Newer Dimension in Harnessing Wind Energy

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Abstract

Harnessing the wind energy and development thereto remains a good consideration since the era of windmills. Many a wind energy converter system (WECS) are in use in practice. Most of such windmachines have basic construction with a single bladeset mounted on a shaft to rotate. What may be the impact of having multiple number of bladesets mounted on the same shaft? Experiment with two bladesets mounted on a shaft provides encouraging hints for venture towards probe and progress as newer dimension in more gainful harnessing the wind energy.

Keywords Windmills, WECS, bladeset, aerodynamics, power coefficient, torque coefficient, rotor, efficiency

1. INTRODUCTION

In the study regarding new and newer technology and harnessing of secondary source of energy, the wind energy being freely available and non-polluting resource of renewable energy remains a widely cultivated dimension in the field of Research and Development. Wind energy potential available in the natural wind over the earth's surface is estimated to be in the order of $1.6*10^7$ MW, which is comparable to the energy consumption on the earth.

Windmills have been in use since long time ago for various purposes viz grain crushing, water pumping like mechanical work. The progressive development activities have brought into reality the methods and processes for conversion of the kinetic energy of the moving air into useful mechanical or electrical or suitable form of energy. Varieties of Wind Energy Converter System (WECS) are in use serving general and specific purposes.

Windmill demonstrated the philosophy behind utilizing the wind energy with the underlying concept of rotating a shaft by way of intercepting the linear motion of moving air by a radial bladeset mounted on the shaft to be rotated.

Windmills (figure 1) located near seacoast or mountains exploited the higher speed of wind at higher altitude. Progressive work provided various findings and data related to speed and behavior of wind, the efficient conversion of wind energy primarily into mechanical energy and other useful form of energy. Measurement of wind speed indicated 20-25 % higher speed at about 10m higher altitude and a non –linear relationship between wind speed and altitude from the earth surface (figure 2).

The development of windmachines and system apparently were focused on many aspects including the probe and progress to theoretical and practical cultivation regarding the following outlines.

a) Deriving wind power from wind of high speed/ high energy domain
b) Constructional and technical features related to types of WECS
c) More efficient conversion of wind energy to mechanical and subsequent suitable form of energy
d) Design of wind rotor
e) Performance and control of WECS

The effect of mounting multiple number of bladesets on the rotor shaft and the investigations there to may render the state-of-the-art newer dimension and technology in improving the exploiting of wind energy. The inter and intra relation of parameters and modification of construction and performance remains a feasible novel addition and prospect in the field.

2. DEVELOPMENT – OUTLINES

2.1 Types of Wind Energy Conversion System (WECS)

Windmills of earlier times, pioneer in field, led to the investigation and development of WECS of varieties categorized into horizontal axis and vertical axis types of equipment.

The horizontal types include

a) Dutch-type grain grinding windmills
b) Multiblade water pumping windmills
c) High-speed propeller type windmachines

The vertical axis turbines come into two different basic design a) The Savonius rotor, b) The Darrieus rotor

Various types of WECS have typical constructional features and design of bladeset to face and interfere the wind input for the purpose of rotating the rotor shaft towards conversion to mechanical energy primarily. A few types of WECS are indicted in figure 3.

2.2 Solidity

Solidity is the ratio of the projected blade area and the area of the wind interfered by the blade.

The multiple water pumping windmills of high torque and low speed has solidity nearly 0.7. The high-speed low torque horizontal axis wind machines have the solidity range from 0.01 to 0.1 and suitable for electric power generator.

Tip Speed Ratio: It is dependent on R, N and V as given by

TSR $\lambda = \frac{2\pi RN}{V}$……………………………………………………………………………………………….(1)

λ = TSR (non-dimensional)

R = Radius of the swept area by the bladeset (m)

N= Rotational speed of the shaft (Revolution per second)

V = The wind speed without rotor interference (m/s)

The TSR of water pumping windmachines is generally low and of high-speed wind machines is high, even may be about 9.

2.3 Efficiency of wind energy conversion and limit

It is considered an ideal converter in the form of a disc of area A which extracts some power from that contained in the wind flowing through it (figure 10. (a))

V_1 = the velocity of the incoming air unaffected by the rotor interference,

v = the velocity of the air passing through the disc,

V_2 = the velocity of the outgoing air at some infinite distance from the disc,

p = the pressure at incoming and outgoing air

$p^+ - p^-$ = the pressure difference between two sides of the disc,

α = factor for axial interference by radial bladeset.

