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CHAPTER 11

Load Sharing by Equal Surge Margin Among Three Compressors on One Header

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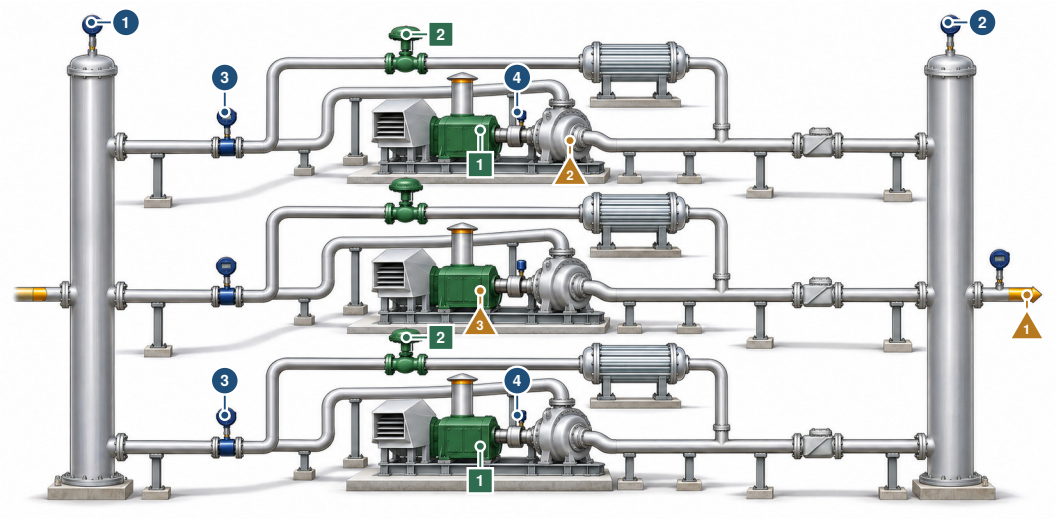
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CHAPTER 11

Load Sharing by Equal Surge Margin Among Three Compressors on One Header



The controller moves 1 gas turbine on each unit, sped up or slowed by the station
2 recycle valve on each unit, which sends gas back to the inlet

The controller reads 1 suction header pressure 2 discharge header pressure 3 flow through each machine
4 speed of each shaft

What disturbs it 1 what the customers take 2 fouling of unit 1 3 a turbine trip on unit 2

Notice that each unit's recycle line leaves its discharge ahead of the check valve, passes the cooler and returns to the suction side, so gas it recycles is compressed for nothing. Illustration, not to scale.

IN PLAIN TERMS Machines That Share a Push, Not a Load

The main idea. A compressor station pushes natural gas down a pipeline with several spinning machines side by side. They all push into one pipe, so each must push as hard as the others, and the gas splits among them by itself.

The challenge. A machine that runs a little slower or is a little dirty carries less gas and drifts toward surge, where its flow stalls and swings backward. To stay safe it sends some gas back around to its own inlet, which burns fuel for nothing.

Why it matters. A good sharing rule keeps every machine out of surge without sending gas in circles.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	This page, the History boxes in Section 11.2, the Did you know? boxes in Sections 11.3 and 11.5.7, the Try it boxes in Section 11.5, and Key points in Section 11.8. No equations.
Study	50 min	The whole chapter in order, stopping at the three pause points, then Exercises 1 to 12.
Practice	20 min	This page, Section 11.5 with Figure 11.4, Section 11.6 and Section 11.7 with its Open challenge box.

The control question Compressors on one header share a head, not a load, so a machine a little slower or a little fouled drifts toward surge while its neighbors take the gas. Which sharing law, start sequence and trip action keep every machine out of surge and off its recycle while the station holds its pressure?

Learning objectives

- Predict where the load goes when one of two machines on common headers changes speed.
- Compute a surge margin from the speed-scaled map, and the speed that gives a fouled machine a clean one's margin.
- Compare equal speed, equal flow and equal surge margin by the gas recycled and the fuel burned in a turndown.
- Explain why a trip needs its own valve action and why a fast station loop oscillates against anti-surge loops on recycle.
- Justify each layer of the challenge by the failure measured without it.

Prerequisites Sections 1.4.6 (map, fan laws and surge margin), 1.4.8, 1.4.5, 1.6.2 and 1.6.4, with Section 1.6.3 only for the MPC.

The app https://apmonitor.com/apps/compressor-station/

See also Volume 4, Chapter 2 for one machine with a Greitzer surge cycle and a protective override, Volume 4, Chapter 3 for a surge margin that is never measured, and Volume 4, Chapter 12 for one total allocated among unlike actuators. Volume 6, Chapter 2 for interacting loops and a static decoupler. Chapter 12 for the line the station feeds.

11.1 Introduction

Two identical compressors that draw from one suction header and deliver into one discharge header must make one head, because the header pressures fix it. In the generic station simulated here each machine carries 150 kg/s at 90.5 % of rated speed, 28.0 % to the right of its surge flow. Holding unit 1's speed and moving unit 2's setpoint to 83 % takes unit 2 to a margin of 12.4 % within 6 s. Five minutes later unit 1 passes 153.5 kg/s without having been asked to and unit 2 passes 127.4 kg/s. The load moved because a speed line crossed a fixed head further to the left, toward the peak of the characteristic, and not because any controller divided it.

A common belief holds that parallel machines share a load by themselves, and the simulator is designed to overturn it. Machines on a common header share a head, and their flows follow from their speeds and their maps. A machine that is a little slower, a little fouled or still coming up to speed drifts toward its surge line while its neighbor takes the gas, and the anti-surge loop that then opens its recycle valve compresses gas only to send it back. With one machine fouled by 6 % of its head and the demand cut to 245 kg/s, sharing by equal speed recycles 15.0 t of gas in an hour and sharing by equal surge margin recycles none. The class of problem is wider than gas transmission. Parallel pumps, fans, chillers and refrigeration compressors on a common header raise the same question of who carries the load, and the stability of pumping systems with two or more elements in parallel was surveyed with the other pumping instabilities in 1981 [1]. In a pipeline station the same question is posed as the distribution of a varying demand among the running units, together with when to start and stop them [2–4], a layer that divides a total among parallel actuators with unequal limits above local loops that protect each one. The car of Volume 4, Chapter 12 allocates one force among three actuators in the same way.

However, the literature a student is likely to meet takes the pieces one at a time. Surge is modeled on a single machine with lumped models of the Greitzer type [5, 6], station dynamics are studied by detailed transient simulation [7, 8], and load sharing is posed as an optimization over identified performance maps [3, 4]. This chapter places a station pressure loop, three sharing laws, three anti-surge overrides, start and trip sequences and a predictive controller around one simulated three-unit station on one clock, and measures what each does to the gas recycled, the fuel burned and the surge count. The speed-scaled map, the proportional-integral (PI) loops, the override and the model

predictive controller (MPC) are established methods. The results are measurements on one generic station at one seed. Among them, a station loop tuned fast enough to ring and settle on clean machines holds a limit cycle of 0.33 bar once both units recycle, changed only in its fifth significant figure when the integration step is halved, and the predictive controller matches equal-margin sharing rather than improving on it.

Section 11.2 follows the domain, from the optimization of pipeline operation to the load-sharing problem. Section 11.3 sets out the station, a twenty-state model whose map and surge margin equal those of the single-compressor plant of Volume 4, Chapter 2 term for term, given to its last default, with controllers that read only instruments. Section 11.4 describes the control layers. Section 11.5 measures nine cases, each with a completion rule that requires both a change the reader makes and a state the station then reaches, and the six-hour challenge. Section 11.6 sets the hardware of a real station beside the model, Section 11.7 states the limitations, and the exercises in Section 11.9 work through the cases on the app.

11.2 Parallel Machines in Gas Transmission

Gas pipelines are powered by compressor stations [2], and the History box below tells how their operation became an optimization subject and their surge protection a technology of its own.

> ⧖ HISTORY **1968 and 1994: Optimizing the Line, Guarding the Machine**
>
> The expense of operating natural gas pipelines made their operation an optimization subject early. In 1968 dynamic programming was applied both to the transient distribution of gas at a terminal and to the steady transmission problem, because the inherent nonlinearities and numerous constraints of a pipeline system suited the method [9]. Protecting the machines took a path of its own. A technology assessment of 1994 described the surge schemes in use on transmission compressors as detection devices, which anticipate surge or catch its inception, joined to control devices that act to prevent it. Its patent search over the previous twenty years found most of the effort in surge control rather than in detection, and a trend likely to continue toward incremental improvement of the conventional scheme [10].

How the units of one station should be controlled together was argued with field operation in view. A 1986 analysis of parallel centrifugal gas compressors compared the common approaches to their control by energy efficiency, stability of control, equipment protection and level of automation, and described an improved system with an example from field operation [11]. Detailed simulation of station dynamics followed. A 1991 model of a station combined pipe flow, the quasi-steady flow through valves, constrictions and compressors and the control system [7]. Whether two units should run in series or in parallel was examined by transient simulation of a two-unit station with variable-speed drivers in 2002 [12]. The emergency shutdown emerged as the hard case for anti-surge systems, as the second History box tells.

> ⧖ HISTORY **1994 and 2004: When a Station Shuts Down**
>
> Models of whole stations made the shutdown a subject of its own. A model of 1994 joined the gas dynamics, the control system and the inertias of the compressor and turbine shafts. It showed that a cooler in the recycle path changes how fast a compressor shaft decelerates on shutdown and, depending on the shaft's inertia against the cooler's volume, can spin the shaft backward, which harms its dry seals [8]. Ten years later the data of a compressor that surged during an emergency shutdown were analyzed. Most anti-surge systems avoid surge in normal operation, the study found, but unplanned emergency shutdowns are a significant challenge, and avoiding surge in them depends largely on the station's layout. Its model gave simpler rules for sizing the piping on either side of the machine and the control elements [13].

