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ABSTRACT

A variable-speed, constant-pitch wind turbine was investigated to evaluate the feasibility of constraining its rotor speed and power output without the benefit of active aerodynamic control devices. A strategy was postulated to control rotational speed by specifying the demanded generator torque. By controlling rotor speed in relation to wind speed, the aerodynamic power extracted by the blades from the wind was manipulated. Specifically, the blades were caused to stall in high winds. In low and moderate winds, the demanded generator torque and the resulting rotor speed were controlled to cause the wind turbine to operate near maximum efficiency. A computational model was developed, and simulations were conducted of operation in high turbulent winds. Results indicated that rotor speed and power output were well regulated.

1. Introduction

Wind energy conversion is the fastest-growing source of new electrical generation capacity in the world, and it is expected to remain so for the next decade. In the United States, there is a growing trend for public utilities to offer renewable energy choices, colloquially called "green power" options, to their customers. In Europe, the number of installed wind turbines is increasing at a dramatic pace.

Although most utility-scale wind turbines are operated at constant speed, there is considerable interest in variable-speed turbines, as demonstrated in commercial applications by Kenetech, Enercon, Zond and others. The primary advantages claimed for variable-speed turbines are increased energy capture and reduced drive-train loads, although secondary benefits in acoustic signature and power quality are also touted. The more that is learned about variable-speed turbines, the more it becomes apparent that their behavior is significantly affected by the control strategy employed in their operation.[1,2,3]

Typically, variable-speed turbines use aerodynamic controls in combination with power electronics to regulate torque, rotational speed (RPM) and power.[4] The aerodynamic control systems, usually variable-pitch blades or trailing-edge devices, are costly and complex and become even more so as turbines get larger. This situation provides an incentive to consider alternative control approaches. In this paper, we evaluate a variable-speed, stall-regulated strategy which eliminates the need for ancillary aerodynamic control systems. The potential benefit is a lower cost of energy resulting from lower capital cost, improved reliability and reduced maintenance expense.

In the strategy to be investigated, the turbine is controlled to operate near maximum efficiency (energy capture) in low and moderate wind speeds. At high wind speeds, the turbine is controlled to limit its rotational speed and output power. This is accomplished by forcing the rotor into an aerodynamically stalled condition. We call this the "soft-stall" approach, because it allows the introduction of rather benign stall characteristics for purposes of

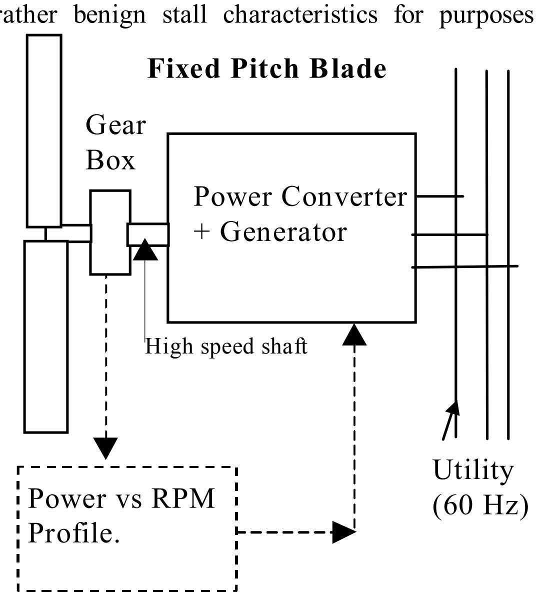

Figure 1. Physical diagram of the system

controlling maximum power. Thus, in contrast to a constant-speed wind turbine, the variable-speed wind turbine has the capability of shaping the RPM-power curve. This concept is explored in terms of its technical feasibility, rather than cost and reliability, which are the subject of future work.

Figure 1 shows the system under consideration, with the dashed lines indicating the main control loop. The wind turbine rotor is connected to a variable-speed generator through a speed-increasing gearbox. The generator output is controlled by the power converter to follow the commanded RPM-power schedule. The generator responds to the torque command almost instantaneously.

