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List of Variables and Parameters

a: wave velocity [m/s].

A: cross section [m^2].

A_c: tunnel cross section [m^2].

A_p: penstock cross section [m^2].

A_s: surge tank cross section [m^2].

A_t: turbine gain [pu].

$c_{1,2,3}$: weight coefficients of the cost function [pu].

D: load-damping constant [pu].

D_1: turbine damping [pu/pu].

$D \cdot \overline{\omega}_r$: frequency-sensitive load [pu].

E: Young's modulus of pipe wall material.

f: wall thickness of penstock [m].

f_0: surge chamber orifice head loss coefficient [pu].

f_p, f_{p1} : penstock head loss coefficient [pu].

f_{p2}: tunnel head loss coefficient [pu].

g: acceleration due to gravity [m^2/s].

G : gate opening [%]

$\overline{G}$: gate opening [pu].

$\overline{G}_0$: initial value of the gate opening [pu].

$\overline{G}_d$: desired value of the gate opening [pu].

H : inertia constant [MW·s/MVA].

$\overline{H}$: hydraulic head at gate [pu].

H_0 : total head [m].

$\overline{H}_0$: initial steady state value of $\overline{H}$ [pu].

H_{base}: base head [m].

$H_l + H_{l2}$: head losses [m].

$\overline{H}_l$: head loss in the penstock [pu].

$\overline{H}_{l2}$: head loss in the tunnel [pu].

$\overline{H}_r$: surge tank head [pu].

$\overline{H}_{rss}$: steady state value of the surge tank head [pu].

$\overline{H}_t$: turbine head [pu].

k_f: Head loss constant due to friction [pu].

K_p: proportional gain of a PID.

K_{p1}: proportional gain of a PID.

K_i: integral gain of a PID.

K_d: derivative gain of a PID.

L_c: length of the tunnel [m].

L_p: length of the penstock [m].

P_{elec} : electric power [MW].

$\overline{P}_{electric}$: electric power [pu], where: $\overline{P}_{electric} = \overline{P}_{load} + D \cdot \overline{\omega}_r$.

$\overline{P}_{mechanical}$: turbine mechanical power [pu].

$\overline{P}_{mecss}$: steady state value of the turbine mechanical power [pu].

$\overline{P}_{load} \equiv P_l$: non-frequency-sensitive load [pu].

Q: flow [m^3/s].

Q_{base}: base flow [m^3/s].

Q_{max}: maximum low [m^3/s].

Q_{rated}: rated flow [m^3/s].

$R_{1,2,3,4}$: feedback gains [pu].

R_p: temporary droop [pu].

T: surge tank natural period [s].

T_e: elastic time [s].

T_{ec}: elastic time of the tunnel [s].

T_{ep}: elastic time of the penstock [s].

T_g: main servo time constant [s].

T_p: pilot valve and servomotor time constant [s].

$T_{\overline{w}}$: water starting time at any load [s].

T_W: water starting time at rated or base load [s].

T_{WC}: water starting time of the tunnel at rated or base load [s].

T_{WP}: water starting time of the penstock at rated or base load [s].

u : control effort [pu].

U : water velocity [m/s]

$\overline{U}$: water velocity [pu].

$\overline{U}_0$: initial steady state value of water velocity or steady-state flow [pu].

$\overline{U}_c$: water velocity in the tunnel or tunnel flow [pu].

$\overline{U}_{css}$: steady state value of the tunnel flow [pu].

$\overline{U}_p$: water velocity in the penstock or penstock flow [pu].

U_{rated} : rated water velocity [m/s].

$\overline{U}_t$: water velocity in the turbine or turbine flow [pu].

$\overline{U}_{tss}$: steady state value of the turbine flow [pu].

$\overline{U}_s$: water velocity in the surge tank or surge tank flow [pu].

$\overline{U}_{NL}$: no-load flow [pu].

x_1, x_2, x_3, x_4: state variables [pu].

x, y, z, w: state variables [pu].

z_1, z_2, z_3, z_4: state variables [pu].

z_0: hydraulic surge impedance of the conduit.

z_c: hydraulic surge impedance of the tunnel.

z_n: normalised hydraulic surge impedance of the conduit.

z_p: hydraulic surge impedance of the penstock.

$\Delta\overline{P}_m$: deviation of the mechanical power [pu].

$\Delta\overline{\omega}$: deviation of the rotor speed [pu].

ϕ: internal penstock diameter [m].

ϕ_i: initial diameter of the penstock [m].

ϕ_f: final diameter of the penstock [m].

Φ_c: friction coefficient of the tunnel [pu].

Φ_p: friction coefficient of the penstock [pu].

κ: bulk modulus of water [$kg/m.s^2$].

$\eta(\overline{G})$: nonlinear function [pu].

ρ: density of water [kg/m^3].

ω: angular frequency [rad/s] ($s=j\omega$).

$\overline{\omega}_r$: rotor speed [pu].

$\overline{\omega}_{ref}$: reference speed [pu].

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