# Appendix A

Tables A.1, A.2 and A.3

**Table A.1** Applied data for the given simulation in Chap. 3 (Fig. 3.2)

| Parameters | Genco | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $MVA_{base}$ (1,000 MW) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Rate (MW) | 1,000 | 800 | 1,000 | 1,100 | 900 | 1,200 | 850 | 1,000 | 1,020 |
| $B_i$ (pu/Hz) | 0.3483 | 0.3473 | 0.3180 | 0.3827 | 0.3890 | 0.4140 | 0.3692 | 0.3493 | 0.3550 |
| $D_i$ (pu MW/Hz) | 0.015 | 0.014 | 0.015 | 0.016 | 0.014 | 0.014 | 0.015 | 0.016 | 0.015 |
| $R_i$ (Hz/pu) | 3.00 | 3.00 | 3.30 | 2.7273 | 2.6667 | 2.50 | 2.8235 | 3.00 | 2.9412 |
| $2H_i/f_0$ (pu.s) | 0.1677 | 0.120 | 0.200 | 0.2017 | 0.150 | 0.196 | 0.1247 | 0.1667 | 0.187 |
| $T_{ti}$ (s) | 0.4 | 0.36 | 0.42 | 0.44 | 0.32 | 0.40 | 0.30 | 0.40 | 0.41 |
| $T_{gi}$(s) | 0.08 | 0.06 | 0.07 | 0.06 | 0.06 | 0.08 | 0.07 | 0.07 | 0.08 |
| $\alpha_i$ | 0.4 | 0.4 | 0.2 | 0.6 | 0 | 0.4 | 0 | 0.5 | 0.5 |
| Ramp rate (MW/min) | 8 | 8 | 4 | 12 | 0 | 8 | 0 | 10 | 10 |

H. Bevrani, *Robust Power System Frequency Control*,
Power Electronics and Power Systems, DOI: 10.1007/978-3-319-07278-4,

**Table A.2** Generating unit parameters for the real-time simulation in Chap. 4

| Parameters | Gen 1 | Gen 2 | Gen 3 |
|---|---|---|---|
| MVA | 100 | 60 | 100 |
| $R$ (Hz/pu) | 3.00 | 3.00 | 3.30 |
| $T_1$ (s) | 0.08 | 0.06 | 0.07 |
| $T_2$ (s) | 0.10 | 0.10 | 0.10 |
| $T_3$ (s) | 0.10 | 0.10 | 0.10 |
| $T_4$ (s) | 0.40 | 0.36 | 0.42 |
| $T_5$ (s) | 10.0 | 10.0 | 10.0 |
| $\beta$ (pu/Hz) | 0.3483 | 0.3473 | 0.3180 |
| $D$ (pu/Hz) | 0.0150 | 0.0150 | 0.0150 |
| $2H$ (s) | 8.05 | 7.00 | 8.05 |
| $T_H$ (s) | 0.05 | 0.05 | 0.05 |
| $T_I$ (s) | 0.08 | 0.08 | 0.08 |
| $T_L$ (s) | 0.58 | 0.58 | 0.58 |
| $K_H$ (pu) | 0.31 | 0.31 | 0.31 |
| $K_I$ (pu) | 0.24 | 0.24 | 0.24 |
| $K_L$ (pu) | 0.45 | 0.45 | 0.45 |
| $M_1$ (pu/min) | 0.50 | 0.50 | 0.50 |
| $M_2$ (pu/min) | 0.050 | 0.050 | 0.050 |
| $M_3$ (pu/min) | 2.00 | 2.00 | 2.00 |
| $N_1$ (pu/min) | −0.50 | −0.50 | −0.50 |
| $N_2$ (pu/min) | −0.20 | −0.20 | −0.20 |
| $N_3$ (pu/min) | −0.50 | −0.50 | −0.50 |

