Load Reduction in Wind Energy Converters Using Individual Pitch Control

Hala J. El-Khozondar, Amani S. Abu Reyala, Mathias S. Müller

Abstract—To capture the maximum amount of energy with low cost, wind turbine should be large and individual pitch control (IPC) technique has to be considered. Asymetric loads on the rotor blades experienced by wind speed and gravitational force might cause fatigue and damage to the blades. Consequently, it is important to consider health monitoring of the wind energy converters to detect early structural problems. For this purpose, reliable and efficient optical grating sensors are added at the root of the blades to sense stresses and strains caused by the wind and the gravitational forces. The purpose of this work is to develop a simple model of the blade to study the moments generated by the wind and the gravity at each blade. It is shown that the calculated values of the strains and stresses agree with the values previous calculations.

Index Terms—Individual pitch control, Wind turbine, Power coefficient, Stress, Strain, Moments.

I INTRODUCTION

Wind energy is one of the renewable energy sources, which does not cause environmental pollution problems. The European Wind Energy Association (EWEA)[1] has set a target till 2020-30 to get more energy from renewable sources including wind energy, resulting in a great growth in wind energy technology. Wind turbines rotor blades may rotate around a horizontal axis or a vertical axis. Their height varies from 40m to 80m, their rotor blades diameter changes from 50m to 130m, and their power may reach 5MW and above [2]. The wind turbine capacity upswings with increasing the rotor blade diameter and the tower height. However, this increase threatened the stability of the turbine which might lead to unrecovered damages due to dynamic load caused by wind turbulence, tower shadow, and rotor unbalance [3]. This requires a reliable control method for load reduction [4]. Various control methods have been proposed for this purpose encompassing individual pitch control (IPC) which employed to lessen loads[5-8]. In IPC the three blades are controlled individually to decrease the rotor unbalanced load by montoring the pitch angle independently.

IPC relies on load sensors to measure the loads acting on the blades. The control algorithm based on load sensors is executed and assessed by different authors [5, 9]. The available load sensor with high performance and reliability is expensive. This causes an increase in the cost of the wind turbine parts and thus the expenses of the energy produced from the wind turbine converter increases. This motivated several companies to produce low cost reliable load sensors.

Optical fiber Bragg grating (FB) sensors are immune to the electromagnetic interference, resist envionemental harshness, are compact in size and provide accurate measurements of stress and strains as shown in previous studies [10-15]. Fos4x installed the FB sensors at the roots of the rotor blades. The complex assembly of the rotor blade makes aeroelastic simulations hard.

The aim of this work is to introduce a simplified model for individual pitch control of wind energy converter to get maximum possible value of power coefficient. The model is used to study the moments on the blades caused by the applied forces, wind and gravity on the blades. Then, the stresses and strains are derived from the related moments and compared with the measured values of FB sensors.

The topic of section 2 is the physics concepts of wind energy and the effect of the tip speed ratio on the power coefficient. Section 3 is dedicated to the need of a reliable and efficient sensor for sensing the bending moment, stresses and strains caused by wind, gravitational and centrifugal forces at the root of the blade. The focus of section 4 is on the analytical model of the moments generated by the wind and the gravity for each blade. Section 5 is devoted to compute the stress and strain from the bending moments and compare them with the real values measured by fiber Bragg grating sensors of Fos4x German Company.

II PHYSICS CONCEPTS OF WIND ENERGY

In wind energy turbine, wind power is converted to electrical power. Understanding the physical concepts of the conversion of wind energy to electricity helps us to enhance the performance of wind turbines. The wind power is related to the wind speed as follows,

$$P = \frac{1}{2} A \rho u^3 \qquad (1)$$

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where A is the rotor blades sweeping area, ρ is air density, and u is relative wind speed. Equation (1) shows that the wind power depends on the cubic power of its speed. Consequently, accurate measurement to wind power requires accurate wind speed data.

