Control of rotation speed using angle change or effective cross-sectional area of blades on wind turbines

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Abstract. To cope with wind changes when the speed is excessive, the turbine needs to be equipped with a speed regulator. To control the turbine rotational speed can be done by changing the variable angle or blade cross-sectional area. Changes in blade angle are automatically followed by changes in blade cross-sectional area. To get a more stable rotational speed, the cross-sectional area of the blades is changed inversely with the wind speed. Experiments were carried out to obtain an effective blade cross-sectional area, in order to obtain a characteristic curve of the change in angle or the effective cross-sectional area of the blade when wind speed changes. Based on the results of this test, a wind turbine prototype has been designed using 3 blades with a maximum area of 0.22 m² each. The change in angle is automatically carried out by adding a centrifugal pendulum at a position half the radius of the blade length. Control of rotational speed using a centrifugal pendulum is quite effective as a control for wind turbine rotational speed. Although the rotating speed is not very constant, it shows better stability.

1. Introduction

Wind speed changes all the time. These changes are not only directional but form a profile due to the stability of the atmosphere. Wind energy with changes in speed and direction when used to rotate wind turbines can also provide various results for the turbine rotational speed [1]. If a fluctuating wind turbine rotational speed is not preferred, a control device is needed to maintain the wind turbine rotational speed so that its rotation is more stable [2]. The variables that affect the wind turbine rotational speed are the wind speed and the effective cross-sectional area of the blades. The purpose of the effective cross-sectional area is the cross-sectional area of the blade which is hit by the wind vertically. One option for controlling wind turbine rotational speed is to change the effective cross-sectional area of the blades. If the wind speed is too large, the effective cross-sectional area of the blade must be reduced, and vice versa. While the effective cross-sectional area of the blade depends on the angle of the blade to the wind direction [3,4]. One of the easiest ways to change the effective cross-sectional area of the blade is to change the blade angle or sweep area [5] to the wind direction. Changing the blade angle can be done with an active or passive control system. Active control system is a control system that uses electric or pneumatic energy. But in this paper, it is focused using the centrifugal force of the pendulum as a blade angle controller which is classified as a passive control system. A speed control model utilizing centrifugal force has been designed in Chena et al [6]. The paper also explains the success of a system at high wind speeds and has good performance at low wind speeds.
2. Literature review

2.1. Wind energy

There are three renewable energies that are very easy and cheap to obtain, namely: (1) solar energy, (2) wind energy, and (3) water potential energy. Besides, there are several other energy sources that are more expensive to use, such as geothermal energy, sea wave energy, and others. The required wind speed is at least in the range of 5.5 m/s and in reality very few areas have continuous winds. But in coastal areas or areas at high altitude, there are quite a lot of winds with a more stable continuity and speed [7]. The advantage of wind energy is that the potential for wind is sufficient to provide a supply of its energy needs. The disadvantage of using wind energy is the need to use moving turbines so that intensive maintenance is required.

The uneven heating of the earth’s surface triggers winds. Warmer air will rise and its position is replaced by cooler air, this movement of air flow is called wind. If examined in more detail, it turns out that the direction of this wind flow is very uneven, moving turbulence, there are ripples and eddies moving in directions. However, the wind flow still has an average flow velocity in the horizontal direction which is the dominant wind direction that occurs which can be used as a source of energy to drive wind turbines. The irregular wind direction causes the wind energy to be not entirely potential to generate energy to rotate the wind turbine, and for the calculation it is necessary to assume a constant known as the power coefficient. The power extractable curve at a particular wind speed has been tested [8]. The energy obtained from wind power is the kinetic energy. If \( A_{ef} \) represents the swept cross-sectional area and \( V \) represents the wind speed, then the available power (\( P \)) is expressed by equation (1) [7]. If \( l \) represents the length of the blade and \( r \) represents the length of the blade arm, the swept cross-sectional area can be expressed as in equation 2 [3,7,9].

\[
P = \frac{1}{2} \rho A_{ef} V^3
\]

(1)

\[
A_{ef} = \pi l (l + 2r)
\]

