Fuzzy Logic Based Intelligent Control of a Variable Speed Cage Machine Wind Generation System

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Abstract—The paper describes a variable speed wind generation system where fuzzy logic principles are used for efficiency optimization and performance enhancement control. A squirrel cage induction generator feeds the power to a double-sided pulse width modulated converter system which pumps power to a utility grid or can supply to an autonomous system. The generation system has fuzzy logic control with vector control in the inner loops. A fuzzy controller tracks the generator speed with the wind velocity to extract the maximum power. A second fuzzy controller programs the machine flux for light load efficiency improvement, and a third fuzzy controller gives robust speed control against wind gust and turbine oscillatory torque. The complete control system has been developed, analyzed, and validated by simulation study. Performances have then been evaluated in detail.

I. INTRODUCTION

A WIND electrical generation system is the most cost-competitive of all the environmentally clean and safe renewable energy sources in the world. It is also competitive with fossil fuel generated power and much cheaper than nuclear power. Although the history of wind power goes back more than two centuries, its potential to generate electrical power began to get attention from the beginning of this century. However, during the last two decades, wind power has been seriously considered to supplement the power generation by fossil fuel and nuclear methods. In recent years, wind power is gaining more acceptance because of environmental and safety problems of conventional power plants and advancement of wind electric generation technology. The world has enormous resources of wind power. It has been estimated that even if 10% of raw wind potential could be put to use, all the electricity needs of the world would be met [1]. There are currently over 1700 MW of wind generators installed worldwide with generation of 6 billion kWh of energy annually. It has been estimated the generation will grow to 60 billion kWh by the year 2000. Of course, the main drawback of wind power is that its availability is somewhat statistical in nature and must be supplemented by additional sources to supply the demand curve.

Traditionally, wind generation systems used variable pitch constant speed wind turbines (horizontal or vertical axis) that were coupled to squirrel cage induction generators or wound-field synchronous generators and fed power to utility grids or autonomous loads. The recent evolution of power semiconductors and variable frequency drives technology has aided the acceptance of variable speed generation systems. In spite of the additional cost of power electronics and control, the total energy capture in a variable speed wind turbine (VSWT) system is larger and, therefore, the life-cycle cost is lower. The following generator-converter systems have been popularly used [2]–[4]:

- doubly fed induction generator with cascaded converter slip power recovery;
- doubly fed induction generator with cycloconverter slip power recovery;
- synchronous generator with line-commutated and load-commutated thyristor converters.

In addition to the above schemes, squirrel cage generators with shunt passive or active VAR (volt ampère reactive) generators [5], [6] have been proposed which generate constant voltage constant frequency power through a diode rectifier and line-commutated thyristor inverter. Recently, a variable reluctance machine [7] and doubly stator-fed induction machine [8] have also been proposed in wind generation systems. The major problems in traditional power conversion schemes are the poor line power factor and harmonic distortion in line and machine currents. The recent IEEE Standard 519 [9] severely restricts line harmonic injection. Therefore, to satisfy the stringent harmonic standard and poor power factor problem, active type VAR and harmonic compensators can be installed at additional cost. Again, the conventional control principles used in these systems make the response sluggish and give nonoptimum performance. Very recently, a double-sided pulse width modulated (PWM) converter system has been proposed to overcome some of the above problems.

This paper, a complete simulation study to validate the theoretical concepts (the experimental work is in progress and will be reported later), describes a VSWT system with a squirrel cage induction generator and a double-sided PWM converter where fuzzy logic control has been used extensively to maximize the power output and enhance system performance. All the control algorithms have been validated by simulation study and system performance has been evaluated
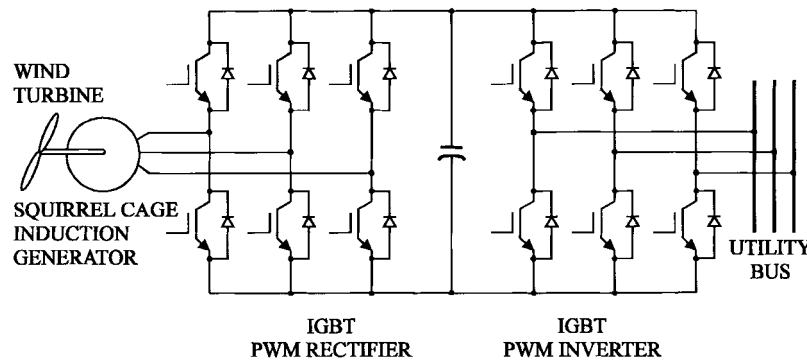
Fig. 1. A voltage-fed double PWM converter wind generation system.

in detail. An experimental study with a 3.5-kW-laboratory drive system is in progress. It will eventually be transitioned into a 200-kW prototype generation system.

II. WIND GENERATION SYSTEM DESCRIPTION

A. Converter System

The voltage-fed converter scheme used in this system is shown in Fig. 1. A vertical (or horizontal) wind turbine is coupled to the shaft of a squirrel cage induction generator through a speedup gear ratio (not shown). The variable frequency variable voltage power from the generator is rectified by a PWM IGBT (insulated gate bipolar transistor) rectifier. The rectifier also supplies the excitation need of the machine. The inverter topology is identical to that of the rectifier, and it supplies the generated power at 60 Hz to the utility grid. Salient advantages of the converter system include the following.

