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Eduard Muljadi
C. P. Butterfield
Paul Migliore

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VARIABLE SPEED OPERATION OF GENERATORS WITH ROTOR-SPEED FEEDBACK IN WIND POWER APPLICATIONS

Eduard Muljadi, C.P. Butterfield, Paul Migliore

Wind Technology Division
National Renewable Energy Laboratory
Golden, Colorado

ABSTRACT

The use of induction generators in wind power applications has been common since the early development of the wind industry. Most of these generators operate at fixed frequency and are connected directly to the utility grid. Unfortunately, this mode of operation limits the rotor speed to a specific rpm. Variable-speed operation is preferred in order to facilitate maximum energy capture over a wide range of wind speeds.

This paper explores variable-speed operating strategies for wind turbine applications. The objectives are to maximize energy production, provide controlled start-up and reduce torque loading. This paper focuses on optimizing the energy captured by operating at maximum aerodynamic efficiency at any wind speed.

The control strategy we analyze uses rotor speed and generator power as the feedback signals. In the normal operating region, rotor speed is used to compute a target power that corresponds to optimum operation. With power as the control objective, the power converter and generator are controlled to track the target power at any rpm. Thus, the torque-speed characteristic of the generator is shaped to optimize the energy capture. The target power is continuously updated at any rpm. In extreme areas of the operating envelope, during start-up, shutdown, generator overload, or overspeed, different strategies driven by other system considerations must be used.

I. INTRODUCTION

The variable-speed operation of wind turbines has been known for a long time. In some applications, isolated operation of variable-speed wind generation may be preferable [1,2]. Computer codes have been developed to investigate different control strategies [3]. However, the actual controls used to optimize energy capture were not realized until recently [4]. With the advanced development of power electronics, the application of variable-speed generation in the wind industry becomes more viable [5-8]. Turbine system-dynamics (structural response, resonances, component interactions, etc.) is an important consideration for variable speed operation [9,10], but this paper focuses only on the control strategy of a wind turbine.

The system we explore consists of the components of variable-speed systems as shown in Figure 1. The system consists of a variable-speed generator, the gearbox, the controller, and the feedback sensors. The only two sensors needed to control the wind turbine operation are the power and rpm.

The development of this paper will be arranged as follows: In Section II, the wind turbine aerodynamic characteristics will be discussed briefly. Detailed discussions about this subject can be found in many text books [11]. The overall control strategy adapted to control the wind turbine will be discussed in Section III. In Section IV, the simulation of the system is presented for different wind conditions. Finally, the conclusion will be presented in Section V.

II. AERODYNAMIC CHARACTERISTICS

A wind turbine is normally characterized by its Cp versus tip-speed ratio (TSR) curve. A typical Cp-TSR curve is given in Figure 2.

The tip-speed ratio (TSR) can be expressed as follows

$$\mathrm{TSR} = \frac{\omega_m R}{V} \qquad (1)$$

where

ω_m = rotor speed - mechanical (rad/s)
R = radius of the blade (m)
V = linear speed of the wind (m/s).

In a fixed-frequency application, the rotor speed of the generator varies within a few percents (based on the slip) above the synchronous speed while the speed of the wind may vary in a very wide range. Thus from Equation 1, the tip-speed ratio may vary in a wide range depending on the turbine design. The power captured by the wind turbine may be written in the following equation:

$$P_{mech} = 0.5\,\rho\,A\,C_p\,V^3 \qquad (2)$$

where

P_{mech} = aerodynamic power (w)
ρ = air density (kg/m^3)
A = swept area (m^2)
C_p = power coefficient of the wind turbine.

From Equation 2, it is apparent that the power production from the wind turbine can be increased if the system is operated at maximum Cp at any wind speed. From Figure 2, it is necessary to keep the rotor speed at constant TSR (i.e., at TSR_{TARGET}) to operate the wind turbine at Cp_{TARGET} for any wind speed. Thus as the wind speed changes, the rotor speed should be adjusted to follow the change. This is possible with a variable-speed wind turbine. Unfortunately, it is suggested that the wind speed cannot be reliably measured, thus it is impossible to have a direct one-to-one relationship between the rpm and the wind speed.

To avoid using the wind speed to control the generator, the equation for target power can be modified to eliminate dependence on wind speed. The P_{TARGET} is computed based on known Cp_{TARGET} and TSR_{TARGET}. Substituting the wind velocity with rotor speed, the power can be derived as a function of rotor speed. As can be seen from the P_{TARGET} equation, the cube law is still valid. The P_{TARGET} is proportional to the cube of the rotor speed.

$$P_{TARGET} = 0.5\ \rho\ A\ C_{p_{TARGET}} \left[\frac{R}{TSR_{TARGET}}\right]^3 \omega_m^3 \qquad (3)$$

where:

Cp_{TARGET} = target power coefficient
TSR_{TARGET} = target tip-speed ratio.

Theoretically, the power generated is unlimited. It is a function of wind-speed cubed. Realistically, there are limits beyond which wind turbine components cannot be operated due to mechanical or electrical limitations. As an illustration, the proposed system is implemented with few limitations.

Some limitations of the system can be listed below:

* Power Limit: The electrical components building the circuit have a power limit.

* rpm Limit: The generator used has an upper-speed limit based on mechanical design.

