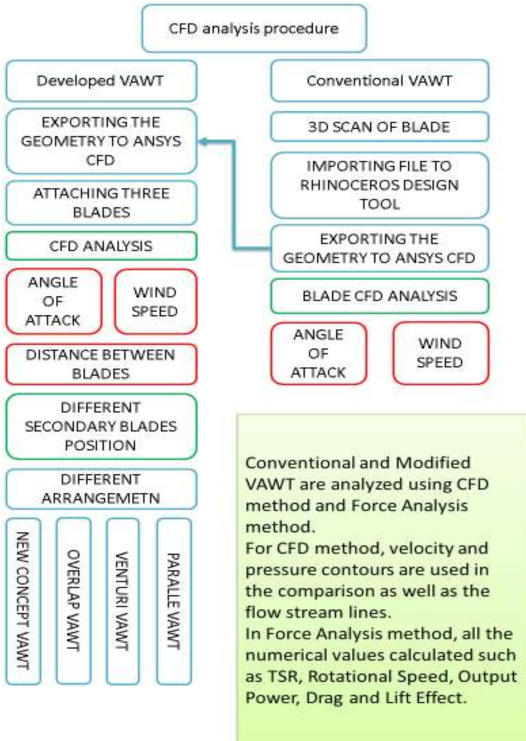

Fig. 1: Research methodology used in the study

design was presented to estimate the aerodynamic effect of twisted blades on the load generated by the turbine. The results obtained from that study was validated with an experimental setup of an actual size of wind turbine and generator. Twisting the blades of the turbine showed that the efficiency could enhanced. A new configuration of vertical axis wind turbine was presented by Badawy and Aly (2000), where the turbine was surrounded by a shrouded area to increase the inlet velocity of wind acting of the blades of the turbine. The numerical analysis of shrouded wind turbine shows a significant effect compared to conventional wind turbine.

Development of vertical axis wind turbine has become very important in the last decades especially when the need of alternative energy sources in some regions (Ragheb and Ragheb, 2011). These regions suffer from low solar energy and low speed wind energy such as some Asian countries. In Malaysia, the average wind speed recorded was in the range of 2-5 m/s. Thus this velocity is not enough to rotate the wind turbine and hence to generate electricity. The need of designing a new wind turbine that could be used in these area is considered as one of main research problems in Malaysia. Therefore, the challenge is to optimize the conventional vertical axis wind turbine that could be operate and generate electricity at low range of wind speed.

A new design of vertical axis wind turbine was proposed byQasim *et al.* (2011). The new design

Fig. 2: Three-dimensional scanning of original blade

presented to have an impeller type vertical axis wind turbine to increase the effective area of the system by using some vanes (Qasim *et al*., 2011). The wind acting on the blades from the closed side of the turbine will increase the torque extracted, while the open side will allow the flow stream of the wind to generate vortices.

In this study, an optimization of conventional vertical axis wind turbine with 300 Watt rated output power is developed by adding new blades attached to its main blades. The concept was defined to have a special effect in aerodynamic behavior of the flow stream around and between the two blades.

MATERIALS AND METHODS

The research methodology used in this study is presented in Fig. 1 to overcome the work done and the relationship between different parameters with their effects on the performance of optimized vertical axis wind turbine. In this part of study, only one configuration shall be discussed which is the parallel six blades vertical axis wind turbine. The study was started in 2012 in Solar Energy Research Institute (SERI) /UniversitiKebangsaan Malaysia (UKM).

The numerical investigation of both conventional and modified vertical axis wind turbine is presented. The first step was defined to analyze a 300 Watt conventional three blades vertical axis wind turbine designed and manufactured by (i-wind SdnBhd). The blade was scanned to convert the geometry file that could be read and modified by a specific modelling software called (Rhinoceros v.4). The scanning procedure consists of three-dimensional scan of one blade as shown in Fig. 2. The output file of geometry was exported to the modelling software to clean it up and create a full-scale modelling of three blades vertical axis wind turbine and then the modified VAWT.

CFD Analysis: CFD analysis of conventional and modified vertical axis wind turbine under different boundary conditions and configurations is presented in this study. The analysis was divided into two parts; the first was to analyze the conventional VAWT which consists three blades with constant airfoil section made of NACA4412 as shown in Fig. 3. The second was to analyze different arrangements of the modified VAWT in which secondary blades was attached to the main blade in parallel position. The new modified vertical axis wind turbine was called six blades vertical axis wind turbine with parallel configuration. The parallel