It is assumed that the flow of wind is axial and that no rotational kinetic energy is imparted to the air stream. Some relations are obtained

$p^+ - p^- = \rho(V_1^2 - V_2^2)/2$……………………………………………………………………………………….……….(2)

ρ = density of air assumed constant throughout the flow.

The thrust T on the disc is given by

$T = \rho A(V_1^2 - V_2^2)/2$……………………………………………………………………………………...……(3)

$v = (V_1 + V_2)/2$…………………………………………………………………………………………………..(4)

Considering the axial interference factor α, it appears

$v = V_1 (1- \alpha)$ ……………………………………………………………………………………….………………(5)

$V_2 = V_1 (1- 2\alpha)$ …………………………………………………………………………...…………………..(6)

Power extraction is given by drop in kinetic energy of the air stream per unit time,

$P_1 = 2 \rho A V_1^3 \alpha (1- \alpha)^2$……………………………………………………………………………………………(7)

i.e., the power output is a non-linear function of α.

At that two extreme values α = 0 and 1, the power output is zero. There is some maximum value of power output at some value of α between 0 and 1. It follows that at α = 1/3, the power extraction appears to be maximum

$P_{max} = 16 P_0 /27$ ………………………………………………………….…………………….…………..(8)

Which is reached when $v = 2 V_1 /3$

This means that the maximum theoretical power extractable from wind is 16/27 of the power P_0 contained in the wind.

2.4 Basic Principle of Wind Energy Conversion

The kinetic energy contained in the moving air given by

$P_1 = \rho A V_1^3/2$……………………… ………………………………………………………………….…………(9)

indicates that this power is proportional to the cube of the wind velocity and also proportional to the area A swept by the bladeset vis-a-vis to the square of the diameter of the bladeset.

The Physical conditions in a wind turbine allows extraction of a part of the available power of the input wind the speed of which subsequently decreases to the minimum at the 'wake'. (Figure 4)

Subsequently the wind stream regains energy from the surrounding air and the free wind speed is restored at a sufficient distance from the rotor. In the process there is corresponding change in air pressure and pressure drop ΔP across the rotor bladeset and consequently the pressure increases to the ambient pressure. The power extraction corresponds to the product of the pressure drop with the wind speed. More is the wind speed and the pressure drop more is the rotor power. But there may appear an increase or decrease of wind speed or the pressure. Hence for the given free wind speed there is a maximum value of rotor power.

2.5 Power Coefficient (C_P)

The power coefficient (C_P) given by the ratio of the power of wind rotor and the power available in the wind provides for the efficiency of conversion of wind energy into mechanical energy.

The graph of the power coefficient against the TSR appeared important in the characteristics of wind energy converters. Typical curves for different types of wind machines are shown in figure 5. It indicated that more is the value of TSR λ, more may be the value of power coefficient C_p in many a cases. When TSR value is nearly 9, the power coefficient tends to reach almost the Betz limit of 16/27 or 0.593.

Even though the power coefficient of an ideal rotor, with propeller type blades of proper aerodynamic design may approaches the Betz limit 0.593, such rotor may not be able to withstand high speed wind. As such the C_P value is kept at 0.4 – 0.45 in practice. In case of conversion into electric power some of the rotor energy is lost and the overall electrical power coefficient of an aerogenerator in practice is about 0.35 or 35%.

2.6 Aerodynamics Of Wind Rotors:

It has been studied the aerodynamics of an aerofoil and developed relations for the various forces acting on a wind mill blade. It provides some typical exposition regarding logical structure which enables estimation of various forces and stresses for preliminary design consideration, although actual design procedure used in industry may involve many complications, particularly for high speed propellor type turbine with electrical power generation. Analysis may progress with vector diagram indicated in figure 6 using the Blade-Element Theory.

The derivations indicated that torque and the aerodynamic power depend on the angle *I*, the angle of inclination, which in turn, depends on the wind speed and rotational speed. The lift and drag coefficients depend on the angle of attack *i*, which is equal to $I - \alpha$ and can be varied by varying the pitch angle α. Thus, a control strategy may be developed whereby a maximum amount of power can be produced at any wind speed by suitably changing the pitch angle α i.e., a design feature of the blade.

The equation for aerodynamic efficiency provides the clue for designing a blade. The typical features like lift coefficient (C_L), the drag coefficient (C_D), angle of incidence provide guidelines for optimizing the aerodynamic efficiency towards better conversion of wind energy to mechanical one.