The load distribution itself became an optimization problem. A 2013 formulation optimized both the load distribution and the on and off switching of parallel units in pipeline stations, with the

Table 11.1 Variables by Role, Design Values With Two Units on Line

Symbol	Role	Design	Range
P_d	CV, discharge header (bar a)	70.00	SP 60–76
SM_i	CV, surge margins (%)	28.05	line 3–25
$n_{SP,i}$	MV, speed setpoints (% rated)	90.47	70–105
$v_{cmd,i}$	MV, recycle valve commands (%)	0	0–100
F^*	MV of the PIC, flow demand (kg/s)	300	0–250N
w_{del}	DV, far-end demand (kg/s)	300	100–500
P_{up}	DV, upstream line (bar a)	47.5	40–55
a_i	DV, head lost to fouling (%)	0	0–12
n_i, g_i	states, speed, turbine (%)	90.47, 74.73	—
v_i, θ_i	states, valve, surge phase	0, 0	—
P_s, P_1, P_2	states (bar a)	45.00, 67.85, 63.34	—
$w_{c,i}$, $w_{f,i}$, $w_{r,i}$	outputs, flows (kg/s)	150, 150, 0	—
h_p, Q	outputs (kJ/kg, m^3/s)	60.13, 4.202	—
M_{pack}	output, gas in the line (t)	1324.05	—

effect of each start and stop on the machines' expected life among the costs [2]. Online tracking of each unit's performance map was then joined to the load sharing optimization [3], and real-time optimization of the sharing under uncertainty followed in 2020 [4]. Model predictive control has meanwhile been applied to the process and anti-surge loops of a single centrifugal machine [14]. A degraded machine changes all of this, because the gas turbine and its driven compressor degrade as one system and change how they match each other and the pipeline [15].

11.3 The Station as Modeled

No station stands behind the simulated one, and every size, rating and threshold is a teaching value. An upstream line at 47.5 bar a feeds a 300 m^3 suction header. Three identical 15 MW gas turbines drive three centrifugal compressors that lift the gas into a 300 m^3 discharge header held at 70.0 bar a. Each machine has a discharge line with a check valve and a recycle line that returns gas from ahead of the check valve through a cooler and an anti-surge valve to the suction header. A 40 km, 0.9 m line in two cells of 20 km carries the gas to customers at the far end. The gas is 17.4 kg/kmol with $Z = 0.90$ at 20 °C. Pressures are in bar absolute, flows in kg/s, heads in kJ/kg, powers in MW and time in seconds. Figure 11.1 shows the layout and every symbol of the equations below, with the values of case 4 at 16 min, and Figure 11.2 shows the three maps at the same instant.

> ✦ **DID YOU KNOW? Up to Sixteen Machines in One Station**
>
> Mainline transmission compressors are usually rated at 1,000 horsepower or more, centrifugal machines driven by turbines or reciprocating ones. The larger stations may hold 10 to 16 units, 50,000 to 80,000 horsepower in all, and pass more than three billion cubic feet of gas a day [16]. Most burn gas drawn from the line they drive.

The model integrates twenty states. Per unit there are the speed n_i as a fraction of rated speed, the power turbine's output g_i as a fraction of its rating, the recycle valve position v_i and a deep-surge phase θ_i. The four holdups are the suction header P_s, the discharge header P_d and the two line cells P_1 and P_2. Four ledgers integrate the gas supplied and delivered, the fuel and the gas recycled, so the mass balance and the scorecard's totals close exactly. The variables are listed by role in Table 11.1.

11.3.1 One Map, Scaled by the Fan Laws

Every machine uses the characteristic of the single-compressor plant of Volume 4, Chapter 2, the Moore–Greitzer cubic [17] with its published shape, scaled to a pipeline machine and to any speed

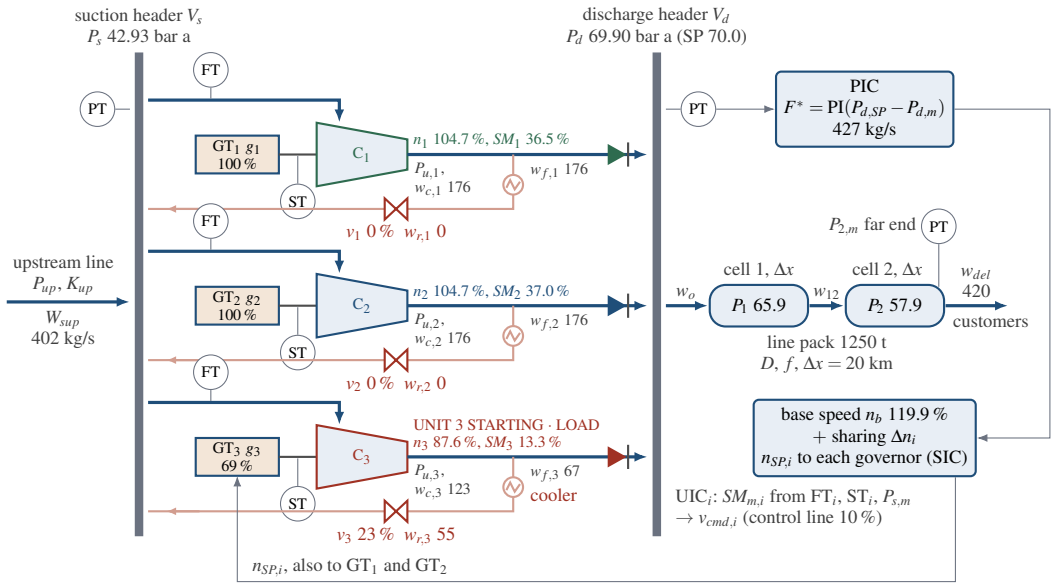


Figure 11.1 The station as modeled, drawn after the Station view of case 4 at $t = 16$ min, with *Start a unit* pressed at 13.7 min: units 1 and 2 on line at 104.7 % speed with their recycle valves shut, unit 3 loading at 87.6 % with 123 kg/s through the machine, 67 kg/s forward through its check valve and 55 kg/s back through its cooler and anti-surge valve, 23 % open. Flow elements (FT), speed pickups (ST) and pressure transmitters (PT) feed the station pressure loop (PIC), the governors and the anti-surge loops (UIC). Flows in kg/s. Process model only, not to scale.

by the fan laws of Equation (1.10), as shown in Equation (11.1).

$$\begin{aligned} \psi_c(\phi, n) &= (1-a)\, n^2\, \Psi(\phi/n) \\ \Psi(t) &= \psi_0 + H\left[1 + \tfrac{3}{2}\left(\frac{t}{W} - 1\right) - \tfrac{1}{2}\left(\frac{t}{W} - 1\right)^3\right] \end{aligned} \tag{11.1}$$

where $\phi = Q/Q_{ref}$ is the inlet volume flow, $\psi = h_p/H_{ref}$ the polytropic head, $\psi_0 = 0.2$, $H = 0.18$, $W = 0.25$, $Q_{ref} = 7.255\,\mathrm{m^3/s}$, $H_{ref} = 160\,\mathrm{kJ/kg}$ and a the fraction of head lost to fouling. The peak of Ψ lies at $\phi/n = 2W$, so the surge line is the parabola through the peaks and the margin is the definition of Section 1.4.6 taken at the present speed, as shown in Equation (11.2).

$$\begin{aligned} \phi_s(n) &= 2Wn, \qquad \psi_s(n) = (1-a)\, n^2 (\psi_0 + 2H) \\ SM &= 100\,\frac{\phi - \phi_s(n)}{\phi_s(n)} = 50\,(x-1), \qquad x = \frac{\phi}{nW} - 1 \end{aligned} \tag{11.2}$$

At $n = 1$ and $a = 0$ both functions equal those of the single-compressor plant term for term. Its own model, imported read only by the technical review's script, gives a largest difference of exactly zero in ψ_c over ϕ from 0.30 to 0.85 and in the margin, with the surge point at $\phi = 0.5$, $\psi = 0.56$ in both. The fan laws hold as written. A similar point ($x = 1.5$) at 70, 80, 90, 100 and 105 % speed keeps $Q/n = 4.5344\,\mathrm{m^3/s}$, $h_p/n^2 = 77.000\,\mathrm{kJ/kg}$ and a margin of 25.0000 %. An alternative convention measures the distance at the same head, in reduced coordinates, and at the design point it reads 41.4 % where Equation (11.2) reads 28.0 %. The choke line at $\phi/n = 0.70$ is drawn as a guide, and the cubic is not cut there. It falls to zero head at $\phi/n = 0.8037$.

Fouling multiplies the head at every flow coefficient by $1 - a$, removes $a/2$ of the efficiency and leaves the surge flow at each speed where it was, so the anti-surge loops' commissioned surge

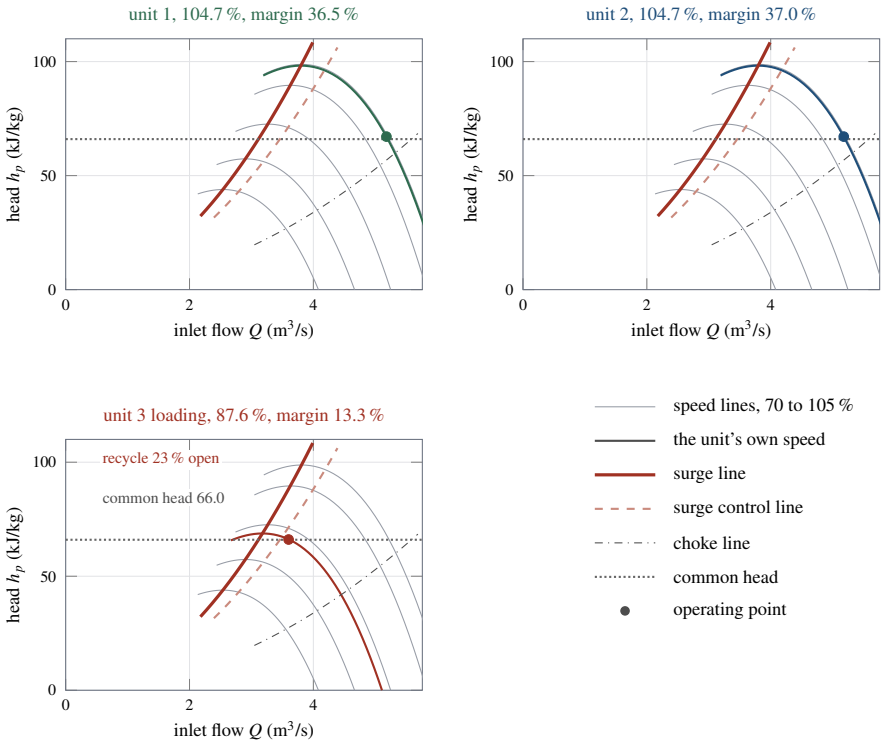


Figure 11.2 The Maps view of case 4 at the instant of Figure 11.1: speed lines from 70 to 105 % (thin), each unit's own speed line (thick), the surge line (very thick), the surge control line 10 % to its right (dashed), the choke line (dash-dotted), the common head of 66.0 kJ/kg between the headers (dotted) and each operating point (dot). The key in the lower right names the line styles.

line stays true. This is a teaching simplification. Deposits degrade the gas turbine and its driven compressor together [15], and whether they also move a centrifugal stage's surge line depends on where they sit. A machine whose surge line had moved toward higher flow would surge while its controller still showed margin, and the app keeps that out so that case 5 teaches one thing.

