LESSON BOOK



Battery Energy Storage Systems

From one cell to what a telemetry record can and cannot determine

Nine lessons · 181 pages

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Battery Energy Storage Systems

From one cell to what a telemetry record can and cannot determine

A nine-lesson tutorial, written up as a book

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How to read this book

This book assumes no prior knowledge of batteries. Each chapter expands one lesson of a tutorial that starts from a single lithium-ion cell and ends at the question an engineer must answer before fitting any model to field data: given the sensors installed, what can actually be known? The progression is

$$\text{the machine} \to \text{electrical quantities} \to \text{the cell} \to \text{the circuit model} \to \text{the hardware} \to \text{heat} \to \text{aging} \to \text{faults} \to \text{information}.$$

One system is used as the running example throughout. The *reference container* is a grid-scale lithium iron phosphate battery of 3,564 cells arranged as nine racks of 396 cells, storing about 3.42 MWh, and the *reference record* is its field telemetry: rack currents and voltages, a reported state of charge, 396 cell voltages and 216 temperatures per rack. Every number attributed to the reference container or its record is a property of that system and is used here to make the general ideas concrete; numbers introduced only to illustrate an equation are labeled illustrative.

Where the field uses a shorthand term, a *Jargon* box expands it once and the text then uses the expanded meaning. Every symbol is defined in the notation chapter that follows and is used with the same meaning in every chapter. Each chapter closes with a statement of what to retain, exercises, and a short section connecting the chapter to the TERRA framework, a graph-based way of modeling physical systems as conservation laws on nodes with flows on edges, in which the question of what a set of measurements can determine is asked before any parameter is estimated.

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Notation and vocabulary

Every symbol below is used with the same meaning in every chapter. Current is positive on discharge and negative on charge throughout.

Symbol	Unit	Meaning
V	V	Terminal voltage: the voltage measured across a cell, rack or bus while it operates.
$U(\mathrm{SOC})$	V	Open-circuit voltage: the voltage of a rested cell with no current, a function of state of charge.
I	A	Current; positive on discharge, negative on charge.
$P = V\,I$	W	Electrical power, the rate of energy transfer.
Q	Ah	Electric charge moved or stored; $Q = \int I \,\mathrm{d}t$.
C	Ah	Charge capacity of a cell or a series string.
E	Wh	Energy; $E = \int P \,\mathrm{d}t$, nominally $E \approx V\,C$.
C-rate	h^{-1}	Current divided by capacity, I/C.
SOC	–	State of charge: charge remaining divided by available capacity. An estimate, not a sensor reading.
C_{assumed}	Ah	The capacity a battery management system divides by when it computes state of charge.
$\mathrm{SOC}_{\mathrm{BMS}}$	–	The state of charge a battery management system reports.
I_{side}	A	Lumped unmeasured side current of a rack: balancing, self-discharge and controller consumption.
R	Ω	Lumped internal resistance of a cell.
R_0	Ω	Ohmic resistance: the instantaneous part of the voltage drop.
R_1, C_1	Ω, F	Resistance and capacitance of the polarization branch; time constant $\tau = R_1 C_1$.
V_1	V	Polarization voltage: the slow, history-dependent part of the voltage drop.
V_{cell}, V_i	V	Voltage of one cell; V_i is cell i of a string.
V_{rack}, V_r	V	Terminal voltage of a rack; V_r is rack r.
V_{bus}, I_{bus}	V, A	Voltage and total current of the common DC bus.
R_{series}	Ω	Lumped resistance of the connection hardware between the cell string and the rack terminals.
V_{off}	V	Constant offset between two voltage measurements of the same quantity.
R_{shunt}	Ω	Resistance of a current shunt.
P_{heat}	W	Heat generated by resistive loss, I^2R.
T, T_{env}, T_{ref}	K	Temperature of the battery, of its surroundings, and a reference temperature.
C_{th}	J/K	Thermal capacitance.

