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Design and analysis of small wind turbine parameter and output characteristics

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Small wind turbines have emerged as a pivotal source for powering stand-alone and offgrid loads. The power rating of such turbines is less than 10 kW. Such turbines operate at a very low value of reynolds number for which the mechanical output characteristics are very much different from that of its MW class counterpart. As a result, it is essential to design the parameters of the turbine. Further, it is imperative to model the small wind turbine behaviour in order to design a suitable control topology for interfacing the Wind Energy Conversion System (WECS) with the load. In this paper, an algorithm is presented to obtain the parameters and mechanical performance of a 3 kW wind turbine. The analytically obtained characteristic is validated against experimental characteristics reported in literature.

Keywords: *Small wind turbine, reynolds number, tip speed ratio, blade pitch.*

1.0 INTRODUCTION

Energy is the main aspect for socio-economic development. At present, the world wide energy consumption is about 540 quadrillion btu, which is estimated to rise by almost 50% to 820 quadrillion btu within three decades [1]. It is assessed that with the present rate of consumption, the fossil reserves are going to deplete in a span of 100 years [2]. Moreover, the usage of fossil fuels leads to emission of greenhouse gases. While, consumption of renewable energy produces minimal amount of greenhouse gases [3]. Thus the scarcity of the fossil fuels and environmental degradation has shifted the focus of research towards renewable energy [4]. In this regard, wind energy, with a matured technology, substantially low cost of electricity production [5] and less emission of greenhouse gases [6] has emerged as a front runner [7] as compared to other available sources. Across the globe, plethora of research is being undertaken in order to extract power from wind energy so as to meet the load demands of grid, off-grid as well as stand-alone sites [8], [9]. But there is a need to choose suitable wind turbines for stand-alone Wind Energy Conversion Systems (WECS). The WT with an output power rating of less than 10 kW are classified as small wind turbines (sWT) [10]. These sWTs have proved to be the most suitable option for stand-alone load applications [9], [10]. However, the characteristics of sWTs differ considerably from those of large WTs. The inertia of such sWT is very low for which the operational performance is greatly affected by the fluctuating nature of wind speed. In a sWT, considerable portion of the blade operates at very low Reynolds number (Re) [10] for which the lift force (F_l) is less while the drag force (F_d) is high. This requires selection of suitable aerofoils while designing small wind turbines. The aerofoil characteristics of a particular blade section depend on 'Re'. This results in the sWT characteristics (power and torque coefficients) to depend on wind speed and tip speed. During starting, the wind strikes perpendicularly to the blade surface. This leads to maximum thrust

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force and minimum lift [10]. If the running performance of all the blade sections is optimized then it results in a very low starting torque for the turbine. Therefore, a compromise [10] between good running and starting performance is made while designing the blade section for sWT. For a finite blade length, there is a sheet of trailing vortices at each blade section [11]. These vortices induce both axial and rotational components in the wind flow which causes a variation in the resultant total wind speed (W) relative to the blade section. The operating 'Re' at a blade section (which is directly proportional to W and is already low for small wind turbines) thus varies significantly with W which in turn affects the performance of sWTs. In order to design an efficient WECS along with its control strategy for a stand-alone application using sWTs there is a need to study the operational modelling of sWT. The performance of sWT not only depends on the angle of attack and pitch angle but also influenced by variation in Re. Thus in order to predict the performance of sWT it is necessary to model its characteristics accurately. So far, apart from [10], no other research work has developed a model incorporating all these effects in sWTs. Even in [10] the performance computation for different pitch angles is not carried out. Therefore, developing a realistic model for a sWT (at least from the point of view of its aerodynamic performance) to examine its performance,is important for improving the performance of sWT driven generation systems.

In the present research work, a suitable aerofoil (SG6043) has been chosen for designing a 3 kW sWT. The choice is made based on the suitability of this particular aerofoil section for sWT blade design as reported in literature [10]. The experimental data for the lift (C_l) and drag (C_d) coefficients with respect to the angle of attack and Reynolds' number (Re) is available from various sources [10], [11], [13] and [14]. An algorithm is developed using MATLAB^{TM} to decide the parameters of a 3 kW turbine such as the turbine radius, 'chord length' and 'setting angles' of the blade sections along the turbine radius. Based on the obtained design parameters a rigorous analysis of the turbine characteristics against variation in the wind speed and blade pitch angle has been carried out. The results from this analysis are presented in this paper.

