Research Article

Modeling and Analysis of Variable Speed Wind Turbine equipped with PMSG

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Abstract

This paper presents the dynamic model and Detail Analysis of a Wind energy conversion system equipped with permanent magnet synchronous generator (PMSG). There are different types of synchronous generators, but the PMSG is chosen, in order to obtain its dynamic model. It offers better performance due to higher efficiency and less maintenance since it does not have rotor current and can be used without a gearbox, which also implies a reduction of the weight of the nacelle and a reduction of costs. Along with the PMSG, wind speed, wind turbine &drive train have been modelled and the mathematical equations that explain their behaviour have been introduced. The generator model is established in the dq–synchronous rotating reference frame. The wind turbine model details the mechanism of variable speed operation of the turbine. In order to verify the presented model simulations with MATLAB/Simulink software have been conducted. Simulation results prove the validity of the model. Moreover, the concept of the Maximum Power Point Tracking (MPPT) has been presented in terms of the adjustment of the generator rotor speed according to instantaneous wind speed.

Keywords: Modelling, MPPT, Wind Speed, Drive train, Wind Turbine, PMSG

1. Introduction

Wind energy is one of the best technologies available today to provide a sustainable supply to the world development, due to abundant, inexhaustible potential, increasingly competitive cost, and environmental advantage. By the end of 2003.According to Global wind energy council the total installed capacity of the wind turbines has reached as much as 39.234GW and will exceed 110GW by the year of 2012. In depth understanding and investigation of wind energy related technologies, such as wind power generators, wind farm integration, grid code and etc., is very meaningful. In terms of the generators for wind-power application, there are different concepts in use today. The major distinction among them is made between fixed speed and variable speed wind turbine generator concepts. In the early stage of wind power development, fixed-speed wind turbines and induction generators were often used in wind farms. But the limitations of such generators, e.g. low efficiency and poor power quality, adversely influence their further application. With large-scale exploration and integration of wind sources, variable speed wind turbine generators, such as doubly fed induction generators (DFIGs) and permanent magnet synchronous generators (PMSGs) are emerging as the preferred technology (M. Chinchilla et al 2006). In contrast to their fixed-speed counterparts, the variable speed generators allow operating wind turbines at the optimum tip-speed ratio and hence at the optimum power efficient for a wide wind speed range. However, the variable-speed directly-driven multi-pole permanent magnet synchronous generator (PMSG) wind architecture is chosen for this purpose and it is going to be modelled: it offers better performance due to higher efficiency and less maintenance because it does not have rotor current. What is more, PMSG can be used without a gearbox, which implies a reduction of the weight of the nacelle and reduction of costs. Optimum wind energy extraction is achieved by running the Wind Turbine Generator (WTG) invariable speed because of the higher energy gain and the reduced stresses. Using the Permanent Magnet Synchronous Generator (PMSG) the design can be even more simplified. However, the recent advancements in power electronics and control strategies have made it possible to regulate the voltage of the PMSG in many different ways. The present research analyses the model of a variable speed wind turbine equipped with 2MW PMSG. It must be noted that the present research focuses neither on the converter (grid side and rotor side) nor on their controls.

2. Wind Energy Conversion

The circuit diagram for WECs system connected to three phase grid at the point of common coupling (PCC) is shown in the Fig. 1. The main components of the system are wind turbine, PMSG, dual-stage converter comprising of AC-DC rectifier and voltage source inverter (VSI),

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local load and the grid. The wind turbine is connected to PMSG through drive train & connected to back to back converter. The AC-DC converter is connected to VSI via DC link capacitor (*C*). The voltage across *C* is maintained constant, through the outer voltage controller loop of VSI, to facilitate complete active power transfer to the AC side of the VSI. The VSI is controlled using sinusoidal pulse width modulation strategy to feed active (P) and reactive power (Q) to the local load and the utility. The system is loaded with both static and dynamic load. The grid with voltage *Vgrid* is connected at the PCC and is assumed to be capable of absorbing active and reactive power, whenever the power generated from the wecs system is more in comparison to the load power demand and vice-versa.
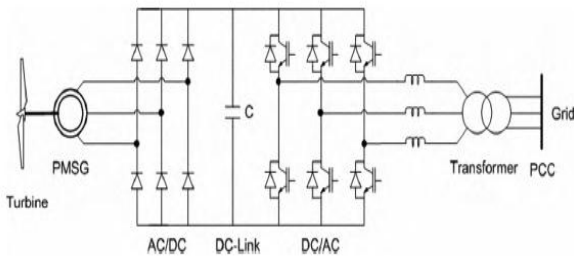

