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CHAPTER 7

Forming the Grid From a Battery When a Campus Microgrid Islands

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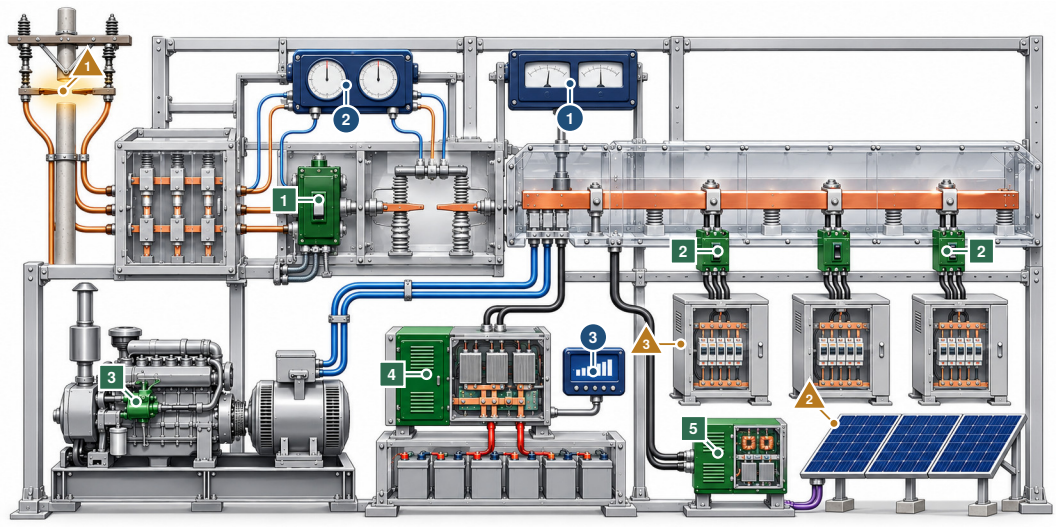
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CHAPTER 7

Forming the Grid From a Battery When a Campus Microgrid Islands



The controller moves 1 utility breaker, closed only through the sync check
2 breakers of the three load blocks that may be shed 3 power setting of the diesel genset, through its governor
4 battery inverter that makes the island's voltage 5 power cap of the solar inverter

The controller reads 1 frequency and voltage of the campus bus 2 synchroscope across the open utility breaker
3 battery charge, from its management system

What disturbs it 1 utility fault that opens the breaker 2 cloud passing over the solar
3 chiller starting on a load block

Notice the open gap of the utility breaker: from that moment the battery inverter alone makes the voltage and frequency that the solar and the loads follow, until the genset starts, and the critical feeder that is never shed is not drawn. Illustration, not to scale.

IN PLAIN TERMS **A Campus That Must Make Its Own Power**

The main idea. When the power line to a campus fails, the campus can run on its own battery, diesel generator and solar panels. One of them must set the beat of the power, its voltage and its frequency, and the others follow it.

The challenge. A battery that only follows cannot hold the campus, and the power dies in a tenth of a second. A battery that sets the beat must slow down gently under a sudden load and warn the safety switches when pushed past its limit.

Why it matters. A hospital wing, a data center and labs stay lit only if these settings are right.

THREE WAYS TO READ THIS CHAPTER

⊘	**Explore**	11 min	The first page, the history box of Section 7.2, the fact box of Section 7.4, the try-it and fact boxes of Section 7.6, and the key points
🕮	**Study**	55 min	The whole chapter with its pause points and the twelve exercises
⏢	**Practice**	20 min	The first page, Section 7.6, Section 7.8, Section 7.9 and its open challenges

The control question When the utility's breaker opens, one of the island's own sources has to make the voltage that the others follow. What does each layer above that source, from virtual inertia and droop to load shedding, charge management and the sync check, buy a campus in hertz, megawatts and critical load kept on?

Learning objectives

- Explain why a grid-following inverter cannot hold an island and a grid-forming one can.
- Compute the first-swing bound, the settling time constant and the droop deviation of a virtual synchronous machine.
- Predict how two droops share a load step from their stiffnesses, and what the secondary loop changes.
- Explain how a power-limit droop lets under-frequency relays hear a battery overload.
- Price an islanded hour in diesel and in stored energy, and judge a dispatch by both.

Prerequisites Sections 1.4.2 (swing equation, ROCOF), 1.4.3 (droop and restoration), 1.4.4 (state of charge), 1.6.2 (velocity-form PID) and 1.6.4 (scenarios and data), with Section 1.6.3 for the energy dispatch only.

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See also Volume 1, Chapter 8 and Volume 1, Chapter 7 for inertia, droop offset, integral restoration and a governor on an islanded load. Volume 7, Chapter 2 and Volume 7, Chapter 6 for an outcome that changes at a threshold and a loop that creates its own operating point.

7.1 Introduction

A microgrid is a cluster of loads and small sources run as one controllable system, which the utility can treat as a single controlled cell and which can give its own customers local reliability when the grid cannot [1]. The campus simulated here is one built for that second role. While the breaker at the point of common coupling (PCC) is closed, the utility makes the voltage, holds the frequency and absorbs every mismatch, so every inverter on site can be a current source that follows a phase-locked loop (PLL). When the breaker opens, one of the island's own sources has to make the voltage that the others follow, and in the first tenth of a second nothing slower than that source can help. Microgrid control is organized as a hierarchy of primary, secondary and tertiary levels [2, 3], and the converters in it are classed by whether they form the grid, feed it or support it [4]. Section 1.4.2 places these levels on the clocks of the whole volume.

A battery on site is often taken to make a campus resilient, and the simulator shows why it does not by itself. A battery whose inverter follows the grid keeps pushing its current after the 10:00 fault opens the breaker, the bus voltage becomes that current through the load, and 40 ms later the bus is at 0.42 pu with both PLLs reading 60.92 Hz. The bus is dead at 60 ms, and the critical feeder loses 11.75 kWh before the genset can restore it. Once the battery forms the grid, two further misreadings remain, and both come from treating the inverter as a source rather than as a control law. Virtual inertia is read as depth, yet on a lone battery three 0.2 MW load steps at 0, 1.5 and 3 s of inertia fall at 2.61, 1.77 and 1.21 Hz/s and bottom at 59.697, 59.728 and 59.729 Hz, so the inertia sets the rate and the droop the depth. Inertia still decides the fault, because the solar rides through 3 Hz/s and no more, and with none the first swing reads 11.18 Hz/s, the solar trips and all three sheddable blocks are lost. A steady frequency is read as a source that copes, yet a grid-forming inverter holds its frequency while it overdraws its battery. With the inverter's power-limit droop turned down from 0.40 to 0.02, the chiller of case 7 keeps the battery 11.7 s over its continuous limit at 59.509 Hz, above the first shedding stage, until the battery's management system trips it and the critical feeder loses 17.57 kWh. At 0.40 the first stage sheds one block 7.1 s after the chiller starts and the critical feeder loses nothing.

The class of problem is general. A fast source with a small store beside a slow one with a large store, sharing load by local feedback without communication, appears wherever inverters run in parallel, and the parallel-inverter literature names isolated ac systems, distributed uninterruptible power supplies and photovoltaic systems as one control problem [5]. The islanding transition has been

studied with the campus's own mix, a rotating synchronous machine beside a converter-interfaced unit [6], and the difference between forming and following inverters is now argued to matter for any power system that inverters dominate [7]. In process terms the battery is a surge volume that answers every disturbance first and must then be refilled, the genset a slow supply that carries the average, and the state-of-charge band an averaging level controller on an energy inventory, as in Section 1.4.4. A block diagram of the droops has no place for the breaker, the trips or the limits that decide how the island ends.

These controls are usually evaluated in electromagnetic transient simulation or on laboratory hardware [6, 8], and the standards that govern islanding and reconnection state requirements rather than consequences [9]. Neither gives a learner a plant where the inertia, the droop, the band and the sync-check window are settings whose effects read in hertz, megawatts and kilowatt-hours of critical load left unserved. This chapter tallies what each layer of an island's control buys, from the inverter that forms the grid to the relay that lets the utility back, on a campus microgrid simulator described closely enough to be rebuilt. Every method in it is established. The virtual synchronous machine, the droop sharing, the shedding stages and the sync check follow the literature and standards cited. The simulator solves a one-bus phasor model whose power balance closes to round-off, switches a battery inverter between following and forming without a bump, pairs a virtual-impedance current limit with a power-limit droop that lets the relays hear an overload, and gives its controller only the meters a microgrid controller has. Its cases and two-hour challenge take one layer at a time and include an islanding that no setting survives whole.

Section 7.2 recounts how small power systems learned to run alone. Section 7.3 builds the campus: the bus, the genset, the battery inverter in both modes, the solar, the loads, the meters and the protection. Section 7.4 derives five relations behind the cases, from the first swing to the voltage across an open breaker. Section 7.5 programs the microgrid controller layer by layer. Section 7.6 measures ten cases and the two-hour challenge, and Section 7.7 adds an optional one-hour energy dispatch and prices the stored energy it leaves behind. Section 7.8 describes the hardware that real microgrids run on, Section 7.9 states the limitations and Section 7.10 draws the conclusions. The exercises of Section 7.11 work through the cases on the app.

7.2 How Small Power Systems Learned to Run Alone

A generator that feeds an isolated load alone can hold its speed exactly. The classical treatment of speed governing separates the isochronous governor, which integrates the speed error away and suits such a unit, from the droop governor, whose speed falls with output so that units in parallel divide a change of load in a fixed ratio [10]. The genset on the simulated campus has both, a droop by default and an isochronous option for a genset left alone on the island. The hydro unit of Volume 1, Chapter 7 also either supplies an islanded town or follows a stiff grid, and shares load through a permanent droop. On an interconnected system an area left short of generation is an emergency, in which an automatic load-shedding program can prevent the collapse of the area, and by 1968 the factors in applying underfrequency relays to such a program, with a method for calculating their settings, were in the transmission literature [11]. An IEEE guide now compiles the practice of shedding and of restoring the load afterward [12].

Power electronics removed the rotating mass but not the sharing problem, and the history box below tells how inverters came to share load by droop.

The microgrid concept gathered such sources into one system. A 2002 overview described a cluster of loads and microsources, each under 100 kW, operated as a single controllable system that the utility sees as one cell and that can give its customers local reliability and uninterruptible supply [1]. The islanding transition was then simulated for a micro-grid with one rotating synchronous machine and one converter-interfaced unit, after both a planned switching event and a fault, and a suitable control of the converter unit kept the island stable through it [6]. A hierarchy of primary droop with a virtual output impedance, a secondary level that restores the deviations the droop leaves, and a

tertiary level that manages the exchange with the distribution system was proposed as a general approach toward standardization [2], and a review of converter control sorted microgrid converters into grid-forming, grid-feeding and grid-supporting configurations [4].

> ⧖ HISTORY **Inverters Learn to Share Load (Early 1990s)**
>
> Droop control, the most established way for an inverter to form the grid, was first proposed in the early 1990s [5, 13]. Each inverter trades its frequency against its real power and its voltage against its reactive power, much as a synchronous machine does in steady state. All the units then settle at one frequency, and each supplies power in proportion to its droop slope, with no communication between them [13]. These controls were first designed for systems with a small footprint, microgrids and small islands. A national laboratory roadmap of 2020 found early grid-forming inverters serving islanded microgrids with a high share of renewable generation, and saw them as the first stage before grid-forming control reaches the bulk power system [13].

The inverter that forms an island was next asked to behave like the machine it replaces. A virtual synchronous machine was proposed in 2007 to make inverter-connected generation appear to the grid as an electromechanical synchronous machine, with the electrical effect of a rotating mass and a share of primary reserve [14]. Synchronverters, inverters operated to mimic synchronous generators, shared real and reactive power through frequency and voltage droop and could run in island mode [8]. A 2014 letter showed that a virtual synchronous machine and a frequency droop are equivalent under certain conditions [15], and the simulator implements the machine in that form. A 2020 review argued that a grid-forming inverter acts on frequency swings as a source of damping rather than of inertia while a grid-following one can aggravate them, and that protection against overload and a reserve of stored energy are what make the damping usable [7].

Interconnection standards came to the island in stages. The first standard of the IEEE 1547 series, approved in 2003, set requirements for interconnecting distributed resources, among them their response to abnormal conditions and to islanding [16], and the application quotes from the series the requirement that a distributed resource detect an unintended island and cease to energize it within 2 s. A 2011 guide addressed island systems that separate from and reconnect to part of the area power system while they serve their own loads [17]. The 2018 revision, whose Category III ride-through and trip defaults the simulated solar carries, treats interconnection and interoperability together [9], and Chapter 8 puts the same revision's Volt-VAR and Volt-Watt curves on a residential feeder. Reconnection rests on an older practice. A synchronizing panel tells the operator what to adjust on the governor and the exciter and when the breaker may close, and an automatic synchronizer with a manual backup often makes the decision [18]. The sync-check relay of the simulator, which the application labels 25, is that decision in software.