- Line side power factor is unity with no harmonic current injection (satisfies IEEE 519).
- The cage type induction machine is extremely rugged, reliable, economical, and universally popular.
- Machine current is sinusoidal—no harmonic copper loss.
- Rectifier can generate programmable excitation for the machine.
- Continuous power generation from zero to highest turbine speed is possible.
- Power can flow in either direction permitting the generator to run as a motor for start-up (required for vertical turbine). Similarly, regenerative braking can quickly stop the turbine.
- Autonomous operation of the system is possible with either a start-up capacitor or with a battery on the dc link.
- Extremely fast transient response is possible.
- Multiple generators or multiple systems can be operated in parallel.
- The inverter can be operated as a VAR/harmonic compensator when spare capacity is available.

Considering all the above advantages, and with the present trend of decreasing converter and control cost, this type of
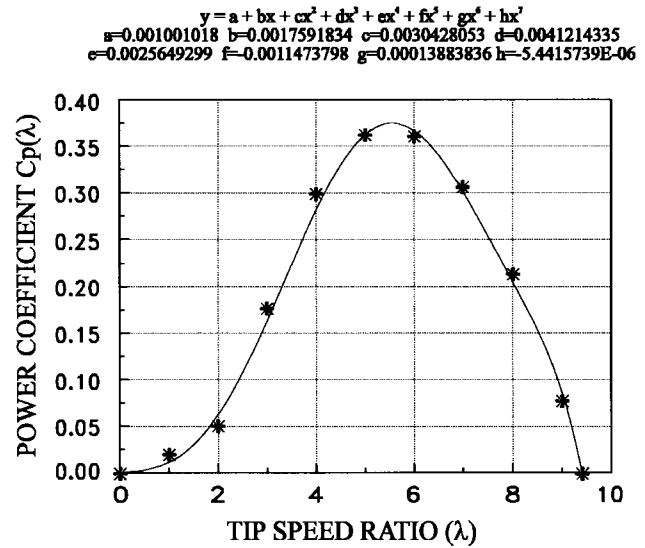

$$y = a + bx + cx^2 + dx^3 + ex^4 + fx^5 + gx^6 + hx^7$$
a=0.001001018 b=0.0017591834 c=0.0030428053 d=0.0041214335
e=0.0025649299 f=-0.0011473798 g=0.00013883836 h=-5.4415739E-06

Fig. 2. Polynomial function curve fitting of turbine power coefficient (C_p).

conversion system has the potential to be universally accepted in the future. Of course, in recent years, soft-switched resonant link and resonant pole topologies have been proposed, but additional research and development are needed to bring them to the marketplace.

B. Turbine Characteristics

Both horizontal and vertical axis wind turbines are used in wind generation systems. The vertical Darrieus (egg beater) type has the advantages of being located on the ground and accepting wind from any direction without any special yaw mechanism. It is, therefore, preferred for high power output. The disadvantages are that the turbine is not self-starting and there is a large pulsating torque which depends on wind velocity, turbine speed, and other factors related to the design of the turbine. The aerodynamic torque of a vertical turbine is given by the equation

$$T_m = C_p(\lambda) \cdot \left[0.5 \frac{\rho \pi R_w^3}{\eta_{\text{GEAR}}}\right] \cdot V_w^2 \qquad (1)$$
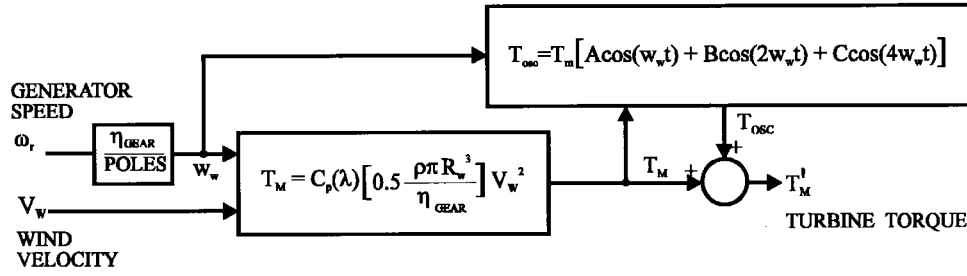
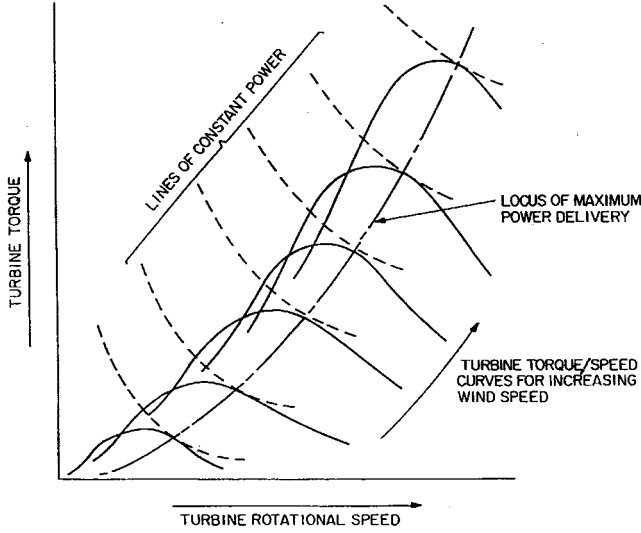Fig. 3. Model of wind turbine with oscillatory torque.

