Novel investigation of the different Omni-direction-guide-vane angles effects on the urban vertical axis wind turbine output power via three-dimensional numerical simulation

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Abstract
The aim of this study is to present the effects of different Omni-direction-guide-vane (ODGV) angles on the performance of the vertical axis wind turbine (VAWT). For this purpose, five different straight-bladed VAWTs have been simulated via three-dimensional (3D) computational fluid dynamics (CFD). Hence, the VAWT without ODGV covering, were simulated and validated via CFD and experimental fluid dynamics (EFD) data, respectively in the first step. Indeed, grid and time step independency test as well as the effect of domain size, have been conducted and a suitable agreement was found based on comparison of the CFD and EFD results. In the next step, the VAWT was shrouded by ODGV cover and the whole system was simulated for 52 angles of the ODGV in four different tip speed ratios (TSR), to investigate the impact of guide vanes angles on the VAWT performance. Results of this study indicated that output power of the VAWT with $\alpha = 20^\circ$ and $\beta = 55^\circ$ ODGV guide vanes, was improved 40.9%, 36.5%, 35.3% and 33.2%, respectively in four different TSR including 0.745, 1.091, 1.901 and 2.53.

1. Introduction

Nowadays, renewable energy sources like solar and wind energy are widely applied to generate electricity and other energy barriers. Using the innovative design play an important role to harvest more energy from different sources [1]. Among the renewable energy resources, wind energy is one of the most promising renewable energy sources and is widely employed to generate electrical power for different areas. Kinetic energy of the wind is captured by wind turbines and calculated by multiplying air flow speed ($v$ (m/s)) and half of air density ($\rho$ (kg/m$^3$)). Typically, wind turbines are divided into two main types, vertical axis wind turbine (VAWT) and horizontal axis wind turbines (HAWT). Among these two types, HAWT is more efficient and employed to produce electrical power in large scale. However, it has some drawbacks especially in the urban areas.

Regarding the requirements of HAWT such as sustained wind velocity and yawing mechanism, VAWTs are more efficient in complex urban terrains in harnessing the wind power. Because of the lower noise emission and construction cost of the VAWTs, it is suitable for urban areas [2–4], however, VAWT has some disadvantages such as lower performance compare with horizontal turbines. To overcome this drawback, Chong et al. [5] introduced an innovative idea named Omni-direction-guide-vane (ODGV) to improve the performance of the VAWT. Indeed, ODGV could be deployed even in weak low wind speed and turbulent conditions commonly found in urban areas where conventional VAWT are not suitable. It is also capable to accelerate with on-coming wind to improve its energy output and starting characteristic of the wind turbine. In general, HAWT and VAWT have differences and that related specifications of these wind turbine types are listed in Table 1.

A review of the past researches indicate that experimental studies have been conducted as a common solution to determine the performances of the novel wind turbine design [6,7]. Furthermore, different methods, taking into considerations cost and time of experimental studies, have been employed to simulate the flow behavior and performance of the vertical axis turbines such as blade-element models [8], vortex methods [9], two-dimensional (2D) models using CFD [10,11] and three dimensional (3D) CFD simulations [12–14]. As an example, Wekesa et al. [10] applied the CFD numerical technique to investigate aerodynamic performance of the VAWT and specifications of the flow. The authors employed an authenticated CFD model and stable wind simulations at two different wind speeds, to forecast $C_P$ for turbine. As well, a set of numerical simulations were done using united 2D CFD code to investigate the aerodynamic performance of a novel
Variations of the torque and power coefficient, was characterized by Lee and Lim [13] to evaluate the best shape of the tower cowling. Then, the optimum specifications of the rotor were achieved based on optimum specifications of tower cowling. In this simulation, optimal parameters of the new component (cowling tower) were evaluated in the first step and the rotor parameters were set as constant. In this simulation, optimal parameters of the new component (cowling tower) were evaluated in the first step and the rotor parameters were set as constant. In this simulation, the efficiency ratios and pitch angles, were scrutinized in that study. The performance of the new VAWT design is similar to the Wekesa simulation [10]. Yao also has not considered some characteristic of blades (i.e. thickness) were not taken into consideration [11], and these parameters were taken as constant. In this simulation, optimal parameters of the new component (cowling tower) were evaluated in the first step and the rotor parameters were set as constant. Then, the optimum specifications of the rotor were achieved based on optimum specifications of tower cowling.

