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CHAPTER 4

Boiler-Turbine Simulator Where Fast Megawatts Are Borrowed From Drum Pressure

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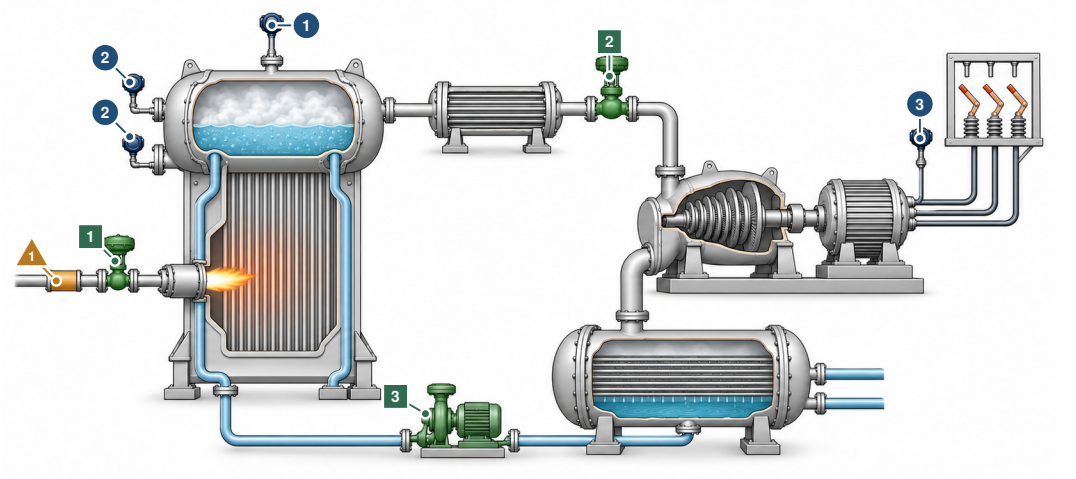
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CHAPTER 4

Boiler-Turbine Simulator Where Fast Megawatts Are Borrowed From Drum Pressure



The controller moves 1 fuel valve to the burner 2 turbine steam valve 3 feedwater pump

The controller reads 1 drum pressure 2 drum level, two taps 3 electrical output

What disturbs it 1 fuel heating value

Opening the turbine's steam valve gives megawatts within seconds by drawing down the drum pressure, which only more fuel can restore. Illustration, not to scale.

IN PLAIN TERMS Borrowing Power From a Boiler

The main idea. A power plant boils water in a drum to make steam that turns a turbine. Opening the steam valve gives more electricity within seconds, paid for by heat stored in the boiler's hot water and steel.

The challenge. That quick power is borrowed, because the steam pressure falls and only more fire can pay it back over minutes. A controller that plans ahead must also keep the pressure under its safe limit when the fuel burns hotter or cooler than it expects.

Why it matters. Plants built for steady output must now follow a grid whose wind and solar supply keeps changing.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the fact in Section 4.1, the history in Section 4.2, the try-it segments in Sections 4.4 and 4.6, the second fact, and the key points
Study	40 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	15 min	the first page, the results (Section 4.6), Technology in Practice (Section 4.7), Limitations (Section 4.8) and the open challenge

The control question A drum boiler stores energy in its saturated water and steel, so the turbine valve can deliver megawatts within seconds by drawing down a pressure that only the fuel can restore. Who should repay that loan, and what must a predictive controller know about a fuel it cannot measure to hold its setpoint and its pressure limit?

Learning objectives

- Compute the steady map and the linearized pressure time constant of the published drum unit, and explain where a valve step's first megawatts come from.
- Compare boiler-following, turbine-following and coordinated control on a load ramp, and explain what the feedforward lead adds under sliding pressure.
- Explain why a nominal MPC settles with an offset under an unmeasured fuel change, and how an input-disturbance state in the estimator removes it.
- Describe how tube MPC tightens a limit by a bound on the fuel's effect, and state what operating range the guarantee costs.
- Weigh the heat-rate credit of sliding pressure against its slower load response and the unit's ceiling below the nameplate.

Prerequisites Sections 1.6.2 (velocity form), 1.4.3 (the quadratic program), 1.4.5 (offset-free tracking), 1.4.6 (soft constraints and tightening), 1.4.7 (steady-state decisions) and 1.6.4 (how an exercise names a run).

The app https://apmonitor.com/apps/boiler-turbine/

See also Volume 6, Chapter 2 for choosing a pairing before any loop is tuned. Volume 17, Chapter 2 for one fuel valve whose two products arrive on different clocks, and Volume 17, Chapter 7 for a fast store and a slow source sharing a load under droop.

4.1 Introduction

A thermal unit asked for more power can answer before its fire changes. In the simulated 160 MW drum unit at its nominal point, 66.65 MW at a drum pressure of 108 kg/cm^2, opening the turbine's steam valve from 69 to 74 % by hand raises the electrical output 6.6 MW in 40 s while the pressure falls 1.5 kg/cm^2 in 100 s. The extra steam is flashed from water and metal that cool with the saturation temperature. Two more points of fuel stop the fall 26 s later, and the pressure recovers only 0.7 kg/cm^2 over the next 280 s. Units built for steady output are now asked to follow load and to cycle with variable renewable supply [1], so how a unit spends and refills that stored energy has become an operating question as well as a design one.

> ✦ DID YOU KNOW? **Built for Baseload, Started 1,760 Times**
>
> At one North American coal station, units designed to run at full output and to start cold only a few times a year have averaged 1,760 starts each, 523 of them cold, and at times have cycled on and off four times a day. Most utilities keep minimum generation at 40 to 50 percent of rated capacity [2].

The dynamics behind this trade have been modeled for half a century, from a simplified nonlinear model of a drum unit's pressure and output [3] to a fourth-order physical model of shrink and swell [4], and boiler-turbine dynamics have been reviewed for the power-plant control audience [5]. A third-order model of a 160 MW unit, fitted to plant data and published with its program listings and a basic coordinated controller [6], became a common test plant, analyzed for its nonlinearity and carried with a seven-point operating table [7]. Control designs tried on boiler-turbine units range from practical optimal control [8] and genetic-algorithm tuning [9] to pressure setpoint scheduling [10], fuzzy model predictive control [11] and robust predictive control [12]. The predictive controllers rest on a theory of constrained receding-horizon control [13], on disturbance models that remove steady offset [14, 15], on industrial practice that does the same with a bias update [16], and on tubes that hold constraints under a bounded disturbance [17].

The simulator is built to correct three beliefs. The first is that a fast actuator gives its effect for free. In a drum unit the valve's megawatts are borrowed from the pressure, so a structure that lets the valve hold the output must also decide who repays the loan, and when. The second is that a model predictive controller with a correct optimizer reaches its setpoint. A fuel 10 % poorer than the model assumes leaves the nominal MPC of case 6 1.3 $\mathrm{kg/cm^2}$ below its pressure setpoint, and the cure is a state in the estimator rather than a change in the quadratic program. The third is that a limit written into the program is a limit the plant respects. In case 7 the nominal MPC, whose pressure limit is a soft constraint at 145 $\mathrm{kg/cm^2}$, reaches 145.35 $\mathrm{kg/cm^2}$ under a 10 % richer fuel, and only a plan tightened by a bound on the fuel's effect stays under it.

These are features of a class rather than of boilers. Any plant whose fast handle draws on an inventory that a slow handle must refill has the same shape, among them the line pack of a gas pipeline (Volume 10, Chapter 12), the thermal mass of a building, a reservoir behind a turbine and the holdup of a distillation column. Any plant whose model carries an unmeasured gain error shows the same offset under a nominal predictive controller [14], and any hard limit approached under bounded uncertainty raises the same question of how much operating range a guarantee costs [17]. The drum unit makes all three visible on one plant whose equations are published.

The material a student usually meets treats these pieces apart. The benchmark appears in papers as a set of equations and a table, the structures of boiler-turbine practice appear in handbooks as block diagrams, and offset-free and tube MPC appear in the literature on linear examples whose disturbance has no physical name. This chapter sets the classical pairings, coordinated control and three predictive controllers side by side on one browser simulator of the published drum unit, sharing its plant, instruments and limits, and measures what each buys and costs. The model is the benchmark unchanged [6], and the methods are established ones. The simulator hides the fuel quality as truth behind a boundary of declared measurements, adds an offset-free estimator and a tube whose bound is recomputed at every decision, and states every equation, constant and default it uses. The analysis also records that the first point of the published operating table is not a steady state of the equations. Eight cases and a graded challenge, whose completion is judged from both the learner's actions and the unit's response, carry the measurements.

Section 4.2 follows the history of the unit and its control. Section 4.3 states the plant, its actuators, instruments and parameters. Section 4.4 shows what the unit does before any control: a pressure that integrates fire minus steam, a level that moves the wrong way first, a ceiling below the nameplate and the heat-rate credit of sliding pressure. Section 4.5 describes the unit master, its PI loops, two estimators, the predictive controller and the tube. Section 4.6 measures the eight cases and the challenge, Section 4.7 describes the instruments, valves and control platforms of real units, Section 4.8 states the limitations and Section 4.9 draws the results together. The exercises in Section 4.10 run the same cases in the simulator.

4.2 From a Peak-Load Unit to a Control Benchmark

The benchmark comes from a 1987 report on a peak-load unit, as the history segment below tells [6]. Its listings are the source of every coefficient in Section 4.3.

> ⧖ HISTORY **1969: Data Logs From a Peak-Load Unit**
>
> The plant behind the benchmark is a 160 MW oil-fired natural-circulation drum unit whose report lists 140 kg/s of steam at 140 $\mathrm{kg/cm^2}$ at rated load, superheated steam at 535 °C, a 40 $\mathrm{m^3}$ drum, and 40 000 kg of water against 2000 kg of steam in the circuit. By then it ran only for peak load, and it was chosen for the extensive dynamic data logged on it in 1969. A simplified nonlinear model that predicted its drum pressure and electrical output appeared in 1972 [3, 6]. A 1979 extension added the drum level, and the 1987 report brought the order back down with a simple evaporation-rate model, fitted six open-loop logs in which one input at a time was varied by pseudo-random steps, three near 70 MW and 110 $\mathrm{kg/cm^2}$ and three at 135 to 140 MW and 125 to 135 $\mathrm{kg/cm^2}$, and released the models, the data and the listings together [6].