2. Wind Turbine Characteristics

The power (P) converted by a wind turbine is related to the wind speed as shown in Equation 1. In the present context, the equation represents net electrical power after considering the aerodynamic efficiency of the rotor blades and the mechanical and electrical system losses.

$$P = 0.5\rho A C_p V^3 \qquad [1]$$

where: ρ = mass density of air
A = area swept by the rotor blades
V = wind speed
C_p = nondimensional power coefficient

For a variable-speed turbine, the objective is to operate near maximum efficiency, where the resulting target power can be expressed as shown in Equation 2.

$$P_{target} = 0.5\rho A C_{ptarget} (R/TSR_{target})^3 \omega^3 \qquad [2]$$

where: R = rotor radius measured at the blade tip
ω = rotational speed of the blade

The tip-speed-ratio (TSR), which is a nondimensional tip speed, is defined as the ratio between the rectilinear speed of the blade tip and the wind speed, as shown in Equation 3.

$$TSR = \omega R/V \qquad [3]$$

Figure 2 illustrates the C_p-TSR relationship for a typical wind turbine. For constant-speed turbines, an attempt is made to design the rotor blades to operate near maximum efficiency (C_{pmax}) at wind speeds that occur most frequently at the design site. The rotor speed varies by only a few percent (the slip) above the synchronous speed of the induction generator, but the wind speed varies over a wide range. Therefore, the operating point is rarely, and randomly, at the TSR for C_{pmax}.

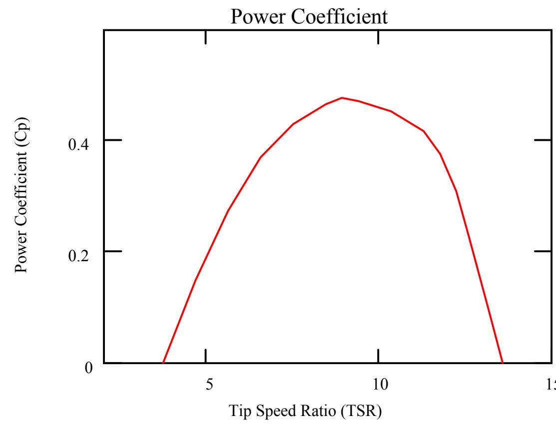

Figure 2. Power coefficient versus tip-speed ratio

It is apparent from Equation 2 and Figure 2 that the power at any wind speed is maximized by operating near the tip-speed ratio that results in the maximum power coefficient. For a variable-speed turbine, this means that as the wind speed changes, the rotor speed should be adjusted proportionally. In the practical matter of operating a wind turbine, the wind speed is not a satisfactory control parameter, because of its erratic nature and the time delays in its measurement. However, by simple manipulation of Equations 2 and 3, the target power can be expressed in Equation 4 as a function of RPM, a reliable and easily measured control parameter.

$$P_{target} = K_1\omega^3 = K_2 (RPM)^3 \qquad [4]$$

The objective of the present study is to evaluate the behavior of a variable-speed, stall-regulated wind turbine operating in turbulent winds. To simplify the analysis, a variable-speed control algorithm is chosen that assumes steady-state operation represented by the turbine's C_p-TSR curve. Although effects such as tracking errors, wind shear and swirl are ignored, it has been shown in other simulations and field-test observations that the steady-state assumption is quite reasonable.

3. Control Strategy

The power available from the wind is proportional to the cube of the wind speed. Therefore, in order to regulate power as the wind speed increases, there must be some mechanism to reduce the efficiency of the rotor blades.

Constant-speed, fixed-pitch wind turbines accomplish this automatically, because in high winds their blades stall. The resulting reduction in lift and increase in drag dramatically reduces the ability of the blades to extract power from the wind. It is important to note that this will be the case only if the generator (and power converter, in our case) can limit the rotor RPM, thereby forcing the blades to stall. It is also desirable that the blades stall gently, so that mechanical loading on the wind turbine components is not significantly increased.