The 3D CFD simulation, performance of a Darrieus VAWT was characterized by Lee and Lim [13] to evaluate the best shape of this turbine. Therefore, variations of the torque and Cp based on shape characteristics including chord length, rotor diameter, thickness ratios and pitch angles, were scrutinized in this study. The rotational impact of the blades was taken into consideration by means of a sliding mesh procedure; besides applying the Reynolds-averaged Navier-Stokes (RANS) formulas to investigate flow variations in this study. In addition, experimental study was conducted by using an open boundary layer wind tunnel and the experimental results were compared with CFD simulation outputs. This comparison indicated that the discrepancy between experimental and CFD results are less than 5%. In the same context, a three bladed VAWT was simulated via 3D CFD to propose aerodynamic characteristics around the blades, in two different TSR (1.52 and 2.5). Similar to Lee’s and Lim [13] research, RANS equations were applied in this research and experimental data were validated by this simulation. RANS equations, which are related to the Reynolds number, are one of the most suitable approaches to simulate fluids (laminar and turbulent) [16]. On the other hand, CFD computational modeling has been applied widely to analyze the multifaceted flows for different areas and applications like helicopters [17] and supersonic jet [18].

In terms of application of guide vane for wind turbines, Takao et al. [19] presented the effect of guide vane on the performance of VAWT performance in a conference paper. The mentioned guide vane that has been used in that study was not optimized and an experimental study has been conducted in a common wind tunnel. The results of that study indicated that the Cp did not depend on the distance between the guide vanes. On the other hand, Nobile et al. [20] have conducted a 2D CFD analysis to determine mesh, turbulence, and scale of time step, for a augmented VAWT. The results of that study showed that the Cp and Cm were not dependent on incident wind speed that has been taken into account.

In the present research, a 3D CFD study was performed in order to predict the power output of the VAWT by changing the ODGV angles, and results of the VAWT CFD simulation were compared with experimental data. In order to select the most accurate ODGV angles, all CFD steps were verified via grid and time step independency test and various turbulence models.

2. Numerical simulation

In the area of numerical simulation, ANSYS Fluent software is commonly employed in industry and cutting-edge research due to the extensive range of physical modeling methods, accurate numerical results and time effective solution. In this study, a three-dimensional transient unsteady CFD simulation was also carried out by ANSYS Fluent 15 (commercial software) to simulate the VAWT and ODGV performance.

2.1. Turbine geometry

A five straight bladed VAWT with identical airfoil shapes was considered in this study. Fig. 1 indicates a schematic diagram of this wind turbine.

As can be seen in Fig. 1, this VAWT consists of two supporting arms and a shaft in the center of the turbine. The specification of this turbine is outlined in Table 2.

2.2. Geometry of the ODGV

The basic issues of novel ODGV design are in full explained in previous studies [5,21], accordingly, the ODGV consists of four sets of double guide vanes as illustrated in Fig. 2.

| Table 1 |
| Comparison of the different features in the two main types of wind turbine. |
| Turbine feature | VAWT | HAWT |
| Power coefficient (Cp) | Low | High |
| Aerodynamic efficiency | Low | High |
| Self-starting | Yes | Yes |
| Noise emission | Low | High |
| Yaw control | Yes | No |
| Dependence from wind direction | No | Yes |
| Capability of harnessing gusty wind | Yes | Poor |

Darius VAWT [15]. Based on the results of this study, Cp of this innovative design improved by about 15% compared to conventional VAWT. In addition, a 2D CFD simulation was conducted by Yao et al. [11] to validate the mechanical performance of a novel VAWT with a tower cowling and found that the mechanical performance of the new VAWT design is similar to the Wekesa simulation [10].
Table 3 summarizes the main specifications of the considered ODGV employed as a power augmentation in this study.