**Table A.3** Power system parameters for the real-time simulation in Chap. 5

| Parameter | Gen 1 | Gen 2 | Gen 3 | Gen 4 |
|---|---|---|---|---|
| MVA | 1000 | 600 | 1000 | 900 |
| $R$ (Hz/pu) | 3.00 | 3.00 | 3.30 | 3.30 |
| $T_1$ (s) | 0.08 | 0.06 | 0.07 | 0.07 |
| $T_2$ (s) | 0.10 | 0.10 | 0.10 | 0.10 |
| $T_3$ (s) | 0.10 | 0.10 | 0.10 | 0.10 |
| $T_4$ (s) | 0.40 | 0.36 | 0.42 | 0.3 |
| $T_5$ (s) | 10.0 | 10.0 | 10.0 | 10.0 |
| $\beta$ (pu/Hz) | 0.3483 | 0.3473 | 0.3180 | 0.3827 |
| $D$ (pu/Hz) | 0.0150 | 0.0150 | 0.0150 | 0.0150 |
| $2H$ (s) | 8.05 | 7.00 | 8.05 | 6.00 |
| $T_H$ (s) | 0.05 | 0.05 | 0.05 | 0.05 |
| $T_I$ (s) | 0.08 | 0.08 | 0.08 | 0.08 |
| $T_L$ (s) | 0.58 | 0.58 | 0.58 | 0.58 |
| $K_H$ (pu) | 0.31 | 0.31 | 0.31 | 0.31 |
| $K_I$ (pu) | 0.24 | 0.24 | 0.24 | 0.24 |
| $K_L$ (pu) | 0.45 | 0.45 | 0.45 | 0.45 |
| $M_1$ (pu/min) | 0.50 | 0.50 | 0.50 | 0.50 |
| $M_2$ (pu/min) | 0.050 | 0.050 | 0.050 | 0.050 |
| $M_3$ (pu/min) | 2.00 | 2.00 | 2.00 | 2.00 |
| $N_1$ (pu/min) | −0.50 | −0.50 | −0.50 | −0.50 |
| $N_2$ (pu/min) | −0.20 | −0.20 | −0.20 | −0.20 |
| $N_3$ (pu/min) | −0.50 | −0.50 | −0.50 | −0.50 |

# Appendix B

- State-space model matrices for simulation example in Sect. 6.1:

$$A = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix},\ A_{ii} = \begin{bmatrix} -\frac{D_i}{2H_i} & \frac{1}{2H_i} & 0 & -\frac{1}{2H_i} \\ 0 & -\frac{1}{T_{ti}} & \frac{1}{T_{ti}} & 0 \\ -\frac{1}{R_i T_{gi}} & 0 & -\frac{1}{T_{gi}} & 0 \\ 2\pi \sum\limits_{j} T_{ij} & 0 & 0 & 0 \end{bmatrix},$$

$$A_{ij}(i \neq j) = \begin{bmatrix} 0 & 0\ 0\ 0 \\ 0 & 0\ 0\ 0 \\ 0 & 0\ 0\ 0 \\ -T_{ij} & 0\ 0\ 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0\ 0 & \frac{-1}{T_{g1}} & 0\ 0\ 0 & 0 & 0\ 0\ 0 & 0 & 0\ 0\ 0 & 0 & 0 \\ 0\ 0 & 0 & 0\ 0\ 0 & \frac{-1}{T_{g2}} & 0\ 0\ 0 & 0 & 0\ 0\ 0 & 0 & 0 \\ 0\ 0 & 0 & 0\ 0\ 0 & 0 & 0\ 0\ 0 & \frac{-1}{T_{g3}} & 0\ 0\ 0 & 0 & 0 \\ 0\ 0 & 0 & 0\ 0\ 0 & 0 & 0\ 0\ 0 & 0 & 0\ 0\ 0 & \frac{-1}{T_{g4}} & 0 \end{bmatrix}$$

$$F = \begin{bmatrix} \frac{-1}{2H_1} & 0\ 0\ 0 & 0 & 0\ 0\ 0 & 0 & 0\ 0\ 0 & 0 & 0\ 0\ 0 & 0 & 0\ 0\ 0 \\ 0 & 0\ 0\ 0 & \frac{-1}{2H_2} & 0\ 0\ 0 & 0 & 0\ 0\ 0 & 0 & 0\ 0\ 0 & 0 & 0\ 0\ 0 \\ 0 & 0\ 0\ 0 & 0 & 0\ 0\ 0 & \frac{-1}{2H_3} & 0\ 0\ 0 & 0 & 0\ 0\ 0 & 0 \\ 0 & 0\ 0\ 0 & 0 & 0\ 0\ 0 & 0 & 0\ 0\ 0 & \frac{-1}{2H_4} & 0\ 0\ 0 \end{bmatrix}$$