The wind attacks the rotor plane at an angle α between the wind direction and the chord line of the airfoil, as displayed in figure 1. The two main components of the wind force acting on the rotor blade are the lift force F_L and the drag force F_D . These forces are given as follows,

$$F_L = \frac{1}{2}\rho c_L u^2 A \quad (2)$$

$$F_D = \frac{1}{2}\rho c_D u^2 A \quad (٣)$$

where c_L is the lift force coefficient and c_D is the drag force coefficient [2]. The drag force direction is parallel to the initial direction of movement while the lift force direction is perpendicular to the initial direction of movement as illustrated in figure 1.

The wind energy changed to mechanical energy on the wind turbine blades is restricted by the Betz' law (maximum 59%). The ratio of the mechanical power of the rotor blades, P_R, to the wind power, P, is defined by the power coefficient of the turbine, c_p:

$$c_p = P_R / P \quad (4)$$

where P_R is determined from the following formula,

$$P_R = \frac{1}{2} c_p A \rho u^3 \quad (5)$$

The dependence of c_p on the tip speed ratio λ and the pitch angle φ can be approximated as in equation (6).

$$c_p(\lambda,\varphi) = c_1\left(c_2\frac{1}{\beta} - c_3\varphi - c_4\varphi^x - c_5\right)\exp\left(-c_6\frac{1}{\beta}\right) \quad (6)$$

where the coefficients c_1-c_6 and x have variant values for different wind turbines and β is a parameter defined as

$$\beta = \frac{1}{\left(1/(\lambda+0.08\varphi) - 0.035/\left(1+\varphi^3\right)\right)} \quad (7)$$

where $\lambda = \omega R / u$, R is the blade length and ω is the blade angular velocity [16]. Equation (6) is plotted in Figure 2 for different values of the pitch angle φ = 0°, 5°, 10°, 15°, 20°. The coefficient values used in figure 2 are: c_1= 0.5, c_2 = 116, c_3 = 0.4, c_4 = 0, c_5 = 5, c_6 = 21 [17].

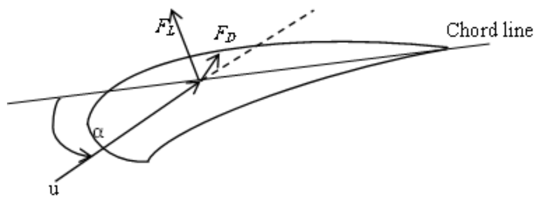

Figure 1: Forces exerted on the airfoil

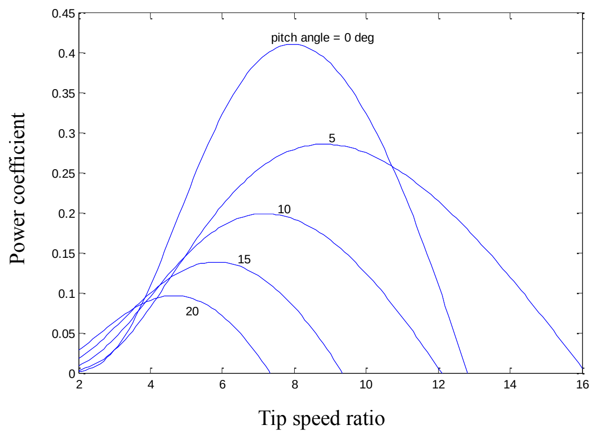

Figure 2: The relationship between the c_p and λ

Figure 2 shows a group of typical c_p-λ curves. It can be noticed that the converted mechanical power from the turbine blade is a function of the rotational speed, and has its maximum value at a particular rotational speed, which varies with the pitch angle φ.

III Individual Pitch Control (IPC)

Wind turbine rotor bears different types of loads; *i. e.*, aerodynamic loads, gravitational loads and centrifugal loads. These loads cause fatigue and vibration in blades, which cause degredation to the rotor blades [18]. These loads can be overcome and the amount of collected power can be controlled using pitch control (PC) by tuning the attack angle of a wind turbine rotor blade into or out of the wind.