Fig.1 Typical grid connected WECS

2.1 Wind speed modeling

The wind speed model consists of a source that generates a wind speed signal to be applied to the wind turbine. The wind speed signal consists of four components, namely the mean wind speed; a wind speed ramp, which is a steady increase in the mean wind speed; a wind gust; and turbulence. The eventual wind speed to be applied to the wind turbine is the sum of these four components as presented by (P. M. Anderson et al 1983)

$$V_w(t) = V_b(t) + V_r(t) + V_g(t) + V_n(t) \qquad (1)$$

Where V_b is the base (constant) wind component, V_r is the ramp wind component, V_g is the gust wind component and V_n is the base noise wind component, all of them in m/s. Fig. 2.Shows the graphics of the non-constant wind speed components: ramp, gust and noise components. The present work considers a constant wind speed equal to 12 m/s. with ramp, gust and random noise component, consequently, the model implementation of the wind speed in Simulink implies the consideration of the base wind speed component, as shown in Fig. 3.
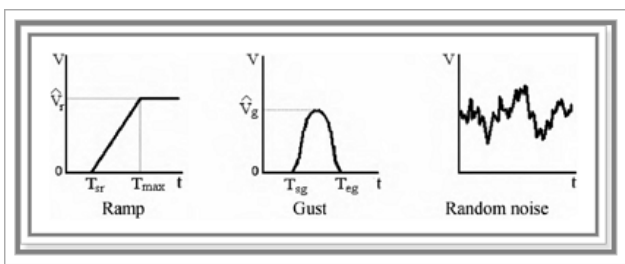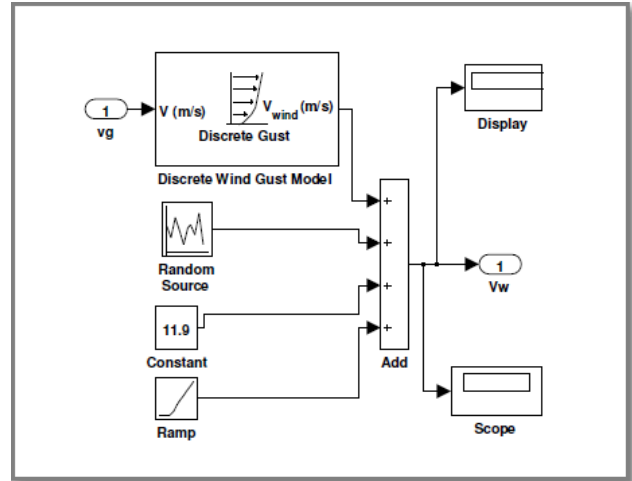

Fig.2 Non constant wind speed components

Fig.3 Wind speed model with Simulink

2.2 Wind turbine modeling

Wind turbines cannot fully capture wind energy. The components of wind turbine have been modeled by the following equations. Output aerodynamic power of the wind-turbine is expressed as

$$P_{Turbine} = \frac{1}{2}C_p(\lambda,\beta)\rho A V^3 \qquad (2)$$

Where, ρ is the air density (typically 1.225 kg/m3), *A* is the area swept by the rotor blades (in m^2) *Cp is* the coefficient of power conversion and *V* is the wind speed (in m/s).The tip-speed ratio is defined as

$$\lambda = \frac{W_{mR}}{V} \qquad (3)$$

Where Wm and *R* are the rotor angular velocity (in rad/sec) and rotor radius (in m), respectively. The wind turbine mechanical torque output *Tm* given as

$$T_m = \frac{1}{2}\rho A C_p(\lambda,\beta)\frac{V^3}{W_m} \qquad (4)$$

The power coefficient is a nonlinear function of the tip speed ratio λ and the blade pitch angle β(in degrees).If the swept area of the blade and the air density are constant, the value of *Cp* is a function of λ and it is maximum at the particular λ *opt* Hence, to fully utilize the wind energy ,λ should be maintained at λ*opt* , which is determined from the blade design. Then

$$P_{Turbine} = \frac{1}{2}\rho A C_{pmax} V^3 \qquad (5)$$

A generic equation is used to model the power coefficient $C_P(\lambda,\beta)$ based on the modeling turbine characteristics described in and. In order to simulate the wind generation system, an empirical expression of $C_P(\lambda,\beta)$ has been considered in ,such that

$$C_p = [\,0.5 - 0.00167(\beta - 2)]\sin\frac{\pi(\lambda + 0.1)}{12 - 0.3(\beta - 2)} - 0.00184(\beta - 2)(\lambda - 3) \qquad (6)$$