- Low order controllers for control areas 2, 3 and 4 of power system simulation example in Sect. 6.1:

$$K_2(s) = \frac{N_2(s)}{D_2(s)}, K_3(s) = \frac{N_3(s)}{D_3(s)},\ K_4(s) = \frac{N_4(s)}{D_4(s)}$$

H. Bevrani, *Robust Power System Frequency Control*,
Power Electronics and Power Systems, DOI: 10.1007/978-3-319-07278-4,

where,

$$N_2(s) = 140.756s^5 + 164530.87s^4 + 194365.253s^3 + 98449.36s^2 + 546138.32s + 723970.37$$
$$D_2(s) = s^6 + 387.75s^5 + 35235.403s^4 + 67819.44s^3 + 2742801.2s^2 + 626558.42s + 126075.23$$

$$N_3(s) = 526.29\,s^5 + 1287.18\,s^4 - 1416.26\,s^3 + 6371.23\,s^2 + 12698.7s + 633.53$$
$$D_3(s) = s^6 + 7229.77\,s^5 + 6809.8\,s^4 + 93877.3\,s^3 + 101675.4\,s^2 + 4632.21s + 23.39$$

$$N_4(s) = 560.94s^6 + 8329.72\,s^5 + 4783.48\,s^4 + 1246.86\,s^3 + 19675.43\,s^2 + 2638.25s + 93.49$$
$$D_4(s) = s^7 + 18945.33\,s^6 + 12511.83\,s^5 + 76432.43\,s^4 + 836228.94\,s^3 + 42388.23s^2 + 1612.47s + 532$$

**Table B.1** Weighting functions for control area loops 2, 3 and 4 of power system simulation example in Sect. 6.1

| Area-2 | Area-3 | Area-4 |
|---|---|---|
| $W_{U2}(s) = \frac{0.1s^2+0.001}{s^2+0.2s+21}$ | $W_{U3}(s) = \frac{0.5s^2+0.005}{s^2+0.05s+10}$ | $W_{U4}(s) = \frac{0.11s^2+0.004}{s^2+0.11s+15}$ |
| $W_{p12}(s) = \frac{0.005s}{10^{-5}s+4.5}$ | $W_{p13}(s) = \frac{0.01s}{10^{-4}s+1}$ | $W_{p14}(s) = \frac{0.009s}{10^{-6}s+15}$ |
| $W_{p22}(s) = \frac{s+0.1}{93(s+0.001)}$ | $W_{p23}(s) = \frac{s+1.1}{100(s+0.1)}$ | $W_{p24}(s) = \frac{s+0.22}{83(s+0.02)}$ |