Symbol	Unit	Meaning
h	W/K	Effective cooling conductance.
k, q_0	W/A^2, W	Lumped heating coefficient and steady unaccounted heat term of the rack thermal balance.
SOH	–	State of health; here most often the capacity ratio C/C_{new}.
SOP	W	State of power: the power that can safely be delivered now.
RUL	time	Remaining useful life: a forecast of the time to an end-of-life criterion.
DoD	–	Depth of discharge: the state-of-charge swing of a cycle.
N_{EFC}	–	Number of equivalent full cycles: total charge discharged divided by capacity.
r	varies	Residual: measured value minus the value a model predicts.
H_0, H_i	–	The normal hypothesis and a fault hypothesis.
θ	varies	Vector of unknown model parameters.

Vocabulary

Cell, module, rack, container The physical hierarchy: a cell is one electrochemical unit; a module is a mechanical group of cells; a rack is a series string of modules; a container holds racks in parallel.

BESS Battery energy storage system: the battery, its management and protection hardware, its cooling and its power conversion system.

BMS Battery management system: the supervisory system that measures, estimates, protects and balances.

PCS Power conversion system: the inverter that connects the DC battery to the AC grid.

LFP Lithium iron phosphate, the cell chemistry of the reference container.

Coulomb counting Estimating state of charge by integrating measured current and dividing by an assumed capacity.

Reference container, reference record The running example of this book and its telemetry, described in “How to read this book”.

Chapter 1

What a battery energy storage system is: cells, series strings, parallel racks and the container

1.1 The machine and its purpose

This book assumes no background in batteries, and so it does not begin with a battery model. It begins with the machine: what is physically inside a grid-scale battery, where its energy goes, what its voltages and currents mean, and why thousands of small cells are arranged the way they are. The running example is the reference container, a grid-scale lithium-ion battery of 3,564 cells arranged in nine racks and storing about 3.42 MWh. Its telemetry, the reference record, contains rack currents and rack voltages, the voltage of every cell, temperatures, the outputs of a battery management system and the operation of a grid inverter. Each of those channels is a measurement taken somewhere in the machine described in this chapter, and none of them can be interpreted until the machine is understood. The question of the chapter is

what a battery energy storage system is physically, and how 3,564 *cells of about 3.2 volts each become one machine that exchanges megawatts with the grid.*

Jargon: BESS, PCS, BMS, cell, module, rack, container, series, parallel, SOC

A *battery energy storage system* (BESS) is a machine that takes electrical energy from the grid, stores it chemically in battery cells and returns it to the grid later; the term covers the cells, their management and protection hardware, their cooling and their power conversion system. The *power conversion system* (PCS), commonly called the *inverter*, converts between the direct current (DC) of the battery and the alternating current (AC) of the grid, and sets how much power flows in or out. The *battery management system* (BMS) is the computer and sensor network that measures the battery, estimates its state, enforces its limits and opens or closes its switches. A *cell* is the smallest electrochemical unit: a sealed device with two terminals and a voltage of a few volts. A *module* is a mechanical group of cells, 44 in the reference container. A *rack* is a string of modules connected end to end, here nine modules or 396 cells. A *container* is the enclosure that holds several racks, here nine, together with their cooling and protection. Components are in *series* when they are connected end to end, so that the same current passes through each of them; they are in *parallel* when they are connected across the same two conductors, so that they share the same voltage. The *state of charge* (SOC) is the fraction of the usable charge that remains, from 0 to 100 %.

Key idea

A battery energy storage system is a very large number of low-voltage cells, connected in series to reach a usable voltage and in parallel to reach a usable current and energy, together with a converter that exchanges that energy with the AC grid and a supervisory system that keeps every cell within its limits. Every channel of the reference record is a voltage, a current or a temperature somewhere in that arrangement, or a number computed from them.

This section describes the machine at its coarsest level: its three blocks and its two modes of operation.

1.1.1 Grid, power conversion system and battery

At the coarsest level a BESS is three blocks in a chain,

$$\text{grid} \overset{\text{AC}}{\longleftrightarrow} \text{PCS} \overset{\text{DC}}{\longleftrightarrow} \text{battery system},$$

and Figure 1.1 draws it. The three boxes are, from left to right, the AC grid, the power conversion system and the battery system. The short double-headed arrows between them are the two electrical connections, labeled with the kind of current each carries. The long blue arrow above the chain is the path of energy during charging and the long green arrow below it the path during discharging. The dashed box at the bottom lists the supporting systems, which act on the battery and on the converter but do not carry the main energy flow.

