Appendix A

(1) Symbols in Sect. 3.3.1.2 for frequency control

$$
\begin{aligned}
& m = T_{wy}s + \frac{2h_{y0}}{H_0},\ a_5 = f_4 T_y(1 + b_P K_P), \\
& a_4 = f_5 T_y(1 + b_P K_P) + f_4(1 + b_P K_P + b_P K_I T_y), \\
& a_3 = f_6 T_y(1 + b_P K_P) + f_5(1 + b_P K_P + b_P K_I T_y) + f_4 b_P K_I + f_1 K_P, \\
& a_2 = f_7 T_y(1 + b_P K_P) + f_6(1 + b_P K_P + b_P K_I T_y) + f_5 b_P K_I + f_2 K_P + f_1, \\
& a_1 = f_7(1 + b_P K_P + b_P K_I T_y) + f_6 b_P K_I + f_3 K_P + f_2 K_I, \\
& a_0 = f_7 b_P K_I + f_3 K_I f_1 = e_y T_F T_{wy},\ f_2 = e_y\left(e_{qh}T_{wy} + T_F\frac{2h_{y0}}{H_0}\right) - e_h e_{qy} T_{wy}, \\
& f_3 = e_y\left(1 + e_{qh}\frac{2h_{y0}}{H_0}\right) - e_h e_{qy}\frac{2h_{y0}}{H_0},\ f_4 = T_a T_F T_{wy}, \\
& f_5 = T_F T_{wy}(e_g - e_x) + T_a\left(T_F\frac{2h_{y0}}{H_0} + T_{wy}e_{qh}\right), \\
& f_6 = (e_g - e_x)\left(T_F\frac{2h_{y0}}{H_0} + T_{wy}e_{qh}\right) + T_a\left(1 + e_{qh}\frac{2h_{y0}}{H_0}\right) + e_h e_{qx} T_{wy}, \\
& f_7 = (e_g - e_x)\left(1 + e_{qh}\frac{2h_{y0}}{H_0}\right) + e_h e_{qx}\frac{2h_{y0}}{H_0}.
\end{aligned}
$$

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(2) Symbols in Sect. 3.3.1.2 for power control

$$
\begin{aligned}
&a_5' = T_{wy}T_FT_yT_a, a_4' = T_{wy}T_FT_yb_2 + T_yT_ab_0 + T_{wy}T_FT_a,\\
&a_3' = T_yb_0b_2 + T_yT_ab_1 + T_{wy}T_ye_he_{qx} + T_{wy}T_Fb_2 + T_ab_0 + e_yT_{wy}T_Fb_4,\\
&a_2' = T_yb_1b_2 + T_ye_{qx}b_3 + b_0b_2 + T_ab_1\\
&\qquad + T_{wy}e_he_{qx} + (e_yb_0 - T_{wy}e_he_{qy})b_4 + e_yT_{wy}T_Fb_5,\\
&a_1' = b_1b_2 + e_{qx}b_3 + (e_yb_0 - T_{wy}e_he_{qy})b_5 + (e_yb_1 - e_{qy}b_3)b_4,\\
&a_0' = (e_yb_1 - e_{qy}b_3)b_5,\ b_0 = \frac{2h_{y0}T_F}{H_0} + T_{wy}e_{qh},\ b_1 = \frac{2h_{y0}e_{qh}}{H_0} + 1,\ b_2 = e_g - e_x,\\
&b_3 = \frac{2h_{y0}e_h}{H_0},\ b_4 = e_pK_IT_a,\ b_5 = e_pK_I(e_g + 1).
\end{aligned}
$$

(3) Coefficients of transfer functions Φ_1 in Sect. 3.3.2.2

$$
\begin{aligned}
&b_{01} = 0,\ b_{11} = -K_pKT_w,\ b_{21} = K_pK - K_iKT_w,\ b_{31} = K_iK,\ a_{01} = 0,\\
&a_{11} = 0.5T_wM\left(1 + b_pK_p\right),\ a_{21} = M\left(1 + b_pK_p\right) + 0.5T_w\left(b_pK_iM + D + b_pK_pD\right),\\
&a_{31} = b_pK_iM + D + b_pK_pD + 0.5T_wb_pK_iD,\ a_{41} = b_pK_iD
\end{aligned}
$$