**Table B.2** Applied data for simulation of power system example in Sect. 6.2

| Quantity | G11 | G12 | G13 | G14 | G21 | G22 | G23 | G24 | G31 | G32 | G33 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rating ($MW$) | 1600 | 600 | 800 | 800 | 600 | 1200 | 800 | 1000 | 1400 | 600 | 600 |
| $H_{\mathrm{i}}$ (s) | 5 | 4 | 4 | 5 | 4 | 5 | 4 | 5 | 5 | 4 | 4 |
| $D_{\mathrm{i}}$ (pu MW/Hz) | 0.02 | 0.01 | 0.01 | 0.015 | 0.01 | 0.02 | 0.01 | 0.015 | 0.02 | 0.01 | 0.01 |
| $R_{\mathrm{i}}$ (%) | 4 | 5.2 | 5.2 | 5 | 5.2 | 4 | 5.2 | 5 | 4 | 5.2 | 5.2 |
| $2H_i/f_0$ | 0.167 | 0.134 | 0.134 | 0.167 | 0.134 | 0.167 | 0.134 | 0.167 | 0.167 | 0.134 | 0.134 |
| $T_{ti}$ | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| $T_{gi}$ | 0.2 | 0.1 | 0.15 | 0.1 | 0.1 | 0.2 | 0.15 | 0.1 | 0.2 | 0.1 | 0.1 |
| $K_{ti}, K_{gi}$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| $T_{\mathrm{i}}$ | 0.2 | 0.1 | 0.1 | 0.2 | 0.1 | 0.2 | 0.1 | 0.2 | 0.2 | 0.1 | 0.1 |
| $T_{\mathrm{ij}}$ (MW/rad) | $T_{12} = 60$ | | $T_{13} = 60$ | | $T_{23} = 100$ | | | | | | |

- Low order controllers for control areas 2 and 3 of power system example 2 in Sect. 8.2 (Tables B.1 and B.2):

$$K_2(s) = \frac{N_2(s)}{D_2(s)}, K_3(s) = \frac{N_3(s)}{D_3(s)},$$

where,

$$N_2(s) = 145s^5 + 1445267s^4 + 178943657s^3 + 96405249s^2 + 274613248s + 323019700$$
$$D_2(s) = s^6 + 288s^5 + 20235s^4 + 767219s^3 + 17402801s^2 + 226558154s + 226075$$

$$N_3(s) = 226.3\,s^5 + 22873\,s^4 - 1616\,s^3 + 137110\,s^2 + 126934s + 533$$
$$D_3(s) = s^6 + 3239.8\,s^5 + 68092\,s^4 + 638727\,s^3 + 3016725\,s^2 + 16332.2s + 13.3$$

(Table B.3)

**Table B.3** Applied data for performed simulation in Chap. 8, Sect. 8.3

| Regions | Region-1 | | | | Region-2 | | | Region-3 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Generator unit | G11 | G12 | G13 | G14 | G21 | G22 | G23 | G31 | G32 | G33 |
| Rating (MW) | 1,200 | 600 | 800 | 800 | 600 | 1,200 | 800 | 1,400 | 600 | 600 |
| $H_i$ (s) | 6.0 | 4.0 | 5.0 | 5.0 | 5.0 | 5.0 | 4.0 | 6.0 | 5.0 | 5.0 |
| $D_i$ (pu MW/Hz) | 0.05 | 0.08 | 0.05 | 0.04 | 0.05 | 0.08 | 0.05 | 0.07 | 0.05 | 0.04 |
| $R_i$ (%) | 3.0 | 3.0 | 3.2 | 2.7 | 2.7 | 2.6 | 2.5 | 2.8 | 3.0 | 3.0 |
| $T_{ti}$ | 0.40 | 0.36 | 0.42 | 0.45 | 0.44 | 0.32 | 0.40 | 0.30 | 0.40 | 0.41 |
| $T_{gi}$ | 0.30 | 0.20 | 0.07 | 0.10 | 0.30 | 0.20 | 0.15 | 0.15 | 0.15 | 0.20 |
| $K_i$ | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| $T_{ij}$ (pu/Hz) | $T_{12} = 0.2$ | | | | $T_{21} = 0.2$ | | | $T_{31} = 0.25$ | | |
| | $T_{13} = 0.25$ | | | | $T_{23} = 0.12$ | | | $T_{32} = 0.12$ | | |

# Appendix C

**Table C.1** Parameters for the DFIG units used in simulation example 1 in Sect. 10.4.1

| Parameter | Value |
|---|---|
| $S_n$ | 1.66 *MVA* |
| $V_n$ | 575 *V* |
| $H_t$ | 5.04 *s* |
| $R_s$ | 0.00706 *pu* |
| $L_s$ | 0.171 *pu* |
| $R_r$ | 0.005 *pu* |
| $L_r$ | 0.156 *pu* |
| $L_m$ | 2.9 *pu* |