Each blade is exposed to different loads due to the variation of the wind speed across the rotor blades. For this reason, individual electric drives are used to control the pitching of the blades in a process called IPC [5]. In this case, the power coefficient c_p, which is defined in equation (6), depends on the wind velocity. The converted mechanical power will be modified to the following expression,

$$P_R = c_p(\lambda(u),\varphi)P = c_p(\lambda(u),\varphi).\frac{1}{2}A\rho u^3 = P_R(u,\varphi) \quad (8)$$

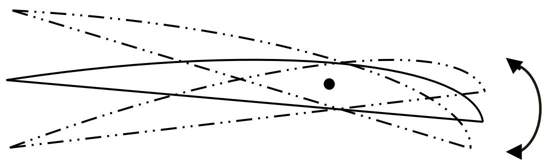

Figure 3 : Adjustable pitch blades

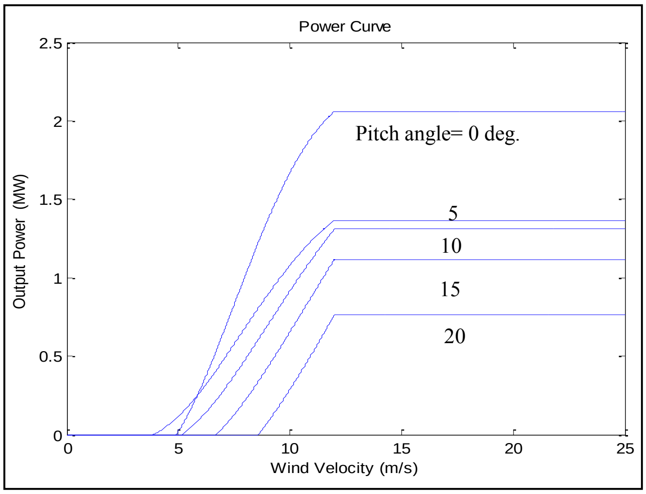

Figure 4 : Effect of the pitch angle on the output power

The variation of the received power with the wind speed and the pitch angle is plotted in figure 4. The figure shows that as the pitch angle changes, the value of the maximum output power varies.

The load sensor is the most important component of IPC to get accurate values of asymmetrical loads on the blades. The measured load values detected by the sensor are fed into the the control algorithm to take the consequential action to pitch the individual blade to the right angle. Measuring stress is very important to obtain the right information about the structural properties of wind turbine tower and jacket under harsh environment [17]. Fiber Bragg grating sensor (FBG) is used to get continuous set of stress and strain data to monitor structure behavior under different load conditions. FBG sensor consists of one cable that transmits data from many different operating points and can bear severe environment.

IV The Mathematical Model :

Four FBG sensors placed at the root of each blade are used to feedback the system with the stress and strain. The values of the stress and strain imposed on the blades are calculated using a mathematical model and analytical simulation. The blade structure is very complex to start with; therefore, the rotor blade is represented by a half cylinder beam to simplify the problem. A full cylinder beam is considered by previous work done by Siddiqi[18]. The half cylinder is used because it is a closer approximation to the shape of the rotor blade than the full cylinder. The half cylinder has length R, cross section area A, outer chord length c_2, and inner chord length c_1 as shown in figure 5. The blade rotates around the horizontal axis taken to be the z-axis by the angle θ and at the same time each blade rotates around its axis, x'-axis, by pitch angle φ as shown in figure 6.

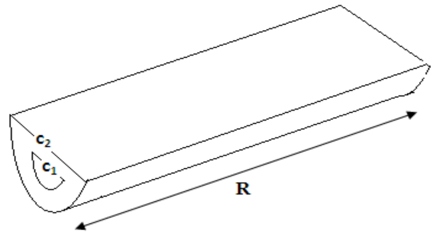

Figure 5 : The half cylinder model of the blade

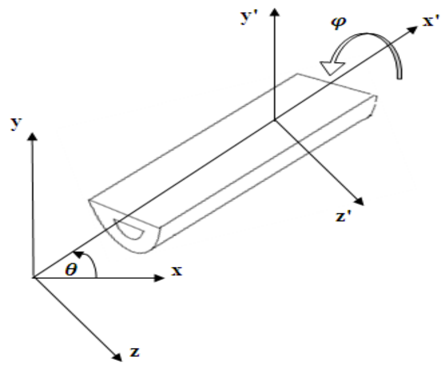

Figure 6 : Rotation of the blade around z-axis and pitching around its x'-axis.

