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Principles and Applications

Volume 17 Control of Energy Conversion and Storage

CHAPTER 1

Introduction: From Inertia to Dispatch

Pages 1–22

Edited by John D. Hedengren

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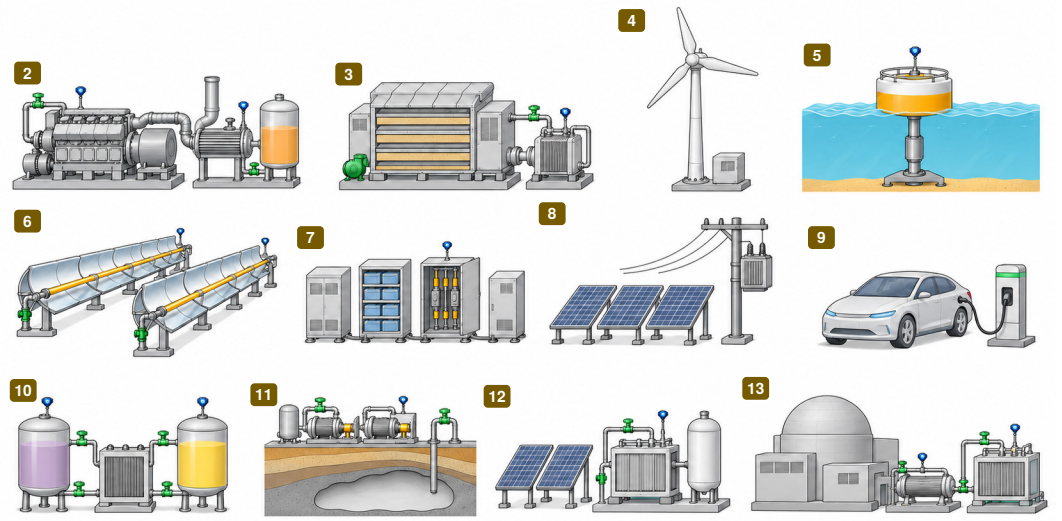
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CHAPTER 1

Introduction: From Inertia to Dispatch



The chapters 2 gas engine cogeneration 3 fuel cell cogeneration 4 wind turbine 5 wave buoy 6 parabolic trough field 7 campus microgrid 8 solar feeder 9 fast charger 10 vanadium flow battery 11 salt-cavern air store 12 solar hydrogen plant 13 nuclear heat and hydrogen

Notice that the top row converts gas, wind and waves, the middle row collects sunlight and runs the networks and a charger, and the bottom row stores energy in electrolyte, air and hydrogen or turns reactor heat into hydrogen. Illustration, not to scale.

IN PLAIN TERMS **Fast Loops and Slow Plans for Energy**

The main idea. Engines, fuel cells, wind turbines, solar fields and batteries turn energy from one form into another or keep it for later. Fast controls act on each one within seconds, and slow plans look hours or days ahead.

The challenge. Electricity must match demand at every moment. Fuel, heat, sun and wind change far more slowly than the electronics that deliver the power. A store can cover the gap only while it is neither full nor empty, and the limit that matters is often not measured.

Why it matters. Good control keeps the lights on while it spends fuel and stored energy at the best times.

THREE WAYS TO READ THIS CHAPTER

Explore	7 min	This page, Section 1.2 with its timeline and two History boxes, Figure 1.2, the Did you know? boxes in Sections 1.4.2, 1.4.4 and 1.4.5, and Key points in Section 1.8. No equations.
Study	45 min	The whole chapter in order, working each number of the example E-1, then Exercises 1 to 10.
Practice	5 min	This page, Section 1.4.7 with Table 1.2, Section 1.5 with Figures 1.6 and 1.8, and Section 1.8.

1.1 The Question This Volume Answers

An energy system is controlled on clocks that span nine decades. A grid-forming inverter answers a load step within milliseconds. A gas engine settles its power in seconds and its recovered heat in about a minute. A solar field passes its fluid from inlet to outlet in minutes, a flow battery empties in hours, and a salt cavern is managed against a reserve that changes with the season. Every plant in this volume converts or stores energy, and every one of them is controlled in layers: fast loops that hold

a frequency, a voltage, a temperature or a current, and slow layers that decide how much to make, store or sell over the next hour, day or season. This volume answers one question: how is each layer designed, and how does a fast regulating layer share a plant with a slow dispatching one?

Seven control problems define the industry, and every chapter meets several of them.

- *Supply and demand must balance at every instant.* Electricity is not stored in the wires, so any imbalance changes the speed of rotating machines, the frequency or a bus voltage within seconds.
- *Fast actuators stand in front of slow supplies.* A power converter moves in milliseconds, while the fuel, heat or wind behind it moves in seconds to hours, and a store must cover the difference.
- *Stores are inventories with two limits.* A battery, a tank of salt, a cavern of air or a vessel of hydrogen integrates what goes in and out, and it is useless both full and empty.
- *One input makes two products.* A fuel valve makes electricity and heat at once, and the two answer on different clocks.
- *The value of energy moves with time.* Prices, loads, sun, wind and waves change through the day, so the best action now depends on a forecast of what comes later.
- *The binding limit is often unmeasured.* An anode potential, the voltage at the far end of a feeder or the fuel arriving at a cell is inferred, not read.
- *Protection outranks economics.* An interlock, an overtemperature override or a shed relay must win over any dispatch, however profitable.

Twelve chapters answer the question on twelve plants, each with an app that the reader runs in a browser. Chapters 2 and 3 make power and heat for data centers from natural gas, in reciprocating engines and in a solid oxide fuel cell. Chapters 4, 5 and 6 take energy from wind, waves and sunlight. Chapters 7 and 8 control the networks that carry it: a campus microgrid that islands from the utility and a distribution feeder with rooftop solar. Chapter 9 charges a vehicle pack. Chapters 10, 11 and 12 store energy in an electrolyte, in compressed air and in hydrogen, and Chapter 13 dispatches the constant heat of a nuclear reactor between a turbine, a salt store and an electrolyzer.

A reader who has worked through the volume can do the following on an energy plant that is new to the reader.

- Place each loop of the plant on the time-scale hierarchy and check that each layer is slow enough to treat the one below as settled.
- Compute the first rate of change of frequency after a load step and the settled deviation that droop leaves, and say which layer removes it.
- Treat a store as an inventory: its duration, its losses, the loop that keeps it in the middle and the limits that taper its power.
- Follow one product of a cogeneration plant and size the store that absorbs the mismatch of the other.
- Say what a forecast and a planning horizon are worth on a given day, and price the energy left in a store at the end of a plan.

This chapter develops each of these on one small example and names the chapter that uses it. PID forms and tuning are taken as known from Volume 2, feedforward and cascade from Volume 3, selectors, overrides and actuators that deplete from Volume 4, estimation and Kalman filtering from Volume 5, inventory control from Volume 6, gain scheduling from Volume 7, state machines and switching from Volume 8, and predictive and economic control from Volume 9. Volume 18 treats nuclear reactor physics.

1.2 A Short History

The milestones of Figure 1.1 follow the plants of this volume, from the first fuel cell to a definition of fast charging.

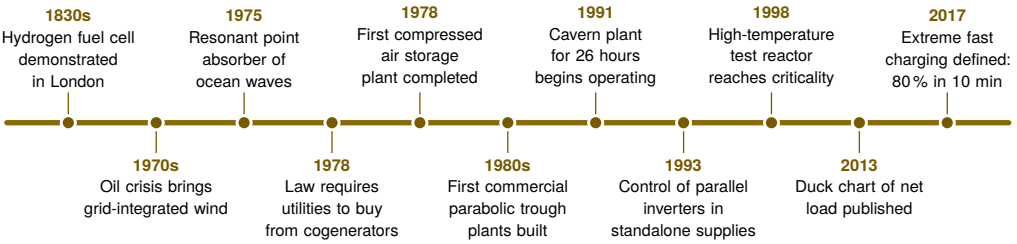


Figure 1.1 Milestones of energy conversion and storage and their control. The dates are from [1] (1830s), [2] (1970s), [3] (1975), [4] (1978, the law), [5] (1978, the air store, and 1991), [6] (1980s), [7] (1993), [8] (1998), [9] (2013) and [10] (2017). Notice that most of the converters came before the controls that join them to a grid. Events are evenly spaced, not to a time scale.

> ⧖ HISTORY **1830s to 1960s: A Fuel Cell Waits for a Use**
>
> A hydrogen fuel cell was demonstrated in London in the 1830s, and the technology then remained without a practical application for over a hundred years. Fuel cells returned to the laboratory in the 1950s, when the United States space program needed new power systems with low or no emissions [1]. In the 1960s the space program demonstrated a 1 kW polymer electrolyte cell in Gemini and a 1.5 kW alkaline cell in Apollo, both on pure reactant gases [11]. Today Chapter 3 runs a solid oxide cell on natural gas, and Chapter 12 runs a membrane cell on hydrogen it made itself.

The energy crises of the 1970s brought the other sources. The oil crisis of that decade rekindled interest in renewable energy and led to the commercial adoption of wind energy systems on the grid [2], the machines of Chapter 4. In 1975 a wave absorber much smaller than a wavelength was named a point absorber, a damped oscillator that passes energy from the wave to a load [3], the device of Chapter 5.

