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Design of wind turbines with shroud and lobed ejectors for efficient utilization of low-grade wind energy

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A B S T R A C T

A one stage horizontal axis wind turbine with a shroud and lobed ejector was designed for the efficient utilization of low-grade wind energy by taking into consideration the effect of the shroud and lobed ejector. The performance of the proposed wind turbine was evaluated using the commercial software CFX. Simulation results indicated that the wind energy utilization efficiency of the proposed wind turbine increased to 66–73% at a low wind speeds ranging from 2 to 6 m/s. It was found that the complex vortices in the flow field outside the wind turbine included stream-wise vortices, normal vortices behind the lobes, and three large scale vortex rings. The shroud and lobed ejector structure in the back of the proposed wind turbine produced such an effect that the pressure at the wind turbine exit was reduced so that the turbine power output was increased by 240%. It is therefore concluded that the proposed wind turbine can be used for efficient utilization of low-grade wind energy.

1. Introduction

Wind energy is a form of renewable energy, which has not only huge reserves, but also a world-wide distribution [1–6]. It is therefore of great significance to design wind turbines for efficient utilization of clean energy for the 21st century. Efficient 30–45% horizontal and vertical axis wind turbines [7–9] with power output ranging from hundreds of kilowatts to megawatts have been designed for wind farms with wind speeds of more than 6 m/s in Europe and the United States. Much work has been done in recent years on the design and development of traditional wind turbines to improve their performance. For example, Shen et al. [10] investigated the edge and flap-wise moments on horizontal axis wind turbine blade roots in wind shear conditions, and pointed out that IPC (individual pitch control) could be used to improve the rotor yaw and tilt moments, to stabilize the power output, and to prolong the lifespan of wind rotor components. Qamar et al. [11] presented the DNS (direct numerical simulation) to research a full stationary wind-turbine blade at Re = 10,000 and zero-incidence. Their work showed the vortice at the root, middle and tip of the blade. Jeong et al. [12] investigated the wake impacts in the aerodynamic and aeroelastic behaviors of a MW-sized horizontal axis wind turbine blade in wind shear and turbulent flow conditions based on using BEM theory and the free wake model. Kishinami [13], Sedaghat [14] and Rocha [15] designed horizontal axis wind turbines using airfoils LS04, NACA44 and RISΦ and studied the aerodynamic performance, power coefficient and wake development in these horizontal axis wind turbines under different conditions. Raciti Castelli [16] and Mohamed [17] designed Darrieus vertical axis wind turbines with better performance using BEM (blade element momentum) theory, and numerically investigated the transient aerodynamic performance using RANS (Reynolds-averaged Navier-Stokes) equations. Nini et al. [18] used the over-set grid solver ROSITA to investigate the interaction between blades and tip vortices of the 3-dimensional Darrieus vertical axis wind turbine and the aerodynamic disturbances from the turbine shaft and the support arms. Tjiu W et al. [19] pointed out that the VAWT (vertical axis wind turbine) had an advantage in the wind turbine design of 5 MW or more power due to gravity, but the efficiency of the horizontal axis wind turbine was higher than that of the vertical axis wind turbine at the design power below the 5 MW. Goldstein L [20] presented a novel concept of a tilted axis wind turbine with mid rotor power take off, and the wind turbine used a fraction of the material in place of the gearbox and the nacelle.

However, according to Betz theory, it is very difficult to have a further substantial increase in the efficiency of the above mentioned high-speed wind turbines, and the power output of a wind turbine and thus can be increased by increasing the size of a wind turbine.