In addition to the gravitational force, the wind flow against the rotor blades is translated into two perpindicular forces which are lift and drag forces as shown in equations (2) and (3). The total forces are transformed into the prime frame (x'y'z') using the transformation matrix in equation (9).

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \sec\theta & -\tan\theta\cos j & -\tan\theta\sin j \\ 0 & \cos j & \sin j \\ 0 & -\sin j & \cos j \end{bmatrix} \begin{bmatrix} a_{x'} \\ a_{y'} \\ a_{z'} \end{bmatrix} \qquad (9)$$

Starting with equation (2), the drag force on one foil is derived over the cross section of one foil as follows:

$$dF_L = \frac{1}{2}\rho c_L u^2\, dA\left(-\sin\theta\, a_x + \cos\theta\, a_y\right) \qquad (10)$$

where

$$dA = dA_2 - dA_1 = 0.5[(2\pi c_2 dr) - (2\pi c_1 dr)] \quad (11)$$

dF_L is transformed to the prime frame using the transformation matrix in equation (9). Similar procedure are followed for the drag force F_D. Then, the two forces in the prime frame are analysed to axial force ($dF_{x'}$) in the x' direction (the beam axis), tangential force ($dF_{y'}$) and normal force ($dF_{z'}$). Integration over the length of the beam is done to get the following forces:

$$F_{x'} = -\frac{1}{4}\rho c_L u^2 \pi (c_2 - c_1) R \tan\theta \quad (12)$$

$$F_{y'} = \frac{1}{4}\rho u^2 \pi (c_2 - c_1)(c_L \sec\theta \cos\varphi + c_D \sin\varphi) R \quad (13)$$

$$F_{z'} = \frac{1}{4}\rho u^2 \pi (c_2 - c_1)(c_L \sec\theta \sin\varphi - c_D \sin\varphi) R \quad (14)$$

Moments in edgewise and flapwise directions can be calculated respectively. Integrating the tangential forces over the blade length produces the rotor torque while integrating the normal forces produces the rotor thrust.

$$\begin{aligned} M_{z'} &= Torque = \int_0^R r a_{x'} \times dF_{y'} \\ &= \frac{1}{8}\rho u^2 \pi (c_2 - c_1)(c_L \sec\theta \cos j + c_D \sin j) R^2 a_{z'} \end{aligned} \quad (15)$$

$$\begin{aligned} M_{y'} &= Thrust = \int_0^R r a_{x'} \times dF_{z'} \\ &= \frac{-1}{8}\rho u^2 \pi (c_2 - c_1)(c_L \sec\theta \sin j + c_D \cos j) R^2 a_{y'} \end{aligned} \quad (16)$$

The axial force from wind produces zero moment because the cross product will equal to zero. The same procedure is applied to calculate the moment due to the gravitational force (F_g). As the blade rotates, the gravitational force acts in the negative y-direction at the center of gravity (C_g) at a distance equals one third of the total length of the blade.

$$F_g = m\,g\,(-a_y) \quad (17)$$

where m is the mass of the blade and g is the acceleration of gravity. In the prime frame the gravitational force is

$$F_g = -mg\cos\theta(\cos j a_{y'} + \sin j a_{z'}) \quad (18)$$

The corresponding gravitational moment (M_g) is

$$\begin{aligned} M_g &= C_g a_{x'} \times F_g \\ &= -mg\cos\theta C_g (\cos j a_{z'} - \sin j a_{y'}) \end{aligned} \quad (19)$$

The static load, the stress and strain, can be calculated from rotor thrust and rotor torque. Strain is a measure of the internal forces acting within a deformable body. Normal stress is the force per unit area applied in a direction perpendicular to the surface of an object. Table 1 summaries the stresses and strains result experienced different type of forces on the blades. The total stress and strain can be found by using superposition principle.

