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MODELING, SIMULATION, HARDWARE IMPLEMENTATION OF A NOVEL VARIABLE PITCH CONTROL FOR H–TYPE VERTICAL AXIS WIND TURBINE

Liqun Liu — Chunxia Liu — Xuyang Zheng *

It is well known that the fixed pitch vertical axis wind turbine (FP-VAWT) has some disadvantages such as the low start-up torque and inefficient output efficiency. In this paper, the variable pitch vertical axis wind turbine (VP-VAWT) is analyzed to improve the output characteristics of FP-VAWT by discussing the force of the six blade H type vertical axis wind turbine (VAWT) under the stationary and rotating conditions using built the H-type VAWT model. First, the force of single blade at variable pitch and fixed pitch is analyzed, respectively. Then, the resultant force of six blades at different pitch is gained. Finally, a variable pitch control method based on a six blade H type VP-VAWT is proposed, moreover, the technical analysis and simulation results validate that the variable pitch method can improve the start-up torque of VAWT, and increase the utilization efficiency of wind energy, and reduce the blade oscillation, as comparable with that of FP-VAWT.

Keywords: H-type, vertical axis wind turbine, force analysis, modeling, simulation, variable pitch

1 INTRODUCTION

Wind energy is free, clean and endless. The use of the wind has a history of thousands of years. Since ancient times wind power has been used in different fields, varying from sailing, grain mills and water pump, nowadays, power generation. Since the oil crisis in the early 1970s, the wind power technology has come into the rapid developmental stage in the past four decades, and the annual growth rate has been 20–30 % in the whole world [1–5]. Today, wind power is by far the fastest-growing renewable energy source. A whole wind power system includes the wind turbine, generator, controller, inverter, yaw device, gear box (if required), and protector, etc. Certainly, the storage battery is necessary for the distributed wind power supply system as compared with that can be omitted for the grid-connected wind power system. The wind turbine can be classified in two basic configurations, namely, vertical axis wind turbines and horizontal axis wind turbines (HAWT). At present, the HAWT gets the dominant position of market, especially, the enormous amount wind power system with MW. The wind power system can be classified types: the speed control and power control. The speed-control type includes the fixed-speed and variable-speed wind turbines, while the power control type consists of the stall-controlled, pitch-controlled and active-stall-controlled wind turbines. At present, variable-speed and pitch-controlled wind turbine are the most used wind power systems and the wind turbines and the normal wind power system have become larger [1]. However, the application of VAWT grows slowly in wind power as compared with that of HAWT, the essential reason is that the conventional VAWT fixed the pitch, certainly, and the FP-VAWT has some shortcomings such as inefficient output efficiency and minimal performance cost ratio. At the same time, VAWT has some advantages to compare with HAWT such as high start-up torque (specially, the resistance type wind turbine), low cost of installation, do not need to yaw device, small oscillation, convenient maintenance, tower can be omitted, and easily integrated with high-building, which gets the expert's favor and attention. In addition, the wind energy utilization rate of the resistance type wind turbine is very low, namely, Savonius type, certainly, the state-up torque is more than that of the lift type wind turbine, that is, Darrieus type, such as Φ type, H type, and Δ type. Moreover, the Φ type is difficult to control, thus the H type lift type wind turbine is considered. To promote the development of VAWT and improve the start-up torque and increase the wind energy utilization rate, in this paper, the variable pitch control method for an H type VAWT (H-VAWT) is discussed based on the modeling and force analysis of the H-VAWT. The main purpose of this paper is to improve the overall efficiency of the vertical-axis wind energy conversion across a full spectrum of wind conditions.

