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Overview and Design of self-acting pitch control mechanism for vertical axis wind turbine using multi body simulation approach

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Abstract. Awareness about wind energy is constantly growing in the world. Especially a demand for small scale wind turbine is increasing and various products are available in market. There are mainly two types of wind turbines, horizontal axis wind turbine and vertical axis wind turbines. Horizontal axis wind turbines are suitable for high wind speed whereas vertical axis wind turbines operate relatively low wind speed area. Vertical axis wind turbines are cost effective and simple in construction as compared to the horizontal axis wind turbine. However, vertical axis wind turbines have inherent problem of self-start inability and has low power coefficient as compare to the horizontal axis wind turbine. These two problems can be eliminated by incorporating the blade pitching mechanism. So, in this paper overview of various pitch control systems is discussed and design of self-acting pitch mechanism is given. A pitch control linkage mechanism for vertical axis wind turbine is modeled by multi-body approach using MSC Software. Aerodynamic loads are predicted from a mathematical model based on double multiple stream tube method. An appropriate airfoil which works at low Reynolds number is selected for blade design. It is also focused on commercialization of the vertical axis wind turbine which incorporates the self-acting pitch control system. These aerodynamic load model will be coupled with the multi-body model in future work for optimization of the pitch control linkage mechanism. A 500 Watt vertical axis wind turbine is designed and it is planned to implement the self-acting pitch control mechanism in real model.

1. Introduction

30% of electrical energy produced worldwide is being used by households, and the demand for energy is increasing rapidly causing a strain on existing electricity solutions. The demand for electricity is rapidly growing in urban areas as people are migrating from the big cities. Electricity demand in developed countries is far more different than the developing countries, and undeveloped countries where large scale projects can be a challenge. Developed countries need massive supply of electricity for its own cities for future exponential demand whereas developing countries needs to lift up their un-electrified population with supplying electricity for livelihood along side with urban demand. The price of electricity is increasing every day as well. In short-the micro electricity generation has gained lot of importance in current energy scenario and many wind turbine designs are under development phase to capture power of wind [1].

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Mainly, there are two types of wind turbines, horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). In recent research work it has been documented that VAWTs are more economical and suitable for urban use due to their noise-free and aesthetic design [2]. Still there is a room to improve the efficiency of the VAWTs since they are not completely understood. The VAWT power efficiency can be increased by various means, one by selecting a proper airfoil shape, and a review of different airfoils is given in [3] in which it is found that the thin airfoil performs better than thick airfoil. Secondly, designing a proper airfoil can improve a power efficiency of VAWT, an optimized airfoil to increase the torque output is designed and patented by [4]. Also use of multi-element airfoil in VAWT blade design has shown improvement in power efficiency, [5], [6]. Thirdly, a pitch control system can improve the power efficiency considerably and also eliminate the self-start problem of VAWT, [7]. The theory of blade pitch control has been explained by [8] in which three different ways of pitch control are given. The practical implementation of these methods is tried on research purpose, but there are very few successful research wind turbines with a pitch control mechanism, one of them can be found at [9]. It is time to implement the research out come to develop an industrial product.

In this work an attempt is made to design a VAWT with self-acting pitch control mechanism. Essentially, a blade pitch angle is changed during the rotation of VAWT which reduces the angle of attack and avoid the blade from stalling. Blade pitching can be done by a linkage mechanism in which all three blade will change there angles by same amount of blade pitch angle. The advantage of self-acting collective pitch control system is, it is very simple in construction and easier to implement in the VAWT prototype. It can work for all rotational speed of the VAWT in other words it can work for various tip speed ratios (TSR). The drawback is it is not the optimum solution to increase a the power efficiency. Another mechanism, which work on aerodynamic forces, in which during rotation of VAWT, a freely moving mass will move in and out along the blade arm to adjust the blade pitch angle. It is also called stabilized mass balance in which aerodynamic force creates the blade pitch movement. The drawback of this system is it can be optimized for particular rotational speed. A VAWT of particular dimensions is designed and a multi body simulation approach is used to design a blade pitch linkage mechanism. A MSC software tool, ADAMS 2013.1 is used to model the VAWT and a blade pitch linkage mechanism. The job of deciding sizes of linkage element had become easier due to the simulations in MSC software tool. Initially single blade with its rotating arm was modeled and rotational joints were defined and then motion was imposed to the rotor arm. It was very convenient to introduce an angle measure for blade pitch which helped to finalize the linkage sizes.