The paper is organized as follows. A brief survey about the scope for small wind turbine technology, and the research work carried out in the area of aerofoil for such sWT has been documented in section 2. A discussion on the algorithm developed for modelling a 3 kW turbine followed by the results obtained are presented in sections 3.0 and 4.0 respectively. Section 5.0 concludes the paper.

2.0 SMALL WIND TURBINE TECHNOLOGY

Across the globe, many home owners and small business firms which comprise~~s~~ of stand-alone loads are willing to opt for greener form of energy [15]. In this regard, converting the available wind power into electrical power has proved to be one of the suitable options [7]. But installation of large wind turbines nearer to residential location requires huge land, which has become a major constraint [16]. Therefore, at present, the focus of research has shifted towards the study of small Wind Turbines (sWT) and developing control strategies to efficiently extract power from them [17]. It has been estimated [18] that sWT technology can be an important contributor to energy security and economic development.

2.1 Aerofoil Operation

The wind turbine operates on the principle of aerodynamics. The aerofoils of the blades are designed to provide a pressure difference between the top and bottom layers which gives rise to an upward force that helps in rotating the blade. The various parameters of an aerofoil are shown in Figure 1. The lift force aids in rotation while the drag force exerts a thrust force on the blade. Thus for maximizing the turbine efficiency, the ratio of lift to drag for the aerofoil has to be high. The blade element theory [11] assumes the turbine to be consisting of infinite number of blades which offers no resistance to the wind flow. Considering the turbine to be

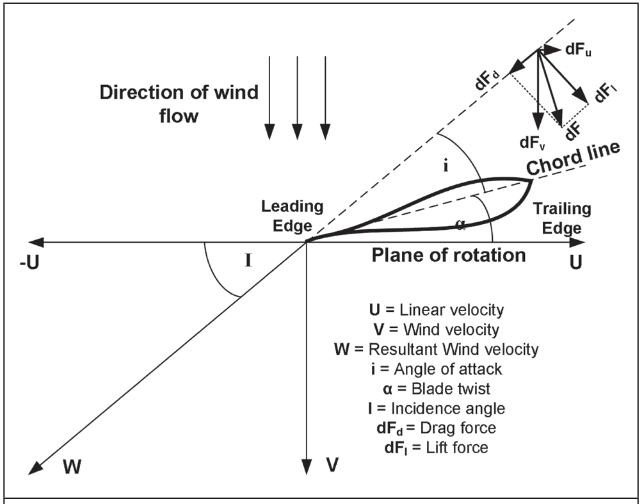

FIG. 1 CROSS SECTION OF THE BLADE AEROFOIL

an ideal rotor, the maximum power coefficient is calculated to be 59.3 % (Betz's limit, [11]). To improve the performance of the turbine the blades sections should be designed in such a way that the lift to drag ratio is maximum throughout the blade. This optimum ratio is obtained at a particular angle of attack [10]. To maintain the same angle of attack over the entire blade span, the blade twist has to be varied. Thus the chord length and twist of the blade is calculated for optimum angle of attack [11]. However, for a finite length the blade rotation induces vortex in the wind flow [10], [11]. This vortex induces velocity component both in axial and rotational directions. The turbine output performance is determined based on this analogy.

2.2 Choice of Turbine Aerofoil

The performance of small wind turbine is highly dependent on the wind flow. Such sWTs operates at a low value of 'Re' which demands the need for a thin aerofoil for designing the turbine blades to obtain better aerodynamic performance [10]. A discussion on the various aerofoils used for blade design can be found in [10], [12]. The most widely used aerofoils for sWT are NACA 6412, 4412, 2412, 0012 [10] from *National Advisory Committee for Aeronautics* (NACA), SG 6043, 6042, 6041, 6040 proposed by *Selig-Giguere* /8(SG) [10], SD7062 and DU06-W-20 [15]. The classification is based on the aerofoil design. These aerofoils have a thinner structure and improved aerodynamic performance at lower 'Re' which makes it suitable for blade design of sWT [15]. From the experimental data it is observed that SG6043 has got the maximum lift to drag ratio as compared to other aerofoils. As the turbine power coefficient increases with increase in the ratio of lift to drag of the aerofoil, in the present work this aerofoil is chosen for calculating the blade parameters of the sWT. However, irrespective of the aerofoil performance, there is a need to study the starting behaviour of the WT. This is essential because during starting the angle of attack is very high [10], [19], [20]. The performance data highlights that at such high angle, the lift coefficient is very low which impedes the rotation of the blades. In [19] a field test is conducted for a 2 m WT to study the starting behavior. An experimental validation of the turbine output performance at rated wind speed is carried out in [20]. Therefore, apart from the choice of aerofoil it is of utmost importance to determine the output performance of the blade at high angle of attack to resolve the issues during starting.