A United States law of November 1978 required electric utilities to offer to buy electric energy from qualifying cogeneration facilities and to sell to them [4], the kind of plant Chapter 2 controls. The first compressed air energy storage plant was completed near Bremen in the same year, and a plant in Alabama designed for 26 hours of generation at full power from a single salt cavern has run since 1991 [5], the store of Chapter 11. The first commercial parabolic trough plants were built in the Mojave Desert in the 1980s [6]. A test reactor built for high-temperature heat reached first criticality in 1998 [8], a step toward the reactor heat for hydrogen of Chapter 13.

In 2013 the California system operator published the duck chart of net load [9], the curve that the flow battery of Chapter 10 serves. In 2017 a gap assessment defined extreme fast charging as recharging up to 80 percent of a battery's capacity in ten minutes or less [10], the goal that Chapter 9 pursues against a limit no instrument reads.

> ⧖ HISTORY **1993 to 2018: Inverters Learn to Hold a Grid**
>
> Droop control for inverters was first proposed in the early 1990s. It trades frequency and voltage against real and reactive power much as a synchronous machine does, so parallel inverters can share a load without communicating [7, 12]. Such controls were first meant for microgrids and small islands [12]. On the grid itself, United States standards long kept inverters from supporting the voltage, until an amendment of May 2014 allowed advanced functions [13]. Chapter 7 forms its island from a battery inverter, and Chapter 8 runs Volt-VAR curves along a feeder.

1.3 Notation and Conventions

Electric power is in megawatts (MW) or kilowatts and energy in megawatt-hours. Where heat and electricity meet, MWth and MWe keep them apart. Frequency f is in hertz with nominal value $f_0 = 60\,\text{Hz}$, and a voltage v is in per unit (pu) of its nominal value. A machine or converter of rating S has an inertia constant H, the stored kinetic energy divided by the rating, in seconds. A droop R is the per-unit fall of frequency that drives a unit from no load to its rating. A store holds at most E megawatt-hours, its state of charge is the fraction SOC, and it charges at power P_c with efficiency η_c and discharges at P_d with efficiency η_d. A cogeneration unit converts fuel power P_f to electricity with efficiency η_e and to recovered heat Q_h with efficiency η_h.

The framework's h is its integration step and its a the controller action, and neither is used for anything else here. Its S_k is a running sum in the PID algorithm and its Q, R and N are the weights and the horizon of a predictive controller, unrelated to the rating, the droop and the heat of this chapter except that N is again a horizon. Loop action follows Section 1.6.2: $a = +1$ is reverse acting, for a process whose measurement rises with the manipulated variable, and $a = -1$ is direct acting. A frequency loop on a generator's setpoint is reverse acting, because more power raises the frequency. A loop that holds a state of charge by discharging is direct acting, because more discharge lowers the charge. A cooling loop on a temperature is direct acting. Three chapters, Chapter 6, Chapter 9 and Chapter 10, write the action flag as γ with the same meaning.

The chapters keep their own symbols, and several collide. H is an inertia constant in Chapter 7, the significant wave height H_s and the forecast horizon H_f in Chapter 5 and an exhaust enthalpy in Chapter 2. R is the governor droop in Chapter 7, the compensator resistance R_{set} in Chapter 8 and the rotor radius in Chapter 4. Q is reactive power in Chapter 8 and Chapter 7, electrolyte flow in Chapter 10, a pack capacity in ampere hours in Chapter 9 and a heat duty in Chapter 13 and Chapter 6. λ is the tip-speed ratio in Chapter 4, the membrane hydration in Chapter 12, the cavern leakage rate in Chapter 11 and a move-suppression weight in Chapter 6 and Chapter 13. φ is the anode potential in Chapter 9, an autoregressive coefficient in Chapter 5 and the idle fuel share φ_0 in Chapter 2, while Chapter 8 writes its Volt-VAR curve $\phi(v)$ and Chapter 13 a pressure ratio ϕ. δ is a machine angle in Chapter 7, the Volt-VAR deadband in Chapter 8, the electrolyte imbalance in Chapter 10 and a degradation state in Chapter 13. S is a rating in Chapter 7 and Chapter 8 and the cavern's state of charge in Chapter 11, and z is the state of charge in Chapter 9 but an overload state in Chapter 7. Chapter 7 also writes its dispatch slot length as h, which is not the framework's step.

1.4 From Inertia to Dispatch

1.4.1 The Flow Scheme

Figure 1.2 places each chapter's plant on the path from primary energy to the user. Gas engines and fuel cells convert natural gas to electricity and heat close to a large user such as a data center [14]. Wind turbines, wave converters and solar fields convert flows that nobody controls, and their output follows the weather. A nuclear reactor makes heat at a constant rate. Networks carry the electricity: a transmission grid, a distribution feeder that ends at houses with their own solar, or a microgrid that can run alone behind one breaker. Stores sit on the network or inside a plant. A flow battery and a compressed-air cavern trade electricity across hours and days, a hydrogen plant across a day

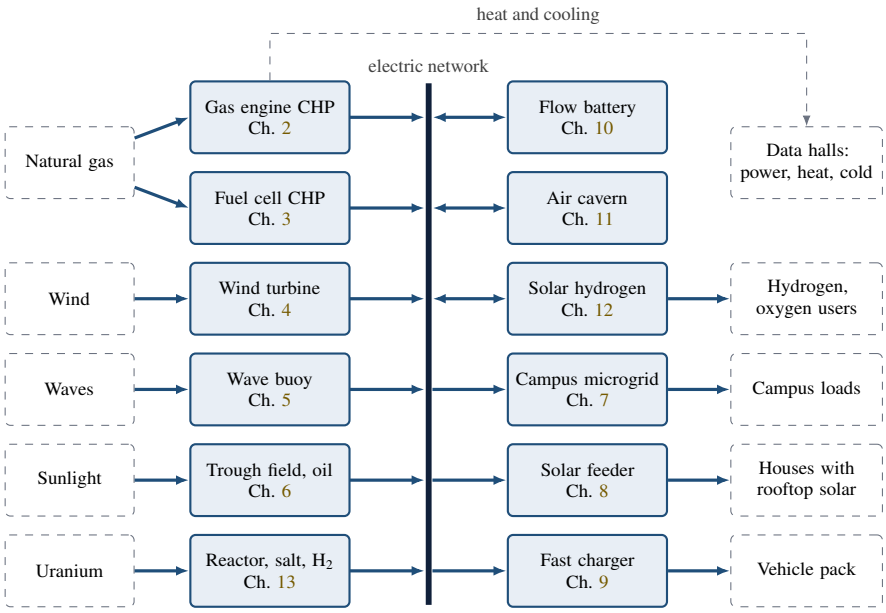


Figure 1.2 The Plants of the Volume on the Path From Primary Energy to the User. Filled Blocks Are the Plants of Chapters 2 to 13, Dashed Blocks Lie Outside the Volume. Converters on the Left Feed the Electric Network (Vertical Bar), Stores Trade With It in Both Directions, and Networks and Chargers on the Right Deliver It. The CHP Plants Also Serve Data Halls With Heat and Cooling (Dashed Arrow), and the Nuclear Plant Also Sells Hydrogen (Not Drawn).

and night, and tanks of hot water or molten salt store heat inside the plants that make it. Electric vehicles are users that are also stores. Planning such systems as a whole, with heat, electricity and fuels coupled, is the subject of multi-energy system studies [15], and the flexibility that storage, dispatchable plant and demand provide is what lets a grid take a large share of variable renewable energy [16, 17].

The techniques the chapters share are developed below on one running example, an island energy system called E-1. A gas engine-generator set rated 6 MW with recovered heat, a battery of 2 MW and 4 MWh, a 3 MW solar array and a hot-water store serve the electricity and heat of a small town. Every number of E-1 is declared here or computed from these declarations by the script kept with this chapter's record. The numbers are chosen for clear arithmetic and are not taken from any one chapter.

1.4.2 The Time-Scale Hierarchy

The rotating machines of a grid store kinetic energy, and that energy is the first buffer against any imbalance. If the mechanical power P_m delivered to the machines differs from the electrical power P_e drawn from them, the frequency changes as Equation (1.1) shows, which is the swing equation of a single machine or of a grid treated as one [18].

$$\frac{2HS}{f_0}\frac{\mathrm{d}f}{\mathrm{d}t} = P_m - P_e, \qquad \mathrm{ROCOF}(0^+) = -\frac{f_0\,\Delta P}{2HS} \tag{1.1}$$

The product HS is the stored kinetic energy. Right after a load step ΔP, before any governor moves, the frequency falls at the rate of change of frequency (ROCOF) on the right. E-1's engine-generator set has $H = 2.5$ s on its 6 MW rating, so it stores 15 MJ, and a 1 MW load step makes the frequency fall at 2.00 Hz/s. With nothing else acting, the island would lose 1 Hz in half a second. Inertia therefore buys time and nothing more. It sets how fast the frequency falls, while the layers above decide where