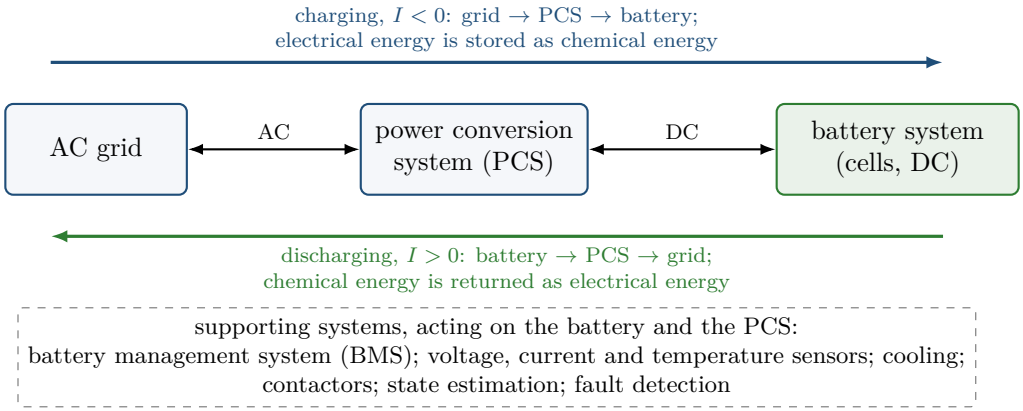


Figure 1.1: The three blocks of a battery energy storage system and the two directions of energy flow. The battery is a DC device and the grid an AC system; the power conversion system sits between them and carries energy in either direction. Current I is measured on the DC side and is positive on discharge.

The battery stores energy chemically and delivers it as *direct current*: current that flows in one direction at a time, between terminals whose polarity does not change. The grid is an *alternating current* system: its voltage and current reverse direction 50 or 60 times per second. The two cannot be connected directly. The power conversion system is the power-electronic device between them; it switches semiconductor devices thousands of times per second to synthesize the grid's alternating waveform from the battery's direct voltage, or to rectify the grid's waveform into a direct current that charges the battery. Because it controls that switching, the PCS also decides how much power flows and in which direction: the battery does not push energy into the grid on its own, the converter draws it. Section 1.6.4 returns to the PCS once the battery side of the chain has been built up.

1.1.2 Charging and discharging as energy conversion

A BESS has two modes of operation, and each is an energy conversion. In *charging*, energy flows from the grid through the PCS into the battery,

$$\text{grid} \rightarrow \text{PCS} \rightarrow \text{battery}: \qquad \text{electrical energy} \rightarrow \text{chemical energy},$$

and the chemical reactions inside every cell are driven in the direction that stores energy. In *discharging* the flow reverses,

$$\text{battery} \rightarrow \text{PCS} \rightarrow \text{grid}: \qquad \text{chemical energy} \rightarrow \text{electrical energy},$$

and the reactions run in the direction that releases the stored energy as a current through the external circuit. Neither conversion is lossless. Part of the energy in transit becomes heat in the cells, in the conductors and in the converter, so the energy returned to the grid in a full cycle is less than the energy taken from it. The losses are small enough that the round trip is worthwhile and large enough that they heat the battery, which Section 1.6.3 takes up.

The two modes are told apart by the sign of the current. Throughout this book the current I on the DC side is positive on discharge and negative on charge, so a rack current of $+100\,\text{A}$ means the rack is discharging and a rack current of $-100\,\text{A}$ means it is charging. The electrical power delivered by the battery, $P = VI$, follows the same sign: positive when the battery supplies the grid, negative when the grid supplies the battery.

Everything else in a BESS exists to make this conversion safe, controllable, measurable and reliable:

Battery management system measures the cells and the racks, estimates quantities that cannot be measured directly, and stops operation when a limit is reached (safe, measurable).

Sensors for voltage, current and temperature supply every number the BMS and the operator see (measurable).

Cooling removes the heat generated by the losses and keeps the cells inside their temperature range (safe, reliable).

Contactors are heavy-duty switches, operated by the BMS, that connect each rack to the rest of the system or isolate it (safe, controllable).

State estimation computes quantities such as the state of charge that no sensor reads (controllable, measurable).

Fault detection looks for cells, sensors or connections that depart from normal behavior before they cause damage (reliable).