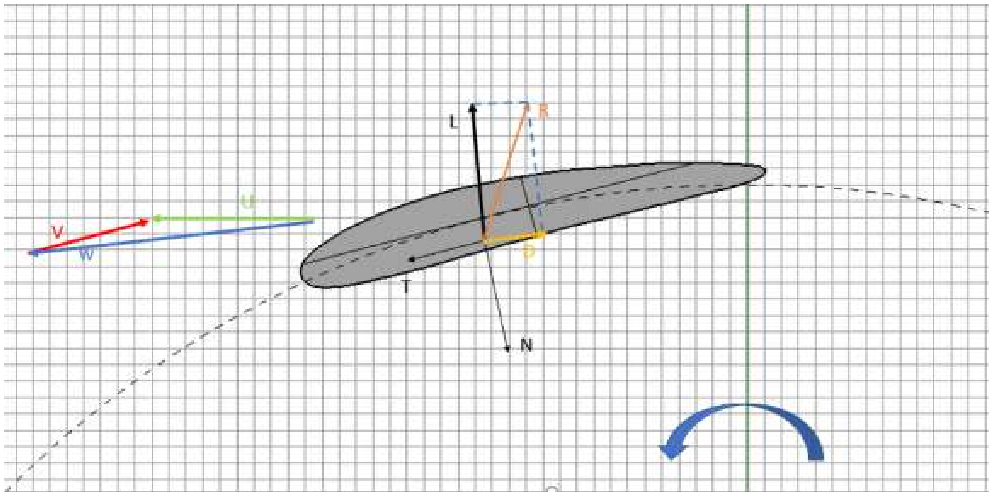

Fig. 3: NACA4412 airfoil configuration used in the analysis

configuration defined in which the secondary blade is attached to the main blade in parallel mode with a specific distance. The distances were defined to be 7, 10, 15 and 20 cm. Both conventional and modified VAWT were subjected to a boundary condition in which the upcoming wind speed is 5 m/s with a rotational speed of 36 rpm. This technical data was recorded from the experimental testing of i-wind three blades vertical axis wind turbine under wind tunnel test.

Governing equations: Navier-Stocks equation is well known as the governing equation used in the computational fluid dynamics analysis. It could be defined as a set of equations in which there is no exact answer or solution. The assumptions of the solution governing this type of equations are that the fluid is considered as Newtonian, where the flow could be explained by the following sets of equations.
The continuity of mass:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho V) = 0 \tag{1}$$

The continuity of momentum:
X-momentum:

$$\frac{\partial(\rho u)}{\partial t} + \nabla.(\rho u V) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \tag{2}$$

Y-momentum:

$$\frac{\partial(\rho v)}{\partial t} + \nabla.(\rho v V) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \tag{3}$$

Z-momentum:

$$\frac{\partial(\rho w)}{\partial t} + \nabla.(\rho w V) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \tag{4}$$

The continuity of energy:

$$\rho\frac{\partial}{\partial t}\left(e + \frac{v^2}{2}\right) = pq + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) - \frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z} \tag{5}$$

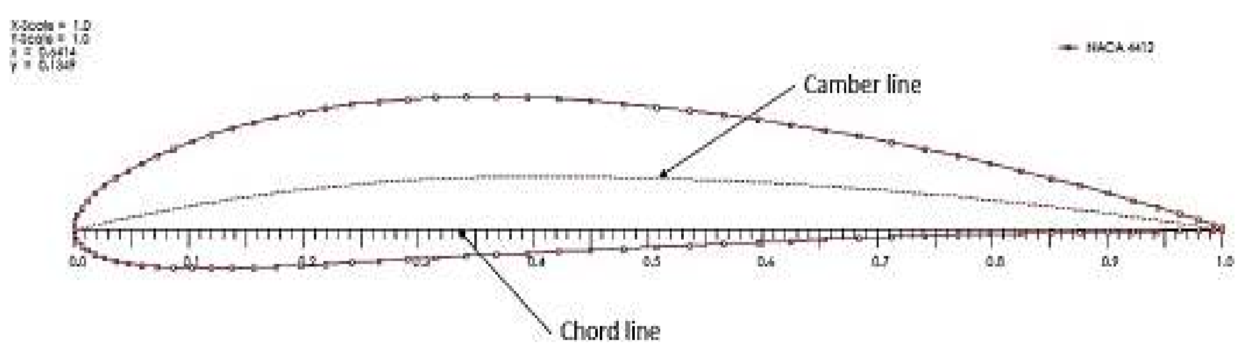

Fig. 4: NACA4412 airfoil profile

In vertical axis wind turbine simulation, the governing solution consists of continuity and momentum equations. Rynolds average Navier Stocks approach are considered for turbulence occurs during the rotation of the wind turbine. It is important when using CFD method to know that the performance prediction of vertical axis wind turbine requires large domain and this domain should include the sliding mesh method (will be described later). Both large domain analysis and sliding mesh solution should be defined with time (transient mode) to overcome all the steady and unsteady performance of the wind turbine especially during rotation.

The approach of six blades parallel vertical axis wind turbine with a specific distance between main and secondary blades is presented in Fig. 4. If the gap is defined by 10 cm (for example), then the attached blade will be at a distance of 10 cm from the main blade. Therefore, secondary radius of rotation will be defined as R_s and it is equal to the main radius of rotation plus 7 cm (i.e., $R_s = R_m + 0.1$ m).

Geometry generation: The first step in defining the CFD analysis and procedure was to define the geometry of the blades in both conventional and modified VAWT. NACA 4-digits series of airfoil is a group of analytical designed airfoil cross sections that are defined by camber and chord lines. The approach of this type of airfoil allows vertical axis wind turbine designs to be easy to test as a symmetrical profile could be enhanced. The coordinates of NACA 4-digits airfoil series used in this study is presented in the following formula founded by Abbot and Doenhoff in 1959 (Castillo, 2011):

$$y = \frac{t_c}{0.2}\left[0.2969\sqrt{x/_c} - 0.126\,(x/_c) - 0.3516\,(x/_c)^2 + 0.3516(x/_c)^3 - 0.3516\,(x/_c)^4\right] \quad (6)$$

where,

c = Chord line
x = Position along chord from 0 to c
y = Half thickness at x value
t = Maximum thickness

The position of this coordinates in the upper position of airfoil curve are represented by (X_U, Y_U) and the lower position are (X_L, Y_L). Figure 4 shows the profile of NACA4412 airfoil.

