LOAD REDUCTION IN WIND ENERGY CONVERTERS USING INDIVIDUAL PITCH CONTROL

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ABSTRACT

With the increase in population, the needs of living a better life are demanding more energy supply. Moreover, environment and safety are important factors in development of any energy producing system. That's why renewable energy systems are most reliable if they are developed with qualitative and quantitative research. The wind energy converters are heavy machines used to convert wind energy to electrical power. The European Wind Energy Association (EWEA) has set different targets till 2020-30 to get more energy from renewable sources as well as wind energy converters. This paper work is to develop the basic concept of individual pitch control of wind energy converter to get maximum possible value of power coefficient. For this purpose, reliable and efficient sensor, sensing bending moment, stresses and strains caused by wind, gravitational and centrifugal forces at the root of the blade, are very important. A simple model of the blade with analysis of the moments generated by the wind and the gravity of each blade, when the blade is rotating is provided and is checked by the real values measured by fiber Bragg grating sensors of Fos4x German Company.

KEYWORDS: Individual pitch control; Power coefficient; Stress; Strain; Moments.

I. INTRODUCTION

With the great development of wind power technology and increase of wind turbine unit capacity, rotor diameter, nacelle weight and tower height of wind turbine increase rapidly. Dynamic load caused by wind turbulence, tower shadow, and rotor unbalance affects large scale wind turbine more and more distinctly, which is an essential factor must be considered[1].

Now, most of turbines use pitch to control power captured by the rotor. Blade derived and controlled by a servo system according to demand come from main controller according to different operating conditions. A lot of advanced intelligent control algorithms had been used in pitch control.

Even intelligent control algorithms applied, the traditional collective pitch control strategies move the three blades synchronal. However, aerodynamic force on three blades is different, so the rotor of the wind turbine endures unbalanced load all the time. The adjustment of pitch angle has an obvious influence on dynamic load. At present, electrical servo system and hydraulic servo system are used to drive blade in most of turbine pitch system. Three blades can be controlled independently with three motors or
cylinders, which make it possible to decrease the rotor unbalanced load by controlling pitch angle independently.

This paper focuses on the basic concept of individual pitch control of wind energy converter to get maximum possible value of power coefficient. Section II explains the physics of wind turbine as the power content of wind and the effect of the tip speed ratio on the power coefficient. Section III states 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. Section IV shows an analytical model of the moments generated by the wind and the gravity for each blade. Section V contains relations to compute the stress and strain from the bending moments and then are checked by the real values measured by fiber Bragg grating sensors of Fos4x German Company.

II. PHYSICS OF WIND ENERGY

A. Power in the Wind

The importance of accurate wind speed data becomes clear when one understands how the speed affects the power. Consider a disk of area $A$ with an air mass $dm$ flowing through that area. In a time $dt$ the mass will move a distance $u \, dt$, creating a cylinder of volume $Au \, dt$, which has a mass $dm = A \rho \, u \, dt$, where $\rho$ is the density of air. The power contained in the moving mass is the time rate of change in kinetic energy, given by[5]:

$$P = \frac{d(KE)}{dt} = \frac{1}{2} \left( \frac{dm}{dt} \right)^2 = \frac{1}{2} A \rho u^3$$

The relationship between the mechanical power of the rotor blade $P_R$ and the power of wind $P$ in the rotor area is given by the power coefficient $c_p$ which indicates the efficiency of the turbine:

$$c_p = \frac{P_R}{P}$$

B. Tip speed ratio

A wind energy converter is classified through the characteristic tip speed ratio. $\lambda_r$ is the local speed ratio, i.e. the ratio of the rotor speed at radius $r$ to the wind speed at $r$.

$$\lambda_r = \frac{\omega r}{u}$$

where $\omega$ is the angular velocity of the blade. When $r = R$ where $R$ is the length of the blade and $\lambda_R = \frac{\omega R}{u} = \lambda$, the tip speed ratio[5]

Figure 1 shows an example of the relationship between the $c_p$ and $\lambda$ according to the approximation of $c_p(\lambda, \phi)$ characteristic by the following form:

$$c_p(\lambda, \phi) = c_1(c_2 \frac{1}{\beta} - c_3 \phi - c_4 \phi^* - c_5) e^{-\frac{1}{\beta}}$$