- The matrix/vector coefficients for state-space model represented in (10.19) of Sect. 10.4.2 (Table C.1):

$$A = \begin{bmatrix} -\frac{D_1}{2H_1} & \frac{1}{2H_1} & \frac{1}{2H_1} & 0 & 0 & \frac{X_2}{2H_1} & \frac{1}{2H_1} & 0 \\ 0 & -\frac{1}{T_{t11}} & 0 & \frac{1}{T_{t11}} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{T_{t21}} & 0 & \frac{1}{T_{t21}} & 0 & 0 & 0 \\ -\frac{1}{T_{g11}R_{11}} & 0 & 0 & -\frac{1}{T_{g11}} & 0 & 0 & 0 & 0 \\ -\frac{1}{T_{g21}R_{21}} & 0 & 0 & 0 & -\frac{1}{T_{g21}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{X_2}{2H} & 0 & 0 \\ -\frac{D_1}{2H_1} & \frac{1}{2H_1} & \frac{1}{2H_1} & 0 & 0 & \frac{X_2}{2H_1} & \frac{1}{2H_1} & -\frac{1}{T_w} \end{bmatrix} \tag{C.1}$$

H. Bevrani, *Robust Power System Frequency Control*,
Power Electronics and Power Systems, DOI: 10.1007/978-3-319-07278-4,

$$B_1 = \begin{bmatrix} -\frac{1}{2H_1} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{1}{2H} & 0 \\ -\frac{1}{2H_1} & 0 & 0 \end{bmatrix} \tag{C.2}$$

$$B_2 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{X_1}{T_1} \\ 0 \\ 0 \end{bmatrix} \tag{C.3}$$

$$C_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & \eta_1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\eta_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{c.4}$$

$$C_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \end{bmatrix} \tag{C.5}$$

$$D_{11} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \eta_2 \\ 0 & 0 & 0 \end{bmatrix}; \quad D_{12} = \begin{bmatrix} 0 \\ 0 \\ \eta_3 \end{bmatrix}; \quad D_{21} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}; \quad D_{22} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{C.6}$$

- The matrix/vector coefficients for state-space model of H∞ controller represented in (10.24) of Sect. 10.4.2:

$$A_k = \begin{bmatrix} -30.6 & 67.3 & -8.2 & 5.5 & -20.0 & 15.2 & 41.0 \\ 79.3 & -334.5 & 59.1 & -8.7 & 96.4 & -12.4 & -10.7 \\ 66.6 & -248.8 & -400.8 & -52.3 & 365.7 & 358.8 & -218.0 \\ 7.6 & -36.4 & -90.3 & -1398.9 & -23.7 & 150.7 & 3.6 \\ 47.1 & -123.7 & 542.3 & -18.2 & -637.7 & -386.2 & -212.9 \\ 41.8 & 98.1 & 619.9 & 229.7 & -561.7 & -606.9 & -186.8 \\ 469.7 & -1488.7 & 165.3 & -24.8 & -87.0 & 28.2 & -1408.8 \end{bmatrix} \tag{C.7}$$

$$B_k = \begin{bmatrix} 15.2 & -7.6 \\ -50.2 & 12.1 \\ -42.5 & 7.4 \\ -3.3 & 1.2 \\ -35.7 & -1.3 \\ -13.4 & 13.1 \\ -301.3 & 51.8 \end{bmatrix} \tag{C.8}$$

$$\begin{aligned} C_k &= [-0.0004 \quad -0.0466 \quad -0.0008 \quad 0.0006 \quad -0.0204 \quad 0.020 \quad -0.0618] \\ D_k &= [0 \quad 0] \end{aligned} \tag{C.9}$$

