INTERACTIVE CONTROL ENGINEERING
Principles and Applications

Volume 17 Control of Energy Conversion and Storage

CHAPTER 2

Gas Engine Cogeneration Where Power Settles in Seconds and Heat in Minutes

Pages 23–48

Edited by John D. Hedengren

How to cite this chapter. "Gas Engine Cogeneration Where Power Settles in Seconds and Heat in Minutes," in *Control of Energy Conversion and Storage*, John D. Hedengren, Ed., vol. 17 of *Interactive Control Engineering: Principles and Applications*. Advanced Process Solutions, LLC, 2026, ch. 2, pp. 23–48.

The page numbers in this file are those of the printed volume.

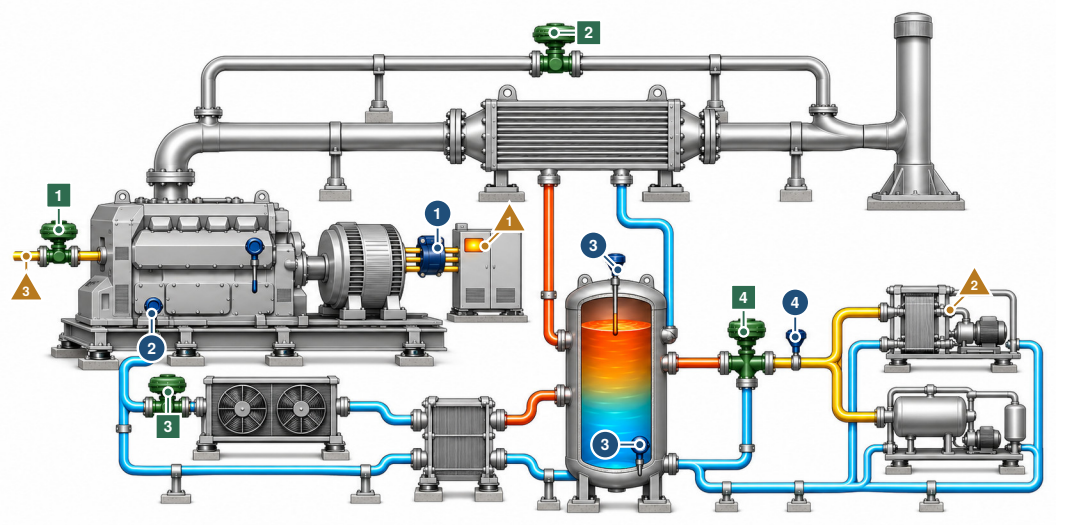
The app for this chapter
https://apmonitor.com/apps/gas-engine-chp/

The volume online: contents, other chapters and citation records
https://apmonitor.com/apps/books/v17-energy/#gas-engine-chp

Copyright © 2026 Advanced Process Solutions, LLC. All rights reserved. Produced by Advanced Process Solutions, LLC.

CHAPTER 2

Gas Engine Cogeneration Where Power Settles in Seconds and Heat in Minutes



The controller moves 1 fuel valve of the engine 2 exhaust bypass around the heat exchanger 3 valve to the cooling radiator 4 mixing valve for the hot-water supply

The controller reads 1 electric power of the generator 2 cooling water leaving the engine 3 buffer tank, top and bottom 4 hot-water supply temperature

What disturbs it 1 electric load of the site 2 heat demand of the customer 3 energy content of the gas

Notice that the fuel valve changes the generator's power within seconds, while its heat must first warm the engine, the exchangers and the buffer tank. One of the plant's three engines is drawn. Illustration, not to scale.

IN PLAIN TERMS **One Fuel Valve, Two Clocks**

The main idea. A gas engine makes electricity, and its hot cooling water and exhaust heat water for a building and a chiller. More fuel raises the power in seconds, but the heat takes minutes, because the engine must warm up first.

The challenge. A tank of hot water soaks up the difference, so a slow cooling loop can look fine for minutes. When the tank is full and the engines run hot, a safety limit cuts their power, and a backup battery must fill the gap.

Why it matters. A plant that cannot store or shed its heat loses power when it needs it most.

THREE WAYS TO READ THIS CHAPTER

Explore	11 min	The first page, the fact box of the Introduction, the history box of Section 2.2, the try-it box of Section 2.5, the try-it and fact boxes of Section 2.5.5, and the key points
Study	50 min	The whole chapter with its pause points and the twelve exercises
Practice	20 min	The first page, Section 2.5, Section 2.6, Section 2.7 and its open challenges

The control question One fuel valve per engine sets both the electricity and the recovered heat, but the power settles in seconds and the heat in minutes. Which control layer of a three-engine plant at a data center holds which balance, and when does a shortfall stop being a tuning problem and become a lack of capacity?

Learning objectives

- Explain from the jacket and exchanger heat capacities why a fuel step moves a module's power long before its recovered heat.
- Compute the Willans-line efficiency, the buffer's stored energy and the UPS reserve from the plant parameters.
- Compare feedback with metered-load feedforward, and a long with a short anti-windup tracking time, on matched runs.
- Tell an overtemperature override or a capacity limit from a badly tuned loop by reading the allowed power, the jackets and the UPS.
- Tune the jacket and supply loops so the plant passes the islanded challenge.

Prerequisites Sections 1.4.5 (heat and power from one fuel), 1.4.4 (storage as an inventory), 1.6.2 (velocity-form PID and anti-windup) and 1.6.4 (scenarios and data). Section 1.6.3 is needed only for the predictive supervisor.

The app https://apmonitor.com/apps/gas-engine-chp/

See also Volume 4, Chapter 2 and Volume 4, Chapter 3 for protective overrides and limiters on one actuator, and Volume 4, Chapter 9 for a trigeneration plant at a data center. Volume 3, Chapter 6 for feedforward from a measured disturbance and Volume 3, Chapter 4 for limits that act on a fuel command.

2.1 Introduction

Reciprocating engines are one of the five prime-mover families of combined heat and power (CHP) that a catalog prepared for the U.S. Environmental Protection Agency describes. The catalog counts more than 2,000 active engine CHP installations in the United States with nearly 2.3 GW of capacity, many of the larger ones built from several units, and puts the heat in an engine's exhaust and cooling systems at 60 to 70 % of its fuel energy [1]. Recovered as hot water that heat can drive a single-stage absorption chiller, and the U.S. Department of Energy lists data centers among the sites with the steady year-round cooling load that such a chiller suits [2]. In the simulated plant three 2 MW modules serve a 2.4 MW data hall. Opening one module's fuel valve from 51.7 to 61.5 % moves its electrical output from 0.985 to 1.213 MW, 63 percent of the way in 2.3 s, while its recovered heat rises from 1.08 to 1.23 MW and needs 68 s for the same share, and its jacket is still warming fifteen minutes later.

> **+ DID YOU KNOW? A Fast-Growing Electric Load**
>
> Data centers in the United States used an estimated 192 TWh of electricity in 2024, 4.7 % of the country's total. The reference case of the same study puts their use in 2030 at 649 TWh, or 11.8 % of the forecast national total [3].

The simulator is built to correct one belief, that a cogeneration plant has recovered once its electrical output has. When one of three modules trips on an island, the UPS carries the lost 1.0 MW for 12.5 s and the other two modules take the load, yet the hot-water buffer goes on losing heat for the next fourteen minutes, from 45 to 34 % of its charge. The same plant shows a second, more expensive version of the belief. A slow engine-cooling loop looks adequate while the buffer still has cool water at its bottom, and in the challenge the buffer hides such a loop for eight minutes, after which the jackets pass 100 °C, the overtemperature override takes capacity for 408 s, and the UPS falls from 80 to 52 % of its charge.

The class of problem is general. One actuator sets two products whose responses are separated in time, a store absorbs the difference between them, and a protective limit takes authority when the store

is full. Section 1.4.5 sets out this coupling on the volume's running example. The boiler-turbine unit, in which fuel, steam and feedwater act on power and pressure together, is a standard multivariable problem of power generation [4], which Volume 9, Chapter 4 treats with predictive control. Combined cooling, heating and power extends the same coupling to a third product [5], and Volume 4, Chapter 9 follows it on a gas turbine at a data center. Whether a CHP plant should follow its electric or its thermal load is a known operating question with measured consequences [6], thermal storage changes how such a plant operates [7], and the controls that keep a saturated loop from winding up and that hand authority to a constraint are general tools of process control [8, 9]. In process terms the buffer is a surge volume on an energy inventory, the dump radiators are its overflow, and the override is a high selector on the fuel valve.

However, these pieces are seldom found on one plant. Operating strategies are compared by primary energy, cost and emissions [6], engine cogeneration models are written and calibrated for energy performance [10, 11], and earlier energy benchmarks pose dispatch as an optimization [12]. A student who wants to watch a cooling loop take engine capacity away needs a plant whose loops, limits and stores are settings with consequences in megawatts, kelvin and kilowatt-hours of reserve. This chapter establishes what each control layer of a three-engine CHP plant at a data center buys, and where control ends and capacity begins, on a simulator that runs in a browser.

Every method used is an established one: the Willans line, the effectiveness exchangers, the velocity-form PID with back-calculation, the high selector and hysteresis staging. The results are a set of matched comparisons measured on one plant at one seed, and one of their findings is that the reserve a slow cooling loop consumes depends on the buffer volume and the jacket heat capacity as much as on the loop. The plant has 33 physical states whose 38 ledgers close the first law to 5×10^{-16} of the fuel, a UPS that cannot pass its floor inside the integrator's stages, and controllers that read only a declared packet of meter readings. Section 2.2 traces the domain. Section 2.3 gives the plant equation by equation, and Section 2.4 the control layers, with the predictive supervisor in Section 2.4.4. Section 2.5 reports the measurements on the eleven cases, from a manual fuel step to the challenge: the predictive supervisor against the PI authorities, three matched comparisons, a demand beyond the engines' capacity, the remaining cases and the challenge, followed by the checks of the code in Section 2.5.6. Section 2.6 describes the hardware of real plants, Section 2.7 states what the model leaves out, and Section 2.8 draws the results together.

2.2 Recovered Heat, the Grid and the Fuel Valve

The straight line of fuel against output that every averaged engine map still uses carries the name of P. W. Willans, whose economy trials of a non-condensing steam engine were reported in 1888 [13]. For a gas engine the same line gives a fixed fuel flow at zero load and a constant marginal efficiency above it, and the EPA catalog puts the efficiency at half load 8 to 10 % below the full-load value [1]. Mean-value engine models of the kind used for engine control add the air path and the torque response as lumped lags [14].

> ⧖ HISTORY **Utilities Must Buy From Cogenerators (1978)**
>
> The Public Utility Regulatory Policies Act became law in November 1978. Its section on cogeneration and small power production told the federal regulator to write rules requiring electric utilities to sell electricity to qualifying cogeneration facilities and to buy electricity from them [15, 16]. The act defined a cogeneration facility as one that produces electricity together with steam or another useful form of energy, such as heat, used for industrial, commercial, heating or cooling purposes [15]. Its efficiency standard counts only half of a plant's useful heat, because electricity is the more valuable product [1]. A cogenerator running in parallel with the grid could now sell a surplus of electricity and buy a shortfall, so the grid could close its electrical balance while the plant chose which load to follow.

Heat recovery from engines settled into a standard arrangement. The jacket coolant carries up to 30 % of the fuel energy and can make 190 to 230 °F hot water, the most common recovery circuit is a closed loop with an excess heat exchanger that sends surplus heat to a cooling tower or a radiator, and most exhaust heat-recovery units are designed for a 250 to 350 °F outlet so that the exhaust does not condense in its piping [1]. Reviews of cogeneration technology place the engine beside microturbines, Stirling engines and fuel cells as a prime mover for buildings [17], and dynamic models of engine cogeneration have been written for residential plants and checked against measured transient and steady operation [10, 11]. Larger plants are often built from several engines, which the catalog notes raises a plant's capacity and availability [1], and which makes load sharing and staging part of the control problem.

Running in parallel with the utility made the control problem what it is now, as the history box earlier in this section tells. A grid-connected plant can follow either load and let the grid close the electrical balance. Over several climates, plants run following the thermal load reduced primary energy use in every city evaluated, while CHP run following the electric load always increased it [6]. Thermal storage loosens the tie between the two products and changes how a CHP unit operates and what it emits [7]. Absorption cooling adds a third product, and single-stage machines driven by 200 to 240 °F hot water are often paired with engine CHP [2, 5].

The control tools themselves came from process practice. Integrator windup against a saturated actuator and the schemes that avoid it were unified in 1989 [8], selectors and overrides that hand an actuator to a constraint are treated together with windup in the constrained-control literature [9], and measured-disturbance feedforward is standard textbook material [18]. The plant simulated here combines these at a data center, where the UPS that already protects the critical load becomes the electrical store that bridges an engine trip or a start delay.