For the generation of NACA4412 airfoils in ANSYS CFD, the geometry first was imported in Ansys Design Modeler to create the rotating domain as shown in Fig. 5. The rotating domain then surroundedby a fixed domain in order to enhance the sliding mesh technique as shown in Fig. 6.

The modified vertical axis wind turbine M-VAWT consists of three main blades representing the conventional vertical axis wind turbine with three secondary blades attached to each blade to form six blades vertical axis wind turbine. All the modified and proposed configurations were compared with each other as well as with the original arrangement represented by conventional vertical axis wind turbine. Attaching three blades to the main blades of the turbine in a form of parallel configuration with 15 cm gap between main and secondary blade are represented in Fig. 7.

Mesh generation: Sliding mesh technique is used to investigate the performance of i-wind vertical axis wind turbine and the proposed VAWT. In order to obtain high accuracy and output efficiency utilizing CFD simulation, transient time step solution method is also predicted. Reynolds-Average Navier-Stokes (RANS) Equations was considered as the most popular simulation technique used in fluid flow especially in the investigation of wind turbine. RANS method is used in this study where it is based on Navier-Stokes equations thatdescribes the conservation of momentum. To simulate the domain, the geometry has been created using Design Modeler with three major steps:

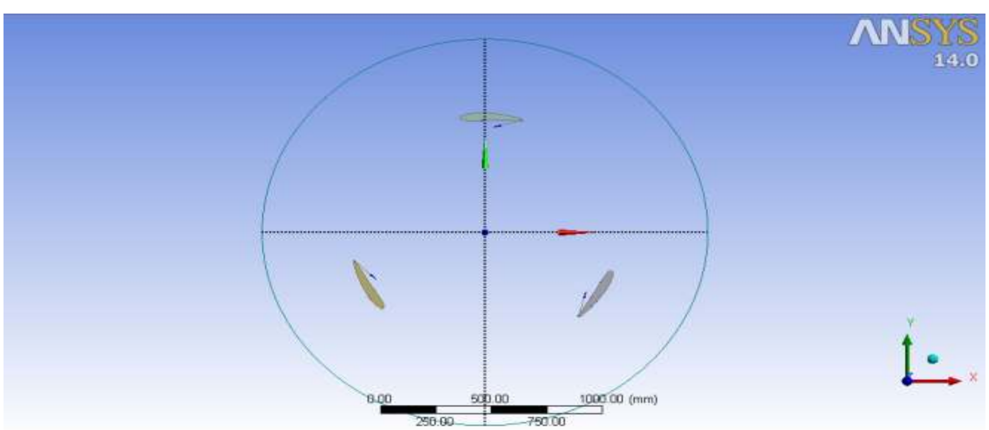

Fig. 5: Two-dimensional geometry imported by ansys design modeler

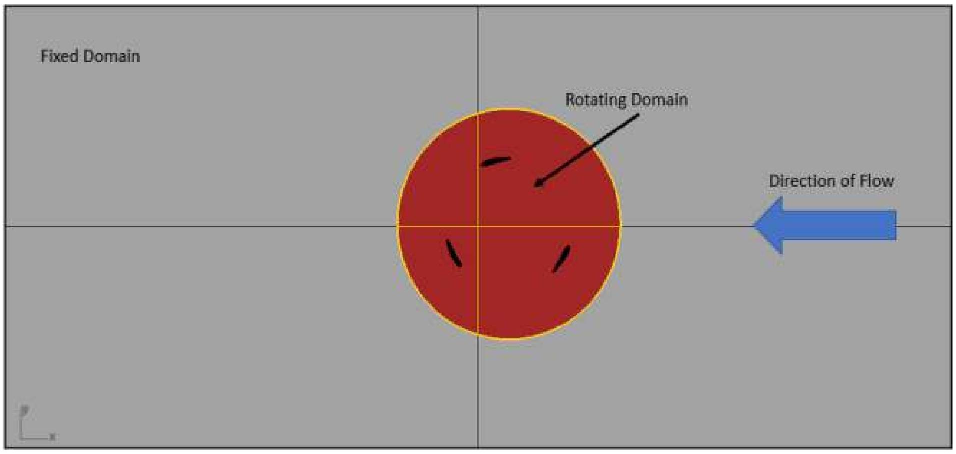

Fig. 6: Two-dimensional geometry showing rotating domain surrounded by fixed domain