7.3 The Campus Behind One Breaker

Figure 7.1 shows the campus as a one-line diagram. Four sources stand above one bus, each on its own breaker: the utility behind the PCC, a 2 MW diesel genset, a 1 MW, 2 MWh battery inverter and 1.5 MW of rooftop solar. Four feeders hang below it. The critical feeder serves a hospital wing, a data center and laboratories and is never shed, and three sheddable blocks serve HVAC with the chiller plant, the dormitories, and the classrooms and offices. Every power is in per unit of a 1 MVA base, so a per-unit power is a megawatt, and time runs in seconds on a clock that starts each case at its own time of day. Table 7.1 gives each signal its role, unit and range.

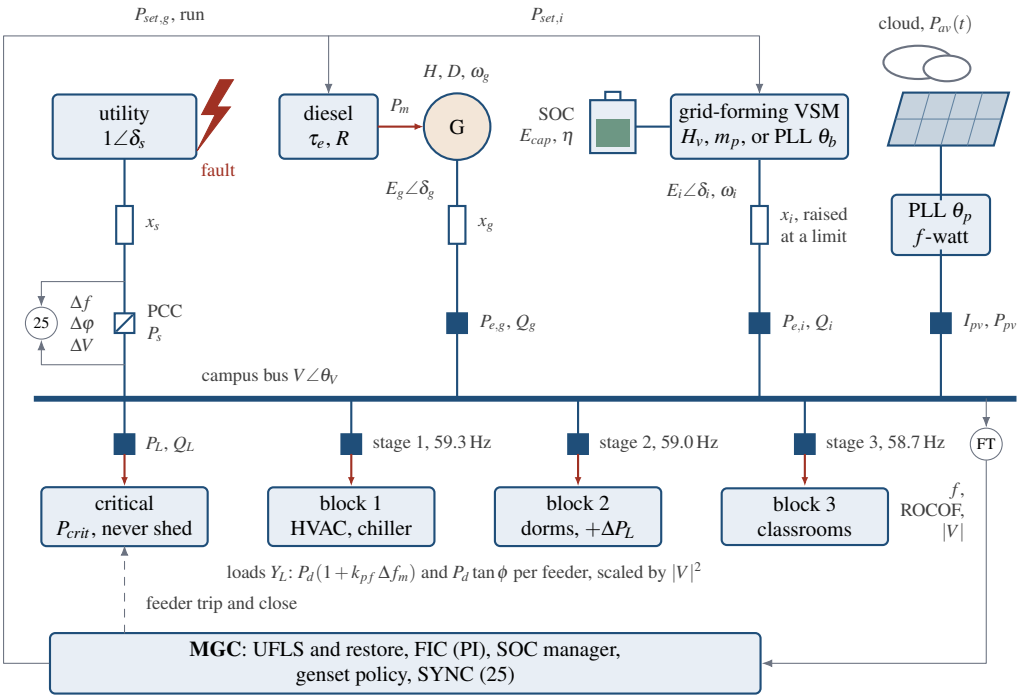


Figure 7.1 One-line diagram of the simulated campus. The utility, the genset and the battery inverter while it forms the grid are voltage sources $E_k\angle\delta_k$ behind the reactances x_s, x_g and x_i, and the solar, with the battery while it follows the grid, injects a current on its PLL angle θ_p or θ_b. The engine turns the governor's command into P_m through τ_e, and the rotor carries H, D and the speed deviation ω_g. The feeders are constant-impedance loads Y_L that depend on the measured frequency deviation Δf_m, and blocks 1 to 3 open at the shedding stages marked. The meter FT gives f, ROCOF and $|V|$ to the microgrid controller (MGC), which sets $P_{set,g}$ and $P_{set,i}$, starts the genset, trips and closes the feeders, and closes the PCC through the synchroscope (25) that compares its two sides. The PCC is drawn open, as it stands after the fault.

Table 7.1 The Campus's Signals by Role, Unit and Range

Symbol	Role	Unit	Range
f	CV of the secondary, measured	Hz	56.5–63
SOC	CV of the SOC manager, measured	%	5–95
$\Delta\varphi$	CV of the synchronizer, measured	°	±180
$P_{set,g}$, $P_{set,i}$	MVs, genset and battery setpoints	MW	0–2, ±1
B_1, B_2, B_3	MVs, block feeder breakers	0/1	—
—	MVs, genset run, PCC close	0/1	—
P_{cap}	MV, solar cap	MW	0–1.5
—	DVs, grid fault and return, chiller, genset or solar trip	event	—
P_{av}, ΔP_L	DVs, sun, cloud and haze, extra load on block 2	MW	0–1.5, 0–1
Δf_{grid}	DV, the utility's frequency offset	Hz	±0.1
δ_g, ω_g, P_m, E_g, ξ_g	states, genset rotor, engine, AVR, isochronous integral	rad, pu, MW	—
δ_i, ω_i, E_i, z	states, grid-forming inverter	rad, pu, MW	—
θ, x, V_m	states, each PLL and its voltage meter	rad, pu	—
P_{pv}, SOC, δ_s	states, solar, charge, utility angle	MW, —, rad	—
—	states, seven energy and fuel ledgers	MWs, L	—
$\lvert V\rvert$, P, Q, Δf, ΔV	measured, bus, every meter, across the PCC	pu, MW, Hz	—

7.3.1 The Bus

The bus has no state of its own. At every evaluation its complex voltage $V = |V|e^{j\theta_V}$ is the solution of one nodal equation, as shown in Equation (7.1).

$$V\left(Y_L + \sum_{k\in\mathscr{V}} \frac{1}{jx_k}\right) = \sum_{k\in\mathscr{V}} \frac{E_k e^{j\delta_k}}{jx_k} + \sum_{m\in\mathscr{C}} I_m \tag{7.1}$$

where $\mathscr{V}$ holds the voltage sources on line, the genset g, the battery inverter i while it forms the grid and the utility s while the PCC is closed, each an EMF E_k at angle δ_k behind a reactance x_k on the 1 MVA base, and $\mathscr{C}$ holds the grid-following currents of the solar p and of the battery b while it follows. Every angle is measured in a frame turning at $\omega_0 = 2\pi f_0$ with $f_0 = 60\,\text{Hz}$. The load admittance is $Y_L = G_{sh} - jB_{sh} + \sum_k [P_{d,k}(1 + k_{pf}\Delta f_m) - jQ_{d,k}]$ over the closed feeders, where $P_{d,k}$ and $Q_{d,k} = P_{d,k}\tan\phi$ are a feeder's demand at rated voltage with the power factor $\cos\phi = 0.97$, Δf_m is the per-unit deviation of the measured frequency held from the previous step, and $G_{sh} = B_{sh} = 0.004\,\text{pu}$ stand for the transformers' no-load losses and magnetizing. A voltage source delivers $S_k = V\,\overline{(E_k e^{j\delta_k} - V)/(jx_k)}$ and the loads take $P_L = |V|^2 \sum_k P_{d,k}(1 + k_{pf}\Delta f_m)$. One complex division gives V, so the power into the bus equals the power out of it to round-off, 3.2×10^{-15} MW at worst over the islanding of case 3.

7.3.2 The Genset

The genset is a classical machine, an EMF behind its transient, transformer and cable reactance $x_g = X_g/S_g$, driven by a diesel engine through a first-order lag and a droop governor, as shown in Equation (7.2).

$$\begin{aligned} 2HS_g \frac{\mathrm{d}\omega_g}{\mathrm{d}t} &= P_m - P_{e,g} - DS_g\,\omega_g \\ \tau_e \frac{\mathrm{d}P_m}{\mathrm{d}t} &= \mathrm{clip}_{[0,S_g]}\left(P_{set,g} - \frac{S_g}{R}\,\omega_g + \xi_g\right) - P_m \\ \frac{\mathrm{d}\delta_g}{\mathrm{d}t} &= \omega_0\,\omega_g \\ \frac{\mathrm{d}E_g}{\mathrm{d}t} &= K_{avr}\left(V_{set} - n_{q,g}\,Q_g/S_g - |V|\right) \end{aligned} \tag{7.2}$$

where ω_g is the rotor's per-unit speed deviation, P_m the mechanical power, $P_{e,g}$ and Q_g the electrical output, $\mathrm{clip}_{[a,b]}$ limits its argument to $[a,b]$, V_{set} is the voltage setpoint plus the synchronizer's trim, and the AVR's EMF stays between 0.2 and 1.6 pu. The isochronous option adds ξ_g with $\mathrm{d}\xi_g/\mathrm{d}t = -(S_g/R)\,\omega_g/T_{iso}$ and $T_{iso} = 4\,\text{s}$, and $\xi_g = 0$ otherwise. The engine burns $q_0 + q_1 \max(0, P_m)$ of diesel, with $q_0 = 110\,\text{L/h}$ running unloaded and $q_1 = 0.205\,\text{L/kWh}$ above it, and q_0 alone while it cranks and warms. A start takes $t_{start} = 45\,\text{s}$ from the crank to the breaker, a timer in the model, after which the breaker closes onto a dead bus or at the live bus's angle, speed and voltage, so the genset's synchronizer is perfect. While it is off its states follow the bus, so a restart is bumpless.

7.3.3 The Battery Inverter, Forming or Following

Forming the grid, the battery inverter is a virtual synchronous machine in the form whose droop is its damping [15], an EMF $E_i\angle\delta_i$ behind its filter, transformer and cable reactance $x_i = X_i/S_i$, as shown

in Equation (7.3).

$$\begin{aligned} 2H_v S_i \frac{\mathrm{d}\omega_i}{\mathrm{d}t} &= P_{set,i} - P_{e,i} - \frac{S_i\,\omega_i + m_{ov}\,z}{m_p} \\ \frac{\mathrm{d}\delta_i}{\mathrm{d}t} &= \omega_0\,\omega_i \\ \tau_{ov}\frac{\mathrm{d}z}{\mathrm{d}t} &= P_{over} - z, \qquad \left|\frac{\mathrm{d}z}{\mathrm{d}t}\right| \le \frac{\sigma_{ov} S_i}{f_0\,m_{ov}} \\ \frac{\mathrm{d}E_i}{\mathrm{d}t} &= K_q\big(V_{set} - n_q(Q_i/S_i - Q_{set}) - |V|\big) \end{aligned} \tag{7.3}$$

where H_v is the virtual inertia, m_p the frequency droop, ω_i the virtual speed deviation, z the lagged, slew-limited overload of Equation (7.4), and $Q_{set} = 0$ the reactive setpoint. With $H_v = 0$ the first line becomes the pure droop $\omega_i = (m_p/S_i)(P_{set,i} - P_{e,i}) - (m_{ov}/S_i)z$. The voltage loop integrates the bus voltage's error on a reactive droop, stays between 0.2 and 1.4 pu, and stops winding up while the inverter is limited.

Two limits make the voltage source a physical one. The inverter presents a larger impedance whenever its current would pass $I_{max} = 1.4$ pu or its power would pass the short-term allowance of its battery, $P_{hard} = \min(1.2S_i,\ P_{dis} + \Delta P_s)$ with $\Delta P_s = 0.5$ MW, multiplying x_i by $\max\left(|I|/I_{max},\ (P/P_{hard})^{0.8}\right)$ until both hold, so the bus voltage sags instead of the current rising. The power the island asks beyond the battery's continuous capability is then fed back, as shown in Equation (7.4).

$$P_{over} = [P_{e,i} - P_{dis}]^+ - [-P_{e,i} - P_{ch}]^+ + \lambda\,(P_{raw} - P_{e,i}) \tag{7.4}$$

where $[x]^+ = \max(0, x)$, P_{dis} and P_{ch} are the continuous limits of Equation (7.7), λ is 1 while the impedance is raised and 0 otherwise, and P_{raw} is the power the inverter would carry at its own reactance. This power-limit droop lowers the frequency in proportion to the shortfall, never faster than $\sigma_{ov} = 1$ Hz/s, so that the shedding relays hear an overload that a voltage source would otherwise hide.

Following the grid, the same inverter injects a current on the angle of its PLL, as shown in Equation (7.5).

$$\begin{aligned} I_b &= \frac{P_{ref} - jQ_{ref}}{V_m}\,e^{j\theta_b}, \qquad |I_b| \le S_i \\ \frac{\mathrm{d}\theta_b}{\mathrm{d}t} &= \omega_0\,(K_p v_q + x_b), \qquad \frac{\mathrm{d}x_b}{\mathrm{d}t} = K_i v_q \\ v_q &= \frac{\mathrm{Im}(V e^{-j\theta_b})}{|V|}, \qquad \tau_m\frac{\mathrm{d}V_m}{\mathrm{d}t} = |V| - V_m \end{aligned} \tag{7.5}$$

where P_{ref} is the battery's power setpoint, $Q_{ref} = 0$, $K_p = 2\zeta\,\omega_n/\omega_0$ and $K_i = \omega_n^2/\omega_0$ with $\omega_n = 2\pi f_{PLL}$, $f_{PLL} = 2$ Hz and $\zeta = 0.7$, $v_q = \sin(\theta_V - \theta_b)$ is the phase error, V_m the measured voltage behind a $\tau_m = 20$ ms lag, and the PLL reads the frequency $f_0(1 + K_p v_q + x_b)$. The current ceases below $V_m = 0.5$ pu, the momentary cessation of the Category III settings. On a grid θ_V belongs to the utility. On an island with no voltage source $V = \sum_m I_m/Y_L$, so θ_V is the PLL's own angle plus the angle of the loads' impedance, and the loop chases a reference that it turns itself. The PLL runs in both modes and in forming mode is only a meter. A change of mode solves the new mode's states from the present current, so the switch is bumpless.