In this, the pitch angle β is set to zero. The rotational speed is calculated by considering the following equation

$$j\frac{dw}{dt} = T_m - T_{em} - F_w \qquad (7)$$

Where is Inertia moment of the turbine, axle and generator F Axle friction Tem Electromagnet torque. The characteristic function *CP* (λ,β) Vs λ for various values of the pitch angle β & mechanical power Vs rotor speed is

illustrated in Fig.4.&5.The maximum value of Cp = 0.593 (L. Rodriguez et al 2003) which means that the power extracted from the wind is always less than 59.3% (Betz 's limit), because of various aerodynamic losses depend on the rotor construction (number and shape of blades, weight, stiffness, etc.). This is the well known low efficiency to produce electricity from the wind. This particular value λopt results in the point of optimal efficiency where the maximum power is captured from wind by the wind turbine. For each wind speed, there exists a specific point in the wind generator power characteristic, MPPT, where the output power is maximized. Thus, the control of the WECS load results in a variable-speed operation of the turbine rotor, so the maximum power is extracted continuously from the wind.
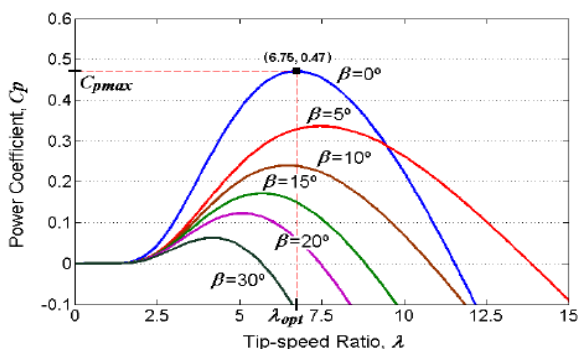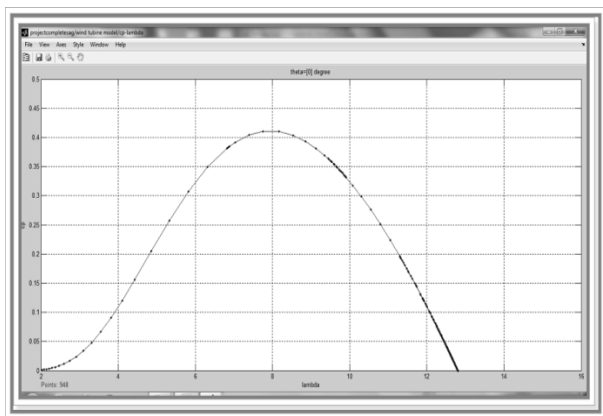

Fig.4. Typical TSR Vs λ curve
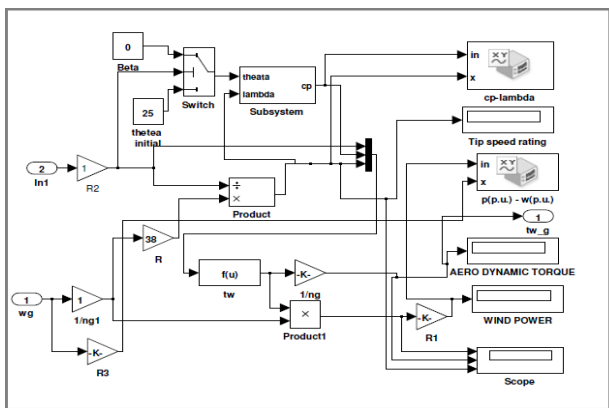

Fig.5. TSR Vs λ curve obtained with Simulink

Fig.6 Wind turbine modeling with Simulink

Table 1 Wind Turbine parameters

Parameter	Symbol	Value and Units
Air density	ρ	1.205kg/ m^3
Rotor radius	*R*	38m
Rated wind speed	V*w* rated	11.8m/s
Maximum *Cp*	*Cp max*	0.4412