(4) Coefficients of transfer functions Φ_2 in Sect. 3.3.2.2

$$
\begin{aligned}
&b_{02} = b_{01},\ b_{12} = b_{11},\ b_{22} = b_{21},\ b_{32} = b_{31},\\
&a_{02} = 0.5T_fT_wM\left(1 + b_pK_p\right),\\
&a_{12} = 0.5T_wM\left(1 + b_pK_p\right) + T_f\left[M\left(1 + b_pK_p\right) + 0.5T_w\left(b_pK_iM + D + b_pK_pD\right)\right],\\
&a_{22} = M\left(1 + b_pK_p\right) + 0.5T_w\left(b_pK_iM + D + b_pK_pD\right)\\
&\qquad + T_f\left(b_pK_iM + D + b_pK_pD + 0.5T_wb_pK_iD\right),\\
&a_{32} = b_pK_iM + D + b_pK_pD + 0.5T_wb_pK_iD + T_fb_pK_iD,\\
&a_{42} = b_pK_iD.
\end{aligned}
$$

(5) Elements of the state matrix in Sect. 3.3.3.2

$$a_{1,2} = \omega_0 = 2\pi f_0,\ a_{2,1} = -\frac{K_1}{T_j},\ a_{2,2} = \frac{e_\omega}{T_j},\ a_{2,4} = -\frac{K_2}{T_j},\ a_{2,5} = -\frac{K_3}{T_j},$$

$$a_{2,8} = \frac{e_y}{T_j},\ a_{2,10} = \frac{e_h}{T_j},\ a_{3,1} = -\frac{K_4\left(X_d - X'_d\right)}{T'_{d0}},\ a_{3,3} = -\frac{1}{T'_{d0}},$$

$$a_{3,4} = -\frac{K_5\left(X_d - X'_d\right)}{T'_{d0}},\ a_{3,6} = \frac{1}{T'_{d0}},\ a_{4,1} = -\frac{K_4\left(X'_d - X''_d\right)}{T''_{d0}},\ a_{4,3} = \frac{1}{T''_{d0}},$$

$$a_{4,4} = -\frac{K_5X'_d - K_5X''_d + 1}{T''_{d0}},\ a_{5,1} = \frac{K_6\left(X_q - X''_q\right)}{T''_{q0}},\ a_{5,5} = \frac{K_7X_q - K_7X''_q - 1}{T''_{q0}},$$

$$a_{6,1} = -\frac{K_aK_8}{T_r},\ a_{6,4} = -\frac{K_aK_9}{T_r},\ a_{6,5} = -\frac{K_aK_{10}}{T_r},\ a_{6,6} = -\frac{1}{T_r},\ a_{6,12} = \frac{K_a}{T_r},$$

$$a_{8,7} = \frac{1}{T_y},\ a_{8,8} = -\frac{1}{T_y},\ a_{9,1} = -\frac{T_we_{q\omega}a_{2,1}}{\alpha T_e^2},\ a_{9,2} = -\frac{T_we_{q\omega}a_{2,2}}{\alpha T_e^2},$$

$$a_{9,4} = -\frac{T_we_{q\omega}a_{2,4}}{\alpha T_e^2},\ a_{9,5} = -\frac{T_we_{q\omega}a_{2,5}}{\alpha T_e^2},\ a_{9,7} = -\frac{T_we_{qy}a_{8,7}}{\alpha T_e^2},$$

$$a_{9,8} = \frac{-T_we_{q\omega}a_{2,8} - T_we_{qy}a_{8,8}}{\alpha T_e^2},\ a_{9,9} = -\frac{T_we_{qh}}{\alpha T_e^2},\ a_{9,10} = \frac{-1 - T_we_{q\omega}a_{2,10}}{\alpha T_e^2},\ a_{10,9} = 1,$$