The rest of this chapter builds the battery side of Figure 1.1 from its smallest unit upward, and then returns to these supporting systems.

1.2 One cell and its energy

The cell is the unit from which the whole machine is built. This section describes it as a two-terminal device, derives its stored energy from its voltage and its capacity, separates energy from power, and shows why a single cell cannot serve the grid.

1.2.1 The cell as a two-terminal device

A cell has two terminals, a positive one (+) and a negative one (−), and a voltage between them. The reference container uses lithium iron phosphate (LFP) cells with a nominal voltage

of $V_{\text{cell}} \approx 3.2\,\text{V}$ and a charge capacity of $C \approx 300\,\text{Ah}$. *Nominal* means a representative value: the actual voltage of a cell changes with how full it is, with the current flowing through it and with its temperature, and the chapters on the cell and on its circuit model describe those changes. The *capacity* is the amount of electric charge the cell delivers between full and empty under defined conditions, measured in ampere-hours: 300 Ah means, in the ideal case, 300 A for one hour, 100 A for three hours or 30 A for ten hours.

Figure 1.2 draws the cell beside a water-tank analogy. On the left is one prismatic cell with its two terminals on top and the voltage V_{cell} between them; its capacity and energy are written beneath it. On the right is an open water tank with an outlet near the bottom. The labels map each part of the tank onto an electrical quantity: the height of the water, which sets the pressure at the outlet, corresponds to the voltage; the size of the tank corresponds to the capacity; the water stored corresponds to the stored charge; and the flow rate through the outlet corresponds to the current.

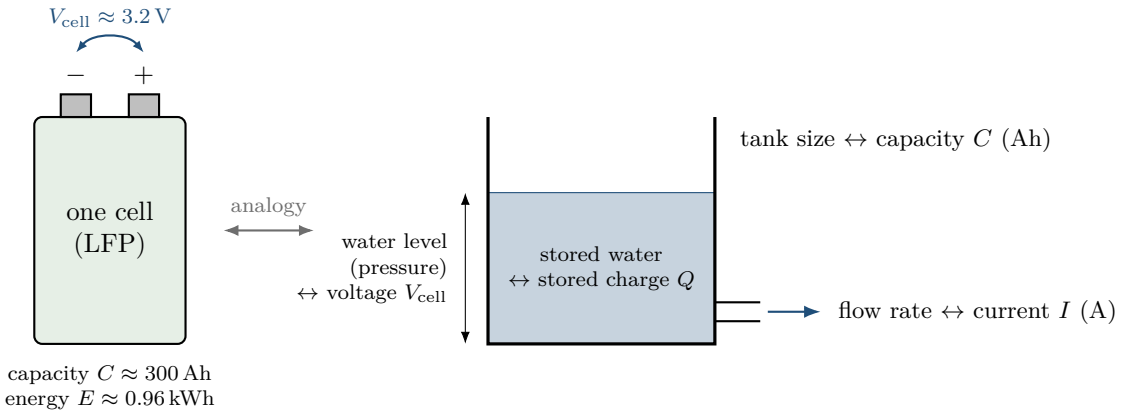


Figure 1.2: One cell as a two-terminal device (left) and the water-tank analogy (right). The nominal values are those of the reference container's cells. The analogy is imperfect: in a tank the pressure falls steadily as the tank drains, whereas the voltage of an LFP cell stays nearly constant over most of its range.

The analogy is useful because it separates two ideas that are easy to confuse. Voltage is a kind of electrical pressure: it is the energy each unit of charge carries, and it determines how hard the cell pushes charge through an external circuit. Capacity is the size of the electrical tank: it says how much charge the cell can move before it is empty. A cell with a high voltage and a small capacity pushes hard for a short time; a cell with a low voltage and a large capacity pushes gently for a long time. The analogy is also imperfect, and the imperfection matters later. In a water tank the pressure at the outlet falls in proportion to the level, so reading the pressure tells how full the tank is. In an LFP cell the voltage stays nearly flat over most of the range between full and empty, so the voltage says little about how full the cell is; the chapter on the cell develops this.