It is worth noting that rotor acceleration can be made zero as long as the power extracted from the wind, less drive-train losses, is equal to the electric power output of the generator. This relationship is described by Equation 5 in terms of torque. The rotor acceleration is inversely proportional to the inertia of the rotating system, essentially the rotor inertia (J), and directly proportional to the difference between the torque applied by the wind (T_{wind}) and the electric torque of the generator ($T_{electric}$). The aerodynamic torque is affected by the operating Cp.

$$\dot{\omega} = (T_{wind} - T_{electric}) / J \qquad [5]$$

Figure 3 illustrates the relationship between power, wind speed, and RPM for a typical wind turbine. The lower the operating RPM of the rotor, the lower the maximum power that can be generated. Thus, the turbine operated at rotor speed RPM_D, will have a maximum power of P_D, while the turbine operated at higher rotor speed RPM_C will have a maximum power of P_C. This concept is the basis of the power profile shown in Figure 4, which illustrates the control strategy. At low and moderate wind speeds (0A), generator RPM is controlled so that maximum power is produced by operating near C_{pmax}.

At high wind speeds the wind turbine is prevented

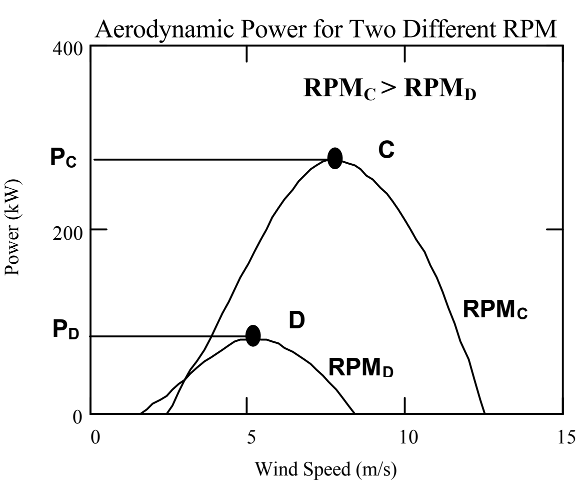

Figure 3. Power versus wind speed at two different rotor speeds

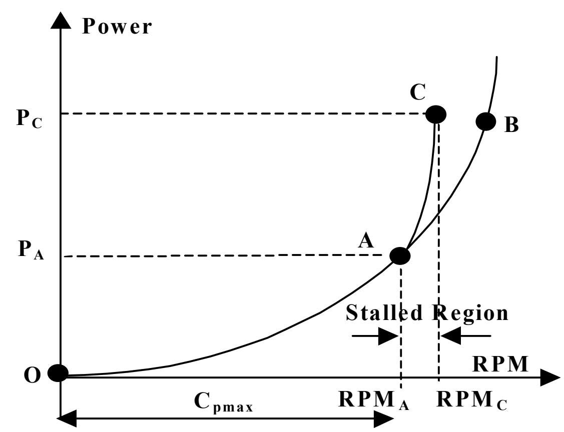

Figure 4. Power target profile

from following the C_{pmax} trajectory (OB) and is forced to operate at a lower TSR and Cp. At RPM_A, the applied generator torque causes the turbine to deviate from C_{pmax} operation. Because the difference between P_{wind} and $P_{electric}$ is positive, the rotor speed continues to increase, but the turbine blades begin to operate in a partially stalled mode. It is expected that the rotor speed will be controllable and constrained to an upper limit of RPM_C. The region between RPM_A and RPM_C is the "soft stall" region. In order to successfully implement this strategy and limit the rotor speed to RPM_C, the capacity of the power converter and generator must be sufficient to process the maximum power (P_C) in order to limit the rotor speed to RPM_C. Thus, when the rotor speed reaches RPM_C, the aerodynamic power and the electric power are in balance, and the rotor acceleration is zero.

4. Computational Model

We investigated a two-bladed, downwind, variable-speed, constant-pitch wind turbine having a nominal rated power of 400 kW. The rotor rpm limit RPM_C (point C in figure 4) is chosen to be 62 rpm. The RPM_A is chosen to be 57 rpm. The power at RPM_C is chosen to be 400 kW. The maximum power coefficient C_{pmax} is 0.457 and the target tip speed ratio TSR_{target} is 8.5. Its wound-rotor induction generator is controlled by a series-resonant power converter using the flux orientation method, which permits torque control at any RPM. The output of the generator stator is fed directly to the utility at 60 Hz and unity power factor.