7.3.4 Solar, Loads and the Battery's Store

The solar is a second grid-following current, $I_p = \min(P_{pv}, P_{av})\,e^{j\theta_p}/V_{m,p}$ on its own PLL with $|I_p|$ capped at $1.1P_{pk}$, so a cloud's edge reaches the bus at once and only a recovery waits for the power

loop. That loop follows the available power through the frequency-droop response of Equation (7.6).

$$\begin{aligned} \tau_{pv}\frac{\mathrm{d}P_{pv}}{\mathrm{d}t} &= P^{*}_{pv} - P_{pv} \\ P^{*}_{pv} &= \mathrm{clip}_{[0,P_{av}]}\big(r\min(P_{av},P_{cap}) - \Delta P_{fw}\big) \\ \Delta P_{fw} &= P_{pk}\frac{f_{pll,p} - f_0 - d_b}{f_0\,k_{OF}} \quad \text{for } f_{pll,p} > f_0 + d_b \end{aligned} \tag{7.6}$$

where P_{cap} is the operator's cap, r ramps from 0 to 1 over 300 s after a re-entry, $d_b = 0.036$ Hz and $k_{OF} = 5\,\%$, and $\tau_{pv} = 2.2$ s gives the 5 s response time that the application takes as the default. The available power is $P_{av} = P_{pk}\,c(h)\prod_n[1 - d_n(a_n - b_n)](1-\varepsilon)$ with $c(h) = [\max(0, \sin(\pi(h - 6.5)/13))]^{1.3}$ at clock hour h, which peaks at 13:00. Each cloud n of depth $d_n = 0.5$ has an entering edge a_n and a leaving edge b_n ten minutes later, each rising from 0 to 1 over 10 s, and ε is the haze.

The critical feeder demands $P_{crit} = 0.90$ MW of its 1 MW connected. Each block demands $P_{blk}\,o(h)$ with $P_{blk} = 0.5$ MW and an occupancy $o(h) = 0.55 + 0.30\exp[-((h-14)/3.5)^2]$, a chiller start adds 0.4 MW to block 1 through a 10 s soft start, and the extra-load disturbance adds to block 2. The power factor is 0.97 and $k_{pf} = 1.5$, so a 1 % fall in frequency takes 1.5 % off the load.

The battery's state of charge integrates its DC power, and its management system sets the continuous limits, as shown in Equation (7.7).

$$\begin{aligned} \frac{\mathrm{d}\,\mathrm{SOC}}{\mathrm{d}t} &= -\frac{P_{dc}}{3600\,E_{cap}}, \qquad P_{dc} = \begin{cases} P_{e,i}/\eta & P_{e,i} \geq 0 \\ \eta\,P_{e,i} & P_{e,i} < 0 \end{cases} \\ P_{dis} &= S_i\,\mathrm{clip}_{[0,1]}\Big(\frac{\mathrm{SOC} - \mathrm{SOC}_{min}}{\Delta}\Big) \\ P_{ch} &= S_i\,\mathrm{clip}_{[0,1]}\Big(\frac{\mathrm{SOC}_{max} - \mathrm{SOC}}{\Delta}\Big) \end{aligned} \tag{7.7}$$

where $P_{e,i}$ is the inverter's output in either mode, $\eta^2 = 92\,\%$ is the round trip and $E_{cap} = 2$ MWh, and the taper $\Delta = 20\,\%$ allows full power from 25 to 75 % and none below 5 % or above 95 %. Seven ledgers integrate each source's energy, the loads', the battery's DC energy and the diesel, and the energy ledgers close to 3.7×10^{-15} of the energy over case 3 and 1.2×10^{-14} over the two-hour challenge.

7.3.5 Meters, Protection and Scores

The frequency meter reads the bus voltage's angle through each step of length Δt, as shown in Equation (7.8).

$$\begin{aligned} f_k &= f_0 + \frac{\big[\theta_V(t_k) - \theta_V^{+}(t_{k-1})\big]_{2\pi}}{2\pi\,\Delta t} \\ \mathrm{ROCOF}_k &= \frac{f_k - f_{k-n}}{n\,\Delta t} \end{aligned} \tag{7.8}$$

where $\theta_V^{+}(t_{k-1})$ is the angle at the start of the step solved with that step's breakers, so the jump a breaker makes in the angle is never read as a frequency, $[\cdot]_{2\pi}$ wraps a difference into $\pm\pi$, and $n\,\Delta t = 0.1$ s is the averaging window the application takes from IEEE 1547 for ride-through. The devices' own protection is listed in Table 7.2. The grid-following inverters carry the Category III default trips that the application quotes from IEEE 1547-2018, cease to energize an island that has no voltage source after 2 s, and re-enter 300 s after the bus returns to 0.917–1.05 pu and 59.5–60.1 Hz. The solar also trips on a ROCOF beyond 3.0 Hz/s, which the application takes as the Category III ride-through and uses as a trip. The run is scored on the truth. The critical feeder counts as served only while the bus is live, its breaker closed and $|V| \geq 0.88$ pu, the frequency counts as out of band outside 59.5–60.5 Hz or with the bus dead, and the worst ROCOF counts from 0.2 s into a run.

Table 7.2 Protection Inside the Devices, as Implemented

Device	Condition	Delay
genset	$f_g < 57.0\,\text{Hz}$ or reverse power over 5 %	3 s
	$f_g > 63.0\,\text{Hz}$	0.5 s
forming inverter	$f_i < 56.5\,\text{Hz}$ or $f_i > 62.0\,\text{Hz}$	0.16 s
	on the current limit	10 s
	$P_{e,i} > 1.05\,P_{dis} + 0.01\,\text{MW}$ (BMS)	10 s
	SOC $\leq 2\,\%$	at once
following inverters	$V_m < 0.50\,\text{pu}$, $V_m < 0.88\,\text{pu}$	2, 21 s
	$V_m > 1.20\,\text{pu}$, $V_m > 1.10\,\text{pu}$	0.16, 13 s
	$f < 56.5\,\text{Hz}$, $f < 58.5\,\text{Hz}$	0.16, 300 s
	$f > 62.0\,\text{Hz}$, $f > 61.2\,\text{Hz}$	0.16, 300 s
	no voltage source on the bus	2 s
solar	$\lvert\text{ROCOF}\rvert > 3.0\,\text{Hz/s}$	at once

A genset trip locks the engine out for 60 s. The following inverters' frequency is their own PLL's reading.

7.3.6 Parameters, Initial State and Numerics

Table 7.3 gives the constants. Every case starts at a steady state for its clock, found by Newton steps on the angles and EMFs until every derivative except those of the state of charge and the ledgers is zero, within 2.7×10^{-12} at worst. The exception is the measured voltage V_m of the following battery in case 2, whose current depends on that reading, and whose derivative starts at 2.1×10^{-7} pu/s. Grid-connected, the battery sits at its schedule and the utility carries the rest. Islanded with the genset online, the genset is the angle reference and the battery's setpoint is iterated onto the dispatch rule of Section 7.5, so a case that starts islanded starts where the controller would hold it. The derivative function is pure. Each 20 ms step applies the controller's commands and any breaker change, solves the bus for the step's topology, holds the demand, the available solar and Δf_m, and advances four fourth-order Runge-Kutta sub-steps of 5 ms. The sub-steps are there because a grid-forming inverter with little inertia has a mode of time constant $2H_v m_p$, 6 ms at 0.1 s and 3 %. The engine and its clocks are those of Section 1.6.1. The meters, the protection and the device sequences act after the step. The controller scans every 20 ms and its slower layers act every second. A row is logged every 0.5 s with the largest ROCOF since the previous row, so a first swing that lasts a tenth of a second survives the log, and the Frequency view keeps every 20 ms step for 30 s. With no random input in the model, a case reloaded, or reset with the same settings, reproduces exactly, and the application passes its 33 verification checks.

7.3.7 Assumptions

One bus, solved as phasors. The campus is one bus at 60 Hz, with no electromagnetic transients, no unbalance, no harmonics, no impedance along the feeders and no fault inside the campus, only the utility's. The first cycle after a breaker operates, which the inverters' inner current loops govern, is outside the model.

A classical genset on a timer. The genset is an EMF behind a reactance with a first-order engine, its start is a timer, its synchronizer is perfect, and its fuel is a straight line. A real engine accepts load in limited steps, which the model represents only through the dispatch's ramp of 0.1 MW/s.

One grid-forming law. The inverter is a virtual synchronous machine of one form with a virtual-impedance current limit and a power-limit droop. Grid-forming controls differ widely in how they limit current, and the application's own assumptions warn that some lose synchronism there.

Ideal following inverters. Their inner current loops are ideal, and their protection is the default set the application quotes plus the 2 s island detection, applied only when no voltage source is on the bus, so the solar never trips for islanding on an island the battery has formed.

Table 7.3 Constants of the Campus Model by Class: V Adjustable in Show Model, H Hidden, C Set by the Code

Symbol	Meaning	Value	Class
Genset			
S_g, X_g	rating, reactance on its rating	2 MW, 0.30 pu	H, V
H, D	inertia constant, damping	1.5 s, 1.0 pu/pu	V
—	minimum load under the dispatch	30 %	V
$n_{q,g}$, K_{avr}	reactive droop, AVR gain	4 %, 6 s^{-1}	V, H
q_0, q_1	fuel, unloaded and per kWh	110 L/h, 0.205 L	V
T_{iso}	isochronous reset time	4 s	C
Battery inverter			
S_i, X_i	rating, reactance on its rating	1 MW, 0.15 pu	H, V
E_{cap}, η^2	energy, round trip	2 MWh, 92 %	V
I_{max}	hardware current limit	1.4 pu	V
K_q, n_q	voltage loop gain, reactive droop	20 s^{-1}, 5 %	H, V
m_{ov}, τ_{ov}, σ_{ov}	power-limit droop, lag, slew	0.40, 1 s, 1 Hz/s	V
ΔP_s	short-term allowance, 10 s	0.5 MW	V
SOC_{min}, SOC_{max}, Δ	BMS floor, ceiling, taper	5, 95, 20 %	V
τ_m, ζ	PLL voltage lag, damping ratio	20 ms, 0.7	C
Solar, utility and loads			
P_{pk}, τ_{pv}	solar rating, power loop lag	1.5 MW, 2.2 s	V
d_b, k_{OF}	frequency-droop dead band, slope	0.036 Hz, 5 %	V
—	ROCOF ride-through, then trip	3.0 Hz/s	V
$X_s = x_s$	utility reactance, 20 MVA short circuit	0.05 pu	V
P_{crit}, P_{blk}	critical demand, each block	0.90, 0.5 MW	V
pf, k_{pf}	power factor, frequency dependence	0.97, 1.5 pu/pu	V
—	chiller, soft start	0.4 MW, 10 s	V
G_{sh}, B_{sh}	transformer shunt	0.004 pu	C

Static loads. The loads are constant impedances with a frequency dependence, with no motor dynamics and no inrush, and the chiller arrives as a 10 s ramp, so a real compressor's starting current would dip the bus more than the model does.

An ideal meter. The relays act on the frequency of Equation (7.8) with no filtering of their own and no breaker time. Section 7.6 shows that the meter's step moves the reading of a first swing.

Thresholds set for teaching. The shedding stages, the restoration rule, the sync-check window, the battery's taper and the genset's trips are all chosen for teaching, and Section 7.9 says where real settings come from.

7.4 Five Relations Behind the Cases

Five relations from the model organize every measured case, and none depends on the microgrid controller above the devices.

7.4.1 The First Swing

At the instant the PCC opens, the virtual speed is still zero, and the inverter's electrical power rises by the import ΔP it must take over. The first line of Equation (7.3) then gives the initial rate of change of frequency of Equation (7.9), the first rate of Equation (1.1) written for the inverter.

$$\mathrm{ROCOF}(0^+) = -\frac{f_0\,\Delta P}{2H_v S_i} \tag{7.9}$$

For the 0.329 MW import of case 3 it is 4.94 Hz/s at 2 s, 6.59 at 1.5 s and 9.88 at 1.0 s, and the application's check, which steps the setpoint rather than the load, confirms the slope to 10^{-9} at 1, 2 and 3 s. The ROCOF a relay reads over 0.1 s is smaller, 2.48 Hz/s at 2 s, because the bus voltage dips from 0.988 to 0.958 pu in the first step and the constant-impedance loads draw 0.110 MW less, and because the window spans the bend of the swing. Equation (7.9) is therefore an upper bound. Kept under the 3 Hz/s ride-through, the bound would ask for 3.3 s of inertia, past the slider's range, while the reading itself clears the ride-through from 1.3 s at the shipped step (2.97 Hz/s).

