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The Rotating Speed Set of Wind Turbine Using the Pendulum as an Angle Blades Control

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Abstract- Besides the wind speed, the blades' angle in the wind turbine can also affect the rotational speed. Therefore, in order to automatically adjust the angle of the blade, it needs to be equipped with a pendulum. This, research aims to design and test the rotational speed of wind turbines using a pendulum, which is positioned at a certain radius to the turbine shaft (X-axis) for the speed sensor's sensitivity and to provide a torsional force on the blade edge of (Y-axis). Furthermore, a wind turbine prototype equipped with a pendulum is designed based on the angular curve's characteristic, which comes to changes in wind speed. The test results show that controlling the rotational speed using a pendulum at a specific position can work quite effectively, irrespective of its ability to provide a completely constant speed..

Keywords: wind turbine; constant speed; pitch angle control; blade angle; pendulum.

1. Introduction

Wind energy is the energy obtained from the wind, that is, the kinetic energy generated by the effect of air currents, and that is transformed into other forms useful for human activities[4]. Wind speed is a fundamental atmospheric quantity caused by the movement of air from high to low pressure due to the temperature changes, while its direction describes the route or area on a compass from which it emanates, for instance, from the North or West. They are always changing, despite possessing an average speed in a certain direction. Therefore, the wind is reported to possess kinetic energy, which is effectively converted into mechanical using wind turbines. The changes in constant speed have an effect on wind turbine rotational speed, and this is dependent on the blade angle. However, in order to stabilize the rotational speed, an electronic or pneumatic control device that is equipped with rotary speed sensors is required. This device is quite expensive and technically difficult, although it is suitable for large-scale wind turbines. On the contrary, an affordable and easier control device that provides fairly effective results is needed for small-scale wind turbines.

Besides producing high rotational speed, excessive wind speed also damages the wind turbine therefore, a stopper is needed. One of the variables used to control the wind turbine speed is changing the blade angle. This is because the larger the blade angle, the smaller the kinetic energy, which is converted to mechanical energy by the turbine shaft. The wind turbine is rotated at an angle of approximately 83°, however, when the mechanical energy of the wind is towards this direction, the rotating speed drastically drops at an angle of 45°, the least occurs at 10°, and it eventually stops rotating at a blade angle of 0°. The rotational speed from 83° to 0° does not change linearly instead it follows the multiplication of a series of alterations resembling a cosine curve. These numbers are obtained from measurements, and irrespective of whether it is not exceptionally accurate, it serves as a benchmark in designing turbine rotational speed control.

A centrifugal force mechanism that allows movable blade angle at high rotation is one of the approaches adopted to ensure that the turbine rotational speed control is stable. Linear bearings are also used to adjust the position. According to Yu-Jen Chena (year), the spring and roller weight are parameters that need to be adjusted to determine the relationship as well as the distance between them [8]. Appropriate placement of the pendulum exerts a torsional force on the turbine blades, which is proportional to the rotational speed. This research focuses on using a pendulum as a wind turbine rotational speed stabilizer, which was realized by placing it at the blades' centre.

2. Wind Turbine Rotary Speed Control

2.1. Wind Energy

Although the existence of wind energy is uncertain, certain places can be predicted to produce it in large qualities. The possibility of wind sources of the renewable energy to generate electric current at any point ofland surface and coastal area of water space make wind power station a promising segment of the global energy [1]. Furthermore, a wind speed above 5 m/s is required to generate electric power effectively. Also, the problem is that the lower limit of the wind speeds range, with which the turbine WPS operate with the rated power, is usually quite high, more than 10 m/s with a maximum efficiency of 0.3 m/s, turbine WPS cannot be used [1] It ranges from 0 m/ s to 15 m/s, although certain places, for example, the coastal areas and highlands (mountains), have wind speeds greater than 5 m/s because it blows throughout the entire day. These areas were selected based on certain weaknesses, namely regions with extreme weather conditions, the air that contains salt or corrosive substances, and occasionally places that are difficult to reach, meanwhile, intensive maintenance is realized using wind turbines. Consequently, coastal regions or areas at high altitude usually experience quite many winds at a constant speed. In a country with numerous coastal areas, wind energy's potential is sufficient to supply its energy needs and is even predicted to have a capacity three times greater than its demand.