2 STRUCTURE ANALYSIS OF VERTICAL AXIS WIND TURBINE

Today, the development of H type VAWT is limited to the research stage only, although large Φ type VAWT had reached the market commercially in the past before disappearing away later. Yet, in the small-scale wind power system, the simple H type Darrieus has more cost

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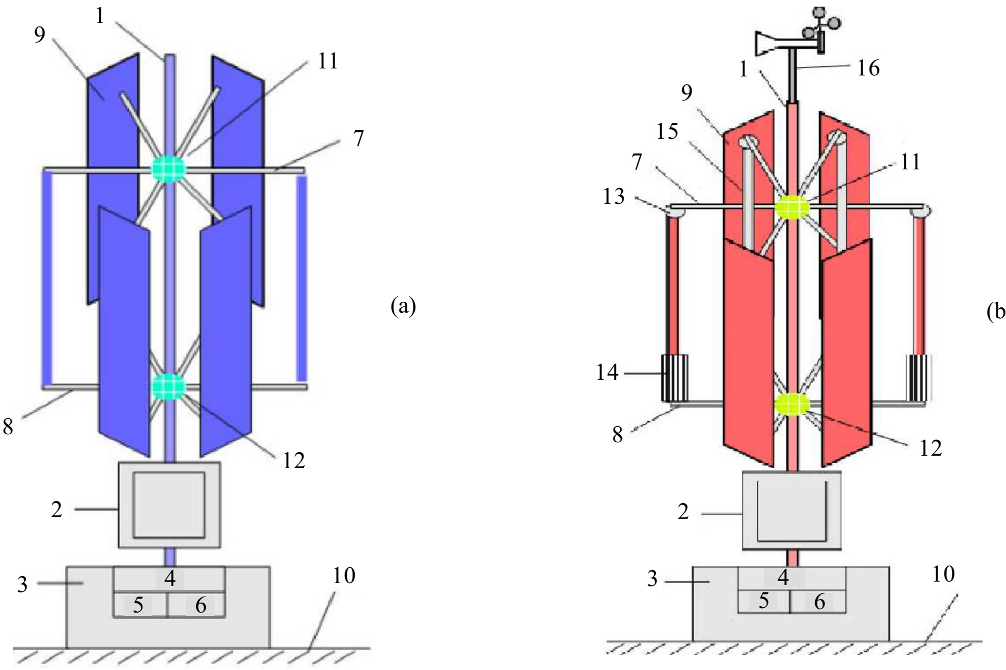

Fig. 1. H type VAWT

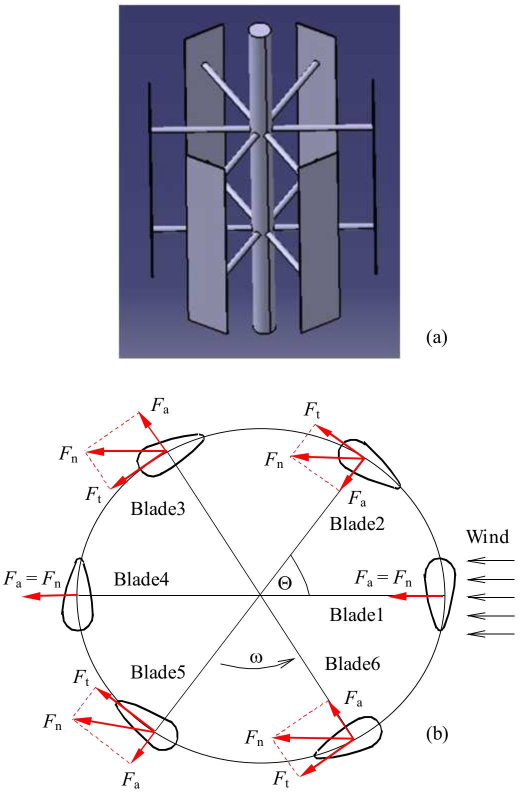

Fig. 2. Force analysis of the six blades FP-VAWT

effective than the Φ type Darrieus. In the small-scale wind generation system, the simple H-VAWT, often called giromill or Cyclo-turbine, is more attractive for its simple blade design [6]. The configuration of H-VAWT falls into two categories: fixed pitch and variable pitch. The previous research activities prove that the fixed pitch VAWTs can not provide adequate starting torque, as shown in Fig. 1(a), and, the variable pitch VAWTs has potential to overcome the starting torque problem, certainly, the configuration is complicated as compared with that of fixed pitch, as can be seen from Fig. 1(b). The comparison of mechanical models between fixed pitch and variable pitch will be discussed in the section 3. The structural components of H type VAWT are composed of