> **DID YOU KNOW? A Continent Against a Campus**
>
> A 2018 report of the European transmission operators shows phasor measurement units recording the forced outage of 1000 MW of generation in Switzerland: the continental frequency fell by only 40 mHz, at 10 to 15 mHz/s [19]. On this campus the loss of a 0.329 MW import starts the frequency falling at 2.48 Hz/s.

7.4.2 Settling Without Inertia

With the battery alone on the bus, $P_{e,i}$ is set by the load and the virtual speed obeys the first-order law of Equation (7.10).

$$2H_v m_p \frac{\mathrm{d}\omega_i}{\mathrm{d}t} = -\omega_i + \frac{m_p}{S_i}\left(P_{set,i} - P_{e,i}\right) \tag{7.10}$$

The time constant $T_v = 2H_v m_p$ is 120 ms at the defaults, and the settled deviation $m_p f_0 \Delta P / S_i$ does not contain H_v. On its droop alone a lone battery would settle 0.36 Hz low after a 0.2 MW step. With the loads' frequency and voltage relief and the secondary already acting, the falls measured in case 4 from the frequency before each step are 0.302 to 0.304 Hz, within 2 mHz of one another from no inertia to 3 s. Inertia buys time, and the droop and the headroom decide where the fall stops. Volume 1, Chapter 8 draws the same division on a single-area grid, where inertia sets the initial rate of change of frequency and the stiffness of droop and load damping sets the arrested offset.

7.4.3 Sharing by Stiffness

With the genset online, both droops act on one frequency. The genset's governor and rotor damping give it the stiffness $K_g = S_g/R + DS_g = 42$ MW per unit of speed and the inverter has $K_i = S_i/m_p = 33.3$ MW per unit, so a load change divides between them and moves the frequency as shown in Equation (7.11).

$$\frac{\Delta P_{e,g}}{\Delta P_{e,i}} = \frac{K_g}{K_i} = 1.26, \qquad \Delta f = -\frac{f_0\left(\Delta P_{e,g} + \Delta P_{e,i}\right)}{K_g + K_i} \tag{7.11}$$

The ratio holds to 2 % in the application's check at governor droops of 5 and 3 %, where it becomes 2.06. Equation (1.2) writes the same division with each stiffness in megawatts per hertz and without the rotor damping, and this chapter quotes stiffness per unit of speed. The frequency stays where the droops leave it until an integral loop moves a setpoint.

7.4.4 The Overload a Voltage Source Hides

A voltage source on its limit holds its frequency, because nothing in its swing equation knows that the battery is overdrawn. At steady state the last term of Equation (7.3) lowers the frequency by $f_0 m_{ov}/S_i = 24$ Hz for each megawatt of shortfall, as shown in Equation (7.12).

$$\Delta f_{ov} = -\frac{f_0 m_{ov}}{S_i} z, \qquad \left|\frac{\mathrm{d}\Delta f_{ov}}{\mathrm{d}t}\right| \le \sigma_{ov} \tag{7.12}$$

A battery 0.05 MW short is driven toward a frequency 1.2 Hz low, through the first stage at 59.3 Hz, at no more than 1 Hz/s, which the solar rides through. The secondary loop cannot cancel the term while the battery carries the island alone, because its total is limited to the battery's continuous capability.

7.4.5 Closing Across the PCC

Two voltages of 1 pu that differ in phase by $\Delta\varphi$ put $2\sin(\Delta\varphi/2)$ per unit across the open breaker, which is 1.95 pu at the 153° of case 10 and 0.04 pu at the 2.4° at which the synchronizer closes. Closing at the wrong moment drives that difference through the utility's 0.05 pu and the island's sources at once, which is why the sync check of Section 7.5 stands between the operator and the breaker.

Table 7.4 Microgrid Controller Settings, Their Defaults and Allowed Ranges

Symbol	Setting	Default	Range
—	inverter mode	forming	following
H_v, m_p	virtual inertia, droop	2.0 s, 3 %	0–3, 2–5
f_{PLL}	PLL bandwidth	2 Hz	0.5–10
R	governor droop	5 %	2–8
τ_e, t_{start}	engine lag, start time	0.3, 45 s	to 1.5, 180
—	genset loading ramp	0.1 MW/s	0.02–1
—	genset start policy	on islanding	or manual, SOC
K_c, τ_I	secondary gain, integral time	0.25 MW/Hz, 2 s	0–2, 0.5–60
SOC_{lo}, SOC_{hi}	SOC band	40, 80 %	10–95
K_{soc}, r_{soc}	SOC gain, largest request	0.05 MW/%, 0.5 MW	to 0.5, 1
P_{gc}	battery schedule on the grid	0.45 MW	±1
f_1, f_2, f_3	shedding stages	59.3, 59.0, 58.7	57.5–59.8
t_{uf}	stage delay	0.2 s	0.06–2
f_{rest}, t_{rest}	restoration frequency, delay	59.9 Hz, 30 s	to 60, 300
Δf_{slip}	synchronizer slip	0.05 Hz	0.01–0.2
—	sync-check window	0.1 Hz, 10°, 5 %	to 0.5, 60, 20
t_{grid}	grid healthy first	60 s	0–300

7.5 The Microgrid Controller, Layer by Layer

The microgrid controller reads what a real one has: the bus frequency meter of Equation (7.8) and its ROCOF, the bus voltage, a power meter on every source, feeder and the PCC, the battery management system's state of charge and limits, the breaker contacts, and the two voltage transformers either side of the PCC. It never reads an EMF or an angle inside a machine. Primary control lives in the devices, the governor's droop, the inverter's virtual inertia and droop, the solar's frequency-watt response and the reactive droops of both voltage regulators. The controller adds five layers on two clocks, listed with their settings in Table 7.4. Every 20 ms it runs the shedding relays and the restoration sequence, the dispatch of the setpoints and the synchronizer, and every second the frequency restoration, the state-of-charge manager and the genset's start policy. Section 1.4.3 sets out the primary and secondary layers in general.

7.5.1 Shedding and Restoration

Stage k opens block k once the measured frequency has read under f_k for $t_{uf} = 0.2\,\text{s}$, ten consecutive scans, with the bus live. The critical feeder is never shed by frequency. A dead bus opens every feeder after 0.5 s, and the critical feeder closes 2 s after the bus is live again. The blocks come back one at a time through a sequencer that the framework provides, shared/src/framework/core/sequencer.js, whose forced stop lets a relay take one stage off at once and whose minimum rest and spacing are both t_{rest}. A block returns only when the frequency has stayed above f_{rest} for t_{rest}, the forming sources have 1.2 times its load plus 0.05 MW of headroom, and t_{rest} has passed since a source last closed. The sequencer starts the lowest priority first, so block 3, the last shed, returns first. Every feeder the controller switches is fed forward. Its load is added to or taken from the secondary's total, its integral and the setpoint carrying it, so a restoration is not first seen as a frequency error, and on a shed the part of the block that a limited battery was not delivering is left out.

7.5.2 Frequency Restoration on the Shared Controller

The secondary is the velocity-form PID of Section 1.6.2, the one implementation every framework app shares, executed once a second with no derivative term and no bias. In the symbols of Equations (1.10) to (1.13) its error is $e_k = f_{SP} - \bar{f}_k$ with $P_k = K_c e_k$, where $\bar{f}_k$ is the meter's average over the period $T = 1\,\text{s}$ and f_{SP} is 60 Hz or, while synchronizing, the utility's frequency plus the slip. The running sum S_k of proportional terms is never clamped, and the back-calculation with $T_t = \tau_I$ corrects the integral alone, so the clip acts only on the emitted total u_k. The limits are the forming sources' range, $[-P_{ch}, P_{dis}]$ for a battery whose SOC loop is in Auto, or its fixed manual setpoint, plus $[0.3S_g, S_g]$

while the genset is online. The tapered limits of Equation (7.7) thus reach the loop as the bounds of its output, the arrangement of Section 1.4.4 that Chapter 10 calls cascade anti-windup. A frequency below its setpoint raises the total, which is reverse action in the ISA sense and the action $a = +1$ of Section 1.6.2, as the application's direction check confirms. The total ramps to each new value over the next second rather than stepping. That ramp and the genset's 0.1 MW/s loading ramp act after the controller's output, so the integral does not see them, and while the genset is still ramping with the battery at its limit the total delivered lags u_k. The loop acts only while the campus is islanded, the bus is live, the loop is in Auto and it has an actuator, the online genset or a forming battery whose SOC loop is in Auto. Otherwise it tracks the dispatched total, $I_k = u_{now} - S_k$, so each hand-over is bumpless.

7.5.3 State of Charge and Dispatch

The SOC manager sets the battery's own share while the genset runs, as shown in Equation (7.13), a banded form of the proportional manager of Equation (1.5).

$$P_{soc} = \begin{cases} -\min\left(r_{soc},\ K_{soc}(\mathrm{SOC}_{lo} - \mathrm{SOC})\right) & \text{below} \\ 0 & \text{inside} \\ \min\left(r_{soc},\ K_{soc}(\mathrm{SOC} - \mathrm{SOC}_{hi})\right) & \text{above} \end{cases} \tag{7.13}$$

for a state of charge below, inside or above the band, with the SOC in percent, r_{soc} the largest request, and the result limited to $[-P_{ch}, P_{dis}]$. Under the by-SOC start policy the band's floor rises to its top while the genset runs, so the genset charges the battery up and can then stop. Without the manager the battery's share is its droop share of the total, $s\,u$ with $s = (S_i/m_p)/(S_i/m_p + S_g/R) = 0.455$. Every scan the genset's setpoint ramps at 0.1 MW/s toward u less the battery's share, between $0.3S_g$ and S_g, and the battery's ramps at 2 MW/s toward whatever the genset has not yet picked up, $u - P_{set,g}$, or toward all of u while it is alone. The battery therefore carries each transient and, once the genset has caught up, sits at its own share, the division of labor of Chapter 2, where a UPS carries the bus while the engines catch up. On the grid the battery follows its schedule P_{gc} at 0.2 MW/s.

7.5.4 Genset Start Policies

On islanding, the genset is cranked at the next execution of the 1 s layer after the PCC opens. Every scripted fault falls on one, so the crank follows the fault by one 20 ms step, and the genset is stopped a minute after the reconnection. By SOC, it starts when the state of charge falls below the band, when the battery has carried more than 90 % of what it may give for 5 s, or when the island has lost its grid former, and it stops above the band once the net load is under 80 % of what the battery may give. A one-stage instance of the same sequencer holds it to a minimum run of 10 min and rest of 5 min. The manual policy starts and stops it on the operator's command.

7.5.5 Synchronizer and Sync Check

Once the utility side has been healthy for t_{grid}, the synchronizer aims the secondary at the utility's frequency plus $\Delta f_{slip} = 0.05$ Hz, so the synchroscope's needle turns once in 20 s, and trims both voltage setpoints by the integral of $2(V_{grid} - |V|)$ per second within ±0.05 pu. The sync-check relay permits a close only while the frequency, phase and voltage differences are within 0.1 Hz, 10° and 5 %, and the synchronizer closes inside a quarter of the phase window. A close asked by hand outside the window is refused with its reason, a dead bus is closed onto the healthy utility without synchronizing, and a disturbance closes the breaker with no check at all, which is what the check exists to prevent. A planned island trims the battery's schedule by $5P_s$ per second until the PCC exchange P_s has stayed under 0.03 MW for a second, then opens the breaker, and abandons the attempt after 90 s.

7.5.6 Manual Mode and the Three Models

Each of the five stations, the frequency loop, the SOC loop, the feeder restoration, the synchronizer and the solar cap, has its own Manual and Auto, and the header's switch throws them all, copying

Table 7.5 Cases Run From the Reference Configuration

#	Setup	Lesson
1	grid, 09:30, 100 s, battery stepped by hand to 1.0, −0.5, 0 and 0.45 MW at 20, 40, 60 and 80 s	power moves, frequency does not
2	inverter following, 09:59, 480 s, fault at 60 s	nothing makes the voltage
3	09:59, 180 s, fault at 60 s	the first swing
4	islanded at 11:00 on the battery, genset manual, 210 s, block 2 +0.2 MW for 25 s at 10, 50, 90 and 160 s with H_v = 0, 1.5, 3 and 3 s set 5 s before, +0.4 MW from 120 s	inertia against headroom
5	09:59, 240 s, frequency loop in Manual at 0.3 MW, SOC loop in Manual at 0.45 MW, fault at 60 s, chiller at 180 s	sharing by stiffness
6	islanded at 11:59:30 with the genset, 150 s, cloud at 30 s	who answers first
7	islanded at 11:00 on the battery, genset manual, 20 % haze, 240 s, chiller at 20 s, genset started at 60 s	the last layer
8	islanded at 10:30 with the genset, SOC 50 %, 50 % haze, SOC manager off, 5400 s	the store and the average
9	09:59 at SOC 15 %, 240 s, fault at 60 s	honestly infeasible
10	islanded at 11:58:30 with the genset, 240 s, utility back at 30 s, 153.9° out of phase	the sync check
ch.	challenge, 09:59 to 12:10, fault 10:00, cloud 10:40, chiller 11:10, utility back 12:00, shipped with $H_v = 0$, SOC manager off, genset manual	a two-hour island

each controller's output into its station first, as Section 1.6.2 describes. In Manual the operator holds the genset's and the battery's setpoints, the three block breakers and the solar cap, and closes the PCC with a button that still passes through the sync check, while the droops in the devices keep acting. The simulation model is Equations (7.1) to (7.8). The controller identifies nothing from data, and the models inside it are small: the declared droops in the share s, the battery's limits and the genset's rating in the headroom test, and the feeder meters in the switched-load feedforward.