Figure 3 is a contour map of a wind turbine generating power as a function of rpm and wind speed. The example of the path to control the generator is superimposed on the same graph. It is shown that in the lower wind speed, the wind turbine is controlled to follow a constant Cp (or constant tip-speed ratio) [illegible] until the rpm limit is reached. From that point on, the wind turbine is controlled to follow a constant rpm until the maximum power is reached. After maximum power is reached, the wind turbine is controlled to follow the constant power.

Figure 3 also shows the variation of the rotor rpm as the wind speed varies. In the constant Cp region, the rpm varies linearly with the wind speed and the slope is proportional to the TSR_{TARGET}. When the rpm limit is reached, the rpm is maintained constant. The constant power region is started by lowering the rpm as the wind speed increases. The relationship between the rpm and wind speed in this region is nonlinear as the relationship between the TSR and Cp is nonlinear. The Cp must be changed as the inverse function of wind speed cubed to maintain constant power.

III. CONTROL ALGORITHM

Overall Control Strategy for Ideal Case:

The overall control algorithm can be illustrated in Figure 4. The operating region can be divided into constant Cp, constant rpm, and constant power regions. A start-up procedure is needed to start generating electricity when the wind energy is available. During start-up, the electric machine operates as a motor. The rotor speed is increased from standstill to bring the Cp to an acceptable value. Once the higher Cp is reached, the electric machine is operated as a generator and the system enters constant Cp region. The constant Cp region is the most important region from which variable-speed generation differs from the fixed-frequency generation. In this region, the wind turbine is operated at its optimum condition. When the wind speed increases, the rpm is also increased. Thus the variation of wind speed is followed by the variation of rotor rpm. As the wind speed continues to increase, the rotor rpm eventually reaches a maximum allowable rpm or maximum allowable power (whichever comes first depends on the design). The maximum allowable rpm is determined by components of the wind turbine (electric generator, wind turbine, etc). In this region, the rpm is maintained constant as long as the power generated is lower than maximum allowable power. As the wind speed continues to increase, the rpm is still constant, and the power increases until the power reaches the upper limit. In the constant rpm region, Cp decreases as the wind speed increases. The upper limit of the power is also determined by the power limit of the components of the wind turbine. When this power limit is reached, the speed must be lowered so that the wind turbine operates at an even lower Cp. The tip-speed ratio decreases at a faster rate than decrement in the constant-speed region.

Figure 5 shows the relationship between power and the wind speed. It is shown that at low wind speed, the wind turbine follows the target power and is proportional to the cube of the wind speed. Then, the constant power rpm is reached. The power increases at a slower rate at constant rpm due to a lower Cp. Finally, as the power limit is reached, the power must be maintained constant.

Constant Cp Region:

When the starting rpm is reached, the wind turbine stops motoring and normal generating operation takes over. The generator is controlled to operate in a scheduled Power-rpm. This scheduled Power-rpm may be programmed in an EPROM or can be an on-line computation. To illustrate the concept, the following figure may help clarify the process. Implementation of the scheduled Power-rpm can be shown below. The control strategy can be implemented in digital, analog, or a combination analog and digital circuit depending on the practicality of the implementation. In this region, the output power of the generator is continuously controlled to follow the P_{TARGET} command as the rpm varies. The target power is computed from the rpm feedback. Thus the power-speed characteristic of the generator is shaped on the basis of Cp_{TARGET} and TSR_{TARGET}. Figure 6 shows the relationship between target power and power generated by the wind turbine (for different wind speeds) as the rpm varies.

As an example, suppose the wind speed is V2. The point A2 is the operating point of the generator at 1500 rpm. A1 is the operating point of the wind turbine. It can be seen that these operating points are not the target point. The mechanical power (A1) is higher than the electrical power (A2). As a result, the wind turbine has excess power to accelerate the rpm. The accelerating power is the power difference between A1 and A2. As the rpm increases, the target power is continuously upgraded following the P_{TARGET} curve. Similarly, the operating point of the wind turbine also varies along the curve V2. The two operating points A1 and A2 eventually will meet at A3 where there is matching power between the wind turbine and the generator.

As another example, consider the wind speed is V3 while the generator speed is approximately 2300 rpm. The operating point of the generator is B2 while the operating point of the wind turbine is at B1. Because the generator load is larger than the mechanical power generated by the wind turbine, the rotor decelerates. As the rotor rpm decelerates, the generator power is continuously updated and it moves along the P_{TARGET} curve. The wind turbine mechanical output power also changes along the V3 curve. As the rotor rpm decreases, the difference between the wind turbine power and the generator power becomes smaller and eventually the two will meet at point B3.

Thus with a computed P_{TARGET} as the guideline, the output power of the generator is continuously controlled to follow P_{TARGET} as rpm varies. The implementation can be done by following the block diagram shown in Figure 7 below, in which the difference between the target and the generated power is used to drive the system into equilibrium.

Constant rpm Region:

As the controller proceeds with constant Cp_{TARGET} (or TSR_{TARGET}), the generator may eventually reach the rpm limit of the generator although the rated power has not been reached yet. In this region the generator speed is kept constant as the wind speed increases. The power increases until the power limit is reached. The power converter operates in its speed control mode. Thus the speed is kept constant at rpm limit. The wind turbine operates in the lower TSR region (to the left of TSR_{TARGET}). Figure 8 shows a flowchart on how the generator is controlled in the constant speed region.

Constant Power Region:

As the power increases, the generator and power converter will eventually reach their power limit. In this region the power must be kept below its power limit by reducing the rpm of the generator. Reducing the rpm of the generator operates the wind turbine at a lower aerodynamic efficiency (lower TSR and lower Cp). As the wind speed increases, the rpm must be decreased to lower the power generated by the wind turbine.

