8.3.2 Control of variable-speed, pitch-regulated turbines

A variable-speed generator is decoupled from the grid frequency by a power converter, which can control the load torque at the generator directly, so that the speed of the turbine rotor can be allowed to vary between certain limits. An often-quoted advantage of variable-speed operation is that below rated wind speed, the rotor speed can be adjusted in proportion to the wind speed so that the optimum tip speed ratio is maintained. At this tip speed ratio the power coefficient, C_p, is a maximum, which means that the aerodynamic power captured by the rotor is maximised. This is often used to suggest that a variable-speed turbine can capture much more energy than a fixed-speed turbine of the same diameter. In practice it may not be possible to realise all of this gain, partly because of losses in the power converter and partly because it is not possible to track optimum C_p perfectly.

Maximum aerodynamic efficiency is achieved at the optimum tip speed ratio $\lambda = \lambda_{\text{opt}}$, at which the power coefficient C_p has its maximum value $C_{p(\max)}$. Because the rotor speed Ω is then proportional to wind speed U, the power increases with U^3 and Ω^3, and the torque with U^2 and Ω^2. The aerodynamic torque is given by

$$Q_a = \frac{1}{2}\rho A C_q U^2 R = \frac{1}{2}\rho \pi R^3 \frac{C_p}{\lambda} U^2 \tag{8.2}$$

Since $U = \Omega R/\lambda$ we have

$$Q_a = \frac{1}{2}\rho \pi R^5 \frac{C_p}{\lambda^3}\Omega^2 \tag{8.3}$$

In the steady state therefore, the optimum tip speed ratio can be maintained by setting the load torque at the generator, Q_g, to balance the aerodynamic torque, that is,

$$Q_g = \frac{1}{2}\frac{\pi \rho R^5 C_p}{\lambda^3 G^3}\omega_g^2 - Q_L \tag{8.4}$$

Here Q_L represents the mechanical torque loss in the drive train (which may itself be a function of rotational speed and torque), referred to the high-speed shaft. The generator speed is $\omega_g = G\Omega$, where G is the gearbox ratio.

This torque-speed relationship is shown schematically in Figure 8.3 as the curve B1–C1. Although it represents the steady-state solution for optimum C_p, it can also be used dynamically to control generator torque demand as a function of measured generator speed. In many cases, this is a very benign and satisfactory way of controlling generator torque below rated wind speed.

For tracking peak C_p below rated in a variable-speed turbine, the quadratic algorithm of Eq. (8.4) works well and gives smooth, stable control. However, in turbulent winds, the large rotor inertia prevents it from changing speed fast enough to follow the wind, so rather than staying on the peak of the C_p curve it will constantly fall off either side, resulting in a lower mean C_p. This problem is clearly worse for heavy rotors, and also if the $C_p - \lambda$ curve has a sharp peak. Thus, in optimising a blade design for variable-speed operation, it is not only important to try to maximise the peak C_p, but also to ensure that the $C_p - \lambda$ curve is reasonably flat-topped.

It is possible to manipulate the generator torque to cause the rotor speed to change faster when required, so staying closer to the peak of the C_p curve. One way to do this

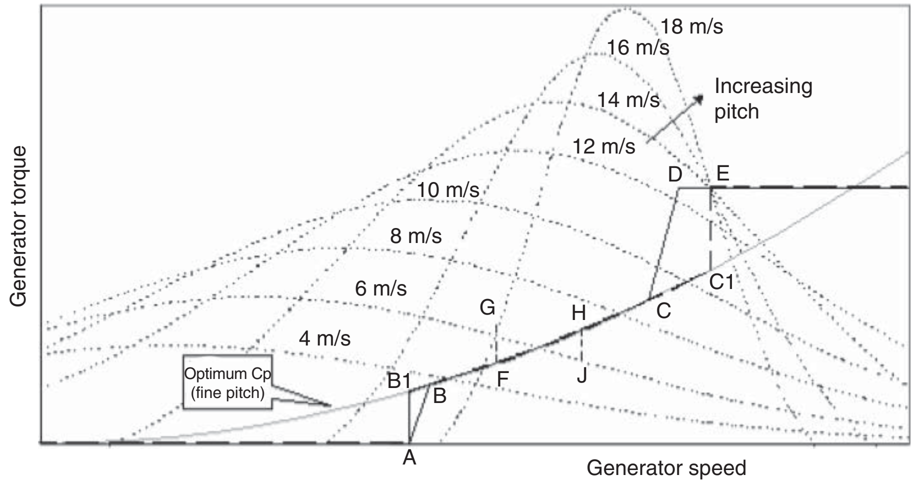

Figure 8.3 Schematic torque-speed curve for a variable-speed pitch-regulated turbine

is to modify the torque demand by a term proportional to rotor acceleration (Bossanyi 1994):