$$a_{11,1} = K_sK_\omega a_{2,1} - K_sK_{Pe}K_2a_{4,1} - K_sK_{Pe}K_3a_{5,1},\ a_{11,2} = K_sK_\omega a_{2,2} - K_sK_{Pe}K_1a_{1,2},$$

$$a_{11,3} = -K_sK_{Pe}K_2a_{4,3},\ a_{11,4} = K_sK_\omega a_{2,4} - K_sK_{Pe}K_2a_{4,4},$$

$$a_{11,5} = K_sK_\omega a_{2,5} - K_sK_{Pe}K_3a_{5,5},\ a_{11,8} = K_sK_\omega a_{2,8},\ a_{11,10} = K_sK_\omega a_{2,10},\ a_{11,11} = -\frac{1}{T_0},$$

$$a_{12,1} = \frac{T_1}{T_2}a_{11,1},\ a_{12,2} = \frac{T_1}{T_2}a_{11,2},\ a_{12,3} = \frac{T_1}{T_2}a_{11,3},\ a_{12,4} = \frac{T_1}{T_2}a_{11,4},\ a_{12,5} = \frac{T_1}{T_2}a_{11,5},$$

$$a_{12,8} = \frac{T_1}{T_2}a_{11,8},\ a_{12,10} = \frac{T_1}{T_2}a_{11,10},\ a_{12,11} = \frac{T_1}{T_2}a_{11,11} + \frac{1}{T_2},\ a_{12,12} = -\frac{1}{T_2}.$$

For opening feedback:

$$a_{(OF)7,1} = -\frac{K_pa_{2,1}}{1 + b_pK_p},\ a_{(OF)7,2} = \frac{-K_pa_{2,2} - K_i}{1 + b_pK_p},\ a_{(OF)7,3} = 0,$$

$$a_{(OF)7,4} = -\frac{K_pa_{2,4}}{1 + b_pK_p},\ a_{(OF)7,5} = -\frac{K_pa_{2,5}}{1 + b_pK_p},\ a_{(OF)7,7} = -\frac{b_pK_i}{1 + b_pK_p},$$

$$a_{(OF)7,8} = \frac{-K_pa_{2,8}}{1 + b_pK_p},\ a_{(OF)7,10} = \frac{-K_pa_{2,10}}{1 + b_pK_p}.$$

For power feedback:

$$a_{(PF)7,1} = -b_p K_i K_1 - b_p K_p K_3 a_{5,1} - b_p K_p K_2 a_{4,1} - K_p a_{2,1},$$
$$a_{(PF)7,2} = -b_p K_i K_1 a_{1,2} - K_p a_{2,2} - K_i,\ a_{(PF)7,3} = -b_p K_p K_2 a_{4,3},$$
$$a_{(PF)7,4} = -b_p K_i K_2 - b_p K_p K_2 a_{4,4} - K_p a_{2,4},$$
$$a_{(PF)7,5} = -b_p K_i K_3 - b_p K_p K_3 a_{5,5} - K_p a_{2,5},\ a_{(PF)7,7} = 0,\ a_{(PF)7,8} = -K_p a_{2,8},$$
$$a_{(PF)7,10} = -K_p a_{2,10}.$$

Here, $K_1 - K_{10}$ are:

$$\begin{cases} P_e = E''_d I_d + E''_q I_q + I_d I_q \left(X''_{q\Sigma} - X''_{d\Sigma} \right) \\ \Delta P_e = \frac{\partial P_e}{\partial \delta} \Delta\delta + \frac{\partial P_e}{\partial E''_q} \Delta E''_q + \frac{\partial P_e}{\partial E''_d} \Delta E''_d = K_1 \Delta\delta + K_2 \Delta E''_q + K_3 \Delta E''_d \end{cases}$$