Key point of this study is first and second angles of the guide vanes as shown by Fig. 3.

As can be calculated from Fig. 3, the maximum figure for $\beta$ is considered as high as $(60^\circ)$ and the minimum value of $\alpha$ is $(-20^\circ)$.

2.3. Operation principles and performance parameters

2.3.1. Governing equation

As can be seen in previous studies, the Navier–Stokes equation is a proper equation for 3D CFD studies [12,13]. In this study, finite-volume was applied as the discretization method to govern the Navier–Stokes equation. The time-averaged RANS for incompressible fluids are as shown in Eqs. (1) and (2).

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0$$ (1)

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + V \frac{\partial^2 \overline{u}_i}{\partial x_j^2} - \frac{\partial \overline{u}_j}{\partial x_i} + f_i$$ (2)

In velocity component, $\overline{u}_i$ and $\partial \overline{u}_i$, represent the mean and fluctuating part respectively. In addition, $\rho$ is the density, $p$ is the mean pressure, $f_i$ signifies the body force and $V$ is the viscosity. In addition to these, Reynolds stresses ($\rho \overline{u} \overline{u}$) are also needed to be modeled, which is a part of the total stress tensor in a fluid, it can be calculated by averaging the Navier–Stokes equations to account for turbulent fluctuations in fluid momentum.

2.3.2. Key performance parameters

Performance of the VAWT can be altered based on the various tip-speed ratios which are abbreviated as the TSR.

$$\text{TSR} = \frac{\text{Tip speed}}{\text{Wind speed}} = \frac{\omega R}{U}$$ (3)

Tip-speed ratio (TSR) of this study varies between 0.4 and 3 for the rotor angular velocity ($\omega$) 9.6 rad/s and 72 rad/s respectively. Additionally, Reynolds number can be obtained as follow:

$$Re = \frac{cUIF}{v}$$ (4)

where $v$ represents the air kinematic viscosity at 20 °C, $c$ is the airfoil chord, and $UIF$ is the total velocity at the interface which can be defined in the following equation:

$$UIF(\theta) = U^2 + \omega^2 R^2 + 2\omega R U \cos \theta$$ (5)
where $R_e$ is the rotating domain radius and $\theta$ is the angular coordinate that varies from 0 to 360 in one rotation of the turbine. In all range of the TSR, the Reynolds number alters between $4.7 \times 10^4$ and $2.5 \times 10^5$ which is identified as a low Reynolds regime.

The $C_p$ is a ratio of the power which produced by the wind rotor to the power available at a specific wind speed. The $C_p$ and $C_m$ are usually employed to analyze the results and they are manifested by Eqs. (6) and (7).

$$C_p = \frac{\text{Moment}}{\frac{1}{2} \rho A V^2}$$  \hspace{1cm} (6)

$$C_m = \frac{\text{Moment}}{0.5 \rho V^2 A R}$$  \hspace{1cm} (7)

where $\rho$, $A$, and $V$ represents the air density, swept area of the turbine and the inlet velocity. In addition, “Moment” is calculated from CFD simulation or experimental data.

2.4. Domain and boundary conditions

Boundary conditions of the CFD simulation in all cases include VAWT and ODGV are listed in Table 4, while inlet velocity is assigned as 6 m/s for all cases.

In order to separate the rotating and fixed parts of the domain, two different zones including rotating and stationary zones have been selected. Accordingly, VAWT is taken as a rotating zone and other parts are in the stationary zone (in Table 5). The connection between these two zones is considered by interface boundary condition, to ensure that the continuity in the flow field is established. In fact flow is not in line with the mesh in most of the time, and all solution variables are solved via second order discretization [22]. The simulation computational conditions are tabulated in Table 6.

