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Design of a 3 kW wind turbine generator with thin airfoil blades

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ABSTRACT

Three blades of a 3 kW prototype wind turbine generator were designed with thin airfoil and a tip speed ratio of 3. The wind turbine has been controlled via two control methods: the variable pitch angle and by regulation of the field current of the generator and examined under real wind conditions. The characteristics of the thin airfoil, called "Seven arcs thin airfoil" named so because the airfoil is composed of seven circular arcs, are analyzed with the airfoil design and analysis program XFOIL. The thin airfoil blade is designed and calculated by blade element and momentum theory. The performance characteristics of the machine such as rotational speed, generator output as well as stability for wind speed changes are described. In the case of average wind speeds of 10 m/s and a maximum of 19 m/s, the automatically controlled wind turbine ran safely through rough wind conditions and showed an average generator output of 1105 W and a power coefficient 0.14.

1. Introduction

Windmills have been used for many centuries for pumping water and milling grain. The discovery of the internal combustion engine and the development of electrical grids caused many windmills to disappear in the early part of the 20th century. However, in recent years wind turbines are used again to produce electricity for many purposes. There has been a large and active research interest in this field. In the previous studies, the theoretical optimum distribution of the rotor blades [1–3], and experimental studies [3,4] of the wind turbine characteristics were researched. On the performance of the turbine, some investigations of the turbine [4,5] were described.

While wind turbine technology is going by the way of larger scale and offshore wind farms, it is also important to develop small wind turbine generators which are sufficiently safe and easy to run on individual homes for self-sufficient and independent power production.

Usually, small wind turbines are designed with a high tip speed ratio as compared to large wind turbines, thus their rotational speed becomes very high. Also, most small wind turbines have fixed pitch type blades while their rotational surface can be furled upward or side wards to prevent the over-rotation. Therefore, small wind turbines are often noisy and dangerous under strong winds in the rough wind area of East Asia including the Southwest Islands of Japan.

In general, the horizontal axis wind turbine efficiency depends on the tip speed ratio and solidity. The relation between tip speed ratio λ and solidity σ is shown in expression (1) which is simplified form of Betz theory on wind turbine aero dynamics [6].

$$\sigma = \frac{1}{c_L}\frac{16}{9}\left(\frac{1}{\lambda}\right)^2 \tag{1}$$

Here, c_L is lift coefficient of a wind turbine blade airfoil. The equation is shown with solid line in Fig. 1 in the case of $c_L = 1.5$ and 0.5. For example, using a usual tip speed ratio of 6, solidity becomes 0.05 at $c_L = 1$. When it is lowered to a tip speed ratio of 3, solidity increases by a factor of 4 to 0.2. Therefore, it is necessary to enlarge the area of the airfoil blade and the weight of the blade may increase by a factor of 16 than in the previous case. With so many disadvantageous points in this case, lighter blades and thinner airfoils would be needed for a low speed-type wind turbine.

In this study, to develop a low speed-type wind turbine generator, a prototype 3 kW wind turbine blade has been designed with the thin airfoil named "Seven arcs thin airfoil" which means the airfoil is composed with seven circular arcs. The proposed thin airfoil as shown in Fig. 2 has appropriate roundness (arc2–arc6) at the front part of the simple arc airfoils (arc1 and arc7) to prevent leading edge stall. The characteristics of the thin airfoil are analyzed with the airfoil design and analysis program XFOIL [7]. The thin airfoil blade is designed and calculated by blade element and momentum theory (BEM) [1]. The performance characteristics of the machine such as rotational speed, generator output, power coefficient, torque coefficient, and tip speed ratio are described. Moreover, the thin airfoil has been manufactured and tested on the bench in the laboratory and then installed on the roof of the five-storied engineering faculty building in the university. The

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Nomenclature

c_L	lift coefficient	P_w	wind turbine power (blade power)
c_D	drag coefficient	Q_b	blade torque
c_f	thrust coefficient	Q_g	generator torque
c_p	power coefficient	R	radius of rotor blades
c_{pb}	blade power coefficient	$R_{L.R}$	load resistance
c_q	blade torque coefficient	V	wind speed
F_c	centrifugal force	A	attack angle
f_r	friction coefficient	η_g	generator efficiency
F_t	thrust force	η_m	mechanical efficiency
I_f	field current	θ	pitch angle of rotor blade
J	inertia moment of the rotor	λ	tip speed ratio (TSR)
K	mutual inductance	ρ	air density
L_a	equivalent inductance	σ	solidity
N	rotational speed	Ø	twist angle
n_z	gear ratio	Ω	wind turbine rotor angular speed
P_g	generator power		

experimental data of the thin airfoil blade are presented. Another feature of this work is variable pitch and generation control system [8].