The purpose of multi body approach is to determine in future the physical properties of the VAWT, such as mass of blade, mass of blade arm and optimized sizes of blade pitch control linkage mechanism. A predicted load of on VAWT will help to parameterize all these physical properties of different element of VAWT. Further, the moment at the VAWT tower can be calculated for design of support structure. A displacement of blade structure due to aerodynamic loading can also be calculated for design of blade arm.

In selection of airfoil and design of VAWT, an overview of airfoils used for VAWT blade design is given and an appropriate airfoil is selected and later on design specifications are given. and design of VAWT is given. In aerodynamics of VAWT and pitch angle calculations, a method to determine the aerodynamic forces is selected and the detail about pitch angle determination is given. In pitch control system modeling, an overview of different pitch control methods are discussed and further a multi body approach is used to design a self acting pitch control linkage mechanism. In simulation and results, power coefficient versus wind speed and tip speed ratio is calculated with and without pitch control. Also a future work is discussed. In conclusion, the outcome of the research work is submersed.

2. Selection of airfoil and design of VAWT

2.1. Airfoil

The airfoil is main concern in the success of VAWT performance. Until recently VAWT is been not in focus of researchers after HAWTs commercial success in late 90's to develop the highly efficient technological product. Now it has become interest for many researchers to look back the aerodynamics of VAWT so that the proper airfoil can be designed. There are few successful commercial product which are developed based on aerodynamic airfoil design for VAWT application [10]-[12]. The result of this ended with interesting discoveries, and lead to the innovative VAWT commercial products [1]. The airfoil shape contributes in the generation of a lift coefficient by pressure difference in upper and lower surface.

In this paper, a recently designed airfoil for a small horizontal axis wind turbine is used which startup at a low wind speed, the airfoil is called *airfish* AF300, [13]. The author has mentioned that, this airfoil works for Reynolds number ranging from Re = 38,000 to Re = 205,000, which means, it is intended for low wind speed condition. AF300 is designed by addition of 1% to 3% in the trailing edge of the airfoil S1223 and 1% to 5% thickness in trailing edge of the airfoil S1210 [14].

2.2. Design of VAWT

A design of rotor for VAWT is very important in which the blade pitch mechanism can be efficiently incorporated with less geometrical complexities. The size of the rotor is based on the solidity and the aspect ratio, for which rotor performance is good at the desired wind speed. The aspect ratio is the ratio of the rotor height to the rotor diameter. The aspect ratio for VAWT of peak power under 20 kW is chosen between 0.5 to 1.5 [15]. The higher the aspect ratio of the rotor, the larger the rotational speed of the rotor due to slenderness. The rotor designed in this work has a height H = 1.5m and a diameter $D_r = 1.25m$ which gives a aspect ratio of 1.2.

Rotor solidity is yet another parameter of VAWT design which is defined as the ratio of the total blade planform area to the turbine swept area. It is well known that, the solidity affects the power coefficient of the rotor and is thoroughly studied by, [16],[17]. The solidity of the rotor can be expressed as,

$$\sigma = \frac{Nc}{D_r} \tag{1}$$

Where N is total number of blades, c is the chord length of the blade and D_r is the rotor diameter. Higher solidity means the higher peak power coefficient due to to fact that it gives more torque as compare to the less solidity rotor. However, the power coefficient over tip speed ratio remains narrow. The solidity of the rotor, is depends on the range of the operating speed of the rotor. The rotor which is designed for low wind speed, will have low rotational speed, and it has to have a high solidity and vice a versa. So, it is better to choose moderate range of operating speed by compromising power coefficient and the total power output. As observed by Kirke, the solidity for the straight-bladed VAWT is good between 0.1 to 0.3 [16]. In this work a solidity $\sigma = 0.27$ which falls within the best range.

It is well known that the VAWT creates cyclic vibrations due to periodic loading which is critical for mechanical structure and electrical power system design. Periodic fluctuation occurs due the number of blades used in VAWT. A two-bladed VAWT has a higher torque fluctuation than the three-bladed VAWT, and so forth, [18]. The position of blade and the variation of aerodynamic forces on these blades causes the torque fluctuations and self starting issues [19]. A three-bladed VAWT with 120° azimuthal angle difference has less torque fluctuations due to the relatively steady aerodynamic forces. Also, three-bladed VAWT has fewer cost than the four-bladed VAWT.

A wind turbine blade is manufactured by hand lay-up process using glass fiber material, for more details on blade manufacturing one may contact corresponding author of this paper. A

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die for AF300 airfoil blade structure is first manufactured and it can be used to make multiple blades. A linkage mechanism is not yet manufactured which will be done after multi-body simulations. An direct electrical alternator of 3 phase is also designed and manufactured. An alternating current and voltage will be measured by a data logger which has a DC current and voltage measuring circuitry. A wind speed, wind direction and a rotor speed can be measured with the customized data logger.



