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A proposal and a theoretical analysis of a novel concept of a tilted-axis wind turbine

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ABSTRACT

A novel wind turbine is proposed with a downwind rotor, tilted upward. An external cable that is attached to the blades' center of force supports each rotor blade, and the tower is supported by guy wires at the top. The nacelle is eliminated and the main axle is replaced by power take off from an annular ribbon, rotating with the rotor; thus most large bending moments are eliminated and replaced by tensile and compressive loads. Further, the proposed wind turbine does not use a gearbox or a direct drive generator. The proposed system is structurally analyzed and compared with a conventional wind turbine. The comparison shows that manufacturing the proposed system may be 2.5 times less expensive than manufacturing a conventional wind turbine of the same power on land. The cost advantage promises to be even bigger offshore.

1. Introduction

Wind energy is still the most promising and widely used scalable renewable source of electrical energy, and it is likely to remain so, according to prognoses in Refs. [1,2] and in an up-to-date US government report [3]. Nevertheless, technological progress in the development of conventional wind turbines has slowed in recent decades. One attempt at a breakthrough was AWES (airborne wind energy systems), introduced by Miles Loyd [4]. Recently, some theoretical works ([5–7]) have shown that AWES can be significantly less expensive than conventional HAWT (horizontal axis wind turbines). The benefits are derived mostly from structural efficiency, rather than from tapping stronger winds at higher altitudes. Nevertheless, development of AWES has not yet brought a cost-efficient system, more because of underestimating the complexity of AWES development and under funding than because of any deficiency in the AWES concept itself. The work in this area continues, as can be seen, for example, from Ref. [8]. Among conventional wind turbine developments, Norsetek [9] wind turbine with a braced rotor deserves notice. Jamieson and Branney [10] have analyzed a hypothetical multi-rotor wind turbine. An attempt at a radically new shrouded wind turbine is INVELOX, reported by Allaei and Andreopoulos in Ref. [11]. The paper by Seamus Garvey [12] should be specially mentioned, as its methodology was used in preparation of this article. Jamieson [13] provided excellent coverage of many relevant subjects, including peripheral power take off, downwind rotors, structural analysis of wind turbines, guy wires (which are very helpful in vertical axis wind turbines), scalability, and costs. Nevertheless, HAWT remains the most cost efficient and the only widely used wind turbine type. This article proposes and analyzes an alternative: a novel structurally optimized tilted-axis wind turbine (STAWT), inspired by airborne wind energy systems.

One uncommon aspect of the proposed design is that the wind rotor is purposefully angled to the wind. The theory of a rotor with the axis, angled to the airflow, was first developed by Glauert in 1926 in Ref. [14]. Many theoretical, simulation, and experimental investigations have been conducted since then. Some of the latest examples are [15–17]. Two most important concerns of the angled rotor are a) power decrease and b) violation of symmetry in the horizontal plane because of the vertical tilt. [18] presents experimental data that amount of the captured power is proportional to the square of the cosine of the angle of the yaw error, at least in the relevant range of angles. This experimentally proven relation is used in this article.

Section 2 explains the STAWT concept. Section 3 presents structural analysis and comparison with HAWT both theoretically and on example of 2 MW wind turbine. Section 4 compares STAWT to HAWT economically. Section 5 discusses additional properties,

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Nomenclature

α	rotor tilt angle
β	tether angle to the horizon, larger or equal α
γ	angle to the horizon of the force, exerted by two tethers
δ	angle in Fig. 4
λ	tip ratio
σ	strength of material
ρ	density of air
A	sectional area
D, D_0	rotor diameter of STAWT and HAWT, respectively
d	blade root diameter
I	second area moment
L	blade length
M	number of generators
N	number of blades
P, P_0	nominal power of STAWT and HAWT, respectively
h	height of the tower
F	acting force
$\mathbf{F_B}$, $\mathbf{F_{B0}}$	aerodynamic force on a blade of STAWT and HAWT, respectively
$\mathbf{F_T}$, $\mathbf{F_{B0}}$	aerodynamic force on the tower top of STAWT and HAWT, respectively
F_R	tangential force exerted on the ribbon by all blades
F_{rb}	tangential force exerted on the ribbon by a single blade
R	reacting force
$\mathbf{R_b}$	reaction force of a blade, longitudinal
$\mathbf{R_{B0}}$	reaction force of the HAWT blade, bending
$\mathbf{R_c}$	reaction force of a cable, supporting the blade
$\mathbf{R_{T0}}$	reaction force of the HAWT tower, bending
$\mathbf{R_t}$	reaction force of a tower
$R_{t,max}$	maximum reaction force of the tower
$\mathbf{R_g}$	reaction force of a tether or tethers
$R_{g,max}$	maximum reaction force of a tether or tethers
r	radius of the tower at the distance x from the top
S	rotor area
s	safety margin and adjustment for dynamic loads
V	volume of material
v	wind speed
W	tower width
X	distance in Fig. 2
x	distance in a moment expression
Y, y	distances in Fig. 5