11.3.2 One Machine Between Its Headers

The gas in an impeller and its piping settles in far less than a physics step, so each machine sits on its characteristic at the head that its own discharge pressure P_u asks for. The head, the flow the map passes and the balance that fixes P_u are given by Equation (11.3).

$$\begin{aligned} h_p &= \frac{ZRT/M}{\sigma}\left[\left(\frac{P_u}{P_s}\right)^{\sigma} - 1\right], \qquad w_c = \rho_s Q_{ref}\, nW(x+1) \\ 0 &= w_c(P_u) - w_r(P_u) - w_f(P_u) \\ w_r &= K_r v\sqrt{P_u^2 - P_s^2}, \qquad w_f = K_d\sqrt{P_u^2 - P_d^2}\ \ (P_u > P_d) \end{aligned} \tag{11.3}$$

where $\sigma = (m-1)/m = 0.2814$, with m the polytropic index, is held at its design value, $ZRT/M = 126.07\,\mathrm{kJ/kg}$, ρ_s the suction density, $x = \phi/(nW) - 1$ the value on the falling branch at which Ψ equals $h_p/(H_{ref} n^2(1-a))$ (a cubic in x solved in closed form), $K_r = 4.44\,\mathrm{kg/s}$ per bar the recycle valve wide open and $K_d = 20\,\mathrm{kg/s}$ per bar the discharge line and check valve, which passes no gas backward. The root is found by an Illinois regula falsi between P_s and the pressure at the curve's peak, each term being monotone in P_u. The machine's flow is then set to $w_r + w_f$, so the unit holds no

gas and the header balances close whatever the solver's tolerance. A stopped, tripped or purging unit has its block valve shut and no forward flow. At design the machine makes 60.13 kJ/kg at 70.40 bar a, while the head between the headers, the dotted line on the maps, is 59.31 kJ/kg, because the discharge line takes 0.40 bar at 150 kg/s.

11.3.3 Surge as a Prescribed Cycle

When no root exists below the peak, the machine's outlets cannot take the peak flow at the peak pressure and the machine is in surge. The flag latches after the step and the flow then follows the cycle of Equation (11.4).

$$w_c = \rho_s Q_{ref}\, 2Wn\left(0.4 + 0.8\sin 2\pi\theta\right), \qquad \frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{1}{T_{surge}} \tag{11.4}$$

with $T_{surge} = 2\,\mathrm{s}$, a teaching value, so the flow falls to –40 % of the surge flow once a cycle. Surge clears when the machine has a steady point at least 2 % right of its surge line. The single-compressor plant resolves this cycle with the Greitzer model [5], while a station stepping at 0.05 s cannot carry each machine's Helmholtz dynamics, so here the cycle is imposed. The onset is therefore the static one, the loss of a steady point right of the peak. With that plant's cubic and a throttle parabola, Greitzer's dynamic onset lies 10.5, 4.6, 1.1 and 0.10 % of flow left of the peak at B of 1, 1.5, 3 and 10, and a 300 m^3 discharge header makes B large. Unit 2 slowed by hand with its recycle held shut latches surge at 80.68 % speed with its last steady margin at 1.55 %, because the margin falls as the square root of the distance to the fold and one step crosses it.

11.3.4 Shaft, Gas Turbine and Fuel

Each shaft follows its torque balance, written in power as Equation (11.5).

$$\begin{aligned} I\,n\frac{\mathrm{d}n}{\mathrm{d}t} &= gP_r - \frac{w_c h_p}{\eta} - k_m P_r n^2, \qquad I = 2H_{in}P_r \\ \tau_{gt}\frac{\mathrm{d}g}{\mathrm{d}t} &= g_{cmd} - g, \qquad \tau_v\frac{\mathrm{d}v}{\mathrm{d}t} = v_{cmd} - v \\ \eta &= \mathrm{clip}\left(\eta_{max} - \kappa_\eta(\phi/n - \phi_\eta)^2,\ 0.3,\ 0.95\right)(1 - a/2) \\ Q_{fuel} &= (P_r/\eta_{gt})\left(a_0 + (1 - a_0)\,g\right) \end{aligned} \tag{11.5}$$

where $P_r = 15\,\mathrm{MW}$, $H_{in} = 4\,\mathrm{s}$ ($I = 120\,\mathrm{MJ}$), $k_m = 0.01$, $\tau_{gt} = 1.5\,\mathrm{s}$, $\tau_v = 1\,\mathrm{s}$, $\eta_{max} = 0.82$ at $\phi_\eta = 0.60$ with $\kappa_\eta = 4$, the turbine efficiency at rating $\eta_{gt} = 0.35$ and $a_0 = 0.30$ of rated fuel at zero output, a Willans line. In surge the efficiency is halved. At design each machine runs at $\eta = 0.8135$ with 11.09 MW of gas power, its turbine at 74.7 % of rating and burning 35.28 MW of fuel. An overspeed trip at 110 % is a teaching value.

11.3.5 Headers, Supply and Line Pack

The headers and the two cells are isothermal holdups, $C = V/c^2$ with $c^2 = ZRT/M$, and the flows between them follow the steady friction law of the gas transmission line of Chapter 12, as shown in Equation (11.6).

$$\begin{aligned} C_s\frac{\mathrm{d}P_s}{\mathrm{d}t} &= W_{sup} - \textstyle\sum_i w_{f,i}, \qquad C_d\frac{\mathrm{d}P_d}{\mathrm{d}t} = \textstyle\sum_i w_{f,i} - w_o \\ C_c\frac{\mathrm{d}P_1}{\mathrm{d}t} &= w_o - w_{12}, \qquad C_c\frac{\mathrm{d}P_2}{\mathrm{d}t} = w_{12} - w_{del} \\ P_a^2 - P_b^2 &= Kw|w|, \qquad K = fLc^2/(DA^2) \end{aligned} \tag{11.6}$$

where W_{sup} comes from the upstream line with $P_{up}^2 - P_s^2 = K_{up}W_{sup}|W_{sup}|$ and $K_{up} = 2.569\times10^{-3}$ bar^2 per $(\mathrm{kg/s})^2$, w_o crosses half a cell and w_{12} a whole one, $f = 0.0095$, $D = 0.9\,\mathrm{m}$, A the pipe's cross section, and L in meters, K being divided by 10^{10} to work in bar. With $c = 355.07\,\mathrm{m/s}$ each

header holds 237.96 kg per bar and each cell 10 092 kg per bar. The customers take their demand w_{del} from the far cell unless it falls below 40 bar a, below which delivery is curtailed linearly to zero at 35 bar a. Recycled gas returns to the suction header, so only the forward flows enter the balances. At design the line holds 1324.05 t, and over the shipped challenge, with a surge, a trip, a restart and the discharge below the suction, the inventory closes to 9.1×10^{-8} kg on 7009 t moved.

11.3.6 Instruments

The controllers read one packet. The three pressures carry 0.01 bar of colored noise (time constant 0.5 s), each machine's flow element 0.4 % of reading (0.3 s), and each speed pickup 0.05 % of rated speed (0.2 s), all from the seeded generator, and the turbine output is read directly. The anti-surge loops compute the margin from the suction pressure, the flow element and the speed pickup alone, as shown in Equation (11.7).

$$SM_{m,i} = 100\left(\frac{w_{m,i}}{\rho(P_{s,m})\,Q_{ref}\,2W\,n_{m,i}} - 1\right) \tag{11.7}$$

One scan's measured margin carries 0.54 point of noise (one standard deviation). The packet carries no fouling, demand or supply value, and of the line's pressures only the far end's, and one of the app's tests fails if a controller touches any other key. In the exported file the simulator's own values carry the prefix `truth_`, beside the measured ones.

11.3.7 Parameters, Initialization and Numerics

Table 11.2 gives every parameter with its default. Every case begins at a steady state set by its own demand and settings. The line's pressures follow from the throughput by the friction law, each loaded machine's speed comes from the case's sharing law by bisection, and when clean machines would sit below the control line their recycle valves are placed where the anti-surge loops would hold them. Fourth-order Runge–Kutta steps of $\Delta t = 0.05$ s advance the states (Section 1.6.1), the controllers execute every 0.1 s and the historian records at 2 Hz, so a 2 s surge cycle shows on the trend. Halving the step changes the challenge's recycled gas by less than 0.001 t and its worst pressure deviation by less than 0.0001 bar, and leaves the time of case 7's surge and case 4's count of surges and cycles unchanged.

11.3.8 Assumptions

Each machine is quasi-steady on its map, which a station model with transient pipe flow also assumes for its compressors [7], and fails within a surge cycle, which is prescribed. Rotating stall is absent. The headers and the line are isothermal at 20 °C, so the recycle coolers are perfect and the heat of compression is not tracked, and the line is two friction-dominated cells with no momentum states and hence no pressure waves. The three machines share one map and the polytropic exponent is held at its design value. Fouling is a single head factor with the surge line fixed. The fuel each turbine burns is metered and not drawn from the suction header. There is no station bypass. If the discharge header falls below the suction header, gas passes straight through the machines and their check valves with no head made, a regime that only the shipped challenge reaches (Section 11.5.7). Every safety number, the 10 % control line, the speed limits, the overspeed trip, the surge period and the curtailment pressure, is a teaching value. API Standard 617 covers the design of centrifugal compressors and API Standard 670 their machinery protection, and a station's own surge tests and protection studies set its real numbers.