The rpm can be reduced by increasing the load of the generator. Unfortunately, the wind turbine has a large inertia. To lower the rpm of the generator, there will be an energy conversion from kinetic energy into electric energy.

As shown in Figure 9, the rpm is reduced at a constant rate to limit the power conversion from kinetic energy into electric energy. Thus to lower the rpm, the generator carries not only the power to counteract the aerodynamic energy from the wind but also the energy released from the inertia. Therefore, it is important to consider the power limit of both the generator and the power converter. One way to avoid excessive power when decreasing the rpm is to limit the deceleration of the generator. For example, in the case under study, the rpm is limited to 1 rpm per second which, with the inertia of the wind turbine, corresponds to approximately 30 kW.

Realizing that there is a large inertia involved in the system, the power limit of the generator must be sized to be larger than the wind turbine. It is necessary to have enough headroom to have control on the wind turbine speed. Thus as soon as the power output of the generator is higher than the set point, the wind turbine is directly controlled to decrease its rpm. It is expected that there will be a certain range of power excursion before it comes back below the power limit as the rpm slowly decreases.

IV. STUDY ANALYSIS: WIND CONDITIONS

The wind condition applied to the simulation is a computed wind source measured at 145 feet. The wind data represents the wind variation including the turbulence. To enhance the simulation of the wind fluctuation, the wind data input is modulated in the following way:

$$v(t) = wind(t) * A \sin(\omega t) + offset \qquad (4)$$

where:

$v(t)$ = wind speed input to the simulation
$wind(t)$ = base wind speed data
A = amplitude of the sine wave modulation
ω = frequency of the sine wave modulation
offset = adjustable average offset.

The intention of modulating the actual data is to enable the program to compute and simulate many possible conditions with a certain level of intensity in a shorter time frame. As an example, Figure 10 below is based on the simulation of wind speed of (8 ± 3) m/sec where the average value is 8 m/sec and the variation is modulated at 3 m/sec.

Two wind conditions were simulated. One is the (8 + 3) m/sec and the other one is (13 + 3) m/sec. The first one is chosen to explore the lower wind speed region at which the rpm limit and power limit are not likely to occur. It is expected that in this range the operation in constant Cp region can be explored. Cp will be nearly constant at Cp_{TARGET}. On the other hand, the constant rpm and constant power region can be explored by applying the higher wind speed region (13 + 3) m/s.

Power Coefficient Cp

Figure 11 below shows the power coefficient Cp of the wind turbine at the lower wind speed region (8+3) m/s. As expected, in this region, the power is within the power limit. The operation is in the constant Cp most of the time. Thus Cp varies within a very small deviation from the target Cp. The deviation of Cp from its target value shows that the rotor speed cannot follow the wind speed very closely due to the large inertia of the wind turbine. It can be expected that a wind turbine with a flatter Cp curve can maintain the operating Cp in an almost constant value. This wind speed region is favorable for constant Cp operation.

In Figure 12, the higher wind speed region is explored. It can be seen that the Cp varies in a wider range showing that in higher wind speeds either or both the rpm limit and the power limit is reached, thus lower Cp operation must be called upon to safely operate the wind turbine within reasonable limits. As the wind speed decreases, the wind turbine operates below power and rpm limit, and thus target Cp can be achieved. It is shown how the Cp varies with the variation of the wind speed. The wind speed that changes very fast cannot be followed by the rotor speed instantaneously because of the sluggishness of the wind turbine inertia. However, the slower variation of wind speed can be tracked very well. Also from both figures, it can be seen how the Cp improves when the turbine is motored during the start-up in an attempt to achieve target Cp before entering the operation as a generator.

Tip-Speed Ratio

From Figure 13, the tip-speed ratio varies with time for the higher wind speed region (13+3) m/s. There are several occurrences at which the TSR varies very widely showing that a fast change of wind speed cannot be followed by the rotor speed instantaneously. Thus the TSR and Cp lag behind the change of the wind speed. The range of Cp variation in the constant Cp region is small; it is narrower than the TSR variation. The flatter the top of the Cp curve, the smaller the Cp variation. On the other hand, if the wind turbine has a very sharp and pointing Cp curve, the variation of Cp can be very wide in a small variation of the TSR. The variation of TSR shows how close the rotor speed tracks the wind speed. In a way, the TSR variation can be viewed as the measure of the sluggishness of the system to follow the wind speed variation. The rpm limit and the power limit also affect the variation of the tip-speed ratio. It is shown in Figure 13 that the lower TSR values relate to the upper limit (rpm or power). In the lower wind speed region, the operation is close to TSR_{TARGET}.

Mechanical and Electrical Power

The mechanical power shown in Figure 14 is the aerodynamic power produced by the wind turbine for wind speeds of (8+3) m/s. The power depends on the wind speed and instantaneous Cp. The power limit of the wind turbine is set to a constant value. The corresponding electrical power output of the wind turbine can be shown in Figure 15. The variation of the electrical power output can be traced from the starting point. It is shown that in the starting region, the electrical power is negative indicating the motoring region. The trace of electrical power is not identical to the trace of mechanical power. When the wind turbine is accelerating, there is less electrical power than the mechanical power generated by the wind turbine. The difference in power can be attributed to the power needed to change the level of kinetic energy. On the other hand, when the rotor decelerates, the electrical power generated is higher than the mechanical power generated by the wind turbine. Again the difference in power can be accounted for by the stored kinetic energy that must be dispensed through the generator and the power converter. The power difference can also be accounted for by the electrical losses in the system. Thus the inertia effect must be taken into account when designing the generator and the power converter to be used in the system.