The report also fixed the two features that make the model a control problem rather than a simulation task. Each actuator is written as a lag, a rate limit, an integrator and a bound, with the fuel limited to 0.007 of its range per second, the feedwater to 0.05 per second and the valve to 0.2 per second opening and 2 per second closing. A basic coordinated controller of three PI loops, with interactions between them and anti-windup by limiting the integral terms, is drawn beside it [6]. Both choices reflect the practice the unit was built in. A turbine valve that opens freely while the fuel moves slowly is the reason the classical pairings exist. Boiler-following holds the output with the valve and leaves the fuel to restore the pressure, turbine-following does the reverse, and coordinated control keeps one pairing while feeding the load demand to both handles. Optimal control of a drum boiler power plant was being formulated for practical use by the early 1980s [8], and the dynamics of the boiler and turbine together were later reviewed as the basis of power-plant control [5].

Sliding pressure came from economics. A unit held at rated pressure at part load throttles its steam across a partly closed valve, while a unit whose pressure slides with the load keeps the valve wider and saves fuel, at the price of filling and emptying the drum's stored energy with every load change. Scheduling the pressure setpoint inside a coordinated controller was framed as a multiobjective trade in the early 2000s [10]. The seven-point operating table that the control literature carries with the benchmark lies on such a line, with the pressure rising 10.8 $\mathrm{kg/cm^2}$ and the valve 0.069 from one point to the next [7].

Model predictive control reached the unit through the process industries, where commercial controllers remove steady offset by a bias between the model and the measurement [16]. The theory followed with disturbance models placed in the estimator, so that a persistent mismatch is explained as an integrating state and the prediction becomes right [14, 15]. Robust MPC for bounded disturbances took the form of a nominal plan surrounded by a tube that an ancillary feedback keeps the real state inside [17], and both fuzzy and robust predictive controllers have since been reported for boiler-turbine units [11, 12]. The fuel's heating value, which changes with every delivery of coal, biomass or residual oil, is the physical disturbance these methods are built for, and the simulator makes it the hidden variable of cases 6 and 7.

4.3 The Unit as Modeled

The simulated plant is the benchmark's drum, downcomers, risers, steam valve, turbine and alternator, with three actuators and a fuel of uncertain quality, as shown in Figure 4.1. Fuel burns in a furnace lined with water-wall tubes. The heated risers return a steam and water mixture to the drum, unheated downcomers outside the furnace return water to the lower header, and the steam leaves through the superheater in the gas pass, the turbine's control valve and the turbine to the condenser. A feed pump returns the water to the drum. The figure is a process drawing only. The model has no superheater, condenser or pump dynamics, and these appear because the simulator's Unit view draws them.

Table 4.1 gives the role of each variable. Six states are integrated, the drum pressure p, the electrical output E, the mean fluid density ρ_f and the three actuator positions a_1, a_2 and a_3, while the drum level is algebraic. Time is in seconds, pressure in the benchmark's $\mathrm{kg/cm^2}$, power in MW, flows in kg/s and densities in $\mathrm{kg/m^3}$. The actuator commands and positions are fractions of their ranges.

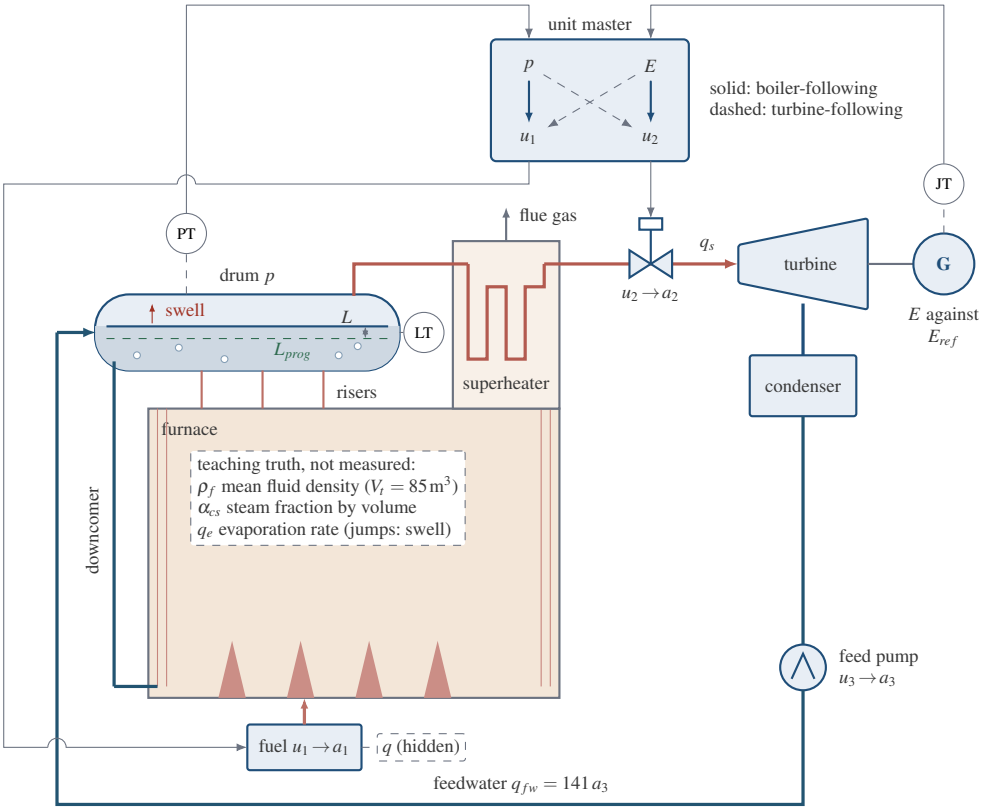


Figure 4.1 Drum unit as modeled, after the simulator's Unit view. The fuel command u_1 moves the fuel actuator a_1, whose heat is scaled by the hidden fuel quality q. The drum at pressure p holds a level L that is read from its program L_{prog} and swells when the valve opens. The fluid density ρ_f, the steam fraction α_{cs} and the evaporation rate q_e of the risers and downcomer are teaching truth. Steam q_s passes the superheater, the valve $u_2 \to a_2$ and the turbine, whose generator delivers E against its reference E_{ref}. The feed pump $u_3 \to a_3$ returns $q_{fw} = 141\,a_3$ from the condenser. The unit master pairs the output with the valve and the pressure with the fuel in boiler-following (solid) and crosses the pairings in turbine-following (dashed). Not to scale.

Table 4.1 Variables by Role, at the Nominal Point #4 of the Operating Table

Variable	Role	Nominal	Range
E	CV, measured output	66.65 MW	demand 15–160 MW
p	CV, measured drum pressure	108 kg/cm^2	SP 70–145
L	CV, measured level from program	0 mm	SP ±150 mm
u_1	MV, fuel command	0.3402	0–1 (14 kg/s oil at 1)
u_2	MV, steam valve command	0.6900	0–1
u_3	MV, feedwater command	0.4358	0–1
q	DV, fuel quality (hidden)	1	0.8–1.2
Δf	DV, grid frequency deviation	0 Hz	±0.5 Hz
noise	DV, instrument noise	100 %	0–300 %
ρ_f	state, fluid density (hidden)	427.9 kg/m^3	—
a_1, a_2, a_3	states, actuator positions	as u	0–1
q_s	output, steam flow	61.45 kg/s	—
q_e, α_{cs}	outputs, evaporation, steam fraction	truth	—

4.3.1 Pressure, Output and Fluid Density

The three balances of the benchmark are written for the actuator positions, with the fuel quality multiplying the fuel's heat, as shown in Equation (4.1).

$$\begin{aligned} \frac{\mathrm{d}p}{\mathrm{d}t} &= -0.0018\,a_2\,p^{9/8} + 0.9\,q\,a_1 - 0.15\,a_3 \\ \frac{\mathrm{d}E}{\mathrm{d}t} &= \frac{(0.73\,a_2 - 0.16)\,p^{9/8} - E}{10} \\ \frac{\mathrm{d}\rho_f}{\mathrm{d}t} &= \frac{141\,a_3 - q_s}{85}, \qquad q_s = (1.1\,a_2 - 0.19)\,p \end{aligned} \tag{4.1}$$

where p is in kg/cm^2, E in MW, ρ_f in kg/m^3, 85 m^3 is the volume V_t of the drum, downcomers and risers, and q_s is the steam flow in kg/s. The fuel adds heat, the steam leaving through the valve takes it in proportion to $p^{9/8}$, and the cold feedwater takes a little. The turbine and alternator answer the valve through a 10 s lag, and the term $-0.16\,p^{9/8}$ is the heat passed to the condenser and feed heaters. The fuel quality q is the simulator's one addition to the equations. It is 1 for the nominal fuel and scales the heat released per unit of fuel position, so a fuel 10 % poorer has $q = 0.9$.

4.3.2 Drum Level, Steam Fraction and Evaporation

The drum level of the benchmark is an algebraic output built from the density, the steam fraction and the evaporation rate, as shown in Equation (4.2).

$$\begin{aligned} L &= 0.05\left(0.13073\,\rho_f + 100\,\alpha_{cs} + \frac{q_e}{9} - 67.975\right) \\ \alpha_{cs} &= \frac{(1 - 0.001538\,\rho_f)(0.8\,p - 25.6)}{\rho_f\,(1.0394 - 0.0012304\,p)} \\ q_e &= (0.854\,a_2 - 0.147)\,p + 45.59\,q\,a_1 \\ &\quad - 2.514\,a_3 - 2.096 \end{aligned} \tag{4.2}$$

where L is in meters, α_{cs} is the steam quality by volume written out with the water's specific volume $v_w = 0.001\,538\,\mathrm{m}^3/\mathrm{kg}$ and the steam density $0.8p - 25.6$ fitted to steam tables, $0.13073 = v_w V_t$, and q_e is the evaporation rate in kg/s with the report's constants multiplied out [6]. The term $q_e/9$ jumps at once with the valve, the fuel and the feedwater, which is the swell and shrink, while the density term carries the slow inventory. The form in meters with zero at the nominal point is the one the control literature uses [7]. It differs from the report's listing, which writes the level in millimeters about a different datum, by a shift of 16 mm.