1 – main shaft, hollow main shaft
2 – direct drive generator or indirect drive generator
3 – stationary base, stationary horizontal base
4 – brake apparatus, protector
5 – power supplies, control system assembly
6 – sensors, data collection system
7 – lower wing spoke
8 – upper wing spoke
9 – wings
10 – earth or base
11 – main shaft upper bearing
12 – main shaft lower bearing
13 – upper wing tube bearing
14 – stepping motor, worm and gear
15 – wing rotation mechanism
16 – anemograph (if required)

3 MECHANICAL EXPRESSIONS FOR THE AERODYNAMIC ANALYSIS OF THE VERTICAL AXIS WIND TURBINE

At present, only excellent sites are economically viable and these sites are frequently distant from population centers. Another purpose is to make wind turbines

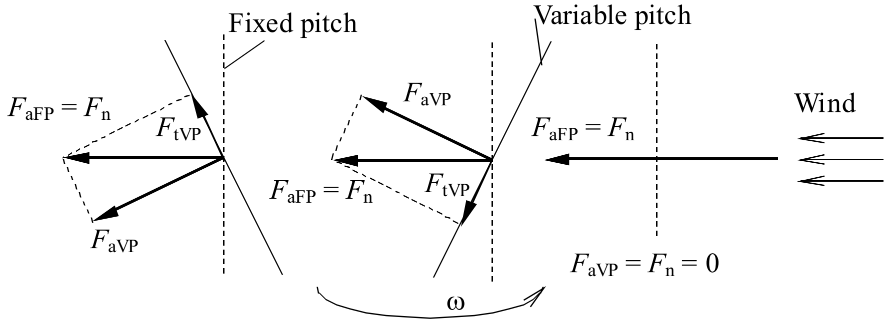

Fig. 3. Force comparison of different pitch angle at stopping

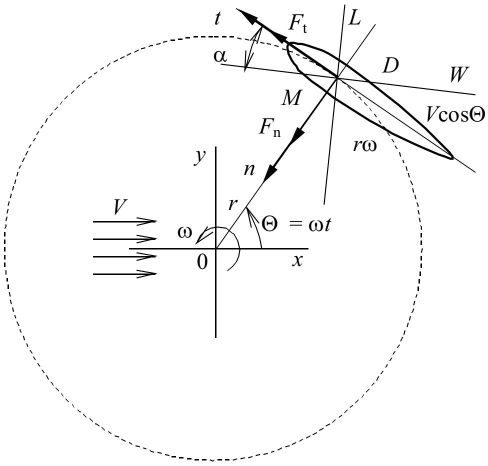

Fig. 4. Force analysis of a blade at running

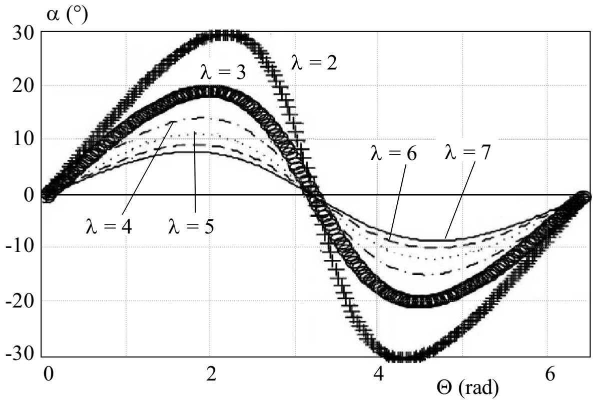

Fig. 5. α–θ curve at different λ of one blade of the FP-VAWT

more practical for home use [6]. Before comparative analysis of the aerodynamic models, the general mechanical expressions, which are common to most of the mechanical models, are described in this section.