The generator, controlled to provide the desired torque-speed relationship, was modeled as a wound-rotor induction generator with its stator connected to the utility and its rotor winding connected to the power converter. The torque-speed relationship was such that the wind turbine operates near its maximum power coefficient in low and moderate wind speeds, which account for most of the energy capture at typical wind sites. In high winds, the torque was controlled to limit rotor speed, which has the effects of stalling the blades and constraining power. The transition from medium to high wind speeds must be done smoothly, and requires a tradeoff between energy capture and load reduction that was not part of the present study.

5. ACSL Simulations

A computer model of the system was developed to predict aerodynamic power as a function of wind speed and rotor RPM using Advanced Continuous Simulation Language (ACSL). Required inputs include blade geometry, rotor inertia, drive-train inertia, and stiffness and damping of the rotating shafts. The aerodynamic characteristics of the wind turbine are defined by the relationship between its nondimensional power output and tip-speed. The wind speed input used to drive the model is stored in a data file. Although any temporal distribution (and turbulence level) can be chosen, we used a 10-minute time series to reduce computational time. Output is in the form of high- and low-speed shaft torques as a function of time.

A segment of the wind speed time series, which ranges from 10 m/s to 35 m/s and has a mean value of 18 m/s, is shown in the upper part of Figure 5. The calculated power coefficient, shown in the lower part of Figure 5, follows the control strategy as evidenced by the dramatic reduction in Cp (blades stalled) at the high wind speeds around t = 120. At the low wind speeds, around t = 110, 140 and 175, the control strategy succeeds in maintaining Cp near its maximum possible value.

The calculated power and RPM are shown in Figure 6. The system is started with the generator operating as

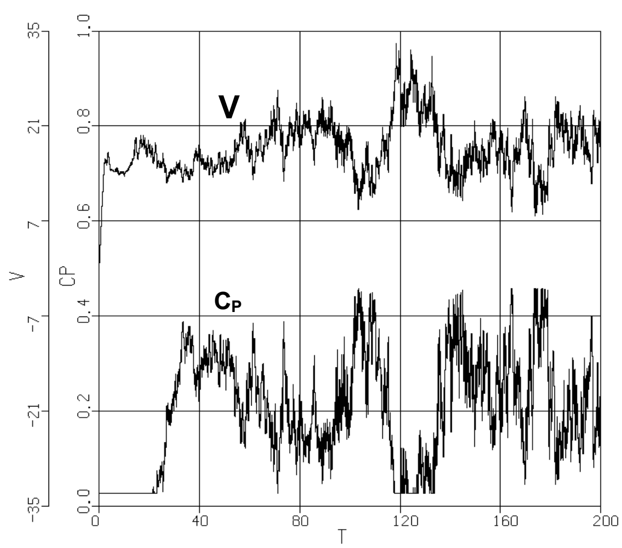

Figure 5. Wind speed (m/s) and power coefficient

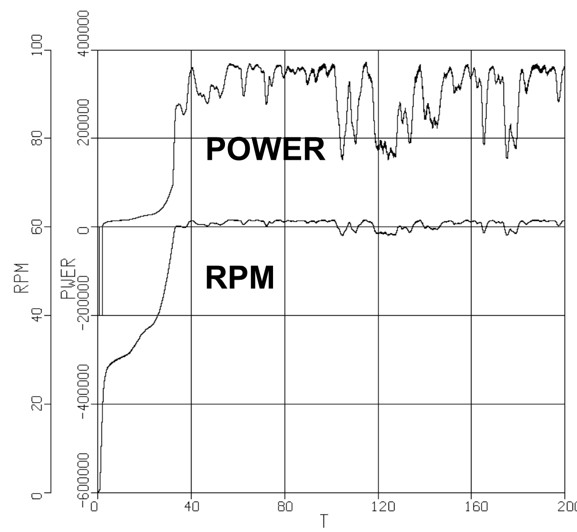

Figure 6. Electrical power (Power) in watts and rotor speed in rpm

a motor at a constant power of 200 kilowatts. As the RPM increases, the start-up procedure is discontinued and the normal operating mode is simulated. At high wind speeds, the rotor speed and power are successfully limited to approximately 61 RPM and 385 kW, respectively. Because the rotor RPM dictates the power output of the generator, the power variation follows the RPM variation. Note that as the wind speed fluctuates at its higher values, the rotor blades operate in a stalled condition. This is evidenced by the reduction in RPM and power at the high wind speeds around t = 120. As hypothesized, the rotor speed never exceeds 62 RPM and the power never exceeds 400 kW. In fact, it appears that the capacity of the power converter and generator may be somewhat conservative.