Since the function depends on the wind turbine rotor type, the coefficients $c_1$-$c_6$ and $x$ can be different for various wind turbines. The proposed coefficients[2] are:
\[ c_1 = 0.5, \ c_2 = 116, \ c_3 = 0.4, \ c_4 = 0, \ c_5 = 5, \ c_6 = 21 \ (x \text{ is not used because } c_4 = 0). \]

These values are used for the plot in figure 1 by taking different values of the pitch angle \( \varphi = 0, 5, 10, 15, 20. \) Additionally, the parameter \( \beta \) is also defined as:

\[
\beta = \frac{1}{(1/(\lambda + 0.08\varphi) - 0.035/(1 + \varphi^3))}
\]

(5)

Figure 1: Example of the relationship between the \( c_p \) and \( \lambda \)

C. Blade element theory

Blade element theory is a mathematical process determines the behavior of propellers. It involves breaking a blade down into several small parts as shown in figure 2 then determining the forces on each of these small blade elements\(^6\). These forces are then integrated along the entire blade and over one rotor revolution in order to obtain the forces and moments produced by the entire rotor.
D. Energy Conversion at the Blade

The wind flows perpendicular to the plane of the rotor at an angle of attack $\alpha$, which is the angle between the wind direction and the chord line of the airfoil, as shown in figure 3. The two main forces acting on the rotor blade are the lift force $F_L$ and the drag force $F_D$. The drag force acts parallel to the initial direction of movement and the lift force acts perpendicular to it as shown in figure 3. The lift force is determined by the following formula:

$$F_L = \frac{1}{2} \rho c_L u^2 A$$  \hspace{1cm} (6)

where $c_L$ is the lift force coefficient. The drag force is determined by a similar formula,

$$F_D = \frac{1}{2} \rho c_D u^2 A$$  \hspace{1cm} (7)

where $c_D$ is the drag force coefficient, and is caused by air friction at the surface of the profile[5].

III. INDIVIDUAL PITCH CONTROL

A. Pitch Control

Blade pitch refers to turning the angle of attack of the blades of a wind turbine rotor into or out of the wind to control the production or absorption of power[6]. It is used to adjust the rotation speed and the generated power.

On a pitch controlled wind turbine, the turbine's electronic controller checks the power output of the turbine several times per second. When the power output becomes too high, it sends an order to the blade pitch mechanism which immediately pitches (turns) the rotor blades slightly out of the wind. The rotor blades thus have to be able to turn around their longitudinal axis (to pitch) as shown in figure 4.
But in most cases, individual electric drives are used to actuate control of blades as shown in figure 5.

Thus;

\[ P_r = c_p(\lambda(u), \varphi) \cdot P \]
\[ = c_p(\lambda(u), \varphi) \cdot \frac{1}{2} A \rho u^3 \]
\[ = P_R(u, \varphi) \quad (8) \]

It is concluded that the received power is a function of the wind speed and the pitch angle. Figure 6 shows a plot of the received power versus the wind speed at different values of pitch angle. It shows how the maximum output power varies with the pitch angle. So a control strategy is needed to give the best pitch angle according to the input wind data.

B. Load cases in wind energy converter

Wind turbine rotor bears different types of load. Wind turbine loads acting on the blades have more significant in comparison with loads acting on downstream components. Aerodynamic loads, gravitational loads and centrifugal loads cause fatigue and vibration in blades and hence the blade can have shorter life. In another way, the loads can be categorized in steady loads, cyclic loads and non-cyclic loads\[3\].

C. Load Sensors

It is indicated that trustworthy sensor are very important in individual pitch control of wind turbine to get accurate value of asymmetrical loads on the blade. The values of these measured loads are fed into the appropriate control algorithm to take corresponding action of pitch angle control of individual blade as shown in figure 7. It is very important to measure stress especially in offshore wind turbines.
to get an idea of structural properties of wind turbine tower and jacket in worst
cases[3].

A continuous data is obtained using optical strain gages that how structure is
behaving under different load conditions. The Optical strain gages is only one cable
transmits data from many different operating points and can work in harsh
environment. Thus, four optical strain gages at the root of the blade are used to
feedback the system with the stress and strain as shown in figure 5.

![Power Curve](image)

Figure 6: effect of the pitch angle on the output power

![Diagram](image)

Figure 7: Individual Pitch Control - basic concept

IV. MATHMATICAL MODEL

The basic element considered for mathematical model is beam element. It is a
mathematical construct used to model beam-type structures[6].