2. Development of wind turbine

2.1. Outline of wind turbine generator

The prototype wind turbine was designed for everyone to be able to easily use and be stopped safely by an automatic variable pitch control system in gusts, which often come unexpectedly.

Table 1 and Fig. 3 show specifications and outline of the prototype wind turbine generator. The prototype is a wind turbine with a power rating of 2.5 kW, 4 m diameter, horizontal, upwind, and free yaw with three variable pitch blades. The rotational center of the turbine blades is 5.7 m above the roof of five-storied building. The main shaft is set on the tower tilting upwards about 3°. The tower pole can be fallen down for maintenance by a hand winch and eight tension wires. After the length of tension wires are adjusted, it is very easy to fall down and setup the tower pole.

The yaw control system is a passive free yaw with a movable tail. The tail can move left and right upward to the nacelle with a tilting pin joint which keeps the centerline by the force of gravity on the tail. When the wind direction changes suddenly, the tail moves first, then the whole nacelle axis moves slowly to the wind direction.

2.2. Design of thin airfoil blade

The characteristics of the thin airfoil are analyzed with the airfoil design and analysis program XFOIL [7]. Fig. 4 and Table 2 show the developed seven arcs thin airfoil compared with the NACA4418 airfoil. From Fig. 4, the upper surface of the developed thin airfoil is close to NACA airfoil, although their wing profiles are entirely different from one another. From Table 2, the developed thin airfoil has 11% camber at 0.35 chords and 8.5% thickness at 0.10 chords.

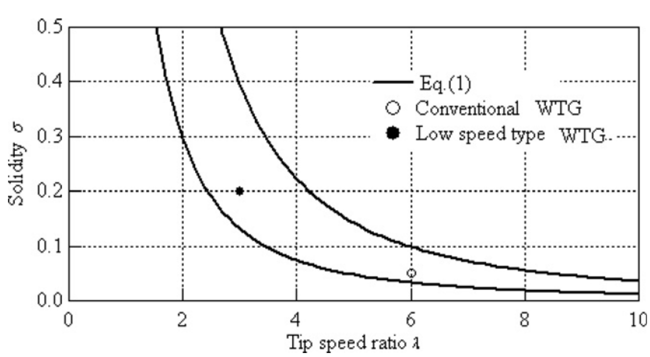

Fig. 1. Relationship between solidity and tip speed ratio.

Table 1
Specifications of the wind turbine generator

Type		Horizontal, up-wind
No. of blades		3
Yaw control		Free yaw
Design	Tip speed ratio	3
	Output	2.5 kW at 160 rpm
	Wind speed	11 m/s
Generator capacity		3 kW

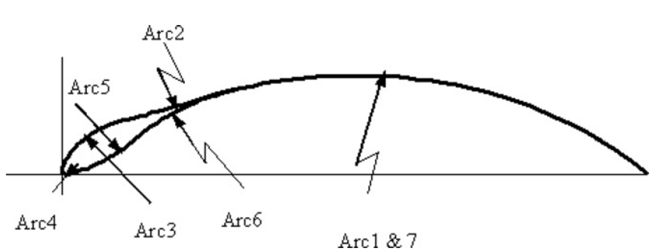

Fig. 2. Proposed thin airfoil.

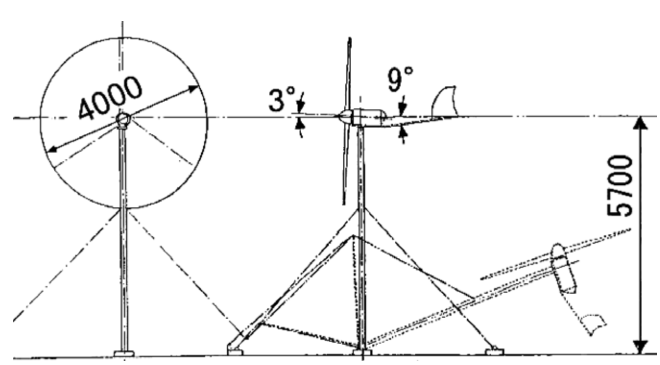

Fig. 3. Outline of the wind turbine generator.