7.6 Ten Cases and a Two-Hour Island

Every case in Table 7.5 starts from one configuration, the battery forming the grid at 2 s of virtual inertia and a 3 % droop with 60 % charge, the genset cold on the on-islanding policy, the SOC manager on, the stages armed and the synchronizer automatic, and alters only the settings its row lists, with event times in seconds into the run. The values quoted below come from headless runs of the engine at the shipped 20 ms step, in simulated time, with each changed setting made at $t = 0$ before the run, and Table 7.6 gathers them. The table marks the challenge ch., since the app lists it apart from its numbered cases.

7.6.1 On the Grid, by Hand

Case 1 runs the campus on the grid at 09:30 with the SOC loop in Manual and moves the battery's setpoint every 20 s. At 1.0 MW the campus exported 0.107 MW and charging at 0.5 MW it imported 1.387 MW, so the battery's swing of 1.5 MW reappeared within 6 kW at the PCC while the meter stayed within 59.975 to 60.025 Hz. On the grid an inverter's setpoint decides only where the power comes from.

7.6.2 Following Against Forming

In case 2 the battery follows the grid. The 0.288 MW import vanished with the utility at 10:00, and with no voltage source left the bus voltage became the inverters' currents through the loads. The solar tripped at 20 ms on a ROCOF of 7.5 Hz/s, the bus was at 0.42 pu at 40 ms with both PLLs at 60.92 Hz, and it was dead at 60 ms. The battery's island detection tripped it at 2 s, the genset closed onto the dead bus at 10:00:45, and the critical feeder followed 2 s later and the blocks from 10:01:23,

Table 7.6 What the Engine Measured, Case by Case

Case and configuration	Result
1, battery at 1.0 and −0.5 MW	PCC exchange −0.107 and 1.387 MW, f within 59.975–60.025 Hz
2, following	solar trip at 20 ms, bus dead at 60 ms, 11.75 kWh critical lost
2, PLL at 0.5 Hz	0.84 pu and 60.70 Hz at 1.4 s, both trip at 2 s, 11.75 kWh lost
3, $H_v = 2$ s	2.48 Hz/s, nadir 59.516 Hz at 0.96 s, no shed
3, $H_v = 3$ and 1.5 s	1.97 and 2.82 Hz/s, nadirs 59.518 and 59.515 Hz
3, $H_v = 1.25$ and 1.0 s	5.44 and 5.83 Hz/s, solar trip, 3 sheds
3, $H_v = 0$	11.18 Hz/s, nadir 58.324 Hz, 3 sheds
4, $H_v = 0$, 1.5 and 3 s	2.61, 1.77 and 1.21 Hz/s, nadirs 59.697, 59.728 and 59.729 Hz
4, 0.07 MW headroom, 3 s	1.41 Hz/s, battery 1.085 MW, block 1 shed, nadir 59.088 Hz
4, $m_p = 2$ and 4 %	nadirs 59.793–59.827 Hz, and at 4 % 7.94 Hz/s with 3 sheds
5, $R = 5$ %	split 0.205 to 0.163 MW (1.26), $\Delta f = -0.294$ Hz
5, $R = 3$ %	split 0.251 to 0.122 MW (2.06), $\Delta f = -0.219$ Hz
5, frequency loop in Auto	60.000 Hz at 240 s, genset 0.726 MW
6, $m_p = 3$, 2 and 5 %	battery peaks 0.203, 0.269 and 0.135 MW, nadirs 59.637, 59.679 and 59.597 Hz
6, frequency loop in Manual	59.461 Hz at 150 s, battery 0.299 MW
7, shedding armed	block 1 shed at 59.23 Hz, nadir 59.182 Hz, 22.4 kWh shed
7, shedding off	BMS trip at 11:00:38, 17.23 kWh critical lost
7, $m_{ov} = 0.02$	59.509 Hz for 11.7 s over the limit, 17.57 kWh lost
8, manager off, on, floor 60 %	SOC to 9.1, 50.0 and 59.7 %, 399, 560 and 601 L
9, shedding armed	block 1 shed 0.58 s after the fault, nadir 59.024 Hz, nothing lost
9, shedding off	BMS trip 10 s after the fault, 9.26 kWh critical lost
10, synchronizer	close at −2.4° and 0.040 Hz, surge 0.327 MVA
10, no check at −153°	8.62 MVA, genset swing 8.42 MW, 57.85–61.92 Hz

about 30 s apart, after 11.75 kWh of critical load had gone unserved. A 0.5 Hz PLL only slowed the drift, to 0.84 pu and 60.70 Hz after 1.4 s, before both inverters tripped at 2 s with the same loss.

Pause. Try Exercise 7.1 before reading on.

Case 3 repeats the fault with the battery forming the grid. In the first 20 ms its output rose from 0.450 to 0.679 MW while the bus dipped to 0.958 pu, the ROCOF peaked at 2.48 Hz/s, the frequency bottomed at 59.516 Hz 0.96 s after the breaker opened, and the secondary brought it within 0.05 Hz of 60 Hz by 10.9 s, as shown in Figure 7.3. By 180 s the genset carried 0.791 MW with the battery at zero and the bus at 60.000 Hz. Figure 7.2 sets five inertias side by side. At 3, 2 and 1.5 s the worst ROCOF was 1.97, 2.48 and 2.82 Hz/s, the solar rode through, and the nadir stayed within 59.515 to 59.518 Hz. At 1.25 and 1.0 s it was 5.44 and 5.83 Hz/s. At 1.0 s the solar tripped 0.10 s after the breaker opened, the battery was asked for the solar's 1.03 MW besides the import, all three stages shed with a nadir of 58.226 Hz, and the inverter's current limit held the bus under 0.88 pu for 0.26 s, which cost even the critical feeder 0.06 kWh. With no inertia the swing read 11.18 Hz/s and the nadir was 58.324 Hz. Set too low, virtual inertia turns a fault the battery could carry into one it cannot.

TRY IT IN THE APP 3 · The Fault With a Grid-Forming Inverter

Load scenario 3 and press Run. Watch the scope of the Frequency view at 10:00, when the utility breaker opens. The bus frequency falls to 59.516 Hz about a second later and climbs back toward 60 Hz, the ROCOF trace stays inside the 3 Hz/s ride-through lines, and no load is shed.

7.6.3 Inertia Against Headroom

Case 4 islands the campus at 11:00 on the battery alone, which carries 0.574 MW of the 1 MW it may give, and steps block 2 by 0.2 MW with the inertia at 0, 1.5 and 3 s in turn. The ROCOF fell from 2.61 to 1.77 to 1.21 Hz/s while the nadir moved only from 59.697 Hz to 59.728 and 59.729 Hz, as Equation (7.10) predicts. With 0.4 MW more on block 2 the battery carried 0.930 MW with 0.070 MW of headroom, and the same step at 3 s fell at only 1.41 Hz/s but did not stop. The battery passed its continuous capability to 1.085 MW, the power-limit droop pulled the frequency down,

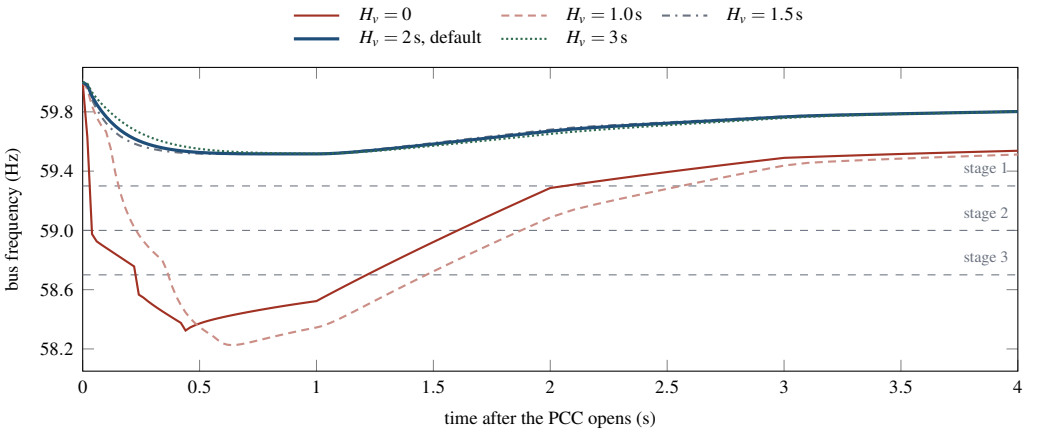


Figure 7.2 The first swing of case 3 at five virtual inertias, from the engine at its shipped 20 ms step, every step to 1.5 s and every 0.1 s after. At 1.5, 2 and 3 s the solar rides through and the curves meet at a nadir of 59.515 to 59.518 Hz. At 1.0 s and with none the swing passes 3 Hz/s, the solar trips and all three stages shed. The dashed lines are the stage thresholds.



Figure 7.3 The campus in case 3, The fault with a grid-forming inverter, at $t = 1.25$ min (10:00:15 on its clock), 15 s after the PCC opened, cropped to the Frequency view with no setting changed. (1) The badges read f 59.979 Hz, SOC 59.4 %, genset starting 30 s, and no load shed or critical load unserved. (2) The scope's last 30 s at every 20 ms show the bus falling from 60.0 Hz to the marked nadir of 59.516 Hz and recovering, and (3) the ROCOF trace under it dips toward the ± 3.0 Hz/s ride-through lines without reaching them. (4) The first-swing panel reads a virtual inertia of 2.0 s and a droop of 3.0 %, a 0.1 MW step's initial ROCOF of 1.50 Hz/s with τ 120 ms, the nadir 59.516 Hz with a worst ROCOF of 2.48 Hz/s, and the battery at +0.74 MW of the 1.00 MW it may give, a headroom of 0.26, with all three stages armed. (5) The status line reads GENSET STARTING · ONLINE IN 30 s.

stage 1 shed block 1 (0.35 MW) at 59.16 Hz, and the nadir was 59.088 Hz. A 2 % droop held the three nadirs within 59.793 to 59.827 Hz, while 4 % with no inertia stepped the frequency so far at

once that the meter read 7.94 Hz/s and all three blocks were shed. Inertia is a setting and headroom is megawatts left unused, and an island that needs a slow swing and a shallow one has to buy both.

🕮 **Pause.** Try Exercise 7.2 before reading on.

7.6.4 Two Droops and a Secondary

Case 5 takes the secondary out of the loop, with the genset held at 0.3 MW once it is online and the battery at 0.45 MW. By the end of the 45 s start the battery alone carried 0.716 MW at 59.521 Hz, and with the genset online the island sat at 59.969 Hz. A minute after the 10:02 chiller the genset had taken 0.205 MW more and the battery 0.163 MW, a ratio of 1.26, and the frequency was 0.294 Hz lower, the fall that Equation (7.11) gives for those two changes. A 3 % governor droop gave 0.251 and 0.122 MW, a ratio of 2.06, and a fall of 0.219 Hz. With the frequency loop in Auto the island sat at 60.154 Hz with the genset at its 0.6 MW minimum until the chiller, and the secondary then returned it to 60.000 Hz on the genset alone, at 0.726 MW by 240 s.

Case 6 runs the island at noon with the genset at its minimum and the battery idle in its band, and a cloud takes half of the 1.44 MW of solar over 10 s. At the bottom of the edge the genset had added 0.48 MW and the battery 0.22 MW, and the nadir was 59.637 Hz with the battery at its peak of 0.203 MW. The secondary then handed the loss to the genset, the battery falling to 0.002 MW by 60 s while the genset carried 1.30 MW, and the frequency was 60.000 Hz by 90 s. A 2 % battery droop raised the battery's peak to 0.269 MW and the nadir to 59.679 Hz, and 5 % lowered them to 0.135 MW and 59.597 Hz. With the frequency loop in Manual nothing hands the loss on, and the island stayed at 59.461 Hz with the battery giving 0.299 MW. The battery covers the first seconds, the engine the minutes, and the secondary decides when one hands over to the other.