The level is a deviation variable valid near the operating line. Along the seven-point table it runs from −0.97 to +0.98 m, at 140 kg/cm^2 and 120 MW no density gives $L = 0$ (the minimum is +0.017 m), and below a density $\rho^* = \sqrt{100/(v_w V_t (1/\rho_s - v_w))}$, which is 276.1 kg/m^3 at 140 kg/cm^2, the level falls as the density rises. The simulator therefore holds and shows the level relative to a level program L_{prog}, the steady L at the table's density for the present load reference and pressure setpoint, followed through a 120 s lag. Over the shipped cases the density comes no closer to ρ^* than a ratio of 1.46.

4.3.3 Actuators and Fuel Quality

Each actuator follows its command through a first-order lag whose speed is capped by the report's rate limits, as shown in Equation (4.3).

$$\frac{\mathrm{d}a_i}{\mathrm{d}t} = \mathrm{clip}\left(\frac{u_i - a_i}{\tau_i},\ -r_i^{\downarrow},\ r_i^{\uparrow}\right), \qquad 0 \le a_i \le 1 \tag{4.3}$$

where the rates are 0.007 per second for the fuel, 0.05 for the feedwater, and 0.2 opening and 2 closing for the valve [6]. Later papers often quote 0.02 per second for the valve's opening limit,

Table 4.2 Parameters. F Fitted (Fixed), T Teaching Value, A Adjustable in Advanced Mode

Symbol	Meaning	Value	Unit	
—	coefficients, Eqs. (4.1)–(4.2)	report	—	F
V_t	drum, downcomer and riser volume	85	m^3	F
τ_1, τ_2, τ_3	fuel, valve, feed lags	20, 2, 10	s	T, A
r_1	fuel rate limit	0.007	s^{-1}	F, A
$r_2^{\uparrow}, r_2^{\downarrow}$	valve open, close limits	0.2, 2	s^{-1}	F, A
r_3	feedwater rate limit	0.05	s^{-1}	F, A
p_{max}, p_{min}	drum pressure limits	145, 70	kg/cm^2	T, A
ΔL	level band	±0.25	m	T, A
E_r	rated output	160	MW	A
R	governor droop	5	%	T, A
LHV	fuel heating value	40	MJ/kg	T, A
$\sigma_p, \sigma_E, \sigma_L$	noise, 1σ	0.03, 0.1, 3	kg/cm^2, MW, mm	T
τ_n	noise correlation time	2	s	T
q	fuel quality	1	—	hidden
p_r	rated pressure, credit basis	140	kg/cm^2	F

and the simulator follows the report. The lags $\tau_1 = 20\,\text{s}$, $\tau_2 = 2\,\text{s}$ and $\tau_3 = 10\,\text{s}$ are teaching values, because the report draws the structure without numbers. Fuel position 1 is 14 kg/s of oil and feedwater position 1 is 141 kg/s, the density balance's coefficient. The fuel quality is the product of a slider (80 to 120 %), the steps that events apply (±10 %) and a drift of −10 % over ten minutes. Every event fires once, at the start of a physics step, with a mark in the historian. The governor adds $-(\Delta f/50\,\text{Hz})/R \times 160\,\text{MW}$ to the output reference with a droop R of 5 %, so the challenge's 0.1 Hz dip asks for 6.4 MW more. The frequency offset that such a droop leaves on a grid is the subject of Volume 1, Chapter 8.

4.3.4 Instruments and the Truth Boundary

One function per physics step fills the only packet the controllers may read. It holds p, E and L with first-order colored noise of 2 s correlation and standard deviations of 0.03 kg/cm^2, 0.1 MW and 3 mm at the default noise setting, the three actuator positions, the steam flow computed from the valve and the measured pressure as a flow computer would, the feedwater flow $141\,a_3$ and the frequency deviation. The fuel quality and the fluid density are truth, logged in columns marked as truth and drawn dashed in the scene, and a test of the application searches the controller, the estimators, the MPC and the tube for any read of a truth field and finds none. The noise draws come from their own stream seeded by the case, so Reset reproduces a run exactly (Section 1.6.1).

4.3.5 Parameters, Initialization and Numerics

Table 4.2 lists every parameter. The plant coefficients are the report's fitted values and are fixed. The actuator, limit and unit parameters are adjustable in the simulator's Advanced mode, and each limit is a teaching value. A real drum's pressure limit comes from its design pressure and safety-valve settings under the boiler code, and its level trips from the drum design. Pressures are read as absolute. The report writes only kg/cm^2, and its steam-density line is a least-squares fit to steam tables, which are absolute. Reading them as gauge would move the saturated steam density by 1.1 to 1.6 % and the saturation temperature by under 1 °C between 75.6 and 145 kg/cm^2, less than the line's own misfit of up to 4.08 kg/m^3 along the table.

In Auto each case starts lined out at its load demand and the pressure its structure asks for. The steady map follows from setting Equation (4.1) to zero, with the valve $u_2 = (E/p^{9/8} + 0.16)/0.73$, the feedwater $u_3 = q_s/141$ and the fuel $u_1 = (0.0018\,u_2 p^{9/8} + 0.15\,u_3)/(0.9\,q)$, and the density is then found by bisection so that the level sits on its setpoint. In Manual the stations set the starting state. At point #4 the map gives a fuel of 0.3402, a valve of 0.6900, a feedwater of 0.4358 and a density of 427.9 kg/m^3, and every derivative there is below 3×10^{-17}. Integration is the classical

fourth-order Runge–Kutta method at 0.1 s, the unit master runs every 1 s, the MPC every 5 s, and the log takes a row every 0.5 s, on the three clocks of Section 1.6.1.

4.3.6 Assumptions

The model is the published fit and inherits its range. Its data came from a peak-load oil-fired unit at two loads, and the report notes its poorest fit at high load for valve moves [6]. There are no superheater or reheater temperatures, no attemperation, no air and flue-gas side and no mills, so the fuel's heat reaches the drum through the fuel actuator's lag alone, and a coal unit's mills would add minutes. The level is a deviation variable and breaks down far from the operating line, which is why the simulator programs its setpoint. The actuator lags, the fuel-quality multiplier, the noise, the droop, the heating value and every limit are teaching values, declared as such in the simulator's Model dialog.

4.4 What the Unit Does Before Any Control

4.4.1 A Pressure That Integrates Fire Minus Steam

Linearized at point #4, the pressure loses $0.002\,51\ \mathrm{s}^{-1}$ of its own excess, a time constant of 399 s, so over the minutes a load change takes the drum is nearly an integrator of fuel minus steam. The output answers the valve through the 2 s actuator and the 10 s turbine, with $0.73\,p^{9/8} = 141.6\,\mathrm{MW}$ of output per unit of valve at fixed pressure. In case 1 the valve step from 69 to 74 % at 20 s gives 6.55 MW in 40 s while the pressure falls $1.50\,\mathrm{kg/cm^2}$ in 100 s and keeps falling, as shown in Figure 4.2a. Raising the fuel from 34.0 to 36 % at 120 s stops the fall 25.9 s later, through the 20 s fuel lag, and the pressure climbs back only $0.73\,\mathrm{kg/cm^2}$ in the next 280 s. The valve is a fast handle on output and on pressure. The fuel is a slow handle on both.

> **TRY IT IN THE APP** **1 · Open Loop: The Valve Spends Stored Energy**
>
> Load the scenario and press Run. Open the Steam valve from 69 to 74 %, as the instructions ask, and watch the output and the drum pressure. The output rises 6.55 MW within 40 s while the pressure falls $1.50\,\mathrm{kg/cm^2}$ in 100 s and keeps falling until the fuel is raised.

4.4.2 The Level Moves the Wrong Way First

The same valve step raises q_e at once, and the level swells 22.6 mm within 6.8 s before the draining inventory takes over and leaves it 82 mm below its start at 400 s, with the feedwater held. In case 5 a 20 MW demand step under boiler-following swells the level 38 mm. A level controller that reads only the level sees too much water at the moment the drum is losing it. Volume 18, Chapter 4 studies the same inverse response in the drum of a steam generator.

4.4.3 A Ceiling Below the Nameplate

At the rated $140\,\mathrm{kg/cm^2}$ a fully open valve gives 148.0 MW, at the $145\,\mathrm{kg/cm^2}$ teaching limit 154.0 MW, and the nameplate's 160 MW would need $150.04\,\mathrm{kg/cm^2}$. The published table itself ends at 128.9 MW. The equations reproduce its fuel and feedwater within 0.65 %, its levels within its printed 0.01 m and its outputs at points #2 to #7 within 0.01 %. Point #1 is the exception. At its pressure of $75.6\,\mathrm{kg/cm^2}$ and valve of 0.483 the equations give 25.00 MW where the table prints 15.27 MW. At the table's own state $\frac{\mathrm{d}E}{\mathrm{d}t} = 0.97\,\mathrm{MW/s}$ while the other two derivatives are below 10^{-4}, so the fuel and feedwater entries agree with the valve and the output entry is the one in error (15.27 MW would need a valve of 0.380). The simulator uses the equations.