11.4 Control Layers as Implemented

Each physics step begins with the controllers, then the states advance, as in Section 1.6.1, and the surge latch, the trips and the challenge's scoring run afterward. The controllers execute every $\Delta t_c = 0.1$ s on the packet of Equation (11.7). All the PI loops use the velocity-form PID of Section 1.6.2, without derivative action. Every loop acts on $e = r - y$, with r the setpoint and y the measurement, and its

Table 11.2 Parameters and Defaults. A, Adjustable in the Advanced Panel. C, a Control on a Card. F, Fixed in the Source

Symbol	Meaning	Value	Unit	
M, Z, T	gas	17.4, 0.90, 293.15	kg/kmol, –, K	A
σ	polytropic exponent	0.2814	—	A
ψ_0, H, W	map shape	0.20, 0.18, 0.25	—	A
H_{ref}, Q_{ref}	map scale	160, 7.255	kJ/kg, m^3/s	A
ϕ_{ch}	choke line, ϕ/n	0.70	—	A
$\eta_{max}, \kappa_\eta, \phi_\eta$	efficiency curve	0.82, 4, 0.60	—	A
P_r, H_{in}	turbine rating, inertia	15, 4	MW, s	A
$\tau_{gt}, \eta_{gt}, a_0$	lag, fuel line	1.5, 0.35, 0.30	s, –, –	A
k_m	mechanical loss	0.01	—	A
—	overspeed trip	110	%	A
K_r, τ_v	recycle valve, lag	4.44, 1.0	kg/s/bar, s	A
K_d	discharge line	20	kg/s/bar	A
T_{surge}	deep-surge period	2.0	s	A
—	surge clears at	2	%	A
V_s, V_d	header volumes	300, 300	m^3	A
P_{up}, K_{up}	upstream line	47.5, 2.569e-3	bar a, see (11.6)	A
$\Delta x, D, f$	line cells	20, 0.9, 0.0095	km, m, –	A
—	curtailment below	40	bar a	A
$\dot{v}_{max}$	recycle stroking	50	%/s	C
$t_{purge}, t_{acc}, t_{load}$	start	20, 60, 120	s	C
t_{unload}	stop sequence	120	s	C
t_{up}, t_{down}	sequencer	60, 300	s	C
—	minimum run, rest	600, 900	s	C
—	noise on P, w, n	0.01, 0.4, 0.05	bar, %, %	F
—	speed range, base clamp	70–105, 55–120	%	F

output is clipped to its range and then rate-limited where the loop declares a stroking rate. The tracking time of Equation (1.19) equals τ_I, so when the output saturates, back-calculation adjusts the integral and nothing else. In Manual the PI solves its integral for the operator's value, so every transfer is bumpless.

11.4.1 Station Loop and Base Speed

The station PIC turns the discharge pressure error into a station flow demand F^* in kg/s, with $K_c = 20\,\text{kg/s}$ per bar, $\tau_I = 60\,\text{s}$ and an output from 0 to 250 kg/s per loaded unit. The demand becomes one base speed for every loaded unit, the speed at which a clean machine passes F^*/N on the commissioned map at the measured pressures, so the loop's gain is nearly constant from turndown to full speed. The base speed is clamped to 55 to 120 %, past the governors' 105 % limit, so that a unit trimmed below the base can still rise. In case 4 it reaches 119.9 % while the discharge sags. When a unit joins or leaves the shared load, the base speed is reset to the loaded units' mean setpoint, their trims to their offsets from it, and the PIC's output to the flow that mean passes, so no setpoint jumps. With the header on Manual the operator holds the three speed setpoints and the PIC tracks what they amount to.

11.4.2 Three Sharing Laws

Each loaded unit's speed setpoint is the base plus a trim, as shown in Equation (11.8).

$$\begin{aligned} n_{SP,i} &= \text{clip}(n_b + \Delta n_i,\ 0.70,\ 1.05) \\ \frac{\mathrm{d}\Delta n_i}{\mathrm{d}t} &= k_b(\bar{e} - e_i), \qquad \textstyle\sum_i \Delta n_i = 0 \end{aligned} \tag{11.8}$$

where $\bar{e}$ is the mean of the loaded units' e_i and $k_b = K_b/(100 \cdot 60)$, with the sharing rate $K_b = 5\,\%$ of speed per point of difference per minute. Equal surge margin sets $e_i = SM_{m,i}$ and equal flow (sharing by capacity, the machines being identical) sets e_i to each unit's measured flow as a percent of the

mean. A trim never pushes a unit further into a speed limit, each is held within $\pm 15\,\%$, and after each scan the trims are re-centered to sum to zero, so the sharing never fights the pressure loop for the total. Equal speed lets the trims bleed away with a time constant of $600/K_b = 120\,\mathrm{s}$. Each governor is a PI from speed setpoint to turbine output, $K_c = 4\,\%$ per percent and $\tau_I = 4\,\mathrm{s}$.

11.4.3 Anti-Surge Overrides

Each unit's anti-surge loop is the single-compressor plant's override on the measured margin, the protective override of Section 1.4.8 that rests at its clamp in healthy operation, a PI from $SM_{SP} - SM_{m,i}$ to the recycle valve with $K_c = 3\,\%$ of valve per point of margin, $\tau_I = 5\,\mathrm{s}$, an output of 0 to 100 % and a stroking limit of 50 %/s, with the surge control line $SM_{SP} = 10\,\%$. Above the line the output rests at zero, and because the tracking time equals τ_I the error terms cancel there and the integral decays toward zero instead of winding down, so the valve opens at the first scan below the line. The loops have their own Auto and Manual switch. A start forces the valve open through the purge and acceleration, a stop through the run-down, and *Open at once* drives a tripped unit's valve open in the trip's own scan.

11.4.4 Starts, Stops, Trips and the Sequencer

A start purges for 20 s with the block valve shut and the recycle open, lights the turbine and ramps the speed setpoint to 70 % in 60 s on full recycle, then loads the unit by ramping its setpoint to the base speed over the load time (120 s by default) while its anti-surge loop closes the recycle from wide open, and joins it to the sharing at the end of the ramp. Setting *Recycle while loading* to *Shut at once* instead closes the valve when loading begins. A stop takes the unit out of the sharing, unloads it to 70 % over 120 s, then cuts its fuel and opens its recycle. A trip cuts the fuel at once. The *Stop a unit* helper stops the running unit with the lowest measured margin. The optional sequencer starts the next stopped unit when every loaded setpoint has sat at 105 % with the measured discharge more than 0.3 bar low for 60 s, and stops the highest-numbered running unit when one fewer could carry the measured forward flow at rated speed for 300 s, with the framework's shared stage sequencer holding a minimum run of 600 s, a minimum rest of 900 s and a minute between changes.

11.4.5 Model Predictive Control on the Speeds

The MPC replaces the PI and the sharing law, in the general form of Section 1.6.3. Every 1 s it linearizes the discharge header about the measured point, from the clean map at the measured pressures and speeds, as shown in Equation (11.9).

$$\begin{aligned} C_d \dot{P}_d &= \textstyle\sum_i k_i (n_i - \bar{n}_i) + C_d b \\ &\quad - \left(k_o + \textstyle\sum_i k_{P,i}\right)(P_d - \bar{P}_d) \\ \tau_n \dot{n}_i &= n_{SP,i} - n_i \\ SM_i &= \bar{SM}_i + a_i (n_i - \bar{n}_i) - c_i (P_d - \bar{P}_d) \end{aligned} \tag{11.9}$$

where k_i, $k_{P,i}$, a_i and c_i are central differences of the clean map, k_o is the outlet line's conductance at the measured flow, $\tau_n = 3\,\mathrm{s}$ stands for the governors, and b is the measured trend of P_d filtered over 5 s, the drift by which the line pack it cannot see enters the model. The exact zero-order-hold discretization at 1 s enters the quadratic program of Equation (11.10) over 60 steps in 12 graduated move blocks.

$$\begin{aligned} \min\ & \textstyle\sum_k w_P (P_{d,k} - P_{d,SP})^2 + w_{\Delta u} \sum_j \|\Delta n_{SP,j}\|^2 \\ & + w_{fuel} \textstyle\sum_{k,i} \gamma_i n_{SP,i,k} + \rho\, \varepsilon^2 \\ \text{s.t. } & 70 \le n_{SP,i} \le 105, \quad |\Delta n_{SP,i}| \le 1\,\% \text{ per step} \\ & SM_{i,k} \ge SM_{min} - \varepsilon, \quad \varepsilon \ge 0 \end{aligned} \tag{11.10}$$

where $w_P = 30$ per bar^2, $w_{\Delta u} = 1$ per percent^2, $w_{fuel} = 1$, γ_i the unit's measured turbine output per kg/s through it times its flow per percent of speed and the fuel per shaft power, $SM_{min} = 10\,\%$ on

Table 11.3 The Nine Cases

#	Case and events	Teaching point
1	Manual, two units, reader slows unit 2	one head, two loads
2	demand 300 to 340 kg/s at 60 s	the station loop, line pack
3	unit 1 fouled 6 %, demand to 245 kg/s at 60 s	equal speed against equal margin
4	demand 360 to 420 kg/s over 1 to 11 min	start the third unit
5	Manual, unit 1 fouls to 8 % over 1 to 6 min	the fouled map
6	unit 1 fouled, demand to 180 kg/s at 60 s	a turndown no law serves
7	three units at 360 kg/s, unit 2 trips at 120 s	a trip
8	200 kg/s, PIC 200 kg/s per bar and 5 s, SP +0.5 bar at 60 s	station against anti-surge
9	Challenge: 6 h profile, unit 1 fouled, trip at 2, restart at 3 h	the whole station

the control line and $\rho = 10$ per percent^2. The framework's shared solver uses the dual method of Goldfarb and Idnani [18], only the first move is applied, and a solve that fails or is not finite hands the speeds back to the PI and the sharing law, which track the MPC's speeds without a bump. The margin floor sits on the control line and its price is soft for a measured reason. On the challenge with the suggested settings, a floor of 12 % priced at 1000 held the margins by letting the discharge rise 12.55 bar above 70 bar a, and a floor of 10 % priced at 1000 recycled 48.09 t, while the shipped price of 10 recycles 31.97 t and passes.

11.4.6 Three Models

The plant is Section 11.3. What a reader identifies from case 1 or case 5 is a static relation, how far one machine's margin moves for a point of speed on a common head. The controllers' models are the commissioned map inside the base speed and the MPC's linearization, which knows neither the fouling nor the line pack beyond the measured trend, and the measured margin of Equation (11.7), which is true because fouling leaves the surge line where it was.