Realizing that inertia may affect the power rating of the equipment, it is necessary to provide some headroom to size the upper limit of the generator and the power converter. For simplicity, the following equation can be used to compute the delta torque applied to the shaft when there is kinetic energy conversion. Assuming there are losses, the instantaneous difference between the mechanical power of the wind turbine and the electrical power generated by the generator is represented by the ΔT in the equation shown below. It is affected by the size of the inertia, the rotor speed, and the rate of change of the rotor speed.

$$J \frac{d\,\omega_m}{dt} = \Delta T \qquad (5)$$

where:

J = total inertia
$\Delta T = T_{wind} - T_{gen}$
ω_m = rotor speed.

$$\frac{1}{2} J\left(\omega_{t_2}^{\,2} - \omega_{t_1}^{\,2}\right) = \int_{t_1}^{t_2} \text{Power}\, dt \qquad (6)$$

The acceleration and deceleration affect the instantaneous power conversion when the rpm must be changed from one speed to another. The larger the inertia, the higher the speed, the faster the deceleration or acceleration, the higher the power required to transfer the kinetic energy. For example, for the wind turbine under consideration, to change the rpm from 70 to 69 rpm in one second (in a no-wind condition), the power transfer will be about 30 kw per second. Thus if the change is made ten times faster, the power required will be 300 kw. Therefore the deceleration and acceleration of the generator should be limited to a certain rpm per second to avoid overloading the generator, or the power converter, or both.

In the power upper limit, the generator and the power converter should be prepared to handle both the aerodynamic power from the wind and the kinetic energy conversion. Another factor to consider is the upper limit of the rotor speed. The higher the upper limit of the rotor rpm, the more energy stored in the inertia of the wind turbine (for double rpm, the kinetic energy will be quadruple).

Rotor Speed of the Wind Turbine:

The rotor speed of the wind turbine is allowed to vary up to an upper limit rpm. The variation of the rotor speed is divided into three different regions. The first region is called the constant Cp region where the rotor speed tracks the wind speed variation. As the wind speed increases, the rotor speed also increases until the rotor speed reaches the upper limit rpm. This maximum rotor speed is determined by the design of the wind turbine components (wind turbine, gearbox, generator, etc.). When the rotor speed reaches its limit, the speed should be kept constant regardless of the wind speed. Therefore, the instantaneous Cp in this region is lower than the target Cp. As the wind speed increases, the power increases at a lower rate than the previous region. At one point, it reaches the power limit. Once the power limit is reached, the wind turbine must be operated at constant power (at reduced Cp). Operation of the wind turbine in constant power requires the wind turbine to operate in a less efficient mode. To trim the power output of the wind turbine, the Cp must be reduced, which is done by decreasing the rpm of the wind turbine (TSR is lower than TSR_{TARGET}). To decrease the rpm, more load must be applied to the wind turbine. Thus more power must be absorbed by the generator, further increasing the electrical power.

The length of time needed to reduce the rotor speed depends on the inertia of the turbine and the decelerating torque applied. The decelerating torque is the difference between the torque of the wind turbine and the generator torque. The generator torque is limited by the absolute current limit of the generator. If the electrical strength of the generator and the mechanical strength of the wind turbine are unlimited, the deceleration time can be made very short. However, in reality, the generator has an upper limit to sustain the load. Although the rpm eventually decreases, it takes some time for the power to return to its normal value. Thus the power limit set by the user should not be the absolute limit of the generator and power converter. The absolute limit should include headroom to account for kinetic energy and additional wind speed. A safer approach to avoid overloading the generator is to plan the rate of deceleration to a certain rpm/s. When deceleration is limited, the energy conversion during the deceleration is capped to a certain predetermined value. Design and control refinement of the wind turbine in this region should be carefully planned.

In Figure 16, the way in which the rpm varies as the wind speed changes is shown. In the beginning, the wind turbine is motored during the start-up to approach $C_{p\ TARGET}$. At $t \sim 10$ seconds, the wind turbine starts entering constant Cp region. When the power reaches the limit ($t \sim 18s$), the rotor speed is reduced at a certain deceleration rate. The controller continues to decrease the rotor speed until the power returns to normal values. It can be seen in the whole range of observation that the controller continues to follow the wind variation while keeping the operation under its upper limit power and upper limit rpm. It is shown that when the wind speed is high, the rpm is reduced ($0 \sim 40s$ and $160 \sim 200s$). When the wind speed decreases ($40 \sim 160s$), the rpm and power varies below the upper limit allowing the rpm to follow the wind speed as is apparent from the Cp curve shown in Figure 12.

Shaft Torque Variation:

As the wind speed varies, the torque transferred through the shaft is affected by the difference in the input and output torque, and the stiffness and damping of the shaft. In Figure 17, the variation of the shaft torque is shown as the wind speed varies for two different wind speed averages. The sharp variations of the wind speed create the higher torque spikes on the shaft. The drive-train dynamics model includes the rotor inertia, drive-train inertia, stiffness and damping.

Another aspect of the shaft torque variation is the controller response. The torque spikes are created when the difference between accelerating torque and decelerating torque is high. This can happen when the controller tries to increase the load too fast or there is a wind gust that suddenly increases the wind turbine torque. Thus the proper setting of the controller gains is needed if the torque pulsation is to be reduced or damped.