# Appendix D

Tables D1, D2, D3, D4, D5 and D6

**Table D.1** Simulation parameters for the MG case study shown in Fig. 11.6

| Parameter | Value | Parameter | Value | Parameter | Value |
|---|---|---|---|---|---|
| $T_w$ | 4 | $K_{p3}$ | 1.4 | $T_{p3}$ | 1.0 |
| $K_{pc}$ | 0.08 | $K_{ig}$ | 1.494 | $K_{tp}$ | 0.004 |
| $K_{p1}$ | 1.25 | $T_{p1}$ | 0.6 | $H_d$ | 1.5 |
| $K_{p2}$ | 1.0 | $T_{p2}$ | 0.041 | $T_d$ | 0.5 |
| $T_{sm}$ | 0.05 | $Gain$ | 272 | $T_{fc}$ | 0.26 |
| $T_{\ln} = T_1$ | 0.04 | $T_{\ln}$ | 0.04 | $T_{smes}$ | 0.03 |
| $T_{IC} = T_2$ | 0.004 | $T_{IC}$ | 0.004 | $T_{fess}$ | 0.1 |

**Table D.2** Parameters for the MG shown in Fig. 11.13

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $V_{L-L}$ | 380 $v_{rms}$ | $C_f$ | 30 $\mu F$ |
| $f$ | 50 Hz | $r_{cf}$ | 5 Ω |
| $P_{nom}$ | 30 kVA | $L_{Lc}$ | 3 mH |
| $f_s$ | 4 kHz | $r_{Lc}$ | 0.1 Ω |
| $L_f$ | 6 mH | $K_f$ | −1.06 |
| $r_f$ | 0.2 Ω | $K_v$ | −100 |

**Table D.3** Loads in the 11-bus MG system shown in Fig. 11.24

| Bus number | Load (kVA) |
|---|---|
| 2 | 20 + j10 |
| 5 | 30 |
| 7 | 45 |
| 9 | 25 + j10 |

H. Bevrani, *Robust Power System Frequency Control*,
Power Electronics and Power Systems, DOI: 10.1007/978-3-319-07278-4,

**Table D.4** Loads change scenario in the 11-bus MG system shown in Fig. 11.24

| | Bus number | Load change (kVA) |
|---|---|---|
| at $t = 0.3$ s | 2 | 10 + j3 |
| at $t = 0.5$ s | 5 | 13 + j5 |
| at $t = 0.7$ s | 9 | 16 + j8 |

**Table D.5** Loads in the 14-bus MG system shown in Fig. 11.26

| Bus Number | Load (kVA) |
|---|---|
| 8 | 4.25 + j2.63 |
| 9 | 15.58 + j9.66 |
| 10 | 13.32 + j8.25 |
| 12 | 20.45 + j12.64 |
| 13 | 4.25 + j2.63 |

**Table D.6** Loads change scenario in the 14-bus MG system shown in Fig. 11.26

| | Bus number | Load change (kVA) |
|---|---|---|
| at $t = 0.4$ s | 8 | j7 |
| at $t = 0.6$ s | 9 | 7 |
| at $t = 0.8$ s | 13 | 3 + j2 |

# Index


**A**
Active power, 350, 352, 354, 355, 363–365, 369, 370, 373
Adaptive LS, 237
AGC, 6, 7, 11
AGC marker, 167, 169, 170, 201
Agent-based control, 163, 185, 186, 190
ANFIS, 338, 343, 345
Angle stability, 14
Area control error, 21, 28, 38
AVR, 9, 10, 14

**B**
Battery, 359
Bilateral contract, 163, 171-173, 175, 180, 185, 202, 205, 206, 208, 217
Bisection search method, 163, 202, 206, 217

**C**
Contingency, 221, 222, 224, 232, 233, 237, 243, 246, 248
Control area, 26-28, 30, 31, 34, 38
Control mechanism, 349, 362
Control performance standard, 34, 35, 38, 281

**D**
Damping, 349-351, 359, 362, 365, 366
Dead-bound, 49, 57, 58, 60, 67
Decentralized control, 131, 132, 136, 153
Deregulation, 163, 167, 169, 171, 189, 206
DFIG, 290, 295-300, 304, 305, 307, 323-325, 329, 331, 333, 336-339, 341, 342
DG, 323–325, 329, 331, 333, 336–339, 341, 342
Diesel generator, 320, 325, 326, 329
Distribution network, 320, 322, 324
Distribution network operator (DNO), 321
*D-K* iterations, 136, 138, 142, 147, 149
Droop characteristic, 24, 50, 52, 65-67
Droop control, 67, 323, 329, 331, 334, 336, 341, 342
Dynamic control, 71, 72, 81
Dynamic impacts, 372
Dynamic performance, 49, 57, 63, 67
Dynamic timescale, 14