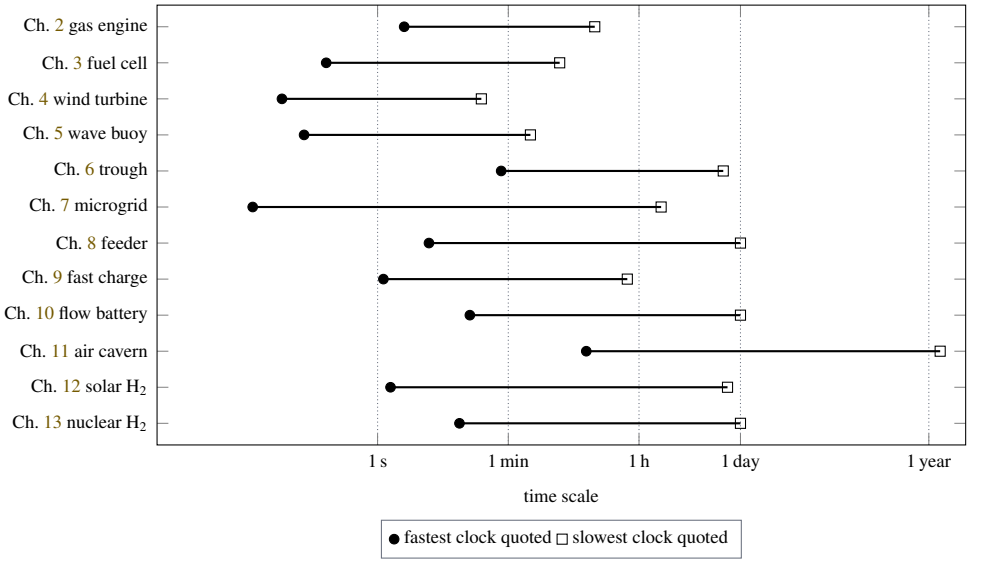


Figure 1.3 The Clocks of Each Chapter's Plant on a Logarithmic Axis. The Filled Circle Is the Fastest Response or Control Period the Chapter Quotes and the Open Square the Slowest Time Constant or Planning Horizon It Quotes, for Example a Module's Power 63 Percent Settled in 2.3 s and a Jacket Still Warming After 15 min (Ch. 2), or a Header Holding 13 s of Reactor Output per Bar and a 24 h Plan (Ch. 13).

the fall stops. Grids with a large share of converter-connected wind and solar lose this stored energy, which is why the first swing has become a design question of its own [17, 19].

Chapter 7 uses Equation (1.1) as its first relation. Its battery inverter forms the grid as a virtual synchronous machine with a virtual inertia of 2 s on 1 MW, and the bound $f_0 \Delta P/(2H_v S_i)$ gives 4.94 Hz/s for its 0.329 MW import, while a relay averaging over 0.1 s reads 2.48 Hz/s. The same balance governs a rotor that is not on a grid. The rotor of Chapter 4, 4.0×10^7 kg m^2 at its rated 1.267 rad/s, stores 32.1 MJ, which is 6.42 s of its 5.0 MW rating, and its open-loop time constant falls from 25.8 to 15.0 s across the range below rated wind. The steam header of Chapter 13 is the thermal equivalent: it stores 3.0 MWh per bar, about thirteen seconds of reactor output, so its pressure loop must close the heat balance continuously. Chapter 2 models its engines on a bus held by an uninterruptible power supply (UPS), so no swing equation appears there and the UPS takes each instantaneous imbalance instead.

> **+ DID YOU KNOW? How Fast a Frequency May Fall**
>
> A 2018 guidance of the European transmission operators asks generating units to stay connected while the rate of change of frequency stays within 2 Hz/s averaged over 0.5 s, 1.5 Hz/s over 1 s and 1.25 Hz/s over 2 s [20]. E-1's first fall, 2.00 Hz/s before any governor moves, is as steep as the limit of the shortest window.

Above inertia, control is arranged in layers that act on longer and longer clocks [21, 22]. Primary control, a droop in each governor or converter, stops the fall within seconds. Secondary control returns the frequency, or a voltage, to its nominal value within tens of seconds to minutes. Tertiary control and economic dispatch set each unit's share over minutes to hours, and commitment and storage policy look a day to a season ahead. Each layer can treat the layer below as settled only if it is several times slower, which is the same rule that sets an outer loop of a cascade several times slower than its inner loop in Volume 3. Figure 1.3 shows how widely the plants of this volume spread across that hierarchy.

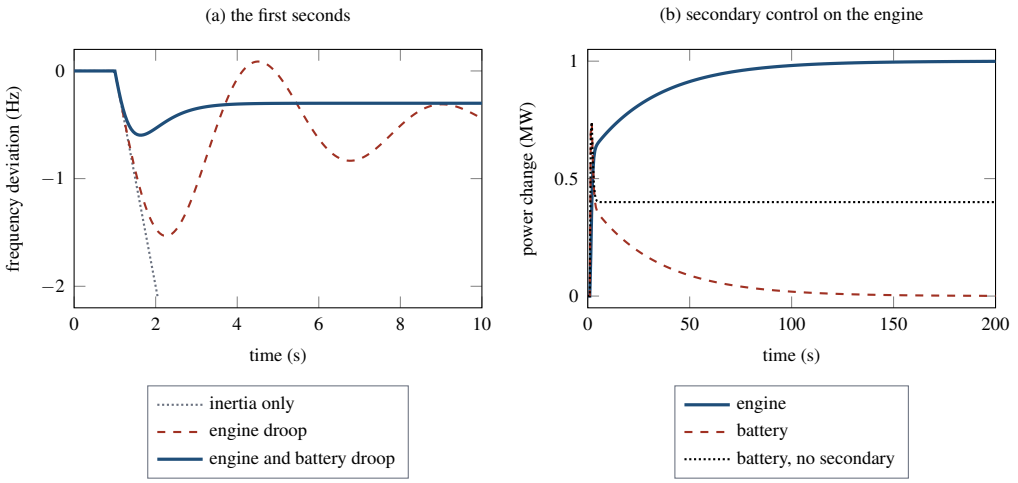


Figure 1.4 E-1 After a 1 MW Load Step at $t = 1$ s. (a) Frequency Deviation on Inertia Alone (Dotted, Leaving the Axis at 2.0 Hz/s), With the Engine's 5 % Droop (Dashed) and With the Battery's 2.5 % Droop Added (Solid). (b) With an Integral Secondary Loop on the Engine's Setpoint, the Engine (Solid) Takes Over the Step and the Battery (Dashed) Returns to Zero, While Without It the Battery Keeps 0.40 MW (Dotted).

1.4.3 Droop and Restoration

A droop makes each unit's power fall in proportion to the frequency's rise, as a proportional controller with no integral action. A unit of rating S and droop R changes its power by $\Delta P = -K\,\Delta f$ with the stiffness $K = S/(Rf_0)$ in megawatts per hertz. When several units share a load step on one frequency, each takes a share in proportion to its stiffness and the frequency settles where the shares add up to the step, as Equation (1.2) shows.

$$\Delta f = -\frac{\Delta P_L}{\sum_i K_i}, \qquad \Delta P_i = \frac{K_i}{\sum_j K_j}\,\Delta P_L, \qquad K_i = \frac{S_i}{R_i f_0} \tag{1.2}$$

E-1's engine governor has a droop of 5 % on 6 MW, a stiffness of 2.0 MW/Hz. Its battery inverter has a droop of 2.5 % on 2 MW, 1.33 MW/Hz. Chapter 7 quotes stiffness per unit of speed, which is f_0 times these numbers. After the 1 MW step the engine alone would settle 0.50 Hz low. With both, the frequency settles 0.30 Hz low and the engine carries 60 % of the step and the battery 40 %.

How deep the frequency falls first depends on how fast each unit answers. Figure 1.4a integrates Equation (1.1) with an engine whose governor and air path lag by 2 s and an inverter that lags by 0.1 s. On inertia alone the frequency falls in a straight line. With the engine's droop alone it falls to a nadir 1.53 Hz low 1.26 s after the step and rings before settling at 0.50 Hz low, because a 2 s lag on a stiff droop is an underdamped loop with a damping ratio of 0.18. With the battery's droop added, the nadir is 0.60 Hz low after 0.63 s, and at its peak the battery carries 0.78 MW, almost the whole step, while the engine catches up. The fast unit takes the transient and the slow unit the steady share.

Droop alone leaves the frequency off nominal and leaves the battery delivering its share for as long as the load stays. At 0.40 MW, a battery at half charge would be empty after 4.5 h. Secondary control removes both. An integral loop on the engine's setpoint, $\mathrm{d}P_{set}/\mathrm{d}t = -k_I\,\Delta f$ with $k_I = 0.1$ MW per hertz-second, is reverse acting and has a time constant of about $\sum K_i/k_I = 33$ s. Figure 1.4b shows the engine taking over the whole step and the battery handing it back. The frequency is 0.12 Hz low 30 s after the step and within 0.003 Hz 150 s after it. Over the whole event the battery delivers 3.70 kWh, less than a tenth of a percent of its capacity. Regulation costs a store power, not energy. Its energy is spent by the dispatch that decides what it does over hours.

Chapter 7 measures every part of this. Its genset and battery share a load in the ratio of their stiffnesses, 1.26 measured against 1.26 declared, its secondary returns the frequency to 60.000 Hz on the genset, and its falls after a step stay between 0.302 and 0.304 Hz from no virtual inertia to 3 s. The same division of labor, a fast actuator that carries a transient and a slow one that takes the steady load, is the structure of Chapter 2 and Chapter 3, where a UPS carries the bus while engines or a fuel processor catch up. Hierarchical control of this kind is the standard arrangement of microgrids and of the converters in them [23, 24].