(2)

In converting the kinetic energy from the wind into mechanical energy, it is greatly influenced by the ability of the blades to capture wind energy. The ability of the blades to capture wind energy from the available resources is called the power coefficient which is closely related to the efficiency of the turbine, as stated in equation 3 [3,10].

\[
C_p = \frac{P_{mec}}{P_{wind}}
\]

(3)

To control the rotational speed can be done by lowering the \( C_p \) value or reducing the efficiency of the wind turbine when the availability of wind energy is excessive. This reduction in efficiency must pay attention to the availability of excessive wind energy. One way to lower the turbine coefficient is to provide interference by turning the blades at a smaller angle. The conversion of energy at the turbine shaft will have high efficiency if the entire surface of the blade is subjected to maximum pressure from the wind. The rotational speed and blade angle greatly affect the formation of the relative speed of the wind so that they also affect the value of turbine efficiency. Error in blade angle or rotation of the turbine too fast can reduce the cross-sectional area of the blades that are gusted by wind. Wind turbine efficiency can be measured through the tip speed ratio (\( \lambda \)) [3,11].

\[
\lambda = \frac{\omega r}{v_w}
\]

(4)

2.2. Centrifugal force on the pendulum in energy

A three-blade turbine model is selected, each 120° mechanical apart, on one side of the blade with a certain distance from the blade shaft (in the middle along the blade) a pendulum is installed as shown in Figure 1. One side of the blade is held using a stopper and the other side is held using a spring, then the pendulum is fixed at a certain distance from the turbine shaft on the rear side equipped with an arm to determine the center of gravity of the blade in rotating conditions.
Figure 1. Mounting the pendulum, stopper, and spring on the blade.

The choice of distance between the pendulum and the rotating axis affects the mass of the pendulum, but does not affect the need for spring strength. For ease of implementation, the spring is installed near the rotary axis. Meanwhile, to obtain a larger centrifugal force with a smaller pendulum size, it is installed some distance from the rotary axis. The installation of the pendulum farther from the rotating axis causes the blade to be subjected to more torsional force and may result in damage. The mass and the mounting distance of the pendulum must be the same in order to obtain a steady balance. It should be done to measure the balance of all blades and pendulums in the attached condition. Figure 2 shows the concept of analyzing the force generated by a pendulum in a wind turbine.

Figure 2. Pendulum centrifugal force on wind turbine blades.

The motion of the pendulum is a vertical circle with radius $R$ and angular velocity $\omega$. The amount of torque caused by the mass of the pendulum is $W=mg$. By referring to Figure 2, the force generated by the pendulum mass can be reflected towards the center of rotation. Then, $\theta_\omega$ starts from $0^\circ$ to $360^\circ$, therefore the value moves from +1 to -1. And the force towards $r$ that is generated because of the rotation. And the total force held towards the center of the axis is:

$$T_w = \frac{m\omega^2 R}{\sin \theta} + \frac{mg}{\cos \theta \cos \theta_\omega} \tag{5}$$

From equation 3, it appears that the magnitude of the force towards the center of the axis changes along its rotation. But in practice three pendulums are used with 120° separate installations, so that the resultant becomes zero. With the effect of angle $\theta_\omega$ the resultant total gravity caused by the pendulum is always
equal to zero, so that it still provides balance to each blade. The torsional force that occurs on each pure blade only remains the centrifugal force of:

\[ T_w = \frac{m\omega^2 R}{\sin \theta} \]  

(6)

The force of the spring \( T_k = k_s x = k \sin \theta_s \), \( k_s \) is the spring constant and \( x \) is the linear torsion distance, \( L \) is half the width of the blade and \( \theta_s \) is the angle of torsion. In equilibrium conditions, for \( \theta = \theta_s \), then:

\[ \theta = \sin^{-1} \left( \frac{m\omega^2 R}{k_s} \right) \]  

(7)

\[ \theta = \sin^{-1} \omega \sqrt{\frac{k_s}{k}} \]  

for \( 0 < \theta < 90^\circ \)  

(8)

If the amount of torsion angle on the blade is expected to be 15° at a rotating speed of 60 rpm or \( \omega = 6.28 \), for radius \( R \) the placement of the pendulum is 40 cm from the center axis, and the blade width \( L \) is 20 cm then \( \theta = \tan^{-1} (0.5 \times 20/40) = 14^\circ \) and the mass required is 3.4 kg (grams).