In the actual sense, the wind is moving air, and when heated, it rises and is replaced by cooler ones. Based on this event, its motion is an extremely uneven, moving turbulence, similar to the flow of water in a river, where ripples and eddies are moving in a three-dimensional direction. The flag's wave-like movement observes the direction and motion of wind flow, and the wind profile influences its size. Additionally, the wind turbine located in any area, has an average flow velocity in the horizontal direction. Wind direction is defined as the dominant direction from which it originates, such as the flow of a north wind, which blows from the north to the south. A wind rose is a graphic tool used by meteorologists to generally calculate the distribution of wind energy in a particular location. Subsequently, to analyze the potential power availability, a constant known as the power coefficient is assumed. In addition, the kinetic energy of time is obtained from wind power. According to Wei Tong and L. Benaaouinate, when A_{ef} and V represents the swept cross-sectional area and wind speed, respectively, then the available power (P) is stated in equation (1-4) [2,3,4,5]. Conversely, supposing *l* and *r* depicts the blade's length and arm, respectively, the swept cross-sectional area is stated in equation 2.

$$P = \frac{1}{2}\rho A_{ef} V^3 = 0,6\, A_{ef} V^3 \left(\frac{watt}{m^2}\right) \tag{1}$$

$$A_{ef} = \pi l(l + 2r) \tag{2}$$

One of the variables that affect the conversion of kinetic energy into mechanical at the turbine shaft is the ability of the blades to capture wind energy against the available power, which is known as power coefficient which is closely related to the efficiency of the turbine, as stated in equation 3 [6].

$$C_p = \frac{P_{mec}}{P_{Wind}} = \frac{P_{mec}}{(\frac{1}{2})\rho A V^3} \tag{3}$$

However, assuming the excessive availability of wind energy does not cause electrical or mechanical damages, the C_p value needs to be controlled in order to reduce turbine efficiency achieved by reducing the blade angle proportional to the change in rotational speed. A certain way to reduce the turbine coefficient is to provide interference by revolving the blades at a smaller angle. Figure 1 illustrates a condition where the wind hits the blades at different angles. Besides, the blade angle in response to the wind direction (angle of attack) affects its rotational speed. High efficiency is obtained when the entire surface of the blade is subjected to maximum pressure. It is also realized when the blade angle is large and at a reduced speed.

In these circumstances, a large part of wind potential is concentrated in the air masses moving at slower speeds for propeller type turbine, and is not exploited. However, this type of wind energy can be exploited with vertical axis wind turbines, which works on the effect of aerodynamic drag, whose main characteristic is that it can operate and produce energy in severe weather conditions [10]. Furthermore, for propeller type turbine when the rotational speed is large enough , there is a possibility that some part of the blade is not subject to wind pressure, which has the potential to generate energy, thereby causing a decrease in the efficiency of energy conversion. Figure 1 shows the relative wind speed and different blade angles. Consequently, when the error obtained from the blade angle or rotating speed is extremely high, it indicates that the wind flow on the front and back of the blade tends to impinge on a smaller surface, Mads Mølgaard Pedersen [9].

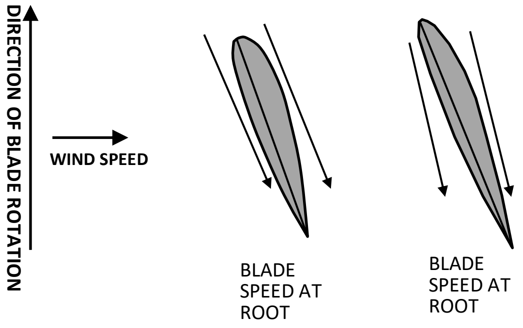

Fig.1: Relative speed of wind on a rotating blade

Wind turbine efficiency is measured by the tip speed ratio (λ), and an increase results in greater efficiency of the turbine. The tip speed ratio is defined as the ratio between the turbine rotational speed (ω) and radius (r) of the wind speed (v_w) [7].

$$\lambda = \frac{\omega r}{v_w} \tag{4}$$

The uniquely designed blade largely determines the wind turbine's efficiency with different ends and bases and the chaotic wind flow pattern. The Himmelskamp effect on the C_p distribution involves two folds firstly, the suction peak decreases, and secondly, it becomes slower. The decline in aerodynamic performance is gradual at the base rather than at the end [11].

2.2. Pitch Control for Wind Turbine

The variables that affect the rotational speed of the wind turbine are wind speed and electric load, which are regulated through the pitch angle control. Furthermore, the turbine is expected to maintain the rated speed as well as the output power. This method is used to carry out the torque control as needed however, using a constant rotor speed [12]. Several studies have been carried out to determine the speed of the wind turbine based on the pitch angle control method. Similarly, data has been reported from the analysis and testing of power, torque and rotational speed, as shown in [13, 14, 15], and this is extremely helpful in this proposed research. The adopted pitch methods, electronically or computationally, utilize the PID control theory, which obtained a high level of precision despite being expensive, complicated, suitable for large power capacities, and its operation and maintenance require experts' services. Howevwe, M. Arbaoui said that under the simulation results,we can deduce that the ADRC controller works efficiently when it comes to sensitivity to disturbances and strong robustness against the parametric variations of the DFIG than the control using a PI regulator that presents less good transient performance and more responses that are undesirable[16].