The force analysis of wind wheel decides the buildup of the model and the variation of pitch angle of H type vertical axis wind turbine. So this paper firstly analyses the force of six blades H type VAWT in its blade and whole wind wheel [7–10].

Assume the FP-VAWT is stopping and the position of blade 1 is perpendicular to the direction of the wind, as can be seen from Fig. 2. Due to the initial velocity of wind turbine is zero, there are only the axis force F_a for blade 1 and blade 4, certainly, the tangential force F_t is inexistent, and the normal force F_n can be expressed as (1). As shown in Fig. 2, the rest of the four blades generate the torque force, however, the combine force is perpendicular to the axis, which leading to the low start-up torque of FP-VAWT, that is, the self-starting ability of FP-VAWT is poor.

$$F_n = \sqrt{F_a^2 + F_t^2}\,. \tag{1}$$

To improve the poor start-up torque, the VP-VAWT is necessary. The force analysis forone blade and the force comparesion at three special pitch angles are depicted in Fig. 3. For a blade of VP-VAWT, how to select the best pitch angle is very important to gain the maximum torque force. Figure 3 shows that the positive torque force can be gained when the change direction of the blade pitch angle and the rotate direction of wind turbine is same. Or else, the negative torque force is gained. Specially, the torque force is zero when the blade is parallel to the wind direction. As a conclusion, the variable pitch is very important to improve the output efficiency and start-up torque of VAWT, certainly, the optimal pitch angle (or angle of attack α is necessary based on different azimuth angle θ.

Assume the FP-VAWT is running, the relative speed W can be expressed as the equation (2), as can be seen from Fig. 4. Here, the wind speed through the blade is V (the unit is m/s), V_t is the axial flow velocity through the rotor, and $V_t = \omega r$. And, c is chord length of blade with the unit of m, and ω is rotating velocity of blade with the unit of rad/s. The blade's radius r with the unit of m is the distance from the central point of the blade element of the main shaft. Azimuth angle θ with the unit of rad/s is the intersection angle between blade and initial position, and $\theta = \omega t$.