In the present work an algorithm to model a sWT in detail is developed taking into account all these effects. The turbine coefficients (both power and torque) are obtained for different tip speed ratio, wind speed and pitch angle. The efficacy of the algorithm is verified by comparing the results with the performance characteristics obtained experimentally in [20].

3.0 ALGORITHM FOR MODELLING TURBINE PARAMETERS

The steps involved for calculating the parameters of a 3 kW turbine are as follows:

Step 1: Extrapolate the C_L and C_D data for angle of attack (i) varying from -5^0 to 90^0 based on the viterna and corrigan proposition [10]. The equations used are:

$$C_{dm} = \begin{matrix} 1.11 + 0.018(AR) & \text{for AR} < 50 \\ 2.0 & \text{for AR} \geq 50 \end{matrix} \quad ....(1)$$

Generally, the aspect ratio is taken to be less than 50 [2]

$$C_D = C_{dm}\sin^2(i) + B_2\cos(i) \qquad ....(2)$$

$$C_L = \frac{1}{2}C_{dm}\sin(2i) + \frac{A_2\cos^2(i)}{\sin(i)} \qquad ....(3)$$

where

$$B_2 = \frac{C_{ds} - C_{dm}\sin^2(i_s)}{\cos(i_s)} \qquad ....(4)$$

$$A_2 = \frac{(C_{ls} - C_{dm}\sin(i_s)\cos(i_s))\sin(i_s)}{\cos^2(i_s)} \qquad ....(5)$$

where i_s corresponds to a low angle of attack and Cls is the lift coefficient corresponding to i_s .

Step 2: Choose an initial value of the power coefficient (C_p), rated wind speed (V_o) and blade number (b) to calculate turbine radius (R). The equation used is

$$R = \sqrt{\frac{P \times 1000}{\frac{1}{2}\rho C_p \pi V_o^3}} \qquad ....(6)$$

Step 3: Choose an initial value of the optimum tip speed ratio (λ_o).

$$\lambda_o = \frac{\omega R}{V_o} \qquad ....(7)$$

Step 4: Divide the blade into smaller subsections (r). Choose the optimum value of angle of attack from the data sheet (i_o). Calculate tip speed ratio (λ), per unit chord length (l) and twist (α) at each blade section by considering the drag force (∂F_d) to be zero. The equations used for calculation are [10]:

$$\lambda = \lambda_o r_1 = \frac{\omega r}{V_o} \qquad ....(8)$$

where, $r_1 = \frac{r}{R}$, ω is the rotational velocity of the turbine

$$l = \frac{16\pi}{9rb\lambda_o^2 C_{lo}} \qquad ....(9)$$

$$\alpha = \tan^{\ 1} \ \frac{2 - 3\lambda_o r\tan(i_o)}{3\lambda_o r + 2\tan(i_o)} \qquad ....(10)$$

Step 5: Calculate the axial induction factor (a), rotational induction factor (a'), wind velocity (V), linear velocity (U), resultant wind velocity (W) and Reynolds number (Re) at each section. The equations involved are given in [10], [11].