7.6.5 The Last Layer

Case 7 islands the campus at 11:00 under 20 % haze on the battery alone, which carries 0.830 MW of its 1 MW, and starts a 0.4 MW chiller on block 1 at 11:00:20 while the operator starts the genset at 11:01. The chiller pushed the battery to 1.044 MW, past its continuous capability, and the power-limit droop pulled the frequency down until stage 1 opened block 1, chiller and all (0.63 MW), at 59.23 Hz 7.1 s after the chiller started. The nadir was 59.182 Hz, the island spent 1.6 s out of band and shed 22.4 kWh, and block 1 returned 30 s after the genset closed. With the shedding off the battery stayed over its limit until its management system tripped it at 11:00:38, and the critical feeder lost 17.23 kWh before the genset closed onto the dead bus. With the shedding armed but the power-limit droop at 0.02, the frequency held at 59.509 Hz while the battery spent 11.7 s over its limit, no stage saw its threshold, and the trip at 11:00:36 cost the critical feeder 17.57 kWh. The relays are only as good as the signal the source gives them.

🕮 **Pause.** Try Exercise 7.3 before reading on.

Case 9 faults the grid with the battery run down to 15 %, 14.6 % by the fault, where its management system allows 0.480 MW continuously against the 0.450 MW it was giving and the 0.329 MW import it must take over. With the genset 45 s away no setting keeps every feeder on. With the shedding armed the battery held the bus on its short-term allowance, stage 1 shed block 1 (0.32 MW) 0.58 s after the breaker opened at 59.10 Hz, the nadir was 59.024 Hz, 24 mHz above stage 2, and the battery then carried 0.445 to 0.448 MW while what it may give fell with its charge from 0.479 to 0.466 MW, until the genset closed at 10:00:45, with nothing lost on the critical feeder. With the shedding off the management system tripped the battery at 10:00:10 and the critical feeder lost 9.26 kWh. Shedding is a controlled failure, the HVAC given up so that the hospital wing keeps its lights.

7.6.6 Diesel Now or Battery Later

Case 8 runs the island for 90 min from 10:30 under 50 % haze with the genset online, the battery at 50 % and the SOC manager off, so the battery carries its droop share of the average. It gave about 0.58 MW for an hour and fell to 19.7 % by 11:30, after which the taper let it give less and less,

0.205 MW at 9.1 % by noon, while the genset took up the difference to 1.10 MW. The run burned 399 L. With the manager on, the battery stayed at 50.0 % carrying nothing while the genset carried 1.28 to 1.30 MW for 560 L, and the 161 L between the runs is the energy the first one borrowed from the battery. With the band's floor at 60 % the genset also recharged it, to 59.7 % by noon, for 601 L.

7.6.7 Back Through the Synchroscope

Case 10 begins islanded at 11:58:30 with the genset online, and at 11:59 the utility side returns 153.9° out of phase. The synchronizer waited 60 s for a healthy grid, aimed the island at 60.05 Hz from 12:00, and closed the PCC at 12:00:20 with the phase difference at −2.4°, the frequencies 0.040 Hz apart and the voltages matched, for a surge of 0.327 MVA, and the genset unloaded and stopped at 12:01:21. Asked to close by hand at −153°, the relay refused. Closed with no check at −153.4°, the PCC carried 8.62 MVA, the genset swung through 8.42 MW, four times its rating, and the frequency ran between 57.85 and 61.92 Hz.

> **TRY IT IN THE APP** **10 · Resynchronization Through the Synchroscope**
>
> Load scenario 10 and press Run on the Synchroscope view. The synchronizer waits 60 s for a healthy grid, slips the island and closes the utility breaker at 12:00:20 with the phases 2.4° apart, for a surge of 0.327 MVA. Asked to close by hand at −153°, the relay refuses. Closed there without the check, the breaker carried 8.62 MVA.

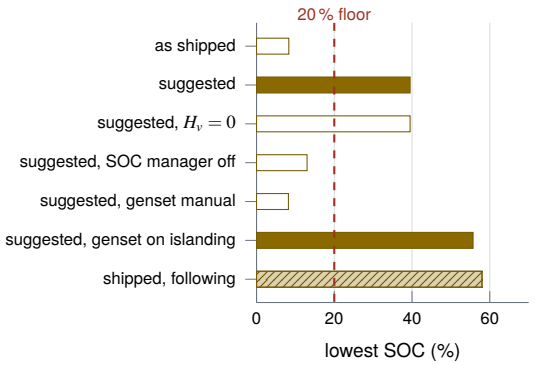
7.6.8 The Two-Hour Island

The challenge runs from 09:59 to 12:10, with the fault at 10:00, a cloud at 10:40, a chiller at 11:10 and the utility's return at 12:00. Its target, in teaching thresholds calibrated on this model, asks for no critical load unserved, at most 10 s outside 59.5 to 60.5 Hz, a ROCOF of at most 3.0 Hz/s, the battery within 20 to 90 % and at most 650 L of diesel, and Table 7.7 lists the configurations tried. As shipped, the fault trips the solar and sheds all three blocks, and block 1 is shed again at the cloud and at the chiller. After 12:01 the synchronizer's voltage trim raises the load past what the drained battery may give, so its management system trips it at 12:02:52 and the bus is dark for one 20 ms step before the PCC closes onto it. Removing the suggested values one at a time shows what each shipped setting costs. With the inertia back at zero the fault still trips the solar, costs 0.050 kWh and reads 11.18 Hz/s, and with the SOC manager off or the genset on manual start the battery falls to 13.0 or 8.2 %. With 2 s of inertia, the SOC manager and the genset started by SOC, the island meets all of it. The genset starts at 10:32:54 as the battery reaches 40 %, the SOC manager then asks up to 0.5 MW of charge, and the genset stops at 12:02:26 after 1.48 h online with the battery at 70.3 %. Started on islanding it also passes, with 583 L against 585 L but 2.03 h online and the battery at 55.7 %, so starting by SOC buys fewer engine hours and a fuller battery for the same diesel. As shipped the run fails four clauses of the target. With the suggested settings it meets every one, with 0.52 Hz/s of ROCOF and 65 L of diesel inside the limits. Revealing the suggested settings and then pressing Reset gives the same run. The challenge is scored on the day as scripted, so changing a model parameter or a disturbance voids the attempt. Figure 7.4 draws the seven configurations of Table 7.7 as a chart.

> **DID YOU KNOW?** **Less Diesel Is Not a Better Island**
>
> From the simulator: with the suggested settings but the SOC manager off, the two-hour challenge burns 347 L of diesel instead of 585 L and keeps the whole critical load on, yet it fails the target, because the battery falls to 13.0 % (Table 7.7).

7.6.9 The Step and the Meter

Halving the step to 10 ms keeps every conclusion that the application tests. Case 2 still collapses, dead at 50 ms instead of 60 ms, case 3 still sheds nothing with its nadir at 59.516 Hz, and case 7 sheds block 1 at 27.14 s at both steps. The reading of a first swing is another matter, because the meter



critical kWh	out s	ROCOF Hz/s	diesel L	verdict
0.055	13.4	11.18	0	fails
0	0.0	2.48	585	meets
0.050	3.2	11.18	592	fails
0	0.0	2.48	347	fails
0	3.3	2.48	0	fails
0	0.0	2.48	583	meets
1815.5	7260.0	8.56	0	fails

Figure 7.4 The seven configurations of Table 7.7 as a chart: the lowest state of charge over the two hours (bars), with the critical energy unserved, the time outside 59.5 to 60.5 Hz, the worst ROCOF, the diesel burned and the verdict against the target in the columns. Solid bars meet the target, white bars fail it, and the hatched bar is the shipped run with a following inverter. Notice that the shipped run, the run with the genset on manual start and the run with the SOC manager off all end below the dashed 20 % floor, and that only the two solid bars clear every clause.

Table 7.7 The Two-Hour Challenge in Seven Configurations

Configuration	Critical kWh	Out s	ROCOF Hz/s	SOC %	Diesel L
as shipped	0.055	13.4	11.18	8.3–60.0	0
suggested	0	0.0	2.48	39.5–73.7	585
with $H_v = 0$	0.050	3.2	11.18	39.5–74.0	592
SOC manager off	0	0.0	2.48	13.0–60.0	347
genset manual	0	3.3	2.48	8.2–60.0	0
genset on islanding	0	0.0	2.48	55.7–60.0	583
shipped, following	1815.5	7260.0	8.56	58.0–60.0	0

Only the suggested line and the genset on islanding meet the target.

of Equation (7.8) averages the frequency over one step, and at 2.5 ms it shows the frequency rising 24 mHz in the first 5 ms as the voltage dips. The default swing of case 3 reads 2.48, 2.62, 2.70 and 2.75 Hz/s at steps of 20, 10, 5 and 2.5 ms, converging under the 3.0 Hz/s ride-through, but at 1.5 s of inertia the readings are 2.82, 3.00, 5.20 and 5.25 Hz/s, and from 5 ms down the solar trips and all three blocks shed. The cliff that lies between 1.25 and 1.3 s at the shipped step lies between 1.6 and 1.7 s once the meter is resolved, while the 2 s default keeps its margin at every step. A ROCOF threshold is a statement about a meter as much as about the plant.

7.7 An Optional One-Hour Energy Dispatch

The Energy dispatch choice leaves Rules as the default and places a mixed-integer plan above the same frequency PI, primary controls and protection. Every 60 s it solves four 15 min commitments on `core/milp`. Its forecast is the measured load minus measured solar power held constant for one hour. It has no access to future scenario events, weather, a chiller start or a reconnection time. The state is the BMS SOC, reinitialized from its measurement at each decision, and the commitment history is the supervisor's own run and rest timer. Section 1.6.3 describes the framework's predictive options in general. This one plans integer commitments on an energy model rather than moves of a linear dynamic model.

Table 7.8 The Added Island: Fuel and Ending Stored Energy

Dispatch	Fuel (L)	SOC (%)	Adj. (L)	Crit. (kWh)
Rules	476.30	77.98	476.30	0
Retuned rules	277.83	43.45	425.43	0.125
One-hour MPC	397.47	62.18	465.02	0
One-slot plan	326.58	45.33	466.15	0

For generation G_k, discharge D_k, charge C_k, end-slot SOC s_k and binary run command u_k, the nominal energy model is

$$G_k + D_k - C_k = P_{\text{net}}, \tag{7.14}$$

$$s_{k+1} = s_k - \frac{hD_k}{\eta E} + \frac{h\eta C_k}{E}, \tag{7.15}$$

where $h = 0.25$ h, $E = 2$ MWh and $\eta = \sqrt{0.92}$. A direction binary prevents simultaneous charge and discharge. The objective prices the nominal fuel curve, 110 L/h while running plus 0.205 L/kWh generated, a cranking allowance and a small positive battery-travel price. The generator's minimum and maximum output and the present BMS limits constrain the moves, with a ten-percent BMS reserve. End-slot SOC lies between 20 and 90 percent and terminal SOC is at least the low edge of the learner's band. These are planning limits, not replacements for the device protection. The model coefficients are the declared defaults, so an edited battery capacity or efficiency is model mismatch.

The commitment grid conservatively exceeds the physical 600 s minimum run and 300 s minimum rest, and the exact sequencer remains underneath. Startup reduces first-slot generation capacity. The energy model omits ramp and frequency dynamics. The applied generator share is corrected by the frequency PI's difference from the forecast net load, while the battery carries the remainder. A stop request first unloads the genset to near zero measured output and near-setpoint frequency before its breaker may open. A rejected, non-optimal, nonfinite, fractional or out-of-bound plan clears the future and returns to the selected rules through their existing ramp. Manual stations, a following-mode battery, a dead bus or grid connection suspend dispatch planning. A browser-only 25 ms frame budget preserves ordered physics steps while reducing playback throughput when necessary.

7.7.1 A Comparison That Prices the Battery Left Behind

Case 11, Rules versus a one-hour dispatch plan, runs a 90 min island from 50-percent SOC with the genset online. Table 7.8 compares by-SOC Rules with the plan, a fixed rule retune and a one-slot counterfactual, all on the same measurements and seed. The counterfactual uses the same constraints and objective but retains only one 15 min slot. No case-specific tuning is applied.

The adjustment values the difference in ending battery energy at the nominal marginal diesel cost of replenishing it, as shown in Equation (7.16).

$$F_{\text{adj}} = F + \frac{1000(0.205)E}{\eta}(s_{\text{Rules,end}} - s_{\text{end}}) \tag{7.16}$$

It excludes additional no-load fuel and is an accounting comparison, not a simulated replenishment. Most of the apparent 78.83 L saving is energy borrowed from the battery. The one-slot counterfactual recovers almost all of the adjusted benefit, so it does not support attributing that headline to an hour of prediction. Rules, MPC and the one-slot plan serve the critical load without loss and remain in the frequency band. The plan starts the genset once more, and the switching raises the peak ROCOF from about 0.0012 Hz/s under Rules to 0.741 Hz/s under MPC.

The fixed rule retune uses a 40–60 percent SOC band, a 0.9 MW charge and discharge cap and an SOC gain of 0.2 MW/%, and the frequency and primary gains remain shipped. These settings were

declared once before measuring this row and retained on every case, without a search for a winning result. Its smaller 425.43 L adjusted number is not an admissible improvement. The original by-SOC rule stops a loaded engine and loses 0.125 kWh of critical energy in the added case, with a peak ROCOF of 4.461 Hz/s. It also loses 0.130 kWh on resynchronization. The MPC's unload-before-stop path avoids that loss. This is one fixed retune, not a globally optimal classical controller.

