Group Project Description

MPC for grid frequency stabilization of a power generation system

Choice 3

1. Introduction/Information

The group project for the course IIA4117 (Model Predictive Control) is an obligatory task that all the students enrolled in this course should fulfill. It counts 40% of the course grading. This is a group project and each student should be a part of a group. The students have the responsibility to form the groups themselves.

A technical report should be delivered by each group. The deadline for submitting the report is available at the course homepage (https://web01.usn.no/~roshans/mpc). Each group will receive a score (from 0 to 40) for the project work. Since there will be no presentation and demonstration, the grade for the project work is solely based on the quality of the submitted report. So make sure that you submit a good report.

1. Objective

The objective of this project is to design, implement, and evaluate a Model Predictive Controller (MPC) for frequency regulation of the simplified power-generation system introduced in Exercise 1. The controller shall adjust the governor power command so that the grid frequency is maintained close to 50 Hz when the electrical load changes.

The same three-state plant model and parameter values from Exercise 1 are used. The emphasis is on MPC formulation and implementation rather than detailed hydropower modelling. The work progresses from open-loop verification to constrained MPC, integral/offset-free control, and state estimation as listed below:

- verify the plant model in open loop before closing the loop;
- derive and discretize a prediction model suitable for MPC;
- formulate and tune a finite-horizon quadratic MPC problem;
- include input and input-rate constraints;
- introduce integral/offset-free action for persistent load disturbances;
- design a Kalman filter for state estimation from noisy measurements; and
- evaluate the complete controller under several loading and modelling scenarios.

2. System and Control Objective

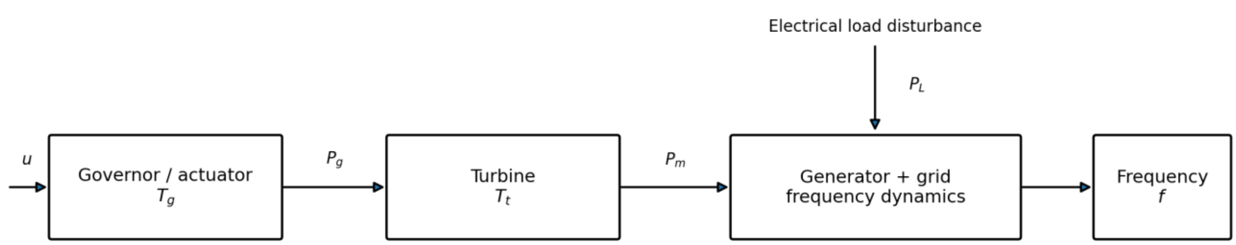


Figure 1: Simplified power-generation system used for MPC design.

The manipulated variable is the governor power command u. The main controlled variable is the grid frequency f. The electrical load P_L is the principal disturbance. The internal states are the governor output P_g, mechanical turbine power P_m, and frequency deviation $\Delta f = f - f_0$ with $f_0 = 50$ Hz for European grid.

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

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

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

$$y = C_c x + f_0$$

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

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

5. Recommended Parameters for the model

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

6. Recommended Starting Values for MPC

Quantity	Symbol	Starting value	Comment
Sampling time	dt	0.10 s	Discretize the continuous-time model.
Prediction horizon	N_p	30	3 s prediction window.
Weighting matrix for error	Q	10	Main tracking objective.
Weighting matrix for rate of change of control input	P	1	Penalizes aggressive changes.
Governor command limits	$u_{min}\ , u_{max}$	0.0, 1.0 pu	Hard constraints.
Governor Command-rate limit	$\lvert\Delta u\rvert_{max}$	0.03 pu/sample	Hard constraint; vary later.
Frequency reference	f_{ref}	50 Hz	Equivalent to $\Delta f_{ref} = 0$.

These values are starting points, not prescribed optimal settings. Investigate the effect of horizons and weights and justify the final choices.

5. Project Tasks

Task 1 – Open-loop verification of the plant model

Before designing the controller, reproduce a short open-loop study using the simulator developed in Exercise 1. Start from $P_L = u = P_g = P_m = 0.6$ pu and f_0 = 50 Hz.

- Use a slider to change the value of P_L by +0.01, +0.02, +0.03, and −0.02 pu while keeping u fixed.
- Plot $P_L(t)$, $P_m(t)$, and $f(t)$ and verify consistency with Exercise 1.
- Use one load-increase case to explain why feedback control is required.

Task 2 – Discrete-time prediction model

Select a sampling time $dt = 0.1$s and discretize the continuous-time state-space model. Construct the discrete time state space prediction model used by the MPC. You can use MATLAB function *c2d* for discretization.