$$W = \sqrt{V_c^2 + V_n^2}\,. \tag{2}$$

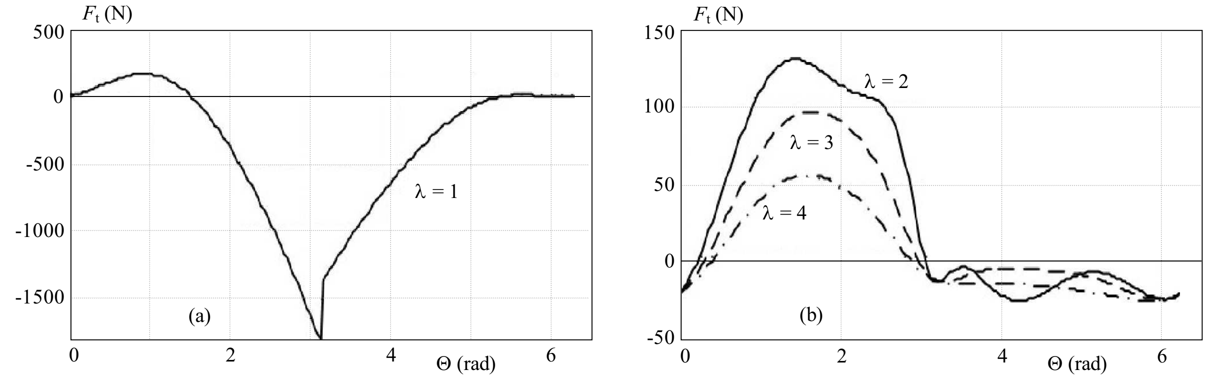

Fig. 6. The change of tangential forces at different λ

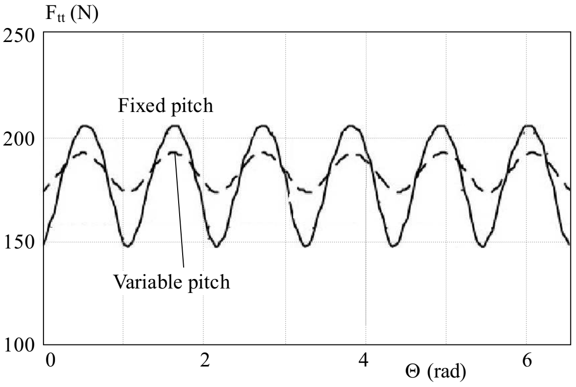

Fig. 7. The tangential forces at fixed pitch and variable pitch

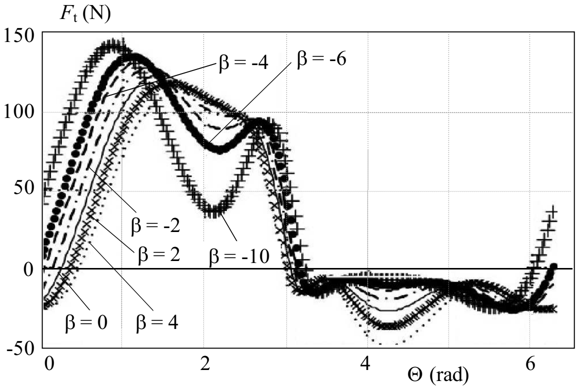

Fig. 8. The change of tangential force at different β

The chordal velocity component V_c and the normal velocity component V_n are, respectively, obtained from the following expressions

$$V_c = V_t + V\cos\theta\,, \tag{3}$$

$$V_n = V\sin\theta\,. \tag{4}$$

The intersection angle of the relative wind speed and blade chord is called the attackangle α with the unit of $^\circ$, which can be represented as (5), and $\alpha \in [-90^\circ, 90^\circ]$. The anticlockwise and clockwise rotation of the blade are named the positive rotation and the negative rotation, respectively.

$$\alpha = \tan^{-1}\frac{V_n}{V_c} = \frac{\sin\theta}{\omega r/V + \cos\theta}\,. \tag{5}$$

Given $\lambda = \omega r/V$, named the tip speed ratio. The α-θ curve of one wind blade of the FP-VAWT at different λ can be seen in Fig. 5. When θ changes from 0° to 180°, α is positive. When θ changes from 180° to 360°, α is negative. Furthermore, with the increase of λ, the change of α is gradually decreasing.

With the rotation of the wind turbine, the reaction force comes from air flow can be divided into two directions, one is perpendicular to the relative wind speed and the other is parallel to the relative wind speed, which are named the lift force F_L and the drag force F_D, respectively.

The expressions of lift and drag forces can be written as

$$F_L = \frac{1}{2}\rho W^2 cCl\,, \tag{6}$$

$$F_D = \frac{1}{2}\rho W^2 cC_{\rm d}\,. \tag{7}$$

Here, ρ is the air density with the unit of kg/m^3, Cl and $C_{\rm d}$ are the lift coefficient and the drag coefficient, respectively. The lift force and drag force are divided into two parts: the tangential part and the normal part which are named the tangential force f_t and the normal force f_n, respectively. H is the height of the turbine.