Table 1 : Stresses and strains in the structural models

Type	Stress	Strain
Normal	$\sigma_{xx} = \frac{N}{A}$ $\sigma_{yy} = 0$ $\sigma_{zz} = 0$ $\tau_{xy} = 0$ $\tau_{yz} = 0$ $\tau_{xz} = 0$	$\varepsilon_{xx} = \sigma_{xx}/E$ $\varepsilon_{yy} = -\upsilon\sigma_{xx}/E$ $\varepsilon_{zz} = -\upsilon\sigma_{xx}/E$ $\gamma_{xy} = 0$ $\gamma_{yz} = 0$ $\gamma_{xz} = 0$
Symmetric bending about z – axis	$\sigma_{xx} = -M_z y / I_{zz}$ $\tau_{xs} = -V_y Q_z / I_{zz} t$ $\sigma_{yy} = 0$ $\sigma_{zz} = 0$ $\tau_{yz} = 0$	$\varepsilon_{xx} = \sigma_{xx}/E$ $\varepsilon_{yy} = -\upsilon\sigma_{xx}/E$ $\varepsilon_{zz} = -\upsilon\sigma_{xx}/E$ $\gamma_{xs} = \tau_{xs}/G$ $\gamma_{yz} = 0$
Symmetric bending about y – axis	$\sigma_{xx} = -M_y z / I_{yy}$ $\tau_{xs} = -V_z Q_y / I_{yy} t$ $\sigma_{yy} = 0$ $\sigma_{zz} = 0$ $\tau_{yz} = 0$	$\varepsilon_{xx} = \sigma_{xx}/E$ $\varepsilon_{yy} = -\upsilon\sigma_{xx}/E$ $\varepsilon_{zz} = -\upsilon\sigma_{xx}/E$ $\gamma_{xs} = \tau_{xs}/G$ $\gamma_{yz} = 0$

Where N is the normal force, A is the area, σ is normal stress, ε is strain, γ is shear strain, v is Poisson ratio, E is young modulus of elasticity, G is modulus of rigidity, M is bending moment, Q is shear force, I is moment of inertia, t is thickness and J is polar moment of area.

IV Simulation Results and discussion:

The results are calculated numerically and summerized in table 1. The calculations are performed on the first blade. Figure 7 shows a variation of stress and strain with time keeping other variables constant; *i .e.*, the nominal value of the wind speed = 12.3 m/s, the attack angle = 10 degrees and the pitch angle value is chosen to give maximum power.

In Figure 8, the stress and strain are plotted as a function of the wind speed keeping all other variables fixed. The fixed variable values are chosen as folows: Time equals to 10 sec, the pitch angle value is selected to give maximum power, and the attack angle value is 10 degrees.

Figure 9 displays the dependence of stress and strain on the pitch angle keeping the other variables constant. The values of these variables are: the wind speed nominal value is taken, the attack angle is equal to 10 degrees and the time value is equal to 10 sec. Note that the stress and strain vary sinusoidally with pitch angle as expected from the theoretical equations.

The variation of stress and strain with the attack angle is illustrated in Figure 10. The other variables are kept contant. The calculated mean value of the strain (ε_{xx}) from figures (7)-(10) is equal to 0.4335 mm/m, 0.4329 mm/m, 0.4152 mm/m, and 0.4388 mm/m respectively. Siddiqi[18] calculated mean value of the strain (ε_{xx}) which equals 0.55 mm/m. The mean value of the strain (ε_{xx}) we obtained from our calculation is deviated by 21% from the expected result [18]. The mean values of $\varepsilon_{yy} = \varepsilon_{zz} =$ -0.4780 mm/m.