2.4.1. Domain size location study

The domain size was studied to scrutinize the wake development after wind turbine to avoid the blockage phenomenon on the CFD simulation. Findings of this study show that the distance of the walls (heights and length of domain) can significantly affect the performance prediction of the VAWT. This impact is also mentioned by other researchers [23,24]. Overall, 36 simulations were carried out for each side wall distance and the domain length, outputs are illustrated in Fig. 4(a) and (b).

As can be seen in Fig. 4(a), the side wall distance of less than 12D makes the blockage effect in CFD simulation and leads to inaccurate prediction of the power output in VAWT. There is no difference in simulation results between 12D and 15D, so 12D is selected as the most optimum length taking the simulation time into account. Effect of the length of this domain is illustrated in Fig. 4 (b), which shows that 30D and 40D have better agreement with experimental results. There is a very small amount of error percentage (1%) between these two observed lengths. Furthermore, heights error for domain length occurred in 5D when the TSR is 3. Based on the comparison of the results in this part, the domain size is selected to be 12D height for side walls distance and 30D for domain length (in Fig. 5). Additionally, the wind turbine is located at 10D from inlet and 4D of the width of the domain.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Boundary condition in domain.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>Boundary condition</td>
</tr>
<tr>
<td>Inlet</td>
<td>Velocity</td>
</tr>
<tr>
<td>Outlet</td>
<td>Pressure</td>
</tr>
<tr>
<td>Turbine</td>
<td>Wall</td>
</tr>
</tbody>
</table>

2.5. Turbulence modeling approach

The $k$–$\omega$ – SST model [25], which is a very common and proper turbulent model in VAWT simulation [5,20,21,23–26], was employed in the present study. The regime of the system (low Reynolds number) is laminar, based on previous studies, $k$–$\varepsilon$ and Spalart–Allmaras model cannot capture and predict the flow development, especially in laminar separation bubble [12,27]. Therefore, the $k$–$\omega$ – SST model can be used as a low Reynolds turbulence model without any extra damping functions. Furthermore, this model is capable of showing very good prediction of the turbulence in adverse pressure gradients and separating flow. On the other hand, the shear stress transport (SST) formulation is formed by combining $k$–$\omega$ and $k$–$\varepsilon$ models. This structure helps SST method switch to the $k$–$\varepsilon$ model to avoids $k$–$\omega$ problem in inlet free–stream turbulence properties and uses the $k$–$\omega$ formulation in the inner parts of the boundary layer. Two mathematical formulas, including $k$ and $\omega$ equations, have been proposed in SST methods as below:

Equation $k$: \[
\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho ku_i) = \frac{\partial}{\partial x_i} \left( \Gamma_k \frac{\partial k}{\partial x_i} \right) + G_k - Y_k + S_k
\]  \hspace{1cm} (8)

Equation $\omega$: \[
\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i} \left( \Gamma_\omega \frac{\partial \omega}{\partial x_i} \right) + G_\omega - Y_\omega + S_\omega
\]  \hspace{1cm} (9)

where $\Gamma_k$ and $\Gamma_\omega$ express the active diffusivity of $k$ and $\omega$, as well $S_k$ and $S_\omega$ that are user-defined source terms. In addition, $G_k$ and $G_\omega$ show the turbulence kinetic energy generation due to mean velocity gradients and $\omega$, $Y_k$ and $Y_\omega$ also mean the dissipation of $k$ and $\omega$ due to turbulence.

2.6. Study of mesh impact on flow field

In order to study the influence of the mesh on the power output results, grid independency test (GIT) was carried out in this study and six types of mesh were conducted. Fig. 6 shows cut plane of mesh in domain, VAWT, ODGV and blade.

As can be seen in Fig. 6, around VAWT and specifically around the blades, meshes are highly denser to capture the complex flow structure with lower expected error. As mentioned, the $k$–$\omega$ – SST model was applied as a proper turbulence model in this study. The findings indicated that prediction of $C_p$ highly depends on the mesh density especially around the blades and vitiates less than 2%
between 10 and 20 million mesh elements. Results of the GIT simulation (at 6 (m/s) velocity and TSR = 1.091) are shown in the Fig. 7. Best result was reported when the number of elements is around ten million, because the time consumption in the ten million numbers of the elements has almost the same result compared with 20 million elements. This mesh has got 10 million elements in the whole domain and the numbers of the nods in different parts of the domain are listed in Table 7.