Voltage has a droop of its own. On a radial feeder the voltage at a node differs from the substation by approximately the resistance times the active flow plus the reactance times the reactive flow, and a smart inverter absorbs reactive power in proportion to how far its voltage exceeds a deadband δ, with slope k. For one inverter at the end of a line of resistance r and reactance x, exporting active power P, Equation (1.3) gives the voltage rise and its settled value under the Volt-VAR droop.

$$\Delta v \approx rP - xq, \qquad q = k\,(\Delta v - \delta) \;\Rightarrow\; \Delta v = \frac{rP + xk\delta}{1 + xk} \tag{1.3}$$

At $r = 0.05$ pu, $x = 0.10$ pu and full export the rise is 0.050 pu without reactive power. With $k = 5$ and $\delta = 0.02$ pu the inverter absorbs 0.10 pu and the rise settles at 0.040 pu. Like the frequency droop, the Volt-VAR droop shares the correction and leaves a deviation. The slow layer that removes it is the tap changer at the substation, which moves the whole feeder in steps after a timer. Chapter 8 shows what happens when the slow layer misreads the fast one. Its tap changer's line-drop compensator reads the inverters' reactive swing as load, and with the Volt-VAR slope raised from 7.33 to 22 the tap changer makes 18 operations on a cloudy day instead of 2.

1.4.4 Storage State as an Inventory

A store is an inventory. Its energy integrates what is charged and what is discharged, with an efficiency on each side and a standing loss, as Equation (1.4) shows.

$$E\,\frac{\mathrm{dSOC}}{\mathrm{d}t} = \eta_c P_c - \frac{P_d}{\eta_d} - \sigma_s E\,\mathrm{SOC}, \qquad 0 \le \mathrm{SOC} \le 1 \tag{1.4}$$

A store has no self-regulation: with charge and discharge equal in power, the state of charge still drifts by the losses. Two numbers size it, the power rating and the energy, and their ratio is its duration at rating. E-1's battery has 2 MW and 4 MWh, a duration of 2 h, and an efficiency of 0.9 each way, a round trip of 0.81. Full to empty it delivers 3.60 MWh, and empty to full it takes 4.44 MWh. Storage technologies differ most in these two numbers and in how independently they can be bought [25, 26]. Chapter 10 buys them separately, 100 MW of stacks on 600.4 MWh of electrolyte, six hours from full to empty and 3.9 h of the working band at rated discharge. Chapter 11 stores 24.6 GWh in a cavern, which is 81.9 h at its expander rating, and Chapter 12 holds 15.7 h of hydrogen at its fuel cell rating.

> **+ DID YOU KNOW? Troughs Now Come With Storage**
>
> Parabolic trough plants can no longer compete with solar panels for daytime power, so the plants built since 2013 have included three hours or more of thermal storage. Their solar fields are oversized to run at full power by day and still charge the store [6].

The losses make even a balanced duty drain the store. If E-1's battery regulates with a square wave of ± 0.5 MW, equal time charging and discharging, its state of charge falls by 1.32 % an hour, about a third of the battery in a day. Something must therefore hold the state of charge, and that loop is an inventory loop of the kind that Volume 6 treats for tanks. A proportional state-of-charge manager adds $P = K\,(\mathrm{SOC} - \mathrm{SOC}_{ref})$ to the battery's discharge, which is direct acting. Against Equation (1.4) without losses it gives the first-order return of Equation (1.5).

$$\frac{E}{K}\,\frac{\mathrm{dSOC}}{\mathrm{d}t} = -(\mathrm{SOC} - \mathrm{SOC}_{ref}), \qquad \tau_{soc} = \frac{E}{K} \tag{1.5}$$

With $K = 2\,\text{MW}$ per unit of charge, 0.02 MW per percent, E-1's manager returns the charge with a time constant of 2 h, and the efficiencies make it 1.8 to 2.2 h depending on the direction. Like an averaging level loop, it should be slow: a fast manager would fight the regulation it exists to support, and a proportional one settles 2.6 points below its reference against the drift of the square wave, which is harmless in a band. The microgrid of Chapter 7 uses such a manager with a band from 40 to 80 % and 0.05 MW per percent outside it, and the UPS reserve loops of Chapter 2 and Chapter 3 hold a stored energy for the next trip or burst.

Near its limits a store loses power, not only energy. A battery management system tapers the allowed charge and discharge power over the last points of the band, and the controller above must receive those limits as the bounds of its output. Chapter 10 calls this cascade anti-windup and Chapter 7 tapers its battery's limits over 20 % of charge. Several plants hold two inventories on two clocks. Chapter 10 passes electrolyte through its stacks in 10 s and through its tanks in 11.1 min, so the charge measured at the stack is a biased estimate of the tank. Chapter 11 stores gas in the ground and heat in a packed bed, and finds that the heat more than the gas decides whether its winter commitment is kept. Chapter 9 fills an inventory as its product: the pack's state of charge is the integral of the current that four limits allow.

1.4.5 Heat and Power From One Fuel

A cogeneration unit makes electricity and heat from one fuel input, as Equation (1.6) shows [14].

$$P_e = \eta_e P_f, \qquad Q_h = \eta_h P_f = \psi P_e, \qquad \psi = \frac{\eta_h}{\eta_e} \tag{1.6}$$

The heat-to-power ratio ψ ties the two products together. E-1's engine converts 40 % of its fuel to electricity and recovers 50 % as hot water, so $\psi = 1.25$. One fuel command cannot hold an electrical balance and a heat balance at once. The plant follows one product and lets the other float: electrical following holds the power and makes heat as a by-product, and thermal following holds the heat and lets a grid or a store take the electrical difference. An island has no grid, so E-1 must follow its electricity. Its hot-water store then integrates the heat mismatch $Q_h - Q_L$ against the heat demand Q_L, and when it is full the surplus goes to a dump radiator, and when it is empty a boiler makes up the deficit.

> ✦ DID YOU KNOW? **Two Products in a Fixed Proportion**
>
> A 2017 federal catalog gives typical power-to-heat ratios of 0.5 to 1.2 for reciprocating engines and 1 to 2 for fuel cells. An engine starts in about 10 s, a fuel cell in 3 hours to 2 days [1]. E-1's engine, with $\psi = 1.25$, makes 0.8 units of electricity per unit of heat.

Figure 1.5 follows one day. The engine supplies the electric demand less the solar output, so at night it runs near 4 MW and recovers 5 MW of heat against a demand near 3.8 MW, and at noon the solar takes most of the load and the engine recovers only about 2 MW while the town still wants 3.8 MW. Over the day the heat recovered, 102.1 MWh, nearly matches the heat demanded, 99.1 MWh, yet a 6 MWh store started half full is full by 02:30 and empty by 12:22. It dumps 6.53 MWh at night and in the evening and buys 6.59 MWh from the boiler in the afternoon. The mismatch is in time, not in quantity, and the store that removes it is set by the range of the cumulative mismatch, as Equation (1.7) shows.

$$E_h \geq \max_t \int_0^t (Q_h - Q_L)\,\mathrm{d}t' - \min_t \int_0^t (Q_h - Q_L)\,\mathrm{d}t' \tag{1.7}$$

For E-1's day that range is 12.6 MWh. A store of that size started at 6.5 MWh neither dumps nor fires the boiler, while one of 12 MWh started half full still dumps 0.12 MWh and buys 0.59 MWh. The starting level matters as much as the size, which is a dispatch decision taken with a forecast of tomorrow's heat.

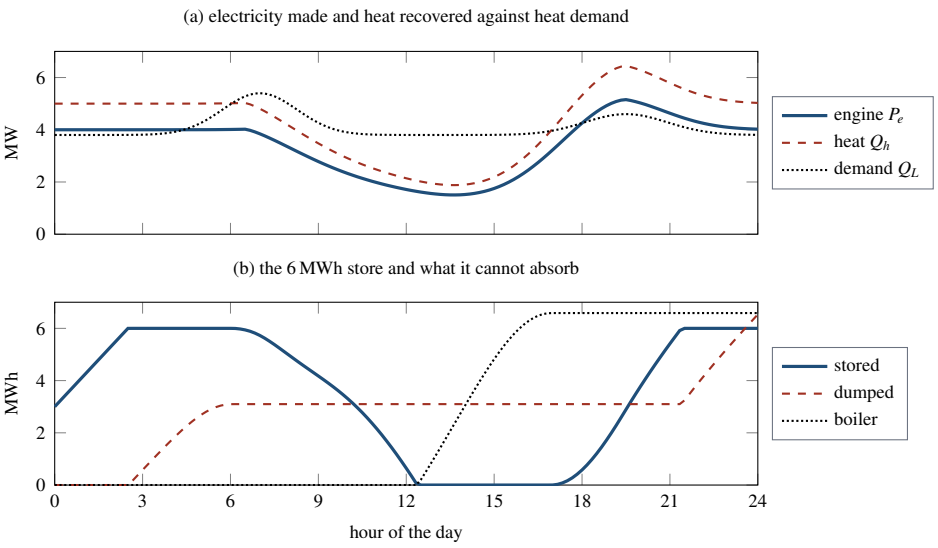


Figure 1.5 One Day of E-1 With the Engine Following the Electric Demand Less the Solar Output. (a) Engine Power (Solid), Recovered Heat (Dashed) and Heat Demand (Dotted). (b) Energy in a 6 MWh Hot-Water Store Started Half Full (Solid), With the Heat Dumped When It Is Full (Dashed) and Bought From a Boiler When It Is Empty (Dotted), Both Cumulative.

