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RENEWABLE ENERGY SOURCES

Effect of Blade Number on Performance of Drag Type Vertical Axis Wind Turbine[1]

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Abstract—The effect of blade number on performance of drag type vertical axis wind turbine (VAWT) is studied by Ansys numerical simulation, it involves 3-blade, 5-blade and 6-blade VAWTs. The optimized width of blade for each VAWT at maximum power efficiency is obtained, and simulation for the wind turbine with different number of blade is conducted for the VAWTs with turbine radius of 2 m at the inlet wind speed 8 m/s. By simulations, it gets the evolution curve of torque with respect to time, and the cyclical characteristics for these wind turbines. The results show that the maximum power efficiency and the stability of the wind turbine increase with the number of blade of the wind turbine, however the optimal d/D decreases with the number of blade of the wind turbine. The maximum power efficiencies are 20.44, 24.30 and 26.82% for 3-blade, 5-blade and 6-blade wind turbines, and the correspondingly optimal d/D are 0.66, 0.40 and 0.35, respectively. While the optimal rotational rate of turbine decreases with blade number.

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1. INTRODUCTION

Renewable energy includes wind, solar, biomass, hydro and geothermal energy. Wind turbine is the main tool for the use of wind energy, through which wind energy can be converted into mechanical energy, and then converted into other types of energy, such as electricity, heat, etc. So the design of wind turbine is the most important part of the study for wind energy utilization. Vertical wind vertical axis wind turbine (VAWT) and the parallel horizontal axis wind turbines (HAWT) are two types of wind turbine.VAWT can be clarified into two main types, i.e., drag-type and lift-type [1]. Drag-type includes Savonius type turbine, wind cup type, flat type and Madras type.

It was studied the effect of tip speed ratio on power efficiency of the Darrieus-type wind turbines [2], it showed that the optimized tip speed ratio is 4. Li et al analyzed the advantages and disadvantages of VAWT and HAWT comparatively [3], it found that the efficiency of VAWT could be improved by changing blade geometry.

The performance of lift-type VAWT was studied numerically for a 3-blades turbine with 8 air concentrated stators around the wind turbine introduced simultaneously [4]. It showed that such stators raise the power and torque coefficients by around 30–35% as compared to the stator-free case.

It was used CFD software to analyze the aerodynamic performance of a new type of vertical axis wind turbine (VAWT). The new turbine is with crescent-shaped blade airfoil, the diameter of the turbine is 1.6 m with 8 blades [5]. In the simulation, the effects of some key operational parameters, such as wind speed, rotation rate, yaw angle and blade pitch angle, etc., are studied. The result shows that the turbulence modeling technique is sufficient to evaluate the performance of the turbine in the definite operating conditions and can give proper predictions.

It was studied the performance of Savonius-type vertical axis wind turbines (VAWT) with varying overlap ratios and shift angles experimentally [6]. Each wind turbine was tested under 4 inlet wind speeds. The results show that a higher overlap ratio has a higher effect on the starting characteristics of the Savonius wind turbine, and the phase shift angle could change its power efficiency. The highest power coefficient is about 18–20% for inlet wind speed 6 m/s at the phase shift angle 15°.

In reference [1], the dynamic characteristics of 5-blade drag-type VAWT for the wind speed from 6.0 to 10.0 m/s is studied, it shows that the critical length of the simulated region and the optimized rotor's rate increase with the inlet wind speed linearly within the scope of the simulation; the power efficiency of 5-blade drag type VAWT increases with the inlet wind speed exponentially.

It can be seen from above analysis that the power coefficient of wind turbine depends upon many factors,

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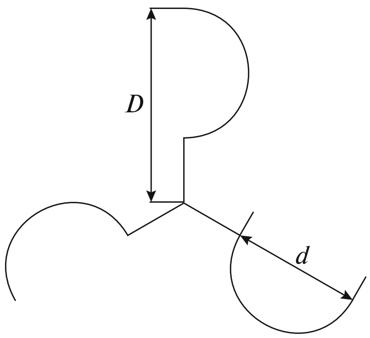

Fig. 1. Schematic view of 3-blade wind turbine.