4.4.4 Sliding Pressure and the Heat-Rate Credit

The table's pressures against the outputs the equations give at its valves form the sliding-pressure line, from 25.0 MW at $75.6\,\mathrm{kg/cm^2}$ to 128.9 MW at $140.4\,\mathrm{kg/cm^2}$, linear between points and flat

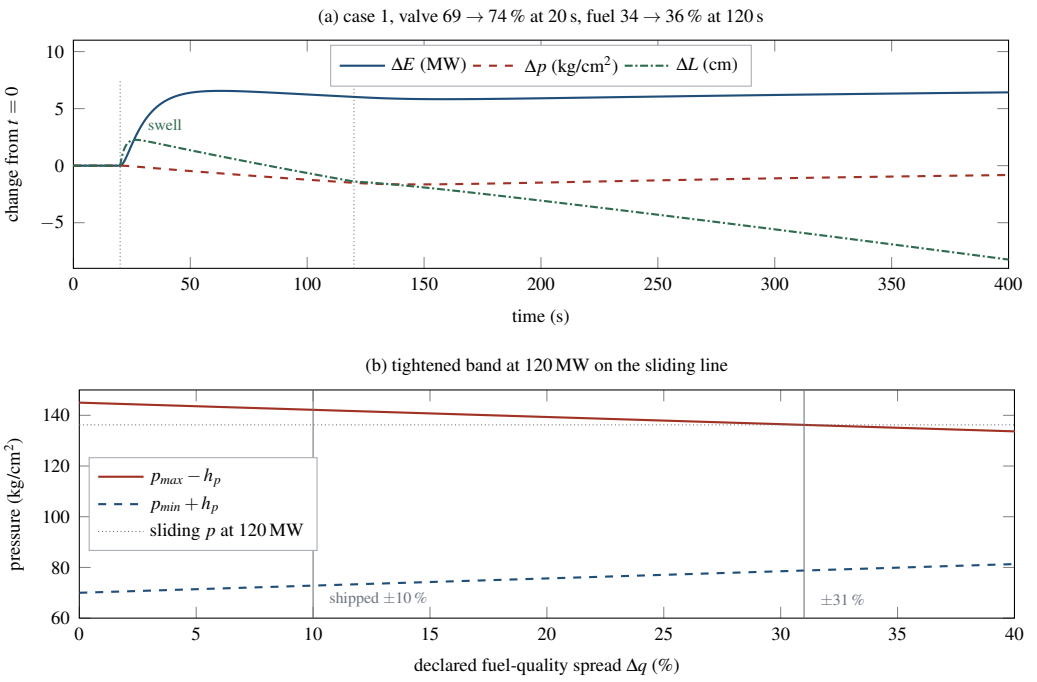


Figure 4.2 Stored energy and the price of a guarantee. (a) Case 1 in Manual, from the simulator's truth: the output (solid) answers the valve at once while the pressure (dashed) falls, and the level (dash-dotted) swells 22.6 mm before draining. (b) The tube's tightened pressure band at 120 MW on the sliding line, from the simulator's bound with the shipped ancillary gains, against the declared fuel-quality spread: the tightened upper limit (solid), the tightened lower limit (dashed) and the sliding pressure (dotted).

outside them. The heat-rate credit compares the steady fuel at the present output and pressure with the same output at the rated pressure, as shown in Equation (4.4).

$$c = 1 - \frac{u_{1,ss}(E,p)}{u_{1,ss}(E,140)}, \qquad HR = \frac{14\,a_1\,q\,\mathrm{LHV}}{E} \tag{4.4}$$

where $u_{1,ss}$ is the steady fuel of the map above and the heat rate HR is in kJ/kWh after unit conversion. A run's credit is the time average of c while $E > 5$ MW. On the line the credit is 7.76 % at 66.65 MW and 0.58 % at 120 MW. It comes from the model's $-0.16\,p^{9/8}$ loss term, which grows with pressure, while a real unit's credit comes from throttling losses and feed-pump power. A run-integrated fuel comparison is not used, because the stored energy that a sliding ramp moves dominates it (−5.5 % for sliding pressure on the challenge). Choosing the pressure along the line is a steady-state decision of the kind Section 1.4.7 sets out.

4.5 The Unit Master as Implemented

The unit master executes every $\Delta t_c = 1$ s on the instrument packet. The load reference E_{ref} ramps toward the demand at the automatic generation control (AGC) ramp rate (8 MW/min by default, zero meaning a step), the governor's share is added to give the target E_t, and the pressure setpoint is either the slider's value or the sliding line at E_{ref}. Six structures share the fuel and valve, and in every automatic structure the feedwater holds the level.

4.5.1 The PI Loops

Every proportional-integral loop is the velocity-form PID of Section 1.6.2 with the derivative off, run every Δt_c on a reference r and a measurement y. A feedforward bias b takes the place of the output bias u_b of Equation (1.16), the output is limited to the range 0 to 1, and anti-windup comes from back-calculation whose tracking time is τ_I. Every loop not in charge solves its integral for the command actually sent, so a change of structure and a switch between Manual and Auto are bumpless. With the noise off, every switch around the six structures at a steady 60 MW moves no command by more than 0.001 in the following 2 s.

Boiler-following sets the valve from the output error at $K_c = 0.005$ per MW (0.5 % of valve per MW) and $\tau_I = 12\,\text{s}$, and the fuel from the pressure error at 2 % per kg/cm^2 and 240 s. Turbine-following crosses the pairing, the fuel on the output at 0.2 % per MW and 40 s, and the valve on the pressure, reverse acting, at 30 % per kg/cm^2 and 30 s. How a pairing is chosen before any loop is tuned is the subject of Volume 6, Chapter 2. Coordinated control keeps boiler-following's loops and gives them biases from the model's steady map, as shown in Equation (4.5).

$$\begin{aligned} b_1 &= u_{1,ss} + \frac{T_{lead}}{\tau_f}\left(u_{1,ss} - \bar{u}_{1,ss}\right) \\ \tau_f \frac{\mathrm{d}\bar{u}_{1,ss}}{\mathrm{d}t} &= u_{1,ss} - \bar{u}_{1,ss} \\ b_2 &= \text{clip}\big(u_{2,ss}(E_t, \max(20, p_m)),\ 0,\ 1\big) \end{aligned} \tag{4.5}$$

where $u_{1,ss}$ is the steady fuel at (E_t, p_{ref}) with the nominal fuel, $\tau_f = 20\,\text{s}$, $T_{lead} = 60\,\text{s}$, and p_m is the measured pressure. The fuel bias is a lead-lag $(1 + (\tau_f + T_{lead})s)/(1 + \tau_f s)$ on the steady fuel, meant for the energy the drum must store when the pressure rises with the load.

The level loop uses the same law at 2 % of feedwater per 10 mm and $\tau_I = 150\,\text{s}$ on L against $L_{prog} + \Delta L_{SP}$. With the steam-flow feedforward on (three-element control) its bias is the measured steam flow through a 15 s filter divided by 141, and without it (single-element) the bias is zero.

4.5.2 Two Estimators

Two constant-gain Kalman filters run every 1 s in every structure, so either MPC takes over warm. The nominal one estimates $\hat{x} = [p, E]$, and the offset-free one adds an input disturbance d on the fuel, the disturbance state of Section 1.4.5, as shown in Equation (4.6).

$$\begin{aligned} \frac{\mathrm{d}p}{\mathrm{d}t} &= -0.0018\,a_2\,p^{9/8} + 0.9\,(a_1 + d) - 0.15\,a_3 \\ d_{k+1} &= d_k + w_k \\ \hat{x}_k &= \hat{x}_k^- + L_K\,(y_k - C\hat{x}_k^-) \end{aligned} \tag{4.6}$$

where $\hat{x}^-$ is the prediction over 1 s with the measured actuator positions held (four Runge–Kutta substeps), $y = [p_m, E_m]$, and the gain L_K comes once from the steady-state Riccati iteration on the model linearized at point #4, with process noise variances of 0.02^2, 0.2^2 and 0.001^2 per step and measurement variances of 0.03^2 and 0.1^2. The nominal gain is $[[0.480, 0.000], [0.003, 0.824]]$ and the offset-free gain adds a row $[0.0235, 0]$ for d, with a steady standard deviation of 0.49 % of fuel. With d, a fuel of quality q appears as $d = (q-1)a_1$, and the pair of the augmented model and the two measurements has rank 3, so the disturbance is observable [15]. The fluid density enters neither predicted balance and is not estimated.

4.5.3 The Predictive Controller

The MPC decides the fuel and valve every 5 s with the feedwater left to the level loop. Its model is the pressure and output balances with the two actuator lags, linearized at the estimate with the exact affine remainder and discretized for a zero-order hold, so its first prediction step is right to first order

wherever the unit is. The quadratic program is Equation (4.7), the objective of Equation (1.19) with the pressure band softened by one slack priced as in Equation (1.7) without the linear term.

$$\begin{aligned} \min \ & \sum_{k=1}^{N} w_k \left[w_E (E_k - E_{t,k})^2 + w_p (p_k - p_{ref,k})^2 \right] \\ & \quad + \sum_j \left(S_1 \Delta u_{1,j}^2 + S_2 \Delta u_{2,j}^2 \right) + 10^4 s^2 \\ \text{s.t. } & 0 \le u_j \le 1, \qquad |\Delta u_{1,j}| \le 0.035 \\ & p_{min} - s \le p_k \le p_{max} + s, \qquad s \ge 0 \end{aligned} \tag{4.7}$$

where $w_k = 1$ except $w_N = 5$, $w_E = w_p = 1$, $S_1 = 2000$, $S_2 = 50$, the references are the unit's own ramped load reference projected ahead (with the governor's share) and the pressure setpoint or the sliding line along it, and the 240 s horizon is $N = 48$ steps in twelve move blocks, four of one step, then 2, 2, 3, 4, 6, 9 and 15 steps, and a last block of 3. The fuel bound 0.035 is the fuel's rate limit over one decision. The nominal MPC predicts with $d = 0$ and the offset-free MPC with $\hat{d}$. A dual active-set solver [18] from the simulators' shared modules computes the plan, and only its first move is applied, the receding horizon of Section 1.4.3 [13]. Any plan the solver does not return as optimal, or whose move is not finite or leaves the unit interval, is discarded and the previous commands stay in force. Over the suggested challenge the offset-free MPC solved 180 programs, rejected none and never took more than 4 active-set iterations, while in case 7 the tube's plans took up to 35 iterations with a pressure slack of up to 0.109 kg/cm^2.