The downstream wind velocity (V_∞) and linear velocity (U_∞) are given as

$$V_\infty = kV_o \qquad ....(11)$$

$$U_\infty = (\omega + \Omega)r = hr\omega \qquad ....(12)$$

where, Ω is the induced rotational velocity, k and h are given as a general function of θ

$$\theta = \frac{1}{3}\cos^{\ 1} \ \frac{1}{\sqrt{\lambda^2 + 1}} \ + \frac{\pi}{3} = \frac{1}{3}\tan^{\ 1}(\lambda) + \frac{\pi}{3} \qquad ....(13)$$

$$k = \left(\sqrt{\lambda^2 + 1}\right)\cos(\theta) \qquad ....(14)$$

$$h = \sqrt{1 + \frac{1 \quad k^2}{\lambda^2}} \qquad ....(15)$$

V and U are expressed in terms of k and h respectively as

$$V = \frac{V_o + V_\infty}{2} = V_0 \ \frac{1 + k}{2} \qquad ....(16)$$

$$U = \omega + \frac{\Omega r}{2} = \frac{1+h}{2}\omega r \quad ....(17)$$

The obtained values of V and U are expressed in terms of a and a’ respectively as

$$V = V_o(1 - a) \quad ....(18)$$

$$U = V_o(1 + a')\lambda \quad ....(19)$$

where a and a’ are given as

$$a = \frac{1 - k}{2}\ ;a' = \frac{h - 1}{2} \quad ....(20)$$

The resultant velocity (W) is given as

$$W = \frac{V}{\sin(I)} = \sqrt{V^2 + U^2} \quad ....(21)$$

where I is the incidence angle as shown in Figure 1.

The Reynolds number (Re) is calculated using the equation [21]

$$Re = \frac{WlR}{\nu} \quad ....(22)$$

where, ν is the co-efficient of viscosity. The value at STP is $\nu = 15.68 \times 10^{6}$ [10].

Step 6: Compare the ‘Re’ value at the blade tip with the rated operating ‘Re’ of the chosen aerofoil. If the error is within 100 proceed. Otherwise decrement the value of λ_o by 0.0001 and go to step 3.

Now consider drag force to be non-zero

Step 7: Choose i from -5^0 to 90^0.

Step 8: Choose r from 0.2 to 1.

Step 9: Calculate various parameters at each section for a particular value of i. Choose an initial Re for iteration. Obtain the value of C_L and C_D by using linear interpolation. Calculate the ratio of C_L and C_D, incidence angle (I), lift (∂F_L), drag (∂F_D), thrust (∂F_T) and moment (∂F_M) forces, k and h at each section. The equations used are given in [10], [11]:

$$\varepsilon = \tan^{\ 1}\frac{C_D}{C_L} \quad ....(23)$$

Using the values of α and l obtained in step 4 calculate

$$I = i + \alpha \quad ....(24)$$

$$\partial F_L = \frac{1}{2}\rho C_L W^2 l \partial r \quad ....(25)$$

$$\partial F_D = \frac{1}{2}\rho C_D W^2 l \partial r \quad ....(26)$$

The resultant forces along the direction of wind flow (∂F_V) and plane of rotation (∂F_U) are given as

$$\begin{aligned}\partial F_V &= \partial F_L \cos(I) + \partial F_D \sin(I) \\ &= \frac{1}{2}\rho l W^2 (C_L \cos(I) + C_D \sin(I))\partial r\end{aligned} \quad ....(27)$$

$$\begin{aligned}\partial F_U &= \partial F_L \sin(I) \quad \partial F_D \cos(I) \\ &= \frac{1}{2}\rho l W^2 (C_D \sin(I) \quad C_L \cos(I))\partial r\end{aligned} \quad ....(28)$$

The thrust force ∂F_T in terms of ∂F_V and blade number is given as:

$$\partial F_T = b\partial F_V = \frac{1}{2}\rho b l W^2 C_L \frac{\cos(I - \varepsilon)}{\cos\varepsilon}\partial r \quad ....(29)$$

The thrust force in terms of Thrust co-efficient (C_T) is given as:

$$\partial F_T = C_T \rho \pi V_o^2 r \partial r \quad ....(30)$$

where, C_T is given as

$$C_T = \begin{matrix} 4a(1-a) = 1-k^2 & \text{for } 0 < a < 0.5 \\ 4a(a-1)+2 = 1+k^2 & \text{for } 0.5 < a < 1 \end{matrix} \quad ....(31)$$

