NREL/TP-440-21412 • UC Category: 1213 • DE96007948

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Prepared for
AWEA Windpower '96
Denver, Colorado
June 23-27, 1996

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Prepared under Task No. WE618330

July 1996

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LABORATORY IMPLEMENTATION OF VARIABLE-SPEED WIND TURBINE GENERATION

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ABSTRACT

To improve the performance of wind turbines, various control schemes such as variable speed operation have been proposed. Testing of these control algorithms on a full scale system is very expensive. To test these systems simulation, we developed programs and small scale laboratory experiments. We used this system to verify a control method that attempts to keep the turbine operating at its peak power coefficient. Both the simulations and the experiments verified the principle of operation of this control scheme.

INTRODUCTION

With the need for reducing the cost of energy generated from wind turbines comes an increased need for improving their efficiency and performance. One method of increasing the performance is to run the turbine at variable speed. Advantages of running an induction machine in this manner include increased compliance to variations in wind, better energy capture, and less aerodynamic noise than systems with pitch control. These advantages come at the price of increased complexity in the system [1].

At the National Renewable Energy Laboratory (NREL),engineers are developing new wind turbine control strategies. Many of these controls are concerned with variable speed generation. In order to advance these control schemes in a cost efficient manner, it is necessary to verify the operation of the control before implementing them in the field. This requires a comprehensive set of simulations and laboratory experiments.

Previous simulations modeled the mechanical system well but basically approached the electrical systems from a steady state point of view. To achieve variable speed, however, the control of the electric machine becomes important, therefore making it necessary to have a dynamic model of the electrical system.

Experimental testing of generators consists of using a dynamometer to turn an electric machine. The dynamometers previously did not have the capability of simulating the behavior of the wind turbine, making their usefulness in testing variable speed controls schemes very limited

NREL developed computer simulations and a small dynamometer system to simulate the behavior of a wind turbine system. The simulations include the full dynamic behavior of the electric machines, and the dynamometer can be controlled to simulate the characteristics of a wind turbine. The dynamometer system in the Power Electronics Laboratory at the National Wind Technology Center consists of off-the-shelf power converters and a standard motor dynamometer set. The system has been shown to be effective in the preliminary study of variable speed wind turbine power control.

VARIABLE SPEED WIND GENERATION

The power developed through a wind turbine is dependent on the wind speed and a power coefficient (c_p). The power delivered to the motor is given by

$$P_T = 0.5 c_p \rho A V^3 \tag{1}$$

where

ρ is the air density
A is the cross-sectional area of the turbine
V is the wind velocity.

The power coefficient is not a constant and is dependent on the tip-speed ratio (Λ) given by

$$\Lambda = \frac{\omega_T R}{V} \tag{2}$$

where

R is the radius of the turbine.

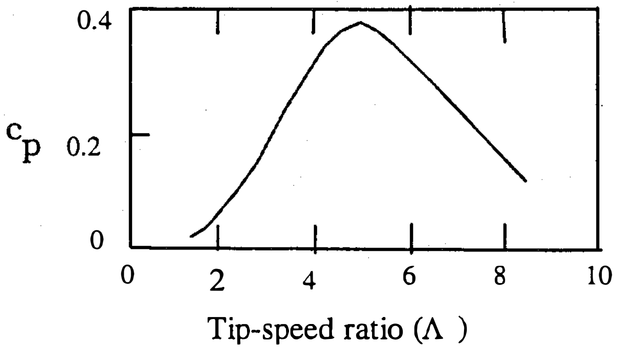

Fig. 1. Power coefficient as a function of tip-speed ratio

A typical relationship between c_p and Λ is complex as seen in Fig. 1. From this relationship there is clearly a value of Λ that will give a maximum c_p and thereby maximize the power for a given wind speed. As Λ is directly related to the turbine speed, there is a turbine speed that corresponds to a maximum power for a given wind velocity. This is illustrated in Fig. 2.

With varying wind speed, it is necessary to vary the turbine speed in order to operate at the maximum value of c_p. To track the maximum c_p power curve shown in Fig. 2, an algorithm was developed that appropriately adjusts the output power of the induction machine using the slip frequency. In an induction machine, slip frequency is the difference between the applied frequency and the mechanical speed of the machine seen by a set of magnetic poles. With an induction machine run at a constant V/Hz, power is related to the slip frequency. The relationship between slip frequency and power is such that a particular frequency could be found that delivers a given power at the desired speed. To implement this control, it is necessary to have the induction machine connected to a variable frequency source.