On the unchanged two-hour challenge with its suggested settings, matched Rules consume 585.31 L and end at 70.32-percent SOC. MPC consumes 550.64 L and ends at 51.38 percent, and its adjusted 631.64 L loses to Rules. Both lose no critical energy and spend no time outside the frequency band. The one-slot plan uses 471.73 L, ends at 36.73 percent and has an adjusted 615.31 L. Lower raw fuel is therefore insufficient evidence of a better dispatch. The fixed rule retune gives an adjusted 585.14 L on this challenge, close to Rules, while its unsafe added-case stop prevents calling it a generally better configuration.

Across all twelve scenarios, every command and output remains finite, the generator command stays at or below 2 MW and the battery command at or below 1 MW in magnitude. The matched comparison loses no additional critical energy. Switching increases ROCOF on the cloud, SOC and added cases, and each stays below 1 Hz/s. The grid-following fault remains infeasible with the planner in standby. The cold, low-SOC case invokes fallback rather than relabeling an infeasible plan. The reduced two-slot MILP agrees with exhaustive binary enumeration over sixteen operating points, and injected non-optimal, nonfinite, fractional and infeasible solutions are rejected. The ten earlier cases and the challenge, shipped and with the suggested settings, remain identical on all their original logged columns. The persistence forecast, the current-limit hold and the coarse energy slots limit the interpretation. The section compares dispatch policies on this campus and makes no claim of economic superiority.

7.8 Technology in Practice

The layers of Section 7.5 run on instrument transformers, relays, breakers and inverters. Figure 7.5 draws the campus's loops with that hardware in place of the schematic's symbols.

What Measures It

Every reading of the microgrid controller starts at an instrument transformer. Potential transformers step the line voltage down to a safe level, typically 120 V, and current transformers step the line current down, typically to 5 A at full load, for the meters and the protective relays to read [20]. The chapter's controller reads the bus frequency meter FT-100 with its ROCOF, a power meter on every source and feeder and on the PCC, the voltage transformers on either side of the PCC, and the charge and limits that the battery's management system reports.

> **TECHNOLOGY** **Sensor: A Frequency Relay on the Bus Voltage**
>
> No instrument reads frequency directly. A relay or meter takes the bus voltage through a potential transformer and estimates the frequency from it, by a phase-locked loop, a Fourier transform, the zero crossings or the change of the voltage phasor's angle [19, 20]. The estimate needs a few cycles, typically 90 to 120 ms, and about 30 mHz of accuracy is typical for underfrequency load shedding. A ROCOF for protection is computed over 180 to 240 ms to within 50 mHz/s. The common failure is a false reading: a short circuit or a breaker operation makes the voltage angle jump, and the local frequency spikes, which can shed load or disconnect solar installations [19]. The chapter's meter reads the angle over each 20 ms step and ROCOF over 0.1 s.

What Moves It

The island is moved by setpoints and breakers. The genset's governor and the battery inverter take power setpoints, and the solar inverter takes a cap. Alternating-current power circuit breakers, device 52 in the IEEE C37.2 numbering, open and close the PCC, the sources and the feeders [20]. The

microgrid controller: 81, JY-100 and 25 every 20 ms, FIC-100 and the SOC manager every 1 s. Relays inside the genset and the inverters trip them apart from it.

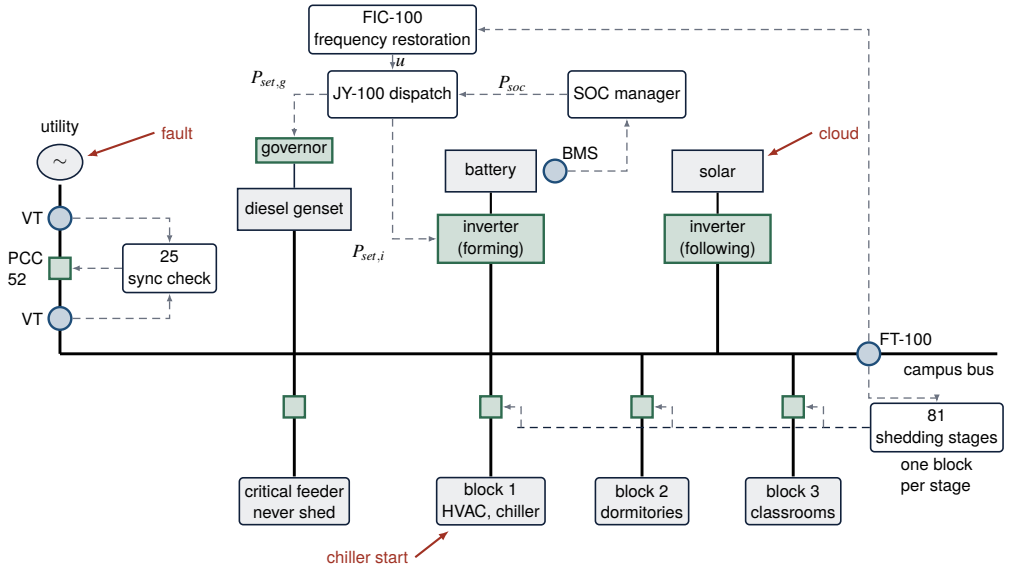


Figure 7.5 The campus's loops drawn with their hardware. The frequency meter FT-100 reads the bus voltage through a potential transformer. The frequency restoration FIC-100 sets the total u, the dispatch JY-100 splits it into the genset's setpoint, carried out by its governor, and the battery inverter's, with the share that the SOC manager asks from the battery management system's reading. The shedding stages 81 open one block breaker each on the same meter, and the sync check 25 compares the voltage transformers either side of the PCC breaker before it may close. Notice that one bus meter feeds both the slow restoration loop and the fast shedding stages.

fastest final element is the battery inverter itself, whose control law, not a moving part, decides the first swing.

> **TECHNOLOGY** **Final Element: The Grid-Forming Battery Inverter**
>
> The battery reaches the bus through an inverter, a power stage of semiconductor switches modulated by a digital controller. Run grid-forming, its terminals behave like a voltage source whose amplitude and frequency vary with its reactive power and with the load, so it adjusts its output nearly instantaneously [13]. Unlike a machine, it cannot give a large current for long. Its short-circuit current is normally held to 4 to 6 times rated for less than ten cycles, a limit set by the semiconductors, and then to less than twice rated [13]. Its behavior is set by firmware, which can change over its service life [13]. The chapter's inverter holds its current under 1.4 pu by raising a virtual impedance.

Where the Controller Runs

IEEE 2030.7 specifies a microgrid controller by the functions above the level of component control that let a microgrid manage itself, run on its own or connected to the grid, and connect to and disconnect from the distribution grid [21]. Supervisory and local control loops of this kind run at cycle times from milliseconds to minutes [22]. The chapter's controller scans every 20 ms for the shedding stages, the restoration sequence, the dispatch and the synchronizer, and every second for the frequency restoration, the SOC manager and the genset's start policy. The primary droops live in the devices, and the relays inside each device trip it apart from the controller, as Table 7.2 lists.

> **IN PRACTICE** **Closing Back Onto the Grid**
>
> Before a breaker joins two live systems, the voltages on its two sides are compared, by operators or by synchronizing relays, and the breaker is not closed until their difference is nearly zero. When the frequencies differ, the two voltages drift in and out of phase at the difference frequency, so a lamp across the open breaker brightens and dims at that rate [20]. Relays are known by the function numbers of IEEE C37.2: 25 is the synchronism check, 81 the under- and overfrequency and 81R the rate-of-change-of-frequency functions, 32 directional power, 27 undervoltage and 59 overvoltage, and technicians and engineers alike call relays by these numbers [20].

What Is Modernizing It

Three developments touch the loops of this chapter. Grid-forming control is expected to move from microgrids to bulk power systems in stages over roughly 10 to 30 years, once protection, controls and interoperability are researched and standards define what a grid-forming inverter must do [13]. Phasor measurement units time-stamp voltage phasors against a satellite clock with sub-microsecond uncertainty, so that angles across a grid can be compared at one instant, which helps to detect an island when breakers split a grid and its generators drift out of step [20]. Ethernet, Internet Protocol and wireless devices replacing older proprietary networks raise the likelihood of cybersecurity vulnerabilities and incidents in control systems [22], a concern for a controller that opens and closes a campus's breakers. The energy dispatch of Section 7.7 is a fourth development, and the chapter measures what it buys and what it costs.

7.9 Limitations

The model is one bus solved as phasors, so it cannot show the inverters' current-control transients in the first cycle after a breaker operates, a fault inside the campus, unbalance or harmonics, and a collapse that the model reports within a few steps may take several cycles on a real feeder. The genset is a classical machine with a timed start and a perfect synchronizer, the grid-forming inverter is one virtual synchronous machine with one current-limiting scheme, and the loads are static, with no motor dynamics or inrush. The relays act on an idealized meter with no filtering of their own, and the first swing's ROCOF depends on the meter's step, as Section 7.6 measured. The scripted days, a fault at 10:00 sharp and a cloud that halves the solar in exactly 10 s, would not arrive so cleanly on a real campus, although they let one layer at a time be seen.

> **OPEN CHALLENGE** **Protection When the Sources Are Inverters**
>
> Traditional protection relies on the high fault currents of synchronous generators, and inverters give much less. Whether grid-forming inverters in place of machines will make protection misoperate more often or less is an open question, and their effect on protection has not been studied extensively. Inverter makers provide no well-defined set of fault models and tests, and a firmware change can alter the fault current and invalidate a protection design [13]. The chapter models no fault inside the campus. Progress would be a consistent framework of models and tests for inverter fault behavior, and adaptive protection that knows which sources are online [13].

Every threshold in the simulator is a teaching value. The following inverters' trips and the ROCOF ride-through are the defaults that the application takes from the Category III settings of IEEE 1547-2018, the shedding stages at 59.3, 59.0 and 58.7 Hz after 0.2 s are patterned after bulk-system programs, and the sync-check window of 0.1 Hz, 10° and 5 % is close to what the application quotes as the standard's limits for a resource above 1.5 MVA, 0.1 Hz, 10° and 3 %. Real ride-through and trip settings come from IEEE 1547-2018 and the interconnection requirements of the utility [9], the design of an island system and its separation and reconnection from IEEE 1547.4 [17], the stages and the restoration of a shedding program from the guidance of IEEE C37.117 and the setting methods of the transmission literature [11, 12], synchronizing practice from the relaying literature [18], and

every number for a real campus from its own protection study. The battery's taper and allowance, the genset's trips and the challenge's targets are illustrative, and none of the numbers measures the performance of an installed microgrid.

OPEN CHALLENGE How Much Headroom Is Enough

With less inertia, the frequency falls faster after a disturbance and control must act sooner. The depth of the swing is tied to the imbalance, so untapped capacity must be held as headroom, in storage, spinning generators or renewable inverters run below their available power, and that unused capacity has an opportunity cost [13]. The same roadmap leaves open what reserves keep the frequency within bounds when grid-forming sources carry it, and what mix of machines and inverters guarantees stability [13]. This chapter prices headroom for one campus. Progress would be reserve rules for grids where inverters dominate.

7.10 Conclusion

An islanding campus needs a source that makes the voltage, and this chapter has measured what that source and each layer above it buy. A battery inverter that follows the grid leaves the bus dead 60 ms after the fault and costs the critical feeder 11.75 kWh, while the same battery forming the grid with 2 s of virtual inertia holds the island through a first swing of 2.48 Hz/s, under the solar's 3 Hz/s, and a nadir of 59.516 Hz. Virtual inertia sets the rate of a fall, while the droop and the headroom decide where it stops. The genset and the battery share a load in the ratio of their stiffnesses, 1.26 measured against 1.26 declared, the secondary returns the frequency to 60.000 Hz on the genset, and the SOC manager decides whether the battery or the diesel pays for the hours. Shedding saves the critical feeder where nothing else can, provided the battery's power-limit droop lets the relays hear the overload, and the sync check turns an 8.62 MVA close into a 0.327 MVA one. The two-hour challenge improves from 0.055 kWh of critical load lost and 13.4 s out of band to neither. The optional energy dispatch lowers the raw diesel only by leaving the battery emptier, and on the challenge its adjusted fuel loses to the rules.

The model is a single phasor bus with an idealized meter and teaching thresholds. A fuller model would add feeder impedances and faults inside the campus, a second grid-forming inverter, electromagnetic detail for the first cycle, and a dispatch that plans against a forecast of load and sun rather than on persistence. The simulator shows which source makes the grid when the utility is gone, and what every setting above that source costs.

KEY POINTS

- When the utility breaker opens, one of the island's own sources has to make the voltage that the others follow.
- A battery inverter that follows the grid leaves the bus dead 60 ms after the fault, while the same battery forming the grid with 2 s of virtual inertia holds the island through a first swing of 2.48 Hz/s.
- Virtual inertia sets the rate of a fall, while the droop and the headroom decide where it stops.
- Shedding saves the critical feeder where nothing else can, provided the battery's power-limit droop lets the relays hear the overload.

