

Errata

Chapter 2

Equation 2.4.13 should read:

$$p(U_a \leq U \leq U_b) = \int_{U_a}^{U_b} p(U) dU \quad (2.4.13)$$

Chapter 5

In section 5.2.3.2:

The relative permeability of ferromagnetic materials is very high, in the range of 10^3 to 10^5 (not 103 to 105).

The second to last paragraph in Section 5.4.4.1 should read:

Induction machines often operate with a poor power factor. To improve power factor, capacitors are frequently connected to the machine at or near the point of connection to the electrical network. Care must be taken in sizing the capacitors when the machine is operated as a generator. In particular it must not be possible for the generator to be 'self-excited' if connection to the grid is lost due to a fault.

The statement after Equation 5.4.17 should read:

The power factor, PF , (which is lagging during motoring and leading during generating), is the ratio of the real power to apparent power:

$$PF = \frac{-P_{out}}{VI} \quad (5.4.18)$$

Equations 5.5.2 and 5.5.3 should read:

$$a_n = \frac{1}{L} \int_0^{2L} v(t) \cos\left(\frac{n\pi t}{L}\right) dt \quad (5.5.2)$$

$$b_n = \frac{1}{L} \int_0^{2L} v(t) \sin\left(\frac{n\pi t}{L}\right) dt \quad (5.5.3)$$

The captions for Figures 5.8 and 5.9 should read:

Figure 5.8 Simple magnetic device; g , width of air gap; i , current, Φ , magnetic flux. From *Electric Machines*, 1st edition, by Sarma © 1985. Reprinted with permission of Brooks/Cole, an imprint of the Wadsworth Group, a division of Thomson Learning. Fax 800 730-2215

Figure 5.9 Simple magnetic torque device; g , width of air gap; i , current, Φ , magnetic flux; L , length of the face of the poles, Q_e , electrical torque; r , radius; θ , rotation angle. From *Electric Machines*, 1st edition, by Sarma © 1985. Reprinted with permission of Brooks/Cole, an imprint of the Wadsworth Group, a division of Thomson Learning. Fax 800 730-2215

Equation 5.2.10 should be:

$$V(t) = \text{Re}\{V_{\max} e^{j\theta} e^{j2\pi ft}\} \quad (5.2.10)$$

Chapter 6

p. 293 The last sentence in the first paragraph should read:

Such hubs are used on only a few commercial machines but they have been employed on some historically important turbines (Smith–Putnam) and are presently receiving renewed attention. Some of the common types of hubs are illustrated in Figure 6.24.

Chapter 7

The following Figures were misprinted:

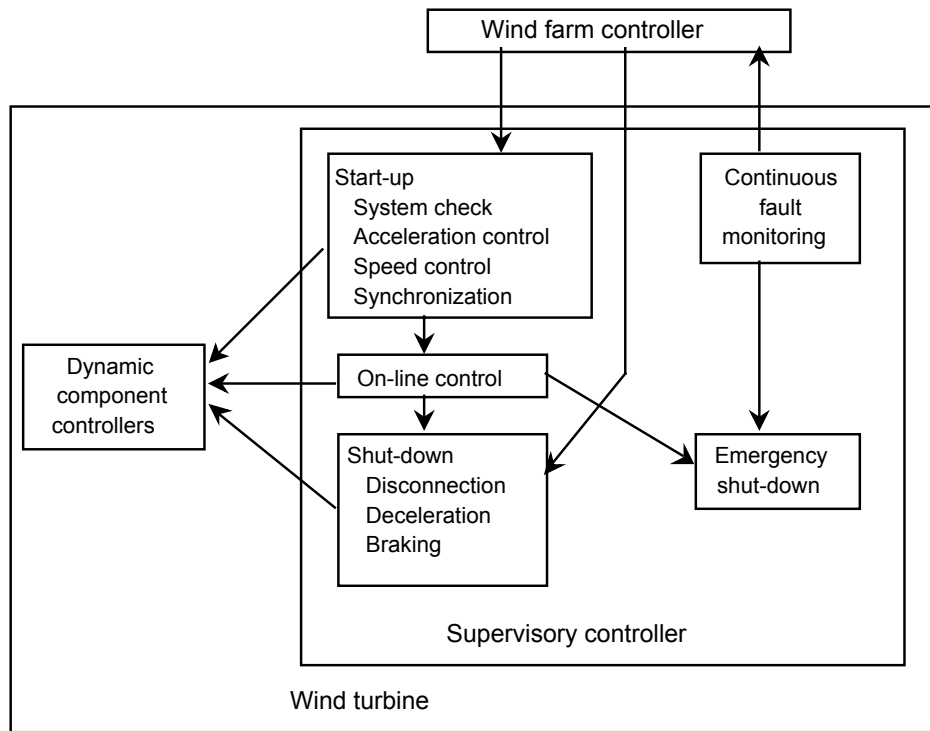


Figure 7.1 Control system components

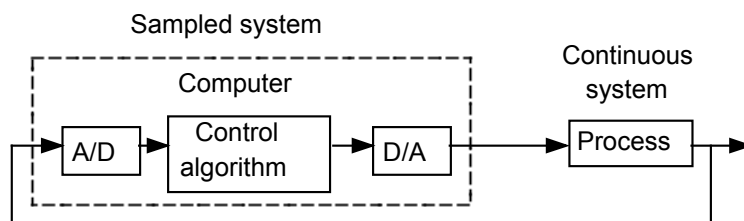


Figure 7.25 Schematic of computer controlled system; A/D, analog-to-digital converter; D/A, digital-to-analog converter

Chapter 8

The caption for Figure 8.18 should read:

Figure 8.18 Typical battery voltage and capacity curve. Reproduced by permission of McGraw-Hill Companies from Standard Handbook for Electrical Engineers, Fink and Beaty, 1978

Chapter 10

The sound pressure level is not correctly defined in the chapter. It should be:

The sound pressure level of a noise, L_p , in units of decibels (dB), is given by:

$$L_p = 10 \log_{10}(p/p_0) \quad (10.4.3)$$

where p is the instantaneous sound pressure and p_0 a reference sound pressure (usually 20×10^{-5} Pa).

Corrected Problems

2.1 Annual Energy Production Estimate

Based on average speed data only, estimate the annual energy production from a horizontal axis wind turbine with a 12 m diameter operating in a wind regime with an average wind speed of 8 m/s. Assume that the wind turbine is operating under standard atmospheric conditions ($\rho = 1.225 \text{ kg/m}^3$). Assume a turbine efficiency of 0.4.

2.10 Autocorrelation of wind speed data and data synthesis

A variety of techniques are available for creating data sets that have characteristics similar to that of real data. The Wind Engineering MiniCodes include a few of these methods. In the ARMA technique the user must input long-term mean, standard deviation, and autocorrelation at a specified lag. The code will return a time series with values that are close to the desired values. (Note: a random number generator is used in the data synthesis routines, so any given time series will not be exactly the same as any other.)

a) Find the mean, standard deviation, and autocorrelation for the Mt. Tom data: MtTom7Hzms.txt. This data is collected at a 25 m height, with a sampling frequency of 7.4 Hz. The data is in meters/second. Plot a time series of the data. Determine the autocorrelation for a lag of up to 2000 points. Determine the autocorrelation at a lag of one time step for use in synthesizing a similar data set.

b) Using the ARMA code, synthesize and plot a time series of 10,000 data points with equivalent statistics to those found in part a. Show a time series graph of the synthesized data.

c) Find the autocorrelation for a lag of up to 2000 points for both synthetic data and plot the autocorrelations of both the real and the synthesized on the same graph.

d) Comment on any similarities or differences between the two plots.

3.3 Ideal Rotor Section Analysis

a) Find φ , θ_p , θ_T , and c for one blade section from $r/R = 0.45$ to $r/R = 0.55$ (centered on $r/R = 0.50$) for an ideal blade (assume $C_d = 0$, $a' = 0$). Assume $\lambda = 7$, $B = 3$, $R = 5$ m, and $C_l = 1.0$ and the minimum C_d/C_l occurs at $\alpha = 7$.

b) Assume that C_d/C_l actually equals 0.02 for the above blade section and that the free stream wind speed, U , equals 10 m/s. Find U_{rel} , dF_L , dF_D , dF_N , dF_T , dQ for the blade section. Don't forget to consider that the wind velocity is slowed down at the rotor. Use $a = 1/3$, $a' = 0$. Assume the air density is 1.24 kg/m^3 (20C).

c) For the same blade section find C_l , α and a using the general strip theory method (including angular momentum). Also find C_l , α and a if the rpm is increased such that $\lambda = 8$. Ignore drag and tip loss. Use a graphical approach. Assume that the empirical lift curve is $C_l = 0.1143\alpha + 0.2$ (α in degrees): i.e. $C_l = 0.2$ at $\alpha = 0$ degrees, $C_l = 1.0$ at $\alpha = 7$ degrees.