Equating (29) and (30), we have

$$G = \frac{C_L bl\cos(I-\varepsilon)}{8\pi\pi rco(\varepsilon)\sin^2(I)} \quad ....(32)$$

$$G = \begin{matrix} \frac{1-k}{1+k} = \frac{a}{1-a} & \text{for } 0 < a < 0.5 \\ \frac{1+k^2}{(1+k)^2} = \frac{4a(a-1)+2}{4(1-a)^2} & \text{for } 0.5 < a < 1 \end{matrix} \quad ....(33)$$

$$k = \begin{matrix} \frac{1-G}{1+G} & \text{for } G < 1 \\ \frac{G-\sqrt{2G-1}}{2(1-G)} & \text{for } G > 1 \end{matrix} \quad ....(34)$$

The moment force (∂M) in terms of ∂F_U is given as:

$$\partial M = rb\partial F_U = \frac{1}{2}\rho blW^2 C_L \frac{\sin(I-\varepsilon)}{\cos\varepsilon} r\partial r \quad ....(35)$$

The moment force (∂M) in terms of change in linear velocity is given as:

$$\partial M = \rho\pi^3 V_o (1+k)\omega(h-1)r\partial r \quad ....(36)$$

Equating (35) and (36), we have

$$E = \frac{h-1}{h+1} = \frac{C_L bl\sin(I-\varepsilon)}{4\pi\pi rco(\varepsilon)\sin(2I)} \quad ....(37)$$

$$h = \frac{1+E}{1-E} \quad ....(38)$$

Step 10: Calculate the 'Re' at each section. Compare the present value of 'Re' with its value obtained in the previous iteration. If the error is within 100 proceed. Otherwise go to step 9.

Step 11: Calculate sectional tip speed ratio (λ) and m_r for the obtained values of k and h. The equations are given as:

$$\lambda = \frac{1+k}{1+h}\cot(I)\frac{1}{r} \quad ....(39)$$

$$m_r = (1+k^2)E\cot(I)r^2 \quad ....(40)$$

Step 12: Increment r by 0.001. Check whether r is equal to 1. If not go to step 8, otherwise proceed.

Step 13: Increment i by 1^0. Check whether i is 90^0. If not go to step 7, otherwise proceed.

Step 14: Interpolate mr versus r for different λ and remove the duplicate elements.

Step 15: Calculate torque co-efficient (C_m) over the entire blade section. The equation is given as:

$$C_m = 2\int_{0.2}^{1} m_r \partial r \quad ....(41)$$

Step 16: Calculate the power co-efficient (C_p) from C_m using Equation (42)

$$C_p = \lambda C_m \quad ....(42)$$

Step 17: Compare the calculated C_p with the value obtained in previous iteration. If the error is within 0.00001, end the process. Otherwise go to step 2.

Step 18: Obtain the final vales of l, α, R, λ_o and Optimum power co-efficient (C_{po}).

This algorithm is used to develop a program in MATLAB™ to calculate the turbine parameters with a rated power output of 3 kW. The rated wind speed is chosen as 9 m/s [20]. The program is used to determine the variation of chord length and twist along the blade section. Further, these parameters are used to determine the torque and power coefficient at rated wind speed and fixed pitch angle of 0^o. Based on the maximum power coefficient, the radius and the optimum angular speed of the turbine are calculated. These parameters are then used to obtain the turbine characteristics at different wind speed and pitch angles.

4.0 RESULTS AND DISCUSSIONS

The small wind turbine operates at low Reynolds number (Re). However, the experimental values of the aerodynamic lift (C_l) and drag (C_d) coefficients of the aerofoils under this operating condition are difficult to obtain. In the present work the extrapolation technique given by Equations (1) – (5) are adopted to generate those data at low Re. Then by linear interpolation method, the data is calculated at smaller step sizes of Re and angle of attack (i). A three dimensional plot of C_l and C_d versus Re and i are shown in Figure 2 and 3 respectively.

It is observed that at Re > 10^5 both C_L and C_d rises with increase in i, reaches a maxima and then falls. The magnitude of C_l is greater than C_d by an order of 10. This is because at higher Re, the wind flow does not remain attached to the blade surface for which lift force is greater than drag. Again, with increase in i till 20^0 both lift and drag coefficients increase. With further increase in 'i' vortices are created while the wind passes through the blade section. This reduces the lift while increasing the drag. At Re < 10^5, the wind flow is laminar and remains attached to the blade section. This exerts more drag force than lift force. The optimum angle of attack (i_o) for the aerofoil is decided based on the maximum value of the ratio between C_l and C_d at a given Re. These calculated data are used to determine the chord length and twist of each blade section assuming i to be held constant at i_o at a Re value of 250,000.