2.7. Study of time dependency

Time step is one of the most important parameters in the unsteady simulation, which should be small enough to ensure temporal \( C_p \) independence. In this study, the largest and smallest time step were set at \( 2\omega^{-1} \) (equivalent to two degree rotation) and \( 5\omega^{-1} \) respectively. Additionally, different cases were considered in TSR = 1.091 and \( V = 6\text{(m/s)} \) and the outputs of this study are reported in Fig. 8.

Simulation results between time steps 0.5 and 1 show that these two time steps have almost have the same results for \( C_m \). Differences between these three simulations and coefficient prediction are presented in Fig. 9.

There is negligible variation (less than 2%) of the \( C_p \) between \( 0.5\omega^{-1} \) and \( 1\omega^{-1} \) time-steps, and results show that using time step \( 2\omega^{-1} \) cannot capture the results accurately. This time step over predict the \( C_m \) especially at peak when azimuthal angle is around 60°. Moreover, after \( \theta = 200° \), huge variation of the results would occur, which causes 50% differences.

2.7.1. Validation of CFD model

Simulations are controlled and validated against the EFD, to verify the accuracy of the CFD model. Experimental test was performed between TSR 0.4 and 3, in Aeronautics Laboratory of the University Technology Malaysia (UTM) and nine different TSRs are considered to validate the CFD results. Dimensions of the wind tunnel are \((2\text{ m} \times 1.5\text{ m} \times 5.8\text{ m})\) for width, height and length respectively and wind speed can go up to of 80 m/s, besides torque, power was measured via a transducer. Comparison between the results of the experimental test and CFD simulation is shown in Fig. 10.

As can be seen in Fig. 10, the comparison shows a very good agreement between 3D simulation and EFD. In the range of TSR between 0.4 and 1.091, decrements of the \( C_p \) prediction is less than 9%. Clearly, the lowest error of the prediction \( C_p \) happened in low TSRs and the best result (5% error) is in TSR 1.091. Conversely, the worst result of 18.43% error, which has occurred in TSR 3. This inaccurate result occurred maybe because of some errors in the
experimental test at high rotational speeds and using the fully turbulent model. In addition, instability mechanisms in the stationary/rotating zones may be one of the reason which lead to these differences [28]. Turkyilmazoglu [29] employed linear stability theory to obtain the stability characteristics of the incompressible boundary layers.

Table 7
Mesh properties.

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of the elements</th>
</tr>
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<tbody>
<tr>
<td>VAWT</td>
<td>5,000,000</td>
</tr>
<tr>
<td>ODGV</td>
<td>3,000,000</td>
</tr>
<tr>
<td>Domain (without VAWT and ODGV)</td>
<td>2,000,000</td>
</tr>
</tbody>
</table>

Fig. 6. Cut plane of mesh in domain, VAWT, ODGV and blade.

Fig. 7. GIT simulation (at TSR = 1.091 and $V = 6 \text{ m/s}$).

Fig. 8. Time dependency study (at TSR = 1.091 and $V = 6 \text{ m/s}$).
3. Results and discussion

3.1. Influence of the guide vane angle

As mentioned earlier, the main goal of this study is to maximize the output power of VAWT by means of correcting guide vane angles. For this purpose, 52 design points have been considered to find the best guide vanes position and to achieve the highest performance of the VAWT. Table 8 shows the position and design points of the different ODGV angles.

In addition, this test was conducted in only four different TSR including 0.745, 1.091, 1.901, and 2.53 to save time and cost of the simulation, so every design point was simulated for the mentioned four different TSRs. Consequently, 208 simulations have been performed.