The two products also answer on different clocks. In Chapter 2 a fuel step moves a module's power 63 percent of the way in 2.3 s and its recovered heat in 68 s, and its jacket is still warming fifteen minutes later. When one of three modules trips on the island, the UPS carries the lost 1.0 MW for 12.5 s, and the hot-water buffer goes on losing heat for fourteen minutes. That chapter's plant offers base load, electrical following and thermal following as selectable authorities, and an overtemperature override that takes engine capacity when heat cannot be stored or rejected. Its fuel cell counterpart, Chapter 3, has the coupling in another form. Its current moves in fractions of a second, while a step of its fuel valve needs 17.3 s to deliver 63 percent of its hydrogen to the anode, so a governor must hold the current back and a UPS must carry the load meanwhile. Chapter 13 reverses the problem. Its reactor makes a constant 860 MWth, and all the flexibility lies downstream in a turbine, a salt store, an electrolyzer and a dump condenser whose duties must add up to that heat at every instant. Chapter 6 collects heat whose best temperature moves with the sun. Its receiver loses heat faster the hotter it runs while the power block converts heat better, and the outlet temperature that maximizes net output falls from the design value at full sun to the bottom of the search interval at a quarter of it.

1.4.6 Forecasts

A dispatch decision depends on what the load, the weather or the price will do, and the forecast that supplies it degrades with the lead time. The simplest model shows how. If a deviation from the expected value follows a first-order autoregression with coefficient φ per step, the best forecast k steps ahead is φ^k times the present deviation, and its skill, one minus the forecast's mean squared error over the variance, is given by Equation (1.8).

$$x_{k+1} = \varphi\, x_k + w_k, \qquad \hat{x}_{k+j} = \varphi^j x_k, \qquad \text{skill}(j) = \varphi^{2j} \tag{1.8}$$

With $\varphi = 0.9$ the skill is 0.81 one step ahead, 0.43 four steps ahead and 0.19 eight steps ahead. Real forecasts of sun, wind and load combine weather models, statistics and recent measurements, but their skill falls with lead time in the same way [27, 28]. Chapter 5 measures exactly this. Its autoregressive

Table 1.1 E-1's Battery, 2 MW and 4 MWh, Over Three Days of Hourly Prices: Margin of Each Policy and Its Share of the Best Possible, $1,812

Policy	Margin ($)	Share
Plan over 1 h, no value on the energy left	54	3.0 %
Plan over 1 h, energy left valued at yesterday's water value	734	40.5 %
Plan over 2 h, no value on the energy left	1,282	70.7 %
Plan over 3 h, no value on the energy left	1,740	96.0 %
Plan over 6 h or longer	1,812	100.0 %
Plan over 24 h, forecast blind to the $400 hour	1,131	62.4 %
Rule: charge below $25, discharge above $60, at rating	1,306	72.1 %

forecast of the wave force has a skill of 0.96, 0.85, 0.82 and 0.78 at leads of 1, 2, 3 and 4 s, and half of what a perfect four-second forecast adds to the energy captured comes from its first 0.5 s.

A dispatch layer plans over a horizon of N steps, applies the first move and plans again, the receding horizon of a predictive controller with an economic objective [29]. The horizon must reach far enough to see why a store should be filled or kept. E-1's battery is dispatched against three days of hourly prices with a perfect forecast, starting half full, by dynamic programming over a grid of 0.1 MWh. Dispatch against a price of this kind is the core problem of power system economics [30]. The prices follow a daily cycle from $12 to $95 per megawatt-hour, 10 % higher on the third day, and on the second day the hour from 15:00 is priced at $400. Table 1.1 gives the margin of each policy as a share of the best possible, $1,812 over the three days. A plan one hour long sees no reason to charge and earns 3 %. A plan of three hours earns 96 %, and from six hours on the plan earns everything, because six hours reach from the cheap midday hours to the dear evening ones.

A short plan treats energy left at its end as worthless and so never stores any. The remedy is a terminal value, the price at which a stored megawatt-hour would be sold later. The merit order gives it, as Equation (1.9) shows. A full store supplies n blocks of length Δ at its rating P_{max}, so the n-th highest price $p_{[n]}$ among the blocks ahead is the price at which its last megawatt-hour would be sold. A megawatt-hour in the store is then worth $p_w = \eta_d\, p_{[n]}$, the marginal value of stored energy, which is the reservoir water value of hydro scheduling [31].

$$n = \left\lceil \frac{\eta_d E}{P_{max}\,\Delta} \right\rceil, \qquad p_w = \eta_d\, p_{[n]}, \qquad \text{charge if } p < \eta_c\, p_w, \quad \text{discharge if } p > \frac{p_w}{\eta_d} \tag{1.9}$$

For E-1, $n = \lceil 0.9 \times 4/2 \rceil = 2$ one-hour blocks, and the second highest price of the first day is $90, so a stored megawatt-hour is worth $81. The battery should charge below $72.90 and discharge above $90. Valuing the energy left at the end of each plan at the previous day's water value lifts the one-hour plan from 3 % to 40.5 %, while at two and three hours it earns 63.9 and 92.9 %, slightly less than without it, because a value learned from yesterday's evening holds energy that a longer view would sell. A terminal value substitutes in part for a horizon that is too short. The last two rows of Table 1.1 show what a forecast cannot give. A plan blind to the $400 hour holds a full battery through it, waiting for the evening, and loses $681. A rule with fixed thresholds that reacts to the measured price sells in the $400 hour but earns only 72 % of the best, because its thresholds are wrong for ordinary hours.

The chapters measure the same trade. Chapter 10 finds its forecast worth nothing on an ordinary day, where feedback books $16 more, and $16,841 on a day with one scarce hour, and shows that a plan with no terminal condition sells its tank at the edge of the horizon. Chapter 13 sets the storage thresholds of its optimizing architecture from a merit order of its forecast block prices, finds that three price thresholds capture 78 % of what its economic optimizer adds over a fixed split on an ordinary day, and shows the two separating by $85,447 when the forecast misses an evening spike. Chapter 11, Chapter 6 and Chapter 12 find a threshold price for what they store by bisection over 30 daily blocks,

Table 1.2 For Each Chapter, the Fast Regulating Layer, the Slow Deciding Layer and What Joins Them

Ch.	Fast layer	Slow layer	What joins them
2	Module power loops, seconds	Authority selector, staging, MPC supervisor	UPS and hot-water buffer, overtemperature override
3	Current governor, voltage guard	Fuel feedforward and trim, reserve loop	UPS, estimate of arriving hydrogen
4	Torque and pitch loops	Region logic, gain schedule	Rotor inertia, wind preview
5	Force law every 0.1 s	Sea-state estimate, 120 s	Forecast of the wave force
6	Outlet loop on field flow	Setpoint optimizer, day schedule	Two-tank store, defocus override
7	Droops, virtual inertia, shedding	Secondary, SOC manager, genset start	Battery charge and its limits
8	Inverter Volt-VAR curves	Tap changer, central program	Compensator, look-ahead
9	Selector of current limits	Charge to target, predictive plan	Anode map, selector preload
10	Power loop, 18 s	24-hour dispatch program	Tanks, bounded net-load trim
11	Grid trim and heat loops	Inventory policy, seasonal reserve	Cavern, thermal store, capacity floor
12	Rectifier loops, 1.5 s	State machine, evening schedule	Gas inventories, interlocks
13	Six PI loops, header pressure	Economic plan every 15 min	Header identity, salt store

28 half-hour blocks and 32 half-hour blocks. Chapter 8 gives its predictive controller a preview of the clear-sky rise, which takes a cloudy day at 150 % solar from 15.9 to 0 minutes out of band. On the shipped challenge a program judged against the declared shapes 2 h ahead spends 10.2 minutes out against the controller's 11.1, and neither holds the band. The predictive controllers of Chapter 4 and Chapter 5 use a preview of the wind or a forecast of the wave force a few seconds ahead.

1.4.7 Fast Regulation and Slow Dispatch

Every chapter of the volume joins a fast regulating layer to a slow deciding one, and the join takes one of four forms. A store lets the two run at different rates: the fast layer draws on it and the slow layer refills it, as E-1's battery lends 3.70 kWh that its engine repays. A setpoint or reference written by the slow layer is held by the fast one, as a dispatch plan is trimmed by a net-load loop. A limit, selector or interlock lets protection take the actuator from either layer. A forecast lets the slow layer act before the fast layer sees anything. Table 1.2 lists the two layers and the join for each chapter. Chapter 14 adds the measured results and compares fast regulation with slow dispatch across the technologies.

1.5 Instruments and Final Elements in This Volume

Figure 1.6 lists what the controllers of each chapter read and what they move. Ten chapters read a power, a voltage or a current, and eight a temperature. Eight control a value that only a model computes, such as a state of charge or an anode potential, and seven act on a price or a forecast. A power converter is the final element in nine chapters.