The proposed turbine rotational speed control uses the pendulums mounted on the blade, with the weight designed based on the center of gravity. The most appropriate design consists of a reaction spring, which is assumed to be an ideal pitch control, although it does not offer precise results as the PID controller. This, this is quite common in changes in the rotational speed of an asynchronous electric motor during the generation of electromotive force (emf). Therefore, this research is focused on the rotary speed and torque controls. The pitch angle control system's particular weakness is the deliberate reduction of turbine efficiency under certain conditions. Therefore, irrespective of the adaptation of a passive control system, it is expected to have a responsive performance because it is influenced by rotational speed. Subsequently, the directional stability control utilizes a tail differential.

Several studies have been carried out to determine ways of adjusting the blade angle to align with wind speed changes. Based on particular research carried out to maximize wind energy, the performance of a six-blade axial type of wind turbine was experimentally studied to estimate the wind power, electrically generated power and the modified power-coefficient [13]. The range of operating conditions is as follows 1) approximately 2 to 5.6 m/s wind speed, 2) relatively 10 % to 100 % of electrical load, and 3) about 10° to 80° blade angles. The modified power coefficients maximum-value was 0.57, which was obtained at a velocity of 5.6 m/s and a blade angle of 80°. Furthermore, a blade angle of 80° is associated with a speed of approximately 3.8 m/s due to the high vibrational level of the wind turbine. This data are extremely useful and is used in completing this research.

The pitch angle control is used to regulate the speed of the wind turbine generator [17]. Furthermore, the production of electrical power and the generator speed adjustment is feasible when the robust controller is applied, and current errors (uncertainties) in the wind turbine system are determined. The spring constant, damping coefficient and insignificant deviations from the linearization process are listed as uncertainties. Subsequently, a decrease in temperature causes the freezing of turbine blades, and this increases its mass. A similar result is reported in specific research, which stated that it is extremely desirable to autonomously operate the wind turbine generators within the speed range in hurricane conditions [18]. This is achieved by regulating the wind turbine speed using a full-scope feedback control scheme, which is currently controlled by modulating the angular position of the rotor blades. Therefore, this research introduces a fuzzy speed controller to autonomously regulate the rotational speed within the range of 0 m/s to 30 m/s. However, after reporting several key concepts concerning small-scale wind turbines, the fuzzy speed controller design is based on a TSK system. A microcomputer involves an unusually sized motor or a complicated bearing [17, 18]. Similar objective was reported in the study titled “Design of Furling Control Mechanisms for Micro-Scale Windmills.” The control is produced by adjusting the swept cross-sectional area, and this is achieved by tipping the blade shaft (yaw angle) using the moment of leverage on the tail of the turbine. This is additionally caused by the wind and force of gravity [19]. The furling control mechanism is equivalent to the method adopted in this research. In accordance with the numerous studies previously carried out, it is evident that the majority of the pitch angle control uses electronic means, thereby causing it to be expensive and difficult in terms of investment and maintenance when implemented in extremely small wind turbines. This leads to the challenge of designing a unique blade that produces an exceptionally stable and less stray rotational speed irrespective of the fluctuation of wind speed.

One of the control models proposed in an international patent by Karimovitch and Kuttybekovitch consists of a blade and pendulum ballast mounted at one end of the lever drive, which encompasses an aerodynamic brake, namely a lever with a return spring while at the other end it is a brake blade. Consequently, when the wind speed exceeds V_{max}, the brake lever is pressed against the pendulum's swing axis, which stops the oscillation [20]. Therefore, this is not to be a regulator of linear velocity, rather protection against storms. A similar patent was reported by 王 川 in a study titled “Pendulum speed control wind driven generator” [21]. In principle, the evaluation is carried out based on the natural kinetic energy and a pendulum partially used to cover the front of the turbine blade, without adjusting the pitch angle or the swept area in order to adjust the rotational speed of the turbine. Therefore the slats need to be inserted in the frame of the blade cover, and its size has to be larger than the diameter of the turbine, thereby making it suitable for only small-scale wind turbines.

2.3. Centrifugal Force on the pendulum

Generally, a wind turbine with three blades needs a pendulum to provide adequate balance. These blades are designed to rotate against the wind direction at an angle between 0° to 83°, while one of the sides is limited using a stopper at a maximum angle of 83°. Furthermore, the other is held by a spring that holds the blade at an angle of approximately 45° to 83°. However, when the angle is smaller than 45° it is released from the spring thereby causing the blades to rotate at angle of 0° mechanically, which is limited to the second stopper. Furthermore, each blade is equipped with a pendulum in order to move its center of gravity towards the Y-axis. This is due to the effect of torsional force on each blade. The pendulum is attached to each blade's back, which is positioned against the direction of rotation and at a certain distance (R) to the shaft. The pendulum is equipped with a support leg, half the blade's width, to exert a torsional force at an angle of 45o mechanical. The installation of the pendulum position is shown in Fig. 2. The distance of the torsion is half of the pendulum's leg, therefore in this event, it also offers a torsional effect at a maximum of 45° because any value greater than this angle causes the turbine to function abnormally. On the contrary, when the torsion angle is less than 45°, the blade is released from the spring's opposing force, which is reported to reach the stopper. In this condition, it is assumed that the wind speed has turned into a storm capable of damaging the turbine.