![Fig. 9. \(C_p\) variation in different time step (at TSR = 1.091 and \(V = 6\) m/s).](image)

![Fig. 10. Comparison of the CFD model and experimental data (at 0.4 < TSR < 3 and \(V = 6\) m/s).](image)

<table>
<thead>
<tr>
<th>Design point</th>
<th>(\beta)</th>
<th>(\alpha)</th>
<th>Design point</th>
<th>(\beta)</th>
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<td>20</td>
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<td>DP44</td>
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<td>50</td>
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</tbody>
</table>

![Fig. 11. \(C_p\) variations based on different angle (\(\beta\) and \(\alpha\)) of the ODGV walls.](image)
been performed with 24 core work stations, that each core has 2 GB of ram to attain the convergence criteria of 10^{-4}. In this part, different results of the simulation are proposed by Figs. 11–15, and then these results are investigated to obtain the best ODGV cover based on best $C_T$ and $C_m$. Fig. 11 shows variations of the $C_T$ based on different ODGV angle ($\beta$ and $\alpha$) of walls. Moreover, variation of $C_T$ in various design points and TSRs are shown in Fig. 12.

As can be seen in Figs. 11 and 12, $C_T$ has changed significantly using various ODGV angle walls ($\beta$ and $\alpha$) at four different TSRs in VAWT. Accordingly, the main improvement of the $C_T$ happened when $\beta$ and $\alpha$ range are between (0° and 30°) and (0° and 60°) and, respectively, in all range of TSR. Conversely, negative effects occurred when $\beta$ and $\alpha$ ranges are between (0° and 40°) and (55° and 60°), respectively. As a result, the highest enhancement through the simulation, is achieved when $\beta$ and $\alpha$ are 20° and 55°, respectively, and $C_T$ development also occurred when $\alpha$ is between (55° and 60°) and $\beta$ is 55°. Furthermore, negative $\beta$ causes non proper effect in two larger tested TSRs (1.901, and 2.53),

$$\alpha=55, \beta=20$$

**Fig. 13.** Comparison of the $C_T$ with and without ODGV in four tested TSR.

$$\text{TSR}=1.091, \alpha=55, \beta=20$$

**Fig. 14.** ODGV impact on $C_m$ of the VAWT in various azimuth angles.
whereas suitable effects occurred when $\alpha$ range are $(-10^\circ$ and $0^\circ)$ for $\beta = -20$ and $(0$ and $10^\circ$) for $\beta = -10$. In addition, based on Fig. 12, impact of the ODGV is a bit higher in lower TSR, and maximum improvements are 40.9%, 36.5%, 35.3% and 33.2% for TSR 0.745, 1.091, 1.901 and 2.53 respectively, while $\alpha$ and $\beta$ are 55$^\circ$ and 20$^\circ$.

Briefly, based on previous figures, maximum output of the VAWT are captured when ODGV is in optimum position ($\beta = 20^\circ$ and $\alpha = 55^\circ$). Hence, comparison of the $C_p$ with and without ODGV in four considered TSRs, investigated in this study and illustrated in Fig. 13.

As can be seen in Fig. 13, maximum $C_p$ of the open and augmented rotor are 0.24 and 0.33, respectively, in TSR = 1.901. In all range of the TSRs, the simulated results also showed that ODGV can improve the $C_p$ more than 35% when $\beta = 20^\circ$ and $\alpha = 55^\circ$.

In terms of $C_m$, prediction of the $C_m$ through one rotation of the VAWT and comparison between one and five blades VAWT simulation results for open and augmented rotor are presented (for optimum ODGV angle and constant TSR) in Fig. 14.
As can be seen in Fig. 14, averages of the $C_m$ for open rotor and augmented rotor are 0.12 and 0.17, respectively (37.3% improvement in the $C_m$). Maximum $C_m$ of one blade open rotor is reported in azimuth angle $60\degree (\theta = 60\degree \beta = 176\degree \alpha = 55\degree)$, while maximum $C_m$ for augmented rotor happened in $\theta = 71\degree$. Significant improvement in $C_m$ is achieved when $\beta = 20\degree$ and $\alpha = 55\degree$ within $\theta = 137\degree - 182\degree$, however negative effect in $C_m$ made after $\theta = 200\degree$.