2.3 Drive train model

The drive train of a wind turbine generator system consists of the following elements a blade-pitching mechanism with a spinner, a hub with blades, a rotor shaft and a gearbox with breaker and generator. It must be noted that gearbox is not considered because the analyzed system consists of a wind turbine equipped with a multi-pole PMSG. The common) way to model the drive train is to treat the system as a number of discrete masses connected together by springs defined by damping and stiffness coefficients. In this study, focuses is on the interaction between wind farms and AC grids ,the drive train can be treated as one-lumped mass model for the sake of time efficiency and acceptable precision(M. Yin, et al 2007) (I. Boldea et al 2006)].It is defined by the following equation

$$\frac{dw}{dt} = \frac{\tau_e - \tau_{w-g}}{J_{eq}} - \frac{B_m}{J_{eq}} \cdot w_g \qquad (8)$$

where the sub-index g represents the parameters of the generator side, wg is the mechanical angular speed [rad/s] of the generator, Bm is the damping coefficient [Nm/s], τe is the electromechanical torque [Nm], τw_g is the aerodynamic torque that has been transferred to the generator side (3), which is equal to the torque produced in the rotor side because there is no gearbox, and Jeq is the equivalent rotational inertia of the generator [kg-m2], which is derived from(M. Yin et al 2007)

$$J_{eq} = j_g + \frac{J_w}{n_g^2} \qquad (9)$$

where *Jg* and *J$_W$*; are the generator and the rotor rotational inertias [kg-m^2] respectively, *ng* is the gear ratio, which is equal to 1, because no gearbox is utilized. The model of the one mass drive train implemented in Simulink is depicted in Fig. 7.
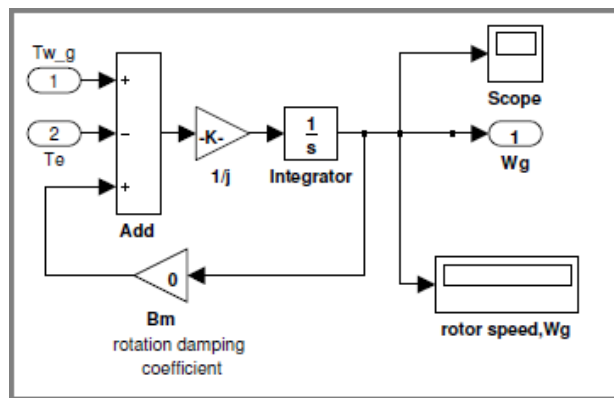

Fig.7 Drive train model with Simulink

Table 2 Drive train parameters

Parameter	Symbol	Value
Gear ratio	ng	1
Rotational damping coefficient	Bm	0
Equivalent Inertia (turbine +generator)	Jeq	0.3 Kg.m2

2.4 Pmsg model

The dynamic model of the PMSG is derived from the two phase synchronous reference frame, which the q-axis is 90° ahead of the d-axis with respect to the direction of rotation. The synchronization between the d-q rotating reference frame and the abc-three phase frame is maintained by utilizing a phase locked loop (PLL) (C. Krause 2002). Fig. 9 shows the d-q reference frame used in a salient-pole synchronous machine (which is the same reference as the one used in a PMSG),
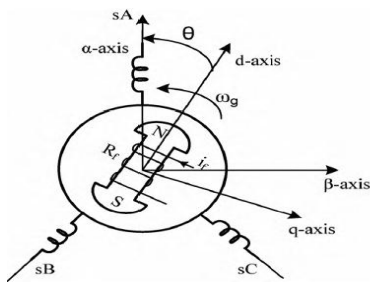
Fig.8 d-q & α-β axis of typical salient pole synchronous Machine.

Where θ is the mechanical angle, which is the angle between the rotor d-axis and the stator axis. The mathematical model of the PMSG for power system and converter system analysis is usually based on the following assumptions.(L.Rodriguez et al2003),(C.Krause 2002).The stator windings are positioned sinusoidal along the air-gap as far as the mutual effect with the rotor is concerned; the stator slots cause no appreciable variations of the rotor inductances with rotor position; magnetic hysteresis and saturation effects are negligible; the stator winding is symmetrical; damping windings are not considered; the capacitance of all the windings can be neglected and the resistances are constant (this means that power losses are considered constant).The mathematical model of the PMSG in the synchronous reference frame (in the state equation form) is given by(C. Krause 2002), (I. Boldea 2003).