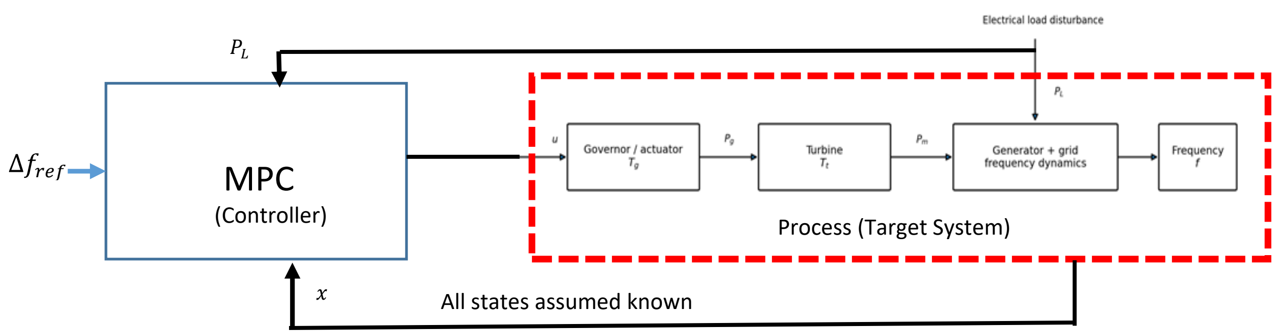
$$x_{k+1} = A_d x_k + B_d u_k + \Gamma_d P_L$$
$$y_k = C_d x_k + f_0$$

- Report the discrete-time matrices A_d, B_d, Γ_{d} and C_d.
- Simulate your discrete-time model and compare with the continuous time model. They should produce exactly same results.
- Explain why the selected dt is sufficiently fast relative to T_g and T_t.

Task 3 – Ideal MPC for frequency regulation

Design an MPC controller that regulates f to 50 Hz by manipulating u. Use a quadratic finite-horizon objective that penalizes predicted frequency error and changes in the governor command.

- For this task, assume that the electrical load disturbance (P_L) is known to the controller at any point of time, i.e. the prediction model in the MPC block sees the same electrical load as the process block (target system). Also assume that all states of the system are known for now, i.e. no need for kalman filter for state estimation for this task.



- The rate of change of control input is defined to be $\Delta u_k = u_k - u_{k-1}$. Now substitute $u_k = \Delta u_k + u_{k-1}$ in the discrete time model and express it in form as shown below.

$$x_{k+1} = A_d x_k + B_d \Delta u_k + B_d u_{k-1} + \Gamma_d P_L \quad (1)$$
$$y_k = C_d x_k + f_0 \quad (2)$$

Using the above state-space representation, design the MPC controller. Remember that for $k = 0, u_{-1}$ is known. Here, u_{-1} is the control input that was applied to the process in the previous time step. Also remember to take all the known terms to the right hand side when you are designing the LQ optimal controller using kronecker product formulation. The vector of unknowns for kronecker product formulation can be $z = [u, \Delta u, x, e, y]^T$. The control objective function can be quadratic as,

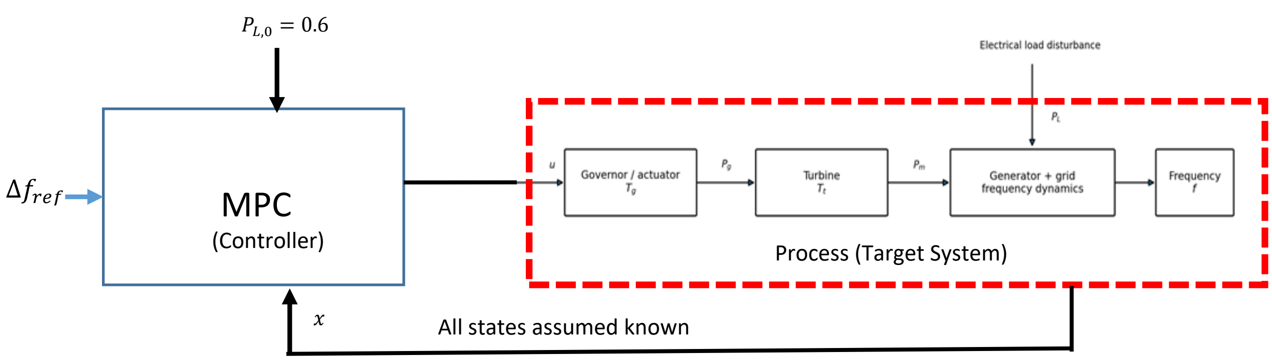
$$\min_{(\Delta u)} \quad J = \frac{1}{2}\sum_{k=1}^{N}(e_k^T\, Q_k e_k + \Delta u_{k-1}^T\, P_{k-1}\, \Delta u_{k-1})$$

with $e_k = r_k - y_k$, and $r_k = f_0 = 50\text{Hz}$. Here, $\Delta u_k = u_k - u_{k-1}$. Remember that equation for e_k and Δu_k should both be considered as linear equality constraints for LQ optimal control formulation.