2.3 Three Engine Modules, a Buffer and a Data Hall

The site in Figure 2.1 is an invented teaching design taken from no particular installation. Three identical lean-burn gas-engine generator modules of 2.0 MW gross each feed one site bus. Each module has its own heat recovery. Recovery water drawn from the bottom of the buffer passes the module's jacket-water plate exchanger (JKT) and then its exhaust exchanger (EXH), and returns to the top of the buffer. Jacket heat that the plate exchanger does not take goes to the module's dump radiator, and an exhaust diverter can send gas around the exchanger to the stack. A three-way mixing valve blends tank water with return water into a distribution loop that passes a single-effect absorption chiller and then the thermal customer. The site is a data hall with electric chillers, a cooling-water loop with a tower, and auxiliary loads, connected either to the grid or, islanded, to a 1.5 MW, 0.25 MWh UPS.

Table 2.1 sorts the variables into controlled, manipulated and disturbance variables and states. Per module, seven states are integrated, the fuel power P_f, the shaft power P_m, the jacket node T_j, the exhaust-exchanger metal T_x, the dump valve d, the diverter b and the recovery flow $\dot{m}_r$. The site adds four buffer nodes, the distribution return node T_u, the mixing valve x, the IT node, the chilled-water node, the electric chiller duty, the absorption capacity, the cooling-water node and the UPS energy,

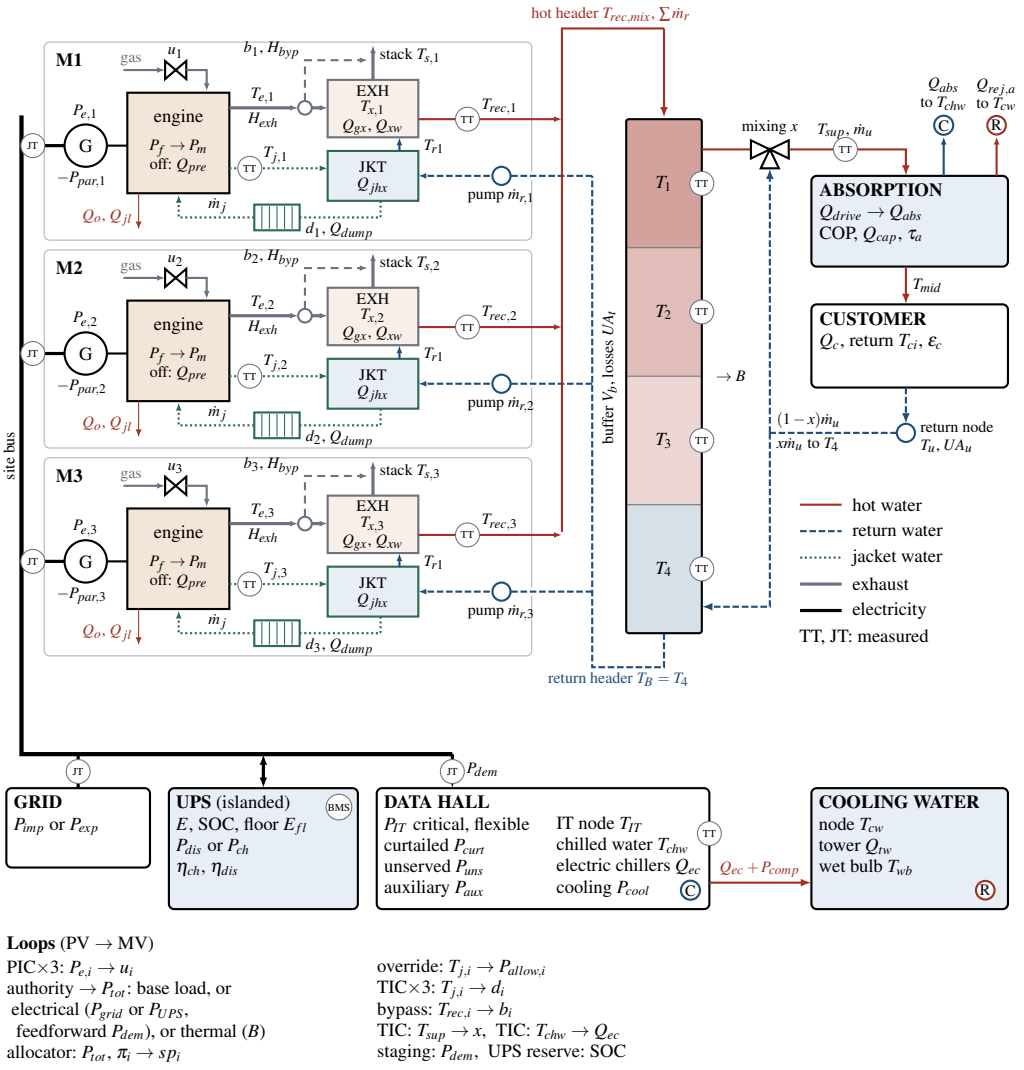


Figure 2.1 The simulated plant as drawn on the application's Plant view. Each module i turns fuel $P_{f,i}$ through valve u_i into shaft power $P_{m,i}$ and electrical output $P_{e,i}$, jacket heat that leaves at $T_{j,i}$ through the plate exchanger (JKT, Q_{jhx}) and the dump radiator (d_i, Q_{dump}), and exhaust at $T_{e,i}$ that passes the exchanger metal $T_{x,i}$ or the bypass b_i to the stack. Recovery water at $\dot{m}_{r,i}$ leaves the buffer bottom at T_B, reaches T_{r1} and $T_{rec,i}$, and returns to the buffer top. The mixing valve x sets the supply T_{sup} to the absorption chiller and the customer, whose return node T_u feeds the valve and the buffer bottom. The grid, the UPS and the data hall hang on the site bus below the modules. Circles C and R carry the absorption cooling to the hall's chilled water and its rejection to the cooling water. Hot water is drawn solid, return water dashed, jacket water dotted, exhaust thick gray and electricity thick black. TT and JT mark the measured temperatures and powers. There is no rotor state. Process model only, not a piping diagram, not to scale.

33 physical states in all, and 38 ledger states integrate every boundary flux so that each balance can be checked independently. Inside the model the units are seconds, watts, joules and kelvin, and the interface shows MW, MWh and °C.

Table 2.1 Controlled, Manipulated and Disturbance Variables and States at the Start of Case 3, Grid-Connected Under Electrical Following. Ranges Use the Units of the Start Column

Variable	Role	Start	Range
P_{grid}	CV, grid import	0.200 MW	SP −0.5–1.5
$P_{e,i}$	CV, module power	0.985 MW	0.5–2.0
T_{sup}	CV, supply	90.0 °C	SP 80–95
$T_{j,i}$	CV, jacket outlet	83.1 °C	SP 95, trip 105
B	CV, buffer charge	43 %	SP 10–90
u_i	MV, fuel valve	51.7 %	0–100
x, d_i, b_i	MV, mix, dump, bypass	93.5, 0, 0 %	0–100
P_{tot}	MV of the authority	2.955 MW	module limits
P_{IT}	DV, IT load	2.40 MW	1.0–3.6
Q_{req}	DV, customer demand	3.20 MW	0–4.0
q	DV, gas heating value	100 %	80–105
T_a, T_{wb}	DV, ambient, wet bulb	25, 20 °C	5–45, 5–30
events	DV, scripted events	—	—
P_f, P_m	states, fuel, shaft	2.587, 1.016 MW	—
T_j, T_x	states, jacket, metal	83.1, 96.2 °C	—
$T_1..T_4$	states, buffer	91.5, 91.5, 68.1, 68.1	—
T_{IT}, T_{chw}, T_{cw}	states, hall, cooling	29.7, 15.0, 29.3	—
E	state, UPS energy	80 % of 0.25 MWh	floor 20

2.3.1 One Module: Fuel, Shaft and the Heat Split

The fuel valve sets the fuel power on the lower heating value (LHV) through a first-order lag, and the shaft follows the Willans line through an air-path lag that is slow on a rise and fast on a cut, as shown in Equation (2.1).

$$\begin{aligned} \tau_f \frac{\mathrm{d}P_f}{\mathrm{d}t} &= u\,q\,P_{f,max} - P_f \\ P_m^* &= \eta_m\left(P_f - \varphi_0 P_{f,r}\right) \\ \tau \frac{\mathrm{d}P_m}{\mathrm{d}t} &= P_m^* - P_m, \quad \tau = \begin{cases} \tau_m & P_m^* > P_m \\ \tau_{dn} & \text{otherwise} \end{cases} \\ P_f &= P_m + \kappa_j P_f + \kappa_o P_f + H_{exh} \end{aligned} \tag{2.1}$$

where q is the gas heating value as a fraction of nominal, $P_{f,max} = 1.05 P_{f,r}$, $P_{f,r}$ the rated fuel, η_m the marginal shaft efficiency, κ_j and κ_o the shares of fuel to the high-temperature jacket circuit and to the low-temperature circuit and radiation ($Q_{jg} = \kappa_j P_f$, $Q_o = \kappa_o P_f$), and H_{exh} the exhaust enthalpy above ambient. The exhaust is the residual of the fuel budget, so the balance closes at every instant and a shaft that lags its fuel heats the exhaust instead of losing energy. At rating the module burns 4.762 MW of fuel for 2.062 MW of shaft power, 0.952 MW to the jacket, 0.510 MW to the low-temperature circuit and 1.238 MW of exhaust at 400.9 °C, so the electrical efficiency is 42.0 %. With $\varphi_0 = 0.10$ the line gives $\eta_m = 0.4811$ and, relative to rated efficiency, 76.9, 90.9 and 96.8 % at a quarter, a half and three quarters of rated shaft power. The generator gives $P_e = \eta_{gen} P_m$, or P_m / η_{gen} while a module without fuel motors. The rating falls by 0.18 % per kelvin of ambient above 25 °C, the EPA catalog's 1 percent per 10 °F above 77 °F [1].

The engine is a grid-connected constant-speed reduction with no rotor state. Grid-connected, the grid holds the speed and the mechanical balance is the algebraic $P_e = \eta_{gen} P_m$. Islanded, the UPS-backed bus of Section 2.3.5 holds the voltage and takes the instantaneous imbalance, so the engines are power sources at constant speed and no swing equation, inertia or droop appears. One consequence is that at a trip the fuel burned during its 0.1 s lag heats the exhaust instead of a rotor, 0.174 MJ of exhaust enthalpy in the first second after module 3 trips in case 6.

2.3.2 Jacket, Exhaust Exchanger and Dump Radiator

The jacket node holds the block, the coolant and the high-temperature circuit. The plate exchanger is a counterflow exchanger between the jacket water and the recovery water, the dump radiator acts on the jacket water leaving it, and the exhaust exchanger is a gas-to-metal-to-water chain, as shown in Equation (2.2).

$$\begin{aligned} C_j \frac{\mathrm{d}T_j}{\mathrm{d}t} &= Q_{jg} + Q_{pre} - Q_{jhx} - Q_{dump} \\ &\quad - UA_{jl}(T_j - T_a) \\ Q_{jhx} &= \varepsilon_{cf}(UA_j, C_h, C_r)\, C_{min}(T_j - T_B) \\ Q_{dump} &= d\,\varepsilon_w(G_d, C_h)\, C_h\, (T_{jm} - T_a)^+ \\ C_x \frac{\mathrm{d}T_x}{\mathrm{d}t} &= Q_{gx} - Q_{xw} \\ Q_{gx} &= \min\big(\varepsilon_w(UA_g, C_{gx})(T_g - T_x), \\ &\qquad (T_g - T_{s,min})^+\big)\, C_{gx} \\ Q_{xw} &= \varepsilon_w(UA_w, C_r)\, C_r\, (T_x - T_{r1}) \end{aligned} \tag{2.2}$$

where $C_h = \dot{m}_j c_p$ and $C_r = \dot{m}_r c_p$ are the jacket and recovery heat-capacity flows, $C_{min} = \min(C_h, C_r)$, ε_{cf} the counterflow effectiveness, which becomes $\mathrm{NTU}/(1+\mathrm{NTU})$ for balanced flows, $\varepsilon_w(UA, C) = 1 - \mathrm{e}^{-UA/C}$ the effectiveness of a stream against an isothermal wall [19], $T_{jm} = T_j - Q_{jhx}/C_h$, $T_{r1} = T_B + Q_{jhx}/C_r$, $T_{rec} = T_{r1} + Q_{xw}/C_r$, and $(\cdot)^+ = \max(0, \cdot)$. The cap in Q_{gx} applies only when the exchanger takes heat from the gas. The exhaust flow is $\dot{m}_g = \dot{m}_{g,r}(0.2 + 0.8 P_f / P_{f,r})$ while the engine turns, the gas reaches the exchanger at $T_g = T_a + H_{exh}/(\dot{m}_g c_{p,g})$, and the diverter leaves $C_{gx} = (1-b)\dot{m}_g c_{p,g}$ on the exchanger and sends $H_{byp} = bH_{exh}$ around it, so the stack carries $H_{exh} - Q_{gx}$. A stopped module's preheater, $Q_{pre} = \mathrm{clip}_{[0,\,15\,\mathrm{kW}]}\big(K_{pre}(60\,^\circ\mathrm{C} - T_j)\big)$ with $K_{pre} = 15\,\mathrm{kW/K}$, holds its jacket near 60 °C. At the start of case 3 each module's recovery water rises from 68.1 to 79.0 °C in the plate exchanger, with the jacket at 83.1 °C and 0.500 MW to the water, and from 79.0 to 91.5 °C in the exhaust exchanger, whose metal sits at 96.2 °C while the gas falls from 396.8 to the 120.0 °C minimum and gives 0.579 MW. The jacket heat reaches the water at the lower temperature level and the exhaust lifts it.