$$Q_g = \frac{1}{2}\frac{\pi\rho R^5 C_p}{\lambda^3 G^3}\omega_g^2 - Q_L - B\dot{\omega}_g \tag{8.5}$$

where B is a gain that determines the amount of inertia compensation. For a stiff drive train, and ignoring frequency converter dynamics, the torque balance gives

$$I\dot{\Omega} = Q_a - GQ_g \tag{8.6}$$

where I is the total inertia (of rotor, drive train and generator, referred to the low-speed shaft) and Ω is the rotational speed of the rotor. Hence

$$(I - G^2B)\dot{\Omega} = Q_a - \frac{1}{2}\frac{\pi\rho R^5 C_p}{\lambda^3 G^2}\omega_g^2 + GQ_L \tag{8.7}$$

Thus, the effective inertia is reduced from I to $I - G^2B$, allowing the rotor speed to respond more rapidly to changes in wind speed. The gain B should remain significantly smaller than I/G^2 otherwise the effective inertia will approach zero, requiring huge power swings to force the rotor speed to track closely the changes in wind speed.

Another possible method is to use available measurements to make an estimate of the wind speed, calculate the rotor speed required for optimum C_p, and then use the generator torque to achieve that speed as rapidly as possible. The aerodynamic torque can be expressed as

$$Q_a = \frac{1}{2}\rho A C_q R U^2 = \frac{1}{2}\rho\pi R^5 \Omega^2 C_q/\lambda^2 \tag{8.8}$$

where R is the turbine radius, Ω the rotational speed, and C_q the torque coefficient. If drive train torsional flexibility is ignored, a simple estimator for the aerodynamic torque is

$$Q_a{}^* = GQ_g + I\dot{\Omega} = GQ_g + I\dot{\omega}_g/G \tag{8.9}$$

where I is the total inertia. A more sophisticated estimator could take into account drive train torsion, etc. From this it is possible to estimate the value of the function $F(\lambda) = C_q(\lambda)/\lambda^2$ as

$$F^*(\lambda) = \frac{Q_a^*}{\frac{1}{2}\rho\pi R^5(\omega_g/G)^2} \tag{8.10}$$

Knowing the function $F(\lambda)$ from steady state aerodynamic analysis, one can then deduce the current estimated tip speed ratio λ^* (see also Section 8.3.16 for a better estimation method). The desired generator speed for optimum tip speed ratio can then be calculated as

$$\omega_d = \omega_g \hat{\lambda}/\lambda^* \tag{8.11}$$

where $\hat{\lambda}$ is the optimum tip speed ratio to be tracked. A simple PI controller can then be used, acting on the speed error $\omega_g - \omega_d$, to calculate a generator torque demand that will track ω_d. The higher the gain of PI controller, the better will be the C_p tracking, but at the expense of larger power variations. Simulations for a particular turbine showed that a below rated energy gain of almost 1% could be achieved, with large but not unacceptable power variations.

Holley et al. (1999) demonstrated similar results with a more sophisticated scheme, and also showed that a perfect C_p tracker could capture 3% more energy below rated, but only by demanding huge power swings of plus and minus three to four times rated power, which is totally unacceptable.

Because such large torque variations are required to achieve only a modest increase in power output, it is usual to use the simple quadratic law, possibly augmented by some inertia compensation as in Eq. (8.5) if the rotor inertia is large enough to justify it.

As turbine diameters increase in relation to the lateral and vertical length scales of turbulence, it becomes more difficult to achieve peak C_p anyway because of the non-uniformity of the wind speed over the rotor swept area. Thus if one part of a blade is at its optimum angle of attack at some instant, other parts will not be.

In most cases, it is actually not practical to maintain peak C_p from cut-in all of the way to rated wind speed. Although some variable-speed systems can operate all of the way down to zero rotational speed, this is not the case with limited range variable-speed systems based on the widely used doubly fed induction generators. These systems only need a power converter rated to handle a fraction of the turbine power, which is a major cost saving. This means that in low wind speeds, just above cut-in, it may be necessary to operate at an essentially constant rotational speed, with the tip speed ratio above the optimum value.

At the other end of the range, it is usual to limit the rotational speed to some level, usually determined by aerodynamic noise constraints or blade leading-edge erosion, which is reached at a wind speed that is still some way below rated. It is then cost-effective to increase to torque demand further, at essentially constant rotational speed, until rated power is reached. Figure 8.3 illustrates some typical torque-speed trajectories, which are explained in more detail below. Turbines designed for noise-insensitive sites may be designed to operate along the optimum C_p trajectory all of the way until rated power is reached. The higher rotational speed implies lower torque and in-plane loads, but higher out-of-plane loads, for the same rated power. This strategy might be of interest for offshore wind turbines.