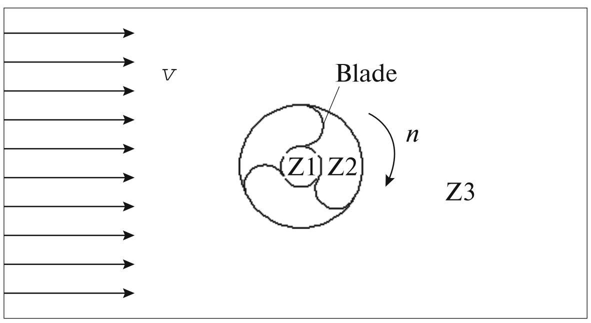

Fig. 2. Simplified two-dimensional flow model for 3-blade turbine.

such as the vane shape, the number and width of blade, etc. Here in this paper the effect of blade number on the performance of drag-typed VAWT at optimized blade width is conducted by numerical simulation.

2. GEOMETRIC PARAMETERS OF BLADE

The shape of drag-type blade VAWT could be in a semi-cylindrical, semi-spherical, spiral, conical forms and so on. The helical and conical blade is complex in machining and inconvenient in long-distance transportation. While the semi-cylindrical blade possesses advantages of larger effective area and easier molding process, which is also widely used in engineering as compared to others [7–9]. Therefore, the analysis in this paper is focused on this type of semi-cylindrical shaped blade, and the simulation is devoted to the effect of blade number on power efficiency of turbine.

The schematic view of 3-blade wind turbine is shown in Fig. 1, in which D is the wheel radius of the wind turbine, which is invariable in the following calculation; d is the width of a wind turbine blade, which varies in the simulations.

3. CALCULATION MODEL

3.1. Two-Dimensional Flow Model

Appropriate simplified model should be considered so as to simplify the computation and keep a suitable accuracy of the calculation.

Since the rotation of the turbine blades belongs to low-speed one, the lateral flow field at any blade height position is almost the same for the same cross-section blade, flow velocity along the direction of the blade height is approximately zero according to the geometric features and operating characteristics of straight blade wind turbine, so the simulation can be reasonable to be simplified as a two-dimensional one so as to reduce the amount of computation [1, 10].

Figure 2 is a simplified 2-dimensional flow model for 3-blade turbine. The geometric parameters of the VAWT are as follows: the rotation radius D of the turbine is 2 m, the blade height is 1 m, and the simulation area is 140 × 70 m [1, 10]. The inlet wind is from the left into the flow field, and flows out from the right edge, wind turbine is at the position 20 m away from the front; the turbine rotates in clockwise direction.

Because the entire simulation process of windmill is dynamic [1, 10], it needs to consider the rotating regional area and the static regional area in the calculation separately. In Fig. 2, the calculation region is divided into 3 parts, i.e., Z1, Z2 and Z3. Z1 is central and static area inside the circular rotating blade, its radius changes with the specific value of blade width, the formula for setting this radius is 2.2 –0.4 m – blade width; Z2 is circular dynamic area with a outer radius of 2.2 m, including the rotating blades; Z3 is static rectangular area excluding Z1 and Z2, the scale is 70 × 140 m.

3.2. Controlling Equations

SST k–ω turbulence model is selected for this research, which is to be amended and improved on the basis of k–ω turbulence model; it has advantages in studying the aerodynamics around the wind turbine blade. It is more convenient to simulate the near-wall boundary layer and free shear flows at low Reynolds numbers, and also convenient to be used to simulate the boundary layer separation under adverse pressure gradient, and the results are comparatively higher accuracy additionally [11]. SST k–ω turbulence model combines the features of the two types of two-equation models in both near wall and far-field, i.e., k–ω equation model at near the wall and k–ε equation model at far-field; it gives good predictions for the flow field of separated flow, and therefore exhibits certain advantages in dealing with rotating machinery problem.