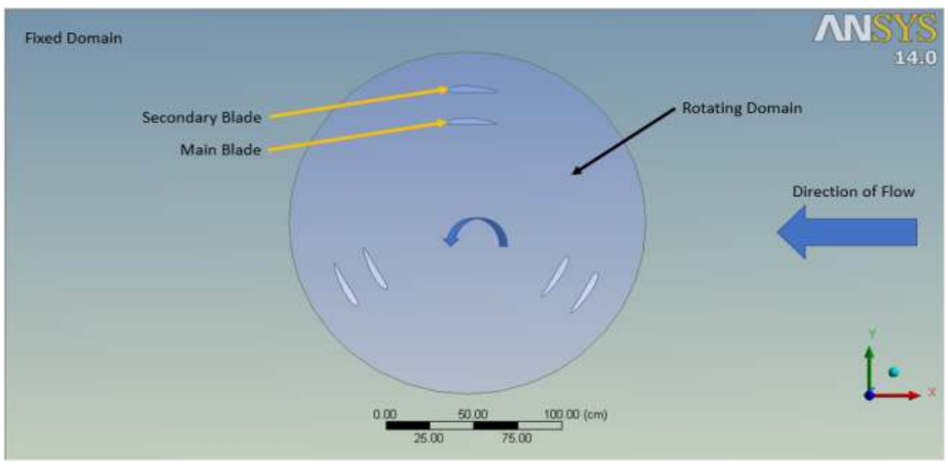

Fig. 7: Two-dimensional six blades parallel VAWT

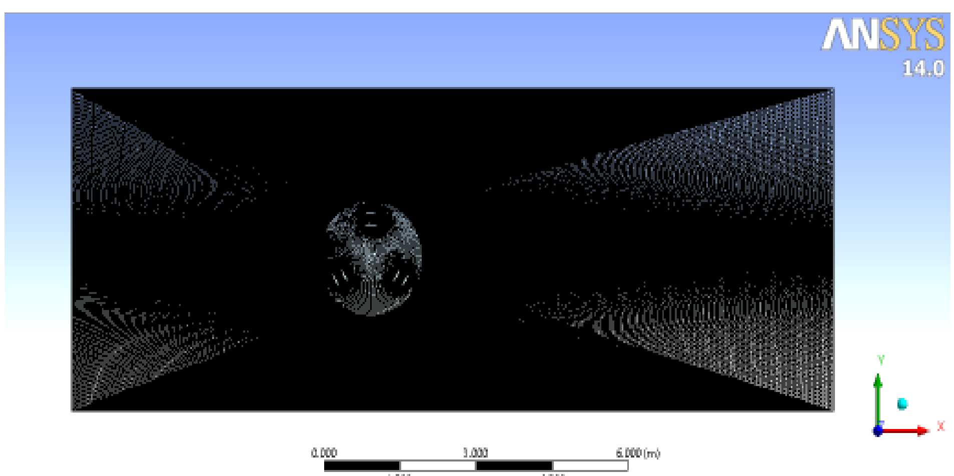

Fig. 8: Two-dimensional sliding mesh method of six blades parallel configuration

- Create the solid structure (i.e., blades)
- Generate the domain
- Boolean the blades inside the domain

Figure 8 shows the meshing technique of two-dimensional fixed and rotating domains.

Figure 9 represents the sliding mesh interface between the fixed and rotating domains where the cells

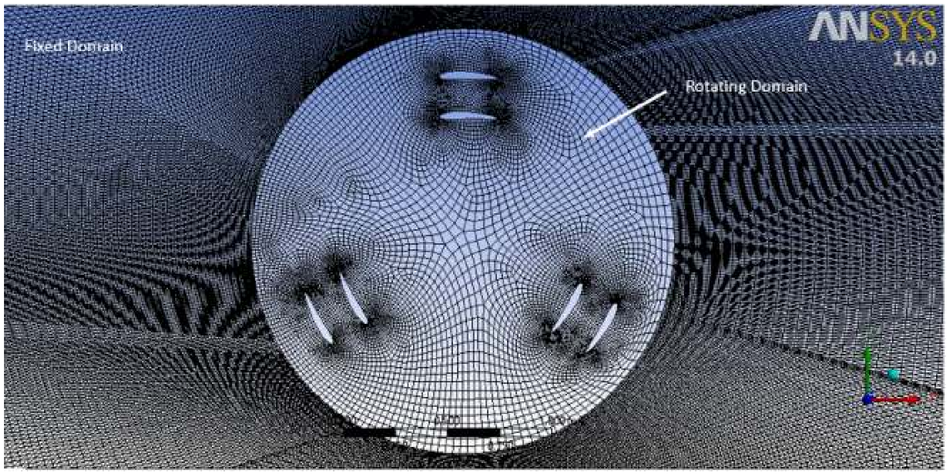

Fig. 9: Sliding mesh interface showing fixed and rotating domains

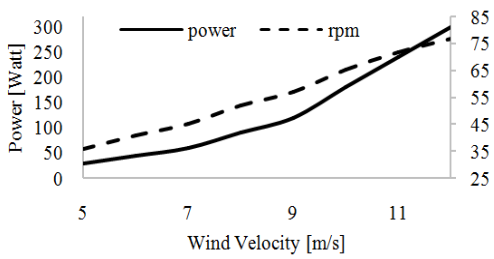

Fig. 10: Rated power and RPM of i-wind conventional vertical axis wind turbine

are created and generated more around the blades and in the contact area of interface.

RESULTS AND DISCUSSION

Conventional three blades VAWT: The simulation investigation was conducted utilizing a Computational Fluid Dynamics (CFD) analysis using ANSYS Fluent v14 to overcome the optimum positions and arrangements of secondary blades attached to main blades. The conventional vertical axis wind turbine was tested under wide range of wind velocity (5 to 12 m/s) to calculate the range of power output and the average rotational speed that could exceed during the subjected wind velocity. Figure 10 represents the profiles of rotational speed in RPM with the rated output power in Watt under a range of wind velocity from 5 to 12 m/s. According to the manufacturing sheet of i-wind, it is mentioned that the rated power of the conventional i-wind vertical axis wind turbine is varied from 10% at low wind velocity and up to 100% at 12 m/s wind speed.