2.7 Wind Turbine Rotor

The performance of wind turbine much depends on the design of wind rotor. The efficient design of a blade maximizes the lift and minimizes the drag. It needs to be considered that wind velocity is constant throughout the rotor area, but the blade velocity increases from inner edge to the tip. Thus neither the magnitude nor the relative velocity is constant throughout the length of the blade. This reflects the importance of blade design of various designed feature involved in the performance of wind machine and control of it. Obviously the design of rotor includes a) diameter of the Rotor, b) choice of the number of blades in the bladeset, c) choice of blade profile and material, d) determination of blade chord, e) choice of pitch angle α (= $I - i$)

2.8 Power- Speed Characteristics

The rotor speed is the factor for extraction of mechanical power from the wind. For each wind speed there is an optimum turbine speed at which the extracted wind power at the shaft reaches the maximum. This is indicated in the $C_p - \lambda$ curve. Also the C_p depends on the pitch angle. Such dependence and variation are indicated in figure 7.

That the optimum value of C_p, say $C_{p\text{-}opt}$ corresponds to optimum value of λ, say λ_{opt}, needs the rotor speed to be adjustable with varying wind speed so as to adhere to the value λ_{opt} for optimum mechanical power output from the wind machine. With $\lambda = \omega R/V$, the maximum value of shaft mechanical power P_{max}, for any wind speed may be expressed as

$$P_{max} = C_{p\text{-}opt}\,\pi\,(R^5/\lambda_{opt}^3)\,\omega^3/2 \qquad (10)$$

It indicates that the maximum power extractable from wind is proportional to the cube of the rotor speed (ω^3).

2.9 Torque-Speed Characteristics

For proper matching of the load with stable operation of the electrical generator, the typical torque speed characteristics of the two-blade propeller type wind turbine is indicated in figure 8. This profile follows from the power curve, since T is proportional to P/ω. At the optimum operating point ($C_{p\text{-}opt}$, λ_{opt}) the relation between aerodynamic torque and rotational speed reduces to, with usual notations

$$T_m = \rho\,C_{p\text{-}opt}\,\pi\,(R^5/\lambda_{opt}^3)\,\omega^2/2 \qquad (11)$$

It indicates that the torque varies with square of the rotational speed and in terms of C_p the aerodynamic torque becomes

$$T_m = \rho\,C_T\,\pi\,R^3\,V^3/2 \qquad (12)$$

Where $C_T = C_p/\lambda$, is called the Torque coefficient.

2.10 Wind Turbine Control Strategy

For every wind turbine there are several different ranges of wind speed and different speed control strategies. The power vs. wind speed characteristics of variable speed wind machines (figure 9) shows the importance of Cut-in speed and the Furling speed (Cut-out speed). There may be various control strategy for different range of wind speed or for constant speed windmachines. Such control measures also depend on the performance variable including the shaft rotational speed.

3. NEWER DIMENSION

Most of the investigations and development in the field of harnessing wind energy apparently have been based on mainframe equipment in WECS in tune with the conventional wind mills, where all important rotation of the shaft with mechanical energy remains the objective to be accomplished with only a single bladeset mounted on the shaft to interfere the incoming moving air. The findings and results in theory and practice have been used for developing WECS.

World body on energy matters continuously emphasized for new and newer technology or method for better and better exploitation of renewable energy resources. In the field of harnessing wind energy, inspite of good achievement, the question is whether there is scope for further improvement with additional dimension.

3.1 Probe and Progress

Obviously the question arises regarding the impact on the process of conversion and control if there is more than one bladeset mounted on the shaft. Schematics may be indicative in figure 10.

The probe and analysis regarding dynamics of both the schemes (a) and (b) may be considered to follow primarily the same derivation principle as have been opted and established earlier.

3.2 Experiment

Although it is considered that the research on wind energy appeared Capital intensive, some preliminary steps undertaken in finding the primary effect of using two bladesets mounted on the same shaft provides thought provoking indication towards gain and development.

3.3 Observation

With experiment undertaken it appears the finding may provide good clues for further evolution and scope for more progress.

The experimental observation are obtained with the rotation of same shaft with one bladeset and two bladesets, herein identical pair of bladesets with angular phase difference (Table 2). The rotation with two bladeset observed experimentally reflect different magnitude of rotation of the same shaft for same wind source. In some cases, compared to the rotation of the shaft with one bladeset, the rotation of the shaft with first and second bladeset are faster and in some other cases the rotation are slower.