Where else this applies. Which loop owns a shared variable and how the other sources divide the load is also the question of the steam header of Volume 18, Chapter 9, and a governor on an islanded load runs Volume 1, Chapter 7.

References

[1] R. H. Lasseter, "MicroGrids," in *2002 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.02CH37309)*, vol. 1, New York, NY, USA, 2002, pp. 305–308.

[2] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, "Hierarchical control of droop-controlled AC and DC microgrids—a general approach toward standardization," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 158–172, 2011.

[3] D. E. Olivares, A. Mehrizi-Sani, A. H. Etemadi, C. A. Canizares, R. Iravani, M. Kazerani, A. H. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke, G. A. Jimenez-Estevez, and N. D. Hatziargyriou, "Trends in microgrid control," *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 1905–1919, 2014.

[4] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodríguez, "Control of power converters in AC microgrids," *IEEE Transactions on Power Electronics*, vol. 27, no. 11, pp. 4734–4749, 2012.

[5] M. C. Chandorkar, D. M. Divan, and R. Adapa, "Control of parallel connected inverters in standalone AC supply systems," *IEEE Transactions on Industry Applications*, vol. 29, no. 1, pp. 136–143, 1993.

[6] F. Katiraei, M. R. Iravani, and P. W. Lehn, "Micro-grid autonomous operation during and subsequent to islanding process," *IEEE Transactions on Power Delivery*, vol. 20, no. 1, pp. 248–257, 2005.

[7] R. H. Lasseter, Z. Chen, and D. Pattabiraman, "Grid-forming inverters: A critical asset for the power grid," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 2, pp. 925–935, 2020.

[8] Q.-C. Zhong and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, pp. 1259–1267, 2011.

[9] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, IEEE Std 1547-2018, 2018.

[10] P. Kundur, *Power System Stability and Control*, ser. The EPRI Power System Engineering Series. New York: McGraw-Hill, 1994.

[11] H. Lokay and V. Burtnyk, "Application of underfrequency relays for automatic load shedding," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-87, no. 3, pp. 776–783, 1968.

[12] *IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration*, IEEE Std C37.117-2007, 2007.

[13] Y. Lin, J. H. Eto, B. B. Johnson, J. D. Flicker, R. H. Lasseter, H. N. Villegas Pico, G.-S. Seo, B. J. Pierre, and A. Ellis, "Research roadmap on grid-forming inverters," National Renewable Energy Laboratory, Golden, CO, Technical Report NREL/TP-5D00-73476, 2020.

[14] H.-P. Beck and R. Hesse, "Virtual synchronous machine," in *2007 9th International Conference on Electrical Power Quality and Utilisation*, 2007, pp. 1–6.

[15] S. D'Arco and J. A. Suul, "Equivalence of virtual synchronous machines and frequency-droops for converter-based MicroGrids," *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 394–395, 2014.

[16] *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*, IEEE Std 1547-2003, 2003.

[17] *IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems*, IEEE Std 1547.4-2011, 2011.

[18] M. J. Thompson, "Fundamentals and advancements in generator synchronizing systems," in *2012 65th Annual Conference for Protective Relay Engineers*, 2012, pp. 203–214.

[19] ENTSO-E RG-CE System Protection & Dynamics Sub Group, "Frequency measurement requirements and usage," European Network of Transmission System Operators for Electricity, Brussels, Report Final Version 7, 2018. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/Regional_Groups_Continental_Europe/2018/TF_Freq_Meas_v7.pdf

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

[21] *IEEE Standard for the Specification of Microgrid Controllers*, IEEE Std 2030.7-2017, 2018.

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

7.11 Exercises

7.1 ⌕ Concept check · 2 min

In case 2 the battery inverter follows the grid. The PCC opens at 10:00 and the bus is dead 60 ms later. Which statement explains the collapse?

(a) No source on the island makes the voltage, so the bus voltage is the inverters' currents through the loads and each PLL chases an angle it turns itself

(b) The battery cannot add the 0.288 MW the campus was importing to its own output, so its current limit pulls the bus voltage down

(c) A PLL bandwidth of 2 Hz is too fast for an island, and at 0.5 Hz the PLLs would hold the bus until the genset closes

(d) The solar trips on its ROCOF relay at 20 ms, and the battery's island detection takes it off the bus with the solar

7.2 Concept check · 1 min

In case 4 the lone grid-forming battery takes three 0.2 MW load steps at virtual inertias of 0, 1.5 and 3 s. What does the virtual inertia change?

(a) The nadir, which rises by about 0.3 Hz from no inertia to 3 s

(b) The initial rate of change of frequency, while the fall stops at about the same depth

(c) The battery's headroom, which grows with the kinetic energy the inertia stands for

(d) The settled frequency, because the inertia adds to the stiffness of the droop

7.3 Concept check · 2 min

Why does the grid-forming inverter carry a power-limit droop m_{ov} in addition to its frequency droop m_p?

(a) To share the island's load with the genset in proportion to the battery's charge

(b) To hold the inverter's current under its hardware limit of 1.4 pu through a fault

(c) To turn an overdraw of the battery into a falling frequency that the shedding relays can see

(d) To slow the first swing after islanding so that the solar rides through its ROCOF limit

7.4 Theory and calculation · 6 min

The battery inverter forms the grid with $S_i = 1\,\text{MW}$, $f_0 = 60\,\text{Hz}$ and a droop $m_p = 3\,\%$. In case 3 it takes over an import of $\Delta P = 0.3293\,\text{MW}$ when the PCC opens.

(a) Use Equation (7.9) to compute the initial ROCOF at $H_v = 2$ and $H_v = 1.5\,\text{s}$. *Checkpoint:* 4.94 and 6.59 Hz/s.

(b) What virtual inertia would hold the bound at the 3.0 Hz/s the solar rides through? Compare it with the slider's range, and give two reasons from the chapter why the relay's reading at 2 s, 2.48 Hz/s, is smaller than the bound. *Checkpoint:* 3.29 s, beyond the 3 s top of the slider.

(c) With the battery alone on the bus, compute the time constant of Equation (7.10) at $H_v = 2\,\text{s}$ and the settled deviation after a 0.2 MW load step on the droop alone. Which of the two depends on H_v? *Checkpoint:* 120 ms and 0.36 Hz. Only the time constant.

7.5 Theory and calculation · 6 min

The genset has $S_g = 2\,\text{MW}$ and the rotor damping $D = 1.0\,\text{pu/pu}$, and the battery inverter has $S_i = 1\,\text{MW}$ on a droop $m_p = 3\,\%$. Both act on one frequency, with the secondary loop in Manual.

(a) Compute the stiffnesses $K_g = S_g/R + DS_g$ and $K_i = S_i/m_p$, in megawatts per unit of speed, and their ratio at a governor droop $R = 5\,\%$. *Checkpoint:* 42 MW, 33.3 MW and 1.26.

(b) Repeat for $R = 3\,\%$. *Checkpoint:* 68.7 MW and a ratio of 2.06.

(c) In case 5 the chiller makes the genset take 0.205 MW more and the battery 0.163 MW more at $R = 5\,\%$, and 0.251 MW and 0.122 MW at 3 %. Use Equation (7.11) to compute the frequency fall in each case, to the nearest millihertz. *Checkpoint:* 0.293 Hz and 0.219 Hz.

7.6 Theory and calculation · 6 min

Case 8 runs a 90 min island with the genset online. With the SOC manager off, the battery falls from 50.0 to 9.1 % and the run burns 399 L. With the manager on, the battery stays at 50.0 % and the run burns 560 L. The battery holds $E_{cap} = 2\,\text{MWh}$ with a round trip $\eta^2 = 92\,\%$, and the engine burns $q_0 = 110\,\text{L/h}$ running plus $q_1 = 0.205\,\text{L/kWh}$.

(a) Compute the DC energy drawn from the battery in the first run and the AC energy it delivered, using Equation (7.7). *Checkpoint:* 0.818 MWh DC and 0.785 MWh AC.

(b) How much diesel would the genset burn to make that AC energy at its marginal rate? Compare it with the difference between the two runs. *Checkpoint:* 161 L, equal to 560 − 399.

(c) With the manager on, the genset carries 1.28 to 1.30 MW for the 1.5 h. Estimate the run's diesel from the fuel line and compare it with the 560 L measured. *Checkpoint:* 559 to 565 L.

7.7 App challenge · 9 min

Load scenario 3, The fault with a grid-forming inverter. The model has no random input, so every run repeats exactly. Run each part at 5× past 10:00:05 ($t = 65\,\text{s}$, about 13 s of wall time) and read the Nadir · worst ROCOF tile and the Load shed tile.

(a) Run as shipped, with $H_v = 2.0\,\text{s}$. *Checkpoint:* 59.516 Hz, 2.48 Hz/s, 0 stage trips.

(b) Press Reset, set the Virtual inertia to 1.0 s on the VSM card before pressing Run, and run again. What happened to the solar, and why did all three stages shed? *Checkpoint:* 58.226 Hz, 5.83 Hz/s, 3 stage trips.

(c) Find the smallest virtual inertia on the slider's 0.1 s grid at which the solar still rides through, pressing Reset and setting the value before each run. State the tile readings at that setting and one step below. *Checkpoint:* 1.3 s rides through at 2.97 Hz/s, and 1.2 s reads 5.52 Hz/s and sheds three stages.

7.8 App challenge · 8 min

Load scenario 5, The genset starts: battery alone, then droop sharing. The frequency loop and the SOC loop are in Manual. Run to the end, 240 s, at 20× (12 s of wall time) and export the CSV file.

(a) From the columns `P_gen_MW`, `P_bat_MW` and `f_Hz`, read the row at `time_s` 180 and the last row. Compute each source's change, the ratio of the changes and the frequency fall, to within 0.002 MW, 0.01 and 0.002 Hz. *Checkpoint:* 0.205 MW and 0.163 MW, a ratio of 1.26, a fall of 0.294 Hz.

(b) Press Reset, set the Governor droop to 3 % on the GEN card before pressing Run, and repeat. *Checkpoint:* 0.251 MW and 0.122 MW, a ratio of 2.06, a fall of 0.219 Hz.

(c) Compare both with your answers to Exercise 7.5, and say why the frequency stays low after the chiller. *Checkpoint:* The droops share the change and nothing moves a setpoint.

7.9 App challenge · 9 min

Load scenario 7, Load shedding: a step the sources cannot meet. Run each part to the end, 240 s, at 20× (12 s of wall time).

(a) Run as shipped and read the Critical load unserved, Load shed and Nadir · worst ROCOF tiles. *Checkpoint:* 0.0 kWh, 22 kWh with 1 stage trip, 59.182 Hz.

(b) Press Reset, turn the Under-frequency load shedding off on the UFLS card before pressing Run, and run again. Read the Critical load unserved tile, and from the CSV file the `time_s` of the first row whose `status` reads BLACKOUT, within 0.5 s. *Checkpoint:* 17.2 kWh and 38.5 s.

(c) Reload the scenario with the reload button beside the scenario list, so the shedding is armed again, open Show Model, set the Power-limit droop to 0.02 and run once more. Read the same tile, the Load shed tile, and `f_Hz` in the rows from 33 to 36 s. Explain why no stage shed. *Checkpoint:* 17.6 kWh, 0 stage trips, `f_Hz` 59.509 to 59.511.

7.10 Application area · 3 min

Two voltages of 1 pu that differ in phase by $\Delta\varphi$ put $2\sin(\Delta\varphi/2)$ per unit across an open breaker.

(a) Compute it at the edge of the sync-check window, 10°, and at the 153.9° of case 10 when the utility returns. *Checkpoint:* 0.174 pu and 1.95 pu.

(b) The synchronizer aims the island 0.05 Hz above the utility rather than at it. Why must the slip be nonzero, and how long does the needle take to turn once? *Checkpoint:* With no slip the phase difference never moves into the window. 20 s.

7.11 Application area · 4 min

A commissioning engineer runs case 3 on the app, finds that the solar rides through at a virtual inertia of 1.3 s, and proposes 1.3 s for the real campus to leave more of the battery's headroom for load.

(a) Using the chapter's results on the step and the meter, say why 1.3 s is not a safe setting and what margin the 2 s default keeps. *Checkpoint:* The resolved cliff lies between 1.6 and 1.7 s. 2 s stays under the ride-through at every step.

(b) Name two effects the model leaves out, from its Assumptions and Limitations, that would make the first swing harder on the real campus. *Checkpoint:* For example motor inrush and the first cycle of current control.

7.12 Review the agent · 5 min

An AI assistant compares the two energy dispatches on the challenge with the suggested settings and replies as follows. "With Energy dispatch on MPC the campus burns 550.64 L against 585.31 L under Rules, a saving of 34.67 L, with no critical load lost and no time out of band. The one-hour forecast earns the saving, so the campus should run MPC." The runs end at 51.38 and 70.32 % of charge. Find the flaw and say how you would check it.