A correlation of rated power and rotational speed as a function of wind velocity was found to estimate all the ranges of wind velocity:

$$Power = -0.0379\, U_\infty^3 + 5.8766\, U_\infty^2 - 52.592\, U_\infty + 153.05 \quad (7)$$

$$RPM = -0.0581\, U_\infty^3 + 1.643 U_\infty^2 - 8.7684 U_\infty + 46.346 \quad (8)$$

Figure 11 shows the velocity contour of conventional vertical axis wind turbine blades subjected to 5 m/s average wind velocity in which to simulate the real average weather data obtained and recorded by weather station. The simulation procedure was defined to be under sliding mesh method, where the blades are rotating with a constant rotational speed of 36 rpm.

Velocity contour shows a significant variation of wind velocity acting on the blades, where the tangential velocities of each blade could be enhanced later by adding a secondary blade as described before. Figure 12 represents the tangential velocity of blade 1 with respect to the rotational position. The tangential velocity of Blade1 was found to be in the range of 2.3 to 2.34 m/s, this range could enhance the rotational speed of the wind turbine. The maximum value of tangential velocity was recorded at the upper position of the wind turbine, in which the blade angle of attack has a value in the range of 0 to 90°.

Modified six blades parallel VAWT: This arrangement represents that the secondary blades are attached to the main blades in parallel mode with a distance of 7 cm between them. The secondary blades are rotating in the same direction with the main blades at a rotational speed of 36 rpm as mentioned before. Figure 13 shows the velocity contour of modified vertical axis wind turbine with three additional blades attached to the main blades with a gap of 7 cm.

The velocity contour shows that the velocity magnitude could be enhanced by increasing thedistance betweenmain and secondary bade. This lead to increase the tangential velocity of secondary blades creating a virtual airfoil between the two blades that has a tangential velocity with the mean value between main andsecondary tangential velocity.