It implies that the position of the second bladeset with respect to the first bladeset is too important and also justifiable in accordance with the basic principle of wind energy conversion.

For first bladeset there is a position of ‘Wake’ (figure 4) and pressure profile. As such the distance l between the two bladeset, setting the position of second bladeset becomes significant.

4. VALIDITY

4.1 Wind Power Conversion

The energy obtained in the moving air being proportional to cube of linear velocity of the wind interfered by a radial blade, the first and second bladeset both interfering the wind are supposed to cause rotation of the shaft when the wind speed before the first bladeset and before the second bladeset are more than cut-in speed. As such by adjusting the position of second bladeset with respect to the ‘Wake’ after the first bladeset, the power due to the second bladeset would be effectively additional to the power converted due to the first bladeset.

Thus, where suffix 1 and 2 belong to first and second bladeset, it appears with usual notation,

$P = P_1 + P_2$

$= \eta_1\ \rho\ A_1 V_1^3/2 + \eta_2\ \rho\ A_2 V_2^3/2$ ………………………………………………………………………………..(13)

It indicates that the second bladeset helps in getting better conversion of wind energy to mechanical energy of the shaft and the improvement in power coefficient of the system.

4.2 Rotation of the shaft

The power is the multiplication of torque and angular velocity. So addition of power contributes to the torque and/or the rotation of the shaft. The change of torque will correspond to the increase or decrease in rotation of the shaft.

4.3 TSR

For the two bladesets it would appear

$\lambda_1 = \pi R_1 N/V_1$ and $\lambda_2 = \pi R_2 N/V_2$ ………………………………………………………………………………….(14)

as the shaft being common will have only one N for both the bladesets. This indicates that R_1/V_1 and R_2/V_2 have effect on the magnitude of λ_1 and λ_2. The figure 7 may correspondingly undergo some modification.

4.4 Aerodynamics of Wind Rotors with Two Bladesets

For the two bladesets of aerofoil shaped blade, there would be two separate diagrams like figure 6 although the rotation of the shaft is same for both the bladesets mounted. The value of axial speed of wind would be V_1 and V_2, but speed of the blade element will be $2\pi r N$ since the value of N is same for both the bladesets i.e., $u_1 = u_2$. With such condition, the two vector diagram may be superimposed giving the evolving finding and derivation and relation regarding the various parameters concerned viz. Lift force, Drag force, Moment, Efficiency and others, keeping in mind the values of V_2 depend on the distance of the second bladeset from the first bladeset.

Estimation in system (b) (figure 10) with two bladesets much depends on the position of the second bladeset with respect to the ‘Wake’ of the system (a) and this ‘Wake’ and other parameters correspond to the free wind behavior before the first bladeset. It reflects that the input condition for the second bladeset depends on the output condition of the first bladeset which output condition is made by the input condition for the first bladeset. It means that impact of second bladeset is largely dependent on the performance of the first bladeset with its given input conditions. The adjustment of the distance between the two bladesets confirming the wind velocity at the exit of the first bladeset is not less than the Cut-in velocity for the second bladeset, the overall phenomena is likely to improve the considerations of conversion of wind power both at first bladeset and second bladeset.

In case where the rotation of the shaft due to first and second bladeset is more than that with only the first bladeset, it means that less than cut-in velocity of wind may also cause rotation of the shaft.

In case when the rotation of the shaft with two bladeset is less than that with only the first bladeset it indicates that when the free wind speed is more than the cut out speed, the adjustment of the position of the second bladeset may help retarding the shaft rotation and help protecting the wind machine from damage. Thus the total power availability in the range of lower cut-in speed to higher Furling (cut-out) speed would be more beneficial.

The adjustability of the position of the second bladeset having effect of increasing or decreasing the shaft rotation stands as a feasible consideration in the control of rotation of shaft. If the second bladeset is mounted on a hub which can slide over a spline shaft, it provides the control on the rotation from cut-in speed to cut-out speed of wind, thus amounting to additional method in controlling the wind machine over and above the prevailing controlling system.

5. CONCLUSION

It may provide good clues that the impact of second bladeset yield corresponding changes in the technological and performance parameter and the selection of favorable changes help improve and modify the WECS for better gain with newer dimension. It remains a state-of-the-art newer technology and dimension towards R&D and an additional feature and novelty in the field of harnessing the wind energy.