Mechanical and Electrical Energy

The energy captured by the wind turbine is affected by the frequency distribution of the wind speed. For the same duration of wind speed, the energy captured is affected by the power coefficient of the wind turbine during those periods. The closer the power coefficient Cp to the maximum value, the larger the energy collected. If the controller can track the wind speed variation, the energy captured during the same period of time will be much higher.

Figure 18 and Figure 19 are the energy capture for wind speeds of (8+3) m/s. As a comparison, the mechanical energy captured by a variable-speed wind turbine (shown in Figure 18) is compared with fixed-speed wind turbine operation (as shown in Figure 19). From the comparison, it is easy to see the difference in the energy capture during the same period of time. The approximate gain is about 1.4 kWh during the 200-second period or about 25.2 kWh/ hour. For the case considered, it is equivalent to about a 20% energy gain.

In cases where the upper limit (rpm and power) has been reached, the operating power coefficient Cp is lower than the Cp_{TARGET}. For example, for the higher wind speed region, the energy gain for variable-speed variation will not be as great as for the lower wind speed region where most of the operating condition occurs in the constant Cp.

V. CONCLUSIONS

From the previous sections, and excluding the impact of structural dynamics on loads, the following conclusions can be made:

- The proposed control strategy seems to be effective in the overall region of observation.
- The wind speed can be tracked relatively well in the constant Cp region allowing the operation of the wind turbine to be close to the Cp_{TARGET}.
- In the rpm limit and power limit, the generator is controlled to operate in the lower TSR region. It is necessary to plan for kinetic energy conversion as part of the design strategy to size the generator and the power converter to avoid the overload condition in the high power region.
- It is necessary to understand the difference between absolute limit (for the generators and power converter) and the regular upper limit (set point of the controller). During operation it is expected that the system will operate with power excursions above the upper limit; however, it is recommended that the power converter and the generator be designed to operate below the absolute limit.
- For the wind speed record studied, a 20% energy gain was calculated. This suggests that significant improvements in energy capture may be achieved.

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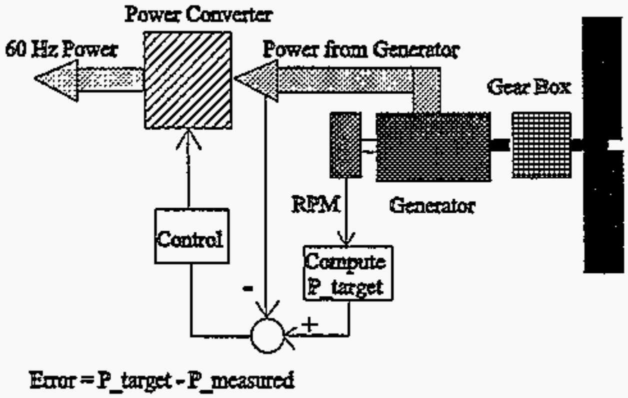