In order to produce a large torsional force at a certain mass, the pendulum is positioned at the centre or radius (R) of the turbine shaft. The change in R's value determines the mass of the pendulum required to produce a similar centrifugal force. Conversely, assuming the pendulum is installed exceptionally far from the rotating axis, it becomes more sensitive to generating torsional force. This also subjects the blade to an excessively large outward centrifugal force results in damaging the bail on the blade and the pendulum arm. Therefore, the mass and the mounting distance of the pendulum require special considerations and need to be the same to obtain a steady balance. Each of these centrifugal forces is generated by a spring positioned near the shaft so that it does not affect the balance of the blade to reduce it and facilitate its implementation. Immediately after the installation, the balance measurement of all the blades equipped with pendulums needs to be taken. The balance is simply adjusted by turning the turbine with a hand and allowing it to stop, assuming it turns backward at the end of the rotation before stopping. It indicates that the turbine is not balanced and needs to be reset. Figure 4 shows the concept of analyzing the force generated by a pendulum in a wind turbine.

When the turbine rotates vertically, the pendulum follows a similar center of axis, where the turbine shaft forms a radius R at an angular velocity ω. The torque obtained by the mass of the pendulum is $W = mg$. Although, when $\cos\theta = R/r$, θ_ω is the instantaneous angle of ω, with reference to Fig. 4 the force generated by the pendulum mass is reflected towards the center of rotation, which is stated as follows:

$$T_w = \frac{mg}{\cos\theta \cos\theta_\omega} \tag{5}$$

The value of θ_ω is between 0° and 360°, $\theta_\omega = 0_o$ and when the pendulum reaches the bottom and topmost position, $\cos\theta_\omega$ moves from +1 to -1, while the force parallel to r is generated by the rotation of the pendulum, stated as follows

$$T_c = \frac{m\omega^2 R}{\sin\theta} \tag{6}$$

the total force held towards the center of the axis is:

$$T_w = \frac{m\omega^2 R}{\sin\theta} + \frac{mg}{\cos\theta \cos\theta_\omega} \tag{7}$$

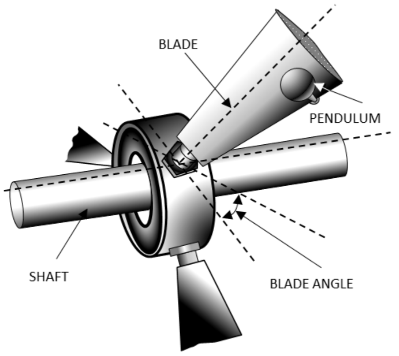

Fig.2: Shaft and Blade Angle

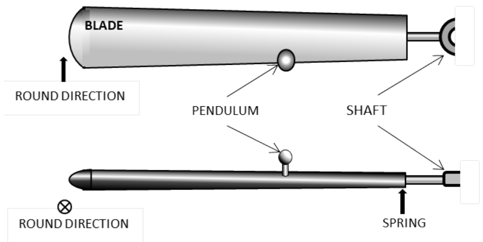

Fig.3: Mounting the Pendulum and Spring on the Blade

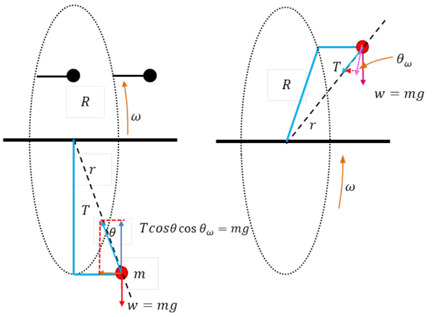

Fig.4: Centrifugal Pendulum Force On Wind Turbine Blades

In equation 7, the value of $\cos\theta_\omega$ is either positive or negative depending on the momentary position of the pendulum, therefore there is a possibility of obtaining a negative T_w value, which is dependent on ω^2. According to equation 3, the force's magnitude towards the center of the axis changes along with its rotation. However, in practice, three pendulums are used with separate installations of 120°, which resulted in the following equation:

$$T_w = \frac{m\omega^2 R}{\sin\theta}\left(\frac{mg}{\cos\theta \cos\theta_{\omega 1}} + \frac{mg}{\cos\theta \cos\theta_{\omega 2}} + \frac{mg}{\cos\theta \cos\theta_{\omega 3}}\right) \quad (8)$$