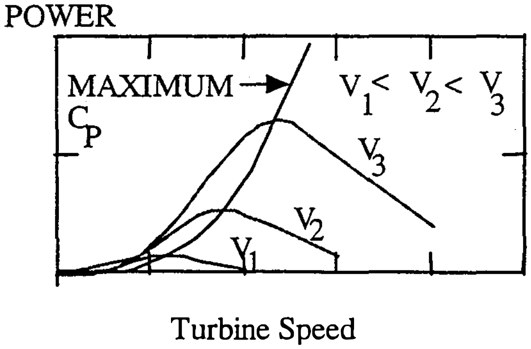

Fig. 2. Typical turbine power relationship for various wind speeds

Although it is generally desirable to have the turbine follow the maximum cp curve, during times of excessive wind gusts it is necessary to limit the speed and power of the turbine. With speed and power limitations, the desired speed power characteristic would appear as shown in Fig. 3. To limit speed, when the maximum speed is reached, the frequency to the induction machine is not allowed to increase. When the maximum power level is reached, the frequency is decreased to move away from the peak power point of the turbine, thereby reducing the overall power generated.

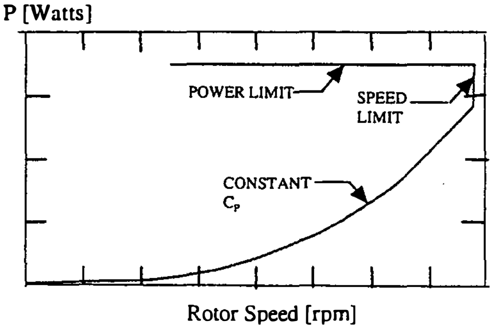

Fig. 3. Desired power speed relationships for induction machine

Development of control systems like the one described is impractical using a full scale system. Therefore it is necessary to use computer programs and small scale systems to develop these control systems. Software simulations and a small scale laboratory experiment were used at NREL to help verify the behavior of maximum c_p curve control strategy.

SOFTWARE SIMULATION

Computer simulations were first used to determine if the control strategy would perform as desired. The computer program used the Advanced Continuous Simulation Language (ACSL). Although many computer languages could have been used, we chose this language because script can be written similar to other computer programs while containing built-in commands especially useful for control systems.

The computer program uses a dynamic model of the system in the simulation. The induction motor is modeled as a fifth order system with four electrical state variables and one mechanical [2]. The turbine was modeled as a simple system with a large inertia and a torque generated by the appropriate wind speed. The power generated by the turbine was calculated using a third order polynomial representation of the c_p curve. Although relatively simple models were used in this simulation, they proved to be effective for operating conditions modeled in the preliminary studies. The program is also very flexible and the complexity of the system model could easily be increased.

To perform the simulation in ACSL the system is basically described in standard state variable form. In addition, constraint and control equations are used as part of the dynamic model. Once the initial conditions are established, ACSL uses numerical integration techniques to determine the behavior of the system. Although ACSL has various integration techniques, the default forth-order Runge-Kutta was used for these simulations.

POWER ELECTRONICS LABORATORY

To further verify the behavior of a system it is usually desirable to have some experimental verification. In the early stages of system development it is not realistic to use a practical turbine to verify the control operation. Therefore, NREL has developed a small scale laboratory model to test new control algorithms.

The laboratory system consists of power electronics modules that can easily interface with small electric machines. The power electronic modules include a voltage source inverter, a current source inverter, a phase controlled rectifier, and a rectifier bridge. These electronic converters are each capable of handling power of up to 15 kW.

The electric machines in the laboratory are small machines typically rated around 250w. The machines include squirrel cage induction machines, wound rotor induction machines, and dc machines. The machines can all be loaded using a dc machine connected as a dynamometer.

It should be noted that the electronic power converters are rated considerably higher than the electric machines. This allows for easy transfer to the next higher level of testing.

For a typical application the dynamometer is used as a prime mover in place of the wind turbine. When operating in this manner the machine is powered from a phase controlled converter with a current feedback control. By controlling the current on the dc dynamometer, the torque of the dc machine can be directly controlled. Command currents are fed into the control based on its speed of rotation and an externally fed wind speed command. Using this method the speed torque characteristics of the wind turbine can effectively be simulated.