Figure 1. 500 Watt VAWT

3. Aerodynamics of VAWT and pitch angle calculation

The aerodynamics of VAWT and the flow around the rotor are mainly studied with the multiple actuator disc theory [20]. The Velocity components at various locations in the flow area are interesting and calculated by the momentum theory and the blade element theory. The double multiple stream tube method (DMSTM) proposed by [21] is used in this work. In DMSTM, the flow field outside the rotor is divided into two subfields placed; upstream and downstream of the rotor. The fluid flow is considered to be inviscid and incompressible for the calculation of the induced velocity through the each stream tube.

3.1. Pitch angle calculation

In a VAWT with blade pitch control mechanism, a blade is rotated by an angle for which the torque is maximum. Change of blade angle causes reduction in the flow angle. From Figure 2, the expression of the flow angle is given by,

$$\varphi_{ij}(\vartheta_{ij}) = \alpha_{ij}(\vartheta_{ij}) + \beta_{pi}(\vartheta_{ij}) \tag{2}$$

where $\alpha_{ij}(\vartheta_{ij})$ is the local angle of attack, and $\beta_{pi}(\vartheta_{ij})$ is the blade pitch angle for blade 1,2 and 3 in upstream and down stream of the rotor respectively. The blade pitch angle for blade 1,2 and 3 in collective pitch control mechanism is given as follows;

$$\beta_{pi}(\vartheta_{ij}) = \beta_i(\vartheta_{ij}) \sin(\vartheta_{ij}) \tag{3}$$

where i = 1, 2, 3 corresponds to the number of blades and in equations (2) and (3) j = u; $m = 0, cn = \pi$ and for j = d; $m = \pi, n = 2\pi$. A numerical simulation is carried out by keeping



Figure 2. Velocity diagram for airfoil

pitch angle amplitude $\beta_i = \pm 5^{\circ}$. The mechanism is able to accommodate blade pitch amplitude in the range of $\pm 40^{\circ}$. The pitch control mechanism designed in this work has a capability of sinusoidal variation of the blade pitch angle with respect to the blade position in rotor plane. Therefore a flow angle and blade pitch angle variation with respect to the azimuthal position of the blade is plotted in the Figure 3. In Figure 3.a flow angle variation with respect to azimuthal



Figure 3. Azimuthal angle of blade and flow angle a) Flow angle , b) Pitch angle --: TSR=1.25. --: TSR=1.5. --: TSR=2.0. --: TSR=2.5.

angle is shown for selected TSR's. For low TSR the flow angle is higher than the high TSR. The amplitude of blade pitch angle is keep constant for this analysis. However it would be

needed to change according to the flow TSR. In future it planed to design such a system which accommodate the change of blade pitch amplitude with respect to the TSR's.

4. Pitch control system Modeling

4.1. Overview of pitch control system

To extract the more power output from VAWT a blade angle with respect to its axis is changed. This can be done by active or passive force. An overview of different methods used for blade pitching are described in, [8]:

- self acting pitch control also called as passive pitch control.
- force pitch control also called as active pitch control.

A Self acting variable pitch mechanism uses aerodynamic forces to actuate self acting devices and works by creating pitching moment about blade pivot [22]. This method is totally based on the individual aerodynamic load balance on each blade. A formulation of the pitch angle is based on the aerodynamic load balance at each blade. To implement this method in practice, it is difficult to design an optimal mechanism which works in the operating range of the VAWT. The mechanism can perform very well at particular wind conditions. It is not yet commercially implemented in the VAWT, but a conceptual design can be found in [8]. In another mechanism, the passive pitch control system uses mass stabilized or mass spring stabilized blades. In which a mass act as a centrifugal force generator during rotation. One such mechanism is given by [23]. In this concept, a blade starts at a higher angle of attack to produce torque at lower speeds. When the rotational speed increases, the mass is forced outwards, and the blade is moved to a reduced angle of attack.

In the individual blade pitch control method, theses problems of large vibration and complexity of design parameters of the collective pitch control system are eliminated. Aerodynamic performance of the individual pitch control system for VAWT showed an increase in performance by 60% as compared with standard VAWT without pitch control [24]. With this method a pitch angle for each blade is calculated separately by two ways, i) based on sinusoidal input where the pitch angle is directly related to the azimuthal angle of the blade and the magnitude of fixed pitch angle or ii) a pitch angle required for each blade is calculated individually to maximize the VAWT rotor torque.