$$\frac{di_d}{dt} = \frac{1}{L_{ds} + L_{qs}}\left(R_s i_d + w_e\left(L_{qs} + L_{is}\right) + u_d\right) \quad (10)$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs} + L_{is}}\left(R_s i_q + w_e(L_{ds} + L_{is})i_d + u_q\right) \quad (11)$$

where subscripts *d* and *q* refer to the physical quantities that have been transformed into the *d-q* synchronous rotating reference frame, *R,* is the stator resistance in ohm, L_d and L_q are the inductances in henry of the generator on

the *d* and *q* axis, *Lid* and *Llq* are the leakage inductances in Henry of the generator on the *d* and *q* axis, respectively,*ʸf* is the permanent magnetic flux in w

Wb and *We* is the electrical rotating speed in rad/s of the generator, defined by

$$w_e = pw_g \quad (12)$$

Where p is the number of pole pairs of the generator. In order to complete the mathematical model of the PMSG ,the mechanical equation is needed, and it is described by the following electromagnetic torque equation given by (C. Krause 2002)

$$\tau_e = 1.5p\left(\left(L_{ds} - L_{is}\right)i_d i_q + i_q \Psi_f\right) \quad (13)$$
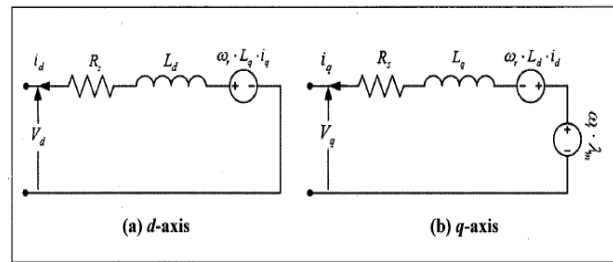
Fig.9 d-q axis equivalent circuit'
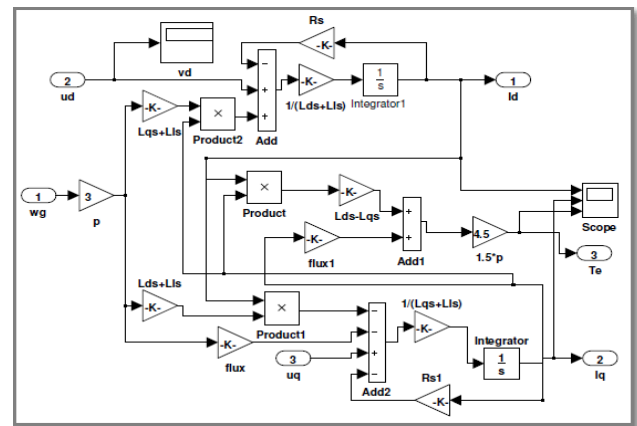
Fig.10 PMSG model with Simulink

Fig. 9. shows the equivalent circuit of the PMSG in de *d-q* synchronous rotating reference frame The model of the PMSG implemented in Simulink is depicted in Fig. 10.By analyzing the power produced by the wind turbine at various wind and rotor speeds, as depicted in Fig. 12, it can be appreciated that an optimum power coefficient constant *Kp opt* exists .This coefficient show the generated power associated with the corresponding optimum rotor speed (Z. Lubosny 2003)- (J. G. Slootweg et al 2003), (Z. Lubosny 2003). *Kp opt* is calculated from individual wind turbine characteristics. By measuring generated power, the corresponding optimum rotor speed can be calculated and set as the reference speed according to(Z. Lubosny 2003)

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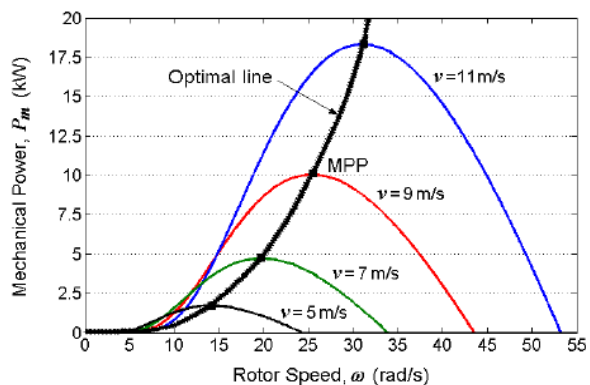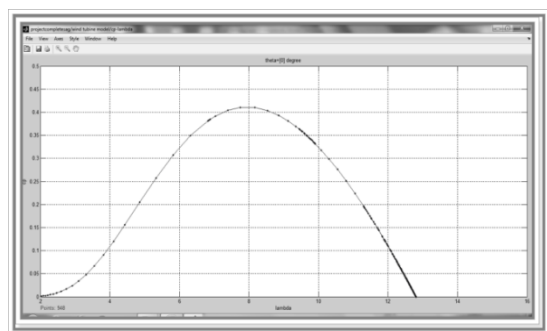