11.5 Nine Cases on the Running Engine

The nine cases appear in Table 11.3. They share the defaults above, Auto with the PI and equal speed, two units on line at 300 kg/s, and a row lists only what differs, and Section 1.6.4 describes how a case is named and run. The figures quoted below were produced by stepping the engine in Node.js at seed 20261022 in the same increments the page uses. The technical review's measuring script, re-run on the app as shipped, reproduced its record line for line. Opening a case first, switching to it from another one and pressing Reset all reproduce the same run bit for bit.

11.5.1 One Head, Two Loads, and the Line Between

In case 1 a single move of unit 2's setpoint to 83 % at 20 s takes its margin from 28.05 to 12.38 % within 6 s, below 18 % 6.05 s after the move. Five minutes later the two units pass 153.5 and 127.4 kg/s, together 280.9 kg/s against the customers' 300, so the line unpacks, the discharge falls to 69.35 bar a and the lower common head lets unit 2 back out to 17.7 %. Brought down a point every 2, 5 or 10 s its margin bottoms at 15.6, 16.1 and 16.0 % instead, because the discharge is falling as the speed comes down. At 82 % the margin dips to 8.1 % and its anti-surge valve opens to 4.0 %.

🕮 **Pause.** Try Exercise 11.1 before reading on.

In case 2 the customers take 40 kg/s more at 60 s. The extra gas comes first out of the line pack, the header dips only 0.14 bar, and the station delivers 322 kg/s 10 min after the step, 330 after 14.2 min and 338 after 26.2 min, and at 1 h both machines run at 99.1 % speed, 34.7 % from surge. Raised to 71.0 bar a, the discharge is within 0.2 bar of the new setpoint 3.8 min after the change.

TRY IT IN THE APP 2 · The station pressure loop

Load the case and press Run. Touch nothing. At 60 s the customers take 40 kg/s more. Watch the Discharge pressure trend: the header dips only 0.14 bar, because the extra gas comes first out of the line. Watch the delivered flow beside the station flow demand: the station delivers 322 kg/s 10 min after the step and 338 kg/s after 26.2 min.

11.5.2 Who Recycles First

In case 3 unit 1 has lost 6 % of its head. At one speed it meets the common head further left on its map, nearer surge and with less gas through it. As the station turns down to 245 kg/s at equal speed, unit 1 reaches its control line at 15.6 min, recycles 15.01 t in the hour and ends 9.9 % from surge against unit 2's 18.8 %, both at 83.2 %. Switched to equal surge margin at 90 s, the trims speed unit 1 to 83.8 % and slow unit 2 to 81.3 %, both sit 12.5 to 12.6 % from surge, nothing is recycled and the hour's fuel falls from 63.33 to 62.76 MWh. Equal flow lands between them at 11.2 and 13.9 %. The reason is a floor. Two clean machines cannot pass less than 234.0 kg/s right of their control lines at 70 bar a. With unit 1 fouled that floor is 237.8 kg/s when both sit on their lines, as equal margin puts them, and 251.6 kg/s at equal speed, where unit 1 reaches its line first, so 245 kg/s lies between the two. Figure 11.3a sweeps the demand on the same plant and confirms the order. After two hours equal speed recycles 6.2 kg/s at 245, while equal flow and equal margin recycle nothing measurable there and only 1.86 and 0.09 kg/s at 240, and at 200 kg/s the three laws recycle 49.2, 40.3 and 36.9 kg/s.

Case 5 isolates the map. Both units hold 90.5 % by hand while unit 1 fouls to 8 %. At 6 min the headers ask 58.8 kJ/kg of both (59.57 and 59.64 kJ/kg at the machines), and unit 1 meets it at 22.9 % and 144.2 kg/s against unit 2's 28.5 % and 150.8 kg/s. At 94.3 % speed the margins match at 27.56 and 27.60 %, unit 1 then passing 155.5 kg/s and unit 2 149.2 kg/s. Equal margin asks more speed of the fouled machine and gives it more of the load.

11.5.3 A Start That Pushes Its Neighbors

In case 4 the demand climbs from 360 to 420 kg/s, more than two units can deliver. Units 1 and 2 reach 105 % at 7.9 min and the discharge passes below 69.5 bar a at 13.4 min (67.44 bar a at 30 min with no start). Started at 13.7 min, unit 3 purges for 20 s, accelerates on full recycle for 55.8 s behind its shut check valve, and 50.2 s into the load ramp its check valve opens. As it delivers, the station loop takes gas back from units 1 and 2, whose margins fall from 38.4 to 17.6 % before all three settle at 20.1 % and 90.3 % speed, while the header overshoots to 71.71 bar a. The load time hardly matters. Ramps of 10, 30, 120 and 300 s leave the neighbors' least margin at 17.20, 17.46, 17.57 and 17.63 %, because the station loop and not the ramp sets their speeds. Shut at once when loading begins, unit 3 is dead-headed and surges eight separate times, 18 prescribed cycles in all, before its head reaches the header's. The instant at 16 min is drawn in Figures 11.1 and 11.2.

Pause. Try Exercise 11.2 before reading on.

11.5.4 A Turndown No Law Can Serve

Case 6 is infeasible on purpose. With unit 1 fouled and the demand cut to 180 kg/s, far below the 237.8 kg/s two machines need, unit 1 recycles from 7.8 min while unit 2 never does, and by 1 h the station recycles 66.8 kg/s with unit 1's valve 28.8 % open, 199.4 t in the hour. Across the three laws and station tunings of 10, 20 and 80 kg/s per bar the recycle at 40 min is 54.8 to 69.9 kg/s, least with equal margin, and the MPC recycles 56.9 kg/s. Stopping unit 1 at 8.8 min leaves unit 2 half an hour later at 95.8 % speed and 36.9 % from surge with no recycle, and the station's fuel falls from 61.5 to 37.7 MW.

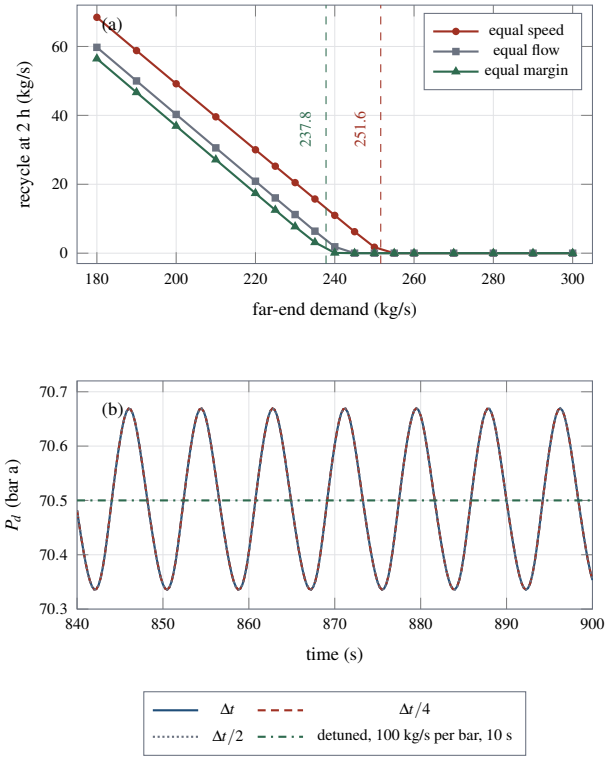


Figure 11.3 Two measurements from the app. (a) Case 3's plant, unit 1 fouled 6 %, with the demand stepped to each value at 61 s: the recycle averaged over the last 10 min of 2 h for each sharing law, equal speed with circles, equal flow with squares and equal margin with triangles. Dashed lines mark the computed floors with unit 1 fouled, both units on their control lines (237.8 kg/s) and equal speed (251.6 kg/s). (b) Case 8 with noise off, the true discharge pressure over 840 to 900 s at Δt (solid), $\Delta t/2$ (dotted) and $\Delta t/4$ (dashed), whose traces coincide within 3.4×10^{-6} bar, and with the station loop detuned (dash-dotted).

TRY IT IN THE APP **6 · A demand too small for two machines**

Load the case and press Run. Unit 1 is fouled, and at 60 s the demand falls to 180 kg/s. Watch the Recycle valves trend: unit 1's valve opens from 7.8 min and unit 2's never does. Press Stop a unit at 8.8 min. Half an hour later unit 2 runs alone at 95.8 % speed, 36.9 % from surge, with no recycle.

11.5.5 A Trip

In case 7 three units share 360 kg/s at 85.4 % speed, 11.4 % from surge, when unit 2's turbine trips at 120 s. Its shaft loses 3.0 % of its speed in the first second, its head falls below the header's, its check valve shuts, and 0.75 s after the trip, at 84.0 % speed, it surges before its PI has opened the valve far enough, entering surge twice for one full cycle. With *Open at once* it coasts down with its margin never below 10.8 % while above 30 % speed. Either way units 1 and 3 run to their 105 % limit, their margins rise to 38.1 %, and the discharge dips to 68.59 bar a 33 s after the trip and holds 69.75 bar a at 15 min. This is the emergency-shutdown problem of field stations [13], in which feedback on the margin is too slow for a shaft that loses head within a second.

Pause. Try Exercise 11.3 before reading on.