Fig. 4. A typical family of torque/speed curves for a fixed pitch wind turbine.

where

C_p	power coefficient;
λ	tip speed ratio (TSR) $\left(\frac{R_w \omega_w}{V_w}\right)$;
ρ	air density;
R_w	turbine radius;
η_{GEAR}	speed-up gear ratio;
V_w	wind velocity;
ω_w	turbine angular speed.

The power coefficient (C_p) is the figure-of-merit and is defined as the ratio of actual power delivered to the free stream power flowing through a similar but uninterrupted area, and tip speed ratio (TSR) is the ratio of turbine speed at the tip of a blade to the free stream wind speed. The parameter C_p is a nonlinear function of λ and is shown in Fig. 2. The oscillatory torque of the turbine is more dominant at the first, second, and fourth harmonics of fundamental turbine angular velocity (ω_w) and is given by the expression

$$T_{\text{OSC}} = T_m \cdot [A\cos(\omega_w) + B\cos(2\omega_w) + C\cos(4\omega_w)] \quad (2)$$

where A, B, and C are constants. Fig. 3 shows the block diagram of the turbine model with oscillatory torque. A

typical family of turbine torque/speed curves at different wind velocities is shown in Fig. 4. Superimposed on the family of curves is a set of constant power lines (dotted) indicating the region of maximum power delivery for each wind speed. This means that, for a particular wind speed, the turbine speed (or the TSR) is to be varied to get the maximum power output, and this point deviates from the maximum torque point, as indicated. Since the torque/speed characteristics of the wind generation system are analogous to those of a motor-blower system (except the turbine runs in reverse direction), the torque follows the square-law characteristics $(T_e = K\omega_r^2)$ and the output power follows the cube-law $(P_0 = K\omega_r^3)$, as indicated in Fig. 4. This means that, at reduced speed light load steady state conditions, generator efficiency can be improved by programming the flux [10], which will be discussed later.

C. Control System

It appears that fuzzy logic based intelligent control is most appropriate for performance improvement of wind generation systems. Fig. 5 shows the control block diagram of the system that uses the power circuit of Fig. 1. The machine and inverter output currents are sinusoidal, as shown. The machine absorbs lagging reactive current, but it is always zero on the line side; i.e., the line power factor is unity. The rectifier uses indirect vector control in the inner current control loop, whereas the direct vector control method is used for the inverter current controller. Vector control permits fast transient response of the system. The fuzzy controllers indicated in the figure will be described in detail in the next section. For a particular wind velocity (V_w), there will be an optimum setting of generator speed (ω_r^*). The speed loop will generate the torque component of machine current so as to balance the developed torque with the load torque. The variable voltage variable frequency power from the supersynchronous induction generator will be rectified and pumped to the dc link. The dc link voltage controller will regulate the line power P_0 (i.e., the line active current) so that the link voltage always remains constant. A feedforward power signal from the machine output to the dc voltage loop (not shown) prevents transient fluctuation of link voltage. Evidently, the system can be satisfactorily controlled for start-up and regenerative braking shutdown modes besides the usual generating mode of operation.
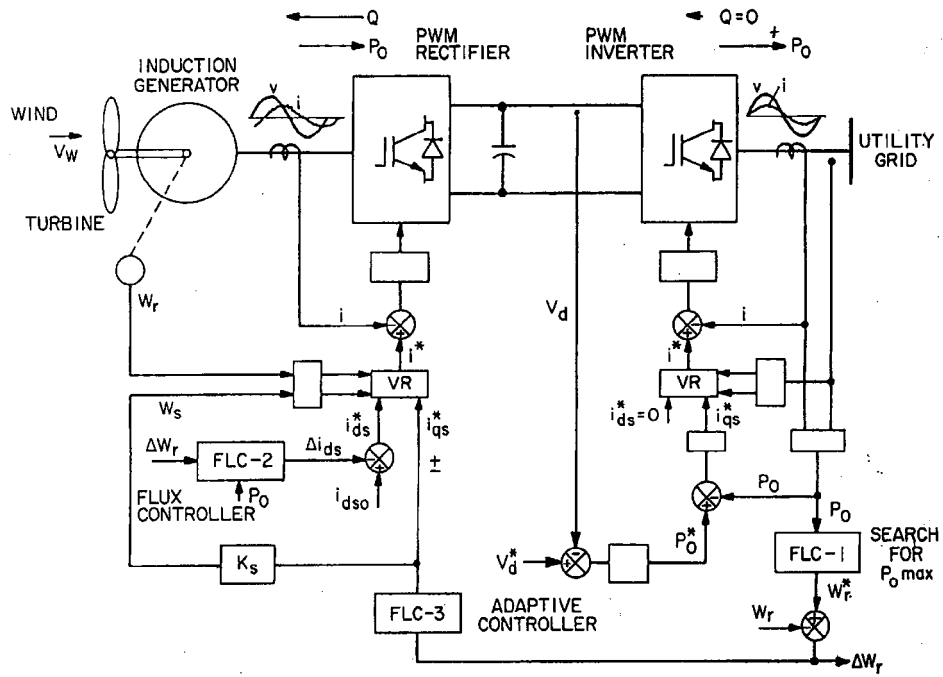
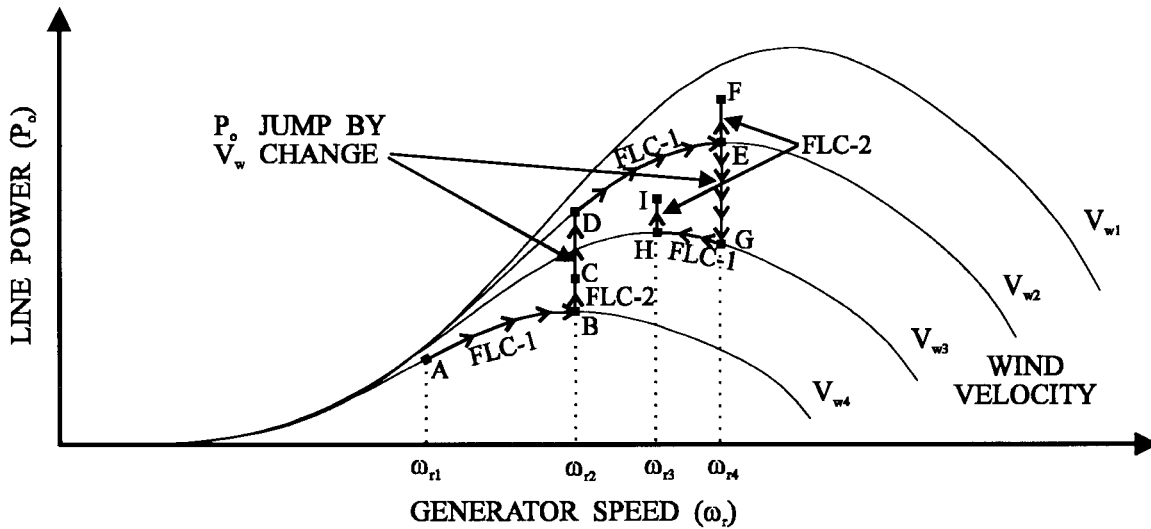Fig. 5. Fuzzy logic based control block diagram of a wind generation system.