2.3.3 Recovery Flow, Buffer, Users and Absorption

Each recovery pump follows its module's measured fuel $\bar{P}_f$ through a 120 s filter on the schedule

$$\dot{m}_r = \dot{m}_{r,max}\,\mathrm{clip}_{[0.15,1]}\big(0.15 + 0.85\bar{P}_f / P_{f,r}\big),$$

reached through a 5 s lag, an equipment schedule rather than a tunable loop. The buffer is four fully mixed nodes of mass M_k, with the recovery flow entering at the top at the mixed recovery temperature, the users' draw $x\dot{m}_u$ leaving at the top and returning to the bottom, and the net flow between nodes carried upwind, as shown in Equation (2.3).

$$\begin{aligned} M_k \frac{\mathrm{d}T_k}{\mathrm{d}t} &= \delta_{k1}\dot{m}_t(T_{rm} - T_1) + \delta_{k4} x\dot{m}_u(T_u - T_4) \\ &\quad + \dot{m}_d^+(T_{k-1} - T_k) + \dot{m}_d^-(T_{k+1} - T_k) \\ &\quad - (UA_t/c_p)(T_k - T_a) \\ T_{sup} &= xT_1 + (1-x)T_u \\ T_{mid} &= T_{sup} - Q_{drive}/C_u \\ Q_c &= \min\big(Q_{req},\ \varepsilon_c C_u (T_{mid} - T_{ci})^+\big) \\ M_u c_p \frac{\mathrm{d}T_u}{\mathrm{d}t} &= C_u\big(T_{mid} - T_u\big) - Q_c - UA_u(T_u - T_a) \end{aligned} \tag{2.3}$$

where $\dot{m}_t = \sum_i \dot{m}_{r,i}$ enters node 1 at the flow-weighted recovery temperature T_{rm}, $\dot{m}_d = \dot{m}_t - x\dot{m}_u$ is the net downward flow with $\dot{m}_d^+ = \max(0, \dot{m}_d)$ acting for $k > 1$ and $\dot{m}_d^- = \max(0, -\dot{m}_d)$ for $k < 4$, δ is the Kronecker delta, $C_u = \dot{m}_u c_p$, and the buffer charge B is the mean over the nodes of $(T_k - 70\,°\mathrm{C})/25\,\mathrm{K}$, clipped to the unit interval. Between 70 and 95 °C the 8 m^3 buffer stores 0.227 MWh, about four minutes of the 3.24 MW recovered at the design point.

The absorption chiller is the capacity-lag reduction with no internal energy storage, in which the cooling and its drive heat are chosen together, as shown in Equation (2.4).

$$\begin{aligned} \tau_a \frac{\mathrm{d}Q_{cap}}{\mathrm{d}t} &= Q_{tgt} - Q_{cap} \\ Q_{abs} &= \min\left(Q_{cap},\ \mathrm{COP}\, C_u (T_{sup} - T_{g,min})^+\right) \\ Q_{drive} &= Q_{abs}/\mathrm{COP} \\ Q_{rej,a} &= Q_{drive} + Q_{abs} + P_{aux,a} \end{aligned} \tag{2.4}$$

where COP is linear in T_{sup} through 0.70 at 87.8 °C and 0.74 at 97.8 °C, the two single-stage hot-water points of the DOE fact sheet [2], and bounded to 0.55–0.76, $T_{g,min} = 70\,°\mathrm{C}$, and the target Q_{tgt} is the chilled-water loop's request held between a 20 % turndown and a capacity map that is linear in T_{sup}, zero at 70 °C and 1.0 MW at 90 °C, capped at 1.15 times that rating, and falls 3 % per kelvin of cooling water above 29.4 °C. Without driving heat there is no cooling, whatever the lag state holds.

2.3.4 Data Hall and Cooling Water

The hall's IT node and the chilled-water and cooling-water loops are Equation (2.5).

$$\begin{aligned} C_{IT} \frac{\mathrm{d}T_{IT}}{\mathrm{d}t} &= P_{IT,del} - UA_{IT}(T_{IT} - T_{chw}) \\ C_{chw} \frac{\mathrm{d}T_{chw}}{\mathrm{d}t} &= UA_{IT}(T_{IT} - T_{chw}) + Q_{aux,IT} \\ &\quad - Q_{abs} - Q_{ec} \\ C_{cw} \frac{\mathrm{d}T_{cw}}{\mathrm{d}t} &= Q_{rej,a} + Q_{ec} + P_{comp} - Q_{tw} \end{aligned} \tag{2.5}$$

where $P_{IT,del}$ is the delivered and not the requested IT power, half of the auxiliary load's heat reaches the chilled water, the electric chillers follow their command through a 30 s lag at a COP of 5.5 that falls 2.5 % per kelvin of cooling water above 29 °C ($P_{comp} = Q_{ec}/\mathrm{COP}_{ec}$), and the tower's duty is $Q_{tw} = fUA_{tw}(T_{cw} - T_{wb})^+$ with a local proportional fan f across 28–30 °C. The cooling electricity P_{cool} is the compressor power plus pumps, tower fans and the absorption chiller's 20 kW of auxiliaries. At the start of case 3 the electric chillers carry 2.46 MW at a COP of 5.47 with the IT node at 29.7 °C, and T_{IT} is an effective equipment node, not a processor or rack-inlet temperature.

2.3.5 The Site Bus and the UPS Boundary Rule

Every electrical term is nonnegative and the balance is evaluated term by term at every step, as shown in Equation (2.6).

$$\begin{aligned} &P_{gen} + P_{imp} + P_{dis} + P_{uns} \\ &\quad = P_{IT} - P_{curt} + P_{cool} + P_{aux} + P_{par} + P_{ch} + P_{exp} \\ &\frac{\mathrm{d}E}{\mathrm{d}t} = \eta_{ch} P_{ch} - P_{dis}/\eta_{dis} \\ &P_{dis} \le \min\left(P_{dis,max},\ \frac{(E - E_{fl})\eta_{dis}}{\Delta t}\right) \end{aligned} \tag{2.6}$$

where P_{gen} is net of each module's auxiliaries, 30 kW plus its dump fans, and P_{par} carries the auxiliaries and preheaters of modules that are stopped or tripped. Grid-connected, the grid takes the imbalance after the UPS's own recharge request, and import and export are never both nonzero.

Islanded, the UPS takes it within the step's limits, and a deficit beyond them is unserved, allocated to flexible IT first, then the auxiliary load, the cooling and the critical IT last, while a surplus beyond the UPS's charge acceptance is refused and its shaft power returns to the exhaust. The step's discharge and charge limits are fixed from the stored energy at the start of the step and held through the integrator's stages. Because the stage weights of the fourth-order Runge-Kutta method are nonnegative and sum to one, the stored energy lands on its floor at most and never past it, and nothing is clipped after integration. A constant 1 MW from 80 % empties the UPS at $0.25 \times 0.60 \times 0.95 = 0.1425$ MWh, 513 s, matched by the model within 3.2×10^{-10} s. Power and energy are separate limits, so at the 1.5 MW rating the same reserve lasts 342 s and a larger deficit goes partly unserved at once.

2.3.6 Events, Instruments and Numerics

Every discrete event happens once, at a step boundary after integration, with a mark on the trends. A module trips when its jacket reaches 105 °C or when it motors below −3 % of rating for 2 s. A trip opens the breaker, removes the shaft at once and the fuel with a 0.1 s lag, and leaves the pumps running, so the heat retained in the jacket and the metal keeps reaching the water. A stopped module started by the staging supervisor or the operator burns idle fuel and closes its breaker 90 s later, and a tripped one may be reset once its jacket is below 90 °C.

The controllers read only a measurement packet. Each signal passes a first-order transmitter lag and then noise, so the noise setting is the noise a trend shows, and every scan draws the same number of random numbers whatever the settings. The module power transducers lag 0.1 s with 2 kW of noise, the jacket and supply RTDs 3 s and 2 s with 0.05 K, the recovery-outlet RTDs 3 s, the four tank sensors 5 s, the grid meter 0.2 s with 3 kW, the UPS power 0.1 s, the chilled water 5 s and the absorption heat meter 10 s. The site demand meter reports the average of each whole second at its end, so a load step reaches the feedforward 1 to 2 s late, the battery management system reports the charge once a second, and the fuel meters read volume at the nominal heating value, so they cannot see a change of gas.

Each case starts at a steady state of its own settings, solved for the data hall, the chillers and the tower by bisection, for each module from the Willans line, and for the recovery chain and the buffer by fixed-point iteration, with the buffer's starting charge as a parameter. The framework's fourth-order Runge-Kutta integration (Section 1.6.1) advances the states every 0.01 s, the controllers scan every 0.05 s, and the historian logs every 0.5 s. Parameters are listed in Table 2.2 with the class of their provenance, and the remaining symbols in Table 2.3.

2.3.7 Assumptions

The engine is an averaged map, a Willans line with fixed heat shares, so knock, emissions, gas composition beyond the heating value, a fully cold start and wear are absent. The value $\varphi_0 = 0.10$ reproduces the catalog's statement of 8 to 10 % less efficiency at half load as a 9.1 % loss [1]. The jacket and the exchanger metal are one node each and the buffer four nodes, so a sharp thermocline is smeared and warm water reaches the buffer bottom a little early. Because the jacket node is the engine outlet, a restricted jacket-water flow widens the rise across the engine rather than heating the outlet, and the hot spots that make low coolant flow dangerous are outside the model. The absorption chiller has no solution chemistry, crystallization or internal heat inventory, and the tower has no water balance, so no water-use claim is made. The island is a power interface that assumes a working voltage source, with no frequency, synchronization or protection coordination. The contracts are scored, not enforced, in base load and electrical following. Every size and threshold is a synthetic teaching value, and real limits come from the equipment manufacturer's data and the applicable codes.

2.4 The Control Layers as Implemented

One framework scan of $\Delta t_c = 0.05$ s runs the instruments, the module power loops, the authority, the override and the allocator. Integer counters inside it run the hot-water, jacket and bypass loops every

Table 2.2 Model Parameters. Class Gives the Provenance (L Literature-Based, F Fitted, T Synthetic Teaching Value) and Whether the Parameters Panel Shows (V) or Hides (H) the Value

Symbol	Meaning	Value	Unit	Class
Engine modules				
P_r	module gross rating	2.0	MW	T, H
η_e, η_{gen}	electrical (LHV), generator	42.0, 97	%	T, V
φ_0	zero-load fuel, share of rated	0.10	—	F, V
κ_j, κ_o	fuel to jacket, to LT circuit	0.20, 0.107	—	T, V
$\dot{m}_{g,r}$	exhaust flow at rating	3.05	kg/s	F, V
$c_{p,g}$	exhaust specific heat	1080	J/(kg K)	T, H
τ_f, τ_m, τ_{dn}	valve, air path, fuel cut	0.3, 2.0, 0.1	s	T, V/H
r, P_{min}	load ramp, minimum load	40, 0.5	kW/s, MW	T, V
P_{par0}, P_{fan}	auxiliaries, dump fans	30, 20	kW	T, V/H
t_{start}	warm start to breaker	90	s	T, V
—	derate above 25 °C	0.18	%/K	L
Heat recovery and protection				
C_j, C_x	jacket node, exchanger metal	8, 2	MJ/K	T, V
$\dot{m}_j$, UA_j	jacket flow, plate exchanger	20, 80	kg/s, kW/K	T, V
G_d, UA_{jl}	dump radiator, surface loss	18, 0.3	kW/K	T, V/H
UA_g, UA_w	exhaust exchanger, gas, water	6.25, 60	kW/K	T, V/H
$T_{s,min}$, $\dot{m}_{r,max}$	minimum stack, recovery flow	120, 18	°C, kg/s	L/T, V
T_{warn}, T_{ov}, T_{trip}	jacket warn, override, trip	98, 100, 105	°C	T, V
Buffer, users and absorption				
V_b, ρ	buffer volume, density	8, 975	m^3, kg/m^3	T, V/H
UA_t	standing loss per node	25	W/K	T, H
$\dot{m}_u$, M_u	distribution flow, holdup	35, 3000	kg/s, kg	T, V/H
T_{ci}, ε_c	customer return, effectiveness	55, 0.8	°C, —	T, V/H
COP	absorption at 87.8, 97.8 °C	0.70, 0.74	—	L
$Q_{abs,r}$, τ_a	absorption rating, lag	1.0, 180	MW, s	T, V
$P_{aux,a}$	absorption auxiliaries	20	kW	T
Data hall and cooling				
C_{IT}, UA_{IT}	IT node, transfer	60, 0.163	MJ/K, MW/K	T, H
C_{chw}, C_{cw}	chilled, cooling water	210, 126	MJ/K	T, H
$Q_{ec,max}$, COP_{ec}	electric chillers	4.0, 5.5	MW, —	T, V
UA_{tw}, P_{aux}	tower, site auxiliaries	0.5, 0.12	MW/K, MW	T, V
UPS and grid				
$P_{dis,max}$, $P_{ch,max}$	UPS discharge, charge	1.5, 0.75	MW	T, V/H
E_{cap}, η	UPS energy, efficiency	0.25, 95	MWh, %	T, V
E_{fl}, E_{ceil}	UPS floor, ceiling	20, 95	%	T, V/H
$P_{imp,max}$, $P_{exp,max}$	import, export contract	1.5, 0.5	MW	T, V

Table 2.3 Notation for the Flows, Temperatures and Bus Terms

Symbol	Meaning	Symbol	Meaning
Q_{jg}, Q_o	fuel heat to jacket, LT circuit	H_{exh}, H_{byp}	exhaust enthalpy, bypassed
Q_{jhx}	jacket heat to recovery water	Q_{dump}, Q_{jl}	dump radiator, surface loss
Q_{gx}, Q_{xw}	gas to metal, metal to water	Q_{pre}	preheater, stopped module
T_g, T_e	exhaust gas, reported value	T_{jm}	jacket water after JKT
T_B, T_{r1}	tank bottom, between exchangers	T_{rec}	recovery water outlet
C_h, C_r, C_u	heat-capacity flows	ε_{cf}, ε_w	exchanger effectiveness
T_k, M_k	buffer node, its mass	T_u	return node
T_{mid}, Q_c	customer inlet, heat	Q_{req}	customer demand
Q_{cap}, Q_{tgt}	absorption capacity, target	Q_{abs}, Q_{drive}	cooling, drive heat
$Q_{rej,a}$	absorption rejection	$T_{g,min}$	lowest generator outlet
$P_{IT,del}$, $Q_{aux,IT}$	delivered IT, auxiliary heat	Q_{ec}, P_{comp}	electric cooling, power
Q_{tw}, f	tower duty, fan	P_{gen}	net generation
P_{imp}, P_{exp}	grid import, export	P_{dis}, P_{ch}	UPS discharge, charge
P_{uns}, P_{curt}	unserved, curtailed	P_{cool}, P_{par}	cooling, stopped modules
P_{dem}	site demand meter	P_{tot}, sp_i	total command, setpoints
π_i, P_{allow}	participation, override cap	P_{rech}	UPS recharge request

0.5 s, thermal following, the chilled water and the UPS reserve every 1 s, and staging every 5 s, each

loop handed the time that actually passed since its own last execution. Every counter, filter, sequencer and PID state is created again on a reset. Table 2.4 lists the loops.

2.4.1 One PID for Every Loop

All of the loops use the framework's velocity-form PID of Section 1.6.2, Equations (1.10) to (1.13), with the action $a = \pm 1$ of Table 2.4, a bias u_b and the back-calculation tracking time T_t, which defaults to τ_I. No loop here uses derivative action or an output slew. In Manual, and for any loop that does not hold authority, `track()` solves the output equation for the integral so that the output equals the applied value, which makes every transfer bumpless, and no PID receives both an update and a track in one scan.

2.4.2 Module Power, Authority and Allocation

Each module's power loop moves its fuel valve on the measured terminal power, with the commissioned engine map as its bias, the valve in percent that the Willans line needs at nominal gas, $u_b = 100\left[\varphi_0 P_{f,r} + sp_i/(\eta_{gen}\eta_m)\right]/P_{f,max}$ clipped to 0–120 %, so the PI only trims. Its tracking time is 2 s by default and 200 s as case 2 ships, and its upper limit falls to the valve the map expects for the override's allowed power while that override derates.

One number, the total engine power P_{tot} in MW, comes from the selected authority. Base load holds the site power target. Electrical following holds the grid import at its target, or islanded the UPS power at minus its recharge request, with the bias $u_b = P_{dem} + P_{par} - SP$ when the metered-load feedforward is on and limits equal to the sum of the modules' limits. When the feedforward is switched on or off, its change of bias is taken out of the integral, so the output does not jump. Thermal following holds the buffer charge from the four tank sensors, with its output clipped to what the grid contract allows, $[P_{dem} + P_{par} - P_{imp,max},\ P_{dem} + P_{par} + P_{exp,max}]$ within the modules' limits. The two controllers that do not hold authority track P_{tot} in the same units, and in Manual both track the measured total of the module powers. An island forces electrical following. If islanded with the UPS at its floor or at 98 % of its rating, every running module goes to its limit and both controllers track, because the demand meter then reads only the load that is served.

The allocator divides P_{tot} among the running modules by their participation factors π_i, inside each module's minimum load and its allowed power, and spills what one cannot take to the others in up to four passes. Each setpoint then moves at most $r\Delta t_c = 2\,\mathrm{kW}$ per scan, and a module handing load to another gives it up only as fast as the other picks it up, so a transfer never takes power off the bus.

2.4.3 Override, Heat Loops, Staging and Reserve

The overtemperature override is protection, separate from the tunable regulation and effective in Manual, as shown in Equation (2.7).

$$P_{allow} = P_r - \mathrm{clip}_{[0,1]}\left(\frac{T_{j,m} - T_{ov}}{T_{trip} - 0.5 - T_{ov}}\right)\left(P_r - P_{min}\right) \tag{2.7}$$

where $T_{j,m}$ is the measured jacket temperature, $T_{ov} = 100\,^{\circ}\mathrm{C}$, $T_{trip} = 105\,^{\circ}\mathrm{C}$ and $P_{min} = 0.5\,\mathrm{MW}$, a slope of 0.333 MW/K. The allowed power falls at once and recovers at the load ramp, and the override flag clears only below 99 °C at full rating. Because it acts on the unfiltered RTD, it turns RTD noise into a slightly lower allowed power. A turbofan's fuel valve carries several such limiters at once, and Volume 4, Chapter 3 shows how a selector lets the most restrictive one win.

The jacket loops open their dump radiators to hold 95 °C at the jacket outlet. The exhaust bypass, also protective and automatic in Manual, opens above a 100 °C recovery outlet. The hot-water loop sets the mixing valve to hold the supply at 90 °C. The chilled-water loop sets a total cooling command that the absorption chiller takes first, with the electric chillers given the rest less the metered absorption duty. The UPS reserve loop, a proportional state-of-charge manager of the kind Section 1.4.4 describes, asks for a recharge of 0.05 MW per point below its target, at most 0.3 MW, and islanded the flexible IT may be curtailed below 35 % of charge and released above 50 %.

Table 2.4 Loops, Their Scan, Default Tuning and Direction. Action +1 Is Reverse Acting, −1 Direct

Loop	PV → MV	Scan (s)	K_c	τ_I	Act.
module power (×3)	$P_{e,i} \to u_i$	0.05	20 %/MW	2 s	+1
electrical following	$P_{grid} \to P_{tot}$	0.05	0.3 MW/MW	10 s	−1
thermal following	$B \to P_{tot}$	1	0.05 MW/%	600 s	+1
hot-water supply	$T_{sup} \to x$	0.5	4 %/K	20 s	+1
jacket (×3)	$T_{j,i} \to d_i$	0.5	10 %/K	60 s	−1
exhaust bypass (×3)	$T_{rec,i} \to b_i$	0.5	10 %/K	20 s	−1
chilled water	$T_{chw} \to Q_{cool}$	1	0.8 MW/K	120 s	−1
UPS reserve (P)	SOC → P_{rech}	1	0.05 MW/%	—	—

Curtailment opens the breakers of the whole flexible share, so the command reads no IT request. The staging supervisor runs every 5 s on the site demand meter. It starts a module when the demand exceeds a start share of the committed capacity and stops one when the others would carry it below a stop share, through the framework's stage sequencer with minimum run and off times and 30 s between moves, and its requests become plant events at the next step boundary. The defaults are shares of 85 and 70 % with 600 s of minimum run and 300 s of minimum off time, and case 8 ships 80 and 75 % with no minimum times.

The original loops keep the plant and their commissioned model apart. The plant is everything in Section 2.3. No model is identified from data. The controllers' original internal model is the commissioned Willans line in the power loops' bias, built from the defaults of Table 2.2 and fixed when the application loads, which assumes nominal gas, and the 70 °C to 95 °C scale of the buffer charge.

2.4.4 A Predictive Power and Dump Supervisor

The grid-connected MPC option, set up as Section 1.6.3 describes, uses an independent aggregate model, with state $x = [P_e, \overline{T}_j, \overline{T}_b]^T$ and commands $u = [P_{tot}, d]^T$. Power is in MW and temperatures in degrees Celsius. The first state follows the command with a 2.3 s surrogate lag. The thermal balances are

$$\begin{aligned} C_j \dot{\overline{T}}_j &= \kappa_j P_f - Q_{jhx} - Q_{dump} - Q_{jl}, \\ C_b \dot{\overline{T}}_b &= n(Q_{jhx} + Q_{xw}) - Q_{water} - Q_{bl}, \end{aligned} \tag{2.8}$$

where n is the number of running modules, $C_b = V_b \rho c_p$, and heat rates are in watts. A homogeneous module uses the declared Willans line and nominal exchanger equations to compute fuel P_f, jacket recovery Q_{jhx}, dump Q_{dump}, surface loss Q_{jl} and quasisteady exhaust recovery Q_{xw}. Tank loss is Q_{bl}. The measured supply-return difference times nominal distribution flow and heat capacity gives Q_{water}. The measured bottom-to-mean tank gradient is held, rather than forecasting a thermocline. Exhaust metal, valve and pump lags and module imbalance are omitted. All physical coefficients remain at their declared defaults. No customer schedule, true exchanger state or altered plant coefficient reaches this model.

Measured power and temperatures initialize all states every 10 s. The model is centrally linearized with its affine term, then exactly discretized. Sixty steps and twelve move blocks give a 600 s horizon in the shared quadratic optimizer, following the finite-horizon approach reviewed in [20]. Bounded thermal rate disturbances correct the previous raw one-step residual with gain 0.2 and limits 0.1 K/s for the jacket and 0.05 K/s for the tank. This is a bias correction, following [21], rather than physical parameter identification. The inner governors, allocation, staging, exhaust protection and trips remain. Islanded operation uses the original electrical authority. Rejected plans hold the handover command, mark the historian and return to tracked site and jacket PIs until recovery.

State tracking weights are 20, 0.03 and 0.15 under electrical or base following, and 0.1, 0.03 and 2 under thermal following. Targets are the selected power or import target, jacket target and $70 + 25B_{SP}$ for mean tank temperature. Move weights are 0.5 and 4, and a linear power price of 0.01 is a nominal

Table 2.5 The Eleven Cases and a Measured Outcome of Each

#	Case and events	Outcome as shipped
1	Manual, grid; learner opens a fuel valve ten points	power 63 % in 2.3 s, recovered heat in 68 s
2	Base load 3 → 6 → 3 MW at 60, 180 s, gas 88 %	valve pinned from 79 s at 1.83 MW
3	Electrical following, IT +0.6 MW at 60 s	import IAE 18.8 MW s (60–180 s)
4	Customer 3.2 → 0.8 MW at 60 s	first rejection 399 s, 2.72 MW at 900 s
5	Customer 3.2 → 2.2 MW at 60 s	electrical against thermal following
6	Island, absorption on, module 3 trips at 60 s	UPS 12.5 s, buffer 45 → 34 % by 900 s
7	Module 1 dump valve stuck at 15 %, 60–900 s	override from 255 s, down to 1.19 MW
8	Island, staging on, IT ±0.9 MW every 6 min	six starts in 30 min
9	Island, module 3 out, IT to 3.5 MW over 60–300 s	UPS floor at 951 s, 32.8 kWh unserved
10	Predictive power and dump, customer loss at 60 s	smaller fuel ledger, larger rejection and import
11	Challenge: customer lost at 30, trip at 120, IT +0.3 MW at 240 s	lowest UPS 52.0 %, fails

fuel proxy. Power commands respect available module and grid-contract limits, with module capacity taking priority if infeasible. Dump bounds 0–1 and planned block moves 0.4 MW and 0.15 are hard. Mean tank 70–98 °C and mean jacket 0.5 K below the override threshold are soft, priced at quadratic 100 and linear 10. Individual module temperatures and actual protective moves are not bounded by these aggregate constraints.

The exact power discretization agrees with its closed form within 1.2×10^{-13}, and a two-control optimizer check agrees with direct normal-equation inversion within 6.7×10^{-16}. In the new case the raw ten-second prediction residual RMS is 0.0322 MW, 0.0378 K and 0.0162 K, respectively. These are local residuals, not horizon-wide accuracy guarantees.

2.5 Matched Experiments, a Capacity Limit and the Challenge

The eleven cases appear in Table 2.5, and Section 1.6.4 describes how a case is loaded and scored. The results come from the shipped engine driven by a script at its default seed. The script loads each case through the same path as the case menu, makes any listed change before the first step, so that the engine treats it as an initial condition, and advances the plant at its own physics step without the browser's frame loop. Integrated absolute error (IAE) is taken on the simulator's truth at the physics step over the stated window, actuator travel is the total variation of the logged command over the same window, and recovery is the last instant the error is outside the stated band, after which it stays inside to the end of the run.

2.5.1 A Small Fuel Reduction With Other Costs

Case 10 repeats the customer loss with MPC and the original PI authorities, with the same seed 20261020, measurements and no event preview. At 900 s, MPC uses 1.9328 versus 1.9414 MWh fuel, a 0.45% reduction, but imports 0.06567 versus 0.050 00 MWh electricity and rejects 0.50885 versus 0.294 01 MWh. Closing tank heat above 0 °C is 0.78519 versus 0.892 63 MWh. This is not a net efficiency gain. Figure 2.2 shows the earlier rejection (dashed) that leaves the store colder. Both hold the supply band without a protective trip. Import IAE is 91.69 versus 2.13 MW s, so the economic/thermal compromise also worsens import tracking. Halving the physics step preserves these orderings.

Total power-command travel is 0.538 versus 18.069 MW, but this is partly the ten-second hold rejecting meter noise. With site-balance gain zero, simple metered-load feedforward achieves 0.006 83 MW travel, 2.135 MW s import IAE and 1.941 35 MWh fuel. Six thermal-PI settings and three fixed powers give further counterfactuals. The full measurement set of 33 rows includes the IT case with feedforward on for both controllers. Table 2.6 keeps the unfavorable comparisons. Under thermal following in case 5, MPC uses 1.661 versus 1.491 MWh fuel. In the stuck-valve case its peak jacket is 99.24 versus 102.30 °C, but import rises to 0.1539 from 0.0501 MWh. Islanded challenge runs are identical because MPC stands by, including the original suggested pass and shipped failure.

Table 2.6 Grid-Connected Comparisons at 900 s, PI / MPC

Case	Fuel MWh	Import MWh	Reject MWh	Plans / µs
New	1.941 / 1.933	.050 / .066	.294 / .509	90 / 1532
Following	1.941 / 1.914	.050 / .063	.011 / .187	90 / 638
IT step	2.263 / 2.261	.057 / .059	.000 / .082	90 / 434
Stuck valve	2.464 / 2.258	.050 / .154	.655 / .642	90 / 594

Plans and mean Node solve microseconds refer to MPC. No plan was rejected in these comparisons.

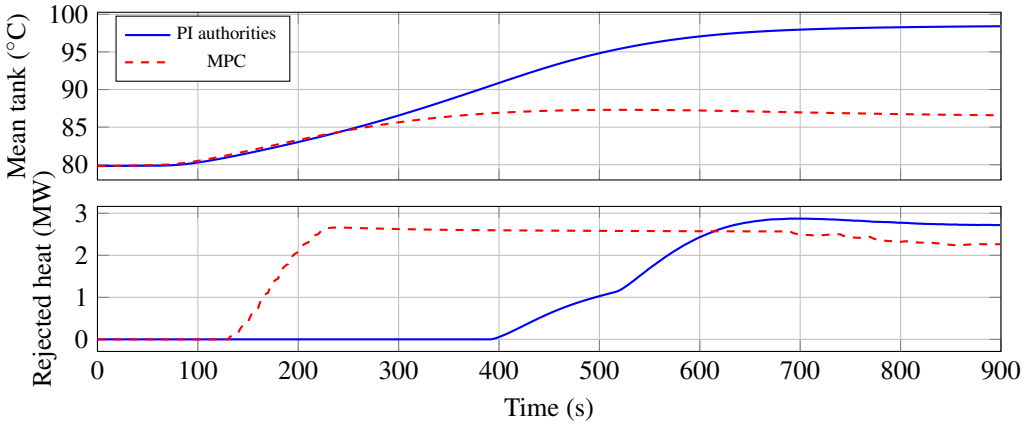


Figure 2.2 Case 10, customer demand reduced at 60 s, under the PI authorities (solid) and the MPC (dashed). The nominal MPC opens rejection earlier, leaving less tank heat. Its small fuel reduction comes with larger electrical import and rejected heat.

Table 2.7 Three Matched Comparisons on the Simulator's Truth. Energies Are Over the 300 s Run, Storage at Its Start and End. Grid-Connected, so No Load Is Unserved or Curtailed and the UPS Holds 80 % Throughout

Comparison, window, band	Setting	IAE (MW s)	Max dev. (MW)	Recovery (s)	Travel	Saturated (s)	Fuel (MWh)	Buffer (%)
A. Case 3, 60–180 s, ±20 kW	feedback only	18.82	0.600	144.4	0.67 MW	0	0.722	43.0 → 48.5
	with feedforward	4.14	0.600	31.4	1.19 MW	0	0.735	43.0 → 49.8
B. Case 2, 60–240 s, ±50 kW	$T_t = 200$ s	30.09	0.772	41.3	81 points	124.5	0.863	43.1 → 61.2
	$T_t = 2$ s	17.97	0.017	4.9	84 points	102.7	0.840	43.1 → 59.8
C. Case 3, 60–180 s, ±20 kW	gas 100 %	4.14	0.600	31.4	1.19 MW	0	0.735	43.0 → 49.8
	gas 88 %	4.40	0.600	39.0	1.18 MW	0	0.735	43.0 → 51.0

A and B compare the settings named, and C runs case 3 with the feedforward on. A and C regulate the true grid import to its 0.2 MW target and B module 1's true power to its setpoint, and recovery is the time to stay inside the band to the end of the run. Every run delivers 0.267 MWh of useful heat. Travel is of P_{tot} in A and C and of module 1's fuel valve in B. In B the maximum deviation is the overshoot above the setpoint after the 180 s drop, and recovery and the band are counted from that drop. Halving the step to 5 ms gives 18.82, 4.14 and 4.40 MW s, and in B overshoots of 0.772 and 0.017 MW with recovery times of 41.3 and 4.9 s.

Across six browser runs at different viewports and themes, sixty plans per run average 1.07–1.33 ms. Planner cost is 0.011–0.013% of one core at real time and 1.07–1.33% at 100-times playback. Measurement and state preparation are outside this timing.

2.5.2 Three Matched Comparisons

Each pair in Table 2.7 shares the initial state, the seed, the measurements, the limits and the disturbance, and differs in one setting. The trajectories are shown in Figure 2.3.

The first comparison is nominal disturbance rejection. In case 3 the IT load rises 0.6 MW at 60 s

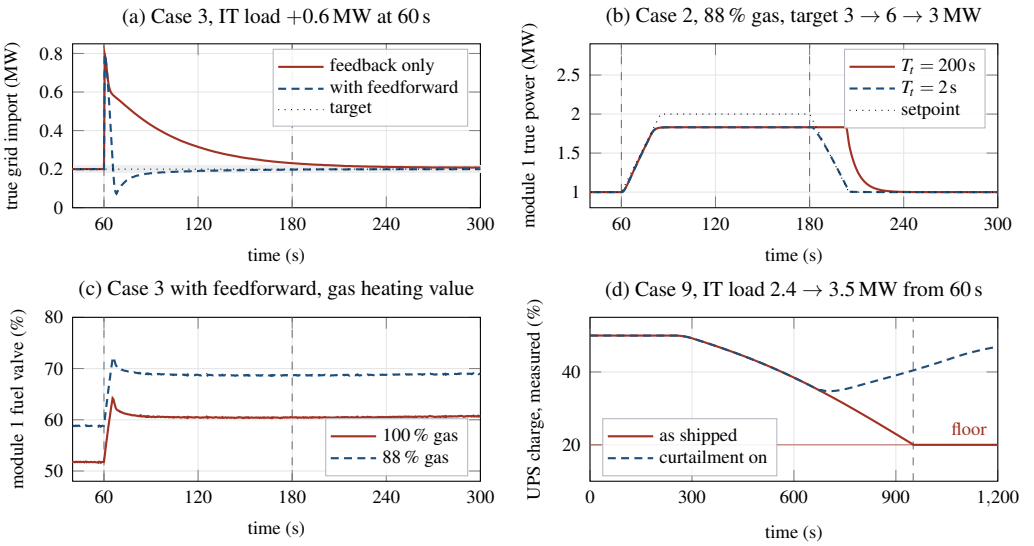


Figure 2.3 The three matched comparisons and the capacity limit, from the exported records. (a) Case 3, true grid import after the 0.6 MW IT step at 60 s with the ±20 kW band shaded, feedback only (solid) and with the metered-load feedforward (dashed). (b) Case 2, module 1's true power on 88 % gas against its ramped setpoint, tracking time 200 s (solid) and 2 s (dashed). (c) Case 3 with the feedforward, module 1's fuel valve at nominal (solid) and 88 % gas (dashed). (d) Case 9, measured UPS charge as shipped (solid) and with curtailment (dashed), the floor reached at 951 s. Dashed verticals mark the events and the IAE windows.

and the full 0.60 MW lands on the grid import in both runs, because nothing measures a load before it arrives. On feedback alone, with $K_c = 0.3$ and $\tau_I = 10$ s, the import stays more than 20 kW off its 0.2 MW target for 144 s. With the demand meter fed forward, the engines take the step once the meter reports it 1 to 2 s later, and the IAE falls from 18.82 to 4.14 MW s, 22 percent of the feedback-only value. Volume 3, Chapter 6 makes the same case for measuring a disturbance before it reaches the loop. The feedforward is not free. Its step and the proportional action both answer the same error, so the true import overshoots to 0.073 MW at 68 s, 0.127 MW below its target, and the total command travels 1.19 against 0.67 MW.

The second comparison is an actuator limit. On gas with 88 % of its heating value, a base-load target of 6.0 MW from 60 s pins module 1's valve at 100 % from 79 s, where the module makes 1.83 MW against a 2.0 MW setpoint. With the shipped tracking time of 200 s the integral holds 140 points of valve when the target falls back at 180 s, the valve stays open 23 s, and the module rides 0.77 MW above its falling setpoint and needs 41 s to come within 50 kW. With 2 s the integral holds 4.8 points, the valve leaves 100 % after 1.8 s, the overshoot is 0.017 MW and the recovery 4.9 s. The shortfall while pinned is 0.174 MW in both runs, because a shorter tracking time adds no capacity. Base load does not enforce the export contract, so the site exports up to 2.34 MW against a contract of 0.5 MW in both runs, which the scene marks.

The third comparison is a model mismatch. The power loops' map and the fuel meters assume nominal gas, so at 88 % gas each loop starts with 7.1 points of valve in its integral that the map does not supply. The site barely notices, with an import IAE of 4.40 against 4.14 MW s and a recovery of 39 against 31 s, because the integral absorbs the mismatch as long as the valve has room, as shown in Figure 2.3c. The same mismatch becomes windup only when the valve saturates, which is the second comparison.

2.5.3 Where Control Stops and Capacity Begins

Case 9 has module 3 out for maintenance, the UPS at 50 %, and the IT load rising from 2.4 to 3.5 MW over four minutes from 60 s. Two modules net 3.94 MW after their auxiliaries, and the UPS's usable energy from 50 % to its floor is $0.25 \times 0.30 \times 0.95 = 0.071$ MWh. Both modules reach their rating at 243 s, the UPS gives up to 0.49 MW and reaches its 20 % floor at 951 s, and 32.8 kWh of flexible IT goes unserved by 1200 s, with none of the critical IT. Two engines at full net capacity throughout would empty the UPS at 955 s, so the shipped settings lose 4 s to their own response. A sweep of the feedforward on and off, site-balance tunings of 0.1 with 100 s, 0.3 with 10 s and 3 with 2 s, and two participation splits reaches the floor between 491 and 951 s in all twelve runs, never later than that bound, with 32.8 to 79.6 kWh unserved, as shown in Figure 2.3d. Changing the gain once both modules are at their rating leaves the floor at 950.90 s exactly, because the loop's output is already pinned. Only less load keeps a reserve. With curtailment, 102 kWh of flexible work is curtailed, nothing goes unserved and the UPS keeps 34.7 %.

Pause. Try Exercise 2.2 before reading on.

2.5.4 The Remaining Cases

Case 1 separates the two clocks within one module. The exhaust part of the recovered heat covers 81 % of its change within a minute, because only the 2 MJ/K of exchanger metal must warm, while the jacket part covers 39 %, because 8 MJ/K of block and coolant must warm first. The buffer goes from 43 to 55 % in fifteen minutes and the grid import from 0.20 MW to an export of 0.03 MW within seconds. In case 4 the customer's cut from 3.2 to 0.8 MW fills the buffer from 43 to 81 % before the first heat is rejected at 399 s, through the exhaust bypasses first and the dump radiators from 519 s, and by 900 s 2.72 MW is rejected, 1.38 MW through the radiators and 1.34 MW around the exchangers, while the engines' 2.955 MW moves by at most 6 kW.

> **TRY IT IN THE APP** **1 · A Fuel Step: Which Arrives First, Power or Heat?**
>
> Load scenario 1 and press Run. After 30 s open module 1's fuel valve by about ten points and watch its power and its recovered heat on the trend. The power covers 63 percent of its change in 2.3 s, and the recovered heat needs 68 s for the same share. The buffer keeps climbing, from 43 to 55 % in fifteen minutes.

Pause. Try Exercise 2.1 before reading on.

Case 5 compares the two authorities after the customer drops to 2.2 MW. Over 1800 s electrical following holds the import at 0.20 MW, burns 3.88 MWh of fuel, imports 0.10 MWh, rejects 0.29 MWh and leaves the buffer at 89 %. Thermal following is held by the 1.50 MW import contract from 481 s, so the buffer stays at 51 to 55 %, above its 45 % target. It burns 2.74 MWh, imports 0.63 MWh and rejects nothing. Both deliver 1.12 MWh of useful heat, at CHP efficiencies on LHV of 65.7 and 73.6 %, but the two runs end with different storage, the buffer gaining 0.146 MWh under electrical following and 0.036 MWh under thermal following, and with 0.53 MWh more electricity from the grid in the second. The pair demonstrates who holds authority. It is not a savings estimate.

In case 6 the UPS takes the whole 1.0 MW at module 3's trip and stops discharging 12.5 s later after 1.9 kWh, and modules 1 and 2 settle at 1.51 MW each. The two recover 2.91 MW at 900 s against the 3.28 MW three recovered, the tripped module's retained heat fades from 0.76 MW at 90 s to 0.16 MW at 300 s, and the absorption chiller keeps drawing 1.4 MW of drive heat, so the buffer falls from 45 to 39 and 34 % at 600 and 900 s while the supply stays within 0.15 K of 90 °C. In case 7 module 1's jacket passes its warning at 151 s and the override threshold at 255 s, the override cuts its allowed power to as little as 1.19 MW and holds the jacket below 102.3 °C, modules 2 and 3 carry 1.35 MW each against module 1's 1.23 MW at 800 s, and the override clears 37 s after the valve is freed. In case 8 the start and stop thresholds of 3.2 MW and 3.0 MW sit 0.2 MW apart on a metered demand that swings 1.85 MW from peak to trough, so the reserve starts six times in 30 min and the

Table 2.8 The Challenge Over 900 s. Critical IT Unserved and Protective Trips Are Zero in Every Row

Configuration	UPS min (%)	Out (s)	Override (s)	T_j peak (°C)	UPS gave (kWh)	Verdict
shipped, 0.5/1200, 1/300	51.97	570	408	102.0	68.9	fails
suggested, 10/60, 4/20	79.19	0	0	96.8	2.2	passes
jacket loop tuned only	79.19	570	0	96.7	2.2	fails
supply loop tuned only	44.40	0	432	102.2	86.9	fails

Settings: jacket K_c in %/K over τ_I in s, then supply K_c over τ_I. Out is the time the supply spent outside ±3 K. T_j peak is the true jacket maximum of modules 1 and 2.

UPS carries up to 0.21 MW through each 90 s start. A 50 % stop share with a 600 s minimum run gives one start, the stop share alone one, and the minimum run alone three.

2.5.5 The Challenge

The challenge runs islanded with the absorption chiller on, three modules at 1.006 MW, the buffer at 67 % and the UPS at 80 %. The customer is lost at 30 s, module 3 trips at 120 s and the IT load rises 0.30 MW at 240 s. Over 900 s the target asks for no critical IT unserved, no protective trip, the supply within ±3 K of 90 °C outside a 90 s allowance after each event, and the UPS never below a 60 % reserve. After the trip and the rise the demand is 3.29 MW, and 3.47 MW even if the electric chillers took all of the absorption cooling, below the two remaining modules' 3.94 MW, so the target is feasible. Table 2.8 lists four configurations, and Figure 2.4 compares the shipped and the suggested runs. Figure 2.5 charts the table.

> ✦ **DID YOU KNOW?** **Tuning One Loop Can Make Things Worse**
>
> From the simulator: in the challenge, tuning only the hot-water supply loop keeps the supply in its band but lets the lowest UPS charge fall to 44.40 %, below the 51.97 % of the shipped tuning, with 432 s of override (Table 2.8). Only the two loops tuned together pass.

As shipped, the jacket loops run at 0.5 %/K with a 1200 s integral time and the supply loop at 1 %/K with 300 s. For eight minutes nothing looks wrong, because the recovery water still comes from cool water at the bottom of the buffer. Once the warm water reaches the bottom, the two remaining engines' jackets pass 100 °C at 492 s, the override takes capacity for 408 s, the UPS makes up 68.9 kWh and falls to 51.97 %, and the slow supply loop leaves the supply up to 5.7 K high for 570 s. The suggested tuning, 10 %/K with 60 s on the jackets and 4 %/K with 20 s on the supply, keeps the jackets at or below 96.8 °C with no override, the UPS at 79.19 % and the supply within 0.63 K. Each loop guards a different part of the target, so either one tuned alone fails the other part. The override's response to RTD noise moves the shipped result. With the RTD noise removed the lowest UPS charge is 52.91 %, at the shipped 0.05 K it is 51.97 % and at three times that 49.62 %, while the suggested run stays at 79.19 % in all three because it never reaches the override. At seeds 1 to 5 the shipped run reaches 51.97 to 52.00 % and fails, and the suggested one reaches 79.19 % and passes. The shipped run at its end is shown in Figure 2.6.

> **TRY IT IN THE APP** **11 · Challenge: A Customer Loss, a Trip and an IT Rise, Islanded**
>
> Load scenario 11 and run it as shipped at 100 times speed. Watch the jackets on Heat recovery. For eight minutes nothing looks wrong, then the jackets pass 100 °C at 492 s and the UPS falls to 51.97 %. Set the jacket loops to 10 %/K and 60 s and the supply loop to 4 %/K and 20 s, then Reset and run. The UPS holds 79.19 %.

Pause. Try Exercise 2.3 before reading on.

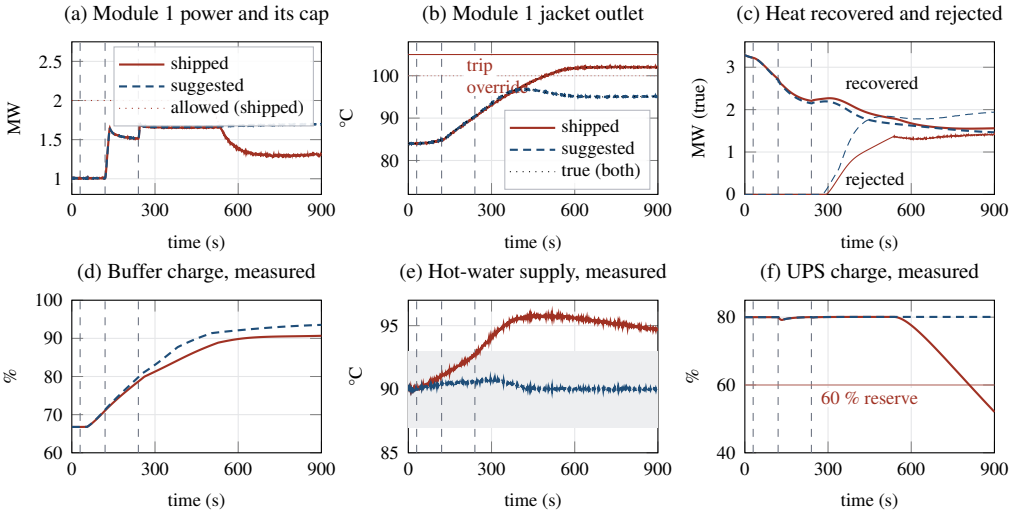


Figure 2.4 The challenge as shipped (solid) and with the suggested tuning (dashed), from the exported records. (a) Module 1's measured power and, dotted, the override's allowed power in the shipped run. (b) Module 1's jacket outlet, measured (solid and dashed) and true (dotted), against the override and trip thresholds. (c) True heat recovered and rejected. (d) Measured buffer charge. (e) Measured supply with the ±3 K band shaded. (f) Measured UPS charge against the 60 % reserve. Gray dashed lines mark the events at 30, 120 and 240 s.

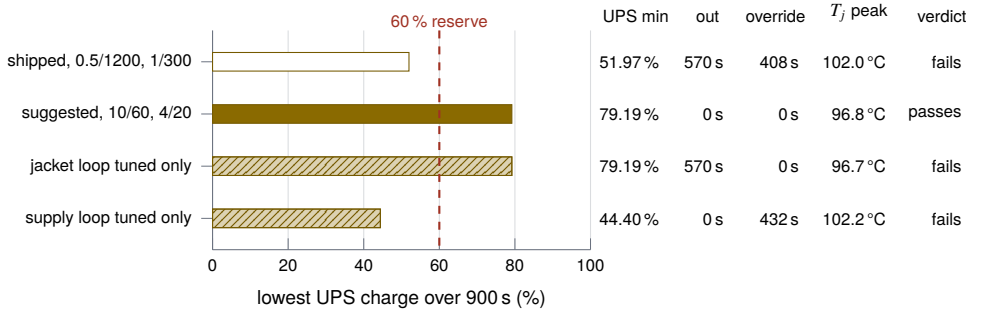


Figure 2.5 The four configurations of Table 2.8 as a chart: the lowest UPS charge over the 900 s (bars and first column), with the time the supply spent outside ±3 K, the time under override, the jacket peak and the verdict in the other columns. Settings are the jacket gain in %/K over its integral time in s, then the supply's. The white bar is the shipped tuning, the solid bar both loops tuned, hatched bars one loop tuned. Notice that tuning only the supply loop leaves less reserve than the shipped tuning, and that only the solid bar both clears the dashed reserve line and keeps the supply in its band.

2.5.6 Verification

These figures verify the code and are not control-performance results. Over a 20-minute base-load run of one module the integrated fuel equals electricity, losses, recovered and rejected heat and the change in stored heat to 5.0×10^{-16} of the fuel, and through case 6's trip with a customer loss the engines' and the hot water's ledgers close to 2.0×10^{-14} of their throughput, each from independent ledger states. The bus balances to 0 W at every one of the challenge's 90,000 steps, with import and export, and charge and discharge, never both nonzero. At case 3's start the recovered heat exceeds the users' heat by 0.25 % of rated fuel input, the 36 kW by which the default demand falls short of

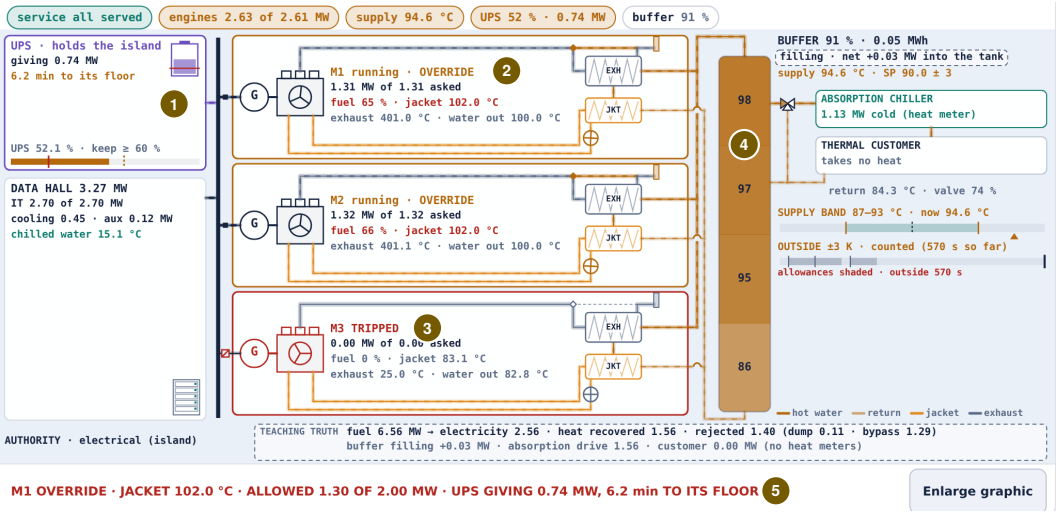


Figure 2.6 The challenge as shipped at $t = 900$ s on the Plant view, cropped to the plant. (1) The UPS stands at 52.1 %, giving 0.74 MW on its meter with 6.1 min to its floor. (2) Modules 1 and 2 run in OVERRIDE at 1.31 MW and 1.32 MW with their jackets at 102.0 °C, and (3) module 3 has tripped. (4) The buffer is 91 % charged with the customer taking no heat and 1.40 MW rejected, 1.29 MW of it through the exhaust bypasses, and the supply reads 94.6 °C against a ±3 K band. (5) The status line names module 1's override and its allowed 1.30 MW.

recovery. Halving the step to 5 ms changes no scored output of any case by more than 0.008 % of its span, a run replays bit for bit after a reset, and playing it at 1 or 100 times real time logs identical rows. A simulated hour costs 2.3 s of computing in a headless engine, and in a browser at the top speed of 100 times real time the challenge takes 9.0 s and the 1800 s staging case 18.0 s. All 72 of the application's checks pass. Agreement with reference data is a separate and narrower claim. The absorption map passes through the DOE fact sheet's two single-stage points exactly [2], and the Willans line reproduces the catalog's half-load statement as a 9.1 % loss [1], while no part of the plant has been compared with measurements of a real one.

2.6 Technology in Practice

The layers of Section 2.4 run on power meters, temperature sensors, fuel valves and water valves. Figure 2.7 draws the loops of module 1 and the site with that hardware in place of the schematic's symbols.

What Measures It

The module powers and the grid import are electrical measurements. Potential transformers step the line voltage down to a safe level, typically 120 V, and current transformers step the line current down, typically to 5 A at full load, for the wattmeter and the protective relays to read [22]. Standard accuracy classes of potential transformers are 0.3, 0.6 and 1.2, an uncertainty of ±0.3, ±0.6 and ±1.2 % of the rated turns ratio. A current transformer must never have its secondary opened while energized, because it may then develop an extremely high voltage [22]. The chapter's module power transducers JT-101 to JT-103 lag 0.1 s with 2 kW of noise, and the grid meter JT-100 lags 0.2 s with 3 kW.

plant controller: JIC-100, JY-100, JIC-101 and TY-111 every 0.05 s, TIC-111 and TIC-120 every 0.5 s. Protective relays trip the breakers apart from it.

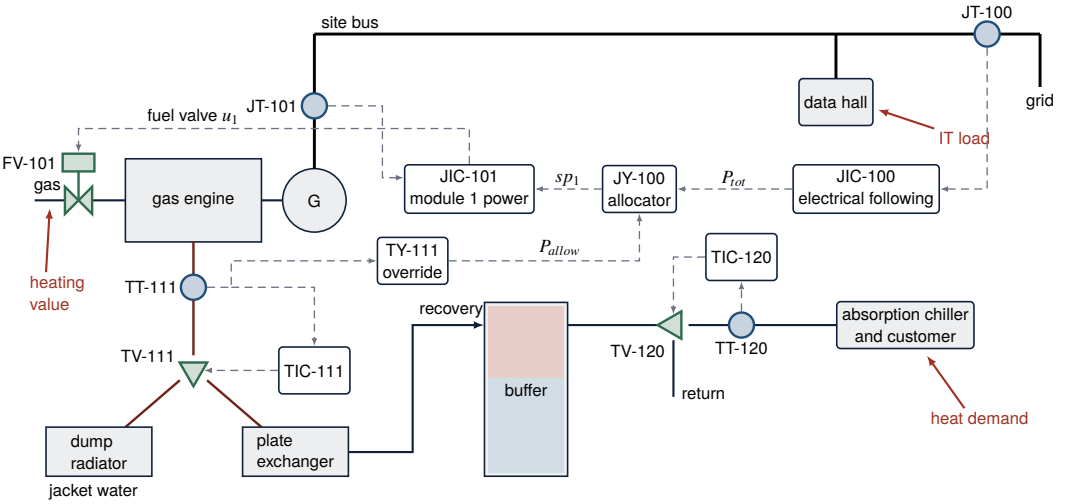


Figure 2.7 Module 1's loops and the site loop drawn with their hardware. The power transducers JT-100 at the grid and JT-101 at the generator read power through instrument transformers. The electrical-following controller JIC-100 sets the total power, the allocator JY-100 shares it, and JIC-101 moves the fuel valve FV-101. The jacket RTD TT-111 feeds both the jacket loop TIC-111, which opens the dump valve TV-111 toward the radiator, and the override TY-111, which caps the module's allowed power. TIC-120 holds the supply with the mixing valve TV-120. The exhaust exchanger and its bypass are left out. Notice that one jacket reading serves both a slow loop and a fast limit on the power.

> **TECHNOLOGY** **Sensor: A Resistance Thermometer in the Jacket Water**
>
> The jacket temperature that the override reads comes from a resistance temperature detector (RTD), a fine wire of pure metal, usually platinum, whose resistance always rises with temperature. It is relatively insensitive but very linear, and 100 Ω at 0 °C is a common reference resistance [22]. It sits in a thermowell, a pressure-tight sheath that adds a first-order lag, and an air gap at the bottom of the well adds a second [22]. A transmitter that drives its current loop below 3.6 mA or above 21 mA reports a failed sensor under the NAMUR signal levels [22]. The chapter's jacket RTDs lag 3 s with 0.05 K of noise.

What Moves It

The electrical side is moved by the fuel. The simplest gas engines draw air and fuel through a carburetor or another mixer, and high performance engines are turbocharged [1]. The chapter folds that fuel system into one valve FV-101 per module with a 0.3 s lag and an air path of 2 s. The heat side is moved by water valves on the jacket and supply circuits.

TECHNOLOGY Final Element: Three-Way Valves on the Water Circuits

A three-way valve has one stem and three ports. At either end of its travel the stem joins the common port to one of the others, and between the ends all three share the flow, so one body divides a stream or blends two, as a diverting or a mixing valve [22]. On an engine an excess heat exchanger sends the jacket heat that the users do not take to a cooling tower or a radiator, because an engine must be cooled even when its heat is not used [1]. The chapter's supply valve x is such a mixing valve, and each dump valve d_i sends jacket heat to its radiator.

Where the Controller Runs

Programmable logic controllers (PLCs) manage local processes by feedback and serve as local controllers under a supervisory scheme, and loops at both levels run at cycle times from milliseconds to minutes [23]. Beside them, protective relays, named by standard function numbers such as 50 for instantaneous overcurrent and 87 for differential current, trip the circuit breakers on their own [22]. Packaged plants that can island leave the grid through an automatic transfer switch and carry critical loads during an outage [1]. The chapter's plant controller scans every 0.05 s for the power loops, the authority, the allocator and the override TY-111, every 0.5 s for the jacket and supply loops, and every 5 s for staging. Its override is a protection layer kept apart from the tunable regulation, as relays are on a real site.

IN PRACTICE Keeping an Engine Plant in Service

An engine plant runs on its maintenance schedule. Oil, filters, coolant and spark plugs are inspected or replaced at short intervals, typically 500 to 2,000 hours, and an analysis of the oil tracks engine wear. A top-end overhaul, a rebuild of the cylinder heads and the turbocharger, falls between 8,000 and 30,000 hours, and a major overhaul with new pistons and liners after 30,000 to 72,000 hours [1]. Fuel quality is watched as well. Engine fuel is delivered by volume, so a gas with a lower heating value needs more volume for the same energy and forces a derating [1], the weaker gas of Section 2.5.2.

What Is Modernizing It

Three developments touch the loops of this chapter. Electronic engine control and better combustion chambers, including precombustion chambers, let engines run on leaner mixtures, and a federal development program set goals of 50 % brake thermal efficiency and more than 80 % CHP efficiency for the next engines [1]. Many service contracts now include remote monitoring of engine performance and allow predictive maintenance [1], so the jacket temperatures and powers of this chapter become data for a fleet. The same connectivity has a cost. Ethernet, Internet Protocol and wireless devices replacing older proprietary networks raise the likelihood of cybersecurity vulnerabilities and incidents in control systems [23]. The predictive supervisor of Section 2.4.4 is a fourth development, and the chapter measures both its gains and its costs.

2.7 Limitations

The sizes, maps and thresholds are synthetic teaching values set inside the published ranges of the EPA catalog and the DOE fact sheet [1, 2], not fitted to any engine, chiller or site. Only φ_0 and the rated exhaust flow are fitted, the first to a sentence of the catalog and the second scaled from its table of example systems. The jacket, the exchanger metal and the buffer are lumped, so the model gives lags of the right size rather than temperature profiles, and the challenge's lesson depends on the small buffer and jacket. With a 15 m^3 buffer and a 14 MJ/K jacket the shipped run still reaches the override, at 758 s for 142 s, but keeps 77.81 % of the UPS charge and fails on the supply alone, and with only one of the two enlarged it keeps 70.55 or 61.75 %, while the suggested tuning passes in all four combinations. There is no rotor, so the island shows power and energy limits rather than frequency, stability or a transfer without interruption. The swing equation of Section 1.4.2 and the island frequency of Chapter 7 are what such a model leaves out.

OPEN CHALLENGE **Hydrogen in the Pipeline Gas**

Gas utilities are beginning to blend hydrogen into their pipelines, and engines that burn pipeline gas will receive the blend [24, 25]. Hydrogen carries less energy per unit volume, so at a 20 percent blend the volume of fuel must rise by 15 percent to deliver the same energy. In tests on a stoichiometric engine whose controller had no warning of the change, a sudden step in hydrogen swung the air-fuel ratio and released a burst of nitrogen oxides, and better tuned controllers released less [24]. Fuels above about 5 percent hydrogen by volume may need special measures [1]. The chapter's power loops meet a weaker gas only as model mismatch. Progress would be fuel control that follows a changing gas without being told.

The original controllers read declared measurements and use the commissioned engine map, so weak gas or an edited engine parameter remains model mismatch. The added MPC has its own nominal aggregate thermal model, with measured states and bounded rate correction. It lacks exhaust-metal dynamics, evolving stratification and module imbalance, and its soft mean limits are not individual temperature guarantees. The protection layer is a teaching guardrail, not certified trip logic, and the load-shed priority is fixed rather than set by a site study. No study with learners has been made, so this chapter claims no measured improvement in learning. The CHP efficiency uses net electricity plus useful heat over LHV fuel at a teaching boundary, and a simulated pass is neither equipment qualification nor a savings or reliability estimate.

OPEN CHALLENGE **Data Center Load That Can Wait**

In the reference case of a national laboratory study, data centers take a third of the national growth in electric load from 2024 to 2030. The study names the work still to be done. The variation of a data center's demand over time should be measured, to learn how such loads can be served by the grid and by on-site generation, and ways to shift the timing of the load should be explored, so that a given set of energy resources serves more computing [3]. The chapter's flexible IT share, curtailed by a fixed rule on the UPS charge, is a first form. Progress would be a supervisor that schedules engines, heat store and flexible computing together against a demand forecast.

2.8 Conclusion

This chapter studied a gas-engine CHP plant at a data center as a laboratory in which one fuel valve per engine serves an electrical load that answers in seconds and a thermal load that answers in minutes. A ten-point fuel step moves a module's power 63 percent of the way in 2.3 s and its recovered heat in 68 s. Metered feedforward cuts the grid-import IAE from 18.82 to 4.14 MW s, a short tracking time cuts a windup overshoot from 0.772 to 0.017 MW, and a gas 12 % weaker than the map assumes costs only 4.40 against 4.14 MW s while the valve has room. When demand exceeds two engines, no tuning in a twelve-run sweep empties the UPS later than the 955 s that capacity allows. In the challenge a slow cooling loop that the buffer hides for eight minutes costs 408 s of override and 28 points of UPS reserve, and the suggested tuning keeps 79.19 %. The predictive supervisor, which plans from current measurements, shows why a smaller fuel ledger can come with more import, more rejection and less stored heat.

The model is lumped and its operating points are synthetic. A fuller model would add an averaged frequency mode on the island, a distributed buffer, a fitted part-load map, a cold start, and a supervisory layer that schedules the buffer against a known demand forecast, the kind of dispatch that Section 1.4.6 sets out. The simulator shows that heat a plant cannot store or reject comes back as lost electrical capacity.

KEY POINTS

- One fuel valve per engine sets both the electricity and the heat, and the electricity answers in seconds while the heat takes minutes.
- Metered-load feedforward cuts the grid-import IAE from 18.82 to 4.14 MW s, and a short tracking time cuts a windup overshoot from 0.772 to 0.017 MW.
- When demand exceeds two engines, no tuning in a twelve-run sweep empties the UPS later than the 955 s that capacity allows.
- In the challenge a slow cooling loop that the buffer hides for eight minutes costs 408 s of override and 28 points of UPS reserve.

Where else this applies. A store that carries the load while its source catches up also serves the fuel cell of Chapter 3, and a limiter that takes a fuel valve away from its loop governs Volume 4, Chapter 3.

References

[1] U.S. Environmental Protection Agency, Combined Heat and Power Partnership, "Catalog of CHP technologies," U.S. Environmental Protection Agency, Washington, DC, Full Report, Sep. 2017. [Online]. Available: https://www.epa.gov/sites/default/files/2015-07/documents/catalog_of_chp_technologies.pdf

[2] U.S. Department of Energy, "Absorption chillers for CHP systems," U.S. Department of Energy, Advanced Manufacturing Office, Washington, DC, Combined Heat and Power Technology Fact Sheet Series, 2017. [Online]. Available: https://www.energy.gov/sites/default/files/2017/06/f35/CHP-Absorption%20Chiller-compliant.pdf

[3] S. J. Smith, A. Hubbard, A. Newkirk *et al.*, "United states data center energy usage report: 2025 update," Lawrence Berkeley National Laboratory, Berkeley, CA, Tech. Rep. LBNL-2001758, 2026.

[4] W. Tan, H. J. Marquez, T. Chen, and J. Liu, "Analysis and control of a nonlinear boiler-turbine unit," *Journal of Process Control*, vol. 15, no. 8, pp. 883–891, 2005.

[5] D. W. Wu and R. Z. Wang, "Combined cooling, heating and power: A review," *Progress in Energy and Combustion Science*, vol. 32, no. 5–6, pp. 459–495, 2006.

[6] P. J. Mago, N. Fumo, and L. M. Chamra, "Performance analysis of CCHP and CHP systems operating following the thermal and electric load," *International Journal of Energy Research*, vol. 33, no. 9, pp. 852–864, 2009.

[7] D. Haeseldonckx, L. Peeters, L. Helsen, and W. D'haeseleer, "The impact of thermal storage on the operational behaviour of residential CHP facilities and the overall CO2 emissions," *Renewable and Sustainable Energy Reviews*, vol. 11, no. 6, pp. 1227–1243, 2007.

[8] K. J. Åström and L. Rundqwist, "Integrator windup and how to avoid it," in *1989 American Control Conference*. IEEE, 1989, pp. 1693–1698.

[9] A. H. Glattfelder and W. Schaufelberger, *Control Systems with Input and Output Constraints*, ser. Advanced Textbooks in Control and Signal Processing. London: Springer, 2003.

[10] H. I. Onovwiona, V. I. Ugursal, and A. S. Fung, "Modeling of internal combustion engine based cogeneration systems for residential applications," *Applied Thermal Engineering*, vol. 27, no. 5–6, pp. 848–861, 2007.

[11] A. Rosato and S. Sibilio, "Energy performance of a micro-cogeneration device during transient and steady-state operation: Experiments and simulations," *Applied Thermal Engineering*, vol. 52, no. 2, pp. 478–491, 2013.

[12] N. S. Gates, D. C. Hill, B. W. Billings, K. M. Powell, and J. D. Hedengren, "Benchmarks for grid energy management with Python Gekko," in *2021 60th IEEE Conference on Decision and Control (CDC)*. IEEE, 2021, pp. 4868–4874.

[13] P. W. Willans, "Economy trials of a non-condensing steam-engine: simple, compound and triple," *Minutes of the Proceedings of the Institution of Civil Engineers*, vol. 93, pp. 128–188, 1888.

[14] L. Guzzella and C. H. Onder, *Introduction to Modeling and Control of Internal Combustion Engine Systems*. Berlin, Heidelberg: Springer, 2010.

[15] U.S. Congress, "Public utility regulatory policies act of 1978, Public Law 95-617, 92 Stat. 3117," United States Statutes at Large, vol. 92, govinfo.gov, Nov. 1978. [Online]. Available: https://www.govinfo.gov/content/pkg/STATUTE-92/pdf/STATUTE-92-Pg3117.pdf

[16] R. F. Hirsh, *Power Loss: The Origins of Deregulation and Restructuring in the American Electric Utility System*. Cambridge, MA: MIT Press, 1999.

[17] H. I. Onovwiona and V. I. Ugursal, “Residential cogeneration systems: review of the current technology,” *Renewable and Sustainable Energy Reviews*, vol. 10, no. 5, pp. 389–431, 2006.

[18] D. E. Seborg, T. F. Edgar, D. A. Mellichamp, and F. J. Doyle, III, *Process Dynamics and Control*, 4th ed. Hoboken, NJ: John Wiley & Sons, 2016.

[19] R. K. Shah and D. P. Sekulić, *Fundamentals of Heat Exchanger Design*. Hoboken, NJ: Wiley, 2003.

[20] S. J. Qin and T. A. Badgwell, “A survey of industrial model predictive control technology,” *Control Engineering Practice*, vol. 11, no. 7, pp. 733–764, 2003.

[21] G. Pannocchia and J. B. Rawlings, “Disturbance models for offset-free model-predictive control,” *AIChE Journal*, vol. 49, no. 2, pp. 426–437, 2003.

[22] T. R. Kuphaldt, *Lessons in Industrial Instrumentation*, version 2.33 ed. Open textbook, Creative Commons Attribution 4.0 license, ibiblio.org/kuphaldt/socratic/sinst, 2024.

[23] K. Stouffer, M. Pease, C. Tang, T. Zimmerman, V. Pillitteri, S. Lightman, A. Hahn, S. Saravia, A. Sherule, and M. Thompson, “Guide to operational technology (OT) security,” National Institute of Standards and Technology, Gaithersburg, MD, Special Publication 800-82r3, 2023.

[24] N. Katsampes, D. Montgomery, G. Arney, and D. B. Olsen, “Hydrogen-natural gas fuel blending in a “rich burn” engine with 3-way catalyst,” *Frontiers in Fuels*, vol. 2, p. 1416716, 2024.

[25] G. Vieira, R. Lorenzen, M. Patterson, and D. Olsen, “Methane emission reduction through hydrogen blending in a large bore 2-stroke lean-burn natural gas compressor engine,” *Frontiers in Fuels*, vol. 2, p. 1404367, 2024.

2.9 Exercises

2.1 Concept check · 2 min

In case 1 a ten-point step of module 1’s fuel valve moves its electrical output 63 percent of the way in 2.3 s, while its recovered heat needs 68 s for the same share. What sets the slower clock?

(a) The jacket node and the exchanger metal, which must warm before more heat passes to the water

(b) The recovery pump, which cuts its flow while the fuel valve is moving

(c) The air-path lag, which delays the exhaust enthalpy as long as the heat takes

(d) The four buffer nodes, whose mixing smears the heat before it is recovered

2.2 Concept check · 1 min

In case 9 both remaining modules reach their rating at 243 s, and the UPS supplies the rest until it reaches its floor at 951 s. The site-balance gain is raised once both modules are at their rating. What happens?

(a) The UPS reaches its floor later, because a faster loop returns the deficit to the engines sooner

(b) The UPS reaches its floor at the same instant, because the loop’s output is already pinned

(c) The UPS reaches its floor sooner, because the higher gain makes the module power cycle

(d) The UPS never reaches its floor, because the integral recovers the energy lost earlier

2.3 Concept check · 2 min

In case 4 the customer’s heat demand falls from 3.2 to 0.8 MW at 60 s under electrical following. Why is no heat rejected for more than five minutes after the cut?

(a) The jacket loops are slow, so the dump radiators open only after their integrals have grown

(b) The exhaust bypasses are held shut until the buffer charge passes 85 %

(c) The recovery water still comes from cool water at the buffer bottom, so the heat goes to the buffer

(d) The engines cut their fuel under electrical following, so less heat is recovered for a while

2.4 Theory and calculation · 6 min

At rating a module burns 4.762 MW of fuel (LHV) for 2.062 MW of shaft power. Its zero-load fuel is $\varphi_0 = 0.10$ of the rated fuel and its generator efficiency is 97 %.

(a) Find the marginal shaft efficiency η_m of the Willans line in Equation (2.1). *Checkpoint:* $\eta_m = 0.4811$.

(b) Find the electrical efficiency at rating. *Checkpoint:* 42.0 %.

(c) Show that at a share s of rated shaft power the efficiency relative to the rated value is $s/\big(\varphi_0 + s(1-\varphi_0)\big)$, and evaluate it at half load. *Checkpoint:* 90.9 %, a loss of 9.1 %.

2.5 Theory and calculation · 6 min

The buffer holds 8 m^3 of water at 975 $\mathrm{kg/m}^3$ with $c_p = 4186\,\mathrm{J/(kg\,K)}$, and its charge counts the band from 70 to 95 °C.

(a) Find the energy the buffer stores across the band. *Checkpoint:* 816 MJ, or 0.227 MWh.

(b) The modules recover 3.24 MW at the design point. How long could the buffer absorb that heat with no user taking any? *Checkpoint:* 252 s, about four minutes.

(c) At the start of case 3 the four nodes read 91.5, 91.5, 68.1 and 68.1 °C. Find the buffer charge B with each node's share clipped to the unit interval, and without the clip. *Checkpoint:* 43 % clipped, 39.2 % without.

2.6 Theory and calculation · 8 min

The UPS stores 0.25 MWh, discharges with an efficiency of 95 % and stops at a 20 % floor. The override follows Equation (2.7) with $P_r = 2.0$ MW, $P_{min} = 0.5$ MW, $T_{ov} = 100\,^{\circ}\mathrm{C}$ and $T_{trip} = 105\,^{\circ}\mathrm{C}$.

(a) Starting from 80 %, find the energy the UPS can deliver before its floor and how long it lasts at a constant 1 MW. *Checkpoint:* 0.1425 MWh and 513 s.

(b) How long does the same reserve last at the 1.5 MW rating? *Checkpoint:* 342 s.

(c) Find the slope of the override and the allowed power at a measured jacket of 102.0 °C. In the challenge at 900 s both running modules read about 102.0 °C while their allowed power is near 1.30 MW. Explain the difference. *Checkpoint:* 0.333 MW/K and 1.333 MW.

2.7 App challenge · 8 min

Load scenario 3, An IT load step: feedback alone, or metered feedforward, which ships with Metered-load feedforward Off. Run to 300 s at 20x with the default seed and export the CSV file. Then switch Metered-load feedforward On, press Reset, run to 300 s again and export a second file. Use the column `truth_grid_import_MW` and the rows up to 300 s.

(a) In each file find the last row after the 60 s step at which the true import is more than 20 kW from its 0.2 MW target. Give the recovery time after the step, within 1 s. *Checkpoint:* 144 s on feedback alone and 31 s with the feedforward.

(b) In the feedforward run, find the lowest true import after the step and the time it occurs, within 0.005 MW and 1 s. *Checkpoint:* 0.073 MW at 68 s.

(c) Both runs show the import near 0.8 MW in the row at 60.5 s. Explain why the feedforward cannot prevent this, and why the meter's delay of 1 to 2 s costs little. *Checkpoint:* Nothing measures the load before it lands; the loop alone needs minutes.

2.8 App challenge · 8 min

Load scenario 2, Tune a module power loop: a pinned valve and windup. It ships on gas with 88 % of its heating value, a base-load target that steps from 3.0 to 6.0 MW at 60 s and back at 180 s, and an anti-windup tracking time of 200 s. Run to 240 s at 5x with the default seed and export the CSV file.

(a) In the row at 150 s, read `fuel1_cmd_pct`, `truth_P1_MW` and `P1_sp_MW`. *Checkpoint:* 100 %, 1.83 MW and 2.00 MW.

(b) After 180 s, find the largest value of `truth_P1_MW` minus `P1_sp_MW`, within 0.01 MW, and the time after 180 s of the last row at which the difference is more than 0.05 MW in size, within 1 s. *Checkpoint:* 0.77 MW and 41 s.

(c) Set Anti-windup tracking time to 2 s, press Reset, run to 240 s and repeat (a) and (b). Give the time within 0.5 s. *Checkpoint:* The same row at 150 s; 0.02 MW and 4.5 s.

2.9 App challenge · 9 min

Load the challenge, case 11 of Table 2.5, which the scenario menu lists as "11 · Challenge · a customer loss, a trip and an IT rise, islanded". Use the default seed and 100x, so each 900 s run takes about 9 s. After each run read the scorecard tiles Lowest UPS charge, Supply outside ±3 K, Override · starts and Challenge target.

(a) Run to 900 s as shipped. *Checkpoint:* 52.0 %, 570 s, 408 s, not met.

(b) Set Jacket gain to 10 %/K and Jacket integral time to 60 s, press Reset and run to 900 s. *Checkpoint:* 79.2 %, 570 s, 0 s, not met.

(c) Also set Supply temperature gain to 4 %/K and Supply temperature integral time to 20 s, press Reset and run to 900 s. Say which part of the target each loop guards. *Checkpoint:* 79.2 %, 0 s, 0 s, met.

2.10 Application area · 3 min

In case 5 the customer's heat demand falls to 2.2 MW. Over 1800 s electrical following reaches a CHP efficiency of 65.7 % and thermal following 73.6 %, both on LHV.

(a) What holds thermal following back from its 45 % buffer target? *Checkpoint:* The 1.50 MW import contract, from 481 s.

(b) A site manager reads the two efficiencies as a saving of about eight points from switching authority. Give two reasons the pair is not a savings estimate. *Checkpoint:* Different stored heat at the end, and more grid electricity.

2.11 Application area · 4 min

The model takes the exhaust only down to a 120 °C stack minimum, and its jacket node is the engine outlet.

(a) Exhaust heat-recovery units are usually designed for a 250 to 350 °F outlet. Convert the lower bound to degrees Celsius and say why the recovery stops there. *Checkpoint:* 121 °C; the exhaust must not condense in its piping.

(b) In the model a restricted jacket-water flow widens the rise across the engine without heating the outlet. Why is the same fault more dangerous on a real engine? *Checkpoint:* Low coolant flow makes local hot spots, which one node cannot show.

2.12 Review the agent · 5 min

An AI assistant summarizes case 10 as follows: "At 900 s the MPC uses 1.9328 against 1.9414 MWh of fuel, a 0.45 % reduction. The predictive supervisor is therefore the more efficient way to run the plant, and it should replace the PI authorities." Find the flaw and say how you would check the claim on the app.