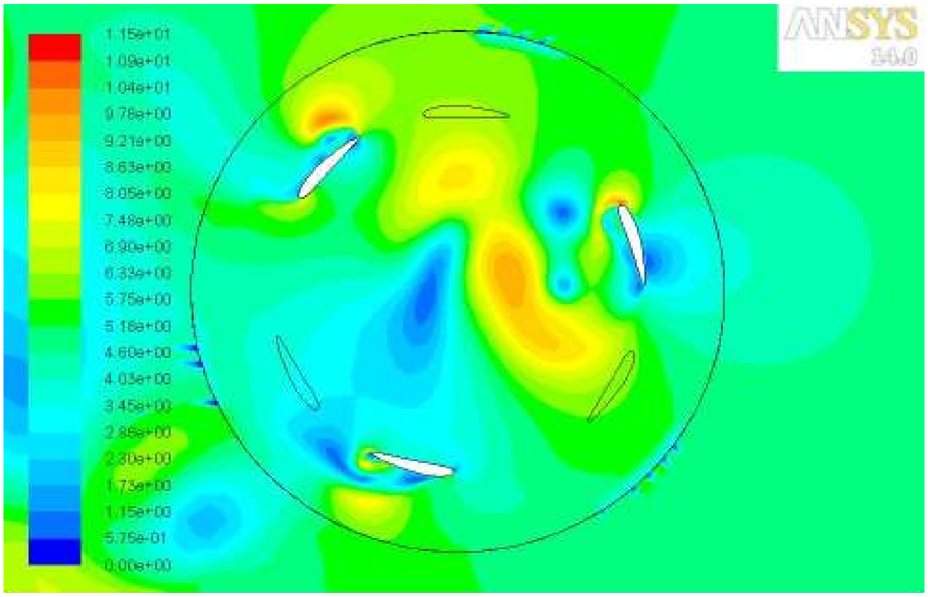

Fig. 11: Velocity contour of three blades conventional VAWT

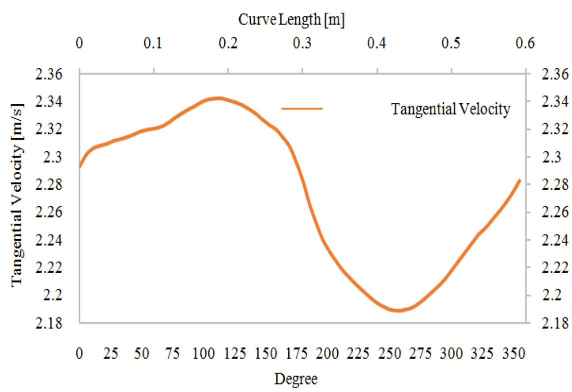

Fig. 12: Tangential velocity profile of main blade

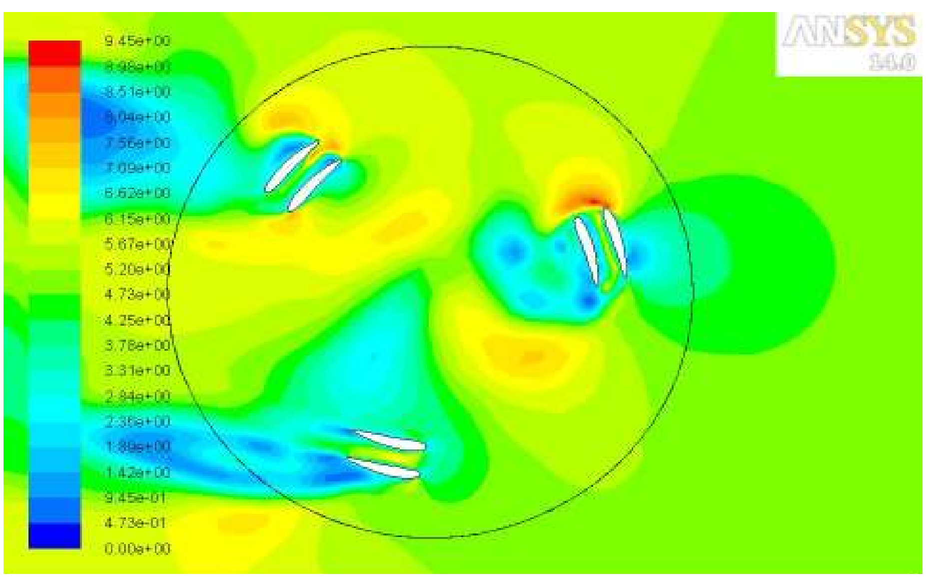

Fig. 13: Velocity contour of six blades parallel modified VAWT with 7 cm gap

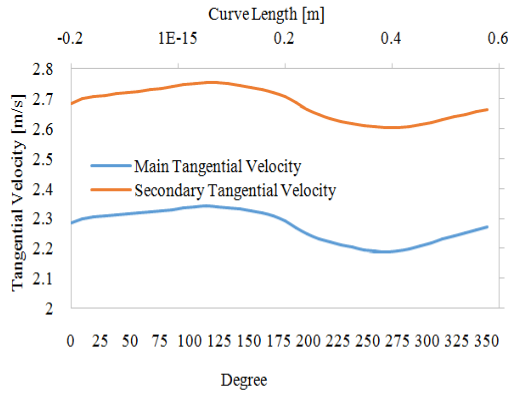

Fig. 14: Tangential velocity profile of main and secondary blades of six blades parallel modified vertical axis wind turbine with 7 cm gap

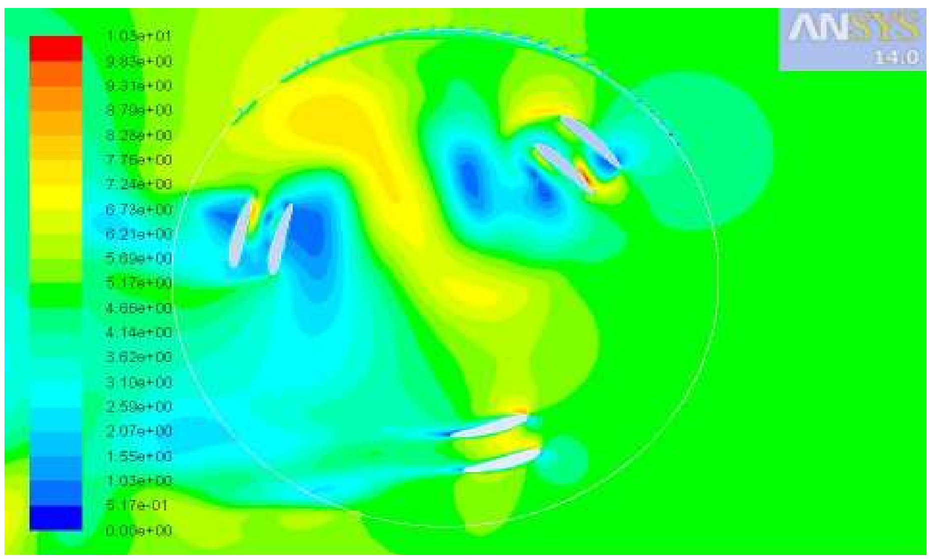

Fig. 15: Velocity contour of six blades parallel modified VAWT with 10 cm gap

Figure 14 shows the tangential velocity of main blade (first blade as an example) with a value range of 2.60 to 2.76 m/s, while the main blade tangential velocity was found to be in the range of 2.18 to 2.34 m/s.

During the simulation analysis of modified vertical axis wind turbine, it was found that increasing the tangential velocity of main and secondary blades combination would enhance the overall performance of the wind turbine. Increasing the distance between main and secondary blade could achieves this. The distance is increased to 10 cm to study this effect, the new arrangement was subjected to 5 m/s inlet wind velocity with 36 rpm rotational speed of the system. Figure 15 shows the velocity contour of modified vertical axis wind turbine with 10 cm gap between main and secondary blades calculated utilizing sliding mesh method.

The tangential velocities of main and secondary blades could be presented in Fig. 16, where the increasing in tangential velocity for secondary blade is recorded to be in the range of 2.70 to 2.86 m/s. This value is 23% increasing as compared with the main blade tangential velocity.