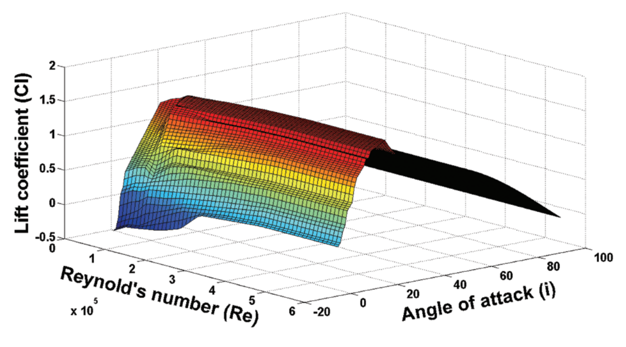

FIG. 2 LIFT

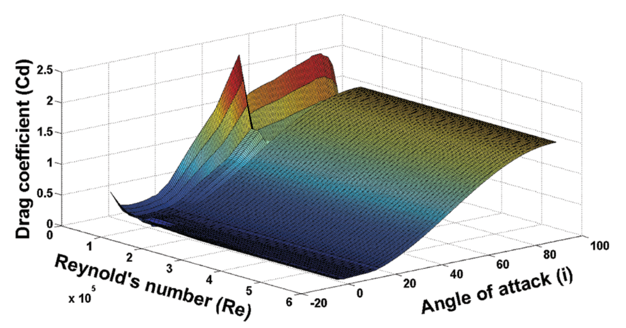

FIG. 3 DRAG CO-EFFICIENT VERSUS ANGLE OF ATTACK AND REYNOLDS NUMBER (RE)

The variation in chord length and twist versus p.u. blade length are shown in Figure 4(a) and 4(b) respectively.

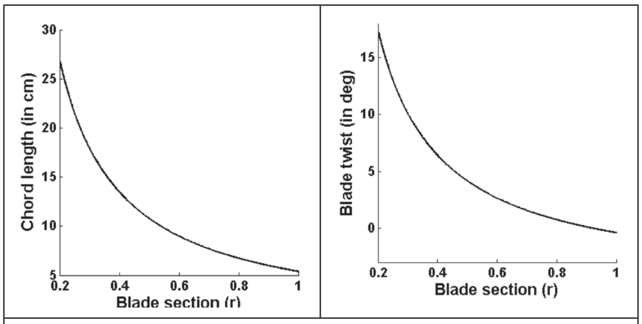

FIG. 4 (A) CHORD LENGTH VERSUS P.U BLADE SECTION. (B) BLADE TWIST VERSUS P.U BLADE SECTION

The variation in chord length maintains a uniform thrust force while that of the twist ensures optimum angle of attack along the blade span. The blade parameters are then used to determine the sectional torque coefficient (m_r) taking into consideration the effect of drag. The turbine torque (C_m) and power coefficient (C_p) at rated wind speed (9 m/s) with a fixed Re (250,000) is obtained. The plot of C_m and C_p is shown in Figure 4. As seen in Figure 5, the optimum value of torque coefficient (C_m) is 0.0645 at a λ equal to 5.5. However, optimum value of power coefficient (C_p) is 0.3812 at a tip speed ratio (λ) of 6.43. The results show that optimum value of C_p is obtained at a higher λ as compared to that of the optimum value of C_m which is in accordance to the characteristics of the turbine [10]. During starting the value of C_m is non-zero while that of C_p is zero. This indicates that the turbine has a positive starting torque. The experimental validation of a 3 kW turbine characteristics with a rated wind speed of 9 m/s is carried out in [20]. The result obtained is reproduced in Figure 6.