3. Methodology and data

3.1. Methodology

A wind tunnel was constructed equipped with an anemometer and a wind turbine to be tested [11]. The anemometer in the form of the windmill and wind turbine being tested is equipped with sensors to record the rotational speed. Each rotating speed is displayed for direct observation. The sensor is also connected to a computer equipped with the PLX-DAQ Excel application program to record data. There are two types of wind turbines tested. The first is a windmill with four blades whose blade angle can be adjusted manually and the second is a wind turbine equipped with a pendulum. Tests are carried out several times at different angles to obtain the characteristics of the blades against changes in wind speed. The wind tunnel which has been installed with a wind speed measuring device and test equipment is operated at a certain speed, and data is taken every 2 seconds for 30 minutes. The data from the wind speed gauge are added up so that they are proportional to the area of the curve. Then the sums are compared. By collecting data, equation 4 can be modified into a comparison between the wind turbine rotational speed and the reference turbine rotational speed. The test result data that has been processed in the form of a curve is shown in Figure 3. From Figure 3 it can be seen that the greater the blade angle, the greater the wind energy extract. Of course this does not happen at a 90° blade angle, this incident is described in Figure 4.

![Figure 3. Comparison of turbine rotation speed to reference windmill speed.](image-url)
measuring instrument, as well as to anticipate changes in wind which are always unstable. The comparison results of the measurement results are shown in Figure 4 in the form of a curve.

![Figure 4. Curve design result of blade angle shift.](image)

4. Results and discussions
Giving the pendulum the same mass and the correct position will not cause imbalance and also will not increase the shaking when it rotates. The gravitational force generated by the pendulum will cancel each other out in obtaining balance at its center of gravity. To reduce the mass of the pendulum and maintain the required centrifugal force, the pendulum can be shifted towards the end of the blade. Selection of a pendulum mass that is too large will be very dangerous for the strength of the blade. The pendulum will not be able to twist the blade to zero degrees; the angle of twist depends on the length of the pendulum arm. This is not a problem because following the characteristic curve in Figure 7, it states that the blade does not need to be twisted to zero degrees. At a twist angle of 45°, the rotating speed has dropped dramatically. The initial setting of the blade angle should be at 83° this is to overcome for easier initial starting. Because it requires a stopper at an angle of 83° and held by the spring on the other side. The strength of the spring can be regulated and compressed by the centrifugal force generated by the pendulum. The centrifugal force will twist the blades when the blades rotate, the higher the rotating speed will cause the twist angle to also increase or the attack angle will decrease and if the rotational speed decreases, the spring will push towards its initial position.

In Figure 3, the characteristic curve of the pit specification ratio is shown, which means that the initial setting angle is at 4 degrees and the greater the angle it can reduce the efficiency as well as reduce the rotational speed at a certain wind speed. Figure 4 shows a characteristic curve compared to the design characteristic curve after being equipped with a pendulum. With the addition of speed control using this pendulum, it is necessary to adjust the strength of the spring to get a curve that matches the design results.

5. Conclusions
Even though the maximum power occurs at the blade angle of 83°, the initial setting value is selected at the angle of the blade of 75° to make it easier in starting. This angle decreases with increasing wind speed. Although the relationship of changes in blade angle to wind speed is not linear, it is sufficient to provide good speed limiting stability. This stability value also depends on the length of the arm of the pendulum. In excessive wind speed, a certain amount of energy is wasted by narrowing the effective cross-sectional area or decreasing the value of the tip speed ratio (λ) so that the output stress and rotational speed are not excessive. The limit of wind speed that can damage the wind turbine can be taken care of by adjusting the setting value of the spring release automatically.

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