Vectors are shown in a bold font. Scalars are shown in normal font. STAWT stands for the proposed structurally optimized tilted axis wind turbine.

possibilities, and challenges related to the STAWT, as well as topics for future research. Section 6 contains the conclusions.

2. Tilted-axis wind turbine: a design

As shown in Fig. 1A, STAWT has a tower, supported by four guy wires at its top. There is a downwind rotor, tilted to the horizon and offset sufficiently to not hit the guy wires. The rotor blades are supported against the aerodynamic lift by cables. The cables are connected to the blades in such a way as not to interfere with blades' pitching. Multiple cables can be attached along the span of the blade, and the cables may have a streamlined profile to decrease drag and turbulence. The cables should be pre-stressed to prevent back-flap motion of the blades.

Further, STAWT design eliminates the rotor hub and drivetrain by introducing a circular ribbon, firmly attached to the rotor by the aforementioned cables. The power is taken off this ribbon by small wheels or gears, connected to rotors of electrical generators (three electrical generators are shown in Fig. 1A). Ribbon's diameter may be about one third of the rotor diameter. In this case, the linear speed of the ribbon surface is about 25 m/s when the tip speed is 75 m/s and does not depend significantly on the size of the turbine. At this speed, it is easy for the wheels to achieve a rotational frequency of 1500–1800 RPM, which allows the lowest cost electrical generators.

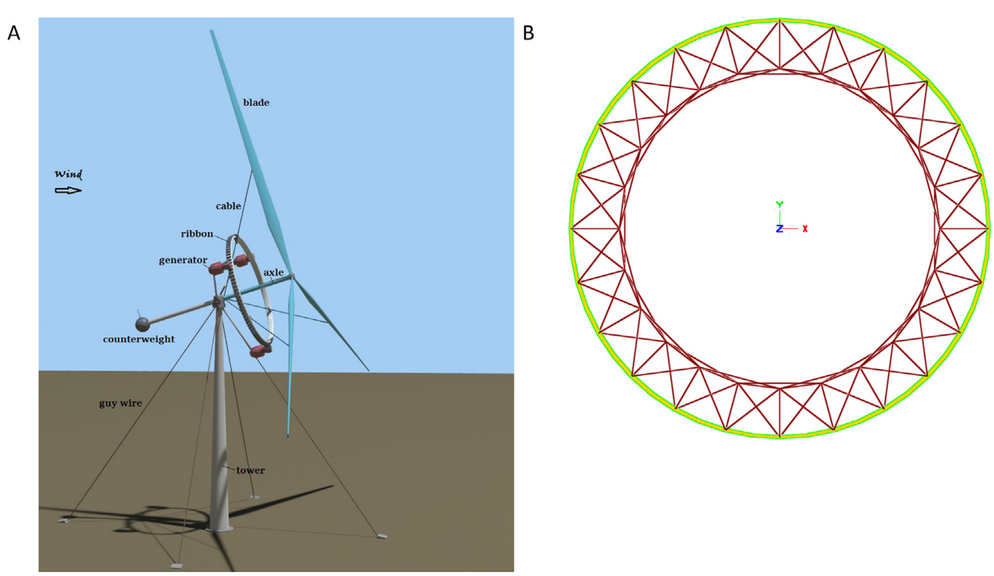

Fig. 1. A. Artist rendering of the tilted-axis wind turbine with three blades. Some elements are explained more accurately in the text. B. Schematic side view of the ribbon, illustrating the external ring and a strengthening 3D frame inside of it.