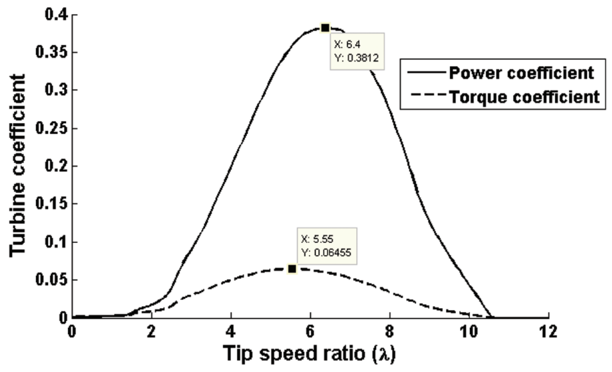

FIG. 5 COMPUTED TURBINE COEFFICIENTS VERSUS TIP SPEED RATIO (Λ)

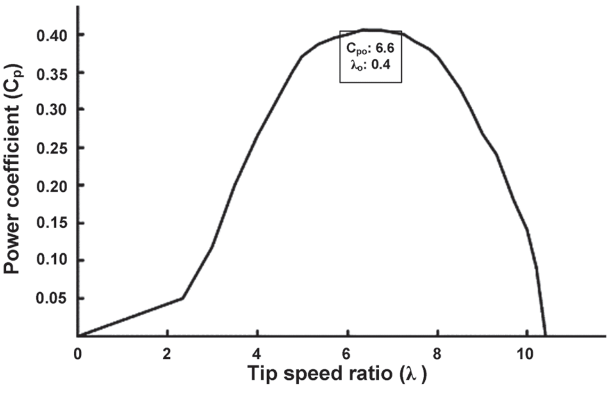

FIG. 6 EXPERIMENTAL C_P VERSUS Λ [20]

It is observed that both the characteristics (in Figure 5 and Figure 6) are similar. This validates the accuracy of the algorithm developed for determining the turbine characteristics. So far, in the available literature, the C_p versus λ characteristics is taken to be constant irrespective of variation in the wind speed. This is based on the assumption that the turbine operates at a fixed Re. However, sWT performance relies on Reynolds number which is a function of the wind speed. To examine this, the turbine characteristics are calculated at varying wind speeds. It is observed that the maximum value of power coeffeceint decreases from 0.37 to 0.3 with decrease in wind speed from 9 m/s to 4 m/s at a pithc angle of 0^0. Further, the turbine characteristics are examined for two different pitch angles (β) i:e 0^0 and 10^0. With increase in pitch angle the optimum power coefficient reduces from 0.37 to 0.19 at rated wind speed of 9 m/s. A three dimensional plot of C_p versus λ, V and β are shown in Figure 7 (a) and 7 (b).

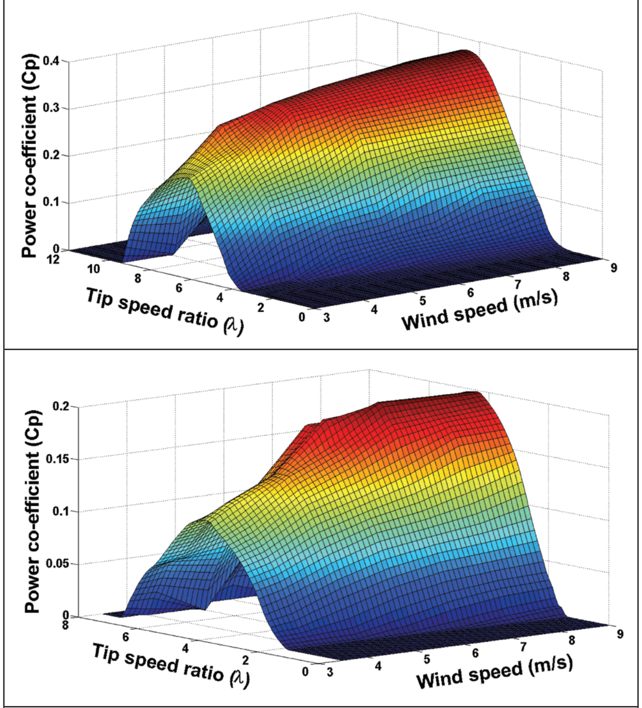

FIG. 7 TURBINE POWER COEFFICIENT VERSUS TIP SPEED RATIO AND WIND SPEED FOR PITCH ANGLES OF (A) 0^0 (B) 10^0

5.0 CONCLUSIONS

A complete modeling of the characteristics of a 3 kW WECS is attempted in this work. To begin with an algorithm to obtainthe exact characteristics of a small wind turbine is developed. This involves incorporating the effect of variation in Reynolds number, tip speed ratio, pitch angle and wind speed. From the algorithm it is concluded that the power and torque coefficients of small wind turbine are highly dependent on the Reynolds number which in turn is a function of the wind speed. Therefore it is imperative to consider the effect of wind speed variation while modeling the power versus tip speed ratio characteristics of a small wind turbine.

