Exercise 1 – Open-Loop Simulation of a Power Generation System

1. Objective

The objective of this exercise is to develop an open-loop simulator of a simplified power generation system. The simulator will later be used as the plant model for MPC design. In this first task, no feedback controller is used. The emphasis is on understanding how an imbalance between generated active power and electrical load changes the grid frequency.

After completing this task, you should be able to:

- implement the continuous-time three-state model in MATLAB/Simulink;
- establish a steady-state operating point;
- simulate different electrical-load disturbances;
- interpret frequency changes from the active-power balance; and
- prepare a verified plant simulator for subsequent MPC design.

2. Simplified Power-Generation System

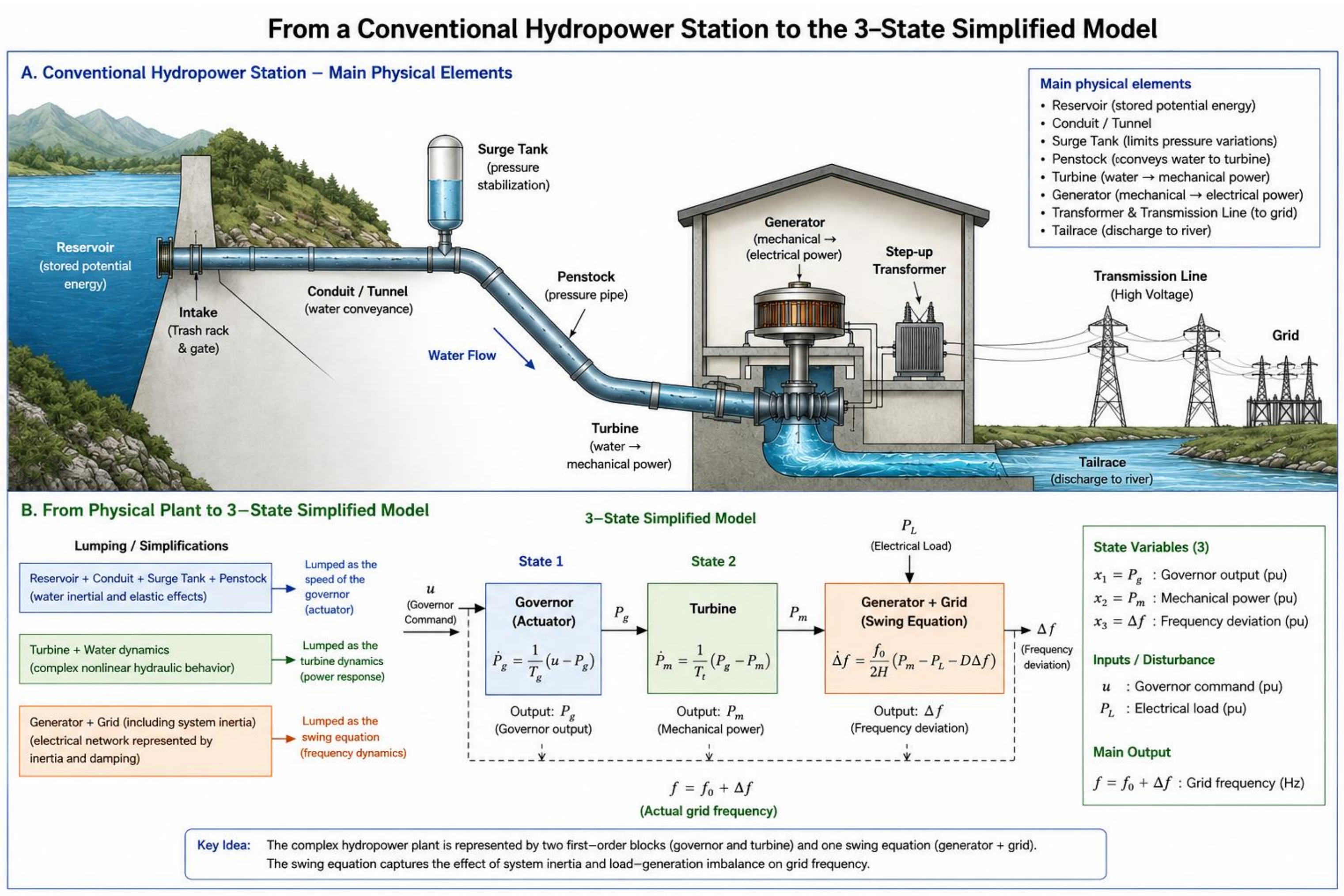

Figure 1: Schematic of a conventional hydropower station

A schematic of a conventional hydropower station is shown in Figure 1. The top half of this figures shows the main physical elements starting from the reservoir, followed by conduit, surge tank, penstock, turbine, generator and grid, all the way down to the tailrace. The lower half of this figure shows how we can simplify and lump the effect of various physical elements to create a simplified model of the system. Only active-power and frequency dynamics are considered. Reactive power, voltage/excitation dynamics, detailed generator electromagnetic transients, and detailed waterway dynamics are neglected. The simplified model consists of a governor/actuator, a lumped turbine, and an equivalent generator-grid frequency model as shown also in Figure 2.