SCALING FACTORS

A problem associated with small scale laboratory implementations is that the system being modeled usually does not scale linearly. Thus it is not possible to have the behavior of the small system match that of the large scale system in all aspects. With proper selection of parameters for the system it is possible demonstrate the principle of operation of a conventional sized system.

As an example in the system described above it is desirable to have the small scale experiment match the c_p characteristic of a larger turbine. For a given turbine the maximum value of c_p would occur at a given value of tip-speed ratio (Λ_{max}). The limits on the small machine are the rated power and speed of the machine. To appropriately compare these values combine (1) and (2) under the conditions the machine operates at c_{pmax} to get

$$P = 0.5\pi\rho c_{p\max}\left(\frac{\omega_t}{\Lambda_{\max}}\right)R^5 . \qquad (3)$$

Using a power and speed operating point for the machine, the scaled radius of the turbine can be calculated. With this and the definition of tip-speed ratio (2) the equivalent wind velocity for these operating conditions can be calculated.

EXAMPLE EXPERIMENT

The laboratory facilities were used to examine the variable speed control scheme that follows the maximum c_p power curve. The experiment was set up as shown in Fig. 4. The dc machine and converter were used to simulate the wind turbine. The induction machine and the converter connected to it were used as the power generating device. An input voltage is used to represent a wind speed while the system was controlled with a microcontroller.

The turbine being evaluated has a c_{pmax} of 0.5 at a Λ_{max} of 0.95. For our setup, we desired that the small machine follow the maximum c_p curve to 1300 rpm (23 rpm at the turbine with a gear ratio of 30:1) with a power of 75 w. From this it was determined that the turbine's radius would be about 4 m while the wind velocity for this point would be 2 m/s. In the simulations and experiments, speed was limited to 1300 rpm and power to 130 w. These limits were chosen to keep the machine well within its speed, power ,and current ratings.

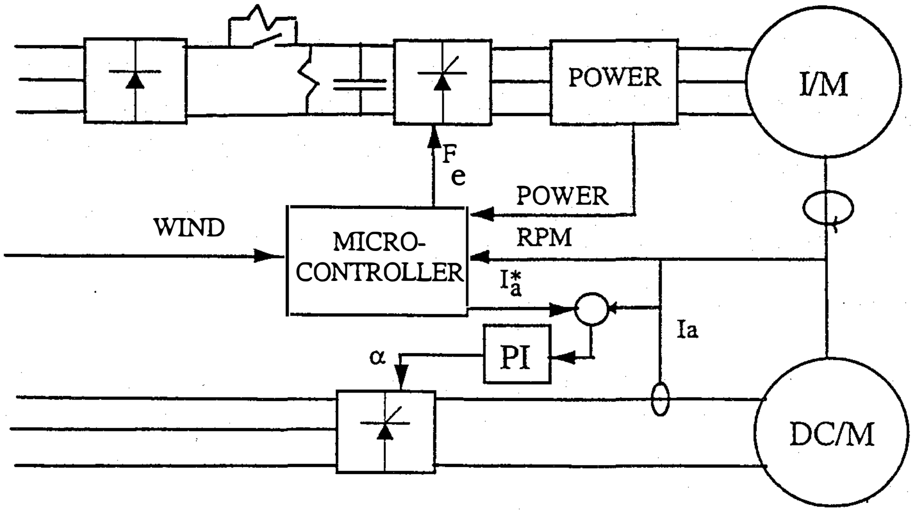

Fig. 4. Laboratory experimental setup

Before running the experiment, we ran computer simulations to test the basic algorithms. In the simulation, wind speed was ramped up to 4 m/s and back down to zero. With this range of wind speeds the system would run beyond the speed and power limits. The results are shown in Fig. 5 in which the power is plotted as a function of speed. In this plot it is seen that the power curve follows nearly the same shape as the ideal power curve shown in Fig. 3. The target power (Ptarget) is the desired power with the machine operating at maximum cp. For this simulation, the power into the generator exactly follows the target power until the speed limit occurs. After the speed limit is reached the speed is maintained at the desired speed of 1300 rpm. In the region where the control is in the power limit, power is seen to fluctuate in a region slightly above the power limitation. Generally this simulation shows that the system behaves as expected.