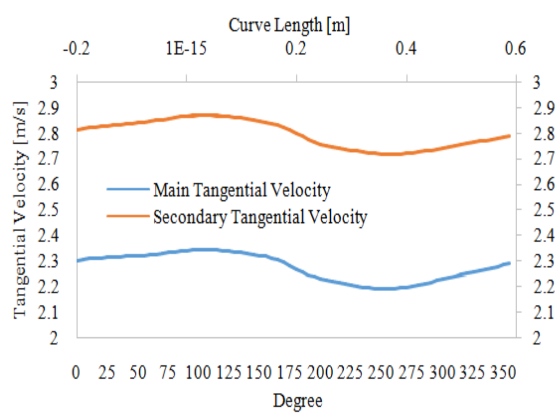

Fig. 16: Tangential velocity profile of main and secondary blades of six blades parallel modified vertical axis wind turbine with 10 cm gap

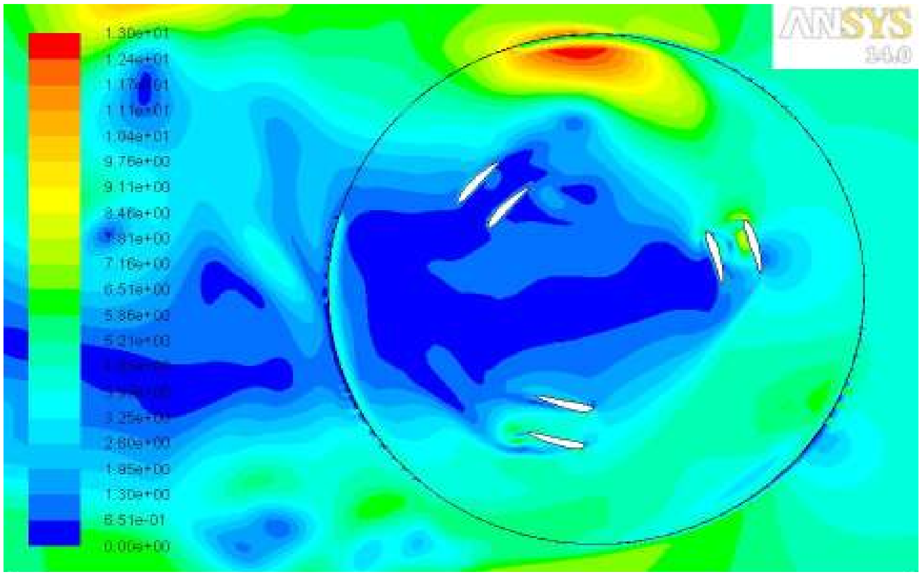

Fig. 17: Velocity contour of six blades parallel modified VAWT with 15 cm gap

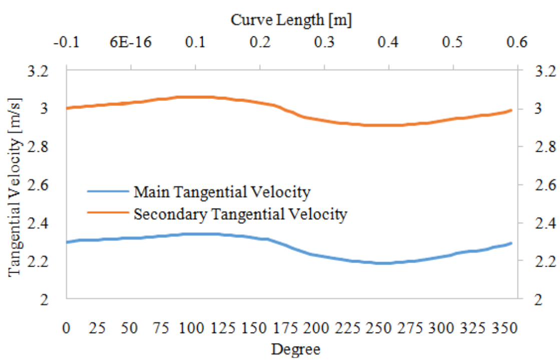

Fig. 18: Tangential velocity profile of main and secondary blades of six blades parallel modified vertical axis wind turbine with 15 cm gap

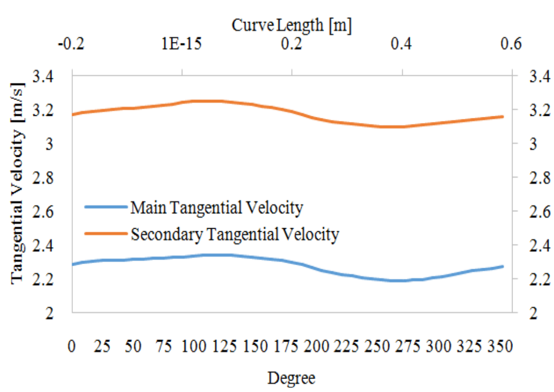

Fig. 19: Tangential velocity profile of main and secondary blades of six blades parallel modified vertical axis wind turbine with 20 cm gap

A new arrangement of parallel modified vertical axis wind turbine was introduced. The distance between main ad secondary blades was increased to 15 cm, this was found to enhance the tangential velocity of the secondary blade forming an increasing value to the tangential velocity of the main blade. Figure 17 represents the velocity contour of 15 cm parallel arrangement of modified vertical axis wind turbine.

The tangential velocities recorded from the siding mesh method used in CFD simulation is presented in Fig. 18. The tangential velocity of main blade with 15 cm gap distance between main and secondary blade was found to be in the range of 2.18 to 2.34 m/s, while the tangential velocity of secondary blade was in the range of 2.90 to 3.06 m/s.

20 cm gap between the main and secondary blades was increased to study the effect ofadding a secondary blade in parallel position to enhance the tangential velocity of vertical axis wind turbine. Figure 19 represents the tangential velocity of main blade subjected to 5 m/s inlet wind velocity and a rotating speed of 36 rpm.

The distribution of velocity values showed in velocity contour gives an indication that the profile of tangential velocity is remain same as the profile of main blade (Fig. 20).