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Nomenclature

D	diameter of one stage turbine (m)
u, v, w	component X, Y and Z of flow velocity (m/s)
V	flow velocity (m/s)
ρ	air density (kg/m^3)
P_t	power output of wind turbine (W)
A_r	rotor disc area (m^2)
Cp	wind energy utilization efficiency, $Cp = \frac{P_t}{\rho A_r U_0^2/2}$
ω_x	non-dimensional X vorticity, $\omega_x = \frac{D}{V_0}\left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)$
ω_y	non-dimensional Y vorticity, $\omega_y = \frac{D}{V_0}\left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right)$
ω_z	non-dimensional Z vorticity, $\omega_z = \frac{D}{V_0}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)$
ω_{xyz}	non-dimensional vorticity, $\omega_{xyz} = \sqrt{(\omega_x)^2 + (\omega_y)^2 + (\omega_z)^2}$
ω_n	non-dimensional Z normal vorticity, $\omega_n = \sqrt{(\omega_x)^2 + (\omega_y)^2}$
A, B, C	quadratic equation coefficient
K	ratio of velocity circulation at different locations to velocity circulation designed at the middle radius
r	radius of one stage turbine (m)
$c_{1u,r}$	circumferential velocity at each radius in axial clearance (m/s)
$c_{1a,r}$	axial velocity at each radius in axial clearance (m/s)
$\alpha_{1,r}$	absolute flow angle of stator vane in axial clearance (°)
$\beta_{1,r}$	relative flow angle at each radius in axial clearance (°)
u_r	circumferential velocity at each radius (m/s)
$c_{2a,r}$	axial velocity at each radius of rotor exit (m/s)
$c_{2u,r}$	circumferential relative velocity at each radius of rotor exit (m/s)
ω	angular velocity of a rotor (rad/s)
$\beta_{2,r}$	relative flow angle at each radius in rotor outlet (°)
$L2$	lobe width (m)
$L3$	lobe height (m)
$R4$	lobe chamfering radius (m)
θ	lobe angle (°)
α	outer lobe angle (°)
β	inner lobe angle (°)
$R1$	internal inlet radius (m)
$R2$	bypass inlet radius (m)
L	shroud endwall length of one stage turbine (m)
$L1$	mixer duct length (m)
$R3$	mixer duct outlet radius (m)
TP	total pressure (Pa)
P	static pressure (Pa)
A	cross section area (m^2)
η	turbine efficiency
ΔE	available kinetic energy (Pa)
ΔP	bypass flow tube mixing loss (Pa)
λ	ratio of bypass flow mixing loss to dynamic pressure
A_{out}	mixer duct outlet area of wind turbine (m^2)
a_2	ratio of rotor outlet area to mixer duct outlet area
a_3	ratio of the shroud outlet to and the mixer duct outlet area
$\dot{m}_1$, $\dot{m}_2$	massflow of inner passage and bypass of wind turbine (kg/s)
χ	ratio of $\dot{m}_1$ to $\dot{m}_2$
a_b	ratio of sum area A_b of any small flow tube with bypass in section b to A_{out}
P_s	local static pressure of experimental turbine (Pa)
P_{out}	static pressure at outlet of experimental turbine (Pa)
TP_{inlet}	total pressure at inlet of experimental turbine (Pa)
Cps	static pressure coefficient $Cps = \frac{P_s - P_{out}}{TP_{inlet} - P_{out}}$

Subscripts

0, 1, 2, 3, 4	inner passage section numerals, standing for the position of far field, turbine import, export, turbine expansion end export, lobe mixer export
21	parameters in section 2 transformed from parameters in section 1 in no loss condition
a, b, c	bypass section numeral, standing for position of bypass inlet, lobe bypass export, export of mixer duct
h, m, t	hub, middle, top of one stage turbine

The efficiency of a traditional wind turbine is only about 10–20% [8] under low wind speed operating conditions, so low wind speed power has not been efficiently utilized. In most areas of the world, wind speeds are less than 4 m/s for about 90% of the year, and therefore, a wind turbine designed for a wind speeds ranging from 8 to 15 m/s does not work efficiently at this low wind speed in these areas [21]. Low-grade wind energy with a wind speed of less than 6 m/s has a wide distribution and the design of an advanced wind turbine for efficient utilization of low-grade wind energy will facilitate the delivery of clean energy into individual households.

Some new concepts and ideas have been used to design wind turbines for efficient utilization of low-grade wind energy. For example, Jung [22] and Lee [23] investigated the aerodynamic performance of a counter-rotating wind turbine through experimental and numerical simulations, and pointed out that the maximum power coefficient of a counter-rotating rotor could reach as high as 0.5. Shen [24] pointed out that the power coefficient of the counter-rotating wind turbine was higher than that of a single rotor wind turbine at low wind speeds. Lampinen et al. [25] used the axial fan theory to design a horizontal-axis wind turbine and developed a wind turbine performance evaluation method. Mohamed [26] designed a lift-drag type wind turbine, and researched the self-starting performance of this kind of wind turbine using the RANS method and through experiments, and found that the wind turbine had a better self-starting performance and a lower power coefficient. Chong et al. [21] designed and developed a vertical axis wind turbine structure with a rainwater collection system. Allaei et al. [27] published the Invelox wind delivery system to capture nearly any free wind flow greater than 1 m/s, and to improve power output. Liu [28] developed a wing-in-ground effect dual-foil turbine for efficient utilization of wind and tidal energy. Ismail et al. [29] presented a RSA-based automated process to maximize the performance of VAWT blades by optimizing the configuration of a Gurney flap in combination with an inward dimple. Werle et al. [30,31] deduced the calculation formula for the standard momentum-balance-based model and pointed out that the wind power utilization coefficient of a duct/shroud turbine system could reach or exceed the Betz limit, but it is lower than the revised Betz limit because of the duct/shroud effect. Werle's research aroused great interest in the design of wind turbines. Toshimitsu et al. [32] investigated the wind turbines with a flanged-diffuser shroud in sinusoidally oscillating and fluctuating velocity flows and found that wind turbine performance depends on vortex structure and turbulence intensity through the PIV (particle image velocimetry) experiment. Kaiser et al. [33] studied a rim-driven multi-blade horizontal axis wind turbine using RANS