3.4. Ideal Rotor Design

a) Find φ , θ_p , θ_T , and c at all 10 locations ($r/R = 0.10, 0.20, \dots, 1.0$) for the Betz optimum blade. Assume $\lambda = 7$, $B = 3$, $R = 5$ m, and $C_l = 1.0$ and the minimum C_d/C_l occurs at $\alpha = 7$.

b) Sketch the shape (planform) of the blade, assuming that all the quarter chords lie on a straight line.

c) Illustrate the blade twist by drawing plausible airfoils with properly proportioned chord lengths, centered at the quarter chord chords for $r/R = 0.10, 0.50, 1.0$. Be sure to show where the wind is coming from and what the direction of rotation is.

3.7 Optimum Rotor C_p

The Better Wind Turbine Company wants to start marketing wind turbines. Their plans call for a turbine that produces 100 kW in a 12 m/s wind at a cold site (-22.8C, -9F) with an air density of 1.41 kg/m^3 . They have decided on a 20 meter in diameter, three-bladed, wind turbine. The rotor is to have its peak power coefficient at a tip speed ratio of 7 in a 12 m/s wind. The airfoil to be used has a lift coefficient of 1.0 and a minimum drag to lift ratio at an angle of attack of 7 degrees.

a) You, as the new blade designer, are to come up with the blade shape as a starting point for the blade design. The design is to be based on the optimum rotor shape assuming that there is wake rotation (but no drag or tip losses). Find the chord length, pitch, and twist at 9 stations of the blade (each 2 m long), assuming that the hub occupies the inner tenth of the rotor.

b) Determine the rotor C_p assuming $C_d = 0$. Again determine the power coefficient assuming that the drag coefficient is 0.02, and that the aerodynamics are the same as the condition without any drag. How much power is lost due to drag? Which part of the blade produces the most power?

c) Does it look like the chosen design is adequate to provide the power that the Better Wind Turbine Company wants?

4.6 Wind Components

The turbine diameter is 24.38 m (80 ft) not 24.38 m/s.

4.8 Steady State Lead-Lag Motion

Just as the flap angle can be represented by a the sum of a constant term, a sine term, and a cosine term, the lead-lag angle in the simplified dynamics model can be represented by the sum of a constant term, a sine term, and a cosine term:

$$\zeta \approx \zeta_0 + \zeta_{1c} \cos(\psi) + \zeta_{1s} \sin(\psi)$$

The following matrix equation for the solution of the lead-lag motion can be derived by substituting this solution into the lead-lag equations of motion (note that flap coupling terms have been omitted for simplicity):

$$\begin{bmatrix} 2B & (K_2 - 1) & 0 \\ 0 & 0 & (K_2 - 1) \\ K_2 & B & 0 \end{bmatrix} \begin{bmatrix} \zeta_0 \\ \zeta_{1c} \\ \zeta_{1s} \end{bmatrix} = \begin{bmatrix} -\frac{\gamma}{2} \left[K_{vs} \bar{U} A_4 - \frac{\theta_p \Lambda}{2} (\bar{V}_0 + \bar{q} \bar{d}) \right] \\ -2B - \frac{\gamma}{2} \bar{q} A_4 \\ \frac{\gamma}{2} \Lambda A_2 \end{bmatrix}$$

where:

$$K_2 = \text{inertial natural frequency (includes offset, hinge-spring)} = \varepsilon_2 + \frac{K_\zeta}{I_b \Omega^2} = \left(\frac{\omega_\zeta}{\Omega} \right)^2$$

$$A_2 = \text{axisymmetric flow term (includes tip speed ratio and pitch angle)} = \frac{\Lambda}{2} + \frac{\theta_p}{3}$$

$$A_4 = \text{axisymmetric flow term (includes tip speed ratio and pitch angle)} = \frac{2}{3} \Lambda - \frac{\theta_p}{4}$$

$$B = \text{gravity term} = \frac{G}{2\Omega^2}$$

$$\gamma = \text{Lock number (ratio of aerodynamic force to moment of inertia)} = \frac{\rho C_{L\alpha} c R^4}{I_b}$$

$$\bar{V}_0 = \text{normalized cross flow term} (= V_0 / \Omega R)$$

$$\bar{q} = \text{normalized yaw rate term} (= q / \Omega)$$

$$\bar{d} = \text{normalized yaw moment arm} = \frac{d_{yaw}}{R}$$

$$\bar{U} = \text{normalized wind velocity} = \frac{U}{\Omega R}$$

$$\Lambda = \text{non-dimensional inflow} = \frac{U - u_i}{\Omega R}$$

$$K_{vs} = \text{linear wind shear constant.}$$

$$\theta_p = \text{pitch angle}$$

a) Write the matrix equation for lead-lag motion, including the terms for the steady mean wind and the hinge spring model, but assuming that gravity is zero and that other aerodynamic forcing functions are zero.