$$I_d = \frac{E''_q - V_s \cos\delta}{X''_{d\Sigma}};\ \Delta I_d = \frac{\partial I_d}{\partial \delta} \Delta\delta + \frac{\partial I_d}{\partial E''_q} \Delta E''_q = K_4 \Delta\delta + K_5 \Delta E''_q$$

$$I_q = \frac{V_s \sin\delta - E''_d}{X''_{q\Sigma}};\ \Delta I_q = \frac{\partial I_q}{\partial \delta} \Delta\delta + \frac{\partial I_q}{\partial E''_d} \Delta E''_d = K_6 \Delta\delta + K_7 \Delta E''_d$$

$$\begin{cases} V_g = \sqrt{\left(\frac{X_s E''_d + X''_q V_s \sin\delta}{X''_{q\Sigma}} \right)^2 + \left(\frac{X_s E''_q + X''_d V_s \cos\delta}{X''_{d\Sigma}} \right)^2} \\ \Delta V_g = \frac{\partial V_g}{\partial \delta} \Delta\delta + \frac{\partial V_g}{\partial E''_q} \Delta E''_q + \frac{\partial V_g}{\partial E''_d} \Delta E''_d = K_8 \Delta\delta + K_9 \Delta E''_q + K_{10} \Delta E''_d \end{cases}$$

$$K_1 = \frac{E''_d V_s \sin\delta}{X''_{d\Sigma}} + \frac{E''_q V_s \cos\delta}{X''_{q\Sigma}} + \frac{\left(X''_{q\Sigma} - X''_{d\Sigma} \right) \left(E''_q V_s \cos\delta - V_s^2 \cos 2\delta + E''_d V_s \sin\delta \right)}{X''_{d\Sigma} X''_{q\Sigma}},$$

$$K_2 = \frac{E''_d}{X''_{d\Sigma}} + \frac{V_s \sin\delta - E''_d}{X''_{q\Sigma}} + \frac{\left(X''_{q\Sigma} - X''_{d\Sigma} \right) \left(V_s \sin\delta - E''_d \right)}{X''_{d\Sigma} X''_{q\Sigma}},$$

$$K_3 = \frac{E''_q - V_s \cos\delta}{X''_{d\Sigma}} - \frac{E''_q}{X''_{q\Sigma}} + \frac{\left(X''_{q\Sigma} - X''_{d\Sigma} \right) \left(V_s \cos\delta - E''_q \right)}{X''_{d\Sigma} X''_{q\Sigma}},\ K_4 = \frac{V_s \sin\delta}{X''_{d\Sigma}},$$

$$K_5 = \frac{1}{X''_{d\Sigma}},\ K_6 = \frac{V_s \cos\delta}{X''_{q\Sigma}},\ K_7 = -\frac{1}{X''_{q\Sigma}},$$

$$K_8 = \frac{V_{gd} V_s \cos\delta X''_q}{V_g X''_{q\Sigma}} - \frac{V_{gq} V_s \sin\delta X''_d}{V_g X''_{d\Sigma}},\ K_9 = \frac{V_{gq} x_s}{V_g X''_{d\Sigma}},\ K_{10} = \frac{V_{gd} x_s}{V_g X''_{q\Sigma}}.$$

The values of the state variables in the coefficients $K_1 - K_{10}$ are initial steady-state values.

Appendix B

(1) Simulation settings in Sect. 4.2 (Table B.1)

Table B.1 The default settings of the simulation of PFC

Upstream level (m)	Downstream level (m)	Initial power (MW)	Frequency step (Hz)	b_p	K_p, K_i, K_d	E_y, E_f
1639.3	1332.3	476	−0.2	0.04	9, 8, 0	0, 0.05

(2) Parameters and settings in Sect. 4.3

- Governor parameters:
  $K_d = 0$, $T_y = 0.02$ s, $b_p = 0.04$ pu, $e_p = 0.04$ pu, $E_f = E_y = E_p = 0$;
- Characteristic coefficient of power grid load: $e_g = 0.0$;
- Transmission coefficient of ideal turbine: $e_h = 1.5$ pu, $e_x = -1$ pu, $e_y = 1$ pu, $e_{qh} = 0.5$ pu, $e_{qx} = 0$, $e_{qy} = 1$ pu;
- Cross section area of surge tank (F): 415.64 m^2;
- Thoma critical section area for stability (F_{th}): 416.08 m^2.