1.2.2 Energy as voltage times capacity

Electrical power is the product of voltage and current, $P = VI$, and energy is power accumulated over time,

$$E = \int P\,\mathrm{d}t = \int V\,I\,\mathrm{d}t. \tag{1.1}$$

If the voltage is held at a constant value V, it comes out of the integral, and the remaining integral of current over time is the charge moved, $\int I\,\mathrm{d}t = Q$. Over a full discharge the charge

moved is the capacity, so the energy stored in a cell is approximately

$$E \approx V\,C. \tag{1.2}$$

The units confirm it: volts times ampere-hours is $\mathrm{V} \cdot \mathrm{A} \cdot \mathrm{h} = \mathrm{W} \cdot \mathrm{h}$, a watt-hour. For one cell of the reference container,

$$E = 3.2\,\mathrm{V} \times 300\,\mathrm{Ah} = 960\,\mathrm{Wh} \approx 0.96\,\mathrm{kWh}.$$

That is about one kilowatt for about one hour. Delivering 1 kW at 3.2 V takes a current of $1000/3.2 \approx 312$ A, which is close to the current that empties a 300 Ah cell in one hour, so the two statements agree. Equation (1.2) ignores two things. The voltage is not exactly constant during a discharge, so the integral in equation (1.1) is the exact statement and $V\,C$ the nominal one; and part of the energy is lost as heat inside the cell, so less than 960 Wh reaches the terminals at high current. It also ignores limits: whether the cell may in fact be discharged at 312 A is set by the manufacturer and enforced by the BMS.

1.2.3 Power and energy

Power and energy are different quantities, and a battery has a limit on each. Power, in kilowatts (kW) or megawatts (MW), is how fast energy moves. Energy, in kilowatt-hours (kWh) or megawatt-hours (MWh), is how much is available. In the water-tank picture, energy is the water in the tank and power is the flow rate through the outlet. They are linked by time: at a constant power P held for a duration t, the energy delivered is

$$E = P\,t. \tag{1.3}$$

A battery that stores 4 MWh can therefore provide 1 MW for four hours, 2 MW for two hours or 4 MW for one hour, as Table 1.1 lists; the product is the same in each row. Which of these it can actually do depends on its power limit, set by the rating of the PCS and by the current the cells tolerate, which is a separate number from its energy. A statement of a battery's size is therefore incomplete unless it gives both: megawatts for how fast and megawatt-hours for how much.

Table 1.1: Ways of delivering the energy of an illustrative 4 MWh battery, equation (1.3), ignoring losses and limits.

Power P	Duration t	Energy $E = P\,t$
0.5 MW	8 h	4 MWh
1 MW	4 h	4 MWh
2 MW	2 h	4 MWh
4 MW	1 h	4 MWh

1.2.4 Why one cell is not enough

A single cell is far too small for the grid in both voltage and energy. Consider voltage first. A power conversion system connected to a medium-voltage grid works with a DC voltage of the order of a thousand volts. At 3.2 V, the current needed to deliver 1.3 MW would be

$$I = \frac{P}{V} = \frac{1.3 \times 10^{6}\,\mathrm{W}}{3.2\,\mathrm{V}} \approx 406{,}000\,\mathrm{A},$$

a current no practical conductor or converter carries. Raising the voltage lowers the current needed for the same power, and the losses in the conductors scale with the square of the current (the heat I^2R of Section 1.6.3), so a high voltage is not a convenience but a necessity.

Energy is the second shortfall. One cell stores about 0.96 kWh; a container that stores 3.42 MWh needs

$$\frac{3{,}420\,\text{kWh}}{0.96\,\text{kWh}} \approx 3{,}560$$

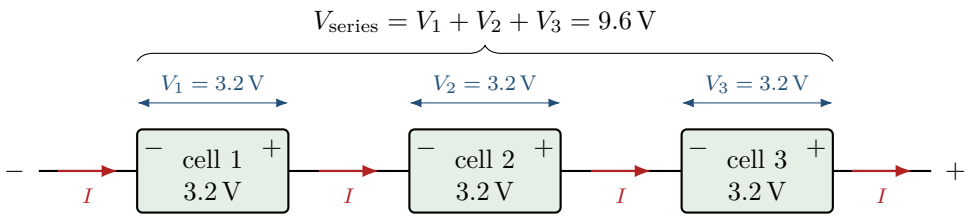
cells. Cells must therefore be connected together, and there are two ways of doing it. Connecting them in series and connecting them in parallel have different effects on voltage, current and capacity, and the arrangement of the reference container uses both. The next two sections take them in turn.