$$f_t = F_L\sin\alpha - F_D\cos\alpha\,, \tag{8}$$

$$F_n = F_L\cos\alpha + F_D\sin\alpha\,. \tag{9}$$

Thus, the torque of one blade expresses as

$$t' = f_t r\,. \tag{10}$$

The whole wind turbine includes six blades, and the net tangential and normal forces and torque can be defined as

$$F_t = \int_0^H f_t \mathrm{d}H \,, \tag{11}$$

$$F_n = \int_0^H f_n \mathrm{d}H \,, \tag{12}$$

$$T = \int_0^H t' \mathrm{d}H \,. \tag{13}$$

To facilitate the discussion of the torque force changes during the wind turbine rotation, the polynomial fitting of the lift and drag coefficients is used in this paper. The polynomial lift coefficient curve of a wind turbine can be described as (14) based on the piecewise fitting of $(-30\,, -0.25)$, $(-20\,, -0.3)$, $(0\,, 0.3)$, $(15\,, 1.1)$, $(40\,, 0.65)$, and $0°$ attack angle is the separation [7].

$$C_l = \begin{cases} -0.0018\alpha^2 + 0.0801\alpha + 0.3\,, & \alpha \geq 0°\,, \\ 0.0012\alpha^2 + 0.0533\alpha + 0.3\,, & \alpha \leq 0°\,. \end{cases} \tag{14}$$

The polynomial of the dray coefficient curve of wind turbine is gained based on the piecewise fitting of $(-20\,, 0.25)$, $(0\,, 0.05)$, and $(30\,, 0.25)$.

$$C_d = 0.0002\alpha^2 + 0.05\,. \tag{15}$$

In this paper, ρ, ω, r, h, c, and V are equal to 1.29, 50, 2, 4, 0.15, and 8, respectively. Figure 6 depicts the $F_t - \theta$ curves. The change of θ at different λ is very different, especially, when $\lambda = 1$, the tangential force fluctuation of one blade is very big, which is negative from 86° to 360°. Furthermore, the rotational speed of the wind turbine islow. So the tangential force is mainly discussed under $\lambda = 2, 3, 4$ conditions.

As shown in Fig. 6(b), when $\lambda = 2$, the tangential force is the largest, so $\lambda = 2$ is adopted in this paper. The first curve in Fig. 6(b) is the force curve of one wind blade during one revolution under $\lambda = 2$ and fixed blade conditions. As shown in Fig. 6(b), when the wind blade is located in the azimuth angle= 1.4451 rad (that is 80°), the tangential force F_t of the wind blade is the largest, and the attack angle α is 0.4367 rad (that is 25°) at this time. Thus, the tangential force distribution of the wind blade is related with the wind flow direction, and the tangential force of the wind blade is positive when the wind blade located in the positive region from 25° to 180°. Moreover, the tangential force is negative when the wind blade located in the negative region from 180° to 360° and from 0° to 25° is negative, which offsets a part of the torque of the wind blade located in the positive region and decreases the whole startup torque of the wind turbine.

Figure 7 shows the whole tangential force of wind turbine with six blades. As shown in Fig. 7, the tangential force of the wind turbine includes six sine waves because of there is six wind blades. In addition, the fluctuation of the tangential force is strong, which results in the fatigue damage and shortens the service life of wind turbine.

4 THE DESIGN AND THE VERIFICATION OF VARIABLE PITCH SOLUTION DESIGN

VAWT has some shortcomings which results in the large scale wind power system normally use the HAWT, such as the poor self-starting, low wind energy utilizing rate, and poor power instability. As mention above, in order to make the VAWT operates under the optimal status, the variable pitch control of wind blades in different azimuth angle is necessary. That is, these wind blades should output the maximum tangential force when the wind blade located in the positive region and should decrease the tangential force when the wind blade located in the negative region. Certainly, the proposed method can improve the start-up torque and the utilization efficiency of the VAWT.