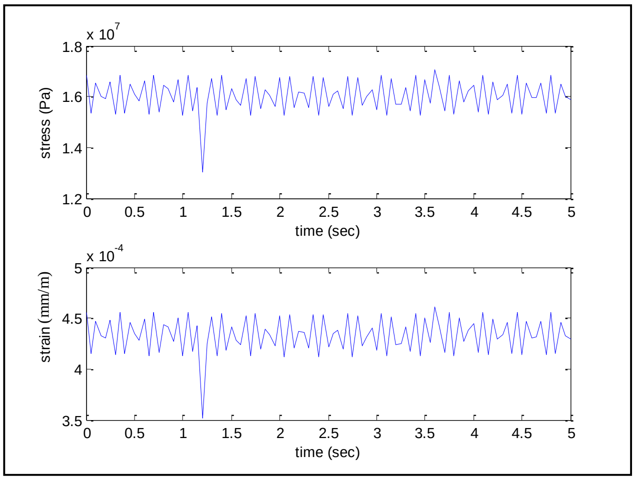

Figure 7 : Stress and strain versus time

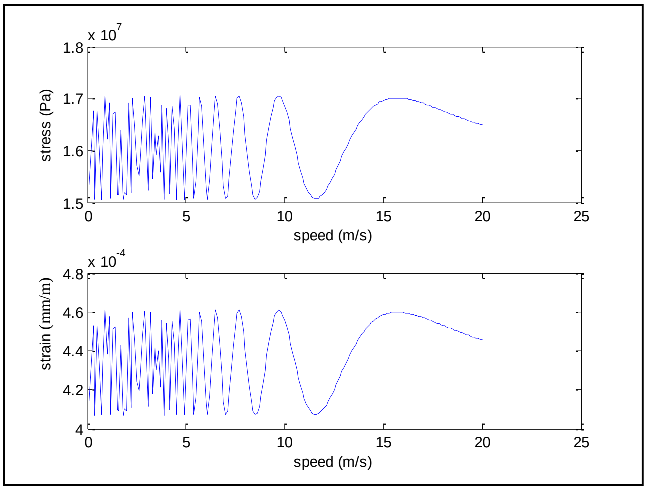

Figure 8 : Stress and strain versus speed

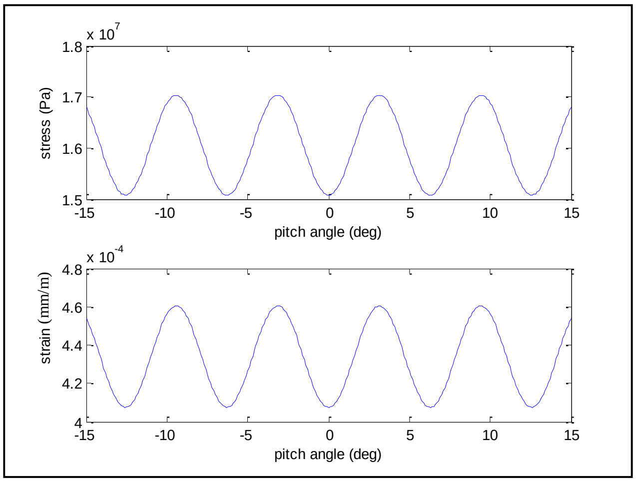

Figure 9 : Dependence of Stress and strain on pitch angle

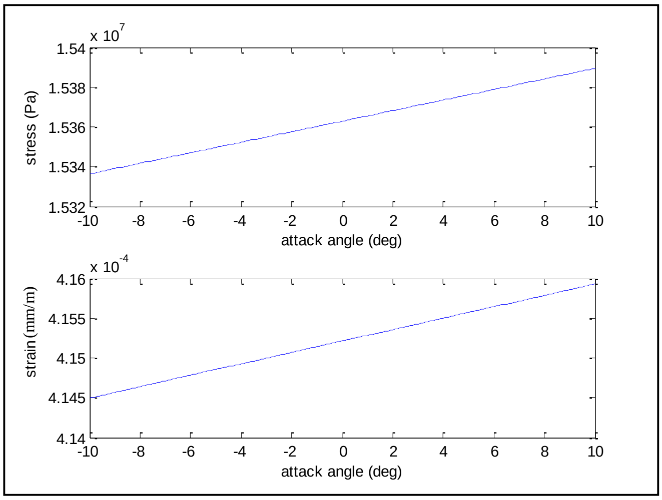

Figure 10 : Variation of stress and strain with attack angle

V CONCLUSION

The basic concept of individual pitch control of wind energy converter to get maximum possible value of power coefficient is developed. We used a half cylinder simple model to represent the blades of the wind energy turbines to analyse and calculate asymmetric loads on the rotor blades. Analytical equations are derived to express the moments generated by the wind and the gravity on each blade. Then, the strains and stresses are calculated. The results agree with the expected values.

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