&EPA **Project Summary**

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

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This report gives results of a demonstration of the successful application of fuzzy logic to enhance the performance and control of a variable speed wind generation system. A squirrel cage induction generator feeds the power to a double-sided pulse width modulation converter system which pumps power to either a utility grid or an autonomous system. Maximum power point tracker control is performed with three fuzzy controllers, without wind velocity measurement. A fuzzy logic controller (FLC-1) searches the generator speed on-line to optimize the aerodynamic efficiency of the wind turbine. A second fuzzy controller (FLC-2) programs the machine flux by 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.

Detailed analysis and simulation studies were performed for development of the control strategy and fuzzy algorithms, and DSP TMS320C30 based hardware with C control software was built for the performance evaluation of a laboratory experimental setup. The theoretical development was fully validated, and the system is ready to be reproduced in a higher power installation.

This Project Summary was developed by EPA's National Risk Management Research Laboratory's Air Pollution Prevention and Control Division, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The report describes work performed by the University of Tennessee on fuzzy logic based control of a variable speed wind generation system. The purpose of this research and development was to optimize efficiency and enhance performance for a variable speed wind turbine electrical generation system by using fuzzy logic principles. The project involved power system topology selection, control strategy formulation, system analysis, performance study by simulation, converter system design, control hardware and software development for digital signal processors, and experimental study in the laboratory with a 3.5 kW generation system to demonstrate performance. In general, all system performance goals have been successfully demonstrated. The control, with a small change, can be easily applied to a larger wind generation system in the field.

System Description

Figure 1 is a block diagram of the power circuit and the fuzzy logic based control of the wind generation system. The wind turbine is coupled to the squirrel cage type induction generator through a speed-up gear box (not shown). The variable frequency variable voltage power generated by the machine is rectified to direct current (dc) by an IGBT PWM bridge rectifier that also supplies lagging excitation current to the machine. The dc link power is inverted to 60 Hz, 220 V alternating current (ac) through an IGBT PWM inverter and fed to a utility grid. Both the line and machine currents are sinusoidal, as shown. The line-side power factor is maintained at unity although it can be programmed to be leading or lagging. The generated power normally flows from the machine to
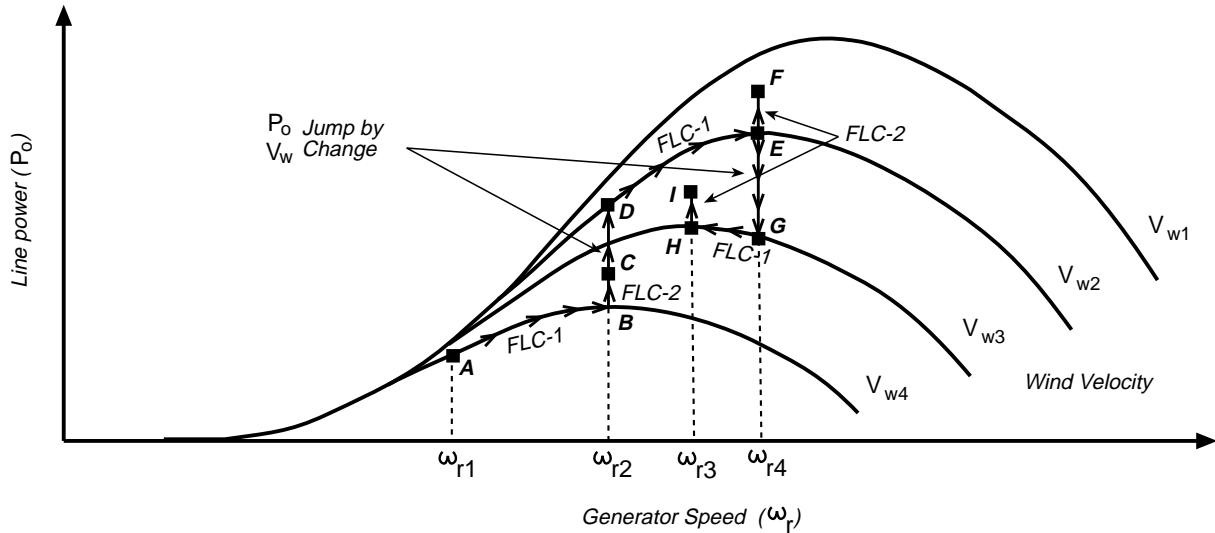
Figure 1. *Fuzzy logic based control block diagram of wind generation system*

the line. However, power can also flow in the opposite direction for the start-up of a vertical turbine. As the speed of the machine builds up, it goes into a generating mode. The machine is shut down by regenerative braking. The generator speed is controlled by indirect vector control with torque control and synchronous current control in the inner loops. The machine flux is controlled in open loop by control of i_{ds} current, but in normal condition, the rotor flux is set to the rated value for fast transient response. The line-side converter is also vector-controlled using direct vector control and synchronous current control in the inner loops. Output power is controlled to regulate the dc link voltage. Since an increase of output power decreases the link voltage, the loop error polarity has been inverted. The tight regulation of Vd within a small tolerance band requires a feed forward power injection in the power loop, as indicated. The system uses three fuzzy controllers (FLC-1, FLC-2 and FLC-3).