(3) Parameter values of HPP 5 in Chap. 5

The values of the generator parameters are estimated from field simulations of standard tests in [1, 2].

- Generator: the nominal apparent power is 206 MVA, and the line-to-line voltage is 21 kV;
  $X_d = 0.768$ pu, $X_d' = 0.249$ pu, $X_d'' = 0.187$ pu, $X_q = 0.512$ pu, $X_q'' = 0.189$ pu, $T_{d0}' = 7.880$ s, $T_{d0}'' = 0.049$ s, $T_{q0}'' = 0.0283$ s, $T_j = 7.0$ s;
- Transformer and transmission line: $X_s = 0.30$ pu;

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- Turbine characteristic (for a normal operating point): $e_{qy} = 0.66$ pu, $e_{q\omega} = 0.1$ pu, $e_{qh} = 0.47$ pu, $e_y = 0.5$ pu, $e_\omega = -0.96$ pu, $e_h = 1.45$ pu;
- Penstock: $T_w = 1.34$ s (calculated under the rated condition: discharge is 275.0 m^3/s and water head is 73.0 m), $\alpha = 0.33$ pu, $T_e = 0.115$ s (length of the penstock is 115 m).

(4) Operating settings of HPP 5 in Sect. 5.1

- Initial steady-state condition: $P_e = 0.90$ pu, $\cos\varphi = 0.90$ ($Q_g = 0.436$), $V_s = 1.00$ pu;
- Turbine governor (for both two feedback modes): $b_p = 0.04$ pu, $K_p = 9.0$ pu, $K_i = 5.0\ s^{-1}$, $T_y = 0.2$ s, Backlash = 0.001 pu, Limiting rate = 0.1 pu/s;
- AVR: $T_r = 0.05$, $K_a = 100$, the regulator output limit is ±2.0 pu;
- PSS (speed input): $K_\omega = 1$ pu, $K_{Pe} = 0$, $K_s = 9.5$ pu, $T_0 = 1.4$ s, $T_1 = 0.154$ s, $T_2 = 0.033$ s;
- PSS (power input): $K_\omega = 0$, $K_{Pe} = 1$ pu, $K_s = 2.5$ pu, $T_0 = 1.4$ s, $T_1 = 0.154$ s, $T_2 = 3.0$ s.

(5) Operating settings of HPP 5 in Sect. 5.2

- Initial steady-state condition: $P_e = 0.90$ pu, $\cos\varphi = 0.90$ ($Q_e = 0.436$), $V_s = 1.00$ pu;
- Governor: $b_p = 0.04$ pu, $K_p = 8.0$ pu, $K_i = 1.0\ s^{-1}$, $T_y = 0.2$ s, the backlash value is 0.001 pu, the limiting rate is 0.1 pu/s;
- AVR: $T_r = 0.05$, $K_a = 100$ pu, the output limit is ±4.0 pu;
- PSS: $K_\omega = 1$, $K_{Pe} = 0$, $K_s = 9.5$ pu, $T_0 = 1.4$ s, $T_1 = 0.354$ s, $T_2 = 0.033$ s; the output limit is ±0.05 pu.

(6) Default simulation settings in Sect. 6.1

- Upstream level and downstream level: 213.1 and 78.3 m;
- Initial power: 122.0 MW;
- Amplitude and period of sinusoidal frequency: 0.1 Hz and 60 s;
- Turbine governor: $K_p = 1.0$ pu, $K_i = 0.833\ s^{-1}$, $K_d = 0$, $b_p = 0.02$ pu, $E_{dz} = 0$, Backlash-$B_y = 0.001$ pu, T_y (lag) = 0.02 s.