In accordance with the effect of angle θ_{ω}, the resultant total weight obtained from the mass of the pendulum is always equal to zero, thereby providing support for each blade however it does not cause vibration in the turbine. The torsional effect on each pure blade is the only centrifugal force, which is stated as follows:

$$T_w = 3\frac{m\omega^2 R}{\sin\theta} \quad (9)$$

This centrifugal force is used to provide a torsional effect on the blade, which is held by a spring. Although, when the blades are symmetrical, the torsional effect caused by the wind is neglected except for the centrifugal force. The force of the spring is equivalent to $T_k = k_s\, x$, where k is the spring constant and x is the linear torsion distance, or it is stated as follows $T_k = k\, L \sin\theta_s$, where L is half the width of the blade and θ_s is the angle of torsion that occurs, which is also equivalent to $T_k = k_s \sin\theta_s$. In equilibrium conditions: $T_w = T_k$. and $\theta_s = \theta$, therefore:

$$k_s \sin\theta = \frac{m\omega^2 R}{\sin\theta} \quad \text{or}$$

$$\theta = \sin^{-1}\sqrt{\frac{m\omega^2 R}{k_s}} \quad (10)$$

$$\theta = \sin^{-1}\omega\sqrt{k} \quad \text{for } 0<\theta<90^{\circ} \quad (11)$$

When the torsion angle is 15° at a rotational speed of 600 rpm or 10 rps then ω = 6.2.8 rad/s, while for the radius (R) the placement of the pendulum is 40 cm from the center of the axis, and the width of the blade (L) is 20 cm, therefore, $\theta = \tan^{-1}$ (0.5 x 20/40) = 14° while the required mass is 34 k (grams).

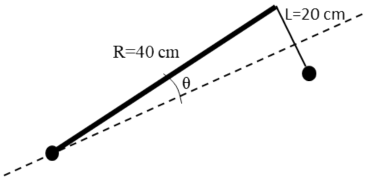

Fig.5: Angle Shift Caused by Centrifugal Force

3. Methodology and Data

A transparent tunnel equipped with two windmills is constructed on the inside. One of them is small and has eight blades installed in the middle, and it functions as an anemometer, while the other is the turbine that needs to be tested. In addition, both the anemometer and the tested windmill are equipped with sensors to measure and record the rotational speed, which is displayed on an LCD for direct observation. The sensors are also connected to a computer equipped with the PLX-DAQ Excel application program to record data. Subsequently, the tested tunnel is shown in figure 6. The anemometer is not calibrated because it is used only for comparison in several tests without altering its position or blade angle. The actual wind speed was obtained using another measuring tool in the form of a calibrated anemometer in order to convert the numbers displayed by the uncalibrated device.

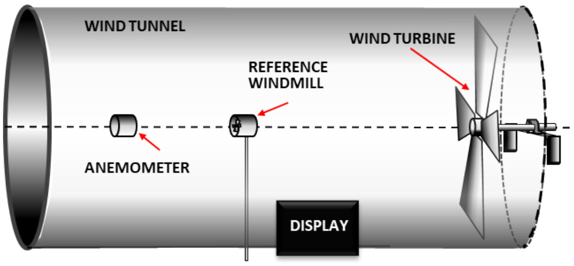

Fig. 6: Wind Tunnel

The tested wind turbine installed in the tunnel is detachable and easily replace. The two types of windmills are tested as follows 1) the first windmill serves as a wind speed gauge, and its measurement is used as a reference, and 2) the blade angles of the tested wind turbine is adjusted manually and automatically. The measurements were obtained by placing the wind tunnel at a height of 10 meters and being blown by natural wind. The test is carried out several and at different angles to realize the blades' characteristics towards wind speed changes. Fig.7 shows some of the raw data from the test results, which were directly, recorded using the PLX-DAQ application program. The red and blue curves signify the change in the reference wheel's rotational speed and turbine, respectively. This data shows the comparison between the two turbines, furthermore the amplitude of the reference wheel was not converted to a calibrated wind speed.

Figure 7 shows that the data is in the form of images, and extremely difficult to understand because the different values are unreadable.

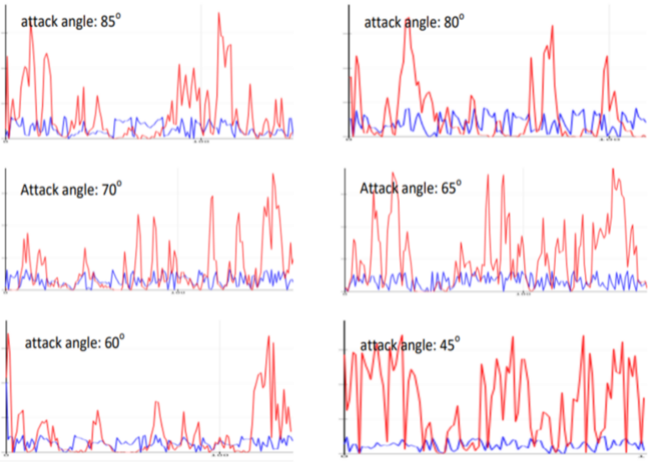

Fig.7: Comparison of Windmill Reference and Wind Turbine Speed Response Curves

Therefore, the difference is determined, by comparing the areas between the two. However, to make it easier, a retest was carried out in accordance with a numeric display. These numbers were added and compared to realize a value called the tip speed ratio.