Although it is difficult to ascertain in Figure 6, the following observations can be made. As the wind speed increases, around t = 110 for example, the captured power also increases. Because the captured power is higher than the electrical power, the rotor accelerates. When the RPM reaches the stalling range, the demanded generator torque is raised to follow a stalling torque-profile. Recall that at rotor speeds less than 57 RPM, the controller follows the Cp_{max} operating mode described by Equation 4. That is, the electric power is controlled to be a cubic function of RPM. From 57 RPM to 62 RPM, the turbine operates in the stalling mode.

6. ADAMS Simulations

Simulations were also performed using Automatic Dynamic Analysis of Mechanical Systems (ADAMS) combined with the AeroDyn aerodynamics routines.[5] The model used is fully flexible as developed by Wright et al. [6] This model was modified to operate in variable

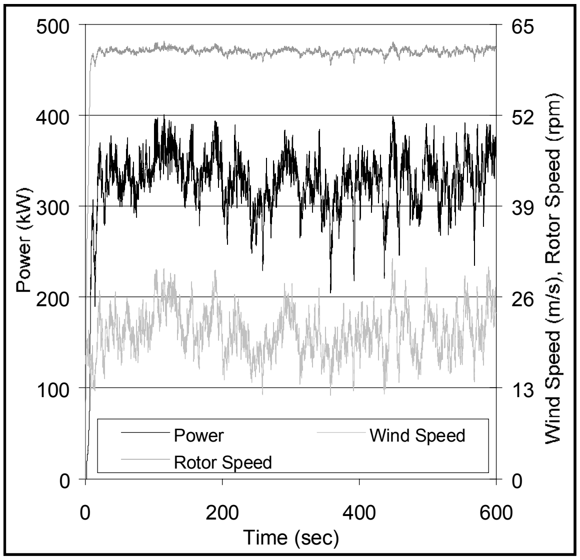

Figure 7. ADAMS simulation using 21 m/s average wind speed Kaimal turbulence

speed using the NREL Soft Stall Method. Simulations were performed using Kaimal turbulence files generated from SNL-Wind 3D[7] over the wind speed range of operation. The method of control was found to perform well for this more complex model as well. Rotor speed, wind speed, and rotor power are shown in Figure 7 for a simulation using an average wind speed of 21 m/s. The power is limited to approximately 400 kW with the rotor speed limited to 62 rpm. Investigation of loads for variable-speed as compared to constant-speed operation indicated that drive-train fatigue loads for variable-speed operation are reduced for all wind speeds. In low winds, the blade-fatigue flap loads are somewhat reduced for the variable-speed operation, although tower loads are slightly increased. In high winds, the blade-flap fatigue loading and tower loading is essentially the same for both the variable speed and constant speed. Also of interest, the twice-per-revolution oscillations seen in power for a teetered rotor were substantially reduced for all wind speeds by variable-speed operation.

7. Conclusions

A control strategy was postulated for variable-speed, stall-regulated wind turbines. Computational models were developed, and simulations were conducted of operation in turbulent winds. Considering the results, the following conclusions may be drawn.

Controlling the rotor RPM, and hence the tip-speed ratio, by controlling the generator torque allows the adherence to a desired power coefficient profile. At low and moderate wind speeds, operation at or near Cp_{max} can be achieved. At high wind speeds, by forcing the rotor blades to stall, RPM and power can be constrained to the desired limits.

These simulations were performed without regard to issues of wind-turbine cost, reliability, or long term structural loads. These matters, as well as those related to changes in atmospheric density, blade soiling and site-specific conditions, will be the subject of future studies on adaptive control systems.

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