Fig. 6. Fuzzy control FLC-1 and FLC-2 operation showing maximization of line power.

III. FUZZY LOGIC CONTROL

The system has three fuzzy logic controllers.

A. Generator Speed Tracking Control (FLC-1)

Since the power is given by the product of torque and speed and turbine power equals the line power (assuming steady state lossless system), the turbine torque/speed curves of Fig. 4 can be translated to line power (P_o)—generator speed (ω_r) curves, as shown in Fig. 6. For a particular value of wind velocity, the function of fuzzy controller FLC-1 is to search the generator speed until the system settles down at the maximum output power condition. For wind velocity of V_{W4} in Fig. 6, the output power will be at A if the generator speed is ω_{r1}. The FLC-1 will alter the speed in steps until it reaches the speed ω_{r2} where the output power is maximum at B. If the wind velocity increases to V_{W2}, the output power will jump to D, and then FLC-1 will bring the operating point to E by searching the speed to ω_{r4}. The profile for decrease of wind velocity to V_{W3} is also indicated. The principle of the fuzzy controller is explained in the block diagram of Fig. 7. With an incrementation (or decrementation) of speed, the corresponding incrementation (or decrementation) of output power P_o is estimated. If ΔP_o is positive with last positive $\Delta\omega_r$, indicated in the figure in per-unit value by $L\Delta\omega_{r(\mathrm{PU})}$, the search is continued in the same direction. If, on the
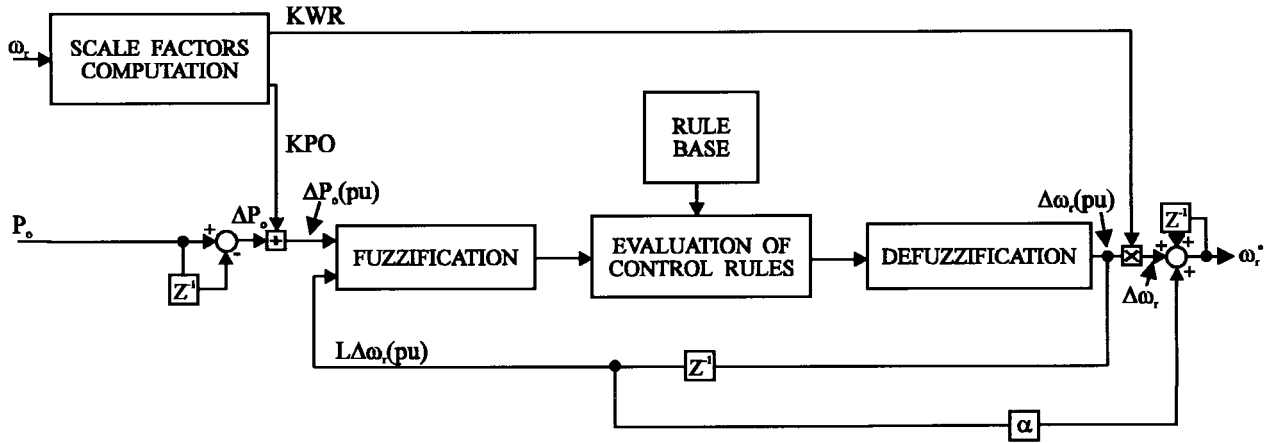
Fig. 7.   Block diagram of fuzzy control FLC-1.