4.5.4 Tube MPC

The tube MPC keeps a nominal unit $z = [p, E, a_1, a_2]$, simulated with the nominal fuel from the state where the tube took over and never reset to the measurements. The same quadratic program plans the nominal commands v with tightened limits, and the commands sent to the plant add an ancillary feedback on the measured gap, $u_1 = v_1 - K_p(p - z_p)$ and $u_2 = v_2 - K_E(E - z_E)$, with $K_p = 0.02$ per kg/cm^2 and $K_E = 0.005$ per MW. To first order the gap $e = x - z$ obeys $e^+ = \Phi_K e + \Gamma w$, where Φ_K is the closed ancillary loop over 1 s including both actuator lags and $w = 0.9(q - 1)a_1$ is the fuel's missing or extra heat. Starting from $e = 0$ every reachable gap lies in the box of Equation (4.8) [17], and the limits are tightened by it, as Section 1.4.6 describes.

$$\begin{aligned} |e_i| \le h_i &= \bar{w} \sum_{k \ge 0} \left| (\Phi_K^k \Gamma)_i \right| \\ \bar{w} &= 0.9 \, \Delta q \, \min(1, \bar{a}_1) \\ p_{min} + h_p \le z_p &\le p_{max} - h_p, \quad h_{a,i} \le v_i \le 1 - h_{a,i} \end{aligned} \tag{4.8}$$

where Δq is the declared fuel-quality spread (10 % by default) and $\bar{a}_1$ starts as the larger of the nominal unit's fuel position and its command, plus 0.05. The bound is recomputed at every decision at the nominal state, the sum stopping when a term adds less than 10^{-10} of the total, and a second pass raises $\bar{a}_1$ to the plan's largest fuel plus its own bound when that is higher. For a scalar disturbance the box is exact on the linear error model. A nominal unit that starts above its tightened limit is brought under it along a declared 0.02 kg/cm^2 per second ramp rather than in one decision, which only the valve could do. The display calls the plant inside the tube when each measured gap is within h_i plus three standard deviations of the declared instrument noise.

4.5.5 Three Models Kept Apart

The plant is Equations (4.1)–(4.3) with the true fuel. The identified model a learner may fit is the response of case 1. The controllers' models are the nominal balances of Equations (4.6) and (4.7), which know neither the fuel quality nor the level, and the tube's linear error model, which leaves out the actuators' rate limits, the plant's nonlinearity away from the nominal unit and the instrument noise.

Table 4.3 The Cases

#	Case and events	Teaching point
1	Manual at #4, valve 69 to 74 %, then fuel to 36 %	stored energy
2	Boiler-following, ramp 66.65 to 85.06 MW at 8 MW/min from 30 s	fast, drifting
3	Turbine-following, same ramp	steady, slow
4	Coordinated, same ramp, then sliding, then no lead	the compromise
5	Single-element level, +20 MW step at 30 s, then three-element	swell
6	Nominal MPC, fuel −10 % at 60 s, offset-free from 600 s	offset
7	MPC at 144 kg/cm^2, 100 MW, −20 MW and fuel +10 % at 300 s, then tube	a hard limit
8	Offset-free MPC at 140 kg/cm^2, 60 to 80 MW at 60 s, then sliding, then 160 MW	credit, ceiling
9	Challenge: 60 to 120 MW at 8 MW/min, fuel −10 % at 285 s, −0.1 Hz at 420–480 s	the whole problem

Table 4.4 Measured Ramps, Cases 2 to 4. Largest Output Gap and Pressure Gap, and Loop IAE on the Measured Signals From 0 to 360 s

Structure	$\lvert E - E_t \rvert$ (MW)	$\lvert p - p_{ref} \rvert$ (kg/cm^2)	IAE_E (MW s)	IAE_p (kg/cm^2 s)
boiler-following	2.69	3.51	372	682
turbine-following	9.67	0.10	1608	17
coordinated	0.81	1.21	69	195
coordinated, sliding	0.81	2.96	69	423
coordinated, sliding, no lead	0.81	4.09	70	633

4.6 Eight Cases and a Challenge, Measured

The cases appear in Table 4.3. All share the default tunings, three-element level control, 100 % instrument noise and the nominal fuel, and depart from them only as the rows say. Each number quoted here was produced by running the shipped engine without a browser at the case's seed, advanced with the browser's physics step, with settings entered at the moments the case's own instructions give. Loading a case first, after another case, or by Reset gives identical runs.

4.6.1 Three Ways to Follow a Ramp

Cases 2 to 4 ramp the demand from point #4 to point #5 over 138 s, and their measured results appear in Table 4.4. Boiler-following keeps the output within 2.69 MW of its reference and lets the pressure fall 3.51 kg/cm^2 below its setpoint, because the valve draws the extra steam before the fuel loop sees any error. Turbine-following holds the pressure within 0.10 kg/cm^2 and falls 9.67 MW behind, because the valve may open only as the fire raises the pressure. Coordinated control holds both, 0.81 MW and 1.21 kg/cm^2, since the static map starts the fuel with the ramp. With sliding pressure the setpoint climbs from 108.0 to 118.8 kg/cm^2 during the ramp and the fire must also fill the drum. The pressure then trails by up to 2.96 kg/cm^2 with the 60 s lead and 4.09 kg/cm^2 without it, while at constant pressure the same lead slightly overfires (1.21 against 0.99 kg/cm^2).

> ✦ **DID YOU KNOW? The Steadiest Pressure, the Largest Output Error**
>
> From the simulator: on the same ramp, turbine-following accumulates an output IAE of 1608 MW s, against 372 for boiler-following and 69 for coordinated control, while its pressure IAE is only 17 kg/cm^2 s against 682 and 195 (Table 4.4). Each classical pairing buys one error with the other.

4.6.2 Swell and the Three-Element Loop

On the 20 MW step of case 5 the level swells 38 mm under either level loop, since the pressure falls within seconds whatever the feedwater does. What differs is the recovery. The single-element loop takes the swell for surplus water and cuts the feedwater, and the level then falls 107 mm below its

setpoint. With the steam-flow feedforward the feedwater rises with the steam from the start and the dip is 73 mm.

🕮 **Pause.** Try Exercise 4.1 before reading on.

4.6.3 The Offset and the Estimator That Removes It

In case 6 the fuel's heating value falls 10 % at 60 s under the nominal MPC, which settles 1.25 $\mathrm{kg/cm^2}$ below its setpoint at 600 s and 1.27 $\mathrm{kg/cm^2}$ at 840 s. Its model predicts that the present fuel will raise the pressure, so it holds fuel back against a rise that never comes, and the estimator's correction each step balances the model's error only with the pressure off its setpoint. A predictive controller has no integral term of its own, so it removes a steady error only through a disturbance model, as Section 1.4.5 shows on the tank. The offset-free estimator has run all along. Its $\hat{d}$ is −3.65 % of fuel at 600 s against a true bias $(q-1)a_1$ of −3.76 %, and after a switch to the offset-free MPC at 600 s the pressure returns within 0.2 $\mathrm{kg/cm^2}$ of its setpoint in 55 s. Both controllers solve the same program. Only the estimate they start from differs.

> **TRY IT IN THE APP** **6 · MPC and the Offset: A Poorer Fuel**
>
> Load the scenario and run it to 600 s. The fuel's heating value falls 10 % at 60 s, and the nominal MPC settles 1.25 $\mathrm{kg/cm^2}$ below its setpoint. Then set Control structure to Offset-free MPC: the pressure returns within 0.2 $\mathrm{kg/cm^2}$ of its setpoint in 55 s.

🕮 **Pause.** Try Exercise 4.2 before reading on.

4.6.4 A Limit Held for Every Fuel

Case 7 holds 144 $\mathrm{kg/cm^2}$ at 100 MW, 1 $\mathrm{kg/cm^2}$ under the limit, and at 300 s cuts the demand 20 MW as a step while a fuel 10 % richer arrives. The nominal MPC reaches 145.35 $\mathrm{kg/cm^2}$ and stays over the limit for 558 s, settling 1.2 $\mathrm{kg/cm^2}$ over its setpoint, the offset of case 6 with the opposite sign. The offset-free MPC peaks at 145.25 $\mathrm{kg/cm^2}$ and is over for 27.7 s while its estimate catches up. The tube MPC computes a bound h_p of 2.56 $\mathrm{kg/cm^2}$ at 100 MW and 2.24 $\mathrm{kg/cm^2}$ at 80 MW, plans its nominal unit under the tightened 142.76 $\mathrm{kg/cm^2}$ and peaks at 144.65 $\mathrm{kg/cm^2}$. Its price is range. It cannot hold 144 $\mathrm{kg/cm^2}$, because its nominal unit may not rise above the tightened limit, and its usable pressure range at 900 s is 70.53 of 75 $\mathrm{kg/cm^2}$. With fuels of quality 0.9 and 1.0 in the same case the nominal MPC peaks at 144.35 and 144.92 $\mathrm{kg/cm^2}$ and the tube at 144.00 $\mathrm{kg/cm^2}$, so only the richest fuel of the set breaks the nominal plan.

🕮 **Pause.** Try Exercise 4.3 before reading on.

The tightened band against the declared spread at the challenge's top, 120 MW on the sliding line at 136.24 $\mathrm{kg/cm^2}$, is shown in Figure 4.2b. The bound grows in proportion to Δq, from 2.83 $\mathrm{kg/cm^2}$ at the shipped 10 %, which leaves a usable range of 69.3 $\mathrm{kg/cm^2}$. The tightened limit falls below the sliding pressure at 120 MW only at a spread of 31 %. Along the whole sliding line at 10 % the usable range stays between 69.3 and 71.6 $\mathrm{kg/cm^2}$, so the tube's price at the declared set is a few $\mathrm{kg/cm^2}$ near the limit rather than lost load.