Power and voltage reach the controller through instrument transformers. A potential transformer steps the line voltage down to a safe level, typically 120 V, and a current transformer steps the line current down, typically to 5 A at full load, for the meters and the protective relays to read. An energized current transformer must never have its secondary opened, because it may then develop an extremely high voltage [32]. Temperatures come mostly from thermocouples (Figure 1.7), whose most common failure is to burn out, after which the open input can read electrical noise as a wildly varying temperature [32].

A grid-following converter latches onto the grid voltage with a phase-locked loop and, for fixed power commands, acts as a constant source of real and reactive power. Unlike a synchronous machine, which can supply large currents for short periods, it has a hard current limit [12], the headroom

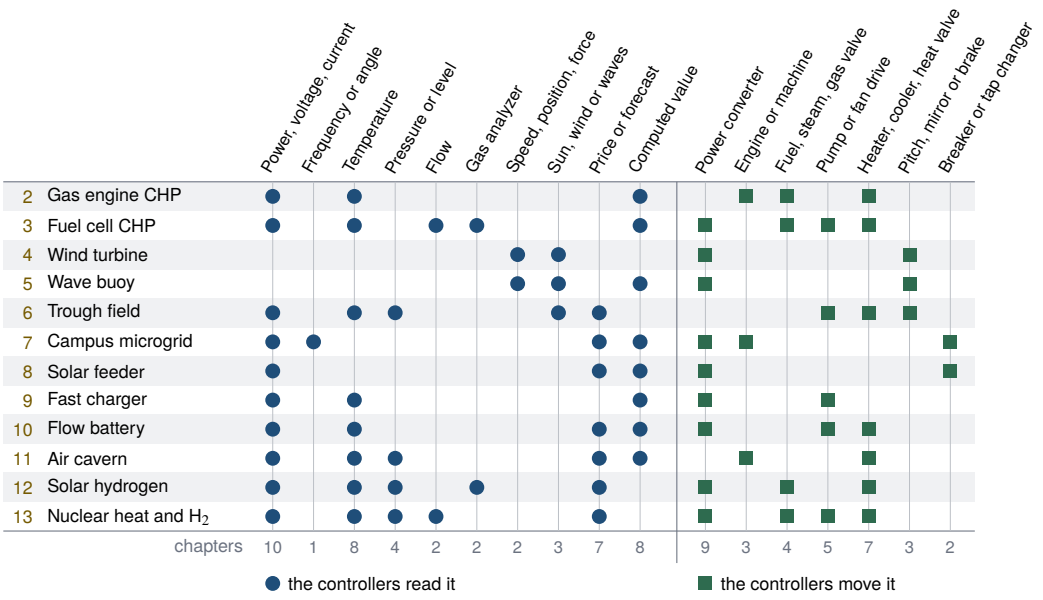
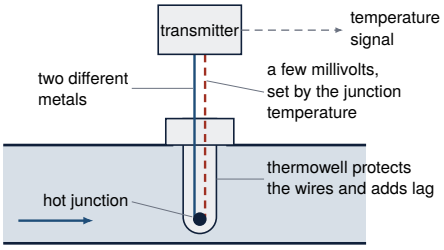


Figure 1.6 Sensors and final elements by chapter: a round mark where the chapter's controllers read the device and a square mark where they move it, as its variables table, control structure or technology section names them. A computed value is not a sensor. Notice that only the wind turbine and the wave buoy work without a power meter, and that the converter is the commonest handle.



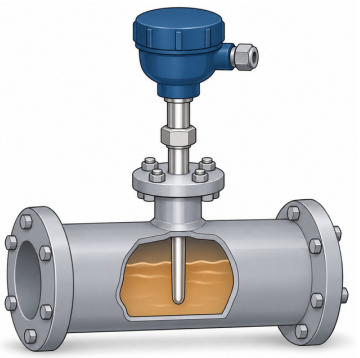


Figure 1.7 Principle of a thermocouple in a thermowell. Notice that the well that protects the junction also adds a lag [32], 2.2 s at the trough outlet of Chapter 6 and 5 s in the stack of Chapter 3.

that Chapter 7 must keep. Pumps and fans are moved by drives that set a motor's speed through the frequency of its supply [32], as for the electrolyte of Chapter 10.

Figure 1.8 places the volume's loops on their platforms. Supervisory and lower loops run with cycle times from milliseconds to minutes. A safety instrumented system is often independent of the control system, so that a failure of the control system does not weaken it [33]. The apps run their fastest laws every 0.02 s on the rotor of Chapter 4 and plan twice a day in the cavern of Chapter 11.

1.6 The Simulator Framework

Every chapter of this book has an app that runs in a web browser, collected with the others at https://apmonitor.com/apps/. About 240 apps exist across the series. All but a few are built on one shared framework, so the engine, the PID algorithm, the trends and the data export behave the same

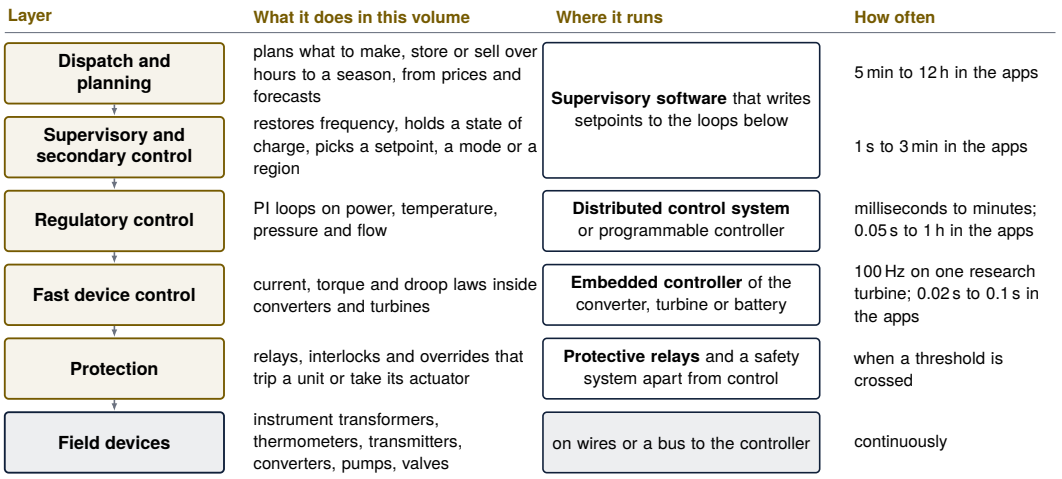


Figure 1.8 The control layers of this volume, the platform that hosts each and how often each acts. Loop periods are from [33], the 100 Hz from the research turbine that Chapter 4 cites and the app ranges from the chapters' technology sections. Notice that the dispatch layer acts once in minutes or hours, while the converter laws below it act many times a second.

Table 1.3 What Every App Provides. Standalone Apps Are Described in Their Own Chapters.

Element	What it does
Run, Pause, Reset	Start, hold and restart the run. Reset keeps the reader's settings.
Speed	Simulated time per second of real time. It changes the pace and never the result.
Manual and Auto	Hand each actuator to the reader or to the controller, without a bump.
Scenario list	Numbered cases, each with a briefing, a completion rule and a reload button.
Control panel	Setpoints, manual outputs, tuning, options and disturbances, at a Beginner or an Advanced level.
Trends	SP and PV above the MV for each loop, with limits, event marks and a cursor.
Scorecard	IAE, overshoot, settling time, MV travel and time at a limit for each loop.
Learn card	Predict, Try It, two hints and Explain, opened by the reader in that order.
Show Model	Equations, live variable values, editable parameters and assumptions.
Export CSV	Every logged sample of the run as a text file with a header row.
Instructions	A separate page with background, an operating guide and the model's limitations.

way in every chapter. The exceptions are standalone studios, such as the cascade studio and the two Temperature Control Lab apps, which follow the same ideas in their own code. This section describes the framework once and states where the standalone apps differ. Table 1.3 lists what a reader meets.

1.6.1 The Simulation Engine

Each app carries a plant model written as ordinary differential equations $\frac{dx}{dt} = f(x,u,d,p)$ in the states x, the inputs u, the disturbances d and the parameters p. The engine integrates the model with the classical fourth-order Runge–Kutta method on a fixed step h set for the fastest dynamics of the app. Some apps supply their own step, such as explicit Euler for a discontinuous right-hand side or an exact update for a model driven by events.

Three clocks run at separate rates. The plant advances every step h. The controller executes every control period Δt, equal to h unless the app declares a slower controller, and holds its outputs between executions. The log takes one sample at a fixed interval of simulated time for the trends, the scorecard and the exported file. The order of work in one step is shown in Figure 1.9. The controller also executes once when a scenario is loaded, so every run starts from an initialized controller.

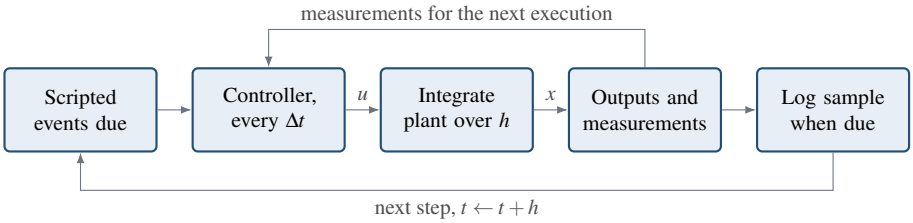


Figure 1.9 Work of the Engine in One Integration Step

Drawing the screen is kept apart from these clocks. A speed of 5 means five units of the app's time base per second of real time. Speed, frame rate and pauses change how fast a run is shown and never what it computes, so a phone and a workstation produce the same trajectory and the same file.

