Appendix 1-A

Need for a Variable-Speed Drive in Wind Turbines and their Control

Figure 1 shows the generic and a simplified version on the wind-electric system where items such as the gear-box and the transformer are not sown. Figure 2 shows the power that can be harnessed for a wind-turbine as a function of wind speed that is in [m/s], where begins to be harnessed beyond the cut-in speed of approximately 3 m/s and all the power is harnessed up to the rated speed of approximately 11.5 m/s.

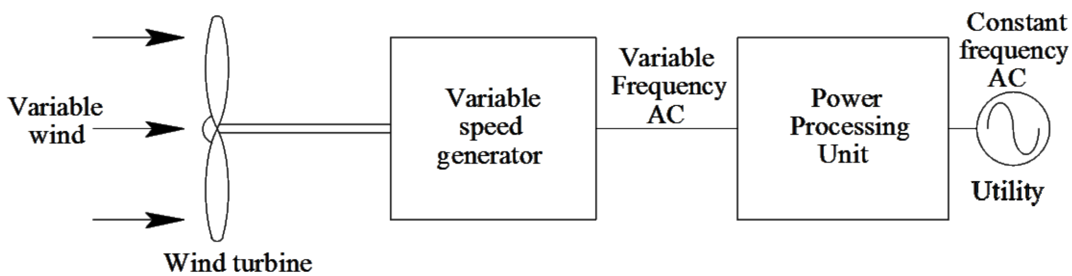

Fig. 1 A simplified version on the wind-electric system.

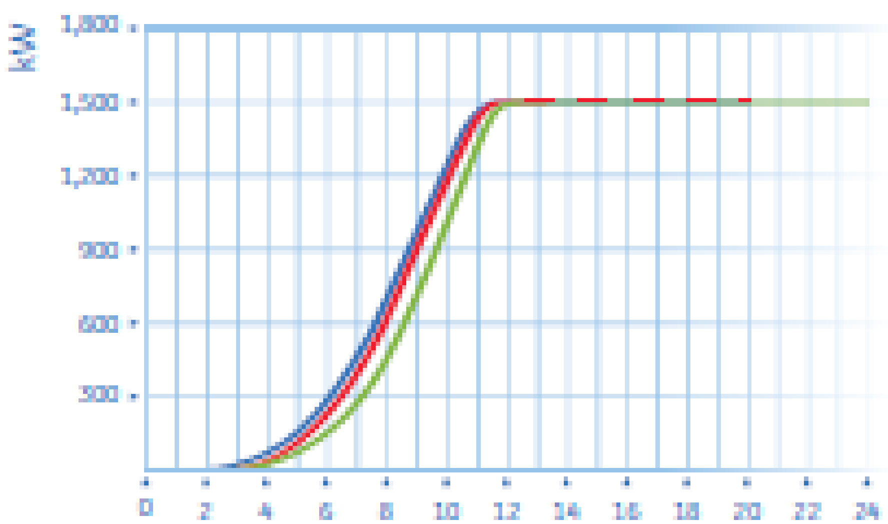

Fig. 2 Power that can be harnessed [1], as a function of the wind speed in [m/s].

The power in the wind is given as:

$$P_{wind} = \frac{1}{2} \rho A V^3 \tag{1}$$

where ρ is the density of air, A is the area swept by the blades, and V is the wind velocity. The power that can be derived and available at the turbine output is the total power times a Coefficient of Performance, C_p (i.e., C_p is the ratio of the power available in the wind to that harnessed):

$$P_{turbine} = C_p P_{wind} = C_p \left(\frac{1}{2} \rho A V^3 \right) \quad (2)$$

where, a detailed derivation shows that in the limit, theoretically, $C_{p,\max} = 0.5926$. The coefficient of Performance C_p in Eq. 2 is a function of the tip-speed ratio λ, as plotted in Fig. 1 where

$$\text{Blade Tip-Speed Ratio } \lambda = \frac{R\,\omega_{mech}}{V} \quad (3)$$

in which R is the radius of the turbine blades in [*m*], and ω_{mech} is the turbine rotational speed in [*rad/s*], and V is the wind speed in [*m/s*].

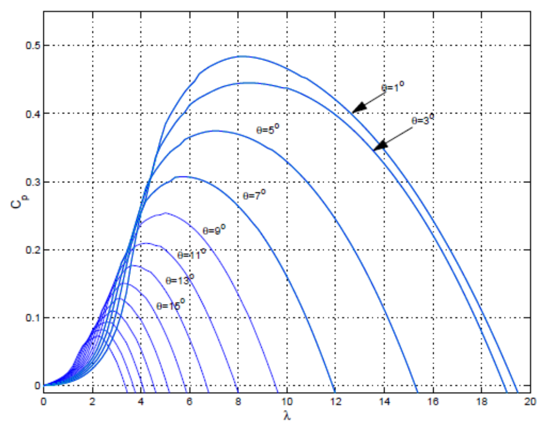

Fig. 3 c_p as a function of λ [1]; these curves vary based on the turbine design.

In practice, the maximum attainable value of C_p is generally around 0.48 at a pitch-angle of approximately $\theta = 0$ degrees to "catch" all the wind. As shown in Fig. 3, for each blade pitch-angle θ, C_p reaches the maximum at a particular value of the tip-speed ratio λ, which, for a given wind speed V, can be obtained by controlling the turbine rotational speed ω_{mech}. The curves for various values of the pitch-angle θ show that the power harnessed from wind can be regulated by controlling the pitch-angle of the blades, and thus "spilling" some of the wind at very high wind speeds to prevent the power output from exceeding its design (rated) value.

Consider the case of the pitch-angle close to $\theta = 0$ in Fig. 3 when the wind speed is somewhere between the cut-in and the rated value in Fig. 2. From Eq. 2, to produce the maximum amount of power, C_p should be at its optimum value of approximately 0.48 in Fig. 3, which is obtained at the Blade Tip-Speed Ratio λ of approximately 8.0. Therefore, Eq. 3 dictates that as wind speed V changes, the turbine rotational speed ω_{mech} should be change to keep λ at its optimum value, **clearly indicating the need for a variable-speed drive in wind turbines**. The way to achieve this control is described in [2].

References

1. Kara Clark, Nicholas W. Miller, Juan J. Sanchez-Gasca, *Modeling of GE Wind Turbine-Generators for Grid Studies*, GE Energy Report, Version 4.4, September 9, 2009.
2. Johnson, K.E.; Pao, Lucy Y.; Balas, M.J.; Fingersh, L.J., "Control of variable-speed wind turbines: standard and adaptive techniques for maximizing energy capture," *Control Systems, IEEE*, vol.26, no.3, pp.70, 81, June 2006