other hand, $+\Delta\omega_r$ causes $-\Delta P_o$, the direction of search is reversed. The variables ΔP_o, $\Delta\omega_r$ and $L\Delta\omega_r$ are described by membership functions and rule table. In the implementation of fuzzy control, the input variables are fuzzified, the valid control rules are evaluated and combined, and finally the output is defuzzified to convert to the crispy value. The wind vortex and torque ripple can lead the search to be trapped in a minimum which is not global, so the output $\Delta\omega_r$ is added to some amount of $L\Delta\omega_r$ in order to give some momentum to continue the search and to avoid such local minima. The controller operates on a per-unit basis so that the response is insensitive to system variables and the algorithm is universal to any system. The scale factors KPO and KWR, as shown in Fig. 7, are generated as a function of generator speed so that the control becomes somewhat insensitive to speed variation. The scale factor expressions are given, respectively, as

$$\text{KPO} = a_1\omega_r \tag{3}$$

$$\text{KWR} = a_2\omega_r \tag{4}$$

where a_1 and a_2 are the constant coefficients that are derived from simulation studies. Such coefficients are converting the speed and power in per-unit values. The advantages of fuzzy control are obvious. It provides adaptive step size in the search that leads to fast convergence, and the controller can accept inaccurate and noisy signals. The FLC-1 operation does not need any wind velocity information, and its real time based search is insensitive to system parameter variation.

B. Generator Flux Programming Control (FLC-2)

Since most of the time the generator is running at light load, the machine rotor flux i_{ds} can be reduced from the rated value to reduce the core loss and thereby increase the machine-converter system efficiency [10]. The principle of on-line search based flux programming control by a second fuzzy controller FLC-2 is explained in Fig. 8. At a certain wind velocity V_w and at the corresponding optimum speed $\Delta\omega_r$ established by FLC-1 (which operates at rated flux $\psi_{R_{rated}}$), the rotor flux ψ_R is reduced by decreasing the magnetizing
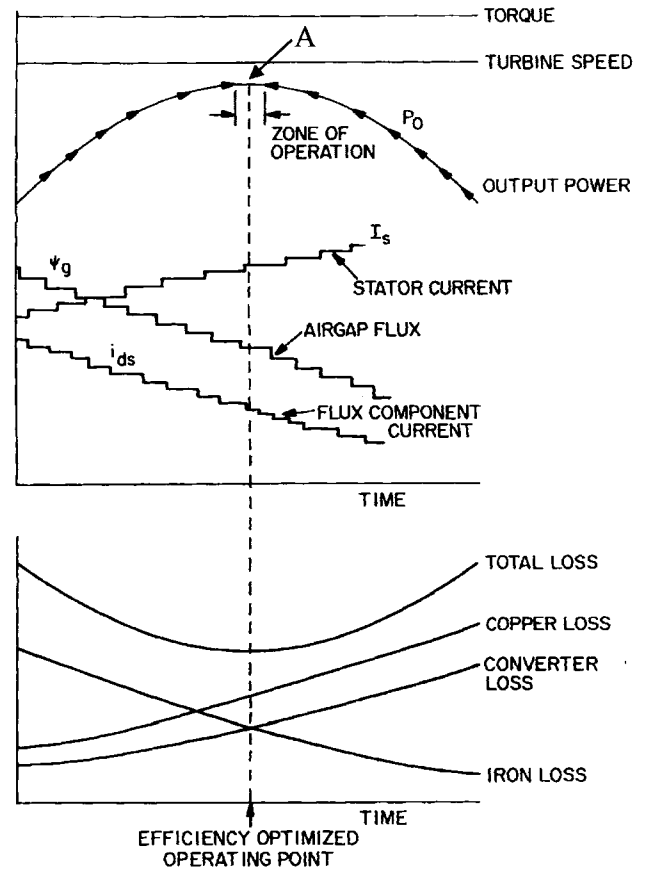

Fig. 8.   Search method of efficiency optimization control of machine by flux programming.

current i_{ds}. This causes increasing torque current i_{qs} by the speed loop for the same developed torque. As the flux is decreased, the machine iron loss decreases with the attendant increase of copper loss. However, the total system (converters and machine) loss decreases, resulting in an increase of total generated power P_o. The search is continued until the system settles down at the maximum power point A, as indicated in Fig. 8. Any attempt to search beyond point A will force the controller to return to the maximum power point. The
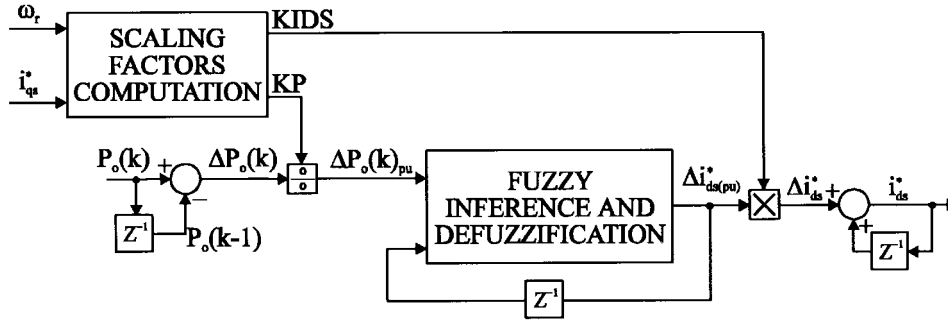
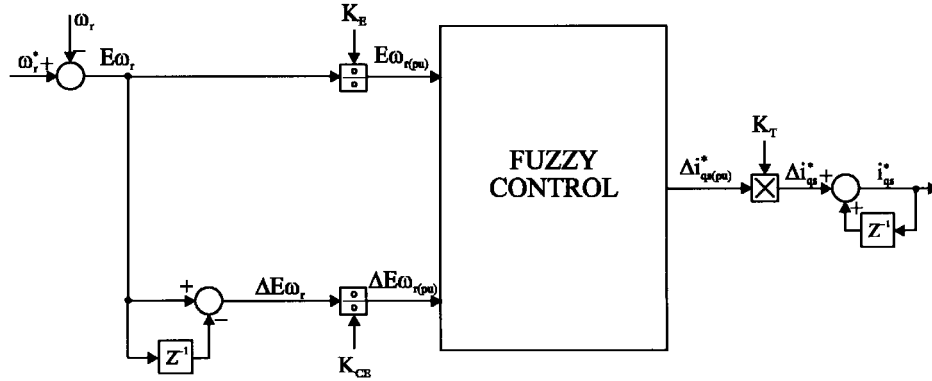Fig. 9.   Block diagram of fuzzy control FLC-2.