Noise comes from a deterministic pseudorandom generator. Its seed is declared by the app, or by a scenario that needs its own noise record, and it is restored whenever a scenario is loaded or Reset is pressed. The framework gives the reader no seed setting, so *default seed* in this book means the seed the app ships with. A run repeats bit for bit when the same scenario is loaded and the same settings are made before Run. A change made by hand during a run lands on a different step each time, which is one reason numeric answers carry a tolerance. The standalone simulators draw noise from the browser's own generator, so a noisy run there repeats in its statistics and not sample for sample.

Run and Pause start and hold the clock. Reset restarts the run at $t = 0$, paused, and keeps the reader's settings: every setpoint, tuning value, option, model parameter, disturbance slider and mode the reader changed is put back before the plant and the controller are initialized. Scripted events replay, and a one-shot disturbance button pressed during the run is cleared. The reload button beside the scenario list restores the scenario's own settings instead.

1.6.2 The Velocity-Form PID Algorithm

One PID implementation serves the PID loops of every framework app. It is the velocity (incremental) form: each execution adds the change in the proportional and derivative terms to a running sum, and the integral is a separate term, as shown in Equations (1.10) to (1.13) for execution k and control period Δt.

$$e_k = a\,(\mathrm{SP}_k - \mathrm{PV}_k), \qquad P_k = K_c\,e_k, \qquad D_k = -a\,K_c\,\tau_D\,\frac{\mathrm{PV}^f_k - \mathrm{PV}^f_{k-1}}{\Delta t} \tag{1.10}$$

$$S_k = S_{k-1} + (P_k - P_{k-1}) + (D_k - D_{k-1}) \tag{1.11}$$

$$v_k = u_b + S_k + I_{k-1}, \qquad u_k = \mathrm{sat}(v_k) \tag{1.12}$$

$$I_k = I_{k-1} + \left[\frac{K_c}{\tau_I}\,e_k + \frac{u_k - v_k}{T_t}\right]\Delta t \tag{1.13}$$

where $a = \pm 1$ is the controller action, PV^f is the measurement after an optional first-order filter, u_b is the output bias, S is the running sum of proportional and derivative increments, v is the output before limiting, u is the output sent to the actuator, I is the integral term and T_t is the tracking time constant, equal to τ_I unless a loop sets another value. The function sat clamps v_k to the actuator range and then applies a rate limit if the loop declares one.

The limit acts on the emitted output u_k only. The sum S_k is never clamped, so it equals $P_k + D_k$ and the output before limiting is the position form $u_b + K_c e_k + D_k + I_{k-1}$. Anti-windup touches the integral alone. While the output is limited, the last term of Equation (1.13) drives I toward the value that reproduces the output applied, which is back-calculation [34]. With no integral action, Equation (1.13) is skipped. Clamping the running sum would instead discard each increment that

crosses a limit and keep each one that returns, so symmetric noise would push the output off the limit even in a proportional-only loop.

The derivative acts on the measurement, so a setpoint step gives a proportional kick and no derivative kick. A change of K_c acts on the whole error at the next execution, as in the position form. The action $a = +1$ suits a process whose PV rises with the MV, a reverse-acting controller in the ISA convention, and $a = -1$ gives the direct-acting one.

In Manual the controller keeps executing and sets $I_k = u_{\mathrm{man}} - u_b - S_k$, so the output it would send equals the manual value u_{man}. The first automatic output differs from it by one period's change in P and D. In Auto the engine copies each controller output to the manual station, so a switch to Manual is also bumpless. The standalone studios with PID loops use velocity-form code of their own, with the limit on the output and anti-windup on the integral alone, in which a gain change applies only to later increments.

1.6.3 The Predictive Control and Estimator Options

More than 100 apps offer model predictive control (MPC) as an option beside the structure they open with, which stays the default. Volume 9 develops the theory. In most of them the controller plans with a small linear model in discrete time as shown in Equation (1.14).

$$x_{k+1} = A\,x_k + B\,u_k + E\,w_k + c, \qquad y_k = C\,x_k \tag{1.14}$$

where w is a measured or scheduled disturbance and c is a constant left by linearization. The model comes from a step test at the design point, from the app's balances linearized there or again at every decision, or from the model the reader fits. It never reads the true states or parameters of the run, so a parameter the reader changes in Show Model is model mismatch, as on a real plant.

At each decision the controller minimizes the objective of Equation (1.15) over a horizon of N steps.

$$J = \sum_{k=1}^{N} (y_k - r_k)^{\top} Q\,(y_k - r_k) + \sum_{j} \Delta u_j^{\top} R\,\Delta u_j + \sum_{i} \rho_i\, s_i^2 \tag{1.15}$$

where r is the setpoint, Q weights the tracking error, R is the move suppression on each input change Δu_j and ρ_i is the price of a slack $s_i \geq 0$ that lets an output band be broken when it cannot be held. Actuator limits are hard constraints. The quadratic program is solved in the browser by a dual active-set method [35]. The first move is applied, and the plan is made again at the next decision.

The plan starts from an estimate of the model state. About half of these apps use a steady-state Kalman filter on the model with an added disturbance state, which absorbs what the model did not predict and removes steady offset without an integral term [36]. Others correct the model output with a filtered bias to the same end. About a dozen apps also offer moving horizon estimation (MHE), which solves the estimation problem over a window of recent samples and can hold bounds that a Kalman filter cannot, such as a concentration that is never negative [37].

With the MPC selected, the tuning fields of the loops it replaces leave the Control panel. In most of these apps the Advanced level shows up to three settings, each a multiple of the shipped value: the prediction horizon, the move suppression and the band price. The trend draws the accepted plan ahead of the present time, and a list of constraint prices shows which limits bind. A plan that is not optimal, not finite or outside its limits is rejected, and a fallback, in most apps the shipped controller, holds the actuator until a plan succeeds. The Model Fitting and Tuning Studio builds the same kind of controller from the reader's own data in its tab, MPC from the fit.

1.6.4 Scenarios, Progress and Data

An app teaches through scenarios, the numbered cases at the top of the Control panel, nine to thirteen in most apps. Loading one sets the model parameters, the controller settings, the disturbances, the mode, the initial state and any scripted events. The information button beside the list opens a briefing in four parts: what the case is, why it matters, what to do and one detail for the practicing engineer.

The Learn card holds the lesson back, with Predict and Try It before the run, hints on request and Explain afterward.

Each scenario has a completion rule that the app judges from the run on the simulated clock: a run length, the scripted events passed, a setting made by the reader, a state held for a stated time or a target met. Choosing a case earns nothing. A completed case is marked in the list, and a badge row shows the count and a level, Explorer after one case, Practitioner at half and Completed at all. Progress is kept in the reader's browser with no account. A certificate of progress or of completion can be issued from it, as a record of self-paced work and not an assessed credential.

One case, usually the last, is the graded challenge. It states a target, such as an error band to hold through a sequence of upsets. Changing the model parameters or the disturbances voids the attempt in most apps, and a record made with Reveal suggested tuning says so.

Show Model opens the equations, live values of the variables, the editable parameters and the assumptions. The trends plot SP and PV above the MV for each loop, with actuator limits and marks at setpoint moves, disturbances, mode changes and scripted events. The scorecard reports for each loop the integral of the absolute error (IAE), overshoot, settling time, MV travel and share of time at a limit, with the app's own measures, and it does not combine them into one score. IAE and travel accumulate from Reset, so two runs are compared at the same clock reading.

Export CSV saves the log as a text file with a header row of column names that carry their units and one row per logged sample. In most apps the time column is in seconds, minutes or hours according to the run length. The log holds the most recent 60 000 samples unless the app sets another size. Apps with the MPC option begin the file with comment lines that start with #, which a script must skip.

An app exercise in this book names the scenario by its number and name as the app shows them, every setting that differs from the scenario's defaults, the run length in simulated time, the seed (the default seed unless stated), what to read and where (a trend, a scorecard tile or a column of the exported file) and a tolerance on a numeric answer. Settings are made before Run unless the exercise gives a time.

1.7 Working With AI Agents While Studying

A reader of this book is likely to have an AI assistant within reach, and the apps make its work easy to test. This section gives the editor's view of how to use one while working through a chapter. In short, the assistant may do the algebra and the scripting, and the reader keeps the checking.

What to delegate. Tasks with a clear input and a result that can be tested are good candidates. An assistant can derive the linearization of a chapter's balance at an operating point and the transfer function that follows from it. It can write a short script that reads the exported CSV file and fits a first-order-plus-dead-time model to a step test. It can propose a first tuning from that fit with a named rule, convert units, explain a term in a model or outline a report. The assistant knows nothing about the app until it is told. Give it the equations and parameter values from Show Model, the column names of the exported file and the scenario that produced the data, as described in Section 1.6.4. Ask it to state its assumptions and the units of every result.

What to check, and how. An assistant returns a fluent answer whether or not the answer is right, so each result needs a test that it could fail. Four tests cover most of the errors a chapter will produce.