Furthermore, $C_m$ variations based on the different azimuth ($\theta$) and ODGV ($\beta$ and $\alpha$) angles, in one rotation and constant TSR are shown in Fig. 15.
Fig. 15 shows that significant improvement in terms of the magnitude of the velocity and angle of the inlet velocity is achieved when the azimuth angle is zero. Therefore, compared with the open rotor, $C_{m}$ starts to reach the higher position in three different angles of the augmented rotor, when $\theta = 0^\circ$. Farther, negative impact of the ODGV can be seen in these different three cases, when azimuth angle is between $105^\circ$ and $136^\circ$. Application of the ODGV with $(\beta = -20^\circ$ and $\alpha = 40^\circ)$ and $(\beta = 20^\circ$ and $\alpha = 55^\circ)$ also helps to improve the torque generation in VAWT, when azimuth angle is between $136^\circ$ and $180^\circ$. Whilst, ODGV with $(\beta = -20^\circ$ and $\alpha = 40^\circ)$ has negative effect on lower azimuth angles. In conclusion, the ODGV with $(\beta = 20^\circ$ and $\alpha = 55^\circ)$, is the best option to improve the torque generation in VAWT. These results can also be validated by velocity vectors explained in the following section.

3.2. Velocity vectors

The inlet velocity to the VAWT is usually enhanced to higher amount, so the velocity of the wind streamlines can be investigated to compare fluids around VAWT with and without augmented ODGV cover. Fig. 16 shows the simulation of streamlines around the VAWT and ODGV guide vane. Based on Fig. 16, inlet velocity and angle magnitude have been considerably enhanced by means of the ODGV cover in the optimal ODGV position. Furthermore, the blade position and guide vane schematic is shown in $\theta = 55^\circ$ by Fig. 17.

Further, velocity vectors in two different locations of the VAWT blades ($\theta = 0^\circ$ and $\theta = 120^\circ$) where three different positions compared with open rotor in each location, are presented in Figs. 18 and 19.

According to Fig. 18, the inlet velocity has been improved by using ODGV cover in all three mentioned range of $\beta$ and $\alpha$.

Comparison between Fig. 19 (part B and D) and Fig. 15 shows that ODGV had positive effects on the velocity, and the outputs of the torque have been enhanced via ODGV. In addition, the main point of these types of figures can be seen in Fig. 19 (part C), where the negative influence of the ODGV is the most in comparison with other positions. Indeed, the role of ODGV is like a barrier for the inlet velocity and has negative impact on the torque.

4. Conclusion

In this study, numerical and experimental simulations were conducted on a Darrieus-type VAWT which has been shrouded by ODGV cover. The main goal of this study is to obtain the best position of the guide vane angles in order to achieve the maximum performance of the VAWT. For this purpose, grid dependency and time dependency studies were designed to determine the best and high quality mesh and time step. Effects of the Domain size were also investigated and the results showed that domain with the size of the a 12D height (side walls distance) and 30D for domain length (in Fig. 5) has no effect on $C_{p}$ prediction of VAWT. Furthermore, outputs of the simulation were compared with experimental data and results showed that good agreement is achieved in three-dimensional simulation (highest error is 18% in TSR = 3). The effects of the ODGV angles on the performance of the VAWT were investigated in this study and the results have been proposed in different Figures (Figs. 11–15). Additionally, 52 different arrangements of the first and second angles of the ODGV ($\beta$ and $\alpha$) were considered in four different TSRs, to obtain the best numerical simulation. In conclusion, the best simulation results were obtained for ODGV with $(\beta = 20^\circ$ and $\alpha = 55^\circ)$, which increased the $C_{p}$ of the VAWT by 40.9%, 36.5%, 33.5% and 32.2% when TSR is 0.745, 1.091, 1.901 and 2.53, respectively.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enconman.2016.03.034.

References