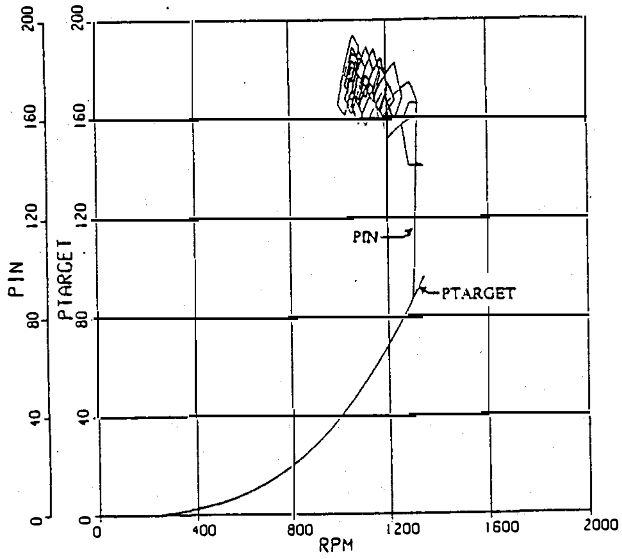

Fig. 5. Comparison of mechanical input power to the generator and targeted power as a function of generator rpm for simulated ramped wind speed

After verifying the basic operation of the algorithm with software, we implemented the hardware. A speed command for the system was input to the microcontroller. From this input the microcontroller determines a current command that creates the desired torque on the dc machine for that wind speed and the present motor speed. The current is regulated using a PI controller external to the microcontroller. In this way the dc machine behaves like the wind turbine.

The microcomputer also controlled the ac generator. The algorithm was the maximum c_p algorithm already described with the desired speed and power limits. To find the proper frequencies for the given speed conditions, a third order polynomial was used. The coefficients of the polynomial were generated in advance based on generator and turbine characteristics. During the experiment the microcontroller calculated the proper frequency using the polynomial and motor speed.

The results of the experiment are plotted in Fig. 6 along with the desired power characteristics. From this data it is seen that the steady state behavior of the system basically follows the desired curve. The power tracks the maximum c_p curve until the speed limit is reached. In the power limit region the power is confined to a value close to the set limit.

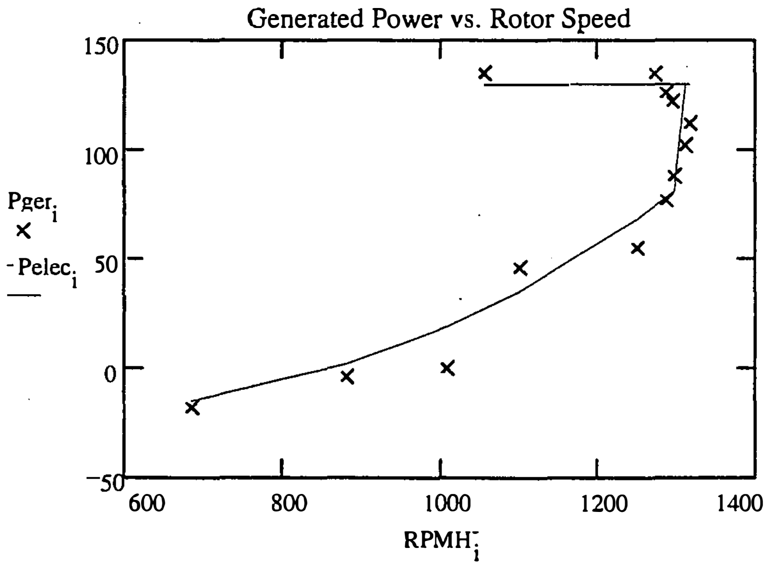

Fig. 6. Experimental steady state power generated (Pgen) compared to desired electrical (Pelect) for a given rotor speed

CONCLUSION

Before implementing new control algorithms for wind turbines it is advantageous to verify the operation of the algorithm in advance using software simulations and small scale laboratory models. We developed simulation software and a small scale laboratory setup for this purpose.

One way of optimizing the power converting capabilities of a wind turbine is to run the turbine at its peak power coefficient. An algorithm was developed for this type of control using a variable speed wind turbine. The algorithm was simulated and run using the small scale laboratory equipment. Both the computer simulations and the laboratory showed this control algorithm to be viable.

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