**E**
Economic dispatch, 166, 202, 208, 210, 217
Emergency control, 6, 7, 12, 20, 34, 37, 221, 222, 224, 225, 227, 229, 232, 234-236, 246-248, 33
EMS, 7, 8
Energy storage system (ESS), 325
ENTSO-E, 168, 169, 171
Excitation system, 2, 14

**F**
FERC, 167, 169
Fictitious uncertainty, 134, 141, 146
Flywheel energy storage system (FESS), 325
Frequency control, 21, 22, 25, 26, 35, 37, 39, 40, 224, 247, 350, 353, 354, 362, 365, 369-371, 373
Frequency control loops, 19, 57, 62, 64, 67
Frequency deviation, 49, 51, 52, 57, 62, 63
Frequency regulation, 105, 251, 254, 255, 257, 272, 274, 275
Frequency response, 49, 52, 54, 56-58, 60, 62-64, 67, 251, 260, 261, 272, 275



H. Bevrani, *Robust Power System Frequency Control*,
Power Electronics and Power Systems, DOI: 10.1007/978-3-319-07278-4,

**F** *(conti.)*
Frequency response model, 21, 23, 25, 221-225, 248, 325-327, 330, 346
Frequency stability, 2, 11, 14, 15
Frequency threshold, 229, 231, 237, 239
Fuel cell (FC), 325
Fuzzy logic, 285, 286, 289, 296

**G**
GA
Generalized droop control, 334, 335, 337, 346
Generalized LFC model, 260
Generation participation matrix (GPM), 172–176, 178, 179, 184, 205
Genetic algorithm (GA), 106, 123, 126–128, 201, 202, 204, 205, 208, 210, 212, 214–216
Global control, 321–325
GRC, 58, 60
Grid code, 253, 263

**H**
H∞ robust, 310, 311, 315
$H_2$ norm, 107, 108, 110–112, 116
H2/H∞-PI control, 71–73, 78, 80, 82–91, 101
H∞ control, 105, 116, 117, 126, 128
H∞ norm, 110, 116
H∞-PI control, 186
H∞-SOF, 108, 109, 112, 113, 115

**I**
Inertia, 23, 25, 36
Inertia response, 259
Intelligent control, 325
Intelligent LFC, 201, 202, 206
IPP, 165, 169
ISO, 165
Isolated power system, 265, 310
Iterative LMI, 71–73, 78–81, 83, 84, 86–89, 101

**L**
LFC, 20, 21, 24, 27, 30, 31, 33, 39, 41, 49, 50, 51, 53, 55, 57–61, 71–73, 75, 76, 78, 83, 85, 89, 90–96, 98, 100, 101, 103, 105, 106, 108, 110, 113, 115–117, 120, 121, 123, 128, 282
LFC synthesis, 134, 149, 159
Linearized model, 49
LMI, 72, 73, 78–84, 88, 90, 92, 94, 95, 103, 105, 106, 108, 112–114, 128
Load controller (LC), 320
Load disturbance, 83, 85, 88, 90, 91, 100, 101
Load shedding (LS), 221, 224, 225, 229–246, 248
Local control, 321–323

**M**
M-Δ configuration, 134, 142, 146, 149
Market operator, 164–167, 170–175, 186
MG central controller (MGCC), 320
MG control, 319, 320, 323, 346
MG structure, 338
Microgrid (MG), 319, 349, 352
Microsource, 320–325, 327
Mixed H2/H∞ control, 105, 106, 108, 117, 123, 128
Model predictive control (MPC), 131, 152–159, 300, 314
Multi-area power system, 20, 21, 27, 28, 30, 40
Multi-objective control, 105, 106, 112, 123
Multiobjective optimization, 212