Neglecting losses, the line power output of the system as a function of generator speed at different wind velocity is ex-

plained in Figure 2. For a certain wind velocity, if generator speed is increased, output power first increases, reaches a maximum value, and then decreases. If the wind velocity increases, the maximum power point also increases and shifts to the right side, as shown. It is desirable that, for any wind velocity, the system should always operate at the maximum power point where the turbine aerodynamic efficiency is maximum. Since wind velocity is an unknown parameter, the speed of the generator can be modified by on-line search until the maximum power point is attained.

Three Controllers

The function of fuzzy controller FLC-1, shown in Figure 1, is to search the generator speed until the system settles down at the maximum output power condition. If, for example, wind velocity is V_{w4}, output power will be at point A for generator speed w_{r1}. The output power can be raised to the maximum value at B by increasing the speed to w_{r2}. If wind velocity now increases to V_{w2}, the power output jumps to point D. However, at this wind velocity,

the maximum power can be obtained by increasing generator speed further to w_{r4}. This means that as wind velocity changes, generator speed has to track it in order to extract maximum power. This control function is done by fuzzy controller FLC-1. The details of the control are described in the full report. Fuzzy control has several advantages: the control algorithm is universal (the same algorithm can be applied to any similar system), control converges fast because of the adaptively decreasing step size in the search, and the system can tolerate noisy and inaccurate signals. Note that it does not need wind velocity information, and the system parameter variation does not affect the search.

The light load efficiency of the generator-converter system is optimized on the basis of on-line search of the machine rotor flux, and is implemented here by fuzzy controller FLC-2. At a certain steady state wind velocity and at the corresponding optimum speed established by controller FLC-1 (see Figure 1), the rated rotor flux is reduced by decreasing excitation current i_{ds}. This causes an increase of the torque component of current by the

Figure 2. *System operation indicating performance of fuzzy controllers*

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 converter-machine system loss decreases, resulting in an increase of total generated power. The search is continued until the system settles down at the maximum power point. The principle of FLC-2 is similar to that of FLC-1, starting when FLC-1 has completed its search at the rated flux condition (Figure 2).

The generator speed control loop uses fuzzy controller FLC-3 to get robust performance against turbine steady state oscillatory torque, the effect of wind vortex and pulsating torque induced by FLC-2. There is also the possibility of mechanical resonance of the turbine-generator system in the absence of robust control. All disturbance torque components are essentially modulated inversely so that their effect on the system is minimal. With fuzzy control, the speed control loop also gives deadbeat response when the speed command is changed.

System Simulation

Once the power circuit and the control system were formulated and the system was analyzed, it was studied in detail by simulation using PC-SIMNON language on an IBM PC. A simplified lossy D-Q model of the machine was used for the simulation study. All the fuzzy controls and the inner loop vector controls were implemented in the simulation, and the control-

ler parameters were iterated until satisfactory control performances were obtained. Considering the complexity of the system, detailed simulation study was necessary prior to experimental study of the system.

A 3.5 kW laboratory breadboard system was designed and built to experimentally verify system performance. The converters were built using POWEREX IGBT intelligent power modules. The induction machine was an ordinary NEMA Class B type. The dc link voltage was designed to be 300 V considering the voltage rating constraint (600 V) of the IGBTs. Since the line-side converter always has to run in PWM mode, the ac line voltage was reduced by a transformer (not shown in Figure 1). A 7.5 hp four-quadrant laboratory dynamometer was used to emulate the wind turbine.

The control hardware is based on two Texas Instruments TMS320C30 digital signal processor (DSP) boards which are placed in the PC slots with the I/O hardware. The 32-bit floating point DSP has 60 nsec instruction cycle time. The multitasking software, principally based on C language, is strategically distributed between the two DSPs. The converters use PWM chips that are basically hybrid ASIC that incorporate dedicated digital hardware and RISC microprocessor.