Figure 1. Physical diagram of the analyzed system

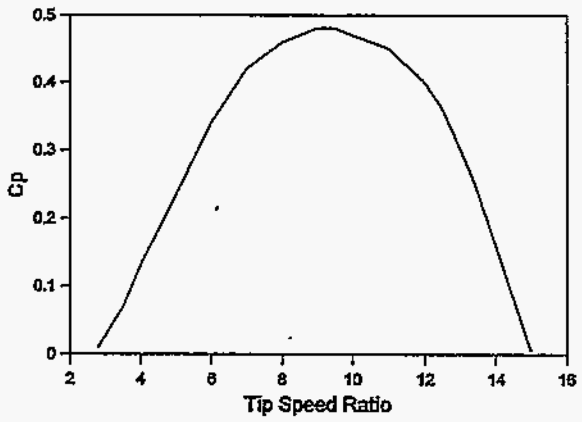

Figure 2. Typical Cp-TSR characteristic of a wind turbine

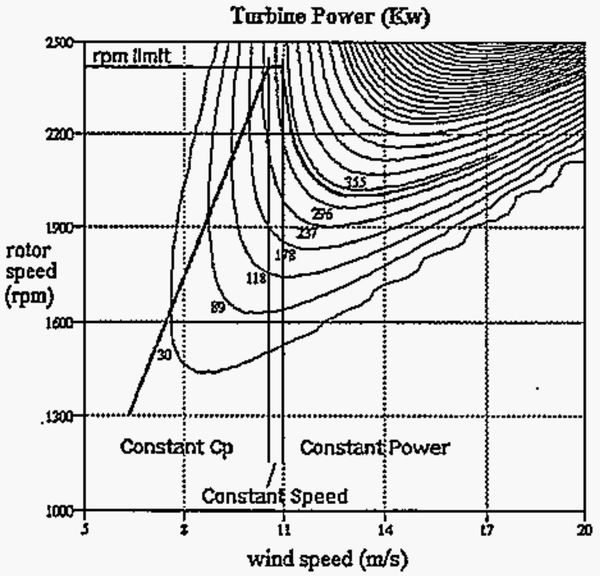

Figure 3. Contour map for a typical wind turbine

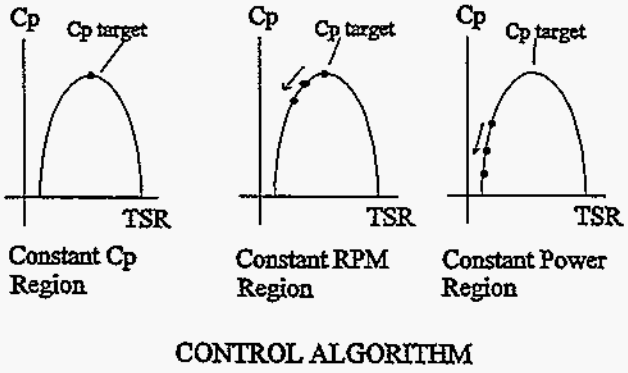

Figure 4. Operating Cp in three different regions

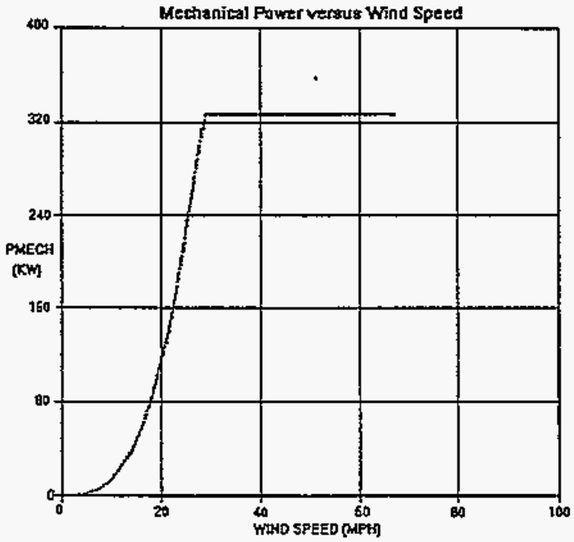

Figure 5. Mechanical power as a function of wind speed in ideal conditions

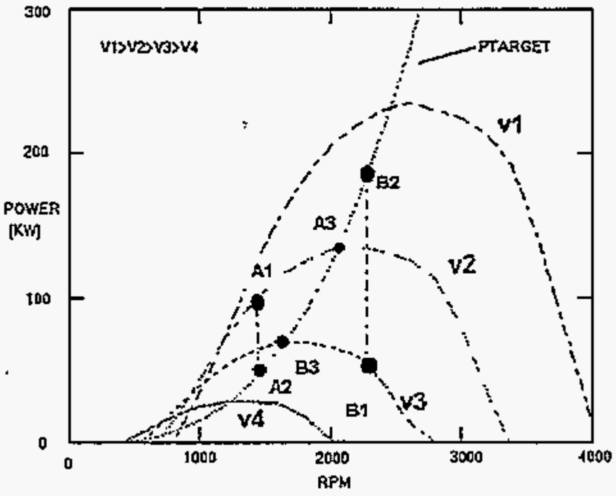

Figure 6. Target power and rotor power of the wind turbin