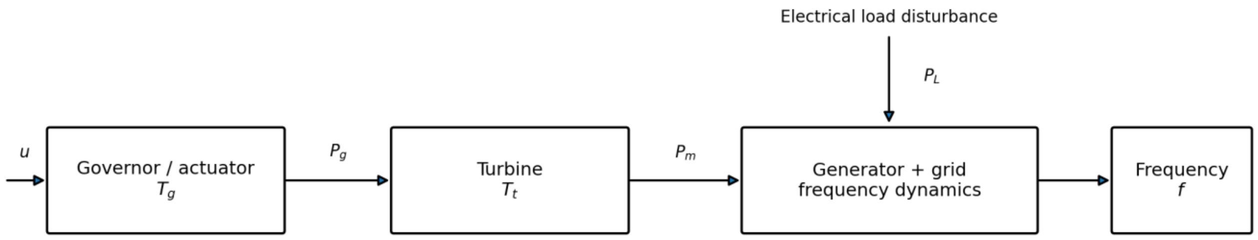

Figure 2: Simplified open-loop power-generation system.

The main variables are: u – governor power command; P_g – governor output; P_m – mechanical turbine power; P_L – electrical load; $\Delta f = f - f_0$ – frequency deviation. All powers are in per unit (pu), and the nominal frequency is **f_0 = 50 Hz**.

3. Mathematical Model

Generator and grid-frequency dynamics. The simplified swing equation is

$$\frac{d\Delta f}{dt} = \frac{f_0}{2H}\left[P_m - P_L - D_f\,\Delta f\right]$$

where H is the equivalent inertia constant and D_f is the load-frequency damping coefficient. If $P_m < P_L$, the rotating system decelerates and frequency decreases; if $P_m > P_L$, frequency increases.

Governor/actuator dynamics. The governor is represented by a first-order lag:

$$\frac{dP_g}{dt} = \frac{u - P_g}{T_g}$$

Turbine dynamics. The lumped turbine response is represented by

$$\frac{dP_m}{dt} = \frac{P_g - P_m}{T_t}$$

This turbine model is intentionally simple. Its purpose is to represent the finite response time from a governor command to mechanical generation, not detailed hydro-turbine or waterway physics.

4. State-Space Representation

$$x = \begin{bmatrix} \Delta f \\ P_g \\ P_m \end{bmatrix}$$

$$\frac{dx}{dt} = A_c x + B_c u + \Gamma_c P_L$$

$$y = C_c x$$

with

$$A_c = \begin{bmatrix} -\frac{f_0 D_f}{2H} & 0 & \frac{f_0}{2H} \\ 0 & -\frac{1}{T_g} & 0 \\ 0 & \frac{1}{T_t} & -\frac{1}{T_t} \end{bmatrix}$$

and

$$B_c = \begin{bmatrix} 0 \\ \frac{1}{T_g} \\ 0 \end{bmatrix}, \quad \Gamma_c = \begin{bmatrix} -\frac{f_0}{2H} \\ 0 \\ 0 \end{bmatrix}, \quad C_c = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$

$$f = f_0 + \Delta f$$

5. Recommended Parameters for the Exercise

Use the following values unless different values are provided by the teacher. They are deliberately selected as simple educational/lumped parameters and should not be interpreted as a parameter set for a particular hydroelectric plant.

Parameter	Meaning	Recommended value	Unit

f_0	Nominal grid frequency	50	Hz
H	Equivalent inertia constant	5	s
D_f	Load-frequency damping coefficient	0.02	pu/Hz
T_g	Governor/actuator time constant	0.20	s
T_t	Equivalent turbine time constant	1.00	s
$P_{L,0}$	Initial electrical load	0.60	pu
u_0	Initial governor command	0.60	pu

Suggested load-step tests:
ΔP_L = +0.01, +0.02, +0.03 and −0.02 pu. Students may add further cases. For the nominal operating point, use $P_{L,0} = P_{m,0} = P_{g,0} = u_0 = 0.6$ pu and $\Delta f_0 = 0$.

6. Tasks

Task 1 – Build the open-loop simulator. Implement the continuous-time model in MATLAB/Simulink. Your model shall accept u(t) and P_L(t) and provide at least f(t), P_g(t), and P_m(t). Organize the model so that the governor, turbine, and generator/grid dynamics can be clearly identified.

Task 2 – Verify the initial equilibrium. Use P_L,0 = 0.60 pu. Determine the required initial values of u, P_g, and P_m for f(0) = 50 Hz. Simulate with constant load and command and verify that the system remains at equilibrium. Explain mathematically why your initial values satisfy the steady-state model equations.

Task 3 – Simulate an increase in load. At t = t_d, increase the load by ΔP_L = +0.02 pu while keeping u unchanged. Plot P_L(t), P_m(t), and f(t). Explain why frequency decreases and determine the final steady-state frequency. Does the frequency return to 50 Hz without changing u? Explain using the model equations.

Task 4 – Compare different load disturbances. Repeat the simulation for at least four different load changes, including both increases and decreases. Compare the frequency responses in one suitable figure. For each case, report the maximum/minimum frequency, the final frequency, and the final values of P_m and P_L. Discuss how disturbance magnitude and direction influence the frequency response.

Task 5 – Manually restore nominal frequency. For one load-increase case, change u after the disturbance so that generated power eventually matches the new load. Plot u(t), P_g(t), P_m(t), P_L(t), and f(t). Explain the sequence u → P_g → P_m → f and determine the steady-state value of u required to restore f = 50 Hz.

Task 6 – Prepare for MPC. Briefly answer: (a) Why does active-power imbalance change frequency? (b) What mechanical power is required for exactly 50 Hz at steady state? (c) Which variable should be the controlled variable? (d) Which variable should be the manipulated variable? (e) Which variable is the main disturbance? (f) Why is automatic feedback control preferable to manually changing u?