In Fig. 8, the tangential force has the maximum value when $\beta = 2°$ at the positive region, which has the maximum value when $\beta = -6°$ at the negative region. A novel variable pitch solution is proposed in this section. That is, when the azimuth angle of the blade located in $0° \sim 30°$, the variable pitch control system lets the blade incidence changes from 0° to 3°. When the azimuth angle of the blade located in $30° \sim 150°$, the pitch angle remains 3°. The blade incidence changes from 3° to 0° when the azimuth angle of the blade located in $150° \sim 180°$. The blade incidence changes from 0° to −6° when the azimuth angle of the blade located in $180° \sim 210°$. When the azimuth angle of the blade located in $210° \sim 330°$, the pitch angle remains −6°. The blade incidence changes from −6° to 0° when the azimuth angle of the blade located in $330° \sim 360°$. Here, β is the change of pitch angle of the wind blade.

The change of attack angle of the wind blade during one revolution, the variable pitch control can be expressed as

$$\mathrm{tg}\, I = \frac{\sin\theta}{2 + \cos\theta} \tag{16}$$

$$\alpha' = A \sin\theta\,. \tag{17}$$

Here, A is the change amplitude of attack angle, and α' is the optimal attack angle, and $I = \alpha' + \beta$. Thus, the change of pitch angle of the wind blade located in every position can be expressed as

$$\beta = \mathrm{tg}^{-1} \frac{\sin\theta}{2 + \cos\theta} - A \sin\theta\,. \tag{18}$$

When A is 3°, the comparison of the tangential forces between the fixed blade pitch and the variable blade pitch can be seen from Fig. 9. When the wind blade located in the negative region, the tangential force has a strongly

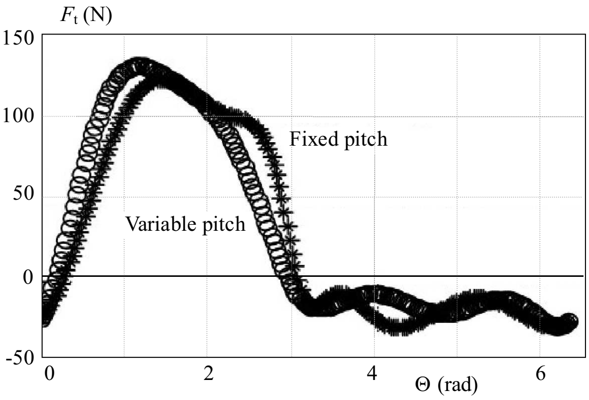

Fig. 9. The tangential force comparison between fixed pitch and variable pitch

improved as compared with that has a slightly improved when the wind blade located in positive region.

The tangential force curve when six blades rotate at the same time. Although the improvement is slight when a single blade rotates, the overall system performance can be improved obviously from the comparison in Fig. 7. Besides, it also shows that, after adopting the variable-pitch control, the tangential force of the whole wind wheel is improved strongly. Thus, it reduces the oscillation of rotor and improves the whole tangential force of VAWT. In addition, it improves the power coefficient of wind energy and the self-starting ability and prolongs the life of the wind turbine. The VP-VAWT power system is designed, which consists of four blades, four worm and gear systems, four stepper motors, four drive circuits, an induction generator, single chip microcomputer, battery, and LED lighting load. At present, the system can realize the real-time variable pitch, however, there are some shortcomings such as the structure is heavy and it is not working at low wind speed. In future, the main working includes the structural weight reduction, wireless power supply, and the whole structural optimizing, *etc.*

5 CONCLUSIONS

Through the theoretical aerodynamic analysis of the blade at any azimuth of VAWT and the force analysis of the blade of VP-VAWT, a novel variable pitch control scheme is proposed in this paper, which is not only quick response and convenient operation, but also improves the torque force at different sites. The variable pitch scheme can also be applied to VAWT with four or eight blades, which improve the self-starting ability and the output power of VAWT power system. In my opinion, the variable-pitch scheme has great significance to promote the development of VAWT, such as the integrated with high-rise building, the water system at the high-rise building roof, and large-scale VAWT generating system with MW.

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