6. FIGURES AND TABLES

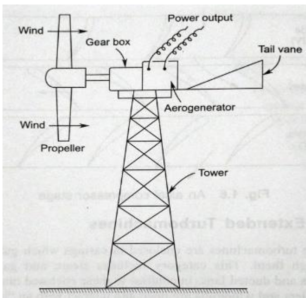


Figure 1: A Windmill (extended turbomachine)

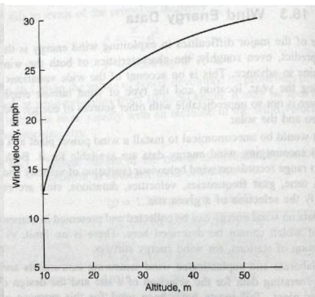
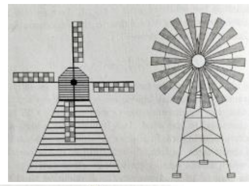
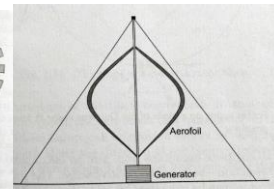
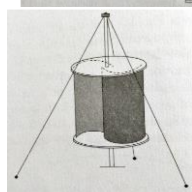


Figure 2: variation of wind velocity with height above ground (a typical curve)

(a) (b) (c)

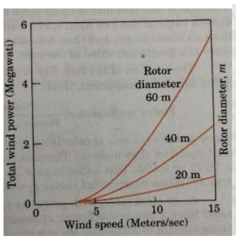






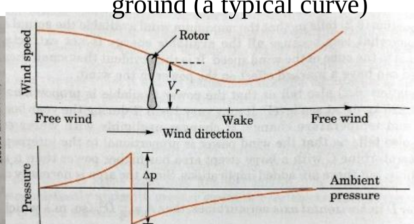
(d)

Figure 3: a) The 'Dutch' wind mill, b) The multiblade water pumping wind mill c) The Darrieus rotor d) Savonius rotor



(a)

Figure 4: (a) Dependence of wind rotor power on wind speed and rotor diameter



(b)

Figure 4: (b) conditions in traversing a wind rotor

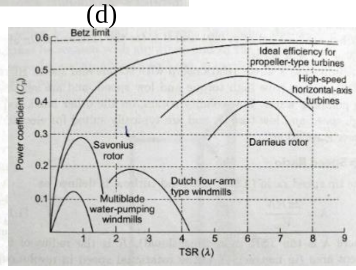


Figure 5: curve for C_P vs TSR for different types of wind mills

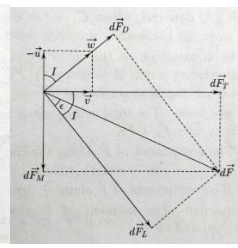


Figure 6: Vector diagram of the velocities and forces, the blade vector is normal to the plane of the diagram

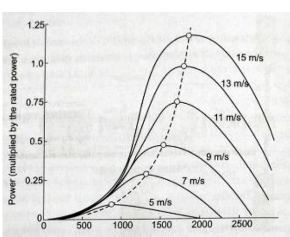


Figure 7: (a) The typical power vs speed characteristics of a wind turbine

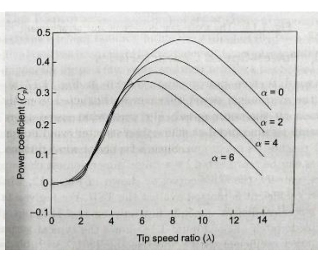


Figure 7: (b) The typical curve of power coefficient vs TSR for various values of pitch angle α