Table 11.4 Measured Cases at the Default Seed

Case	Configuration	Result
1	unit 2 to 83 % in one move	margin 28.05 to 12.38 % in 6 s
2	demand +40 kg/s	dip 0.14 bar, 322 kg/s after 10 min
3	equal speed / margin / flow	15.01 / 0 / 0.01 t, 63.33 / 62.76 / 62.76 MWh
3	MPC	0.84 t, 62.72 MWh, within 0.046 bar
4	load 10 to 300 s	neighbors' least margin 17.20–17.63 %
4	recycle shut at once	8 surges, 18 cycles
5	fouled 8 %, both 90.5 %	22.9 / 28.5 %, match at 94.3 %
6	3 laws × 3 tunings	54.8–69.9 kg/s recycled at 40 min
7	trip to the PI / open at once	surge after 0.75 s / none, $\geq$ 10.8 %
8	Δt, $\Delta t/2$, $\Delta t/4$	0.333869 / 0.333882 / 0.333885 bar
8	detuned 100, 10 s	4.4×10^{-5} bar

Table 11.5 The Six-Hour Challenge at the Default Seed

Settings	Surges	$\lvert P_d - 70\rvert$ (bar)	Recycled (t)	Fuel (MWh)	Verdict
shipped	1	24.97	6.90	380.54	fails
suggested	0	1.048	30.74	499.28	passes
at equal speed	0	1.237	97.75	501.31	fails
at equal flow	0	1.056	38.68	498.86	fails
sequencer by hand	0	24.95	0.00	380.02	fails
trip to the PI	2	1.049	30.74	499.28	fails
station 20, 60 s	0	1.714	37.52	499.65	fails
station 120, 15 s	0	1.020	30.48	499.21	passes
on MPC	0	1.281	31.97	499.78	passes

11.5.6 Two Loops on One Flow

In case 8 two clean units at 200 kg/s sit on their control lines at 79.4 % speed with their valves 7.1 % open, recycling 33.2 kg/s, and the station loop is tuned at 200 kg/s per bar and 5 s. On recycle a unit's forward flow answers both its speed and its valve. When the station loop raises a speed the margin rises, the override closes the valve, and more gas goes forward than the speed alone would send, so the anti-surge loop adds gain and lag to the station loop. With the noise off the discharge then swings 0.333 869 bar peak to peak over the last 300 s of 900 s, with an 8.353 s period, the valves swinging 12.2 % and the speeds 1.73 %. The swing is 0.333 882 bar at $\Delta t/2$ and 0.333 885 bar at $\Delta t/4$, and it is 0.3309 over 300 to 600 s and 0.3351 bar over 1200 to 1500 s, a limit cycle of the tuning and not of the integration, as shown in Figure 11.3b. Detuned to 100 kg/s per bar and 10 s it falls to 4.4×10^{-5} bar. The same fast tuning at 300 kg/s, with no recycle, rings 0.74 bar between 60 and 180 s and then settles to 0.0003 bar. At 180 and 230 kg/s, recycling 39.2 and 35.6 kg/s, it holds 0.303 and 0.286 bar, and at 250 kg/s, where nothing recycles, 2×10^{-5} bar.

11.5.7 The Six-Hour Challenge

The challenge's demand runs at 300 kg/s, climbs to 400 for the peak from 1.4 to 1.9 h, falls to 340 for the trip of unit 2 at 2 h, rises again and runs down to 250 for the night, with unit 1 fouled 6 % and unit 2 started again at 3 h. Its target, scored from the simulator's truth at every physics step over the whole run, is no surge on any unit, the discharge within ± 1.5 bar of 70.0 bar a from 10 min on, at most 35 t recycled by units on line, and the surge control line kept at 10 % or above, on the plant as shipped. It ships with equal speed, starts and stops by hand, a tripped unit's valve left to its PI and the station at 20 kg/s per bar and 60 s. The outcomes are in Table 11.5.

As shipped nobody starts unit 3 for the peak, unit 2 surges on its trip, and with one unit left the discharge falls 24.97 bar by 3.01 h. In that run the discharge header falls below the suction header from 2.87 h, by up to 1.10 bar. With no bypass in the model, gas then passes straight through the machines and their check valves with no head made. Unit 1 runs out to $\phi/n = 0.8027$, past the drawn

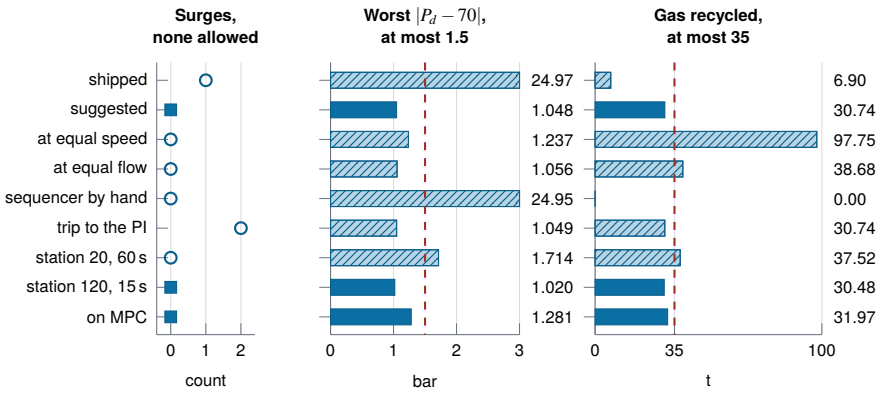


Figure 11.4 The six-hour challenge of Table 11.5 against its target. Solid bars and filled squares are the three settings that pass, hatched bars and open circles the six that fail, and dashed lines the limits. The rows below the suggested one each change one setting of it. Two pressure bars are cut at the axis end, and the column beside each panel gives the table's value. Notice that each failing row misses a different limit, and that the trip left to the PI misses only by its two surges. The fuel, not graded, is in the table.

choke line at 0.70 and next to the cubic's zero-head end at 0.8037, off the map from 2.28 to 3.18 h, and unit 2, restarting at 3.0 h, reads a measured margin of 821 % at one scan and 517.5 % logged, from a flow that is not on its curve, while its margin on the curve never exceeds 60.7 %. This windmill regime is documented rather than modeled, because only the failing shipped run reaches it.

The suggested settings change four layers, equal surge margin, the automatic sequencer, *Open at once* and the station at 80 kg/s per bar and 20 s, and pass with no surge, 1.048 bar at the trip and 30.74 t recycled. Dropping any one fails. Equal speed recycles 97.75 t through the night with unit 1 fouled, the trip left to the PI surges unit 2 twice, the slow station loop lets the discharge stray 1.714 bar at 3.06 h, and without the sequencer the peak and the trip are never covered. The predictive controller passes too, at 1.281 bar, 31.97 t and 499.78 MWh. In case 3 it recycled 0.84 t on 62.72 MWh against equal margin's 0 and 62.76 MWh, so it matches equal-margin sharing within 0.07 % of fuel and does not beat it. Figure 11.4 sets the nine settings of Table 11.5 against the three limits of the target.

The target grades the gas recycled rather than the fuel, because across the three laws the six hours' fuel differs by less than half a percent (498.86, 499.28 and 501.31 MWh) while the gas recycled differs threefold (38.68, 30.74 and 97.75 t). The 35 t budget was first checked at eleven seeds. The suggested settings recycle 28.34 to 32.80 t (mean 30.17) and pass throughout that initial set, equal flow recycles 37.11 to 41.51 t (mean 39.24) and fails at every seed, so the budget sits 2.2 t above the worst passing run and 2.1 t below the best failing one, and halving the step moves the recycle by less than 0.001 t. A wider check of the default seed and seeds 0–29 gives 29 of 31 passing runs at each step. Seeds 12 and 21 recycle 35.21 t and 37.17 t, respectively, while retaining zero surges and worst pressure deviations below 1.06 bar. Both misses persist at half the step. The default certificate is reproducible, but the suggestion does not satisfy the recycle budget for every tested noise realization. The band is 1.5 bar because over eleven station tunings the trip's dip never fell under 1.001 bar, and from 160 kg/s per bar on the units surge through case 8's interaction (3 to 6 surges). The verdict was tightened in the technical review. Judged against the setpoint in force with nothing else checked, equal speed with a 66 bar a setpoint, equal flow with an 8 % control line and equal speed with unit 1's fouling removed had each passed (the first 5.07 bar off 70 bar a) without the lesson. The band is now judged against 70.0 bar a, a control line under 10 % is a miss, and a changed disturbance or model parameter makes the run read "not graded", so all three now fail or go ungraded while the shipped and suggested verdicts and every run's log are unchanged. At the top speed of 600 s per second,

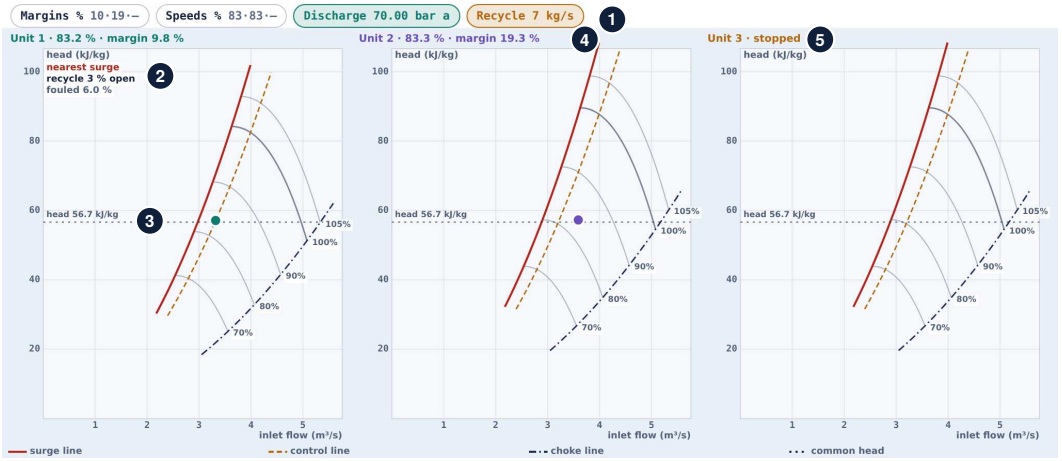


Figure 11.5 Case 3 at equal speed, $t = 40$ min, on the Maps view, light theme, cropped to the maps. Both units run at 83.2 % and 83.3 % on a common head of 56.7 kJ/kg, the dotted line at callout 3, and fouled unit 1 (left) sits on its control line with measured margin 9.8 %, flagged nearest surge with its recycle valve 2.9 % open (callout 2; the flag rounds to 3 %), while clean unit 2 stands 19.3 % from surge (callout 4) and unit 3 is stopped (callout 5). The badges at callout 1 read the discharge at 70.00 bar a and 7 kg/s recycled.

sustained in Chrome at 1366×768 (599.8 s/s) and 390×844 (599.6 s/s), the six hours play in 36 s. The lesson of case 3 at 40 min is shown in Figure 11.5.

> **DID YOU KNOW? Two Surges That the Totals Do Not Show**
>
> From the simulator (Table 11.5). Over the six hours the suggested settings, and the same settings with the tripped unit's valve left to its loop, both recycle 30.74 t and burn 499.28 MWh, and their worst pressure deviations are 1.048 and 1.049 bar. Only the surge count tells them apart, 0 against 2.