1.3 Series strings and the rack

Connecting cells end to end is how a battery reaches a voltage the power conversion system can use. This section states the two rules of a series connection and applies them to the rack of the reference container.

1.3.1 Voltages add in series

In a series connection the positive terminal of one cell is joined to the negative terminal of the next. Figure 1.3 shows three cells connected this way. Each box is a cell with its negative terminal on the left and its positive terminal on the right; the short blue arrow above each cell is that cell's voltage V_i, and the brace above all three is the voltage across the whole chain. The red arrows on the wires are the current, drawn in the direction it flows during discharge.



the same current I enters and leaves every cell:
if $I = 100\,\text{A}$ at the terminals, each of the three cells carries 100 A

Figure 1.3: Three cells in series during discharge. The voltages add; the current is common to all three cells.

The voltages add. Three cells of 3.2 V in series give

$$3.2\,\text{V} + 3.2\,\text{V} + 3.2\,\text{V} = 9.6\,\text{V},$$

and in general a string of N cells in series has the voltage

$$V_{\text{series}} = \sum_{i=1}^{N} V_i. \tag{1.4}$$

The reason is that voltage is energy per unit charge. A unit of charge that passes through the whole string passes through every cell in turn, and each cell adds its own energy to it, so the energy per unit charge across the string is the sum of the energies per unit charge across the cells. The same statement in circuit language is Kirchhoff's voltage law: around any closed path, the voltages sum to zero, so the voltage between the two ends of the string equals the sum of the voltages between the intermediate junctions. Equation (1.4) holds for unequal cells as well: if one cell sits at 3.1 V and the others at 3.2 V, the string voltage is 9.5 V.

1.3.2 The common current

The second rule of a series connection is that the same current flows through every cell. In Figure 1.3 there is only one path for charge: whatever enters cell 1 at its negative terminal leaves it at its positive terminal, enters cell 2, and so on. Charge does not accumulate at the junction between two cells, because charge is conserved and the junction stores none, so the current leaving one cell equals the current entering the next. If the current at the terminals of a rack is 100 A, then every cell in that rack carries 100 A. The current is not divided by the number of cells in series: it is not 100/3 in a string of three nor 100/396 in a string of 396.

An analogy is a line of runners roped together at the waist. Whatever the speed of the line, every runner moves at that speed; adding runners to the line does not make each of them slower or faster. The rope also makes the line only as fast as its slowest runner, and a series string has the corresponding property: because every cell carries the same current, the string must stop discharging when any one cell reaches its lower limit, whatever the state of the others. Section 1.6.2 returns to that consequence.

The common current has a second consequence that runs through the whole book. A single current sensor at the end of a string measures the current of every cell in the string. One measured number drives the charge balance of hundreds of cells at once, which makes the current measurement the most consequential sensor in the battery.

1.3.3 The rack of the reference container

The rack of the reference container applies these two rules at scale. Each module holds 44 cells and each rack holds nine modules, so a rack holds

$$44 \times 9 = 396$$

cells, all connected in series. The module is a mechanical and electrical grouping for assembly and maintenance; electrically the rack is one string of 396 cells. Figure 1.4 draws it. The nine rounded boxes are the modules, numbered along the string; the small green rectangles and the dots inside each module stand for its 44 cells; the short wires between modules join the positive end of one module to the negative end of the next; and the two leads at the ends are the rack's terminals, with the rack current I entering at the left. The brace over the first module gives the module's numbers and the brace under the whole row gives the rack's.