Fig. 10.   Block diagram of fuzzy control FLC-3.

principle of fuzzy controller FLC-2 is somewhat similar to that of FLC-1 and is explained in Fig. 9. The system output power $P_o(k)$ is sampled and compared with the previous value to determine the increment ΔP_o. In addition, the last excitation current decrement $(L\Delta i_{ds})$ is reviewed. On these bases, the decrement step of i_{ds} is generated from fuzzy rules through fuzzy inference and defuzzification, as indicated. It is necessary to process the inputs of FLC-2 in per-unit values. Therefore, the adjustable gains KP and KIDS convert the actual variable to pu variables with the following expressions

$$\text{KP} = a\omega_r + b \tag{5}$$

$$\text{KIDS} = c_1\omega_r - c_2 i_{qs} + c_3 \tag{6}$$

where a, b, c_1, c_2, and c_3 are derived from simulation studies. The current i_{qs} is proportional to the generator torque, and $\Delta\omega_r$ is zero because the fuzzy controller FLC-2 is exercised only at steady-state conditions. The effect of controller FLC-2 in boosting the power output is shown in Fig. 6. The FLC-2 controller operation starts when FLC-1 has completed its search at the rated flux condition. If wind velocity changes during or at the end of FLC-2, its operation is abandoned, the rated flux is established, and FLC-1 control is activated.

C. Closed-Loop Generator Speed Control (FLC-3)

The speed loop control is provided by fuzzy controller FLC-3, as indicated in Fig. 5. As mentioned before, it basically provides robust speed control against wind vortex and turbine oscillatory torques. The disturbance torque on the machine shaft is inversely modulated with the developed torque to attenuate the modulation of output power and prevent any possible mechanical resonance effect. In addition, the speed control loop provides a deadbeat type response when an increment of speed is commanded by FLC-1. Fig. 10 explains the proportional-integral (PI) type fuzzy control [11] used in the system. The speed loop error $(E\omega_r)$ and error change $(\Delta E\omega_r)$ signals are converted to per-unit signals, processed through fuzzy control, and then summed to produce the generator torque component of current i_{qs}^*. Note that, while fuzzy controllers FLC-1 and FLC-2 operate in sequence at steady (or small turbulence) wind velocity, FLC-3 is always active during system operation.

IV. Performance Study

A 3.5-kW wind generation system, shown in Fig. 5, was simulated by PC-SIMNON [12] to validate all the control strategies and then evaluate performance of the system. The results will be verified by a 3.5-kW laboratory drive system. The parameters of the system under study are shown in Table I. In the beginning, the turbine was simulated with the model given in Fig. 3, and its performance was verified with and without the oscillatory torques. A simplifie d lossy D-Q model of the machine and the converter system with conduction and switching losses were simulated with the respective vector controls. At successful operation of the basic system, fuzzy