4.6.5 Sliding Pressure and the Nameplate

In case 8 the offset-free MPC takes a step from 60 to 80 MW at 60 s. At the constant 140 $\mathrm{kg/cm^2}$ the output settles inside its ±2 MW band 8.5 s after the step with a credit of 0.05 % over 300 s. With sliding pressure it takes 20.0 s, because the fire must raise the pressure from 103.5 to 115.8 $\mathrm{kg/cm^2}$ as the load rises, and the credit is 6.70 %. Asked for 160 MW, the output stops at 153.96 MW with the valve wide open and the pressure riding its soft limit at up to 145.05 $\mathrm{kg/cm^2}$, over it for 120 s of the 600 s after the request. A logged sweep of 72 runs (six structures, both pressure policies, setpoints of 140 and 145 $\mathrm{kg/cm^2}$ and ramps of 0, 8 and 16 MW/min) found none that holds 160 ± 2 MW for

Table 4.5 The Challenge Over 900 s. Largest Pressure Gap, Level Gap, Final Output and Pressure Gaps, Credit, and Seeds Passed of 11

Configuration	Δp (kg/cm^2)	ΔL (m)	E_{fin} (MW)	p_{fin} (kg/cm^2)	c (%)	Pass
BF, constant (shipped)	8.4	0.07	0.25	1.07	0.6	0
BF, sliding	10.0	0.07	0.18	0.73	3.7	0
TF, sliding	0.8	0.16	2.90	0.04	3.4	0
coordinated, sliding	4.6	0.07	0.09	1.81	3.1	0
MPC, sliding	2.7	0.09	0.29	2.05	3.2	0
offset-free MPC, constant	1.4	0.08	0.13	0.10	0.0	0
offset-free MPC, sliding (sugg.)	1.6	0.09	0.13	0.12	3.0	11
tube MPC, sliding	3.5	0.08	1.49	2.74	3.2	0

120 s under the limit, and the best output under it was 154.66 MW for an instant. The nameplate is the case's honestly infeasible variant. The plan's alternative, a ramp of 10 % of rating per minute, is not infeasible, because it needs a fuel rate about seven times below the 0.007 per second limit, and the offset-free MPC held 32 MW/min at constant pressure within 1.39 kg/cm^2.

4.6.6 The Challenge

The challenge starts lined out at 60 MW and 140 kg/cm^2 in boiler-following and runs 900 s. Its target is the pressure within ± 5 kg/cm^2 of its setpoint and under 145 kg/cm^2 at every instant, the level within ± 0.25 m of its setpoint, the output within ± 2 MW and the pressure within ± 1 kg/cm^2 of their setpoints over the last 120 s, and a credit of at least 2.5 %, all judged on the truth every physics step. The ramp stops at 120 MW because the nameplate is out of reach. Eight configurations appear in Table 4.5. The shipped settings fail on the pressure band, the final pressure and the credit, and every structure except the suggested one misses at least one part. Only the offset-free MPC with sliding pressure passes, and it does so on all eleven seeds tried (the case's and seeds 1 to 10), while every other configuration fails on all eleven. An attempt is not graded once a model parameter or a disturbance slider has been moved.

The pattern in Table 4.5 is the chapter's argument in one place. Sliding pressure alone earns the credit but lets boiler-following stray 10.0 kg/cm^2. Coordinated control holds the band but ends 1.81 kg/cm^2 off its setpoint, still settling under PI action. The nominal MPC ends 2.05 kg/cm^2 off, the offset of case 6, and the tube MPC 2.74 kg/cm^2, inside its tube but with no disturbance model. Turbine-following misses the final output by 2.90 MW. Figure 4.3 draws four of the table's columns against the challenge's targets. Case 7 at 600 s under the tube MPC is shown in Figure 4.4.

4.6.7 Verification

The application's 49 checks pass. Halving the step to 0.05 s with the noise off moves the challenge's largest pressure gap under the suggested settings from 1.699 to 1.704 kg/cm^2, 0.26 %. Over the shipped challenge $V_t \Delta\rho_f$ equals $\int (141\, a_3 - q_s)\, dt$ to 0.016 kg of 9.41×10^4 kg moved, a relative residual of 1.7×10^{-7}. The MPC's linearization agrees with central differences of the balances to 1.4×10^{-11}. For the tube's bound, the worst sign sequence of the disturbance reaches h_p exactly (2.811 against 2.811 kg/cm^2) and 200 random sequences reach at most 0.897 kg/cm^2, and an independent bound computed by integrating the error model rather than taking its matrix exponential gives 2.2357 against the simulator's 2.2361 kg/cm^2 at case 7's end. In a desktop browser at 1366 by 768 and on a 390 by 844 phone viewport, each 900 s case runs in 7.5 s of wall time at 120 times real time, and the slowest MPC solve measured was 4.8 ms, a wall-clock figure that varies between runs.

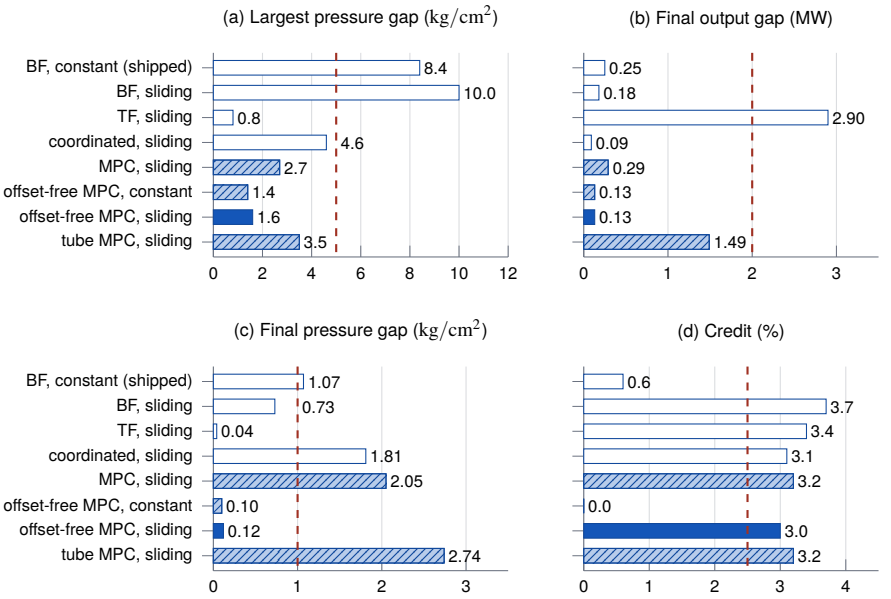


Figure 4.3 The challenge of Table 4.5 against its targets (dashed lines): (a) the largest pressure gap against the $\pm 5\,\mathrm{kg/cm^2}$ band, (b) the final output gap against 2 MW, (c) the final pressure gap against $1\,\mathrm{kg/cm^2}$ and (d) the heat-rate credit against its 2.5 % floor. White bars are the PI structures, hatched bars the predictive controllers, the dark bar the suggested offset-free MPC with sliding pressure. A value whose label would cross its target line is printed beyond the line. Notice that it is the only row inside all four targets, and that every other row fails at least one.

4.7 Technology in Practice

What Measures It

The unit master of a real plant reads the same three measurements as the simulator: the drum or main steam pressure, the electrical output and the drum level. Pressure detectors serve three functions, indication, alarm and control, and some of them also feed protective features [19]. The drum level and its differential-pressure measurement are the subject of Volume 18, Chapter 4. The chapter's instrument packet holds p, E and L with colored noise of 2 s correlation and standard deviations of $0.03\,\mathrm{kg/cm^2}$, 0.1 MW and 3 mm.

> **TECHNOLOGY** **Sensor: The Steam Pressure Transmitter**
>
> A pressure transmitter starts from an elastic element. A bourdon tube, a flattened tube bent into an arc of 270 to 300 degrees, straightens slightly under internal pressure, and a bellows expands against a spring. A strain gauge on a beam moved by the element changes its resistance as its wire stretches, and a bridge circuit turns that change into the pressure signal. Ambient temperature shifts the calibration of the circuitry, humidity can short or corrode it, and the pressure around the detector moves the reading. A failed detector is replaced by a spare element where one is installed, or read at a local mechanical gauge [19]. The chapter's pressure reading carries colored noise of $0.03\,\mathrm{kg/cm^2}$ standard deviation and no calibration shift.

What Moves It

Three final elements move the unit: the fuel supply to the burners, the turbine's main steam control valve and the feedwater. The simplest turbine-governor models assume a constant steam pressure and an unlimited supply of steam from a boiler that follows the turbine. Grid study guidance calls