According to Fig. 7, the turbine's rotational speed at 45° is flat and always low. A significant change in wind speed slightly alters the speed of the turbine. A method of translating the curve is to compare the areas under the two's rotational speed curve, which is known as the tip speed ratio, as shown in Table 1 and Fig.8.

Table 1: Tip Speed Ratio

No.	Attack angle	Tip speed ratio
1.	85	0.170447
2.	80	0.284669
3.	70	0.411112
4.	65	0.575033
5.	60	0.207012
6.	45	0.145732

Fig.8 shows that the most appropriate energy conversion occurs at the attack angle between 63° and 75°, which has a tip speed ratio greater than 3. Therefore, it is better to set the initial attack angle between 75° and 80°. Although at 80° there is no torsional force from wind energy, 75° is selected by adjusting the springs to obtain a dead area. This implies that it is unable to change the attack angle to a certain turbine rotational speed. Conversely, selecting an initial attack angle greater than 80° tends to be problematic at a tip speed ratio that is extremely low.

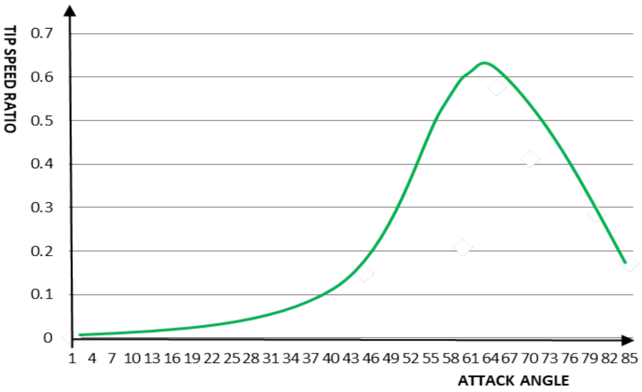

Fig.8: Tip Speed Ratio

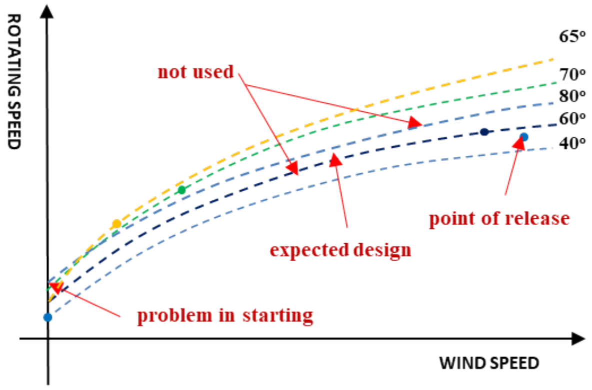

Fig.9: Design of Windmill Response to Changes in Wind Speed

Figure 9 shows a miniature four-blade wind turbine equipped with four pendulums, which serves as a control for the rotational speed, is shown in Fig.10. The test is carried out by installing a wind tunnel placed at a height of 10 meters to expose it to the natural wind. A recorder is used to record and observed system performance. Based on the responses obtained, a tuning action was carried out in accordance with the level of spring strength to obtain a response curve according to the design. This facility made it possible to realize a response in accordance with expectations.

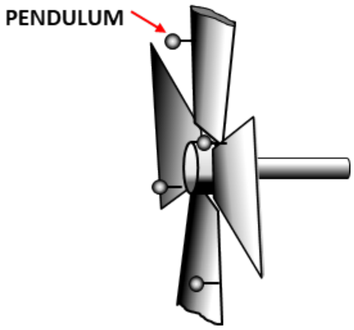

Fig.10: Wind Turbine Cut Equipped with Pendulum

This observation is continued by creating a wind turbine prototype with a diameter and a blade width of 230 cm and 25 cm, respectively. The prototype is equipped with a pendulum and tail tracer of different models for the turbine to always move in the direction of the wind. The observation of the response system is carried out similar to the wheel in the tunnel previously tested.