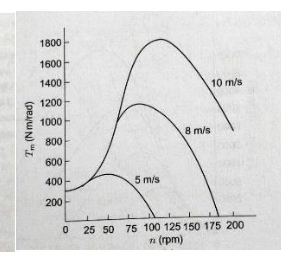


Figure 8: The torque-speed characteristics of two blade propellor type rotor

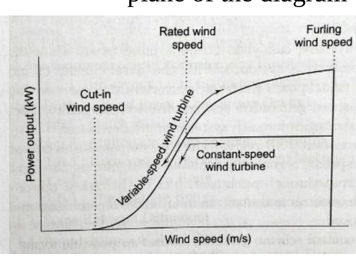
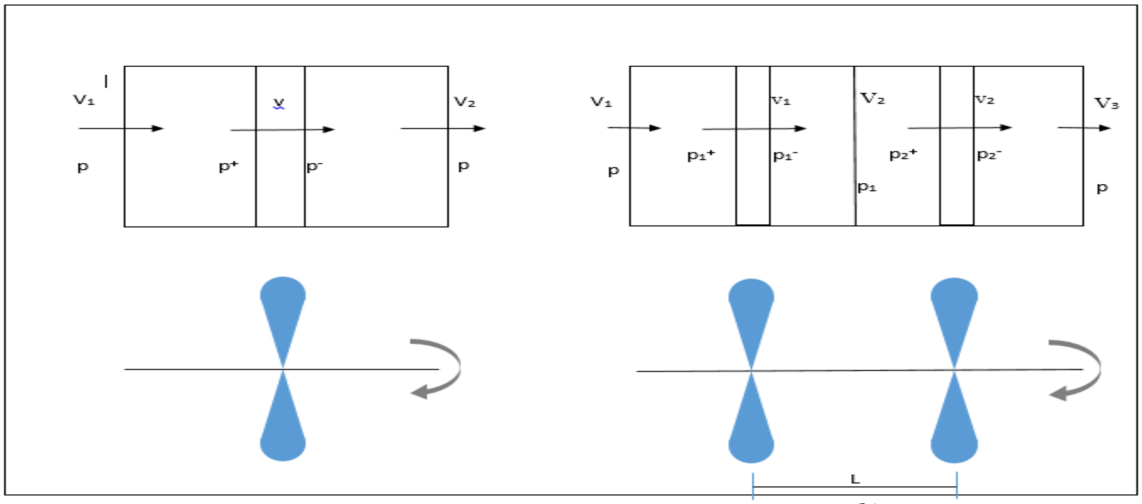


Figure 9: The typical power vs speed characteristics of variable speed wind machines

Experiment with Single and Double blade sets				
S. No	**Wind Input (kmph)**	**Blade Set 1**	**Blade Set 2**	**Shaft speed (rpm)**
01	37.7	Active	Active	280
02	37.7	In-active	Active	200
03	37.7	Active	In-active	230

Table 1: Observation from Experiment 1 with Wind Input velocity



(a) (b)

Figure 10: Schematic of WEC with (a) one bladeset (b) two bladesets

Experiment with Single and Double blade sets				
S. No	**Wind Input (kmph)**	**Blade Set 1**	**Blade Set 2**	**Shaft speed (rpm)**
01	13.3	Active	Active	80
02	42.5	In-active	Active	382
03	25.8	Active	In-active	225

Table 2: Observation from Experiment 2 with varying Wind Input values

Experiment with Single and Double blade sets				
S. No	**Wind Input (kmph)**	**Blade Set 1**	**Blade Set 2**	**Shaft speed (rpm)**
01	12.6	Active	Active	115
		In-active	Active	107
		Active	In-active	143
02	26.9	Active	Active	251
		In-active	Active	239
		Active	In-active	310
03	40.9	Active	Active	439
		In-active	Active	392
		Active	In-active	472

Table 3: Observations from Experiment 3 with varying Wind Input values

7. REFERENCE

1. S. M. Yahya, “Turbines, Compressors and Fans”, TMH, New Delhi, 2011.
2. G. D. Rai, “Non-convesional Energy Sources”, Khanna Publishers, New Delhi, 2018.
3. S. N. Bhadra, D. Kastha, S. Banerjee “Wind Electrical Systems”, Oxford University Press, New Delhi, 2018.
4. The Indian National Committee, Energy, “A Nomograph on the 9th World Energy Conference, Detroit, USA, September 1974, The institute of Engineers (India), Kolkata, 1975.
5. S. J. Jayadev, R Lynette et al, “harnessing the wind” IEEE Spectrum, 1995.
6. O. Wasynczuk, D. T. Man and J. P. Sullivan, "Dynamic behavior of a class of wind turbine generators during random wind fluctuations", IEEE Trans. Power App. Syst., vol. 100, pp. 2837-2845, June 1981.
7. E. Simiu and R. H. Scanlan, “Wind Effects on Structures an Introduction to Wind Engineering”, New York: Wiley, 1986.
8. D. C. Aliprantis, S. A. Papathanassiou, M. P. Papadopoulos and A. G. Kladas, "Modeling and control of a variable-speed wind turbine equipped with permanent magnet synchronous generator", Int. Conf. on Elect. Mach., vol. 1, pp. 558-562, 2000-Aug.
9. E. Muljadi and C. P. Butterfield, "Pitch-controlled variable-speed wind turbine generation", IEEE Trans. Ind. Applicat., vol. 37, pp. 240-246, Jan./Feb. 2001.