For different range of velocities subjected on the wind turbine, the comparison between the selected concept(parallel) with three blades conventional VAWT will be discussed. The profile of rated power and RPM obtained by utilizing the modified VAWT was compared with the profile of power and rotating speed obtained and illustrated in Fig. 10. Figure 21 represents the rated power and rotating speed profiles for six blades parallel vertical axis wind turbine with 20 cm gap. The power and rotating speed were estimated under a wide range of wind velocity (5 to 12 m/s), where a minimum wind velocity (5 m/s) is selected as a start as this is the minimum value to obtain a rated

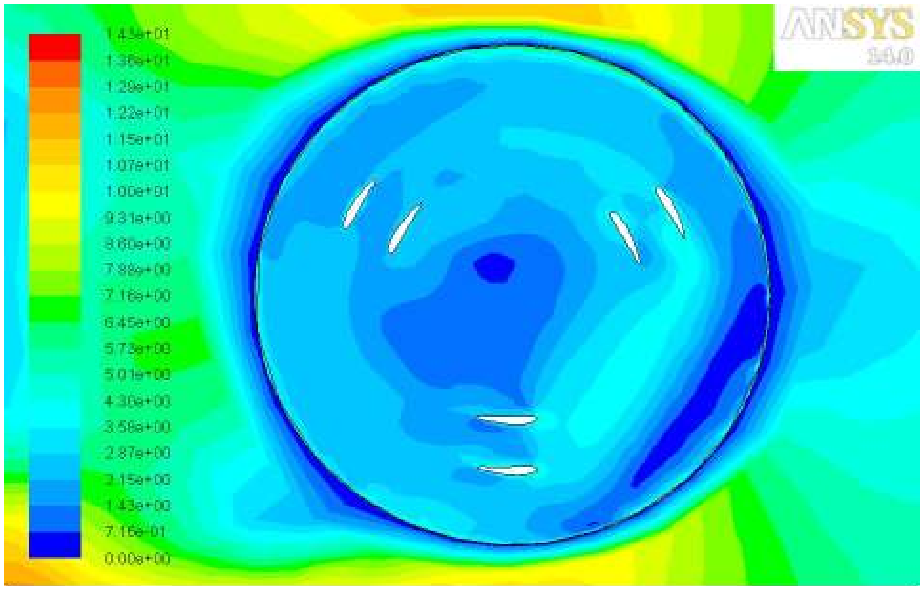

Fig. 20: Velocity contour of six blades parallel modified VAWT with 20 cm gap

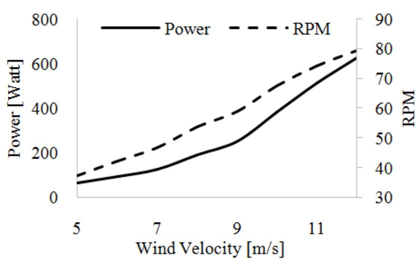

Fig. 21: Rated power and RPM of six blades parallel VAWT with 20 cm gap

power of 30 kW as illustrated in i-wind data sheet. While a maximum rated power of 300 kW could be obtained at a wind velocity of 12 m/s. It is illustrated from the Fig.21 that the rated power is increased as the wind velocity attacking the wind turbine blade is increased. Compared with i-wind conventional vertical axis wind turbine behavior of rated power and rotational speed, it is found that the modified vertical axis wind turbine with parallel blades reached a rated power of 300 W at only 9.5 m/s wind velocity. While in the conventional VAWT with three blades, the rated power reached its maximum value of 300 W at 12 m/s wind speed. This approach leads to the fact that modified vertical axis wind turbine will have the possibility to improve a maximum rated power at low wind speed range. Therefore, for low wind speed (5 m/s as an example) the rated power of three blades conventional VAWT is 36 Watt, while it is 64.0352 Watt in six blades modified VAWT. This is due to the increasing of tangential velocity by adding the secondary blades and hence the power is related to (Tangential Velocity)^3 of blade.

The correlation of rated power and rotational speed as a function of wind velocity is represented in equations 9 and 10 below:

$$Power = -0.294\,U_\infty^3 + 17.645\,U_\infty^2 - 149.02\,U_\infty + 414.45 \quad (9)$$

$$RPM = -0.0602\,U_\infty^3 + 1.7037\,U_\infty^2 + 9.1231\,U_\infty + 48.051 \quad (10)$$

In order to compare the results conducted from this study with previous researches done in the field of vertical axis wind turbine, the tangential velocityobtained was found to be 17% more than conventional three blades VAWT. Thus, enhance the output power of
the system as the power of the turbine is proportional to the cubic of the tangential velocity.

CONCLUSION

From the study and investigation of both conventional and modified vertical axis wind turbine designed and manufactured by i-wind and the proposed designs, the following conclusions could be presented:

- The rate of power generated from conventional vertical axis wind turbine is related to the wind velocity attacking the blades. This is due to the relation between the power and the tangential velocity as well as the swept area.
- Enhancing the performance of conventional vertical axis wind turbine could be done by adding secondary blades attached to the main blades in a position that creates a parallel arrangement. This could improve the tangential velocity of the system by taking the mean value between tangential velocity of main and secondary blade. The tangential velocity is increased by 17% at 5 m/s wind velocity.

- The correlations of rated power and rotational speed was estimated from velocity profile for the wide range of wind velocity. The correlation as a function of wind velocity was extracted in which it is able to calculate the rated power and rotational speed of vertical axis wind turbine in terms of any value of wind velocity.

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