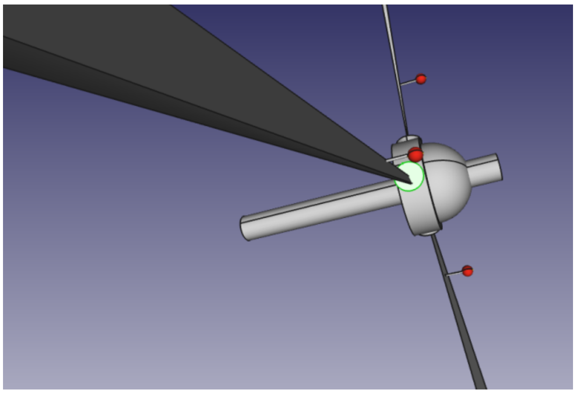

Fig.11: Wind Turbine Prototype

4. Results and Discussions

Based on the constantly changing wind speeds, the test is carried out by recording the data used for analysis. This is because it is impossible to measure the natural wind speed under the same conditions. The torque is closely related to the rotational speed of the turbine in accordance with the same load. Therefore, it is assumed that the maximum rotational speed at a specific load tends to have the highest torque. Furthermore, during data collection and analysis, it is appropriate only to record the rotational speed data, which represents the optimization of the torque obtained. The blade angle also affects the ease of starting conditions, this is because the greater the angle or assuming it is above 70° to the wind direction, the more difficult it is to provide initial rotation on the wind turbine when the angle is extremely small. The difficulty in starting conditions implies an initial low torque. Therefore, this analysis is facilitated by creating a reference windmill that its rotational speed is compared to the turbine. This is carried out because the wind speed is always changing, and it is not repeated. In accordance with the results from this comparative analysis, the tip speed ratio shows that the blade angles between 65° and 70° have the highest efficiency. It is used to design a pendulum with rational size. As long as the results from the mass and rough positioning of the pendulum are rational, it does not result in any problem due to a tuning facility on the spring used to obtain responses according to the curve derived in Fig.9. The numbers that indicate the occurrence of an error is not reported in this study. The selection of spring strength and tuning proficiency is carried out through the try and error tests. However, the unresolved problem is that the blade angle function curve is not a linear equation, therefore the control is limited to a certain angle, namely 1) the control model with an angle of 70° down or 2) the control model at an angle of 60° and above. One advantage of controlling the blade angle of 70° down is that when the wind speed is excessive or a storm occurs, it releases the springs, and the angle becomes 0° or does not rotate. The control model adopting this type of pendulum has disadvantages, namely: 1) the design for poor starting conditions and 2) reducing the efficiency of the wind turbine in order that a larger turbine is needed to obtain similar energy, and this is not liked by some people.

5. Conclusion

This research developed a three-blade wind turbine speed control model by attaching a pendulum with an arm length of ¾ to the edge of the blade protruding forward. This attachment helps to change the blades' center of gravity to produce a resultant overall force that generates a torsional impact. The torsional force is affected by the weight of the pendulum, arm length, and wind turbine rotational speed. It is also held back by the spring with an adjustable force. Subsequently, it is predicted that the rotational speed is not constant because it needs additional speed to provide an extra twisting force. Irrespective of this, the control model reduces the influence of fluctuating wind speeds and narrows the range of changes in the turbine's rotational speed.

Based on the test results, the maximum power of a wind turbine without a pendulum occurs at a blade angle of approximately 65° to 70°, although some studies reported that it occurs at 85°. However, this is not recommended because it produces vibrations. The default setting value is selected at a blade angle of 75° for easy starting, and when the wind is much, it causes the blade angle to drop between 65° and 70°, which is the angle with the highest tip speed ratio approximately 0.6. Although the correlation between the change in blade angle and wind speed is not a perfect linear relationship, it sufficiently provides adequate speed limiting stability. This stability value also depends on the length of the pendulum arm.

During the implementation, it is necessary to control the spring's opposing force to obtain the narrowest range of rotational speed. Furthermore, when there are excessive wind speeds, a certain amount of energy is automatically wasted by narrowing the effective cross-sectional area at an angle of 45° or decreasing the value of the speed ratio (λ), thereby reducing the rotational speed. The model is implemented and validated in accordance with experimental data with or without a wind tunnel. This consists of a reference windmill, anemometer, and wind turbines under study. Although all measurements were carried out using wireless telemetering, it was recently discovered that the natural wind speed at each measurement point shift is different, therefore only wind tunnels are valid. Theoretically, is the wind speed is calculated with certainty, while in the field, it is extremely difficult to obtain a definite speed range due to the inaccuracy of the measured wind speed, which is always fluctuating as well as the influence of constant springs and the tuning effect of the opposing force. However, the pendulum control system functions appropriately within a narrow range of changes in velocity. One disadvantage of using a speed control such as a pendulum is obtaining precise mechanical measurements to prevent vibrations in rotational conditions.

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References

[1] K. Sholanov, A. Kabanbayev, K. Abzhaparov, “Study and Selection of Parameters ofAutomatically Controlled Wind Power Station with Swaying Sails”, International Journal of Renewable Energy Research-IJRER, vol.10, No.2, pp.765-779, June 2020 (Artikel).

[2] Wei Tong, “Wind Power Generation and Wind Turbine Design”, Boston, WIT Press Southampton, pp.3-48, 2010. (Book).