(7) Detailed information of measurements in Sect. 6.2

The original sampling frequency is 200 Hz, and the sampling time of the signals is averaged to 0.2 s. The governor parameter in the simulation is the same as the values in the HPP during the measurement, which are the standard parameter settings EP1 in Vattenfall HPPs, see Table B.2. The values of the lag, the backlash and the delay are set to 0.25 s, 0.00029 pu and 0.097 s respectively. The default parameter settings of the actuator in Sect. 6.2 is shown in Table B.3.

Table B.2 Standard controller parameters in Vattenfall HPPs

Parameter	Ep0	Ep1	Ep2	Ep3
b_p (or E_p)	0.1	0.04	0.02	0.01
K_p	1	1	1	2
K_i	1/6	5/12	5/6	5/3

Table B.3 The default parameter settings of the actuator in Sect. 6.2

Parameter	Servo (T_y)	Saturation	Rate limiting	Backlash
Value	0.2	(0,1 pu)	±0.1 pu/s	0.05×10^{-2} pu

Table B.4 Parameters of the plant and the grid in Sect. 6.2

Symbol	Parameter	Value
K	Scaling factor	$10 \times b_p$ (pu)
T_w	Water time constant	1.5 (s)
M	System inertia	13 (s)
D	Load damping constant	0.5 (pu)

(8) Detailed information for Sect. 6.3 (Tables B.5 and B.6)

Table B.5 Parameters of the plant and the grid in Sect. 6.3. The value of M and D are updated, comparing from the values in Table B.4

Symbol	Parameter	Value
T_w	Water time constant	1.5 (s)
M	System inertia	14.6 (s)
D	Load damping constant	0.66 (pu)

Table B.6 Parameter values of the HPP 6 and HPP 7 for simulation settings. There is no surge tank in HPP 7, hence the values of T_{wt}, T_s and f_t are shown as N/A

HPP 6				HPP 7			
Para.	Value	Para.	Value	Para.	Value	Para.	Value
T_y	0.25 s	T_{wt}	13.2 s	T_y	0.25 s	T_{wt}	N/A
T_{ya}	0.90 s	T_r	0.1 s	T_{ya}	0.90 s	T_r	0.07 s
$T_{del\text{-}gv}$	0.097 s	T_s	350.0 s	$T_{del\text{-}gv}$	0.097 s	T_s	N/A
$T_{del\text{-}a}$	0.410 s	α	0.33	$T_{del\text{-}a}$	0.410 s	α	0.33
BL_{gv}	0.00029 pu	f_t	$0.0065 \times q_0$	BL_{gv}	0.00029 pu	f_t	N/A
BL_a	0.00132 pu	f_p	$0.0120 \times q_0$	BL_a	0.00132 pu	f_p	$0.010 \times q_0$
T_{wp}	1.7 s	D_t	0	T_{wp}	1.01 s	D_t	0

Author Biography

Dr. Weijia Yang is presently working as a faculty member at the School of Water Resources and Hydropower Engineering (the State Key Laboratory of Water Resources and Hydropower Engineering Science) in Wuhan University, Wuhan, China.

He received his B.S. and M.S. degrees from School of Water Resources and Hydropower Engineering, Wuhan University, Wuhan, China in 2011 and 2013, respectively. He obtained his Ph.D. degree in 2017 at Division of Electricity, Department of Engineering Sciences, Uppsala University, Uppsala, Sweden. During the Ph.D. study, he mainly cooperated with the Vattenfall R&D in Sweden, and had short-term study visit to the Energy-Water Resource Systems team at the Oak Ridge National Laboratory, USA and the SMart grid And Renewable energy Technology (SMART) Lab at the University of Saskatchewan in Canada.

He mainly works in the interdisciplinary field regarding hydraulics, mechanics, electrical and control engineering, by applying theoretical analysis, numerical simulations, physical model tests and on-site measurements. His current research interests include dynamic characteristics of hydropower systems (pumped storage systems), interaction between hydropower plants and power systems, etc.

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Dr. Weijia Yang's full list of publications is available at: www.researchgate.net/profile/Weijia_Yang2

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