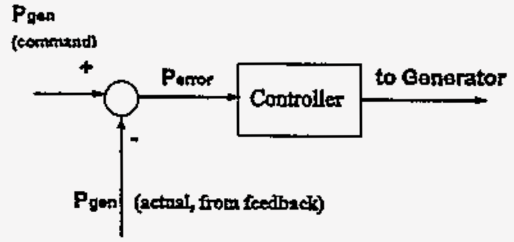

Figure 7. Constant Cp region implementation

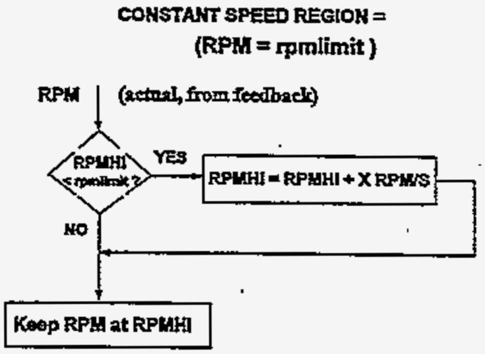

Figure 8. Constant speed region implementation

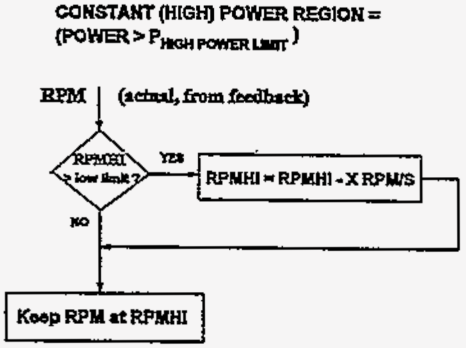

Figure 9. Constant power implementation

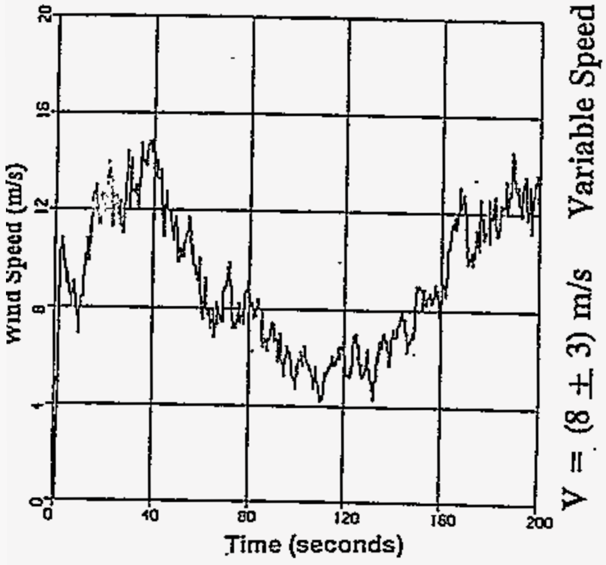

Figure 10. Wind variation for an average wind speed of 8 m/s

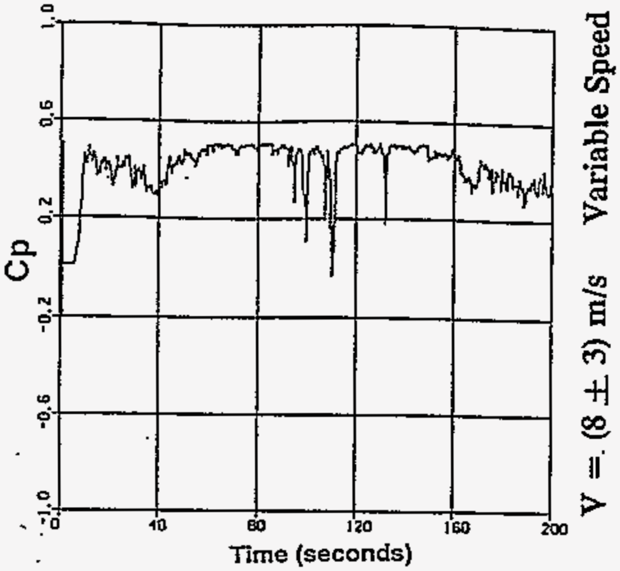

Figure 11. Cp variation for lower wind speed region

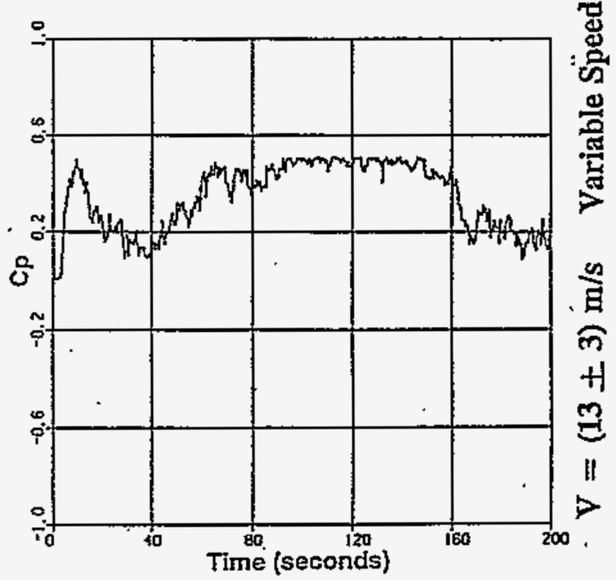

Figure 12. Cp variation for higher wind speed region

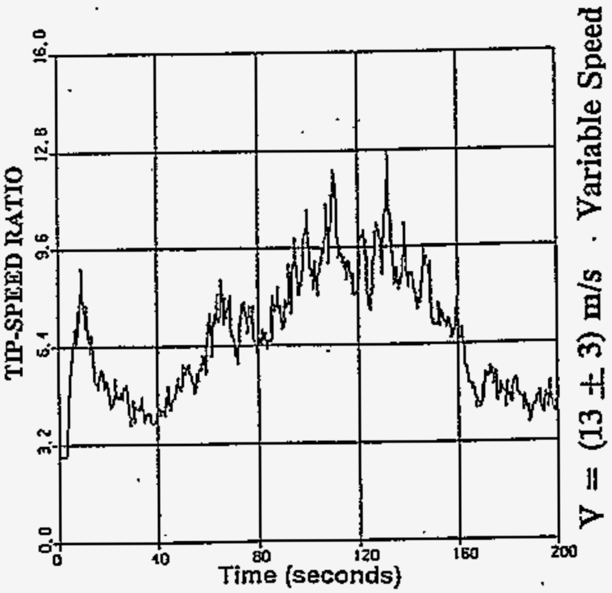