Fig.11 typical *Pm-W Curve*

Fig.12 Pm-W obtained with Simulink

$$w_{r\ opt} = \sqrt[3]{\frac{P_{gen}}{K_{p\ opt}}} \qquad (14)$$

where wr opt is the optimum rotor speed [rad/s] and Pgen is the measured generated power [W].This is the base of the well-known Maximum Power Point Tracking (MPPT) (G. Ramtharan et al, 2007), from the prior treatment of the wind turbine model it can be appreciated that in order to extract the maximum amount of power from the incident wind, Cp should be maintained at a maximum. In order to achieve this objective, it can be appreciated from Fig.11 that the speed of the generator rotor must be optimized according to instantaneous wind speed (this optimization is achieved by using (14)

Table 3 PMSG parameters

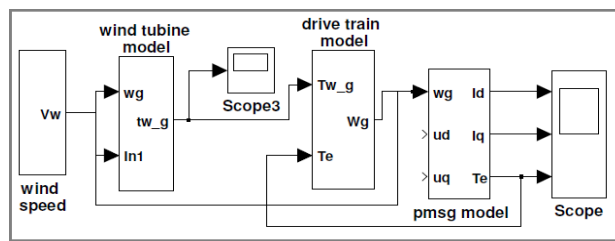| Parameter	Symbol	Value
Rated generated power	P_g rated	2MW
Rated mechanical Speed	W_g rated	2.18
Stator resistance	R_s	0.08Ω
Stator *d*-axis inductance	L_{ds}	0.334 H
Stator *q*- axis inductance	L_{qs}	0217 H
Stator leakage inductance	L_{is}	0.0334 H
Permanent magnet flux	$\mathbf{\Psi}_f$	0.4832 Wb
Pole pairs	P	3

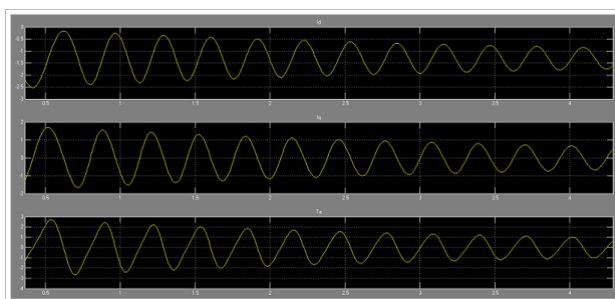**Fig.13** Complete proposed model of WECS with Simulink

Fig. 14.Graph shows variation of Id,Iq and Torque Vs Time

Conclusions

The paper presents the complete model of the variable speed wind turbine with PMSG The complete model consists of a PMSG model, wind speed model, wind turbine model and a drive train model. MATLAB/Simulink is implemented to build the dynamic model of the wind turbine with PMSG and simulations have been conducted to validate the model. *Cp* curves and power-speed characteristics have been obtained. The generator has been modelled in the d-q synchronous rotating reference frame, taking into account different simplifications. Moreover, the concept of the maximum power point tracking has been presented in terms of the adjustment of the generator rotor speed according to instantaneous wind speed.

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Author's biography

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Prof. R A Gupta (M'08) received the B.E. degree in electrical engineering and the M.E. degree in control systems from the University of Jodhpur, India, in 1980 and 1984, respectively, and the Ph.D. degree from IIT Roorkee, Roorkee, India (formerly University of Roorkee) in 1996. In 1982, he was an Assistant Professor in the Department of Electrical Engineering, University of Jodhpur, Jodhpur, India. In November 1990, he joined as a Reader and became a Professor in 1999 at the Department of Electrical Engineering, Malviya National Institute of Technology, Jaipur, India. His current research interests include power electronics, electrical machines, and drives. Prof. Gupta is a Fellow of Institute of Engineers, India, and a Life Member of the Indian Society for Technical Education and the Indian Society for Continuing Engineering Education.