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REFERENCES

[1] EIA international energy outlook 2014.

[2] B P Statistical Review of World Energy June 2014.

[3] M Höök and X Tang, Depletion of fossil fuels and anthropogenic climate change—A review, Energy Policy, Vol. 52, pp. 797–809, Jan. 2013.

[4] D Nugent and B K Sovacool, Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey, Energy Policy, Vol. 65, pp. 229–244, Feb. 2014.

[5] T C Kandpal and L Broman, Renewable energy education: A global status review, Renew. Sustain. Energy Rev., Vol. 34, pp. 300–324, Jun.

[6] M Premalatha, T Abbasi, and S A Abbasi, Wind energy: Increasing deployment, rising environmental concerns, Renew. Sustain. Energy Rev., Vol. 31, pp. 270–288, Mar. 2014.

[7] D Y C Leung and Y Yang, Wind energy development and its environmental impact: A review, Renew. Sustain. Energy Rev., Vol. 16, No. 1, pp. 1031–1039, Jan. 2012.

[8] A S Satpathy, N K Kishore, D Kastha, and N C Sahoo, Control Scheme for a Stand-Alone Wind Energy Conversion System, IEEE Trans. Energy Convers., Vol. 29, No. 2, pp. 418–425, 2014.

[9] Z Alnasir and M Kazerani, An analytical literature review of stand-alone wind energy conversion systems from generator viewpoint, Renew. Sustain. Energy Rev., Vol. 28, pp. 597–615, Dec. 2013.

[10] D Wood, Small Wind Turbine Analysis, Design, and Application. Springer, 2006.

[11] Désiré Le Gouriérès, Wind Power Plants Theory and Design. Pergamon, 1982.

[12] M S Selig and B D McGranahan, Wind Tunnel Aerodynamic Tests of Six Airfoils for Use on Small Wind Turbines, J Sol Energy Eng., Vol. 126, No. 4, pp. 986, 2004.

[13] S Worasinchai, G Ingram, and R Dominy, A low-Reynolds-number, high-angle-of-attack investigation of wind turbine aerofoils, Proc. Inst. Mech. Eng. Part A J. Power Energy, Vol. 225, No. 6, pp. 748–763, Jul. 2011.

[14] J Wata, Faizal M, Talu B, Studies on a low Reynolds number airfoil for small wind turbine applications, Sci. China Technol. Sci., Vol. 54, No. 7, pp. 1684–1688, Apr. 2011.

[15] The U.S. Small Wind Turbine Industry. Roadmap, Awea Small Wind Turbine Committee, June, 2002.

[16] G M Joselin Herbert, S Iniyan, and D Amutha, A review of technical issues on the development of wind farms, Renew. Sustain. Energy Rev., Vol. 32, pp. 619–641, Apr. 2014.

[17] Z Simic, J G Havelka, and M Bozicevic Vrhovcak, Small wind turbines – A unique segment of the wind power market, Renew. Energy, Vol. 50, pp. 1027–1036, Feb. 2013.

[18] M Carolinmabel and E Fernandez, Growth and future trends of wind energy in India, Renew. Sustain. Energy Rev., Vol. 12, No. 6, pp. 1745–1757, Aug. 2008.

[19] P R Ebert and D H Wood, Observations of the starting behaviour of a small horizontal-axis wind turbine, Renew. Energy, Vol. 12, No. 3, pp. 1–13, 1997.

[20] H M Kojabadi, L Chang, S Member, and T Boutot, Development of a Novel Wind Turbine Simulator for Wind Energy Conversion Systems Using an Inverter-Controlled Induction Motor, IEEE Trans. ENERGY Convers., Vol. 19, No. 3, pp. 547–552, 2004.