In forced pitch variation, individual blades are actuated by gears or cam actuator devices called pinson cycloturbine, [25], [26] and [27]. This method is also called collective blade pitch because the change of the pitch angle is same for all blades which varies with the azimuthal position of the blade. To implement this method in practice, it is less complicated than the individual pitch control system. One problem found in this type of mechanism is that blades cannot be configured for high efficiency at high rotational speeds, which results in loss of performance [28]. A study carried out by Hwang et al. showed that the collective pitch control has generated 30% more power output than the similar wind turbine with fixed pitch control system [24]. Also, it is found by Kirke and Lazauskas that, the collective pitch control wind turbine has a higher starting torque and efficiency along with large vibration forces [29]. In this work a forced collective pitch mechanism is designed and will be implemented in VAWT.

4.2. Pitch control linkage mechanism : multi body simulation approach

Multi body system is defined for the VAWT in this section. The purpose of multi body system analysis is to design the parameters of the pitch control system, theses parameters are mainly length of links used to connect the blades. A linkage mechanism is utilized to change the pitch angle of the blade in a cyclic method, which makes this turbine to be a cyclo VAWT. The amplitude of pitch angle is decided by mathematical calculations for which the VAWT can perform well.

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As shown in Figure 4, a pitch angle is changed by a linkage mechanism in cyclic order. Three blades are connected with the three links of same length (L_l) . All three links are pivoted at one end of offset link of length (L_o) , and the other end of the offset link is pivoted at the center of the rotor. The amplitude of offset is decided based on the total amount of blade pitch angle required which is calculated in next section. Ω represents the rotational speed of the rotor, β_p



Figure 4. Schematic of pitch control mechanism

is the pitch angle of the blade. There is a need of the initial setting of the linkage mechanism with respect to the direction of wind flow. Therefore, a offset link is attached with a vane which remains in the direction of wind flow. Vane will rotate the link about its pivot at wind turbine rotor axis, causing the three link pivot to change its orientation at required position. Figure 5 shows the vane attached to the linkage mechanism. The specifications of the VAWT in this are given in Table 1.

| Table 1 | • | Specifications | of | VAWT |
|---------|---|----------------|----|------|
|---------|---|----------------|----|------|

| Description | Symbol | Value | Unit |
|-----------------------|---------|------------------|------|
| Rotor diameter | D_r | 1.250 | m |
| Rotor height | H | 1.5 | m |
| AF300 Airfoil | | | |
| Chord length | c | 0.2 | m |
| Length of Blade link | L_l | 0.625 | m |
| Length of Offset link | L_o | 0.065 | m |
| Range of pitch angle | β | $\pm 40^{\circ}$ | |



Figure 5. Vane for initial setting of mechanism

5. Simulation and Results

A VAWT performance is given by the power coefficient and the total power output. In this work a DMSTM is used to calculate the total power from the VAWT with and without pitch control mechanism. Figure 6.a shows the power coefficient of the VAWT with respect to the wind speed and the Figure 6.b shows the power coefficient of the VAWT versus the tip speed ratio. The



Figure 6. Power coefficient of VAWT a C_p Vs V_{∞} b C_p Vs TSR ——: results without pitch control – – – -: results with pitch control

performance parameters power coefficient and power output of the VAWT are compared with the reference wind turbine (NREL) [30] and it is fund that the mathematical model deviates by 10% from the experimental results. It is accepted to proceed with the accuracy of the mathematical model used in this work. The use of 5° blade pitch angle amplitude has shown improvement of power coefficient by 12%. Also it can be seen from the Figure 7 that the maximum total power output from the VAWT is increased by 20%.



Figure 7. Total power output ——: results without pitch control - - - -: results with pitch control

Conclusion

In this paper overview of various pitch control systems is discussed and design of collective pitch control linkage mechanism carried out with use of multi-body model. Aerodynamic loads are predicted from a mathematical model based on double multiple stream tube method. An appropriate airfoil which works at low Reynolds number is selected for blade design. It is also focused on commercialization of the vertical axis wind turbine which incorporates the collective blade pitch control system. It is observe from the mathematical model that with only 5° of blade pitch angle amplitude there has been increase in the power coefficient of the VAWT by 12%. Further a 500 Watt vertical axis wind turbine is manufactured and it is planned to implement the collective pitch control linkage mechanism. Multi-body model is going to be used for force analysis so that the linkage mechanism can be optimized. Also the purpose of using MSC Software tool was to further develop the dynamic simulation model of VAWT coupled with wind loads for detail structural analysis.

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