b) Solve the equations and find the expression for the steady state lead-lag angle as a function of the Lock number, the non-dimensional wind speed, the lead-lag natural frequency, and the blade pitch.

c) Suppose the pitch were 5.7 degrees, the rotor speed were 50 rpm and the diameter were 9.14 m (30 ft). By what factor would the steady state lead-lag angle increase if the wind speed increased from 7.62 m/s (25 ft/s) to 15.24 m/s (50 ft/s)? Assume that the axial induction factor decreases from 0.30 to 0.25 as the speed increases to 15.24 m/s (50 ft/s).

5.2 Electromagnet

An electromagnet is used to hold a wind turbine's aerodynamics brakes in place during operation. The magnet supplies 30 lbs (133.4 N) of force to do this. The magnet is supplied by a 60 V DC source. The coil of the electromagnet draws 0.1 A. The core of the electromagnet is assumed to have a relative permeability of 10^4 . The diameter of the core is 3 in (7.62 cm).

Find the number of turns in the coil and the wire size. Assume that the relation between force, magnetic flux, and area of the core is given by $F = 397840 B^2 A_c$: where: F = force (N), B = magnetic flux (Wb/m²), A_c = area of core (m²). Also, assume that the length of each turn is equal to the circumference of the core. The resistivity of copper is $\rho = 1.72 \times 10^{-6} \Omega \text{ cm}$.

7.6 Pitch System Step Responses

The hint in problem 7.6 should read:

Hint: perform a partial fraction expansion of the general form of the closed-loop response:

$$\frac{d}{(s+a)(s^2+bs+c)s}$$

and find the inverse Laplace transform of each term, using the a, b, c, d variables. This symbolic form will be handy, as it will be used twice in the solution.

For parts a) and b), find the real root, a, of the denominator by graphing $s^3 + s^2 + s + d$, using the appropriate d . The values of s at the zero crossing is -a. The second order root is found using long division:

$$\frac{s^3 + s^2 + s + d}{(s+a)} = s^2 + (1-a)s + (1-a+a^2)$$

Thus, the roots of the denominator are s, (s + a) and

$$s^2 + bs + c = s^2 + (1-a)s + (1-a+a^2)$$

Insert the solutions for a, b, c, d into the general solution and plot the result.

7.8 Pitch Control Power

A pitch control system is being designed for a wind turbine. The response of the pitch control system to a unit step command has been determined to be:

$$\theta_p = \theta_{p,ref} [1 - 1.67e^{-1.6t} \cos(1.2t - 0.93)]$$

where θ_p is the pitch angle change and $\theta_{p,ref}$ is the magnitude of the commanded pitch angle change. In order to shut down the turbine in high winds the pitch must change by 16 degrees. This motion is opposed by three torques, those due to friction, the pitching moment and inertial. The total friction torque, $Q_{friction}$, is assumed to be a constant 30 Nm, and the total pitching moment, $Q_{pitching}$, in high winds is assumed to be a constant 1000 Nm. Finally, the inertial torque is a function of the inertial moments: $Q_{inertia} = J \ddot{\theta}_p$. The total moment of inertia, J , of the blades is 100 kg m². The total power needed to pitch the blades is:

$$P_{total} = \dot{\theta}_p (J \ddot{\theta}_p + Q_{friction} + Q_{pitching})$$

What is the peak power required to pitch the blades 16 degrees (.279 radians)?

8.5 Grid Fault Level and Voltage Fluctuations

Consider a wind turbine generator connected to a grid system (see Figure B.9) with a line-neutral system voltage, V_S . The voltage at the wind turbine, V_G , is not necessarily the same as V_S . The distribution system resistance is R , and the distribution system reactance is X .