- *Units.* Every term of an equation carries the same units, and a process gain is in PV units per MV unit. A gain computed with the valve as a fraction is 100 times the gain of a loop whose valve is in percent.
- *Signs.* Decide from the physics which way the PV moves when the MV rises. Compare that with the sign of the fitted gain and with the controller action of Section 1.6.2.
- *Steady state.* Set the derivatives to zero. The model must return the operating point that Show Model reports, and a linearization must give zero deviation there.

Table 1.4 Roadmap of the Volume

Ch.	Plant	The lesson	Level	Time
2	Gas engine CHP	Power recovers in seconds and heat in minutes.	introductory	2.5 h
3	Fuel cell CHP	Current must wait for its fuel, paid from storage.	intermediate	2.5 h
4	Wind turbine	Two actuators hand over one speed, with a scheduled gain.	intermediate	3 h
5	Wave buoy	The best force depends on waves still to come.	advanced	2 h
6	Trough field	The best setpoint moves with the sun.	intermediate	3 h
7	Campus microgrid	Inertia sets the fall, droop and headroom stop it.	introductory	3 h
8	Solar feeder	Devices right alone can hunt together.	intermediate	2.5 h
9	Fast charger	The limit that ends a charge has no instrument.	advanced	3 h
10	Flow battery	The inventory, not the converter, sets the value.	introductory	2.5 h
11	Air cavern	Heat, stored or bought, defends the commitment.	intermediate	2.5 h
12	Solar hydrogen	Interlocks choose the mode, economics the setpoint.	intermediate	2.5 h
13	Nuclear heat and H_2	A horizon is insurance that looks dear on ordinary days.	advanced	2.5 h

- *A run on the app.* Load the named scenario at the default seed, enter the proposed numbers and run. The trend and the scorecard decide. A tuning that reads well on paper and holds the valve at a limit for half the run has failed.

A fitted model gets one more test: compare it with data it was not fitted to, such as a second step in the opposite direction. When a check fails, report the failure to the assistant with the evidence and ask for the cause, then check the correction the same way.

How the exercises train the habit. One exercise in each chapter is marked *Review the agent*. It presents a tuning, a model or a claim as an AI assistant might propose it, with a flaw, and asks the reader to find the flaw in about five minutes. The flaws are ordinary ones: a unit, a sign, a steady state that does not close, a result measured on the wrong scenario or at a different run length, or a limit that was ignored. Each is found with one of the tests above. The purpose is not distrust. An engineer who can say why an answer is right can hand an assistant much larger tasks and still stand behind the result. That larger picture, in which agents do most of the routine work and the engineer supervises and checks, is the subject of Chapter 14.

1.8 Chapter Roadmap

Table 1.4 lists the chapters with the lesson each adds to this one. The level says how much of Section 1.4 a chapter assumes. The time is an estimate for reading the chapter once and running each case of its app once, at about eight minutes a case.

Chapters 2, 7 and 10 form a first course: two products on two clocks, inertia, droop and restoration on one bus, and a store whose value is set by when it is spent. They rest on Sections 1.4.3 to 1.4.5. Chapters 3, 4, 6, 8, 11 and 12 add a slow supply behind a fast actuator, a scheduled gain, a moving optimum, interacting devices, a seasonal inventory and a supervisory state machine. Chapters 5, 9 and 13 combine prediction or inference with constraints and are best left until Section 1.4.6 is familiar. A reader who follows the energy can read the chapters in their order, which runs from conversion through networks to storage and dispatch.

KEY POINTS

- An energy system runs in layers: fast loops hold a frequency, a voltage, a temperature or a current, and slow layers decide how much to make, store or sell.
- Inertia sets how fast the frequency falls, while the layers above decide where the fall stops.

- Droop shares a step by stiffness and leaves an offset that secondary control removes, and regulation costs a store power, not energy.
- A store has no self-regulation, so a slow state-of-charge manager must hold it.
- A terminal value substitutes in part for a horizon that is too short.

Where else this applies. Droop and restoration on one machine are the subject of Volume 1, Chapter 8, inventory control returns in Volume 6 and economic predictive control in Volume 9.

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1.9 Exercises

1.1 Theory and calculation · 3 min

An island grid has 50 MW of synchronous machines with an inertia constant of 4 s on that rating, at 60 Hz. A 2 MW unit trips.

(a) Find the stored kinetic energy and the rate of change of frequency right after the trip. *Checkpoint:* 200 MJ, a fall of 0.30 Hz/s.

(b) What is the smallest inertia constant on the same rating that keeps the first rate of change at or below 0.5 Hz/s? *Checkpoint:* 2.40 s.

1.2 Theory and calculation · 4 min

Two units share an island load on one frequency at 60 Hz: a 10 MW unit with a droop of 4 % and a 5 MW unit with a droop of 2.5 %. The load rises by 1.5 MW and only primary control acts.

(a) Find each unit's stiffness in megawatts per hertz. *Checkpoint:* 4.17 MW/Hz and 3.33 MW/Hz.

(b) Find the settled frequency deviation and each unit's share of the step. *Checkpoint:* 0.200 Hz low, 0.833 MW and 0.667 MW.

1.3 Concept check · 2 min

An island with droop-only primary control loses 1 MW of generation. What does doubling the inertia constant of its machines do?

(a) it halves the frequency deviation at which the island settles

(b) it halves the first rate of fall and leaves the settled deviation unchanged

(c) it halves both the first rate of fall and the settled deviation

(d) it leaves the first rate of fall unchanged and halves the settled deviation

1.4 Theory and calculation · 4 min

E-1's engine and battery droops have stiffnesses of 2.0 and 1.33 MW/Hz, and after a 1 MW load step the battery first takes its droop share of 0.40 MW. A secondary loop moves the engine's setpoint at $\mathrm{d}P_{set}/\mathrm{d}t = -k_I \Delta f$ with $k_I = 0.05$ MW per hertz-second.

(a) Estimate the time constant with which the frequency returns. *Checkpoint:* about 67 s.

(b) The battery's share decays with the same time constant. Estimate the energy the battery delivers over the event. *Checkpoint:* about 26.7 MJ, or 7.4 kWh.

1.5 Theory and calculation · 4 min

A solar inverter at the end of a feeder exports 1 pu through a line of resistance 0.04 pu and reactance 0.12 pu. Its Volt-VAR curve absorbs reactive power with a slope of 4 beyond a deadband of 0.01 pu.

(a) Find the voltage rise without reactive power and the reactive power that would cancel it entirely. *Checkpoint:* 0.040 pu, 0.333 pu.

(b) Find the settled rise and the reactive power absorbed under the Volt-VAR curve. *Checkpoint:* 0.0303 pu, 0.081 pu.

1.6 Theory and calculation · 6 min

A battery of 5 MW and 20 MWh has an efficiency of 0.92 each way.

(a) How much energy must the grid supply to charge it from 30 to 80 %, and how long does that take at rating? How much does it return discharging back to 30 %? *Checkpoint:* 10.87 MWh, 2.17 h, 9.20 MWh.

(b) A proportional manager adds 0.1 MW of discharge per percent of charge above its reference. Find its time constant and the time to remove 95 % of an offset, ignoring losses. *Checkpoint:* 2.0 h, 6.0 h.

(c) The battery regulates with a square wave of ± 1 MW, half the time each way. At what mean rate does its charge drift, and how far below its reference does the manager settle? *Checkpoint:* 0.0835 MW, 0.42 % an hour, 0.84 points.

1.7 Theory and calculation · 4 min

An engine converts 38 % of its fuel to electricity and recovers 46 % as heat. On an island it makes 3 MW of electricity while the heat users take 2.5 MW, and an empty 6 MWh hot-water store takes the surplus.

(a) Find the heat-to-power ratio, the fuel power and the heat recovered. *Checkpoint:* 1.211, 7.89 MW, 3.63 MW.

(b) How long until the store is full, and what happens after that? *Checkpoint:* 5.3 h, the surplus is dumped.

1.8 Concept check · 2 min

E-1's engine follows the island's electric demand less the solar output. At 03:00 its hot-water store is full and the recovered heat exceeds the heat demand. Which statement is right?

(a) the power loop lowers the fuel until the heat matches the demand

(b) the store goes on absorbing heat beyond its capacity until the morning

(c) the engine switches to thermal following and the frequency is held by the store

(d) the surplus heat is rejected in the dump radiator while the electricity is held

1.9 Concept check · 2 min

A battery is dispatched by a plan that applies only its first move each hour and is replanned, with a perfect price forecast and no value placed on the energy left at the end of the plan. Prices are lowest at midday and highest in the evening, six hours later. How long must the plan be?

(a) long enough to reach from the cheap hours to the dear ones

(b) one hour, because only the first move is ever applied

(c) as long as the whole run, or it will empty the battery each hour

(d) any length, because a perfect forecast makes the horizon irrelevant

1.10 Theory and calculation · 5 min

A forecast error follows a first-order autoregression with coefficient 0.9 per 15 min step. A battery of 2 MW and 4 MWh, with an efficiency of 0.9 each way, faces hourly prices of \$95, 90, 70, 70, 55 and 48 per megawatt-hour over the next six hours.

(a) Find the forecast's skill one hour ahead, and the lead at which it falls to one half. *Checkpoint:* 0.43, about 49 min.

(b) Find the number of hours a full battery can supply at rating, the water value of a stored megawatt-hour, and the charge and discharge thresholds. *Checkpoint:* 2 hours, \$81, charge below \$72.90, discharge above \$90.