- Use constraints on the governor command and its rate of change. Use $0 \le u \le 1$ pu for governor command and $-0.03 \le \Delta u \le 0.03$ pu/sample for its rate of change.
- Test for various load step and plot f, u, P_g, and P_m.
- Change the weighting matrices systematically and discuss their influence. Report maximum frequency deviation, settling time, and steady-state error.

Task 4 – Basic MPC with nominal electrical load ($P_{L,0}$) in the prediction mode

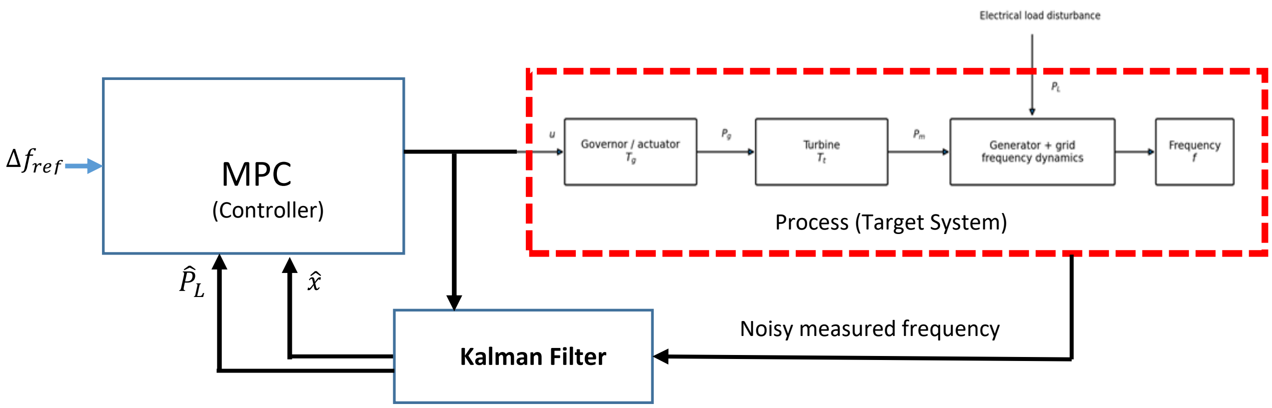
The assumption that the electrical load changes taking place in the target system is always known to the prediction model in the MPC block is not realistic. In this task we will test the MPC designed in task 3, but this time we will consider that the prediction model in the MPC block only sees the fixed nominal value of the electrical load, i.e. $P_{L,0} = 0.6$**.** In other words, the controller is designed for nominal value of the electrical load. The target system in itself will experience various load changes.



- Test the MPC controller for various electrical power load changes. Comment on your simulation results in detail. Is the controller able to stabilize the frequency at 50 Hz for various electrical load changes?
- Do you see any offset or steady state error in frequency stabilization?

Task 5 – Combined offset-free MPC and state estimation

A persistent unknown load change can produce steady-state offset if the nominal MPC formulation has no disturbance/integral mechanism. In this task you will design an MPC controller so that constant load disturbances are rejected and frequency returns to 50 Hz. In addition, assume now that only grid frequency is measured directly and that the measurement contains noise. In this task, you will also design a discrete-time Kalman filter to estimate the three plant states as well as unknown electrical load change. The estimated state ($\hat{x}$) and the estimated load disturbance ($\hat{P}_L$) will then be further used in the controller block by MPC.



- Choose process-noise and measurement-noise covariance matrices W and V for the kalman filter.
- Add appropriate zero-mean measurement noise to f in the process (target system) block. The kalman filter will take in the noisy measured frequency. In Simulink, you can use the block *Random Number* to create white Gaussian noise with zero mean and a very small standard deviation. The output of the *Random Number* should be added to the measurement f to make it noisy.
- Design an offset free MPC by augmentation with integrating constant non-zero disturbance model. For this you should use a kalman filter to estimate both the states and the unknown electrical load disturbance simultaneously. The estimated states will be fed back to the controller block for MPC, and thus creates the feedback action. The estimated disturbance will be used in the prediction model for the MPC, instead of using the constant $P_{L,0} = 0.6$.
- Apply a various electrical load step or changes in the process (target system) block that is not supplied directly to the nominal prediction model.
- Compare basic MPC and integral/offset-free MPC on the same plots.
- Verify all input and input-rate constraints are satisfied.
- Report frequency nadir/peak, settling time and steady-state error.
- Demonstrate that the steady-state frequency error is removed and explain why.

6. Recommended Report Structure

Keep the report concise and engineering-focused. Suggested structure: (1) plant and open-loop verification; (2) discrete prediction model; (3) ideal MPC formulation; (4) constraints and tuning; (5) basic MPC formulation (6) Kalman filter and output-feedback MPC; and (7) conclusions.