**N**
$N-1$ contingency, 236, 238
NERC, 169, 171
Nominal model, 134, 135, 140, 146

**O**
Operating state, 6
Optimization, 105, 112, 113, 123, 126, 128
Order reduction, 142, 143, 149, 150

**P**
Participation factor, 30, 31, 165, 166, 172, 173, 179, 186, 190–192, 198, 199, 202
Performance index, 78, 79, 82, 83, 100, 110, 112, 116, 123, 128
Performance tracking, 106, 112, 123, 126, 128
Physical constraint, 49, 57, 67
PI control, 71, 75, 76, 82–88, 91, 98, 100, 101, 108, 115, 116, 118, 121, 128, 287, 303
PI controller, 23
Point of common coupling (PCC), 320
Power fluctuation, 251, 255–257, 260, 261, 263, 268, 269
Power inverter, 357
Power reserve, 365, 369

Power system control, 1–3, 5, 7, 13–15
Power system stability, 1, 3
Primary control, 7, 11, 12, 20, 22, 36, 295, 304
Primary frequency control, 65, 67, 254, 255
Proportional control, 289
Protection, 221, 224, 225, 231, 232, 237–239, 248
PSO, 286, 287, 292
PSS, 3, 5, 9, 10
PV, 253, 256–258, 265, 267, 325, 327, 319
PWM, 360, 366

**R**
Rate of frequency change, 264, 269
Real power compensation, 19
Real-time simulation, 90, 100, 286
Reference current, 357, 359, 366
Regulation power, 164, 167–171
Renewable energy, 251–254, 263, 275
Reserve power, 35
Robust control, 71, 81, 85, 111, 118, 121, 134, 136, 138, 140, 144, 145
Robust frequency control, 13
Robust performance, 81–83, 87, 88, 101
Robust stability, 40, 116, 140, 146–148, 159
Root locus, 328–330, 346
Rotating mass, 22, 33
Rotor-side converter, 297, 300, 304

**S**
SCADA, 2, 7–9
Secondary control, 7, 10–12, 14, 20–22, 24, 28, 31–33, 37, 282, 290, 291, 301, 304, 307, 315, 321, 323, 341
Secondary frequency control, 50, 55, 57, 62–65, 72, 75, 256, 257
Sequential design, 132, 137
Shared LS, 233, 236, 239, 241, 242, 248
Speed governor, 22, 24, 35
Stability, 321, 326, 328–330, 345
Stability improvement, 372
Stabilization, 73, 74, 78
State of charge (SOC), 350
State-space model, 53
Static LS, 231
Static output feedback, 71–74, 92
Stator-side converter, 297
Structured singular value theory, 131, 132, 142, 145, 159
Swing equation, 23
Synchronous generator, 22, 349, 350, 352, 361

**T**
Targeted LS, 233, 234, 236, 238, 239, 248
Tertiary control, 7, 10, 12, 20, 21, 35
Time delay, 49, 58–60, 67, 72, 89, 90, 94, 100–102
Turbine-governor, 30

**U**
UFLS, 224, 225, 229, 231–234, 237–239, 242, 243, 245, 246, 248
Uncertainty, 61, 62, 105, 106, 108, 110–112, 116, 120, 128
Uncertainty weight, 140, 148
Under frequency/voltage LS (UFVLS), 242, 243, 246, 248

**V**
Variable speed wind turbine, 296, 297
Vertically integrated utility, 165, 169
Virtual inertia, 350, 351, 354, 363–365, 369, 371
Virtual synchronous generator (VSG), 349
Voltage stability, 9, 10, 13, 14
VSG topology, 350, 357, 362

**W**
Weights selection, 80
Wind energy, 252–254
Wind power, 281, 282, 284–287, 291, 295, 296, 298, 300, 302, 304, 306–309, 314, 315
Wind turbine, 284, 295, 297, 300, 303–305, 314, 325–327, 281, 283, 290, 296, 298, 309, 319

**X**
XCSR, 202–206