A. The half cylinder model
Consider a half cylinder with outer chord length \( c_2 \), and inner chord length \( c_1 \) as shown in figure 8. The length of the half cylinder is \( R \) whereas its cross-section area is \( A \). Axis configuration is shown in figure 9.

![Figure 8: The half cylinder model of the blade](image)

![Figure 9: Axis configuration of the model](image)

**B. Rotation matrix between frames**

The blade rotates around \( z \)-axis by the angle \( \theta \) in the \( xyz \) frame. It also rotates around \( x' \)-axis by the angle \( \phi \) in the \( x'y'z' \) frame as shown in figure 9. Finding the total forces and moments acts on the blade needs getting a transformation matrix between these two frames.

\[
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix} = \begin{bmatrix}
  \sec \theta & -\tan \theta \cos \phi & -\tan \theta \sin \phi \\
  0 & \cos \phi & \sin \phi \\
  0 & -\sin \phi & \cos \phi
\end{bmatrix} \begin{bmatrix}
  x' \\
  y' \\
  z'
\end{bmatrix}
\]

(9)

**C. Forces and moments**

The wind flow against the rotor blades is translated into two normal forces which are lift and drag forces as shown in equations 6 and 7. The axial, the normal and the tangential forces in \( x'y'z' \) coordinate with axis configuration shown in figure 9 are derived.
Moments in edgewise and flapwise directions respectively can be calculated. Integrating the tangential forces over the blade length produces the rotor torque. But integrating the normal forces produces the rotor thrust.

\[ \text{Torque} = \int_0^R ra_x X dF_y' \]
\[ = \frac{1}{8} \rho u^2 \pi (c_2 - c_1)(c_L \sec \theta \cos \phi + c_D \sin \phi) R^2 a_x' = M_z \]  

\[ \text{Thrust} = \int_0^R ra_x X dF_x' \]
\[ = -\frac{1}{8} \rho u^2 \pi (c_2 - c_1)(c_L \sec \theta \sin \phi - c_D \cos \phi) R^2 a_y' = M_y \]

The \( F_{axial} \) produce zero moment since it is in the direction of \( a_r \).

D. Gravitational moment

As the blade has weight, the downward gravitational force has an effect on it. As the blade rotates the gravitational will be in \((-a_y)\) direction at a distance equals one third of the total length of the blade which is the center of gravity (G).

\[ F_{\text{gravitational}} = mg(-a_y) \]

Where \( m \) is the mass of the blade and \( g \) is the gravity acceleration. Transforming equation 15 into the \( x'y'z' \) frame results in:

\[ F_{\text{gravitational}} = -m g \cos \theta (\cos \phi a_y' + \sin \phi a_z') \]

And the gravitational moment is:

\[ \text{Moment}_{\text{gravitational}} = ra_x X F_{\text{gravitational}} \]
\[ = ra_x X (-m g \cos \theta (\cos \phi a_y' + \sin \phi a_z')) \]
\[ = -mgG \cos \theta (\cos \phi a_z' - \sin \phi a_y') \]
V. STRESS AND STRAIN

From rotor thrust and rotor torque, the static load which is the stress and strain can be calculated. Stress 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.

Strain is the change in dimensions per unit original dimensions. In engineering, it is expressed as the ratio of total deformation to the initial dimension of the material body in which the forces are being applied.

\[ \text{strain} = \frac{\Delta l}{L} \]  \hspace{1cm} (18)

For example, if your stretch a 100 cm long wire by 5 cm, strain = 5/100 = 0.05\(^6\).

Table 1 includes the stress and strain results in different types of forces affect the rotation of the blades. They can be added using superposition method to find the total stress and strain. In table 1 we referred to the following symbols: \(N \) : normal force, \(A \) : area, \(\sigma \) : normal stress, \(\varepsilon \) : strain, \(\gamma \) : shear strain, \(\nu \) : poisson ratio, \(E \) : young modulus of elasticity, \(G \) : modulus of rigidity, \(M \) : bending moment, \(Q \) : shear force, \(I \) : moment of inertia, \(t \) : thickness, \(J \) : polar moment of area.