3.3. Calculations

Once the turbulence model is determined, the most important thing is to solve the equations in the calculation process numerically. The finite volume method is selected in this study [12], which concerns the division of the computing grid so that the control body doesn't overlap each other around each mesh node; it derives discrete equation group by integrating the differential equations for each control body. The PISO algorithm is employed to solve the discrete equation numerically, a multi – step correction is involved at each calculation step; it derives an accurate pressure equation from continuous and discrete equations, and then the velocity field is obtained from the pressure field, the calculation continues repeatedly until the convergence velocity field and pressure field are obtained [13]. In addition, the sliding mesh technique is chosen for rotational flow field simulation of the two-dimensional flow field in the VAWT, this technique is the most accurate method in solving flow field of multi-body problem directly. Meshed region rotates as a whole with time, the mesh nodes at both sides can not be overlapped, while remaining the flux equal at the interface, it enables the region-coupling problem to be solved [14], the detail of the grid division can be found in [10].

3.4. Boundary Conditions

In this paper, the boundary conditions are set as follows:

(1) The wind from infinite position is set to be as the initial value of the entrance, i.e., the inlet wind velocity (velocity inlet) is chosen for the entrance boundary conditions.

(2) The free outflow (outflow) is set for the outlet boundary condition. In this case, the disturbance of the air flow due to wind turbine wake could be observed.

(3) The initial symmetry boundary (symmetry) is set down for both sides of the border; while the flow field in the dynamic area of blade rotates together with the ring-shaped region, without sliding relative to the surrounding fluid, so setting at the blade surface boundary is wall (wall) condition.

(4) The interface boundary conditions are set for the interfaces of the regions, since the numerical results of the flow field need exchange mutually to get interpolation at the interface.

3.5. Treatment of the Calculated Results

Since only a part of wind energy can be absorbed by wind turbine, which is converted into mechanical energy, so the power efficiency of wind energy is introduced to measure wind capacity of turbine to absorb the kinetic energy from the wind, the greater the power efficiency the higher the conversion of the wind energy into mechanical energy. The definition of power efficiency of wind energy into mechanical energy is as follows:

$$C_p = P\Big/\left(\frac{1}{2}\rho S v^3\right), \quad (1)$$

where P is the actual power of the wind turbine, ρ is the air density, S is the swept area of the wind turbine blades, and v is the wind speed.

The wind power efficiency C_p is an important parameter to assess the aerodynamic performance of wind turbine, and it might change with the variations of wind speed and rotational rate of turbine. After a lot of simulation trial, the time step is chosen as 0.02 s, a total of 4000 steps, i.e., the simulation is conducted in 80s. Since the output from computer is a dimensionless quantity, a coefficient is need to be transferred from the instantaneous torque C_m into the actual moment M. Figure 3 shows variation of the instantaneous torque C_m with time. The torque coefficient changes periodically with time, it achieves to a steady state after some cycles. One could take the average in one or two cycles in steady state as the final calculated value for the torque.

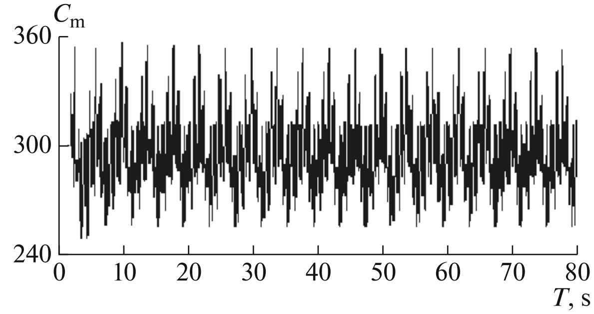

Fig. 3. Variation of moment coefficient with time.

The actual moment M can be obtained from the torque coefficient C_m through Eq. (2),

$$M = C_m C, \quad (2)$$

where C_m is the instantaneous torque with the unit of $N \cdot m$, and the coefficient $C = 0.6125$.

The actual power of wind turbine can be obtained through Eq. (3),

$$P = M 2\pi n/60, \quad (3)$$

where n is the rotational rate of turbine, in rpm. Then the power efficiency can be further calculated from the actual power of wind turbine, i.e.,

$$C_p = P\Big/\left(\frac{1}{2}\rho v^3 h D\right), \quad (4)$$

where h is the height of the turbine, D is the diameter of the turbine, and $\rho v^3 hD/2$ is power of inlet wind.

Table 1. Variation of power efficiency with blade width and rotation rate for 3-blade turbine (%)

n (rpm) \ d (m)	1.26	1.28	1.30	1.32	1.34
17	19.31	19.32	19.02	18.95	18.92
18	19.44	19.78	19.69	19.67	19.80
19	19.64	20.07	20.43	20.53	20.40
20	19.56	19.77	20.02	20.54	20.52
21	19.20	19.36	19.86	20.09	20.20

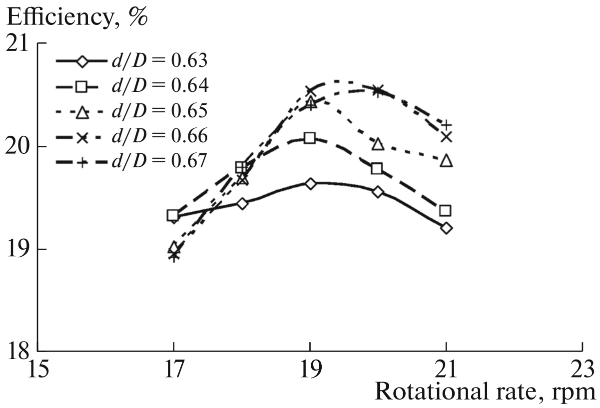

Fig. 4. Variation of power efficiency with rotation rate for 3-blade turbine at different d/D.

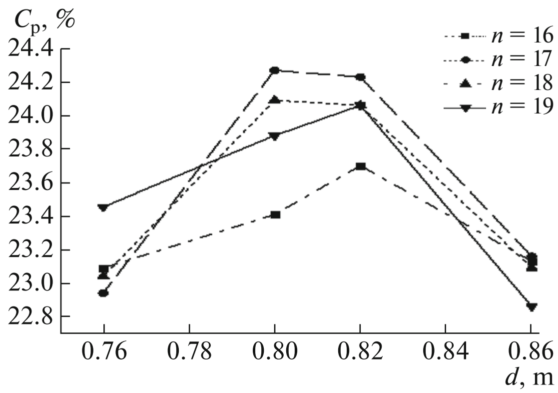

Fig. 5. Variation of power efficiency with blade width and rotation rate for 5-blade turbine.

4. CALCULATION RESULTS

4.1. Calculation Result and Analysis for a 3-Blade Wind Turbine Case

As to the case of 3-blade wind turbine, the width of blade d is set as 1.26, 1.28, 1.30, 1.32 and 1.34 m for the simulation, respectively. The turbine radius is fixed at $D = 2$ m. In addition, the rotational rate n of turbine is set as 17, 18, 19, 20 and 21 rpm, respectively, for the inlet wind speed of 8 m/s. The result of power efficiency is shown in Table 1 for the above cases.

Table 1 shows that the maximum power efficiency for the 3-blade turbine is 20.54% at the inlet wind speed 8 m/s, it corresponds to the rotational rate of 20 rpm and the blade width of 1.32 m for this 3-blade turbine.

Figure 4 shows the variation of power efficiency with rotation rate for 3-blade turbine at different ratio of blade width d to the wheel radius of the wind turbine D. Figure 4 indicates that the most highest power efficiency occurs at d/D about being 0.66 to 0.67 for the 3-blade turbine.

Analyzing the results of power efficiency in Table 1 and Fig. 4, it can be found that the power efficiency varies with width of the blade and rotation rate of turbine, the optimal value of blade width might correspond to the greatest area for sweeping the wind field without the blades shading each other, the optimal value of rotation rate of turbine might correspond to the optimal rotation rate for adsorbing wind energy.

4.2. Results of the 5-Blade Wind Turbine

For the 5-blade wind turbine, the turbine radius is fixed at $D = 2$ m. The blade width d takes 0.76, 0.80, 0.82 and 0.86 m, etc, to simulate the effect of blade width and rotation rate on power efficiency. The inlet wind speed is 8 m/s. Four rotation rates for n, 16, 17, 18 and 19 rpm are selected. The power efficiency is obtained and shown in Fig. 5. It can be seen from Fig. 5 that the maximum power efficiency for the 5-blade turbine is 24.30%, it corresponds to the rotational rate of 17 rpm and the blade width d of 0.80 m (i.e., $d/D = 0.40$) for the 5-blade turbine at the inlet wind speed 8 m/s.

4.3. Results of the 6-Blade Wind Turbine

For 6-blade wind turbine, the turbine radius is fixed at $D = 2$ m. Six blade widths for d, 0.60, 0.66, 0.68, 0.70 and 0.72 m are selected for the simulation, the inlet wind speed is 8 m/s. The results are shown in Table 2.

From Table 2, it can be seen that the maximum power efficiency for the 6-blade turbine is 26.82%, it corresponds to the rotational rate n of 18 rpm and the blade width d of 0.68 ~ 0.70 m (i.e. $d/D = 0.34$ ~ 0.35) for the 6-blade turbine at the inlet wind speed 8 m/s.

Table 2. Variation of power efficiency with blade width and rotation rate for 6-blade turbine (%)

n (rpm) \ d (m)	0.60	0.66	0.68	0.70	0.72
16	23.11	24.45	26.47	26.51	24.89
17	23.57	24.73	26.51	26.64	25.07
18	23.69	24.64	26.82	26.82	25.82
19	23.64	24.48	26.59	26.34	25.48
20	23.39	24.18	26.18	26.16	25.20

4.4. Comparison of Wind Turbine Performance with Different Blade Number

Above results indicate that the optimal blade width for each type of wind turbine varies with blade number. From the data above, the optimal blade width d is 1.32 m for 3-blade wind turbine at inlet wind speed 8 m/s, the corresponding power efficiency is 20.44%; the optimal blade width d is 0.80 m for 5-bladed wind turbine, the corresponding power efficiency is 24.30%; the optimal blade width d is 0.70 m for 6-blade wind

Table 3. Relative standard error of moment for three wind turbines

Number of blades	3	5	6
Averaged Torque (N m)	122.48	171.31	178.51
Relative standard error (%)	13.42	6.82	6.55

turbine, the corresponding power efficiency is 26.81%. This indicates that the optimal power efficiency of wind turbine increases and optimum blade width decreases with the number of blades for the same wind turbine and inlet wind speed.

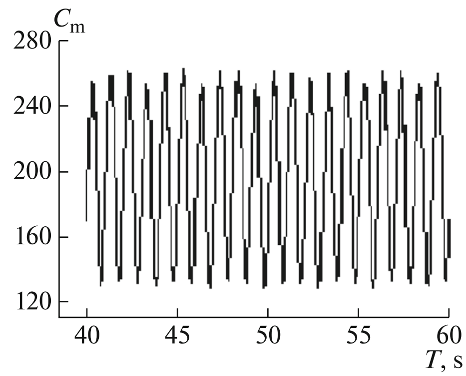

Fig. 6. Variation of steady torque coefficient–time for 3-blade wind turbine.