11.6 Technology in Practice

Figure 11.6 draws one unit's loops and the station loop of Section 11.4 with the hardware of a transmission station in place of the schematic's symbols.

What Measures It

The station loop reads one pressure transmitter, on the discharge header, and the base speed adds the one on the suction header. Each anti-surge loop reads three instruments, the suction pressure, its machine's flow element and its speed pickup, and computes the margin of Equation (11.7) from them, so one scan's margin carries the noise of all three, 0.54 point in the model.

> **TECHNOLOGY Sensor: The Flow Element Behind Every Margin**
>
> A pressure-based flow element such as an orifice plate or a venturi accelerates the gas, and the flow follows the square root of the pressure drop across it divided by the density [19]. The square root makes the reading less certain as the flow falls, the direction of surge. The practical turndown of such a meter is often no more than 3 to 1, perhaps 10 to 1 with a modern transmitter, and a worn element or uneven liquid in the impulse tubes then gives large flow errors at the low end of the range [19]. The model's element carries 0.4 % of reading as noise behind a 0.3 s lag.

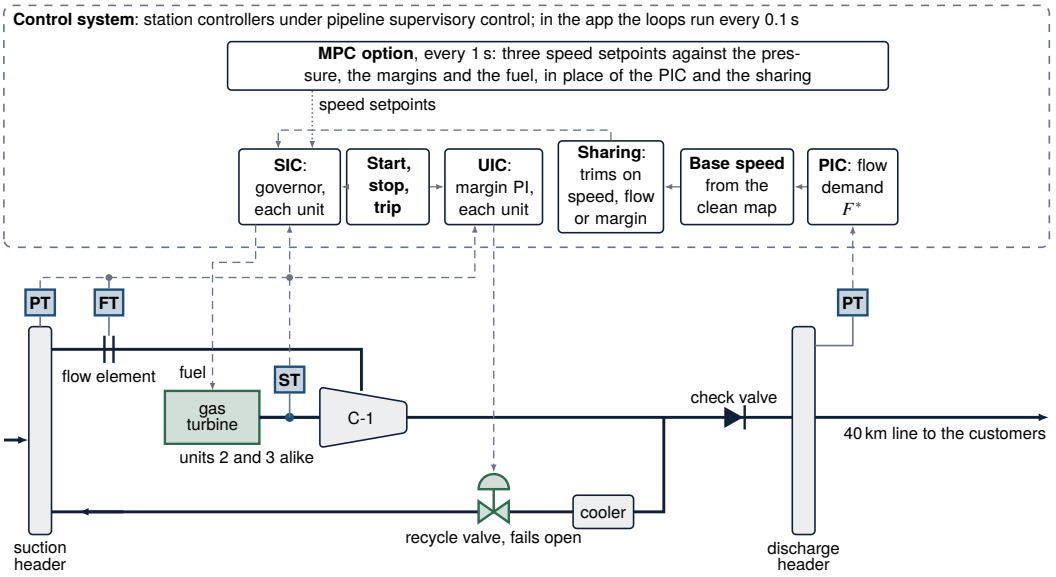


Figure 11.6 The loops of one unit and of the station with their hardware. Lettered boxes are sensing devices with the chapter's tags: PT on each header, FT on the machine's inlet and ST on its shaft. Green symbols are final elements: the gas turbine's fuel, set by the governor (SIC), and the anti-surge recycle valve, which fails open. Dashed arrows are signals, dotted arrows the speed setpoints that the MPC option writes in place of the sharing law. Notice that the anti-surge loop reads three instruments and no controller reads the fouling, and that the trip reaches the recycle valve without passing through the margin. Units 2 and 3 repeat unit 1. Not to scale, and not a piping diagram.

What Moves It

Two final elements per unit carry the chapter's handles. The gas turbine's fuel moves the shaft speed, through a governor whose setpoint comes from the sharing law, and the recycle valve moves the flow through the machine without moving the flow delivered. Speed is the efficient handle and recycle the protective one, because gas sent around the recycle has been compressed for nothing. A start, a stop and a trip also drive the valve open.

> **TECHNOLOGY** **Final Element: The Anti-Surge Recycle Valve**
>
> Surge is a violent and potentially self-destructive action of a centrifugal compressor when the pressure across it is too high and the flow through it too low. A recycle valve from discharge to suction prevents it, keeping enough flow through the machine while unloading the pressure across it [19]. A textbook loop diagram for surge control makes the valve air-to-close, so that it opens when it loses its air, and the transmitter of the pressure across the machine reverse-acting, so that a broken wire reads as a high pressure and the controller opens the valve. The safest failure decides: a process safer with the valve open needs an air-to-close valve [19]. The model's valve strokes at 50 %/s behind a 1 s lag, and case 7 shows when that is too slow.

Where the Controller Runs

A gas pipeline is run through supervisory control and data acquisition. A control server at a control center gathers the field data, while programmable logic controllers or remote terminal units at the field sites control each local process, and control loops run with cycle times from milliseconds to minutes [20]. Compressor surge control is a standard example of a safety function that must respond within a guaranteed time [19]. The app's controllers execute every 0.1 s and its MPC every 1 s. The

chapter's structure maps onto standard blocks: a pressure PI whose output is a flow demand, a characterizer that turns it into a base speed, sharing trims that re-center to zero, a PI governor per unit, an anti-surge PI per unit that rests at its clamp above the control line, and a sequence for the start, the stop and the trip. A predictive controller for one centrifugal machine has been timed on an industrial programmable logic controller [14].

> ⚠ **IN PRACTICE** **What the Federal Rules Ask of a Station**
>
> United States pipeline safety rules set a station's last layer of protection. Every station, except an unattended one of 1,000 horsepower or less, must have an emergency shutdown system that blocks gas out, blows down the piping and shuts down the compressors, operable from two places or more outside the gas area [21]. Every prime mover but an electric motor needs an automatic shutdown before it or its compressor passes a maximum safe speed, and every unit a shutdown or alarm for inadequate cooling or lubrication [22]. Each remote shutdown device is tested at least once each calendar year and within 15 months of the last test [23]. The chapter's overspeed trip at 110 % is a teaching value.

What Is Modernizing It

Three developments touch this chapter. The first is the drive: most compressor units burn gas taken from the line, but electric drives have been growing, mainly for environmental reasons [16], and converting rotating machines to variable speed is an ongoing trend [24]. The second is the sharing layer. A 2022 study ran online feedback optimization of a station's load sharing, with Gaussian process regression learning the mismatch between the assumed and the real maps: imperfect maps had cost 5 % more power than perfect ones, and the learning cut that to 0.8 %, by a method meant for programmable controllers and edge devices [24]. The third is security. In May 2021 more than 5,500 miles of refined products pipeline shut down after ransomware encrypted the operator's business systems, with no evidence then that it had reached the control systems [20]. The pipeline of Chapter 13 carries such products.

11.7 Limitations

Every size, rating and threshold is a teaching value picked so that the design point is consistent, two 15 MW units carrying 300 kg/s at 70 bar a, and none was fitted to a station. Each machine is quasi-steady, surge is a prescribed 2 s cycle whose onset is the static surge line and not Greitzer's dynamic boundary, rotating stall is absent, and the three machines share one map. Fouling is one head factor that leaves the surge line fixed, a simplification that keeps the controllers' margins true where real deposits may not. The headers and line are isothermal, the recycle coolers perfect and the line two cells without pressure waves. There is no station bypass, so the shipped challenge's windmill regime is outside the model's intended range. The margin is the same-speed distance of Section 1.4.6, which reads lower than the same-head distance many industrial controllers use.

The controllers carry the commissioned map, the declared defaults of every model parameter, so the base speed and the MPC meet fouling and any change of the plant's parameters only through the measurements, while the anti-surge loops' surge line, a protection limit, follows the plant's map. The MPC is linearized every second on the clean map with a drift for the line pack and carries no guarantee beyond its horizon. There is no decoupling between the station loop and the anti-surge loops, so case 8's remedy is detuning. A static feedforward between two interacting loops, the remedy of Volume 6, Chapter 2, is not modeled. The challenge grades recycle in place of fuel because the fuel differs by less than half a percent. Every number comes from one model at seed 20261022. The challenge was also run at ten other seeds initially, then over 31 seeds at both steps, with the two recycle-budget misses reported above. Case 8 uses two further refinements, $\Delta t/2$ and $\Delta t/4$.

OPEN CHALLENGE **Sharing the Load With Maps That Drift**

Every sharing law of this chapter trusts a map, and a real map drifts. Predicting how wear and tear change an engine's performance is still a matter of discussion, and a gas turbine and the compressor it drives degrade as one system [15]. Rotating machines degrade over time, accurate models of them are generally not available, and the optimizers that track each machine's map fit a polynomial of fixed degree online, which may give low model fidelity and so a poorer share [24]. Progress would be a sharing layer that learns each machine's map as it fouls, runs on the station's own controller and still keeps every unit right of its control line.

11.8 Conclusion

A compressor station is a set of machines that share a head and not a load, and this simulator logs each machine's speed, flow, margin and recycle beside the station's pressure, fuel and line pack. Slowing one of two machines to 83 % moves its margin from 28.05 to 12.38 % in 6 s while its neighbor takes the gas. With one machine fouled, equal speed recycles 15.01 t in an hour of turndown where equal surge margin recycles none, because the two laws reach the control lines at 251.6 and 237.8 kg/s. A start pushes the running units to about 17.6 % whatever the load time, a trip handled by feedback alone surges the tripped unit in 0.75 s, and a fast station loop on recycling units holds a 0.33 bar limit cycle that halving the step does not move. The predictive controller matches equal-margin sharing, and the six-hour challenge needs all four suggested layers. The model is lumped and its surge cycle imposed. A fuller model would add a station bypass, distinct maps with a surge line that fouling moves, a decoupler between the station and anti-surge loops, and a Greitzer duct for each machine at a finer step. The simulator shows that a station's surge count and its recycle are decided by the layers above its loops.