TABLE I
INDUCTION MACHINE AND TURBINE PARAMETERS

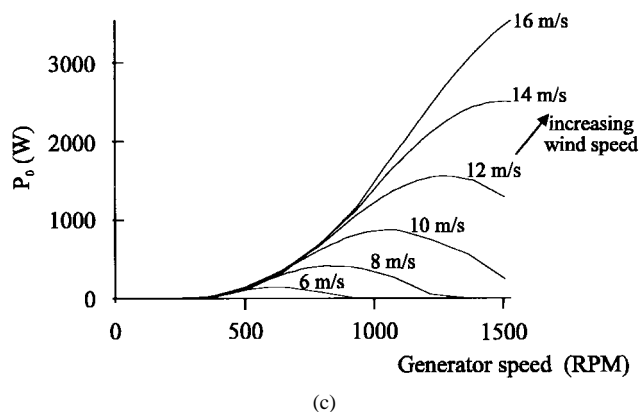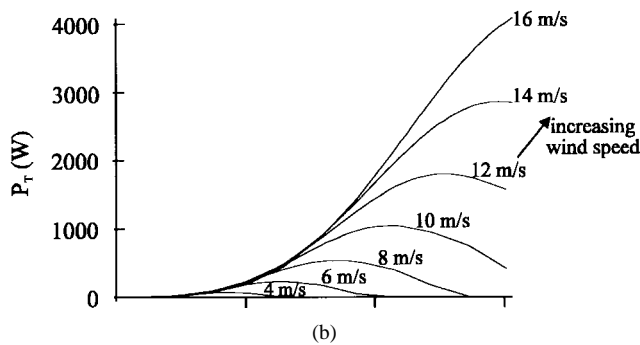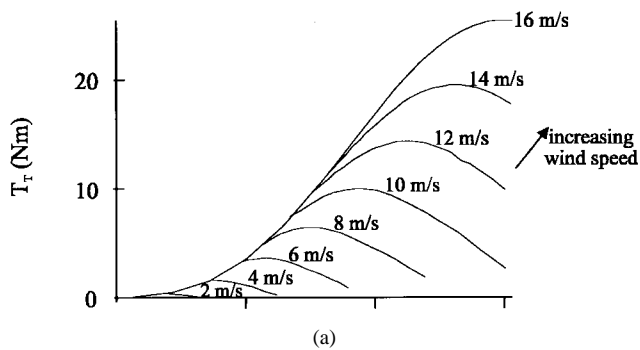| Machine Parameters:		
5 hp	230/460 V	13.4/6.7 A
4 poles	1800 RPM	NEMA Class B
$R_s = 0.370\Omega$		$R_r = 0.436\Omega$
$L_{ls} = 2.13$ mH	$L_{lr} = 2.13$ mH	$L_m = 62.77$ mH
Turbine Parameters:		
A = 0.015	B = 0.03	C = 0.015
$\eta_{GEAR} = 5.7$		

Fig. 11. Turbine and system model simulation curves (without fuzzy control. (a) Turbine developed torque, (b) turbine developed power, and (c) line side generated power.
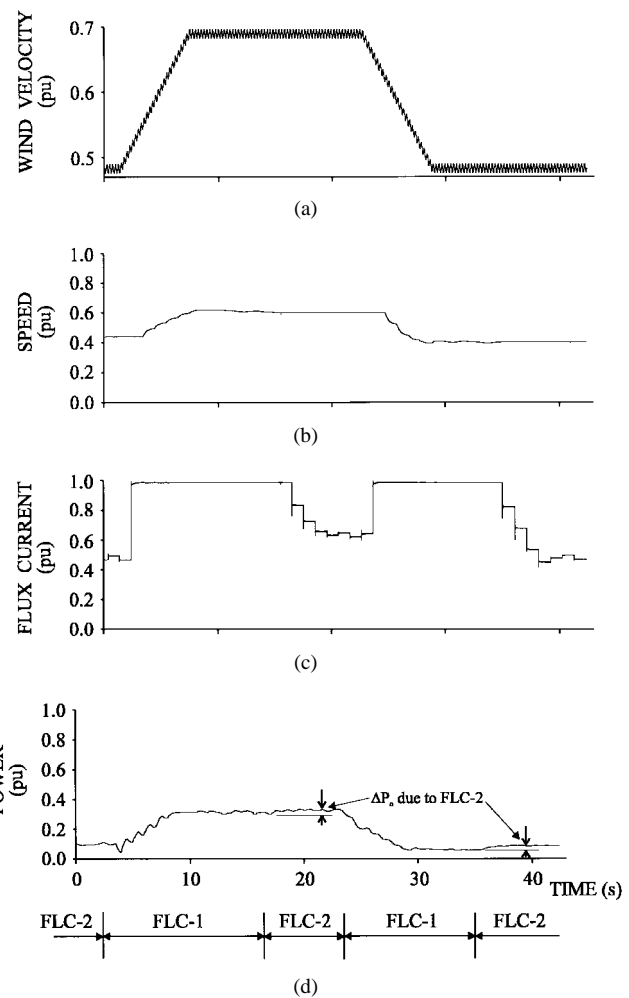

Fig. 12. Time domain operation of fuzzy controls FLC-1 and FLC-2 (FLC-3 is also working): (a) wind velocity, (b) generator speed, (c) flux current, and (d) output power.

controllers FLC-1, FLC-2, and FLC-3 were added in sequence and their membership functions and rule tables were iterated extensively until the performances were optimum.

Fig. 11(a)–(c) shows, respectively, the steady state turbine torque (T_t), turbine power (P_t), and generated power (P_o) as functions of wind velocity (V_w) and generator speed (ω_r) when none of the fuzzy controllers are in operation. For simplicity, the turbine oscillatory torques are ignored on such system results.

The turbine was modeled with oscillatory torque and some turbulence was added with the wind velocity to verify the robustness of controller FLC-3. Fig. 12 shows the performance of the system with FLC-1, FLC-2, and FLC-3 when the wind velocity is ramped up and down. As the generator speed is increased by FLC-1, the line output power gradually increases, but the line power indicates some dips which require explanation. As generator speed command is incremented by FLC-1, the machine accelerates to the desired speed with the power extracted from the turbine output power. As a result, line power temporarily sags until boosted by the turbine power at steady state. With a large increment of speed command, the direction of P_o can even reverse. In order to prevent such conditions, the maximum speed command increment was limited to a reasonably small value (75 RPM) (that increases the search time) and had a ramp
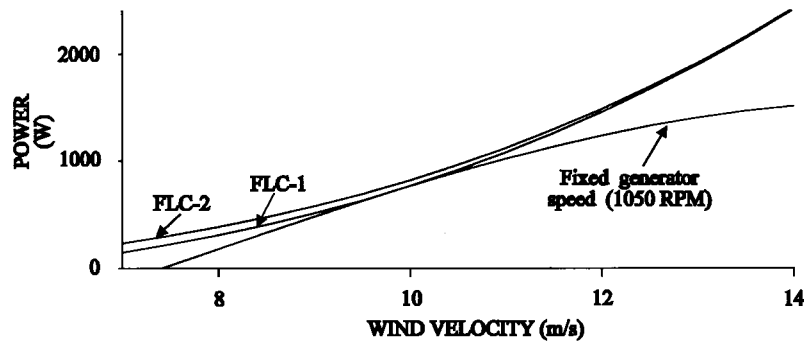
Fig. 13.   Steady-state line side power boost with FLC-1 and FLC-2 control.