Table 1 : Stresses and strains in the structural models

<table>
<thead>
<tr>
<th>Type</th>
<th>Stress</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\sigma_{xx} = \frac{N}{A} )</td>
<td></td>
<td>(\varepsilon_{xx} = \frac{\sigma_{xx}}{E} )</td>
</tr>
<tr>
<td>(\sigma_{yy} = 0 )</td>
<td>(\sigma_{zz} = 0 )</td>
<td>(\varepsilon_{yy} = -\nu \frac{\sigma_{xx}}{E} )</td>
</tr>
<tr>
<td>(\tau_{xy} = 0 )</td>
<td>(\tau_{xz} = 0 )</td>
<td>(\varepsilon_{zz} = -\nu \frac{\sigma_{xx}}{E} )</td>
</tr>
<tr>
<td><strong>Symmetric bending about z-axis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\sigma_{xx} = -\frac{M_y}{I_{zz}} )</td>
<td>(\varepsilon_{xx} = \frac{\sigma_{xx}}{E} )</td>
<td></td>
</tr>
<tr>
<td>(\tau_{zz} = -\frac{V_y Q_z}{I_{zz} t} )</td>
<td>(\varepsilon_{yy} = -\nu \frac{\sigma_{xx}}{E} )</td>
<td></td>
</tr>
<tr>
<td>(\tau_{xy} = 0 )</td>
<td>(\tau_{xz} = 0 )</td>
<td>(\varepsilon_{zz} = -\nu \frac{\sigma_{xx}}{E} )</td>
</tr>
<tr>
<td><strong>Symmetric bending about y-axis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\sigma_{yy} = -\frac{M_y}{I_{yy}} )</td>
<td>(\varepsilon_{yy} = \frac{\sigma_{yy}}{E} )</td>
<td></td>
</tr>
<tr>
<td>(\tau_{yy} = 0 )</td>
<td>(\tau_{yz} = 0 )</td>
<td>(\varepsilon_{zz} = \frac{\sigma_{yy}}{E} )</td>
</tr>
<tr>
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<td></td>
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</tr>
<tr>
<td>(\sigma_{zz} = 0 )</td>
<td>(\sigma_{zz} = 0 )</td>
<td>(\varepsilon_{zz} = \frac{\sigma_{zz}}{E} )</td>
</tr>
<tr>
<td>(\tau_{yz} = 0 )</td>
<td>(\tau_{yz} = 0 )</td>
<td>(\gamma_{yz} = 0 )</td>
</tr>
</tbody>
</table>

VI. SIMULATION RESULTS

By calculating the forces assert the blade (equations 10-12) and the moments (equations 13-14), the three types of stress and strain affect the blade can be found by applying the relations of table 1. Superposition method is used to find the total stress...
and strain. Matlab program is written to do the numerical calculations. The stress and strain were calculated at different time steps (rotation angle), wind speed, pitch angle and attack angle. The results are plotted as shown in figures 10-14.

In the calculation, the first blade is considered. Figure 10 shows the plot of the stress and strain with respect to time while fixing all other variables. The nominal value of wind speed is 12.3 m/s. The pitch angle value is selected to give the maximum power. The attack angle is 10 degree. Figure 11 shows the plot of the stress and strain with respect to wind speed while fixing all the other variables. The value of time is fixed at 10 sec. The pitch angle value is selected to give the maximum power. The attack angle is 10 degree. Figures 12 and 13 represent the results of stress and strain with respect to attack angle and speed respectively with keeping the other variables constant.

Figure 10 : Stress and strain versus time

Figure 11 : Stress and strain versus pitch angle
VII. DISCUSSION

From figures (10-13) we found the following:

1. The mean value of the strain is as follows: Figure (10) \( \varepsilon_{xx} = 0.4335 \) mm/m, Figure (11) \( \varepsilon_{xx} = 0.4329 \) mm/m, Figure (12) \( \varepsilon_{xx} = 0.4152 \) mm/m, Figure (13) \( \varepsilon_{xx} = 0.4388 \) mm/m.

2. Comparing with results in [3], \( \varepsilon_{xx} = 0.55 \) mm/m. (error: 21%)

3. By using a simpler model comparing with [3], expected results are found.

4. The mean value of the strains in y and z direction are \( \varepsilon_{yy} = \varepsilon_{zz} = -0.4780 \) mm/m.
VIII. CONCLUSION:

In this paper, the basic concept of individual pitch control of wind energy converter to get maximum possible value of power coefficient is developed. The half cylinder simple model to represent the blades of the wind energy turbines is used in this paper. This model is used to make the analytical measurements of the moments generated by the wind and the gravity of each blade. The results were compared by the real values measured by fiber Bragg grating sensors of Fos4x German Company and the results were agreeable. We recommend our simple to be used to give feedback information regarding the stress and strain on the wind turbine blades.

REFERENCES:


