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CHAPTER 9

Valve-Position Control of Chilled Water in a Gas Turbine Trigeneration Plant

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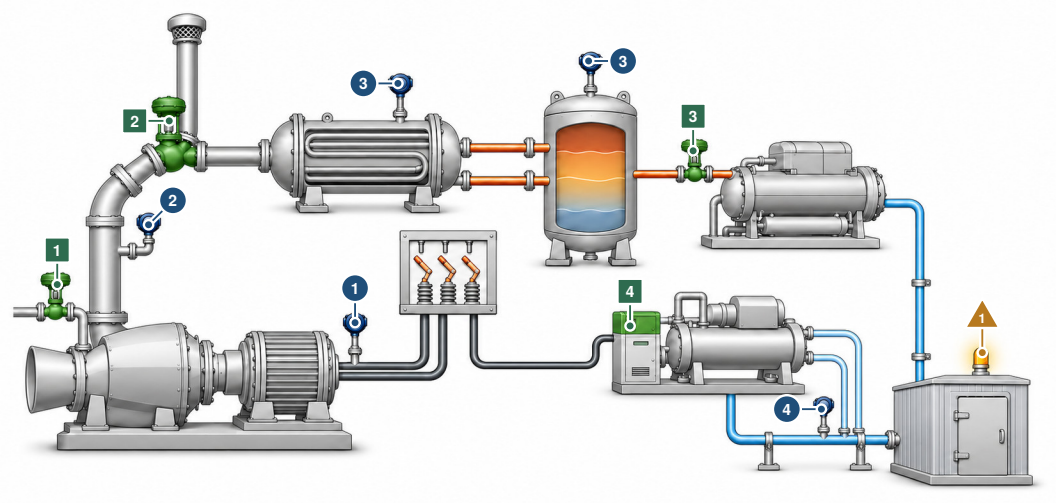
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CHAPTER 9

Valve-Position Control of Chilled Water in a Gas Turbine Trigeneration Plant



The controller moves 1 fuel valve 2 exhaust bypass 3 hot-water valve of the absorption chiller 4 electric chillers' cooling duty

The controller reads 1 generator power 2 exhaust temperature 3 hot-water temperature 4 chilled-water temperature

What disturbs it 1 heat of the computers in the data hall

Notice that the cheap cooling comes from the turbine's exhaust heat through the slow hot-water chain, while the electric chiller answers fast from the generator's power. Illustration, not to scale.

IN PLAIN TERMS **One Turbine, Power and Cooling**

The main idea. A gas turbine at a computer center makes electricity. Heat from its exhaust warms water, and the hot water drives a cooling machine that runs on heat, not on electricity.

The challenge. The heat-driven cooler is cheap but slow, while the heat of the computers comes fast, so electric coolers catch each change and then hand the work back. No setting helps once the turbine and the power lines have nothing more to give.

Why it matters. Done well, the computers stay cool at the lowest cost in fuel and electricity.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the fact on availability (Section 9.1), the history segment (Section 9.2), the two try-it segments and the fact on the predictive allocator (Section 9.5) and the key points
Study	60 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	20 min	the first page, the results (Section 9.5), Technology in Practice (Section 9.6), Limitations (Section 9.7) and the open challenge

The control question A data center's gas turbine makes electricity, hot water and chilled water from one fuel valve, and recovered-heat cooling is cheap but loads up over minutes while the hall's heat arrives in about a hundred seconds. How should a fast electric chiller and a slow absorption chiller share one chilled-water temperature, and where does control stop and missing capacity begin?

Learning objectives

- Trace a fuel step through power, recovered heat, hot water and absorption cooling, and name the inventory behind each delay.
- Explain why the hot-water bypass loop decouples a power change from the cooling in automatic operation.
- Compute the absorption chiller's operating point, its valve gain and the heat it rejects from the model's equations.
- Predict the handover energy of a valve-position controller and compare the electric trim with absorption cooling alone.
- Tell a tuning problem from a capacity limit by the runway of a depleting store or UPS.

Prerequisites Sections 1.4.7 (mid-ranging and valve-position control), 1.4.3 (selectors and override), 1.4.4 (external reset), 1.4.9 (actuators that deplete) and 1.6.4 (scenarios and exported files). Chapter 3 shows an exhaust-temperature limiter on a fuel valve. Sections 1.6.3 and 1.4.8 are needed only for the predictive allocator.

The app https://apmonitor.com/apps/gas-turbine-trigeneration/

See also Volume 17, Chapter 2 for gas engines on the same site model, whose power and heat also answer on two clocks, and Volume 17, Chapter 4 for one variable handed between two actuators. In this volume, Chapter 10 for three mid-ranging layers on one power block.

9.1 Introduction

Gas turbines make up 63 percent of the combined heat and power (CHP) capacity installed in the United States, 51.5 GW, according to a catalog prepared for the U.S. Environmental Protection Agency, and the thermal energy in their exhaust is generally 60 to 70 % of the fuel energy [1]. The same catalog describes a campus whose 5 MW turbine sends about 8 MW of recovered heat to space heating in winter and to single-effect absorption chillers in summer. The U.S. Department of Energy counts data centers among the sites with steady year-round cooling that suit an absorption chiller, and notes that such a chiller needs a larger cooling tower than an electric one of the same capacity because it also rejects its driving heat [2]. In the simulated plant a turbine of about 10 MW carries a 6.0 MW data hall at 6.80 MW net, burns 26.2 MW of fuel on its lower heating value (LHV), and returns 11.6 MW of exhaust heat as 95 °C hot water, from which an absorption chiller makes 5.79 MW of the hall's 6.29 MW of cooling.

DID YOU KNOW? Gas Turbines Available 93 to 97 Percent of the Year

A review of on-site generation made for a national laboratory, quoted in a 2009 report on data centers, found that gas turbines in CHP service averaged 93 to 97 % availability and reciprocating engines 96 to 98 %. More than half of the downtime of every kind of on-site generator was scheduled maintenance [3].

The simulator is meant to dislodge a common expectation, namely that more power from a gas turbine buys more cooling a few minutes later. In Manual, with every valve held, a six-point step of the fuel valve moves the net power 63 % of the way in 0.8 s, the recovered heat in 39 s, the hot water in 454 s and the absorption cooling in 573 s. In Auto the same chain is cut. The hot-water loop holds its setpoint by opening the exhaust bypass, so a 1 MW rise of the turbine's setpoint sends 2.73 MW more heat to the stack and changes the absorption cooling by −0.03 MW. Absorption cooling rises only when a controller asks the chiller for it, and the electrical coupling runs the other way, since an

absorption trip adds 0.61 MW of electric-chiller load that the turbine and an import-limited grid must carry.

The control problem has a general shape. One output, the chilled-water temperature, has two manipulated inputs, a fast, expensive electric chiller and a slow, cheap absorption chiller, and the fast one should take every disturbance and then hand the duty back. This is mid-ranging control (Section 1.4.7), which in industry is mostly built as valve-position control, with examples from pilot plants and paper mills [4, 5], and the oxygen concentration of a bioreactor and the temperature of a cooling system [6]. The fuel side has the selector shape of a regulator and a protective limit acting on one valve (Section 1.4.3), and the site carries a store and an import limit. Combined cooling, heating and power is one form of the distributed multi-generation that couples these services at one site [7], while published grid benchmarks solve a tri-generation dispatch by dynamic optimization with perfect foresight [8].

However, the usual teaching material keeps the parts apart. Gas turbine models for power system studies end at the generator terminals and the exhaust [9, 10], trigeneration and absorption-cooling studies assess energy performance of a design or an installation [11, 12], and the mid-ranging literature treats the two-actuator loop without the plant that makes one actuator slow [5]. This chapter works with a data center's gas turbine trigeneration plant simulated in a browser. It measures what a fast electric trim and a slow valve-position return buy against absorption cooling alone, where the turbine's derating and the cooling electricity meet on the bus, and where control stops and capacity begins. The methods are established ones: the cycle calculation, the capacity-lag chiller, the velocity-form PID with back-calculation, the low selector and valve-position control. The results are matched comparisons on a single plant and seed, among them the finding that in automatic operation the plant's own bypass loop decouples a power change from the cooling. The plant's ledger states close every balance independently, its site components are shared with the gas engine cogeneration plant of Volume 17, Chapter 2, and its controllers read only declared meters.

Section 9.2 traces the gas turbine from peaking duty to trigeneration. Section 9.3 builds the plant model, from the gas path at constant speed to the site bus, and Section 9.4 the controllers as implemented, with a predictive chiller allocator as an option. Section 9.5 reports the measurements: the app's cases, electricity against driving heat, where a power change goes, three matched comparisons, the capacity that no tuning adds, the challenge under five policies, and the verification of the implementation. Section 9.6 sets the loops on plant hardware, Section 9.7 states the limitations, Section 9.8 concludes, and Section 9.9 holds the exercises.

9.2 From Peaking Turbines to Trigeneration

The turbine's road from peaking duty to on-site heat and power is told in the history segment below, and the thermodynamics of a trigeneration plant are treated in the cycle literature [13] on the compressor, combustor and turbine relations of gas turbine theory [14].

> ⧖ HISTORY **From Peaking Duty to On-Site Heat and Power, 1930s to 1980s**
>
> Gas turbines have generated stationary electric power since the late 1930s, went on to transform aircraft propulsion in the 1940s, and long served utilities as peaking capacity. By the early 1980s the efficiency and reliability of machines of 1 to 40 MW made them an attractive choice for industrial and large institutional CHP. In the EPA catalog's count, close to 80 % of the gas turbine CHP capacity in the United States sits in large combined-cycle plants that export power, and the rest in simple-cycle systems typically below 40 MW. The catalog also draws a line that this chapter keeps. A turbine whose exhaust raises steam only for a steam turbine is a combined cycle and not CHP, because no end use takes the heat [1], so a plant whose recovered heat drives an absorption chiller is trigeneration and not combined-cycle generation.

The dynamic picture came from the grid. Simplified representations of heavy-duty single-shaft turbines from 18 to 106 MW, with gas and liquid fuel systems and droop and isochronous governors,

Table 9.1 Variable Roles and Starting Values at the Reference Start (25 °C Dry Bulb, 20 °C Wet Bulb, 6.8 MW Site Power Target)

Variable	Role	Start	Range
P_{net}	CV, turbine net power	6.80 MW	SP 1–12
T_4	CV, exhaust (limit)	425.9 °C	limit 490, trip 520
T_h	CV, hot-water supply	95.0 °C	SP 85–98
T_{chw}	CV, chilled-water supply	12.0 °C	SP 9–16, ±1 K
$Q_{ec,cmd}$	CV of the VPC, electric duty	0.50 MW	SP 0–4
u_f, b, v_g	MV, fuel, bypass, absorption valve	65.4, 4.9, 75.9 %	0–100
$Q_{ec,cmd}$	MV of the trim	0.50 MW	0–4.0
P_{IT}	DV, IT load (80 % critical)	6.00 MW	3–8
Q_{req}	DV, heat-export demand	3.60 MW	0–7
T_a, T_{wb}	DV, dry and wet bulb	25, 20 °C	0–45, 5–30
events	DV, trips, pulses, ramps	—	—
$\dot{m}_f$	state, fuel flow	0.5236 kg/s	$\leq$ 0.80 kg/s
T_d, T_x	states, duct, tube metal	413.8, 111.7 °C	—
Q_{cap}, Q_{ec}	states, chiller duties	5.79, 0.50 MW	map, 4.0
T_{IT}, T_{cw}	states, IT node, cooling water	27.0, 29.3 °C	trip 37
E_{cs}, E	states, cold store, UPS	80, 90 %	floors 0, 20

were published in 1983 for power system studies [9], and an IEEE working group extended them in 1994 to combined cycles with waste-heat recovery boilers and steam turbines [10]. Those models say how fast a turbine's power moves and leave the heat after the exhaust duct to the plant downstream.

Absorption refrigeration has been reviewed across its working pairs and cycles [15], and absorption chillers and heat pumps have a book-length treatment of their own [16]. The DOE fact sheet gives the present practice for CHP [2]. Single-stage machines run on hot water at 200 to 240 °F or low-pressure steam and are often paired with reciprocating engines, two-stage machines need hot water near 350 °F or steam near 115 psig and are often paired with combustion turbines, and the thermal coefficient of performance (COP) is 0.70 to 0.79 for the single-stage examples and 1.35 to 1.42 for the two-stage ones. The performance of a trigeneration system built on a micro gas turbine and an ammonia and water absorption chiller has been analyzed [11], absorption refrigeration has been evaluated for recovering the low-grade heat of data centers themselves [12], and multi-generation at one site has been reviewed as a whole [7].

Two facts about the turbine shape the coordination. A turbine reduces its power by lowering its turbine inlet temperature, so part-load efficiency can be substantially below full-load efficiency, and on a hot day its power and its efficiency both fall, for a nominal 7.5 MW machine to 80 % of its ISO power at 100 °F, while in many parts of the United States electricity costs most in summer, when the turbine performs worst [1]. A site that backs up its absorption cooling with electric chillers therefore adds load to its turbine exactly when the turbine has least to give. The control answer to two actuators of different speed on one output is mid-ranging, whose design and tuning were largely done case by case before a systematic method was proposed [5], and whose standard anti-windup schemes can degrade performance while one actuator saturates [6]. Measured-load feedforward and cascade structure are textbook material [17].

9.3 Plant Model

The plant in Figure 9.1 is an invented teaching design, set against public reference data but taken from no installation. Its exhaust passes a duct and a diverter that sends the share b around a heat-recovery unit (HRU) to a bypass stack, the HRU heats a mixed hot-water buffer that supplies a heat-export customer and, through the valve v_g, an absorption chiller, and the chilled-water loop of the data hall also carries two lumped electric chillers and a cold store. There are 13 physical states, $\dot{m}_f$, T_d, b, T_x, T_h, v_g, Q_{cap}, Q_{ec}, T_{IT}, T_{chw}, E_{cs}, T_{cw} and E, and 46 ledger states that integrate every boundary flux. Units inside the model are seconds, watts, joules, kilograms and kelvin, and Table 9.1 gives the roles of the variables.

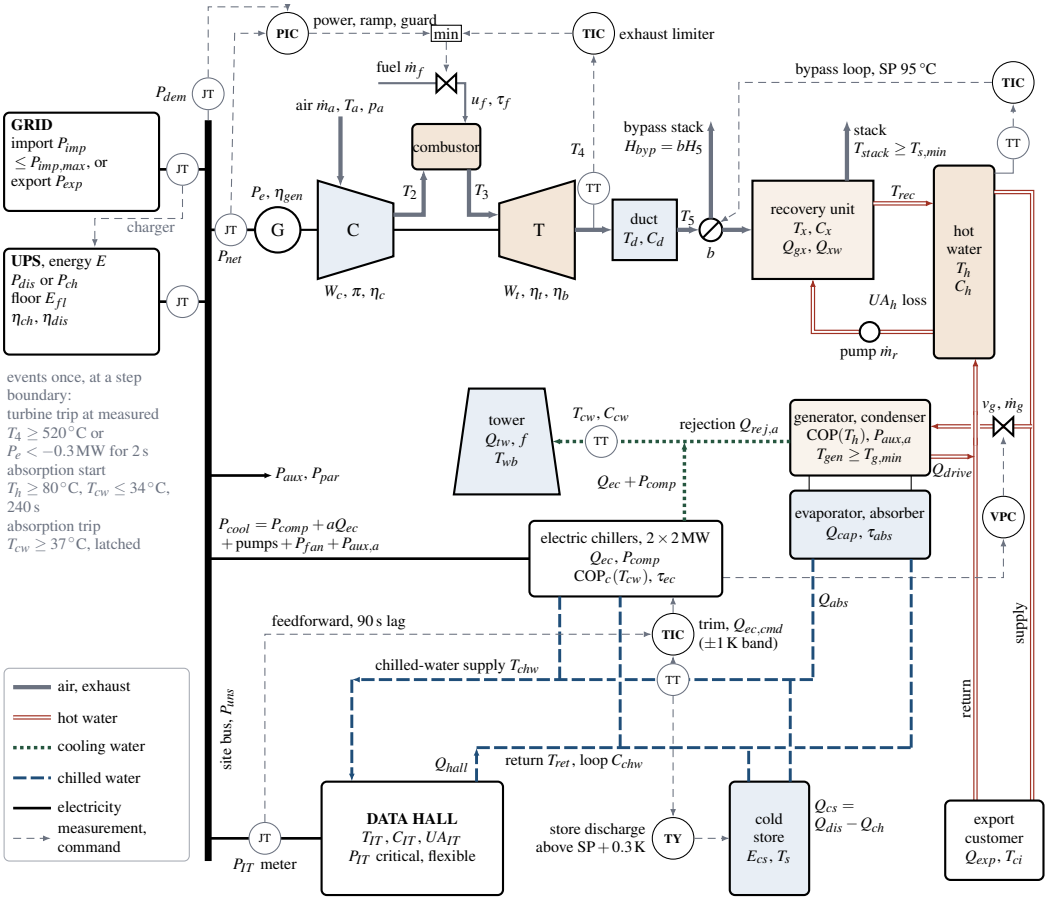


Figure 9.1 The simulated plant, after the application's Plant view. Fuel $\dot{m}_f$ through the valve u_f and air $\dot{m}_a$ pass the compressor C, the combustor and the turbine T at constant speed, and the generator G delivers P_e to the bus. The exhaust at T_4 warms the duct metal T_d, leaves it at T_5, and is split by the diverter b between the bypass stack and the recovery unit, whose tubes T_x heat the recovery water into the buffer T_h. The buffer feeds the export customer and, through v_g, the absorption generator, both chillers reject to the cooling water T_{cw} and the tower, and the electric chillers, the evaporator, the cold store and the hall sit on the chilled-water rails. Air and exhaust are thick gray arrows, hot water a hollow double line, cooling water dotted, chilled water long-dashed and electricity solid black. Thin short-dashed lines are measurements and commands: PIC and the exhaust limiter (TIC) meet at a low selector on u_f, the bypass TIC holds T_h, the trim TIC sets $Q_{ec,cmd}$ with metered-IT feedforward, VPC returns the electric duty to its reserve $Q_{ec,SP}$ through v_g, and TY discharges the store. The scripted events and the legend sit left of the bus. There is no rotor state. A process model, drawn without piping detail or scale.

9.3.1 Gas Path at Constant Speed

The grid holds the shaft speed, so the turbine has no rotor state and its shaft balance is algebraic. At fixed inlet guide vanes the compressor swallows a fixed volume, the combustor's outlet follows from the actual fuel and air flows, and the turbine's choked first nozzle ties the pressure ratio to the gas flow and the firing temperature, as shown in Equation (9.1).

$$\begin{aligned} \dot{m}_a &= \dot{m}_{a,d}\,\frac{p_a}{p_{ISO}}\,\frac{T_{ISO}}{T_a}, \qquad \dot{m}_g = \dot{m}_a + \dot{m}_f \\ T_2 &= T_a\left[1 + \frac{\pi^{(\gamma_a-1)/\gamma_a} - 1}{\eta_c}\right] \\ \dot{m}_g c_{pg}(T_3 - T_r) &= \dot{m}_a c_{pa}(T_2 - T_r) + \eta_b \dot{m}_f \,\mathrm{LHV} \\ \pi &= \pi_d\,\frac{p_{1,ISO}}{p_1}\,\frac{\dot{m}_g}{\dot{m}_{g,d}}\sqrt{\frac{T_3}{T_{3,d}}} \\ T_4 &= T_3 - \eta_t T_3\left(1 - \rho^{-(\gamma_g-1)/\gamma_g}\right) \\ \rho &= \pi(1-\Delta p_b)p_1 / \left[p_a(1+\Delta p_x)\right] \end{aligned} \tag{9.1}$$

where $T_{ISO} = 288.15\,\mathrm{K}$ and $p_{ISO} = 101.325\,\mathrm{kPa}$, $p_1 = p_a(1-\Delta p_{in})$ is the compressor inlet pressure, $T_r = 298.15\,\mathrm{K}$ is the one enthalpy reference on which the fuel's LHV is also given, and c_{pa}, γ_a and c_{pg}, γ_g are two constant specific heats, for air through the compressor and for products through the turbine. The three unknowns T_2, T_3 and π are found by eight fixed passes of substitution, whose contraction is about 0.1 per pass. The work, the generator and the first law of the gas path are Equation (9.2).

$$\begin{aligned} W_c &= \dot{m}_a c_{pa}(T_2 - T_a), \qquad W_t = \dot{m}_g c_{pg}(T_3 - T_4) \\ P_{sh} &= W_t - W_c - P_{mech} \\ P_e &= \eta_{gen} P_{sh} \ \text{ if } P_{sh} \geq 0, \quad \text{else } P_{sh}/\eta_{gen} \\ P_{net} &= P_e - P_{GT,aux}, \qquad H_4 = \dot{m}_g c_{pg}(T_4 - T_r) \\ \dot{m}_f \mathrm{LHV} + \dot{m}_a c_{pa}(T_a - T_r) &= P_e + P_{gl} + P_{mech} \\ &\quad + (1-\eta_b)\dot{m}_f \mathrm{LHV} + H_4 \end{aligned} \tag{9.2}$$

where P_{gl} is the generator loss. Because every stream's enthalpy is $c_p(T - T_r)$ on the same reference, the first law holds at every instant by construction. Load falls by lowering the firing temperature at constant air flow, as the catalog describes [1], so the exhaust cools at part load. At the reference start the turbine passes 40.01 kg/s of air at a pressure ratio of 16.20, with $T_2 = 446.5\,^{\circ}\mathrm{C}$, $T_3 = 947.4\,^{\circ}\mathrm{C}$ and $T_4 = 425.9\,^{\circ}\mathrm{C}$, $W_c = 16.95\,\mathrm{MW}$ and $W_t = 24.31\,\mathrm{MW}$, and of its 7.05 MW at the terminals the 6.80 MW net is 25.98 % of the fuel. The fuel follows its valve through $\tau_f\,\mathrm{d}\dot{m}_f/\mathrm{d}t = \min(u_f\dot{m}_{f,max}, F_{max}/\mathrm{LHV}) - \dot{m}_f$ while the turbine runs. The available net capacity $P_{cap}(T_a)$ is the output at which the exhaust reaches its 490 °C limit or the fuel its supply limit, 9.21 MW at 25 °C and 7.95 MW at 38 °C.

9.3.2 Exhaust, Recovery Unit and Hot Water

The duct metal and the HRU tubes are the gas path's heat stores, each stream meets an isothermal metal node with the effectiveness $\varepsilon(UA, C) = 1 - \mathrm{e}^{-UA/C}$, and the buffer and its loop are one mixed

node, as shown in Equation (9.3).

$$
\begin{aligned}
Q_d &= \varepsilon(UA_d, C_g)\, C_g (T_4 - T_d), \qquad T_5 = T_4 - Q_d / C_g \\
C_d \frac{\mathrm{d}T_d}{\mathrm{d}t} &= Q_d - UA_{dl}(T_d - T_a), \qquad \tau_b \frac{\mathrm{d}b}{\mathrm{d}t} = b_{cmd} - b \\
Q_{gx} &= \min\big(\varepsilon(UA_g, C_{gx})(T_5 - T_x),\ T_5 - T_{s,min}\big) C_{gx} \\
Q_{xw} &= \varepsilon(UA_w, C_r)\, C_r (T_x - T_h) \\
C_x \frac{\mathrm{d}T_x}{\mathrm{d}t} &= Q_{gx} - Q_{xw}, \qquad H_{byp} = b(H_4 - Q_d) \\
C_h \frac{\mathrm{d}T_h}{\mathrm{d}t} &= Q_{xw} - Q_{drive} - Q_{exp} - UA_h (T_h - T_a) \\
Q_{exp} &= \min\big(Q_{req},\ Q_{perm},\ \varepsilon_c \dot{m}_c c_p (T_h - T_{ci})^+\big)
\end{aligned}
\tag{9.3}
$$

where $C_g = \dot{m}_g c_{pg}$, $C_{gx} = (1-b)C_g$ and $C_r = \dot{m}_r c_p$ are heat-capacity flows, the minimum caps the gas side only while it gives heat, the stack carries $(1-b)(H_4 - Q_d) - Q_{gx}$, $Q_{rec} = Q_{xw}$ leaves in water at $T_{rec} = T_h + Q_{xw}/C_r$, $C_h = M_h c_p = 209\,\mathrm{MJ/K}$, Q_{perm} is the export the priority logic permits, and $(\cdot)^+ = \max(0, \cdot)$. At the reference start the bypass is 4.9 % open and sends 0.91 MW to the stack, the HRU gives 11.61 MW to water leaving at 108.9 °C, and its stack is at 160.5 °C.

9.3.3 The Absorption Chiller Reduction and Its Sink

The absorption chiller is the capacity-lag reduction of the framework's shared site module `core/cogen.js`, which the gas-engine cogeneration application wrote and this application extracted with the engine's runs unchanged. The lag state is available capacity, not stored energy, and the chiller's internal energy is held constant, so cooling and drive heat are chosen together inside that capacity, as shown in Equation (9.4).

$$
\begin{aligned}
Q_{dc} &= v_g \dot{m}_{g,max} c_p\, (T_h - T_{g,min})^+ \\
\mathrm{COP} &= \mathrm{clip}_{[0.55,\,0.76]}\big(0.70 + 0.004\,(T_h - 87.8\,^\circ\mathrm{C})/\mathrm{K}\big) \\
Q_{map} &= Q_{abs,r}\, \mathrm{clip}_{[0,\,1.15]}\big((T_h - 70\,^\circ\mathrm{C})/20\,\mathrm{K}\big) \\
&\quad \times \big(1 - 0.03\,(T_{cw} - 29.4\,^\circ\mathrm{C})^+/\mathrm{K}\big) \\
Q_{tgt} &= \mathrm{clip}_{[f_{td} Q_{map},\, Q_{map}]}\big(\mathrm{COP}\, Q_{dc}\big) \\
\tau_{abs} \frac{\mathrm{d}Q_{cap}}{\mathrm{d}t} &= Q_{tgt} - Q_{cap} \\
Q_{abs} &= s_{cool} \min\big(Q_{cap},\ \mathrm{COP}\, Q_{dc}\big) \\
Q_{drive} &= Q_{abs}/\mathrm{COP} \\
Q_{rej,a} &= Q_{drive} + Q_{abs} + s_{cool} P_{aux,a}
\end{aligned}
\tag{9.4}
$$

where Q_{dc} is the most heat the generator's water can give before it leaves at $T_{g,min} = 70\,^\circ\mathrm{C}$, $Q_{abs,r} = 6.0\,\mathrm{MW}$ is the rating at 90 °C, $f_{td} = 0.2$ the turndown, the target is zero unless the chiller runs, and s_{cool} is the served fraction of the cooling plant's electricity, 1 whenever the bus serves it. The valve follows its command through $\tau_v = 10\,\mathrm{s}$ and is interlocked shut unless the chiller is starting or running. The COP passes through 0.70 at 87.8 °C and 0.74 at 97.8 °C, which are the DOE fact sheet's single-stage examples on hot water [2], while the capacity map is a teaching map. No driving heat means no cooling, however large the lag state. At the reference start the valve passes 75.9 kg/s, the COP is 0.729, the chiller makes 5.79 MW against a map of 6.90 MW, takes 7.94 MW of drive heat, and rejects $7.94 + 5.79 + 0.06 = 13.79\,\mathrm{MW}$.

The sink boundary is the cooling-water node of Equation (9.5), whose tower is bounded by the wet bulb and run by its own proportional fan control.

$$\begin{aligned} C_{cw}\frac{\mathrm{d}T_{cw}}{\mathrm{d}t} &= Q_{rej,a} + s_{cool}(Q_{ec} + P_{comp}) - Q_{tw} \\ Q_{tw} &= f\,UA_{tw}(T_{cw} - T_{wb})^{+} \\ f &= \mathrm{clip}_{[0,1]}\big((T_{cw} - 28\,^{\circ}\mathrm{C})/2\,\mathrm{K}\big) \end{aligned} \tag{9.5}$$

with fan power $P_{fan} = P_{tw} f^3$. Per megawatt of cooling the absorption chiller rejects 2.37 MW to this node and an electric chiller at 29 °C 1.17 MW, which is the DOE statement about tower size in numbers. A hotter sink acts on both machines. Raising the cooling water from 29 to 37 °C cuts the absorption map at 95 °C from 6.90 to 5.33 MW, the electric COP from 6.00 to 4.80 and the electric capacity from 4.00 to 3.60 MW, while the absorption COP, read at the hot-water inlet only, does not change.

9.3.4 Electric Chillers, Cold Store and Data Hall

The two 2 MW electric chillers are one lumped machine whose duty is a state, as shown with the hall, the chilled water and the store in Equation (9.6).

$$\begin{aligned} \tau_{ec}\frac{\mathrm{d}Q_{ec}}{\mathrm{d}t} &= \mathrm{clip}_{[0,\,Q_{ec,max}(T_{cw})]}(Q_{ec,cmd}) - Q_{ec} \\ P_{comp} &= Q_{ec}/\mathrm{COP}_c(T_{cw}), \qquad P_{ec} = P_{comp} + aQ_{ec} \\ C_{IT}\frac{\mathrm{d}T_{IT}}{\mathrm{d}t} &= P_{IT,del} - UA_{IT}(T_{IT} - T_{chw}) \\ Q_{hall} &= UA_{IT}(T_{IT} - T_{chw}) + \tfrac{1}{2}s_{aux}P_{aux} \\ &\quad + UA_{env}(T_a - 22\,^{\circ}\mathrm{C}) \\ C_{chw}\frac{\mathrm{d}T_{chw}}{\mathrm{d}t} &= Q_{hall} - Q_{abs} - s_{cool}Q_{ec} \\ &\quad - (Q_{dis} - Q_{ch}) \\ \frac{\mathrm{d}E_{cs}}{\mathrm{d}t} &= Q_{ch} - Q_{dis} - UA_s(T_a - T_s) \end{aligned} \tag{9.6}$$

where $\mathrm{COP}_c = \max\big(1.5,\, 6.0[1 - 0.025(T_{cw} - 29\,^{\circ}\mathrm{C})]\big)$ excludes the auxiliaries $a = 10\,\mathrm{kW/MW}$, $Q_{ec,max}(T_{cw}) = 4.0\,\mathrm{MW}\,\mathrm{clip}_{[0.3,1]}\big(1 - 0.02(T_{cw} - 32\,^{\circ}\mathrm{C})^{+}\big)$, and $P_{IT,del}$ is the IT power actually delivered rather than requested. The store's state is its stored cooling, $E_{cs} = M_s c_p(18\,^{\circ}\mathrm{C} - T_s)$ with 1.5 MWh between 18 and 12 °C, so its temperature is derived and never integrated twice. Discharge cools the return water at $T_{ret} = T_{chw} + Q_{hall}/(\dot{m}_{chw} c_p)$ and is limited by $\varepsilon_s C_s(T_{ret} - T_s)$, charge by $\varepsilon_s C_s(T_s - T_{chw})$, with $\varepsilon_s = 0.8$ and C_s the store loop's 250 kg/s. At the reference start the hall's 6.29 MW is 6.00 MW of IT, 0.20 MW of auxiliary heat and 0.09 MW through the envelope, $T_{IT} = 27.0\,^{\circ}\mathrm{C}$, and T_{IT} lumps the equipment into one effective node that stands for no chip or inlet-air temperature. The air side of a hall, with its inlet temperature, is the subject of Volume 9, Chapter 8. The electric chillers carry their 0.50 MW reserve at a COP of 5.96 in 29.29 °C cooling water, whose tower rejects 14.38 MW at 64.5 % fan.

9.3.5 Site Bus, UPS and Import Limit

The shared module closes the electrical balance with nonnegative terms, evaluated term by term, as shown in Equation (9.7).

$$\begin{aligned} &P_{gen} + P_{imp} + P_{dis} + P_{uns} \\ &\quad = P_{IT} - P_{curt} + P_{cool} + P_{aux} + P_{par} + P_{ch} + P_{exp} \\ &\frac{\mathrm{d}E}{\mathrm{d}t} = \eta_{ch} P_{ch} - P_{dis}/\eta_{dis} \\ &P_{dis} \le \min\left(P_{dis,max},\ (E - E_{fl})\eta_{dis}/\Delta t\right) \end{aligned} \tag{9.7}$$

where $P_{gen} = P_{net}^{+}$, the turbine's auxiliaries appear as P_{par} on the demand side when $P_{net} < 0$, P_{cool} is the compressor power plus aQ_{ec}, the chilled-water, cooling-water and hot-water pumps (0.12 MW, 0.15 MW, 0.05 MW), the tower fans and the absorption chiller's 60 kW, and $P_{aux} = 0.40$ MW. The grid covers whatever remains once the UPS's charging is counted, it never imports and exports at once, and import above $P_{imp,max} = 1.0$ MW is taken back from the UPS's charging, then met by discharge inside its step limit, and the rest is unserved, flexible IT first, then auxiliaries, cooling and critical IT. Each step's limits are computed once from the inventory that the step begins with and held through the four Runge-Kutta stages, whose nonnegative weights cannot carry the stored energy past its floor, so no inventory is clipped and no step is split, and the cold store obeys the same rule. The electric chillers' electricity comes from their state in the same evaluation as the bus, so backup feeds the generation balance with no hidden delay. The UPS and the cold store are depleting stocks in the sense of Section 1.4.9. Usable UPS energy from 90 % to the floor is $0.5 \times 0.70 \times 0.95 = 0.3325$ MWh.

9.3.6 Instruments, Events and Numerics

Controllers read only a measurement packet. Every analog reading is the truth filtered by a first-order transmitter lag with noise added afterward, so the trends show the configured noise, and each scan makes a fixed count of random draws. The generator power transducer lags 0.1 s with 5 kW of noise, the averaged exhaust thermocouples 4 s with 0.3 K, the water RTDs 3 s with 0.03 K on the buffer, the chilled-water RTD 5 s with 0.01 K, the cooling-water RTD 5 s, the absorption and store heat meters 10 s, the electric chillers' duty signal 2 s, the grid meter 0.2 s with 5 kW and the UPS meter 0.1 s. The demand and IT meters publish one-second averages as each second closes, which delays a load step by 1 to 2 s before the feedforward sees it, and the UPS charge comes from its battery monitor at 1 Hz. The turbine's and the chiller's states are digital status words.

Discrete events fire once each, between integration steps, and leave a mark on the trends. The turbine trips when the measured exhaust reaches 520 °C or when P_e stays below −0.3 MW for 2 s, and a trip opens the breaker and stops the gas path at once, leaving 0.08 MW of auxiliaries on the bus. The absorption chiller starts when its measured permissives hold ($T_h \ge 80$ °C, $T_{cw} \le 34$ °C), runs 240 s later, and trips and latches at a cooling water of 37 °C, while a scripted fault clears at its time and resets itself. Every case begins lined out at the steady state its own settings imply, found by bisection for the tower and the bypass and by 40 fixed-point passes for the coupled plant. Classical fourth-order Runge-Kutta advances the states (Section 1.6.1) every 0.05 s, whose fastest retained mode is the 0.5 s fuel valve, and the historian logs one row per second. The parameters are listed in Table 9.2 and the remaining symbols in Table 9.3.

9.3.7 Assumptions and Where They Fail

The constant-speed reduction fits a grid-connected machine and leaves out the rotor, frequency, a coast-down, a restart and a cold start, and the fixed inlet guide vanes leave out the schedules that hold exhaust temperature at part load. The two constant specific heats make η_c and η_t effective values of this model rather than component efficiencies, and Section 9.5.6 gives the size of that approximation. The duct, the tubes and the buffer are single nodes, so a stratified tank or a distributed HRU would add delay of its own. No solution chemistry, crystallization risk or internal heat storage is modeled

Table 9.2 Model Parameters. The Class Is the Source of Each Value (L From the Literature, F Fitted, T Invented for Teaching) and Its Visibility in the Parameters Panel (V Shown, H Hidden)

Symbol	Meaning	Value	Unit	Class
Gas turbine				
$\dot{m}_{a,d}$	air flow at ISO	41.4	kg/s	F, V
π_d, $\dot{m}_{g,d}$, $T_{3,d}$	swallowing reference	17.7, 42.1, 1078	—, kg/s, °C	L, L, F, V/H
η_c, η_t	effective efficiencies	0.86, 0.87	—	F, V
η_b, P_{mech}	combustion, mechanical loss	0.995, 0.13	—, MW	T, H
c_{pa}, γ_a	air	1005, 1.4	J/(kg K), —	T, H
c_{pg}, γ_g	products	1150, 1.333	J/(kg K), —	T, H
LHV	fuel at 25 °C	50.0	MJ/kg	T, H
Δp_{in}, Δp_b, Δp_x	pressure losses	1, 4, 3	%	T, H
η_{gen}	generator	0.975	—	T, V
$P_{GT,aux}$	running, tripped	0.25, 0.08	MW	T, V/H
$\dot{m}_{f,max}$, F_{max}	valve open, supply	0.80, 40	kg/s, MW	T, H/V
τ_f, r	valve lag, setpoint ramp	0.5, 1.0	s, MW/min	T, V
$T_{4,lim}$	exhaust limit	490	°C	F, V
$T_{4,al}$, $T_{4,tr}$	alarm, trip	500, 520	°C	T, V
Heat recovery				
C_d, UA_d, UA_{dl}	duct metal	1.5, 15, 0.4	MJ/K, kW/K	T, V/H
C_x, UA_g, UA_w	HRU tubes, gas, water	20, 82, 1500	MJ/K, kW/K	T, V/H
$T_{s,min}$, $\dot{m}_r$	stack minimum, water flow	120, 200	°C, kg/s	T, V
M_h, UA_h, τ_b	buffer, loss, diverter lag	50, 1.0, 5	t, kW/K, s	T, V/H
$\dot{m}_c$, T_{ci}, ε_c	customer loop	60, 60, 0.8	kg/s, °C, —	T, H/V
$T_{h,SP}$	hot-water setpoint	95	°C	T, V
Absorption chiller				
$Q_{abs,r}$, τ_{abs}	rating at 90 °C, capacity lag	6.0, 180	MW, s	T, V
COP	at 87.8, 97.8 °C	0.70, 0.74	—	L
$T_{g,min}$, f_{td}	generator outlet, turndown	70, 0.2	°C, —	T, H
$\dot{m}_{g,max}$, τ_v	valve open flow, lag	100, 10	kg/s, s	T, V/H
$P_{aux,a}$, t_{start}	pumps, start sequence	60, 240	kW, s	T, H/V
Electric chillers, store and hall				
$Q_{ec,max}$, τ_{ec}	capacity, loading lag	4.0, 30	MW, s	T, V
COP_c	at 29 °C, −2.5 %/K	6.0	—	T, V
E_{cs}, ε_s	store, 18 to 12 °C	1.5, 0.8	MWh, —	T, V/H
Q_{dis}, Q_{ch} max	store ratings	3.0, 1.5	MW	T, V/H
UA_s	store heat gain	2	kW/K	T, H
C_{IT}, UA_{IT}	IT node	40, 0.4	MJ/K, MW/K	T, H
C_{chw}, $\dot{m}_{chw}$	chilled-water loop	400, 250	MJ/K, kg/s	T, V/H
UA_{env}	envelope above 22 °C	30	kW/K	T, H
Cooling water, site and UPS				
C_{cw}, UA_{tw}	loop, tower at full fan	200, 2.4	MJ/K, MW/K	T, H/V
P_{tw}	tower fans at full	0.20	MW	T, H
P_{IT} shares	critical, flexible	80, 20	%	T, V
$P_{imp,max}$	grid import limit	1.0	MW	T, V
$P_{dis,max}$, E_{cap}	UPS rating, energy	2.0, 0.5	MW, MWh	T, V
η_{ch}, η_{dis}, E_{fl}	UPS efficiencies, floor	95, 95, 20	%	T, H/V

in the absorption chiller, and its COP and capacity read the hot-water inlet only, so the DOE points anchor the COP at the inlet and not the capacity at the model's flow, since the generator cools its water from 95 to 70 °C where the DOE examples cool it by 5 and 10 K. The plant runs a single-stage machine on hot water although the DOE sheet associates two-stage machines with turbine CHP [2], a choice of one hot-water circuit for teaching. The tower carries no water balance and supports no claim about water use, and the grid is an import-limited source with a working voltage. All sizes, settings and thresholds are invented for teaching, and actual limits belong to the manufacturers' data and the governing codes.

9.4 Controllers as Implemented

One framework scan of $\Delta t_c = 0.25$ s runs the instruments, the import guard, the setpoint ramp, the power loop and the exhaust limiter. An integer counter inside it runs the hot-water, chilled-water,

Table 9.3 Symbols for Heat Flows, Temperatures and Electrical Terms

Symbol	Meaning	Symbol	Meaning
T_2, T_3, T_4	compressor, firing, exhaust	π, ρ	pressure, expansion ratio
W_c, W_t	compressor, turbine work	P_e, P_{net}	terminals, net power
H_4, H_{byp}	exhaust, bypassed heat	T_5, Q_d	after duct, to duct
Q_{gx}, Q_{xw}	gas to tubes, to water	Q_{rec}, T_{rec}	recovered heat, outlet
Q_{exp}, Q_{req}	export taken, asked	Q_{perm}	export permitted
Q_{dc}, Q_{drive}	drive capacity, drive heat	Q_{map}, Q_{tgt}	capacity map, target
Q_{abs}, $Q_{rej,a}$	absorption, its rejection	s_{cool}, s_{aux}	served fractions
$Q_{ec,cmd}$, Q_{ec}	electric command, duty	P_{comp}, P_{ec}	compressor, total
Q_{hall}, T_{ret}	hall heat, return	Q_{dis}, Q_{ch}	store out, in
T_s, S	store temperature, charge	Q_{tw}, f	tower duty, fan
P_{gen}, P_{par}	generation, parasitics	P_{cool}, P_{aux}	cooling plant, auxiliaries
P_{imp}, P_{exp}	grid import, export	P_{dis}, P_{ch}	UPS out, in
P_{uns}, P_{curt}	unserved, curtailed	P_{dem}, P_{cap}	demand meter, capacity

Table 9.4 Loops, Scans, Default Tuning and Action (+1 Reverse Acting, −1 Direct), With the Measured Response to a Manual Step From the Reference Start

Loop	PV → MV	Scan (s)	K_c	τ_I (s)	Act.	Step: response
power	$P_{net} \to u_f$	0.25	1.5 %/MW	2	+1	2 pt: +0.344 MW
limiter	$T_4 \to u_f$	0.25	0.5 %/K	10	+1	2 pt: +9.35 K
hot water	$T_h \to b$	1	10 %/K	300	−1	5 pt: −0.60 K
trim	$T_{chw} \to Q_{ec,cmd}$	1	4 MW/K	300	−1	0.2 MW: −0.145 K
abs. alone	$T_{chw} \to v_g$	1	8 %/K	900	−1	5 pt: −0.25 K
VPC	$Q_{ec,cmd} \to v_g$	5	10 %/MW	200	−1	—
store (P)	$T_{chw} \to Q_{dis}$	1	5 MW/K	—	—	0.5 MW: −0.40 K

store-discharge and UPS-charger logic every 1 s and the reserve layer, the valve-position controller, the store's recharge and the export priority, every 5 s, each given the interval elapsed since it last ran. Counters, filters and PID states are created again at every reset. Table 9.4 lists the loops with their measured plant signs.

9.4.1 One PID Implementation

All loops run the velocity-form PID of Section 1.6.2, Equations (1.12) to (1.15), with the action $a = \pm 1$ of Table 9.4, the tracking time $T_t = \tau_I$ and, as the control period, the interval since the loop last ran. Derivative action and output slew limits are unused in every loop. In Manual, and for any loop that is not in charge of its actuator, `track()` sets the integral so that the output matches the applied value, which makes every transfer bumpless, and no PID is both updated and tracked during the same scan.

9.4.2 Power, Exhaust Limit, Import Guard and Bypass

The power loop and the exhaust limiter meet at a low selector on the fuel valve, as the speed governor and the exhaust limiter of a jet engine do in Chapter 3, and the limiter waits just above the valve that was selected, so it cannot wind up while it does not limit, as shown in Equation (9.8).

$$
\begin{aligned}
u_x &= \mathrm{PI}_x\big(T_{4,lim} - T_{4,m}\big) \text{ on } [0,\ \bar{u}_x] \\
\bar{u}_x &= \min\big(u_{cap},\ u_{k-1} + 2\big) \\
u_p &= \mathrm{PI}_p\big(P_{sp} - P_{net,m}\big) \text{ on } [U_{min},\ \bar{u}_p] \\
\bar{u}_p &= \max\big(U_{min},\ \min(u_{cap}, u_x)\big) \\
u_k &= \min(u_p,\ u_x) \\
P_{req} &= \mathrm{clip}_{[1,12]\,\mathrm{MW}}\big(\max(P_{site},\ P_{need})\big) \\
P_{need} &= P_{dem,m} + P^{-}_{UPS,m} - P_{imp,max} + m
\end{aligned}
\tag{9.8}
$$

where valves are in percent, u_{cap} is the valve the fuel supply allows, $U_{min} = 20\,\%$ holds stable combustion, $P^{-}_{UPS,m}$ is the metered UPS charging, $m = 0.2\,\text{MW}$ is the guard's margin, and the setpoint P_{sp} moves toward P_{req} at 1 MW/min. The power loop's ceiling is the limiter's output, so back-calculation holds its integral against whichever constraint binds, the external reset of Section 1.4.4. The limiter is protection and stays effective in Manual, where its ceiling sits two points above the operator's request.

A PI on the buffer's RTD moves the diverter, opening it when the water is above its 95 °C setpoint. The bypass can only reject heat, so when recovered heat falls short the loop shuts it, reads LIMITED, and the hot water falls. This loop decouples electricity from cooling in Auto, because it rejects any surplus that a power change sends down the exhaust.

9.4.3 Chilled Water: Electric Trim or Absorption Alone

With the trim on, a PI on the chilled-water RTD computes the hall's total cooling demand in megawatts, with the IT meter's reading as its bias, and the electric chillers make that demand less what the absorption chiller and the store deliver on their own heat meters, as shown in Equation (9.9).

$$\begin{aligned} B &= Q_{abs,m} + Q_{cs,m}, \qquad u_b = \hat{P}_{IT} + 0.2\,\text{MW} \\ C &= \text{PI}_t\left(T_{chw,SP} - T_{chw,m}\right) \\ &\quad \text{on } [B,\ B + Q_{ec,max}(T_{cw,m})] \\ Q_{ec,cmd} &= \text{clip}_{[0,\,Q_{ec,max}]}(C - B) \end{aligned} \tag{9.9}$$

where $\hat{P}_{IT}$ is the IT meter through a 90 s first-order lag, matched to the hall node's $C_{IT}/UA_{IT} = 100\,\text{s}$, and 0.2 MW is the commissioned estimate of the hall's other heat. Turning the feedforward on or off shifts its bias change into the integral, so the output holds. With the trim off, a PI on the same RTD moves v_g through the absorption chiller alone and the electric chillers hold their manual duty of 0.5 MW.

9.4.4 Valve-Position Control of the Electric Reserve

The valve-position controller (VPC) is a PI every 5 s whose measurement is the trim's electric command and whose setpoint is the reserve $Q_{ec,SP} = 0.5\,\text{MW}$. While the electric chillers carry more than their reserve it opens the absorption valve, $v_{cmd} = \text{PI}_v(Q_{ec,SP} - Q_{ec,cmd})$ with action -1, so the cheap recovered-heat cooling takes the load back and the trim, seeing the absorption meter rise in B, gives the electric duty up. This is the VPC law of Equation (1.8) with a proportional term added, acting on the trim's command before the electric chillers' lag. Chapter 10 stacks three such layers on one power block. The VPC runs only with the trim on and the chiller running, and otherwise it tracks the valve that is applied. Its output saturates at a wide-open valve when the absorption map is reached, and its tracking time keeps the integral from winding up there, which is the situation that the mid-ranging anti-windup literature studies [6].

9.4.5 Store, Export Priority, Charger and Curtailment

On automatic the cold store discharges in proportion to how far the measured chilled water is above its setpoint plus 0.3 K, $Q_{cs,req} = \text{clip}_{[0,3]\,\text{MW}}\left(K_{c,s}(T_{chw,m} - T_{chw,SP} - 0.3\,\text{K})\right)$, with $K_{c,s} = 5\,\text{MW/K}$ by default. It recharges at 0.6 MW toward its 80 % target when the chilled water is within 0.3 K of its setpoint, the electric chillers have more than 1 MW of room, and neither the import guard nor the exhaust limiter acts. The optional export priority cuts the permitted export by 0.5 MW per 5 s scan while the hot water is more than 2 K below its setpoint. The UPS charger asks for 0.3 MW when the charge is below 90 % and the grid meter is 0.5 MW below its limit, and it stops at 92 % or within 0.3 MW of the limit. Curtailment sheds the flexible 20 % of the IT load by plan.

Three models are kept apart. The plant is Section 9.3, no model is identified from data, and the original controllers know only commissioned constants, the 90 s feedforward lag, the 0.2 MW heat

estimate (the hall's other heat is 0.29 MW), the electric capacity against the measured cooling water, and the store's charge from its own temperature sensor.

9.4.6 Predictive Chiller Allocation

The optional MPC (Section 1.6.3) makes a joint decision on absorption valve fraction v and electric duty request q_e in MW, an allocation of one cooling demand between two actuators with prices as in Section 1.4.8. Its four-state reduction carries absorption cooling q_a, electric cooling q_{ed}, chilled water T_c and hot water T_h, with temperatures in degrees Celsius. All states initialize from the instruments every 15 s. Nominal balances are

$$\begin{aligned} \dot{q}_a &= (v\bar{q}_a(T_h, T_{cw}) - q_a)/\tau_a, \\ \dot{q}_{ed} &= (q_e - q_{ed})/\tau_e, \\ C_c\dot{T}_c &= 10^6(q_{hall} - q_a - q_{ed} - q_{cs}), \\ C_h\dot{T}_h &= 10^6(q_{rec} - q_a/\mathrm{COP}_a - q_{cust}) - Q_{hl}. \end{aligned} \tag{9.10}$$

Here $\bar{q}_a$ is the smaller of nominal full-valve map capacity and COP times the generator's nominal driving-heat limit. Capacities, COP, flows and inventories use declared defaults. The absorption approximation omits turndown, instantaneous heat clipping and startup capacity history. A shut valve has a zero target rather than free turndown cooling. At 95 °C hot and 29 °C cooling water, its sampled steady error reaches 0.545 MW at 75% valve, 7.9% of full map capacity. This approximation keeps a nonzero local valve gain for restarting.

Available return/supply and HRU-outlet/buffer temperature differences, with nominal flows, infer q_{hall} and q_{rec}. Current store flow q_{cs}, customer request, cooling-water and ambient readings are held. No future workload, fault, true capacity state or changed plant coefficient is read. Previous raw one-step thermal residuals update rate biases with gain 0.2, bounded at 0.02 K/s cold and 0.05 K/s hot. These enter the affine water balances rather than identifying physical parameters, consistent with disturbance correction in [18]. The local model is centrally linearized and exactly discretized. Sixty steps and twelve move blocks span 900 s in the shared quadratic optimizer [19]. Nominal lags are 180 and 30 s. A closed-form electric lag check agrees within 3.4×10^{-14}, and a two-control optimizer check within 8.9×10^{-16}. Raw one-step residual RMS in the new case is 0.112 and 0.143 MW for the duties, and 0.0158 and 0.0395 K for the water temperatures. Long-horizon accuracy is not implied.

Tracking weights on $[q_a, q_{ed}, T_c, T_h]$ are $[0, 0, 100, 0.05]$ and move weights are $[1, 0.05]$. Linear duty prices 0.005 for absorption and 0.2 for electric are relative resource proxies, not tariffs. Valve 0–1, zero valve when absorption is unavailable, current electric actuator capacity and block moves of 0.12 and 0.6 MW are hard. Chilled water within ±1 K and hot water 80–100 °C are soft, with quadratic prices 1000 and 20 and linear prices 10 and 1. Turbine control, bypass, store and protection retain their original logic. Cooling and valve-position PIs track the selected commands once per scan. A rejected plan holds the handover within current capacities, marks fallback and returns to those loops until a valid allocation resumes. The priming call computes the first plan.

9.5 Measured Behavior

A script drives the shipped application at its default seed (Section 1.6.1). It opens each case the way the case menu does, applies any change named in the text before time starts, which the engine then treats as part of the starting state, and integrates at the model's 0.05 s step. The chilled-water error is $e = T_{chw} - T_{chw,SP}$ on the simulator's truth at every step. Integrated absolute error (IAE) is $\int |e|\,\mathrm{d}t$ over the stated window, recovery marks the final moment inside the window when $|e|$ is outside the stated band, the reserve return is the first instant after the electric peak from which the delivered duty Q_{ec} stays within 0.1 MW of its reserve to the end of the run, travel is the total variation of a state at the physics step, saturation counts the seconds with v_{cmd} at 100 % or $Q_{ec,cmd}$ at its capacity, and energies are ledgers from $t = 0$. Table 9.5 lists the eleven cases with their completion rules (Section 1.6.4).

Table 9.5 The Eleven Cases, a Measured Outcome of Each as Shipped, and What Completes Each

#	Case and events	Outcome as shipped	Required to complete (kind)
1	Manual, 25 °C, the learner opens the fuel valve 65.4 → 71.4 %	63 % of the rise in power 0.8 s, recovered heat 39 s, hot water 454 s, absorption 573 s	after 30 s open the valve to at least 71 %, run on to 900 s, confirm the comparison of clocks (experiment)
2	30 °C, target 6.8 → 9.8 → 6.8 MW at 60, 420 s	slow loop 8.16 MW at 600 s, with $\tau_I = 2$ s limiter from 204 s at 8.7 MW, back within 0.05 MW at 648 s	set $\tau_I \leq 5$ s, see EXHAUST LIMIT, run past 660 s with power within 0.1 MW of setpoint (experiment)
3	Trim off, store off, export 3.0 MW, IT +0.6 MW at 60 s	T_{chw} peak +0.76 K at 1192 s, +0.57 K at 1800 s	see $e > 0.5$ K, raise $K_{c,a}$ to at least 20 %/K, Reset, run 1200 s, confirm (experiment)
4	As case 3 with the trim on, pulse +1 MW for 10 min pressed by the learner	$\lvert e \rvert \leq 0.012$ K, electric peak 0.97 MW, back within 0.1 MW of reserve from 806 s	see the trim above its reserve, see it back after 900 s, press the pulse, run 300 s, confirm (experiment)
5	Target 8.6 MW, 25 → 38 °C dry bulb, 20 → 26 °C wet bulb, 60–660 s	capacity 9.21 → 7.95 MW, limiter from 372 s, T_{cw} 29.3 → 32.3 °C, cooling electricity 0.52 → 0.70 MW	run to EXHAUST LIMIT and to 900 s, confirm the comparison of both sides (exploration)
6	Export customer lost at 60 s	bypass 4.8 → 52 % at 600 s, up to 9.6 MW to the stack, turbine moved 0.004 MW	run until the bypass is more than 40 % open, confirm (demonstration)
7	Absorption trip at 60 s, fault cleared at 360 s	electric at 4.0 MW by 69 s, store up to 2.4 MW, T_{chw} peak 12.76 °C, demand +0.61 MW, store 80 → 57 %	see the chillers at capacity and the store giving, run until it recharges, confirm (demonstration)
8	One electric chiller out, absorption lost at 60 s, not cleared	band lost at 207 s, store empty at 1549 s, T_{chw} 19.4 °C at 1800 s	run until $\lvert e \rvert > 1$ K, curtail flexible IT, run on to 900 s, confirm (demonstration)
9	38 °C, UPS 60 %, IT 6.0 → 8.5 MW over 60–360 s	limiter from 262 s, UPS floor at 954 s, 226 kWh of flexible IT unserved, critical 0	see the limit with the UPS giving, change K_c, run until the floor with load unserved, confirm (demonstration)
10	MPC allocation, same workload step as case 4	compressor energy increases while drive heat decreases	select MPC and run 900 s, compare both chillers and water temperatures (experiment)
11	Challenge, Table 9.8	chilled water outside ±1 K for 600 s, store 23.6 %, fails	pass the shared verdict at 1800 s with the given parameters and disturbances (challenge)

The app's menu numbers the predictive case 10 and the challenge, the last entry, 11, marked with a target.

9.5.1 Electricity Against Driving Heat

Case 10 repeats case 4's workload step with the store Off. The minimum completion run is 900 s, while the comparisons below cover 1800 s at seed 20261021. Both controllers have the same instruments and no event preview. Table 9.6 uses the framework's IAE on the measured chilled-water signal, matching its scorecard. For comparison with the original truth-based results, physical-step true IAE is 13.881 for MPC versus 5.164 K s for PI. Figure 9.2 plots the true water error and requested electric duty.

The MPC uses 0.079 49 MWh of compressor electricity against 0.049 94 MWh under the loops, and 0.304 90 MWh of total cooling electricity against 0.275 95 MWh. Absorption drive heat falls to 4.04096 from 4.287 69 MWh. Closing hot-water heat above 0 °C is 5.51923 versus 5.524 25 MWh, and cold store 1.188 22 MWh in both. Thus the relative heat price trades more compressor work and error for less driving heat, not a net efficiency gain. The 31 runs measured for this comparison also hold six hindsight trim and valve-position settings and three constant-electric alternatives with zero absorption gain. Halving the physics step preserves the new-case orderings.

After the heat customer is lost, MPC instead uses 0.02547 versus 0.041 93 MWh compressor electricity, but drive heat rises to 4.0909 from 3.9586 MWh and true IAE to 21.975 from 7.286 K s. On the hot afternoon it improves true IAE to 13.131 from 29.328 K s, but total cooling electricity rises to 0.33130 from 0.329 59 MWh. After an absorption trip, its simplified startup forecast spends more backup energy and closes with 0.809 versus 1.019 MWh cold reserve. It adds no missing chiller capacity. The suggested challenge passes with both, but MPC has greater measured IAE 435.67 versus 400.52 K s, and closes with 0.769 versus 0.872 MWh cold reserve. Both fail the shipped challenge settings.

Table 9.6 Matched 1800 s Allocation Runs, PI / MPC

Case	Meas. IAE	Compressor MWh	Drive MWh	Plans / μs
New	15.95 / 20.04	.0499 / .0795	4.288 / 4.041	121 / 1052
Hot day	35.18 / 19.41	.0498 / .0512	4.146 / 4.134	121 / 720
Heat loss	16.77 / 26.37	.0419 / .0255	3.959 / 4.091	121 / 676
Abs. trip	505.65 / 544.76	.1812 / .2980	2.630 / 1.326	121 / 933

IAE in K s. Plans and mean Node solve microseconds are MPC values, with no rejected plan in these runs.

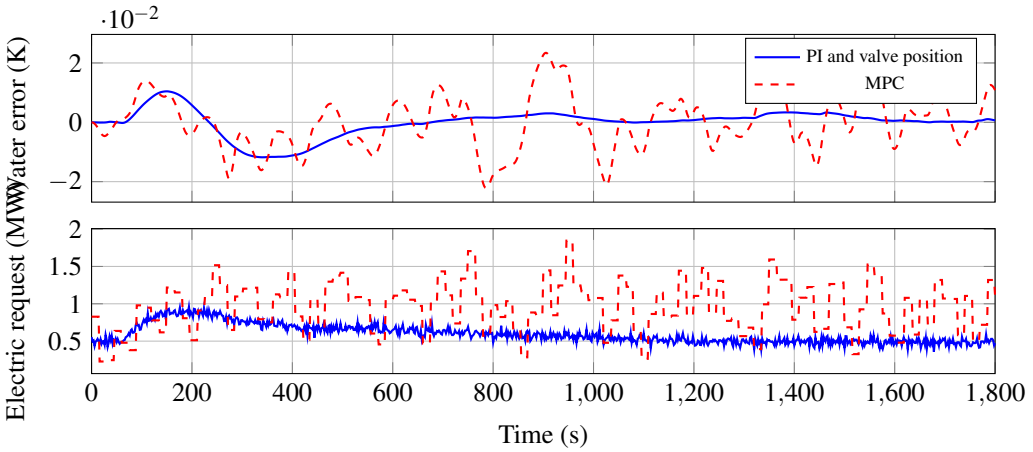


Figure 9.2 Case 10, workload increase at 60 s, PI and valve position (solid) and MPC (dashed). MPC prices driving heat and therefore keeps more electric cooling than the original valve-position loop. Both remain inside the soft band, but the larger forecast horizon does not improve tracking on this case.

Across six Chrome viewport/theme runs, forty plans per run average 2.43–4.87 ms. Planner duty is 0.016–0.032% core utilization during real-time playback, rising to 1.62–3.24% at 100-times playback, excluding state preparation.

> ✦ DID YOU KNOW? **A Longer Look Ahead, a Larger Error**
>
> From the simulator: planning 900 s ahead does not buy tighter control here. On the new case the predictive allocator's measured IAE is 20.04 K s against 15.95 K s for the PI and valve-position loops, because it prices driving heat and uses less of it, 4.041 against 4.288 MWh (Table 9.6).

9.5.2 Where a Power Change Goes

A power change reaches the chillers minutes later only in Manual, so the app's one-line description names what Auto does: electric chillers take the step and hand it back to the absorption chiller. In case 1, with the bypass, the absorption valve and the electric chillers held, the six-point valve step raises the measured power from 6.80 to 7.83 MW, the recovered heat from 11.6 to 12.5 MW, the hot water from 95.0 to 97.3 °C and the absorption cooling from 5.79 to 6.33 MW by 930 s, and the chilled water drifts from 12.0 to 11.5 °C, as shown in Figure 9.3a. The four clocks are the valve lag, the 21.5 MJ/K of duct and tube metal, the 209 MJ/K of hot water and the 180 s capacity lag, with no rotor store between fuel and shaft.

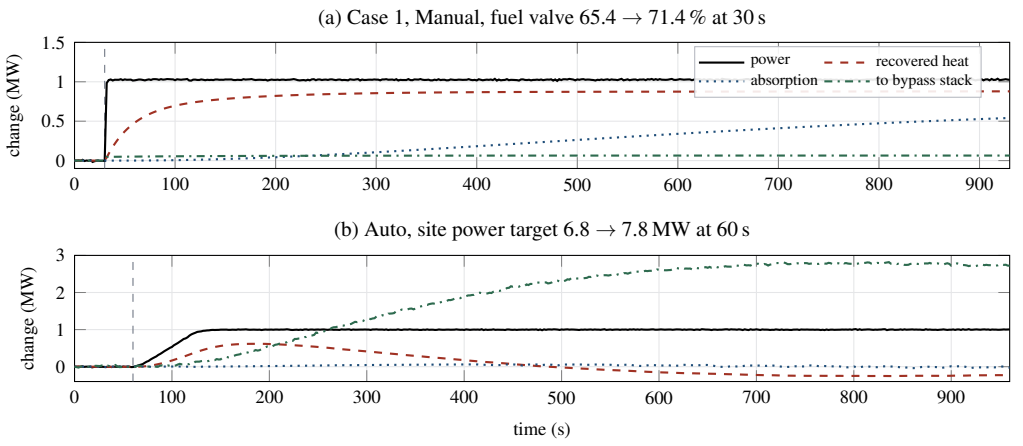


Figure 9.3 A power change in Manual and in Auto, from the exported records. Each series is its change since the first logged row: power measured (solid), recovered heat (dashed), absorption cooling (dotted) and the heat sent round the HRU to the bypass stack (dash-dotted), all true except the power. (a) Case 1, the fuel valve stepped by hand at 30 s. (b) The reference plant in Auto with its site power target raised by 1 MW at 60 s.

> **TRY IT IN THE APP** **1 · A Fuel Step: Power, Heat and Cooling on Three Clocks (Manual)**
>
> Load the scenario and press Run. After 30 s type 71.4 into Fuel valve on the turbine's card, open the Cooling response view and watch the trend Change since the start. The power covers 63 % of its rise in 0.8 s, the recovered heat in 39 s, and the absorption cooling only in 573 s.

In Auto the bypass loop answers first. With the reference plant's site power target raised from 6.8 to 7.8 MW at 60 s, the turbine gains 1.01 MW on its ramp, the bypass opens from 4.83 to 18.33 %, 2.73 MW more exhaust heat goes to the stack, the recovered heat ends 0.23 MW lower than it began, and the absorption cooling changes by –0.03 MW at 960 s, as shown in Figure 9.3b. Case 4's workload pulse confirms it from the cooling side. Pressed at 1200 s, it raises the turbine from 6.79 to 7.86 MW through the import guard and the absorption cooling from 6.38 to 6.85 MW, 63 percent of the way in 202 s, while the bypass opens from 0.25 to 9.09 % and sends 1.81 MW to the stack. With the turbine held at 6.80 MW instead (import guard off, import limit raised to 5 MW), the absorption cooling rises identically, to 6.85 MW in 203 s, with its valve wide open 369 s after the press in both runs. The rise comes from the VPC opening the valve against the electric duty above its reserve, not from the turbine's heat. In Auto the coupling that matters runs from the chillers to the bus. Case 7's absorption trip adds 0.61 MW of electric-chiller load, and in case 5 the site's room below the turbine's capacity plus the import limit falls from 3.28 to 1.85 MW, 1.25 MW of it to derating and 0.18 MW to the cooling plant.

Pause. Try Exercise 9.1 before reading on.

9.5.3 Three Matched Comparisons

Within each group of Table 9.7 the runs start identically and see the same seed, meters, limits and timed upset, changing one setting only. The trajectories are shown in Figure 9.4.

Group A tests nominal disturbance rejection. Absorption alone, at 8 %/K and 900 s, lets the water rise for twenty minutes, to 0.757 K at 1192 s, and it is still 0.57 K up at 1800 s while the valve creeps from 76 to 89 %. The electric trim holds the error within 0.012 K and cuts the IAE from 951.41 to 5.16 K s. Its command rises from 0.50 to 0.969 MW by 208 s, first on the feedforward and then on the trim, and the VPC opens the absorption valve from 76 to 85 % by 900 s, so the delivered electric duty

Table 9.7 Three Matched Comparisons on the Simulator's Truth. Grid-Connected, No Load Unserved, the UPS at 90 % at Start and End in Every Run

Setting	IAE (K s)	Max $\lvert e \rvert$ (K)	Recovery (s)	$Q_{ec,cmd}$ peak (MW)	Reserve (s)	Travel Q_{ec}, v_g (MW, %)	Sat. (s)	Store (%)	E_{cool} (MWh)
A. Rejection, 60–1800 s, IT +0.6 MW, *band* ±0.1 K									
case 3, absorption alone	951.41	0.757	not reached	0.50 held	n/a	0, 16.2	0	80 → 79.2	0.267
case 4, trim and VPC	5.16	0.012	never left	0.969	806	2.13, 54.8	0	80 → 79.2	0.276
case 4, no feedforward	45.09	0.090	never left	0.969	845	2.04, 53.7	0	80 → 79.2	0.276
B. Capacity, 0–1800 s, band ±1 K									
case 8 as shipped	5614	7.41	not reached	2.0 at cap	n/a	1.55, 77.7	1737	80 → −0.06	0.329
$K_{c,s} = 10$ MW/K	5431	7.41	not reached	2.0 at cap	n/a	1.55, 77.7	1737	80 → −0.07	0.329
curtail at 207 s	3356	3.57	not reached	2.0 at cap	n/a	1.55, 77.7	1737	80 → 2.4	0.329
C. Mismatch, 60–1800 s, case 4, band ±0.1 K									
$\tau_{abs} = 60$ s	3.80	0.008	never left	0.863	807	2.03, 54.3	0	80 → 79.2	0.276
$\tau_{abs} = 180$ s, tuned	5.16	0.012	never left	0.969	806	2.13, 54.8	0	80 → 79.2	0.276
$\tau_{abs} = 540$ s	6.83	0.013	never left	1.072	807	2.23, 55.7	0	80 → 79.2	0.277

Recovery is when the error last leaves the band inside the window. Reserve is the instant from which the delivered electric duty stays within 0.1 MW of its 0.5 MW reserve. Travel is of the delivered duty and the valve position, while the trim's command travels 77.1 MW in every group A and C run because it answers the 0.01 K RTD noise at 4 MW/K, which the 30 s loading lag smooths. E_{cool} is the cooling plant's electricity over the run. Every run burns 13.09 MWh of fuel. In B the time outside ±1 K is 1593.1, 1546.5 and 1593.1 s and 531 kWh of flexible IT is curtailed in the third run. Halving the step to 0.025 s changes the IAE values to 951.37, 5.16, 45.09, 5613.9, 5430.1, 3356.1, 3.80, 5.16 and 6.83 K s.

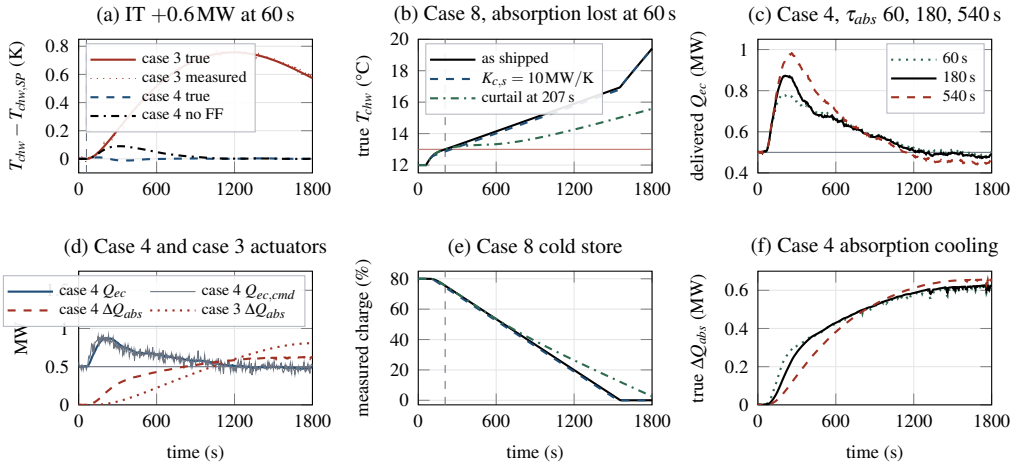


Figure 9.4 The three matched comparisons, from the exported records. (a) The chilled-water error after the 0.6 MW IT step at 60 s, case 3 true (solid) and measured (dotted), case 4 true (dashed) and case 4 without the feedforward (dash-dotted). (d) The actuators of the same runs: case 4's delivered electric duty and its command, and the rise of the absorption cooling in case 4 and in case 3, against the 0.5 MW reserve. (b) and (e) Case 8 after the absorption chiller is lost at 60 s, true chilled water against the 13 °C band edge and the measured store charge, as shipped (solid), with a store gain of 10 MW/K (dashed) and with the flexible IT curtailed at the band exit at 207 s (dash-dotted). (c) and (f) Case 4 with the absorption capacity lag at 60 (dotted), 180 (solid) and 540 s (dashed), delivered electric duty and the rise of the absorption cooling.

stays within 0.1 MW of its reserve from 806 s. Without the feedforward the IAE is 45.09 K s, nine times the value with it. The fast loop costs 0.276 MWh of cooling electricity against 0.267 MWh, while both runs end with the store at 79.21 %, the UPS at 90 % and 3.29 MWh of IT delivered. Across seeds 1 through 5 the IAE is 950.4 to 952.4 K s alone and 4.59 to 5.66 K s with the trim.

The second comparison is a capacity limit. In case 8 one electric chiller is out and the absorption

chiller is lost at 60 s for good, so 2.0 MW of electric cooling and the store's 3.0 MW rating leave the hall short by about 1.3 MW. As shipped the water leaves its band at 207 s, the store is empty at 1549 s and the water reaches 19.41 °C. A store gain of 10 MW/K only brings the store to its rating sooner, holding the band to 254 s and emptying the store at 1530 s. Curtailing the flexible IT at the band exit removes 1.2 MW of heat, so the water reaches only 15.57 °C and the store lasts to 1856.5 s in a run continued to 2400 s, at the price of 531 kWh of flexible work by 1800 s. No setting adds cooling capacity.

The third comparison is a model mismatch. The trim and the VPC were tuned for a 180 s capacity lag, and case 4 is run with the lag at 60 and 540 s. A faster chiller cuts the electric peak to 0.863 MW and the IAE to 3.80 K s, and a slower one raises them to 1.072 MW and 6.83 K s, with the error at most 0.013 K in all three. The electric command first comes back within 0.1 MW of the reserve at 429 s with 60 and 180 s and at 611 s with 540 s, while the delivered duty settles inside that band at 806 to 807 s in all three, which suggests that the VPC's own 200 s integral time, more than the chiller's lag, sets the end of the return. The valve's total travel moves only from 54.3 to 55.7 % over a ninefold range of lag, so the two actuators do not trade the load back and forth. With the hall node twice as slow as the feedforward's 90 s lag assumes, the water undershoots by 0.034 K against 0.012 K when matched.

🕮 **Pause.** Try Exercise 9.2 before reading on.

9.5.4 Capacity That No Tuning Adds

Case 9 is the example in which added control cannot overcome missing capacity. On a 38 °C afternoon with a 26 °C wet bulb the turbine can make 7.95 MW, the grid 1.0 MW, and the UPS from 60 % holds $0.5 \times 0.40 \times 0.95 = 0.19$ MWh above its floor. The IT load rises from 6.0 to 8.5 MW over five minutes from 60 s, the turbine reaches its exhaust limit at 262 s, the demand rises to 10.10 MW, the UPS gives up to 1.18 MW from 268 s and reaches its floor at 954.30 s, and 226.35 kWh of flexible IT goes unserved by 1800 s with none of the critical IT. A much faster power loop, 5 %/MW with 1 s set when the turbine reaches its limit, reaches the floor at the same 954.30 s with the same unserved energy, because its output is pinned. A sweep of 54 settings over power gains of 0.5, 1.5 and 5 %/MW, integral times of 1, 5 and 30 s, the import guard off or on with a margin of 0 or 0.6 MW, and the trim on or off empties the UPS between 601.4 and 1517.8 s in every run and leaves 48.9 to 680.9 kWh unserved, never critical. The trim-off runs leave less unserved only by trading cooling for IT, since as shipped with the trim off 59.72 kWh goes unserved while the chilled water peaks 0.785 K high, against 0.031 K with the trim. Curtailing the flexible IT by plan lowers the demand to 8.03 MW, the turbine stays at 7.23 MW below its limit, the UPS never discharges and nothing goes unserved, and 820.9 kWh of flexible work is curtailed instead.

🕮 **Pause.** Try Exercise 9.3 before reading on.

> **TRY IT IN THE APP 9 · More Demand Than the Turbine and the Grid Can Give (Demonstration)**
> Run the scenario on the Margins view. The turbine reads EXHAUST LIMIT from 262 s while the UPS gives. Then set Power gain to 5 and Power integral time to 1 s and keep running: the UPS still reaches its floor at 954.30 s, the same second as with the shipped tuning, because the loop's output is pinned.

9.5.5 The Challenge Under Five Policies

The challenge runs 1800 s with the import limit at 1.0 MW, the fuel supply at 30 MW, the store at 80 % and the UPS at 90 %. The IT load rises 1.2 MW for ten minutes from 120 s, the wet bulb goes from 20 to 27 °C from 480 s and back from 1380 s, and the absorption chiller trips at 840 s and clears at 1140 s. The verdict asks for the chilled water within ± 1 K outside a 120 s allowance after each of six scripted events, no measured exhaust above 500 °C and no protective trip, no critical IT unserved, and the store at least 20 % charged at 1800 s. Table 9.8 gives five policies on identical initial states,

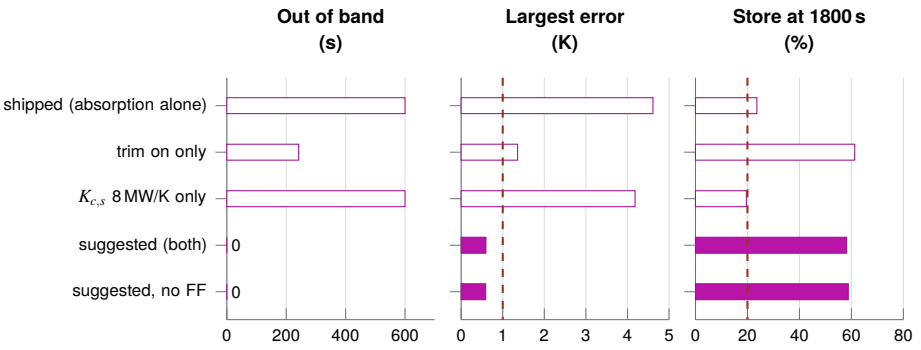


Figure 9.5 Table 9.8 redrawn. Solid bars pass the challenge's verdict and white bars fail it. Dashed lines mark the 1 K band, which the verdict applies outside a 120 s allowance after each event, and the 20 % floor for the store at the end. Notice that the trim alone shortens the time out of band but still fails, that the stronger store discharge alone ends with the store just under its floor, and that only the two together keep the water in the band and the store well above the floor.

Table 9.8 The Challenge Over 1800 s Under Five Policies. No Run Left IT Load Unserved or Tripped on Protection

Policy	Out (s)	Max $\lvert e \rvert$ (K)	Store (%)	UPS (%)	Import (MWh)	E_{cool} (MWh)	Verdict
shipped (alone, $K_{c,s}$ 2)	600.0	4.613	23.63	92.01	0.178	0.264	fails
trim on only	241.8	1.358	61.27	91.81	0.340	0.444	fails
$K_{c,s}$ 8 MW/K only	600.0	4.183	19.57	92.01	0.178	0.263	fails
suggested (both)	0	0.596	58.15	91.81	0.330	0.433	passes
suggested, no FF	0	0.590	58.80	90.71	0.328	0.438	passes

Out is the time outside ±1 K outside the allowances, store and UPS are final charges from 80 and 90 %. Every run delivers 3.200 08 MWh of IT and burns 13.314 to 13.355 MWh of fuel, and the measured exhaust peaks at 444.9 to 448.2 °C.

measurements, events and limits, and Figure 9.6 compares the shipped and suggested runs. Figure 9.5 draws the table's verdict columns as bars.

As shipped, the absorption chiller holds the water alone and the store's gain is 2 MW/K. At the trip nothing fast is left, the electric chillers hold their 0.5 MW, the store gives its 3.0 MW rating, and the water rises 4.61 K, out of band for 600 s, and the store ends at 23.63 %. The trim alone fixes the burst and the hot sink, but at the trip the weak store gain lets the water drift 1.36 K and out of band for 241.8 s. The store's gain alone cannot help without the trim and empties the store to 19.57 %. Together they pass. The electric chillers reach 4.0 MW, the store gives up to 2.56 MW, the water stays within 0.596 K, and the store ends at 58.15 %, the same verdict as without the feedforward, 0.590 K and 58.80 %, because the burst is slow enough for feedback. The suggested run imports 0.330 against 0.178 MWh and its cooling plant draws 0.433 against 0.264 MWh, but it ends with 34.5 points more stored cooling, so the comparison rewards service and the store and is not a savings estimate. At the burst the import reaches its limit and the UPS gives up to 0.32 MW, 1.45 to 1.50 kWh in every run, while the guard ramps the turbine. Across seeds 1 through 5 the shipped run is out of band for 600 s and the suggested run passes with 0.595 to 0.598 K and 58.14 to 58.17 %. Its state at 1000 s is shown in Figure 9.7.

9.5.6 Verification, Reference Data and Cost

These numbers check the implementation and say nothing about control performance. The gas-path first law closes to 5.6×10^{-16} of the fuel across fuel flows of 0.2 to 0.8 kg/s and ambient temperatures of 0 to 45 °C. Integrated from boundary fluxes with formulas written apart from the application, by the trapezoid rule over every step of nine disturbed runs, the gas path closes to

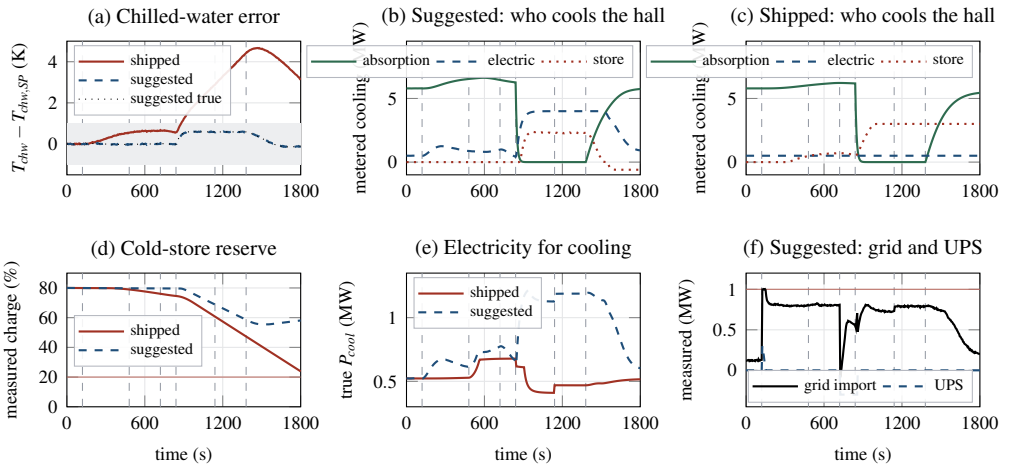


Figure 9.6 The challenge as shipped and with the suggested tuning, from the exported records. (a) Measured chilled-water error, shipped (solid) and suggested (dashed), and the suggested run's true error (dotted), with the ±1 K band shaded. (b) and (c) Metered cooling from the absorption chiller, the electric chillers and the store, suggested and shipped. (d) Measured store charge against the 20 % reserve. (e) True electricity drawn by the cooling plant. (f) Measured grid import against its 1.0 MW limit and the UPS power, suggested run. Gray dashed lines mark the events at 120, 480, 720, 840, 1140 and 1380 s.

6.1×10^{-14} of its fuel, the hot water to 2.8×10^{-5}, the chilled water to 1.5×10^{-5}, the IT node to 6.5×10^{-6} and the cooling water to 7.1×10^{-5} of their throughput, and the bus to 2×10^{-9} W at every step, where no step imports while exporting or charges the UPS while discharging it. With the turbine tripped and the UPS at its 2.0 MW rating from 90 %, the floor arrives 598.50 s later, the analytic $(0.90 - 0.20) \times 0.5\,\text{MWh} \times 0.95/2\,\text{MW}$. With the absorption valve shut by hand the cooling is 0.0001 MW at 410 s while the lag state still holds 3.85 MW, and a fuel valve shut at 60 s motors the turbine to −3.41 MW until the reverse-power relay trips it at 62.6 s. Halving the step to 0.025 s leaves the challenge verdicts unchanged, changes no other entry of Table 9.7 by more than one unit of its last digit, moves the IAE by at most 0.46 K s in 5614 K s, and moves case 9's floor from 954.30 to 954.27 s. All 71 of the application's checks pass. Headless, a simulated hour takes 0.46 s of computation, and at the browser's fastest setting, 100 times real time, the 1800 s challenge finishes in 18.0 s.

Comparison with published data is a different and more limited claim. At ISO conditions and the exhaust limit the model makes 10.28 MW net at 30.21 % LHV on 34.01 MW of fuel, with 42.08 kg/s of exhaust at 490.0 °C and a pressure ratio of 17.72, against the catalog's System 3 at 9.95 MW, 27.34 percent on the higher heating value or 30.38 percent on LHV with its ratio of 0.9, 32.76 MW of LHV fuel, 334 000 lb/h (42.08 kg/s) at 913 °F (489.4 °C) and a pressure ratio of 17.7 [1]. The model keeps 77.6 % of its ISO capacity at 100 °F with 9.1 % less efficiency, against the catalog's 80 % and 8 % for a different, nominal 7.5 MW machine. The constant specific heats carry an error of their own. With ideal-gas heat capacities from CoolProp 8.0.0 [20] and the same η_c and η_t, the ISO point gives 10.58 MW at 32.2 %. With η_t refitted to 0.854 for the model's 30.21 %, the model at 6.80 MW and 25 °C burns 3.4 % more fuel, runs its exhaust 13.4 K cooler with 2.9 % more heat above 120 °C (14.26 against 13.86 MW), credits itself with 9.21 MW of capacity at 25 °C against 8.60 MW, and derates to 77.6 against 77.2 % at 100 °F. The absorption COP passes through the DOE points at 0.6999 and 0.7399 [2]. No part of the model has been tested against field measurements, and no learner study has been made.

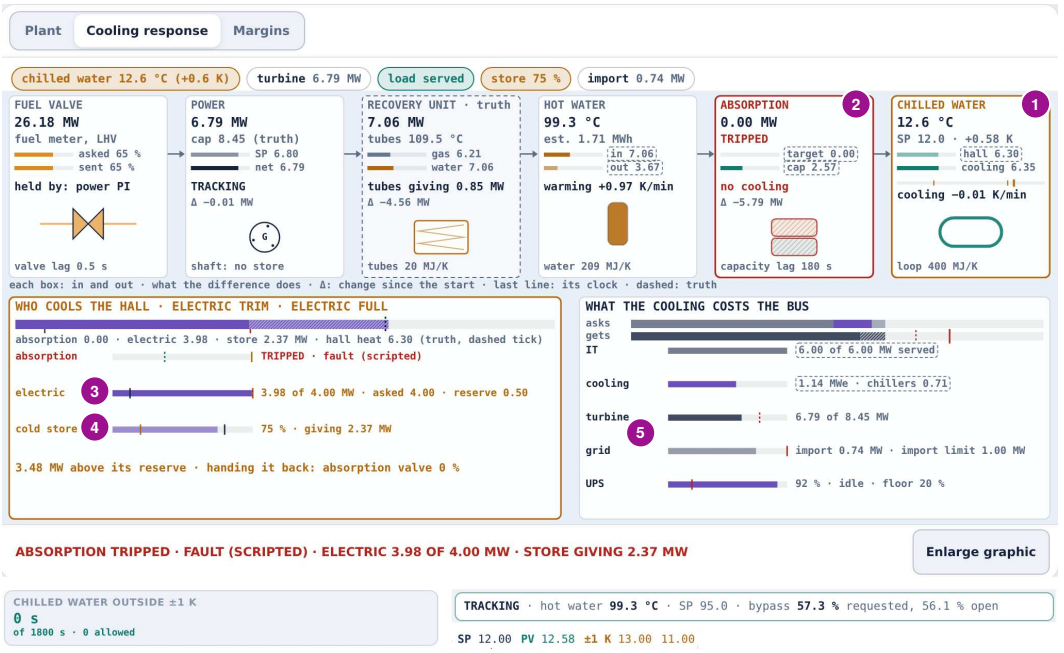


Figure 9.7 The challenge with the suggested tuning at $t = 1000$ s on the Cooling response view, in a composite of the application window: the view itself, with the lead scorecard tile, the hot-water loop's tracking line and the chilled-water trend label set below it. The absorption chiller has been tripped since 840 s (2), so the electric chillers deliver 3.98 MW of their 4.00 MW (3) and the store gives 2.37 MW on its meter at 75 % charge (4), while the chilled water reads 12.58 °C, 0.58 K above its setpoint and inside its band (1). The turbine makes 6.79 MW of its 8.45 MW capacity, the grid imports 0.74 MW against its 1.00 MW limit (5), the cooling plant draws 1.14 MW, and with no drive heat taken the hot water stands at 99.3 °C with the bypass 56 % open. The lead scorecard tile reads 0 s outside the band.

9.6 Technology in Practice

A real trigeneration site reads and moves the same quantities as the loops of Section 9.4. Figure 9.8 draws the fuel selector and the chilled-water loops with plant hardware in place of the schematic's symbols.

What Measures It

The chilled-water loop reads one supply temperature, and its bias reads two heat flows, which a real plant measures with thermal energy meters. The federal metering guide notes that clamp-on ultrasonic flow meters are attractive because they are completely non-intrusive, but their coupling gel must be rated for the pipe's temperature, or it may lose viscosity and melt away [21]. On the gas side, the exhaust of smaller industrial turbines reaches 800 to 900 °F [1], and the limiter reads averaged thermocouples, as in Chapter 3. The model's chilled-water RTD lags 5 s with 0.01 K of noise and its averaged thermocouples 4 s.

TECHNOLOGY Sensor: A Thermal Energy Meter

A thermal energy meter on a hot-water or chilled-water circuit finds the energy flow as the mass flow times the temperature difference across the load. A flow meter gives the flow, two temperature sensors give the supply and the return, and a flow computer integrates the three readings over each interval. Most fluid meters measure volume, so the computer also accounts for density and specific heat, which change with temperature. Orifice, turbine, vortex and ultrasonic meters serve these circuits, with turndown from under 5:1 for an orifice to 20:1 for a vortex meter, and a meter is sized for the expected flow range, never for the pipe. It is calibrated yearly, or sooner if trended data show miscalibration [21]. The model's absorption and store meters lag 10 s and form the trim's bias B in Equation (9.9).

What Moves It

The fuel valve meters gas that must already be compressed above the combustion air, because the fuel joins the air after the compressor. The pressure it needs is set by the turbine's pressure ratio, and where the site's supply pressure is low a fuel gas compressor adds cost and power consumption [1]. The model's valve answers with a 0.5 s lag behind a 40 MW supply limit. On the cooling side the valve-position controller moves the absorption chiller's hot-water valve, and the trim sends a duty command to the capacity control of the electric chillers, which load with a 30 s lag.

TECHNOLOGY Final Element: The Absorption Chiller's Thermal Compressor

An absorption chiller replaces the motor and compressor of an electric chiller with a thermal compressor made of an absorber, a solution pump and a generator. In the absorber a solution takes up the refrigerant vapor coming from the evaporator, a small pump lifts the dilute solution to the generator, and there heat boils the refrigerant out toward the condenser while the absorbent returns to the absorber. For chilled water at 40 °F or above the usual pair is water as refrigerant and lithium bromide as absorbent. Service includes periodic purging of non-condensable gases and checks of the tower and chilled-water quality [2]. The fact sheet gives no response time. In the model the valve v_g sets the drive heat, and a 180 s capacity lag stands for the machine's slow loading.

Where the Controller Runs

Supervisory and lower-level loops run with cycle times from milliseconds to minutes, and programmable logic controllers serve as local controllers under the supervision of a distributed control system [22]. The application's scans sit inside that range, 0.25 s for the power loop and the exhaust limiter, 1 s for the water and store loops and 5 s for the valve-position controller. In a function-block system the low selector of Equation (9.8) is a control selector block, whose back-calculation output tells each upstream controller whether it was selected so that a deselected one halts its integral action [23]. Here the limiter's output, set as the power loop's ceiling, does that work.

IN PRACTICE Electric Backup Behind Recovered-Heat Cooling

A 2009 report for a national laboratory describes how data centers with CHP are built. Cooling from absorption chillers must be backed up by electric chillers that can assume the load whenever the CHP plant is not running, and the favored arrangement is redundant parallel paths with redundant control systems, chilled-water pumps and electrical boards. In the most reliable tiers of data center, thermal storage may carry the cooling through a transfer. With proper design and controls an absorption chiller is as reliable as an electric chiller at comparable maintenance cost, and it can run with tower water down to 60 °F [3]. This chapter's trim and cold store are that backup in miniature.

What Is Modernizing It

The first development is inlet air cooling. Cooling the air entering a turbine by 40 to 50 °F on a hot day can raise its power by 15 to 20 %, by refrigeration, evaporative cooling or thermal storage, and

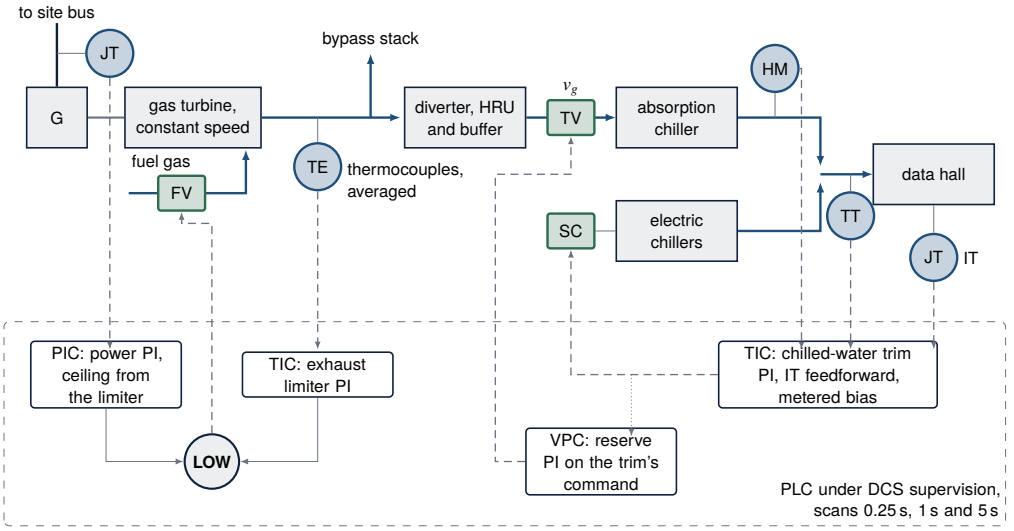


Figure 9.8 The loops of Figure 9.1 on plant hardware. The power transducer (JT) and the averaged exhaust thermocouples (TE) feed the power PI (PIC) and the exhaust limiter (TIC), whose lower output goes to the fuel valve (FV). The chilled-water RTD (TT), the IT meter (JT) and the heat meter on the absorption chiller (HM: a flow meter, two temperature sensors and a flow computer) feed the trim, which sends a duty command to the electric chillers' capacity control (SC). The valve-position controller (VPC) reads that command, dotted, and moves the absorption chiller's hot-water valve (TV). Notice that the turbine and the chillers meet only at the bus and the hot water: no signal runs from the power loops to the cooling loops. The bypass loop, the store and its meter are not drawn.

an absorption chiller on the turbine's own waste heat cuts the parasitic loss of an electric one at a cost in complexity [1]. The second is chillers in series: one developer was designing data center plants with the absorption chiller in series with a larger electric chiller with a screw compressor, which then sees cooler entering water and runs efficiently at part load, and which takes the full load when the CHP plant is down [3]. The third is supervisory dispatch. Heuristic, linear-optimization and model predictive dispatch of generators, chillers and storage proved feasible in real time on a campus plant and could outperform manual operation [24].

9.7 Limitations

Every size, map and threshold here is a teaching value chosen against the EPA and DOE documents [1, 2] and fitted to neither a turbine nor a chiller beyond $\dot{m}_{a,d}$, η_c, η_t, the swallowing reference and the exhaust limit. The gas path's constant specific heats overstate the turbine's capacity at 25 °C by 0.61 MW against a property-correct model refitted to the same ISO efficiency, and the absorption chiller's capacity at the model's hot-water flow is a teaching map. In Manual a fuel-valve step to 100 % lets the true exhaust reach 546.8 °C and stay above the 520 °C trip setting for 1.75 s, while the averaged thermocouples that the limiter, the alarm and the trip read peak at 490.8 °C, which is how protection on an averaged measurement behaves. The lumped nodes give lags of realistic size but no spatial temperature profile, so no thermocline claim is made. The added MPC uses a nominal valve-fraction approximation and held current conditions. It omits startup history and finite future store delivery, and its bias correction and soft bands do not ensure temperature or reserve limits. The trips are a teaching safeguard and not certified protection logic, the load-shed order is fixed, passing a case qualifies no equipment and estimates neither savings nor reliability, and no gain in learning has been measured.

OPEN CHALLENGE **Controls for Heat and Power That Do Not Peak Together**

A 2013 report to the U.S. Department of Energy named a lack of controls able to deal with highly dynamic thermal and electrical loads that do not peak together as one of three high-priority barriers to combined cooling, heating and power at smaller sites. On a campus plant whose thermal store could shift a full day of cooling, real-time dispatch saved 8 to 25 %, but the savings depended on pricing, season, forecast accuracy and grid constraints, and the store added complexity to the optimization [24]. Progress would be dispatch that keeps its benefit when the forecasts are wrong.

9.8 Conclusion

This chapter studied a gas turbine trigeneration plant for a data center whose single fuel valve makes power in 0.8 s, recovered heat in 39 s and, with every valve held, absorption cooling in 573 s. In Auto the hot-water bypass sends a power change to the stack, so absorption cooling follows the valve-position controller rather than the turbine, and a 1 MW power step moves it by −0.03 MW. On the same 0.6 MW workload step, a fast electric trim with a slow valve-position return cuts the chilled-water IAE from 951.41 to 5.16 K s and hands the duty back to its reserve by 806 s, and a capacity lag mismatched by a factor of three either way moves the electric peak between 0.863 and 1.072 MW without breaking the return. When the absorption chiller and one electric chiller are lost, or when demand exceeds the turbine and the grid, only less load helps, and under the original controllers the challenge passes only with both the trim and a stronger store discharge. Its nodes are lumped and its operating points invented. A fuller model would add a two-stage chiller on a steam circuit, a stratified buffer and store, variable gas properties, an inlet guide vane schedule, and a supervisory layer that schedules the store against a forecast. The simulator shows that cooling a data center from turbine exhaust is a two-actuator control problem before it is a heat-recovery one. The predictive allocation adds a measured tradeoff between driving heat and electricity, with benefits that depend on the current heat customer rather than the horizon alone.

KEY POINTS

- One fuel valve makes electricity within a second, but the cooling it pays for comes only after minutes, so a fast electric chiller and a slow absorption chiller share the chilled water.
- In Auto the hot-water bypass sends a power change to the stack, so a 1 MW power step moves the absorption cooling by −0.03 MW.
- A fast electric trim with a slow valve-position return cuts the chilled-water IAE from 951.41 to 5.16 K s and hands the duty back to its reserve by 806 s.
- When demand exceeds the turbine and the grid, only less load helps.

Where else this applies. Chapter 3 holds an exhaust-temperature limit with the same low selector on a jet engine's fuel valve, and Chapter 10 stacks three valve-position layers on one power block.

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 DOE/EE-1608, May 2017. [Online]. Available: https://www.energy.gov/sites/default/files/2017/06/f35/CHP-Absorption%20Chiller-compliant.pdf

[3] K. Darrow and B. Hedman, "Opportunities for combined heat and power in data centers," Oak Ridge National Laboratory, Oak Ridge, TN, Tech. Rep. ORNL/TM-2009/052, Mar. 2009, prepared by ICF International.

[4] B. J. Allison and A. J. Isaksson, "Design and performance of mid-ranging controllers," *Journal of Process Control*, vol. 8, no. 5–6, pp. 469–474, 1998.

[5] B. J. Allison and S. Ogawa, "Design and tuning of valve position controllers with industrial applications," *Transactions of the Institute of Measurement and Control*, vol. 25, no. 1, pp. 3–16, 2003.

[6] S. Haugwitz, M. Karlsson, S. Velut, and P. Hagander, "Anti-windup in mid-ranging control," in *Proceedings of the 44th IEEE Conference on Decision and Control*. IEEE, 2005, pp. 7570–7575.

[7] G. Chicco and P. Mancarella, "Distributed multi-generation: A comprehensive view," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 3, pp. 535–551, 2009.

[8] 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.

[9] W. I. Rowen, "Simplified mathematical representations of heavy-duty gas turbines," *Journal of Engineering for Power*, vol. 105, no. 4, pp. 865–869, 1983.

[10] Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies, "Dynamic models for combined cycle plants in power system studies," *IEEE Transactions on Power Systems*, vol. 9, no. 3, pp. 1698–1708, 1994.

[11] M. Moya, J. C. Bruno, P. Eguia, E. Torres, I. Zamora, and A. Coronas, "Performance analysis of a trigeneration system based on a micro gas turbine and an air-cooled, indirect fired, ammonia–water absorption chiller," *Applied Energy*, vol. 88, no. 12, pp. 4424–4440, 2011.

[12] K. Ebrahimi, G. F. Jones, and A. S. Fleischer, "Thermo-economic analysis of steady state waste heat recovery in data centers using absorption refrigeration," *Applied Energy*, vol. 139, pp. 384–397, 2015.

[13] J. H. Horlock, "The gas turbine as a cogeneration (combined heat and power) plant," in *Advanced Gas Turbine Cycles*. Pergamon, 2003, pp. 167–181.

[14] H. I. H. Saravanamuttoo, G. F. C. Rogers, and H. Cohen, *Gas Turbine Theory*, 5th ed. Prentice Hall, 2001.

[15] P. Srikhirin, S. Aphornratana, and S. Chungpaibulpatana, "A review of absorption refrigeration technologies," *Renewable and Sustainable Energy Reviews*, vol. 5, no. 4, pp. 343–372, 2001.

[16] K. E. Herold, R. Radermacher, and S. A. Klein, *Absorption Chillers and Heat Pumps*, 2nd ed. CRC Press, 2016.

[17] 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.

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

[19] 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.

[20] I. H. Bell, J. Wronski, S. Quoilin, and V. Lemort, "Pure and pseudo-pure fluid thermophysical property evaluation and the open-source thermophysical property library CoolProp," *Industrial & Engineering Chemistry Research*, vol. 53, no. 6, pp. 2498–2508, 2014.

[21] S. A. Parker, W. D. Hunt, K. McMordie Stoughton, B. K. Boyd, K. M. Fowler, T. M. Koehler, W. F. Sandusky, G. P. Sullivan, and R. Pugh, "Metering best practices: A guide to achieving utility resource efficiency, release 3.0," Pacific Northwest National Laboratory, Richland, WA, Tech. Rep. PNNL-23892-Rel.3.0, Mar. 2015.

[22] 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.

[23] 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.

[24] S. Samuelsen and J. Brouwer, "Novel controls for time-dependent economic dispatch of combined cooling heating and power (CCHP)," University of California, Irvine, Irvine, CA, Final Report DOE-UCI-01113, 2013.

9.9 Exercises

9.1 ⌕ Concept check · 2 min

In Auto, with the reference plant's site power target raised from 6.8 to 7.8 MW, the turbine gains 1.01 MW, yet the absorption cooling changes by −0.03 MW fifteen minutes later. In Manual, with every valve held, a fuel step of the same size raises the absorption cooling by 0.54 MW. What makes the difference?

(a) In Auto the absorption chiller is already at the limit of its capacity map
(b) In Auto the hot-water loop opens the exhaust bypass and sends the extra heat to the stack
(c) In Auto the import guard holds the turbine below its new setpoint
(d) In Auto the absorption valve is interlocked shut while the turbine ramps

9.2 Concept check · 2 min

Case 4 is run with the absorption chiller's capacity lag at 60, 180 and 540 s. The electric peak moves from 0.863 to 0.969 to 1.072 MW, but the delivered electric duty settles within 0.1 MW of its reserve at 806 to 807 s in all three runs. What does this suggest sets the end of the return to the reserve?

(a) The electric chillers' 30 s loading lag
(b) The absorption chiller's capacity lag
(c) The valve-position controller's own 200 s integral time
(d) The feedforward's 90 s lag on the IT meter

9.3 Concept check · 2 min

In case 9 the turbine reaches its exhaust limit at 262 s and the UPS reaches its floor at 954.30 s. A much faster power loop, set when the limit is reached, reaches the floor at the same 954.30 s with the same unserved energy. Why does its tuning not matter?

(a) The import guard switches the power loop off once the UPS discharges
(b) A faster loop winds up its integral and comes back later, which cancels its speed
(c) The UPS always discharges at its 2.0 MW rating, whatever the demand
(d) The exhaust limiter holds the fuel valve through the low selector, so the power loop's output is not the one applied

9.4 Theory and calculation · 6 min

The absorption chiller at the reference start, from Equation (9.4). The hot water is at 95 °C, the cooling water at 29.29 °C, the valve passes 75.9 kg/s, and water's specific heat is 4.186 kJ/(kg K).

(a) Find the COP and the capacity map Q_{map}. *Checkpoint:* 0.729, 6.90 MW

(b) Find the drive capacity Q_{dc}, the cooling the chiller can make, and which limit binds. Then find the heat it rejects to the cooling water, with the 60 kW of auxiliaries. *Checkpoint:* 7.94 MW, 5.79 MW, the drive heat binds, 13.79 MW

(c) The cooling water rises to 37 °C. Find the absorption map at 95 °C, the electric chillers' COP and their capacity from Equation (9.6). *Checkpoint:* 5.33 MW, 4.80, 3.60 MW

9.5 Theory and calculation · 7 min

The handover of case 4. At the reference start the absorption chiller is limited by its drive heat (Exercise 9.4), so $Q_{abs} = \mathrm{COP}\, v_g\, \dot{m}_{g,max} c_p (T_h - T_{g,min})$ with COP 0.729, $\dot{m}_{g,max} = 100\,\mathrm{kg/s}$, $c_p = 4.186\,\mathrm{kJ/(kg\,K)}$ and T_h held at 95 °C. The VPC has $K_c = 10\,\%$ per MW and $\tau_I = 200\,\mathrm{s}$.

(a) Find the valve's cooling gain k in MW per percent of stroke. *Checkpoint:* 0.0763 MW per percent

(b) The workload step raises the hall's load by 0.6 MW. How far must the VPC open the valve from 75.9 % to carry it, if the hot water stays at 95 °C? *Checkpoint:* 7.9 points, to 83.8 %

(c) Following Equation (1.9), show that the energy the electric chillers spend above their reserve during the handover is $E_h = \Delta v / K_I$ with $K_I = K_c/\tau_I$, whatever the lags, and evaluate it in MJ and kWh. *Checkpoint:* about 157 MJ, 44 kWh

9.6 Theory and calculation · 6 min

Two stocks that deplete, with the runway of Equation (1.11).

(a) The turbine trips with the UPS at 90 % of its 0.5 MWh, and the UPS discharges at its 2.0 MW rating with a discharge efficiency of 95 % to its 20 % floor. How long does it last? *Checkpoint:* 598.5 s

(b) In case 8 the absorption chiller is lost at 60 s and one electric chiller is out, so the chillers give 2.0 MW against the hall's 6.29 MW. The cold store starts at 80 % of 1.5 MWh and discharges at its 3.0 MW rating. Estimate when it is empty and compare with the chapter. *Checkpoint:* about 1500 s against 1549 s

(c) The store gives $K_{c,s}(e - 0.3\,\mathrm{K})$, clipped at its rating, for a chilled-water error e. At what error does it reach its rating with the shipped 5 MW/K, and about how long does the remaining gap then take to warm the 400 MJ/K chilled-water loop to the 1 K band edge? *Checkpoint:* 0.9 K, about 30 s

9.7 App challenge · 8 min

Scenario 2, *Tune the power loop and meet the exhaust-temperature limit*, default seed. Run each case to 900 s at 20× (about 45 s each) and export the CSV file after each run.

(a) As shipped, read `P_meas_MW` at 420 and 600 s and `P_sp_MW` at 600 s. Does the turbine ever read EXHAUST LIMIT? *Checkpoint:* 8.43 MW, 8.15 MW against 6.8 MW, no

(b) Reload the case, set *Power integral time* to 2 s before Run, and run again. Find the first row with `exh_limiting` at 1, the power at 300 s and the largest `T4_meas_C`. *Checkpoint:* 204 s, 8.71 MW, 491.6 °C

(c) In the same file, find the last row after 420 s in which `P_meas_MW` differs from `P_sp_MW` by 0.05 MW or more. Why does the power come back so soon after the target falls? *Checkpoint:* about 651 s

Tolerance: 0.02 MW, 0.3 K and 3 s.

9.8 App challenge · 8 min

Scenarios 3, *Absorption cooling alone: a slow loop on a slow chiller*, and 4, *Electric trim and the slow return of its reserve*, default seed, as shipped. Run each to 1800 s at 50× (36 s each), read the chilled-water IAE on the scorecard, and export the CSV file. The chilled-water error is `truth_Tchw_C` less 12.

(a) Scenario 3: find the largest error and its time, the error at 1800 s and `abs_valve_pct` at 1800 s. *Checkpoint:* 0.757 K at 1192 s, 0.57 K, 89.0 %

(b) Scenario 4: find the largest error, the peak of `ec_cmd_MW`, and the last row in which `truth_Qec_MW` is 0.1 MW or more from 0.5 MW. *Checkpoint:* 0.012 K, 0.969 MW, 806 s

(c) The scorecard shows a chilled-water IAE of about 949 and 15.9 K s, while the chapter gives 951.41 and 5.16 K s on the simulator's truth. Explain the larger value for scenario 4.

Tolerance: 0.005 K, 0.01 MW, 3 s, 0.3 points and 1 K s.

9.9 App challenge · 7 min

The challenge, scenario 11 and listed last in the scenario menu, *Challenge · a workload burst, a hot sink and an absorption loss*, default seed. Run each policy for the full 1800 s at 100× (18 s each), then change the settings, press Reset and run again. Leave every parameter and disturbance as shipped, and read the *Challenge target* tile and the status line.

(a) Run as shipped. Read the time outside the band and the cold store at the end. *Checkpoint:* 600 s, 23.6 %

(b) Run with only *Electric backup trim* On, then with only *Store discharge gain* at 8.0 MW per K. *Checkpoint:* 242 s and 61.3 %, then 600 s and 19.6 %

(c) Run with both changes. Read the same two values and the *Grid import* tile, and compare it with the shipped run. *Checkpoint:* 0 s, 58.1 %, 0.33 MWh against 0.18 MWh

Tolerance: 2 s, 0.2 points and 0.01 MWh.

9.10 Application area · 4 min

In Manual, a fuel-valve step to 100 % lets the true exhaust reach 546.8 °C and stay above the 520 °C trip setting for 1.75 s, while the averaged thermocouples, which lag the gas by a first-order 4 s, peak at 490.8 °C. No trip occurs.

(a) What fraction of a sudden step does a 4 s first-order lag show after 1.75 s? *Checkpoint:* about 35 %

(b) What should a practicing engineer conclude about the trip, and what keeps the turbine away from such a step in Auto?

9.11 Application area · 4 min

The DOE fact sheet pairs single-stage absorption chillers on hot water at 200 to 240 °F with engines, and two-stage machines on hot water near 350 °F or steam near 115 psig, with COPs of 1.35 to 1.42, with combustion turbines. The chapter's plant uses a single-stage machine at a COP of 0.729.

(a) How much drive heat would a two-stage machine at a COP of 1.4 need for the same 5.79 MW of cooling, and how much heat would it reject to the tower per MW of cooling? *Checkpoint:* 4.14 MW, 1.71 against 2.37

(b) Why does the chapter keep the single-stage machine, and what would the plant need to run a two-stage one?

9.12 Review the agent · 5 min

An AI assistant reviews case 8 and writes: "The chilled water leaves its band at 207 s because the cold store answers too weakly and the trim is too slow. Raise *Store discharge gain* from 5 to 10 MW per K and *Trim gain* from 4 to 8 MW per K, and the water will stay in its band." Find the flaw and say how you would check it in the application.