shape. The slope of the ramp can be adjusted to control the power dips. Note that the speed command decrement will have an opposite effect; i.e., the generator tends to decelerate, giving bumps in the output power. Fig. 13 shows the performance of the system at variable wind speed when the three fuzzy controllers are in operation. If the generator speed (ω_r) remains fixed and FLC-1 and FLC-2 are not working, line power increases with increasing wind velocity. The operation of FLC-1 will give higher power except at a wind velocity of 10 m/s where it is tangential because the generator speed is optimum for that wind velocity. The incremental power gain due to FLC-2 is also indicated in Fig. 13. This power gain gradually diminishes to zero as the wind velocity increases. In all modes of system operation, the line current was verified to be sinusoidal at a unity power factor.

V. Conclusion

A complete fuzzy logic control based wind generation system has been described in the paper. The system was analyzed and designed, and performances were studied extensively by simulation to validate the theoretical concepts. The experimental work is in progress and will be reported later. There are three fuzzy logic controllers in the system. Controller FLC-1 searches on-line the optimum generator speed so that aerodynamic efficiency of the wind turbine is optimum. A second fuzzy controller FLC-2 programs the machine flux by an on-line search so as to optimize the machine-converter system efficiency. A third fuzzy controller FLC-3 performs robust speed control against turbine oscillatory torque and wind vortex. Advantages of fuzzy control are that it is parameter insensitive, provides fast convergence, and accepts noisy and inaccurate signals. The fuzzy algorithms are universal and can be applied retroactively in any system. System performance, both in steady state and dynamic conditions, was found to be excellent.

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From 1986 to 1989, he worked for Fundacão para o Desenvolvimento Tecnológico da Engenharia—FDTE, a research institution that belongs to the University of São Paulo. He also ran a small company for the development of switching power supplies. He has been a Professor at the University of São Paulo, Brazil, since 1989. He was awarded a Brazilian scholarship to pursue his doctoral degree at The University of Tennessee, Knoxville, where he actively worked in the research of fuzzy logic and neural networks applications to power electronics, drives, and machines control. He is currently working as a full-time Professor at The University of São Paulo, where he is involved in the research and development of systems on the application of artificial intelligence in power electronics and drives for renewable energy systems.

Mr. Simoes has published several papers in IEEE conferences; three were accepted for publication in IEEE Transactions. There are two patents pending for the new strategies presented in his Ph.D. dissertation in the control of drives and performance enhancement of wind generation systems.

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Dr. Bose received the IEEE Industry Application Society Outstanding Achievement Award (1993) for "outstanding contributions in the application of electricity to industry," the IEEE Industrial Electronics Society Eugene Mittelmann Award (1994) in "recognition of outstanding contributions to research and development in the field of power electronics and a lifetime achievement in the area of motor drives," the IEEE Region 3 Outstanding Engineer Award (1994) for "outstanding achievements in power electronics and drives technology," and the IEEE Lamme Gold Medal (1996) for "contributions to the advancement of power electronics and electrical machine drives."

Ronald J. Spiegel (M'73) received the Ph.D. degree in electrical engineering, with a minor in optical physics, from the University of Arizona, Tucson, in 1970.

His area of expertise is electromagnetics, and his Ph.D. dissertation dealt with the detection of atmospheric pollutants using laser radar (lidar) techniques. Subsequent to graduation, he was a Post Doctoral Fellow in biomedical engineering at Duke University, Durham, NC, from 1971 to 1972, where he conducted research in the interaction of electromagnetic fields with biological media. After completing his Fellowship, he held positions in private industry such as the Boeing Aerospace Company and at research institutes such as the IIT Research Institute and Southwest Research Institute where he worked in the Department of Defense on military-related research. This research included electromagnetic compatibility (EMC), nuclear electromagnetic pulse (EMP), radar cross-section analysis, and antennas. In 1980, he joined the U.S. Environmental Protection Agency (EPA) as Chief of the Bioengineering Branch where he supervised a multidisciplinary team of researchers with the mission of conducting research in the area of electromagnetic field interaction with biological objects relating to experimental methods, dosimetric methods, model development, and mitigation approaches. After Congress terminated funding for the EPA's program on the biological effects of electromagnetic radiation, he relocated to the Air Pollution Prevention and Control Division and is currently researching cutting-edge environmental technology development. This area includes fuel cell application to landfill methane gas, intelligent control (fuzzy logic, neural networks, and genetic algorithms) of electric motors and wind turbines, and solar photovoltaics.

Dr. Spiegel is a Member of Sigma Xi and is a Registered Professional Engineer. He was awarded the EPA's Scientific and Technological Achievement Award for 1984 and 1990 and was a Finalist in the 1996 Discover Awards for Technological Innovation.