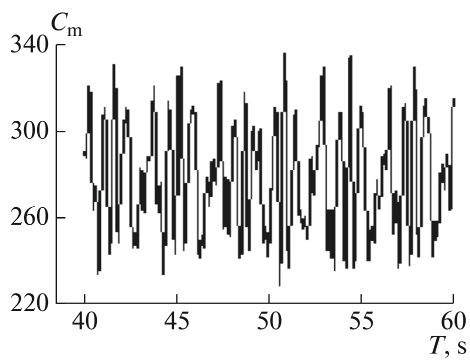

Fig. 7. Variation of steady torque coefficient–time for 5-blade wind turbine

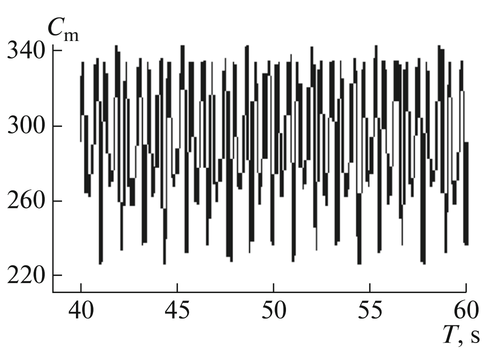

Fig. 8. Variation of steady torque coefficient–time for 6-blade wind turbine.

In addition, for the same wind turbine (turbine radius of 2 m) and inlet wind speed 8 m/s, the tend of optimal rotation rate deceases with the number of blades for the same wind turbine. This is helpful to the design of windmill.

Figures 6–8 display the variations of steady torque with time after reaching to steady state for the 3-blade turbine, 5-blade turbine and 6-blade turbine, respectively. Figure 6 is for the 3-blade wind turbine at a wind speed of 8m/s, rotation rate of 20 rpm and blade width 1.32 m. Figure 7 indicates that the curve changes periodically with period of about 3.24 s; Fig. 7 is for the 5-blade wind turbine at a wind speed of 8m/s, rotation rate of 17 rpm and blade width 0.80 m. Figure 7 indicates that the curve changes periodically with period of about 3.18 s; Fig. 8 is for the 6-blade wind turbine at a wind speed of 8m/s, rotation rate of 18 rpm and blade width 0.70 m. Figure 8 indicates that the curve changes periodically with period of about 2.98 s. In addition, Figs. 6, 7 and 8 show that the averaged torque of the corresponding wind turbine increases with number of blades for the same turbine radius and inlet wind speed. The values of torque for the above three wind turbines are, 199.97, 279.69 and 291.44, respectively. By using Eq. (2), it gives the values of the averaged moment for the above three wind turbines, and the corresponding values are 122.48, 171.31 and 178.51 N m, respectively. By using the relative standard deviation analysis, the relative errors of the instant moment with respect to the averaged one can be obtained, which is shown in Table 3 as well. Table 3 shows that the relative standard deviation decreases with the number of blades, which indicates that the stability of the wind turbine increases with the number of blades, this is helpful to the design of windmill.

5. CONCLUSIONS

Through the above analysis for wind turbine with the same turbine radius (2 m) and the inlet wind speed 8 m/s, it concludes:

(1) The optimal d/D varies with blade number of wind turbine.

(2) The optimal d/D for the 3-blade wind turbine is 0.66–0.67; its optimum power efficiency is 20.44%, the corresponding rotation rate is 20 rpm.

(3) The optimal d/D for the 5-blade wind turbine is 0.40, its optimum power efficiency is 24.30%, and the corresponding rotation rate is 17 rpm.

(4) The optimal d/D for the 6-blade wind turbine is 0.34 ~ 0.35, its optimum power efficiency is 26.82%, and the corresponding rotation rate is 18 rpm.

(5) The stability of the wind turbine and the optimum power efficiency increase with the number of blades for turbine with the same radius and the inlet wind speed.

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