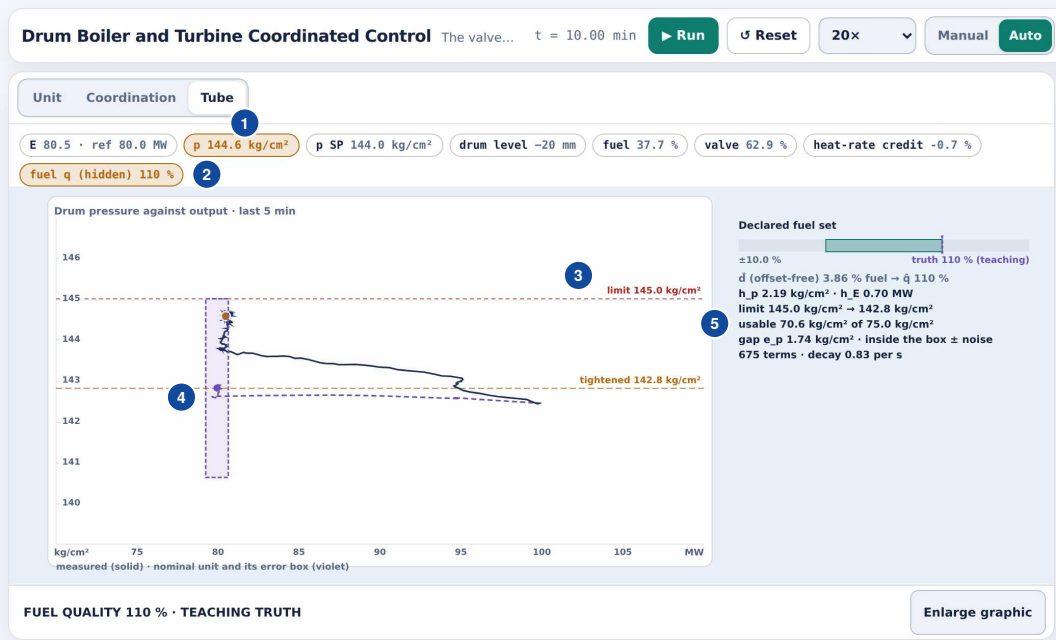


Figure 4.4 Case 7 under the tube MPC at $t = 600\,\mathrm{s}$ on the Tube view, five minutes after the 20 MW load drop and the 10 % richer fuel, cropped to the header and the Tube view. (1) The measured pressure badge, $144.6\,\mathrm{kg/cm^2}$. (2) The hidden fuel quality, shown as teaching truth. (3) The $145.0\,\mathrm{kg/cm^2}$ limit (upper dashed line) and the tightened $142.8\,\mathrm{kg/cm^2}$ (lower dashed line), with the measured trajectory (solid). (4) The nominal unit (dashed) with its error box. (5) The panel, which reports $h_p = 2.19\,\mathrm{kg/cm^2}$, $h_E = 0.70\,\mathrm{MW}$, a usable range of 70.6 of $75\,\mathrm{kg/cm^2}$ and a gap $e_p = 1.74\,\mathrm{kg/cm^2}$ inside the box, from a sum of 675 terms decaying 0.83 per second, with an offset-free estimate $\hat{d} = 3.86\,\%$ of fuel.

both assumptions extreme simplifications: any significant sudden change of the main control valve drops the throttle pressure, the turbine output drops with it, and more fuel must be burned to restore the steam [20]. Under sliding pressure the control valves are left wide open and the output follows the boiler controls [21]. The chapter's three actuators follow their commands through lags and the report's rate limits, as in Equation (4.3).

> **TECHNOLOGY** **Final Element: The Main Steam Control Valve**
>
> The turbine's main steam control valve sets the steam admitted to the turbine. Turbine-governor models for grid studies carry its maximum opening and closing rates as parameters, estimated with the droop and the valve time constant from tests or recorded disturbances, and measured power against valve position on a large unit is not quite linear. In a recorded frequency event under coordinated control the valve opened at once by droop action, the main steam pressure dropped, and the controls began to close the valve to restore it. A separate fast-valving action suddenly closes the intercept valves after a nearby grid fault [20]. The chapter's valve opens at 0.2 and closes at 2 of its range per second.

Where the Controller Runs

In a plant the boiler master and the turbine master run in the distributed control system, where a load demand controller selects the operating mode [21]. One recorded response of a large steam unit to a grid frequency event was sampled by the plant's control system at one sample per second,

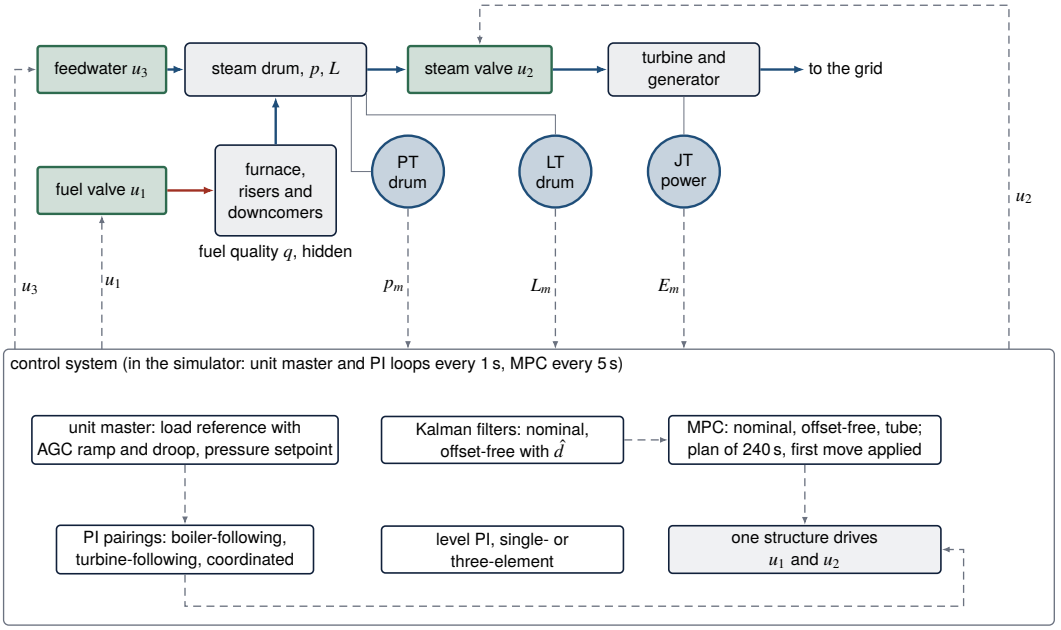


Figure 4.5 The drum unit's loops on plant hardware, drawn from Sections 4.3 and 4.5. Green boxes are the three final elements, blue circles the drum pressure, drum level and power transmitters, dashed arrows signals. In a plant the boiler master and turbine master run in the distributed control system. Notice that one structure at a time drives the fuel and the steam valve, while the level loop always keeps the feedwater.

and field tests on that unit confirmed a droop of 5 %. Some units add a limit-pressure controller: when the pressure strays beyond a preset limit, the governor valve takes over the pressure and closes quickly, and the output first drops sharply [20]. The simulator's unit master executes every 1 s, the same period, and its predictive controller every 5 s above the PI loops. Figure 4.5 draws the loops on plant hardware.

> **IN PRACTICE** **Checking That the Governor Still Answers**
>
> A steam unit's load demand controller offers turbine follow, boiler follow, coordinated turbine follow and coordinated boiler follow modes, and a technician must make sure the coordinated modes include a frequency trim. Grid reliability guidance lists what silences a governor: turbine-follow mode, in which the output follows the boiler slowly, sliding pressure with the control valves left wide open, and a deadband programmed far too large, such as plus or minus one hertz. Under coordinated control a falling steam pressure partly offsets the governor's response [21]. The chapter's governor acts through a 5 % droop with no deadband.

What Is Modernizing It

Units built for baseload are being asked to cycle, and the change is mostly in how they are run. One coal station that starts and stops within a day operates at sliding pressure, from 8 to 9 megapascals, for efficiency and flexibility at part load. Its owner credits about 90 % of the later savings to operating procedures, among them trained boiler ramp rates and monitoring equipment that limits ramp rates and tracks temperature changes in headers, heavy fittings and the main steam line [2]. Grid study guidance shows a turbine-governor model that assumed constant pressure failing to match a unit under coordinated control until a simple boiler and a coordinated pressure loop were added, and it recommends validating such models against on-line disturbance recordings [20]. This chapter's

predictive controller carries the pressure, its limit and the fuel's rate limit in one plan, which is where such a ramp procedure would enter as a constraint.

4.8 Limitations

The plant is a 1987 fit to a peak-load oil-fired unit at two loads, with its poorest fit at high load for valve moves, and its level is a deviation variable that the simulator has to program. The missing superheater, flue-gas and mill dynamics make the fuel faster than on a coal unit, and the heat-rate credit is the model's loss term rather than a throttling calculation. The actuator lags, the fuel-quality multiplier, the noise and every limit are teaching values. A simulated pass is not a safety case, and a real unit's pressure and level limits come from its design, its safety valves and its grid code.

The MPC is linear, re-linearized at every decision, and plans two handles with the feedwater held. The estimators use one constant gain designed at point #4. The tube is a box on a linear error model with a declared ancillary gain, recomputed at the nominal state, not a polytopic reachable set, and its bound leaves out the actuators' rate limits, the nonlinearity away from the nominal unit and the instrument noise. In case 7 at fuel qualities of 0.9, 1.0 and 1.1 the true pressure gap reaches at most $0.97\,h_p$, while the true output gap reaches $1.81\,h_E$, because the ancillary feedback acts on noisy measurements that the bound leaves out. The disturbances arrive as scheduled steps and do not imitate the variability of a real fuel supply.

> **OPEN CHALLENGE** **Pricing the Damage of a Fast Ramp**
>
> Every start and load swing puts the boiler, steam lines and turbine through large thermal and pressure stresses, worsened by creep-fatigue interaction, and the failures can take several years to appear [2, 22]. A cycling cost study found that faster ramps do more damage, in a relation that is not linear and needs more research [22]. Equation (4.7) prices moves with fixed weights that stand for no damage. Progress would be a damage rate known well enough to enter the cost.

4.9 Conclusion

The simulator runs the published third-order model of a 160 MW drum unit as its authors fitted it, with declared actuators and a fuel whose quality no controller can see. A five-point valve step gives 6.6 MW in 40 s by spending $1.5\,\mathrm{kg/cm^2}$ of drum pressure, and the fuel needs 26 s only to stop the fall. On one ramp boiler-following drifts the pressure $3.51\,\mathrm{kg/cm^2}$, turbine-following lags the output 9.67 MW, and coordinated control holds both to 0.81 MW and $1.21\,\mathrm{kg/cm^2}$. A 10 % poorer fuel leaves the nominal MPC $1.3\,\mathrm{kg/cm^2}$ low until the estimator gains a fuel bias, and a 10 % richer fuel at the limit is held only by the tube, at the cost of $4.5\,\mathrm{kg/cm^2}$ of range. The analysis found that point #1 of the published table is not a steady state of the equations. A fuller model would add superheater temperatures, a mill model for coal, a polytopic tube with the rate limits inside it, and a measured fuel analysis with its delay. The unit shows that a fast actuator borrows its effect from an inventory, and that the controller that repays it must know what it cannot measure.