[3] L. Benaaouinate, M. Khafallah, D. Voyer, A. Mesbahi, T. Bouragba, “Nonlinear Control Based on Fuzzy Logic for a Wind Energy Conversion System Connected to the Grid”, International Journal of Renewable Energy Research-IJRER, vol.10, No.1, pp.193-204, March, 2020. (Artikel)

[4] D. Icaza, F. Cordova, F. Toledo,”Modeling, Simulation and Construction of a Wind Turbine with Chain Multiplication System9 Destined to Rural Areas of the Canton Cuenca-Ecuador”, Conference: 2018 7th International Conference on Renewable Energy Research and Applications (ICRERA), Dec 2018 (Conference Paper)

[5] A. Belkaida, I. Colak, K. Kayisli, R. Bayindir, “Modeling of a Permanent Magnet Synchronous Generator in a Power Wind Generation System with an

Electrochemical Energy Storage", International Journal of Smart Grid, Vol.2, No.4, pp.197-202, December, 2018. (Article)

[6] S. Wharton and J.K. Lundquist, "Atmospheric Stability Affects Wind Turbine Power Collection", IOP Publishing, Environ. Res. Lett. 7 014005, Vol. 7 Iss.1, (2012) 014005 (9pp), January 2012 (Article)

[7] N.S. Çetin , M.A. Yurdusev, R. Ata and A. Özdamar, "Assessment of Optimum Tip Speed Ratio of Wind Turbines", Mathematical and Computational Applications, Association for Scientific Research, Vol. 10, Iss. 1, pp.147-154, April 2005. (Article)

[8] Yu-Jen Chena, Yi-Feng Tsaib, Chang-Chi Huangc, Meng Hsien Lid, Fei-Bin Hsiaoe, "The Design and Analysis of Passive Pitch Control for Horizontal Axis Wind Turbine", The 6th International Conference on Applied Energy - ICAE2014, Published by Elsevier Ltd., Energy Procedia, vol. 61 (2014) pp. 683-686. Januari 2015. (Conference Paper)

[9] M.M. Pedersen, T.J. Larsen, H.A. Madsen, and S.J. Andersen, "Free-flow Wind Speed from A Blade-mounted Flow Sensor", Wind Energ. Sci., vol. 3, pp.121–138, March 2018 (Article)

[10] Rus T., Rus L.F., Abrudan A., Domnita F.,Mare R., "Experimental Tests in Equipping Vertical Axis Wind Turbines withElectric Generator", International Journal of Renewable Energy Research-IJRER, vol.6, No.2, pp.465-471, 2016. (Artikel)

[11] I. Herráez, B. Akay, G.J.W. van Bussel, J. Peinke1, and B. Stoevesandt, "Detailed Analysis of The Blade Root Flow of a Horizontal Axis Wind Turbine", Wind Energ. Sci., vol. 1, pp.89–100, Januari 2016 (Discussion paper)

[12] D. K. Arya, L. Dewan, "Speed Control of Variable Speed Wind Turbine System", 2015 International Conference on Energy, 2015 International Conference on Energy, Power and Environment: Towards Sustainable Growth (ICEPE), IEEE, DOI: 10.1109/EPETSG.2015.7510078, Shillong, India, July 2016. (Conference Paper)

[13] F. Zhou, J. Liu, "Pitch Controller Design of Wind Turbine Based on Nonlinear PI/PD Control, Shock and Vibration", Xi'an University of Technology, DOI: 10.1155/2018/7859510, 14 pages, Xi'an-China, October 2018.

[14] R. Gao, Z. Gao, "Pitch Control for Wind Turbine Systems Using Optimization, Estimation and Compensation", Renewable Energy, vol. 91, Pages 501-515. June 2016. (Article)

[15] S. Baburajan1, A. Ismail, "Design and Control of the Pitch of Wind Turbine through PID", International Research Journal of Engineering and Technology (IRJET) , vol. 04, Iss. 09, pp. 657-661, September 2017. (Article)

[16] M. Arboui, A. Essadki, T. Nasser, H. Chalawane, "Comparative Analysis of ADRC & PI Controllers Used in Wind Turbine System Driving a DFIG", ", International Journal of Renewable Energy Research-IJRER, vol. 7 No.4. pp.1816-1824, 2017. (Article)

[17] T. Pourseif, A. Afzalian, "Pitch Angle Control of Wind Turbine Systems in Cold Weather Conditions using μ Robust Controller", International Journal of Energy and Environmental Engineering, vol.8, pp.197–207, DOI 10.1007/s40095-017-0231-y, March 2017. (Article)

[18] R. Garduno, M. Borunda, M. A. Hernandez, and G. Zubeldia, "Speed Control of a Wind Turbine Using Fuzzy Logic", Advances in Soft Computing, pp.522-536, DOI: 10.1007/978-3-030-33749-0_42, October 2019 (Book Chapter)

[19] M. Chirca, M. Dranca, C. A. Oprea, P. D. Teodosescu, A. M. Pacuraru, C. Neamtu and S. Breban, "Electronically Controlled Actuators for a Micro Wind Turbine Furling Mechanism", Energies, vol.13 Iss. 14, August 2020. (Article)

[20] B.O. Karimovitch, B.Z . Kuttybekovitch, (Publication), "Pendulum wind turbine", Patent, International application published with international search report, French, Russian, Publication of WO2010098648A1. 2010. (Patent)

[21] 王川, "Pendulum speed control wind driven generator", Patent, Application CN200910073819A (China), 2010. (Patent)