Figure 3 shows the static characteristics of the wind turbine at different wind velocities. Basically, these are families of curves for turbine output power, turbine torque, and line-side outpower as func-

tions of wind velocity and sets of generator speed. For example, if the generator speed remains constant and the wind velocity increases, the turbine power, turbine torque, and line power will increase and then will tend to saturate. The slope of increase is higher with higher generator speed. For a fixed wind velocity, as the generator speed increases, the torque and power outputs first increase and then decrease. The efficiency improvement by controllers FLC-1 and FLC-2 are shown in Figure 4. The turbine-generator system was operated at constant speed (940 rpm) and wind velocity was varied. At each operating point, the FLC-1 and FLC-2 controllers were operated in sequence and the corresponding boost of power was observed. From the data, the efficiency improvements were calculated and plotted in Figure 4 which indicates significant efficiency gain with FLC-1 for constant generator speed operation. This gain falls to zero near 0.7 pu wind velocity where generator speed is optimum for that wind velocity. The efficiency gain due to FLC-2 is about 30% at 0.5 pu wind velocity but decreases as wind velocity increases because of higher generator loading. During all operation modes, line current was sinusoidal with a unity power factor, as shown in Figure 5 (out-of-phase current indicates the generating mode). System performance was found to be excellent in all control modes. In general, all performance goals of the project were met satisfactorily.
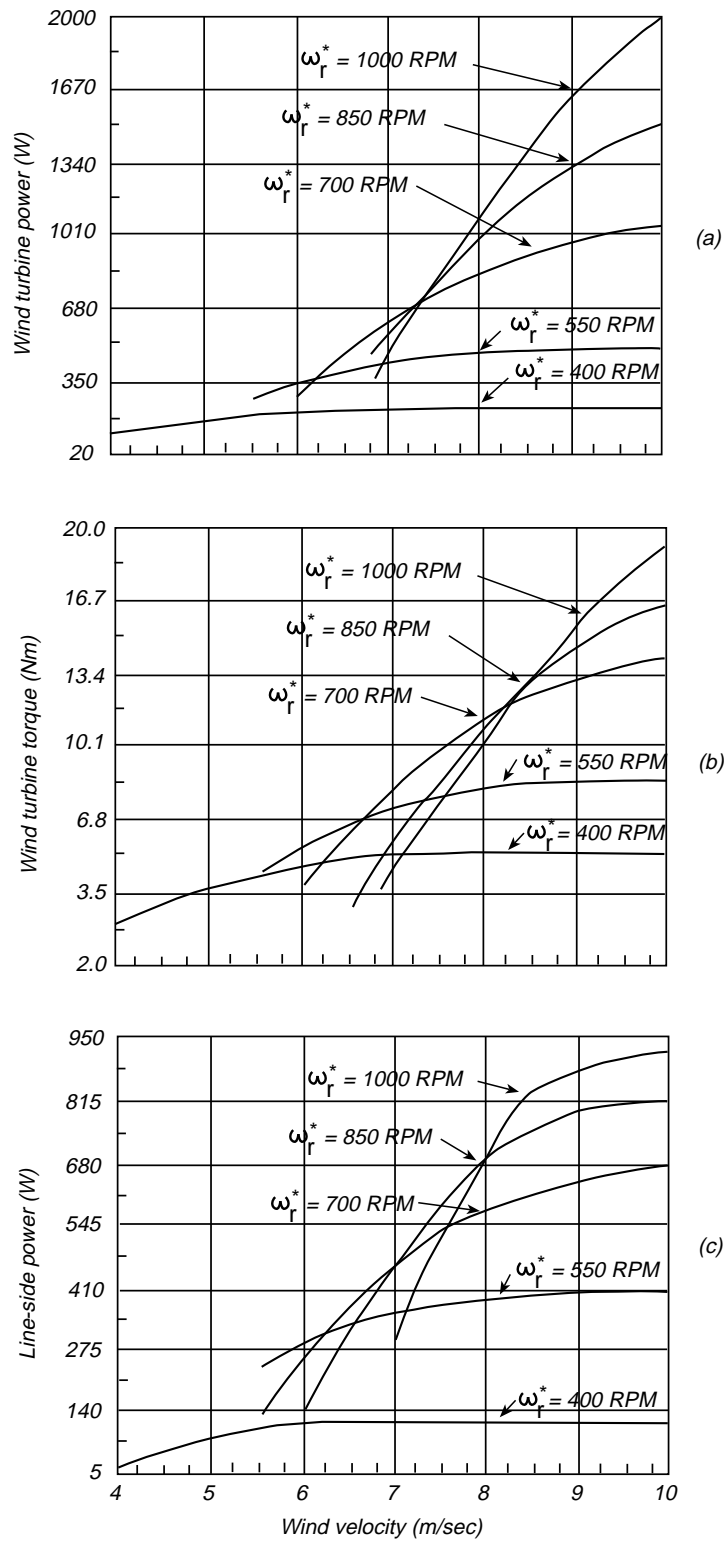
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Figure 3. *Wind turbine static characteristics, (a) turbine power, (b) turbine torque, and (c) line power.*
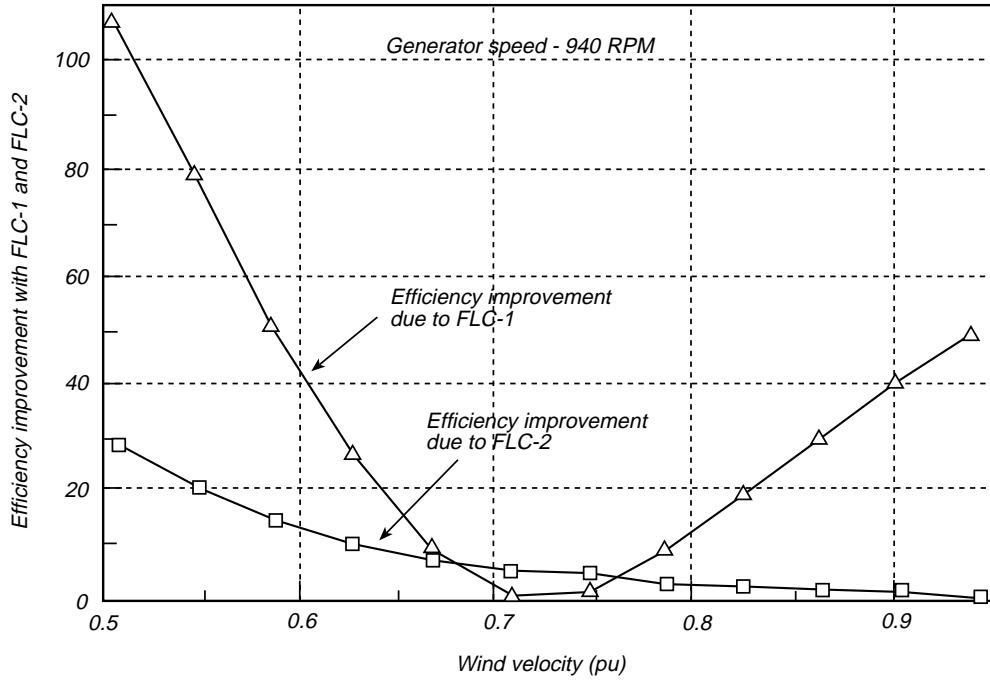
Figure 4. Efficiency improvement by controllers FLC-1 and FLC-2 at different wind velocities (1.0 pu - 31.5 mph)
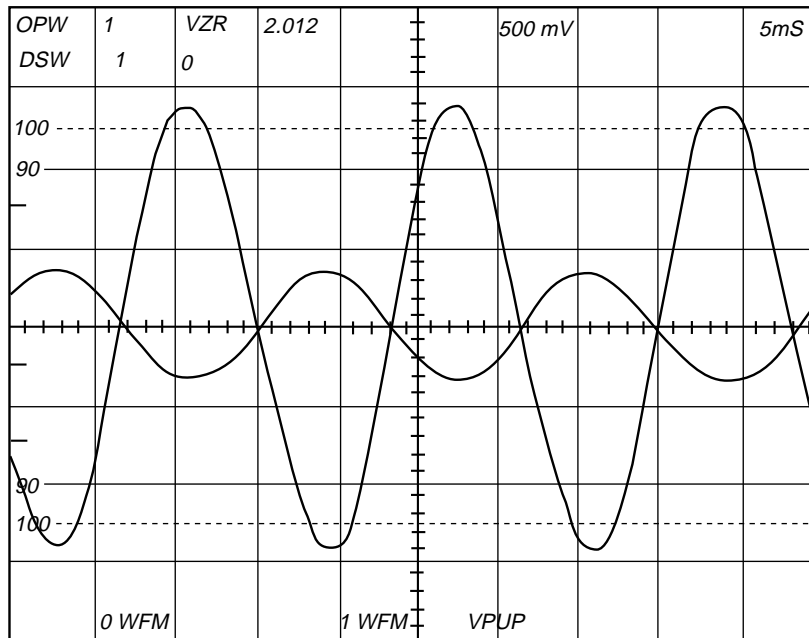

Figure 5. Line-side voltage and current waves showing unity power factor operation

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