Figure 13. Variation of the TSR in the higher wind speed region (13 + 3) m/s

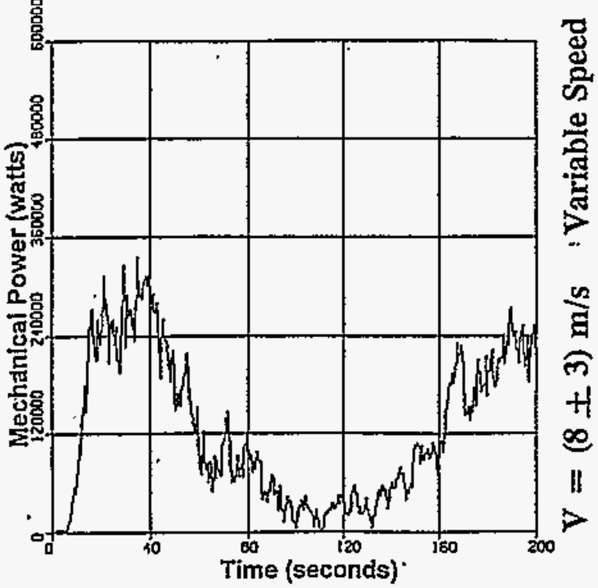

Figure 14. Mechanical power variation for lower wind speed region

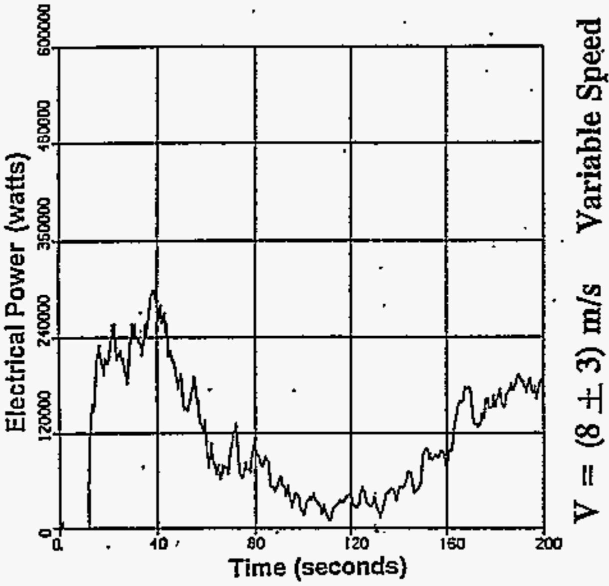

Figure 15. Electrical power

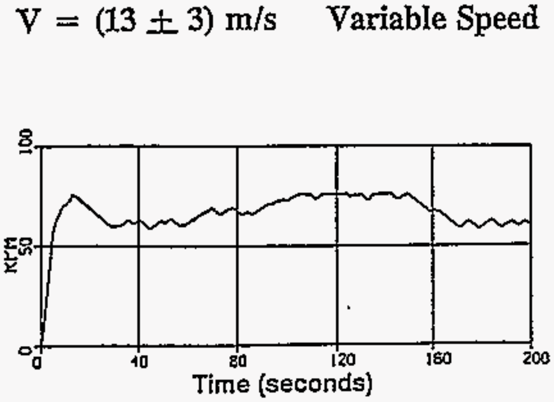

Figure 16. Rotor speed rpm

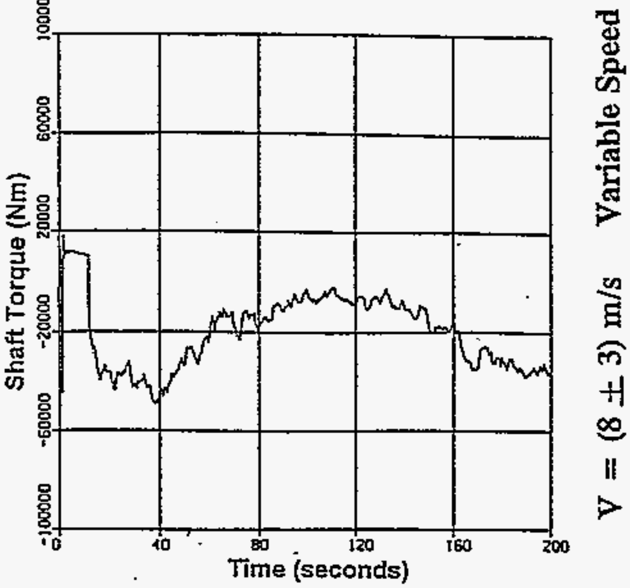

Figure 17. Shaft torque

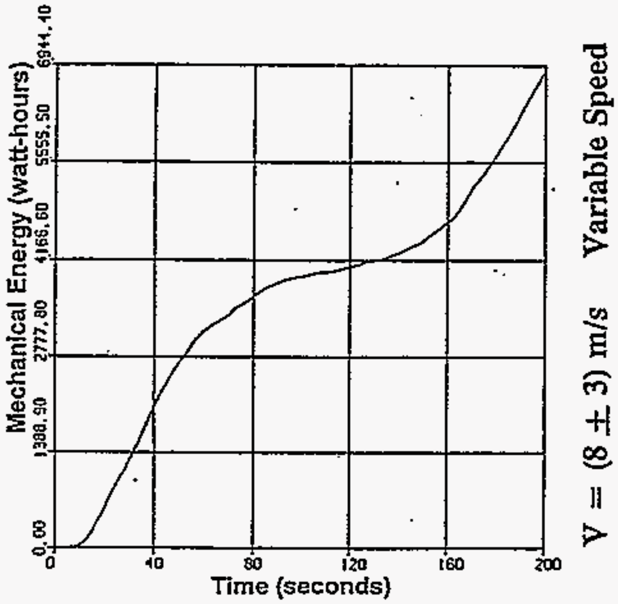

Figure 18. Mechanical energy for variable speed operation

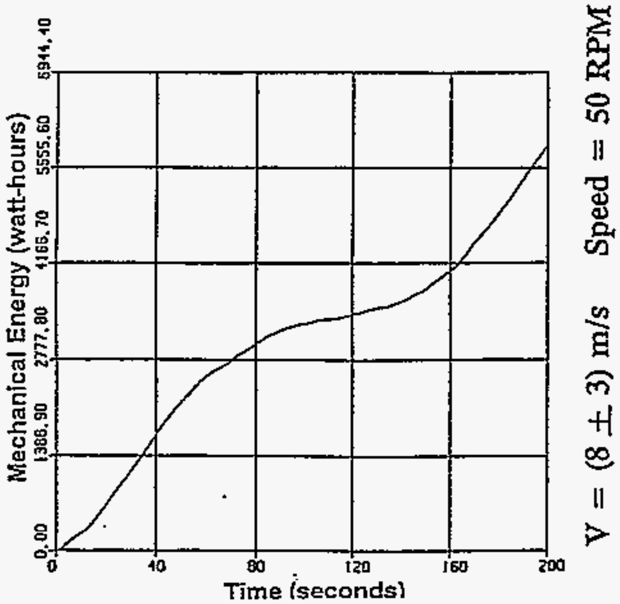

Figure 19. Mechanical energy at 50 rpm