KEY POINTS

- Compressors on one header share a head, not a load, so a machine a little slower or fouled drifts toward surge while its neighbors take the gas.
- With one machine fouled, equal speed recycles 15.01 t in an hour where equal surge margin recycles none.
- A trip handled by feedback alone surges the tripped unit in 0.75 s, and a valve opened by the trip signal prevents it.
- A fast station loop on recycling units holds a 0.33 bar limit cycle that halving the step does not move.
- The predictive controller matches equal-margin sharing and does not beat it.

Where else this applies. Three producers on one shared header return in Volume 18, Chapter 9, one total divided among unlike actuators in Volume 4, Chapter 12, and parallel pumps started and stopped under minimum run and rest times in Volume 9, Chapter 11.

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11.9 Exercises

11.1 Concept check · 2 min

Case 1 starts with both units on Manual at 90.5 % speed, each passing 150 kg/s at 28.0 % from surge. The reader lowers unit 2's speed setpoint to 83 % and leaves unit 1 alone. What has happened five minutes later?

(a) Unit 1 still passes 150 kg/s, because its speed setpoint and its map have not changed

(b) Unit 1 passes more gas, because the discharge has fallen and unit 1 meets the lower head at a larger flow

(c) Both units pass about 140 kg/s, because the anti-surge loops split the station's flow between them

(d) Unit 2 is in deep surge, because its 83 % speed line no longer reaches the header's head

11.2 Concept check · 1 min

In case 4 the reader starts unit 3 while units 1 and 2 run at their 105 % limit. Load ramps of 10, 30, 120 and 300 s leave the two running units' least margins at 17.20, 17.46, 17.57 and 17.63 %. Why does the length of the ramp hardly matter?

(a) The running units' anti-surge loops open as unit 3 starts and pin their margins at one value

(b) Unit 3's check valve stays shut through the ramp, so units 1 and 2 never see its gas

(c) The station loop sets the running units' speeds from the discharge pressure and takes back what unit 3 delivers

(d) The sequencer's minimum run time overrides the ramp and loads unit 3 on a schedule of its own

11.3 Concept check · 2 min

In case 7 three units share 360 kg/s at 85.4 % speed, 11.4 % from surge. Unit 2's turbine trips at 120 s with *Recycle on a trip* on *Anti-surge loop*, and unit 2 surges 0.75 s later. Which single change, made before Run, keeps unit 2 out of surge?

(a) Raise the anti-surge gain to its maximum of 20, so the PI opens the valve faster

(b) Raise the surge control line to 15 %, so the valves start the trip partly open

(c) Choose equal surge margin sharing, so units 1 and 3 take unit 2's gas more quickly

(d) Set *Recycle on a trip* to *Open at once*, so the trip itself opens the valve

11.4 Theory and calculation · 6 min

At the design point a clean unit runs at $n = 0.9047$ with an inlet flow of $Q = 4.202\,\mathrm{m^3/s}$, and the suction header is at 45.00 bar a. Use Equations (11.1) and (11.2) with $\psi_0 = 0.2$, $H = 0.18$, $W = 0.25$, $Q_{ref} = 7.255\,\mathrm{m^3/s}$ and $H_{ref} = 160\,\mathrm{kJ/kg}$, and $ZRT/M = 126.07\,\mathrm{kJ/kg}$.

(a) Find ϕ, ϕ/n and the surge margin, once from the definition and once as $50(x-1)$. *Checkpoint:* $\phi = 0.5792$, $\phi/n = 0.6402$, $SM = 28.0\,\%$.

(b) Find $\Psi(\phi/n)$ and the polytropic head the machine makes. *Checkpoint:* $\Psi = 0.4592$, $h_p = 60.1\,\mathrm{kJ/kg}$.

(c) Find the suction density, the mass flow and the surge flow in kg/s at this speed, and check the margin from the two mass flows. *Checkpoint:* 35.69 kg/m^3, 150.0 kg/s and 117.1 kg/s.

11.5 Theory and calculation · 6 min

Fouling multiplies a machine's head by $1-a$ at every flow coefficient and leaves its surge flow where it was.

(a) Two machines make the same head. Show from Equations (11.1) and (11.2) that they have equal margins when $n_1\sqrt{1-a_1} = n_2\sqrt{1-a_2}$. State what the result neglects. *Checkpoint:* Equal margin means equal ϕ/n, so $(1-a)n^2$ must match.

(b) In case 5 unit 2 is clean at 90.47 % and unit 1 has lost 8 % of its head. Find the speed that gives unit 1 unit 2's margin. *Checkpoint:* 94.32 %.

(c) In case 3 with equal surge margin, unit 1 is fouled 6 % and clean unit 2 runs at 81.25 %. Predict unit 1's speed. *Checkpoint:* 83.80 %.

11.6 Theory and calculation · 7 min

The gas is $M = 17.4\,\text{kg/kmol}$ with $Z = 0.90$ at 293.15 K. The line is two cells of 20 km with $D = 0.9\,\text{m}$ and $f = 0.0095$, the headers hold $300\,\text{m}^3$ each, and the outlet flow w_o crosses half a cell. Use Equation (11.6).

(a) Find c, and the gas held per bar by one header and by one cell. *Checkpoint:* 355.07 m/s, 237.96 kg and 10 092 kg per bar.

(b) Find K for one cell in bar^2 per $(\text{kg/s})^2$, and the steady pressures P_1 and P_2 for 300 kg/s with the discharge at 70.00 bar a. *Checkpoint:* $K = 6.576 \times 10^{-3}$, $P_1 = 67.85\,\text{bar}\,a$, $P_2 = 63.34\,\text{bar}\,a$.

(c) Find the gas held in the two cells. *Checkpoint:* 1324.05 t.

11.7 App challenge · 9 min

Load scenario 3, "Equal speed against equal margin, one machine fouled", at the default seed. Play at speed 60, so an hour takes a minute, and pause just after 60 min. Read the row at 3600 s of the exported file.

(a) Run the case as shipped, at equal speed. Read the gas recycled (column `recycled_online_t`) and the fuel (`fuel_MWh`). *Checkpoint:* 15.0 t and 63.33 MWh, within 0.1.

(b) Press the reload button, set *Sharing law* to *Equal surge margin* before Run, and repeat. Read the same two columns, both units' speeds in their titles on the *Maps* view, and the columns `truth_u1_margin_pct` and `truth_u2_margin_pct`. *Checkpoint:* 0.0 t, 62.76 MWh, 83.8 % and 81.3 %, margins 12.5 and 12.6 %, within 0.1.

(c) Explain why the fouled unit runs faster under equal margin, and why the fuel falls by less than one percent while the recycle falls to zero. *Checkpoint:* The fan-law result of the second theory exercise, and gas compressed for nothing costs only its compression work.

11.8 App challenge · 8 min

Load scenario 7, "A trip: the others take the load", at the default seed, and play at speed 10.

(a) Run to 300 s as shipped, with *Recycle on a trip* on *Anti-surge loop*. Read the *Surges* tile. *Checkpoint:* 2.

(b) Set *Recycle on a trip* to *Open at once*, press Reset and run to 900 s. Read the *Surges* tile. In the exported file, find the lowest value of the column `truth_pd_bara` and its time. At 900 s, read that column and two more, `truth_u1_margin_pct` and `truth_u3_margin_pct`. *Checkpoint:* 0 surges, 68.59 bar a at 153 s, then 69.75 bar a and 38.1 % for both units.

(c) The discharge dip is the same 68.59 bar a with either trip action. Explain why, and why the discharge settles short of 70.0 bar a. *Checkpoint:* The dip comes from the loss of unit 2's forward gas and the limit of the other two.

11.9 App challenge · 8 min

Load scenario 8, "Station loop against anti-surge loops", at the default seed. Set *Instrument noise* to *Off* in the Advanced disturbances before Run, play at speed 10 and run to 900 s.

(a) In the exported file, find the peak-to-peak swing over 600 to 900 s of two columns, `truth_pd_bara` and `u1_recycle_pct`, and the period of the pressure swing. Read the *Lowest margin* tile. *Checkpoint:* 0.334 bar within 0.005, 12.2 % within 0.3, a period of 8.4 s within 0.2, and 5.9 %.

(b) Press Reset, set *Station gain* to 100 kg/s per bar and *Station integral time* to 10 s before Run, and repeat. *Checkpoint:* Below 1×10^{-4} bar, and 9.9 %.

(c) Explain why the same fast tuning rings and then settles when the units carry 300 kg/s with no recycle. *Checkpoint:* Without recycle the anti-surge loops are idle and add no gain.

11.10 Application area · 4 min

A station manager asks why the six-hour challenge grades the gas recycled and not the fuel, since fuel is what the station pays for. Use Table 11.5.

(a) For the suggested settings at equal speed, equal flow and equal margin, find the spread of the six hours' fuel as a percent, and the ratio of the largest recycle to the smallest. *Checkpoint:* 2.45 MWh, just under half a percent, and 3.2 times.

(b) Give two reasons, from the table and the chapter, why fuel is a poor grade for this lesson. *Checkpoint:* It barely separates the laws, and the failing shipped run burns the least.

11.11 Application area · 5 min

The chapter measures the surge margin at the present speed. Many industrial anti-surge controllers measure it at the same head, on a map in reduced coordinates. On this map the surge line is $\psi = 0.56\, n_s^2$ at $\phi = 0.5\, n_s$.

(a) At the design point, $\phi = 0.5792$ at $n = 0.9047$ with $\Psi = 0.4592$, find the speed n_s whose surge point has the same head, and the same-head margin. *Checkpoint:* $n_s = 0.8193$, 41.4 %.

(b) On the 10 % control line, $\phi/n = 0.55$ and $\Psi = 0.5485$. Find the same-head margin there. *Checkpoint:* 11.2 %.

(c) A vendor states a control line of 10 % in the same-head convention. What does this mean for comparing the vendor's numbers with this chapter's, and where do a real station's numbers come from? *Checkpoint:* About a point apart at the line, thirteen at design, set by surge tests.

11.12 Review the agent · 5 min

An AI assistant reviews the six-hour challenge. It writes: "The suggested settings pass with a worst pressure deviation of 1.048 bar, set by the trip at 2 h, and that is the binding target. Keep equal surge margin, the automatic sequencer and *Open at once*, and stiffen the station loop to 200 kg/s per bar with a 20 s integral time. A faster loop recovers the trip's dip sooner, so it can only improve the result." Find the flaw, and say how to check it on the app.