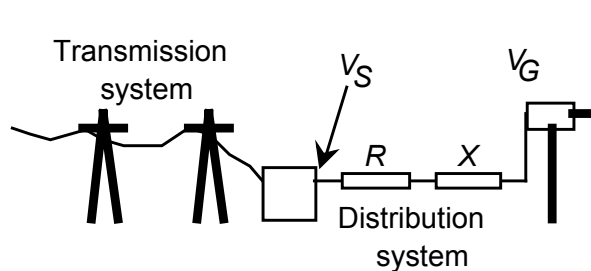


Figure B.9

The real generated power is P and reactive power consumed by the wind turbine generator is Q . Suppose $R = 8.8 \Omega$, $X = 4.66 \Omega$, $V_S = 11 \text{ kV}$, $P = 313 \text{ kW}$, $Q = 162 \text{ kVAr}$ and the power factor at the generator is $\text{pf} = 0.89$. Determine the voltage difference between the grid and the generator, the voltage drop as a percent of the grid voltage, the fault level at the generator and the installed generator capacity as a percent of the fault level.

8.8 Hybrid System Design Rules

An isolated power system serving the community of Cantgettherefromhere uses a 100 kW diesel generator. The community plans to add 60 kW of wind power. The hourly average load and power from the wind turbine over a 24 hour period is detailed in Table B.9. The diesel generator has a no-load fuel usage of 3 liter per hour and an additional incremental fuel use of 1/4 liter per kilowatt-hour.

For the day in question, using the hybrid system design rules, determine:

- The maximum renewable energy that can possibly be used in an ideal system.
- The maximum renewables contribution without storage, and the maximum with storage.
- The maximum fuel savings that can be achieved (with intelligent use of controls, storage and renewables).

d) The minimum diesel fuel use that can be achieved with intelligent use of storage and controls (and without renewables).

Table B.9

Hour	Load (kW)	Wind (kW)	Hour	Load (kW)	Wind (kW)
0	25	30	12	85	45
1	20	30	13	95	45
2	15	40	14	95	50
3	14	30	15	90	55
4	16	20	16	80	60
5	20	10	17	72	60
6	30	5	18	60	48
7	40	5	19	74	50
8	50	15	20	76	55
9	70	20	21	60	60
10	80	25	22	46	60
11	90	40	23	35	55

9.3 Simple Cost of Energy

A small 50 kW wind turbine with an initial cost of \$50,000 is installed in Nebraska. The fixed charge rate is 15% and the annual operation and maintenance cost ($C_{O\&M}$) is 2% of the initial cost. This system produces 65,000 kWh/yr (E_a). Determine the cost of energy (COE) for this system.

9.4 Small Wind Turbine Economics

A small wind machine, with a diameter of 6 m, is rated at 4 kW in an 11 m/s wind speed. The installed cost is \$10,000. Assuming Weibull parameters at the site to be $c = 8$ m/s and $k = 2.2$, it is claimed that the capacity factor is 0.38.

The interest rate, b , is 11% and the period of the loan, N , is 15 years. Find the cost per unit area, per kW, and the levelized cost per kWh. The lifetime of the turbine, L , is assumed to be 20 years and the discount rate, r , is 10%. You do not have to include factors such as inflation, tax credits, or operation and maintenance costs.

9.6 Wind–Diesel System Economics

This problem is intended to assess the relative economic merits of installing a wind–diesel system rather than a diesel-only system at a hypothetical location. Assume that the existing diesel is due for replacement and that the annual system demand will remain fixed during the lifetime of the project.

Your problem is to calculate the levelized cost of energy for the diesel only and for the wind–diesel system. The following system and economic parameters hold:

System

Average system load	96 kW (841,000 kWh/yr)
Diesel rated power	200 kW
Mean diesel usage- no wind turbine generator	42.4 l/hr (371,000l/yr)
Wind turbine rated power	100 kW
Average annual wind speed	7.54 m/s
Annual wind speed variability	0.47

Average wind turbine power	30.9 kW
Useful wind turbine power (based on 25% lower limit on diesel loading)	21.1 kW
Mean diesel usage with WTG	34.8 l/hr (305,000 l/yr)
<i>Economics</i>	
Wind turbine cost	\$1500/kW installed
Diesel cost	\$350/kW installed
System life	20 yr
Initial payment	\$30,000
Loan term	10 yr
Interest	10%
General inflation	5%
Fuel inflation	6%
Discount rate	9%
Diesel fuel cost	\$0.50/l
Wind turbine O&M cost	2% of capital cost/yr
Diesel O&M cost	5% of capital cost/yr