KEY POINTS

- Opening a drum unit's steam valve gives megawatts within seconds by drawing down the drum pressure, and only the fuel can restore it.
- On one ramp boiler-following drifts the pressure $3.51\,\mathrm{kg/cm^2}$, turbine-following lags the output 9.67 MW, and coordinated control holds both to 0.81 MW and $1.21\,\mathrm{kg/cm^2}$.
- A 10 % poorer fuel leaves the nominal MPC $1.3\,\mathrm{kg/cm^2}$ low until the estimator gains a fuel bias.
- A 10 % richer fuel at the limit is held only by the tube MPC, at the cost of $4.5\,\mathrm{kg/cm^2}$ of range.

Where else this applies. The line pack of a gas pipeline is the same kind of borrowed inventory (Volume 10, Chapter 12).

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4.10 Exercises

4.1 Concept check · 2 min

In Scenario 5 the demand steps up 20 MW under boiler-following. With either level loop the drum level first rises 38 mm. With the single-element loop it then falls 107 mm below its setpoint, and with the steam-flow feedforward only 73 mm. Why does the single-element loop do worse?

(a) It is tuned with a higher gain, so it overshoots on the way back to the setpoint

(b) It reads the level through a slower filter, so it acts only after the swell has passed

(c) It reads the swell as surplus water and cuts the feedwater while the drum is losing water

(d) It lacks the feedforward that lowers the swell by raising the feedwater before the valve opens

4.2 Concept check · 1 min

In Scenario 6 the fuel's heating value falls 10 % at 60 s, and the nominal MPC settles 1.25 $\mathrm{kg/cm^2}$ below its pressure setpoint. Which change removes the offset?

(a) Raising the pressure weight, so that the plan values the pressure error more

(b) Lengthening the prediction horizon, so that the plan sees the pressure settle

(c) Removing the fuel's move bound of 0.035, so that the fuel can move faster

(d) Adding a fuel-bias state to the estimator, so that the prediction carries the error

4.3 Concept check · 2 min

In Scenario 7 the tube MPC keeps the drum pressure under its 145 $\mathrm{kg/cm^2}$ limit through the load drop and the richer fuel, but its plan no longer aims at the 144 $\mathrm{kg/cm^2}$ setpoint. Why?

(a) Its nominal unit must stay under the tightened limit, 145 $\mathrm{kg/cm^2}$ less the bound h_p, which lies below 144

(b) Its ancillary feedback is proportional only, so it leaves the same 1.2 $\mathrm{kg/cm^2}$ offset as the nominal MPC

(c) Its slack price of 10^4 pushes every plan away from the limit by a fixed margin of a few $\mathrm{kg/cm^2}$

(d) The richer fuel drives its fuel command to zero, so the plan has no handle left to hold the pressure

4.4 Theory and calculation · 6 min

Use Equation (4.1) at point #4 of the table, $E = 66.65$ MW and $p = 108\ \mathrm{kg/cm^2}$, with the nominal fuel $q = 1$.

(a) Find the steady valve position u_2 and the steam flow q_s. *Checkpoint:* $u_2 = 0.6900$, $q_s = 61.45\ \mathrm{kg/s}$.

(b) Find the steady feedwater u_3 and fuel u_1, and the fuel flow in kg/s at 14 kg/s per unit of fuel position. *Checkpoint:* $u_3 = 0.4358$, $u_1 = 0.3402$, 4.76 kg/s.

(c) Find the steady output gain of the valve at fixed pressure, and the output a five-point valve step would add if the pressure were held. Say why case 1 shows less than this, 6.55 MW, 40 s after the step. *Checkpoint:* 141.6 MW per unit of valve, 7.08 MW.

4.5 Theory and calculation · 7 min

Linearize the pressure balance of Equation (4.1) at point #4 ($p = 108\ \mathrm{kg/cm^2}$, $a_2 = 0.6900$, $u_1 = 0.3402$, $u_3 = 0.4358$).

(a) Find $\partial(\frac{\mathrm{d}p}{\mathrm{d}t})/\partial p$ and the time constant of the pressure. *Checkpoint:* $-0.002\,51\ \mathrm{s^{-1}}$, 399 s.

(b) The valve opens from 69 to 74 % with the fuel and feedwater held. Find the initial rate of pressure fall and, treating the pressure as a first-order lag with the time constant of (a), the fall

after 100 s. Compare with case 1. *Checkpoint:* 0.0175 $\mathrm{kg/cm^2}$ per second, 1.54 $\mathrm{kg/cm^2}$ after 100 s.

(c) How many points of fuel cancel the valve's extra steam at the original pressure? Compare with case 1. *Checkpoint:* 1.94 points.

4.6 Theory and calculation · 6 min

The heat-rate credit of Equation (4.4) compares the steady fuel at the present output and pressure with the same output at 140 $\mathrm{kg/cm^2}$.

(a) Find the steady valve, feedwater and fuel at 66.65 MW and 140 $\mathrm{kg/cm^2}$, and the credit of point #4, where the steady fuel is 0.3402. *Checkpoint:* $u_2 = 0.5708$, $u_3 = 0.4348$, $u_1 = 0.3689$. 7.76 %.

(b) Find the output with the valve fully open at 140 and at 145 $\mathrm{kg/cm^2}$, and the pressure the 160 MW nameplate would need. *Checkpoint:* 148.0 MW, 154.0 MW. 150.04 $\mathrm{kg/cm^2}$.

(c) Which term of the model produces the credit, and what produces it on a real unit?

4.7 App challenge · 9 min

Load Scenario 2, *Boiler-following on an AGC ramp*, at the default seed and change nothing. Run at the default speed 20 until the run pauses at $t = 360$ s (about 18 s), read the first tile, *Ramp error · heat-rate credit*, and the *Pressure range* tile, and export the CSV file. Do the same with Scenario 3, *Turbine-following on the same ramp*, and Scenario 4, *Coordinated control with load feedforward*, as loaded.

(a) From the last row of each file give the largest output gap, `output_err_max_MW`, and the largest pressure gap, `pressure_dev_max_kgcm2`, to 0.02. *Checkpoint:* 2.69 and 3.51. 9.67 and 0.10. 0.81 and 1.21.

(b) In Scenario 4 set Sliding pressure On, press Reset and run to the pause again. Then set Feedforward lead to 0 s, press Reset and run a third time. Give the largest pressure gap of each run. *Checkpoint:* 2.96 and 4.09 $\mathrm{kg/cm^2}$ (the tile shows ± 3.0 and ± 4.1).

(c) Explain the order of the three structures in (a), and why the lead matters under sliding pressure.

4.8 App challenge · 8 min

Load Scenario 6, *MPC and the offset: a poorer fuel*, at the default seed. The fuel quality falls 10 % at $t = 60$ s.

(a) Change nothing. Run at speed 60 until the run pauses at $t = 900$ s (about 15 s), read the *Pressure range* tile and export the CSV file. From `pressure_ref_kgcm2` and `truth_pressure_kgcm2` find the mean gap over the rows from 780 to 900 s, to 0.02, and read `est_fuel_bias_pct` and `truth_fuel_bias_pct` in the row at 600 s. *Checkpoint:* Tile 106.7 to 108.0 $\mathrm{kg/cm^2}$, ± 1.3. Mean gap 1.25 $\mathrm{kg/cm^2}$. $\hat{d} = -3.65$ % against –3.76 %.

(b) Press the reload button, set Control structure to Offset-free MPC before Run, and run to the 900 s pause again. Read the tile and, from the file, find the last row after the fuel drop in which the true pressure is more than 0.2 $\mathrm{kg/cm^2}$ from its setpoint. *Checkpoint:* Tile 107.2 to 108.0 $\mathrm{kg/cm^2}$, ± 0.8. Last row at 149 s, 89 s after the drop.

(c) Both runs solve the same quadratic program. Explain why only the second returns to the setpoint.

4.9 App challenge · 9 min

Load the challenge, *the AGC ramp through a fuel change*, at the default seed. Use speed 60, at which each 900 s run takes about 15 s.

(a) Run it as shipped until it pauses at 900 s and read the *Challenge target* tile. *Checkpoint:* Not met: pressure ± 8.4, final pressure $\pm 1.07\,\mathrm{kg/cm^2}$, credit 0.6 %.

(b) Set Control structure to Coordinated and Sliding pressure On, press Reset and run to the pause again. Which part of the target does it miss? *Checkpoint:* Final pressure, $\pm 1.81\,\mathrm{kg/cm^2}$. Pressure ± 4.6, credit 3.1 %.

(c) Set Control structure to Offset-free MPC, keep sliding pressure, press Reset and run again. Read the tile, and explain why this configuration passes where (a) and (b) fail. *Checkpoint:* Met: pressure ± 1.6, level ± 0.09 m, final output ± 0.13 MW, final pressure $\pm 0.12\,\mathrm{kg/cm^2}$, credit 3.0 %.

4.10 Application area · 3 min

The challenge's frequency dip is 0.1 Hz on a 50 Hz grid, and the governor has a droop of 5 % on the 160 MW rating.

(a) How much extra output does the governor ask for?

(b) Which handle supplies it within seconds, and what does that cost the drum?

(c) Why does the challenge's ramp stop at 120 MW rather than at the nameplate?

4.11 Application area · 4 min

The simulator's pressure limit of $145\,\mathrm{kg/cm^2}$ is a teaching value, and the nominal MPC treats it as a soft constraint.

(a) Where does a real drum's pressure limit come from?

(b) In Scenario 7 the nominal MPC reaches $145.35\,\mathrm{kg/cm^2}$ and stays over the limit for 558 s. What role should such a soft constraint play on a real unit?

(c) The report gives pressures in $\mathrm{kg/cm^2}$ without saying absolute or gauge. Does the reading matter for the model?

4.12 Review the agent · 5 min

An AI assistant reviews Scenario 6 and writes: *"The nominal MPC's offset is a tuning problem. Raise the Pressure weight from 1 to 10 and the plan will drive the pressure error to zero, with no need for a disturbance model."* Find the flaw in the claim and say how you would check it in the app.