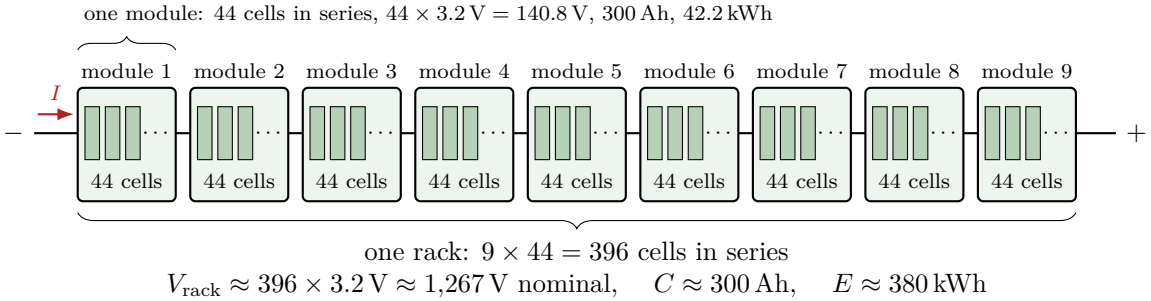


Figure 1.4: One rack of the reference container: nine modules of 44 cells, all 396 cells in one series string. The rack current I passes through every cell; the rack voltage is the sum of the 396 cell voltages.

By equation (1.4), a module has a nominal voltage of $44 \times 3.2 = 140.8$ V and the rack a nominal voltage of

$$V_{\text{rack}} \approx 396 \times 3.2\,\text{V} \approx 1{,}267\,\text{V}. \tag{1.5}$$

The rack voltages measured in the reference record lie between about 1,250 V and 1,350 V. Dividing by 396, that range corresponds to an average cell voltage between $1{,}250/396 \approx 3.16$ V

and 1,350/396 ≈ 3.41 V; the variation comes from the state of charge and from the current, both described in later chapters. What is sold or described as a "1,300 V battery" is therefore 396 small cells of about 3.2 V stacked in series.

1.3.4 Capacity and energy of the rack

A series connection increases the voltage but not the charge capacity. Every cell in the string carries the same current for the same length of time, so every cell passes the same charge. When 300 Ah has flowed through the rack terminals, 300 Ah has flowed through each of the 396 cells, and each of them is empty. The capacity of the string is therefore the capacity of one cell,

$$C_{\text{rack}} = C_{\text{cell}} \approx 300\,\text{Ah},$$

for identical cells. If the cells differ, the string's usable capacity is set by the cell that empties first, which is the property of the roped runners in Section 1.3.2. The energy of the rack follows from equation (1.2) with the rack voltage,

$$E_{\text{rack}} \approx V_{\text{rack}}\, C \approx 1{,}267\,\text{V} \times 300\,\text{Ah} \approx 380{,}000\,\text{Wh} \approx 380\,\text{kWh}. \tag{1.6}$$

The same number comes from the cells: $396 \times 960\,\text{Wh} = 380{,}160\,\text{Wh}$. The two routes agree because series connection adds energy as well as voltage: each cell contributes its own 960 Wh, and the string merely delivers them all at a higher voltage through the same 300 Ah of charge. Series connection thus multiplies the voltage and the energy by the number of cells and leaves the capacity in ampere-hours unchanged.

1.4 Parallel racks and the container

A rack has the voltage the converter needs but only a ninth of the container's energy. This section connects nine racks in parallel, states the rules of a parallel connection beside those of a series one, and assembles the whole container.

1.4.1 Racks in parallel on a common DC bus

The nine racks of the reference container are connected in parallel to a common *DC bus*, a pair of heavy conductors to which every rack and the PCS connect. In a parallel connection every rack is connected across the same two conductors, so every rack has the same voltage, and the currents of the racks add.

Figure 1.5 draws the arrangement. The thick blue line at the top is the positive conductor of the DC bus (the return conductor is not drawn); the nine green boxes below it are the racks, each a string of 396 cells; and the vertical line from each rack to the bus carries that rack's current I_r, drawn as a red arrow in the direction of discharge. On the right the bus enters the PCS, and the red arrow on the bus is the total current I_{bus}. The note beneath the racks states the two rules. In this section the subscript of V and I indexes racks, $r = 1, \ldots, 9$.

The two rules are

$$V_1 \approx V_2 \approx \cdots \approx V_9 \approx V_{\text{bus}}, \qquad I_{\text{bus}} = I_1 + I_2 + \cdots + I_9 = \sum_{r=1}^{9} I_r. \tag{1.7}$$

The current rule is conservation of charge at the bus: the bus stores no charge, so the current leaving it toward the PCS equals the sum of the currents arriving from the racks. This is Kirchhoff's current law. The voltage rule is approximate because each rack reaches the bus through its own cables, fuses and contactors, which have a small resistance; the voltage at a rack's terminals differs from the bus voltage by the product of that resistance and the rack's

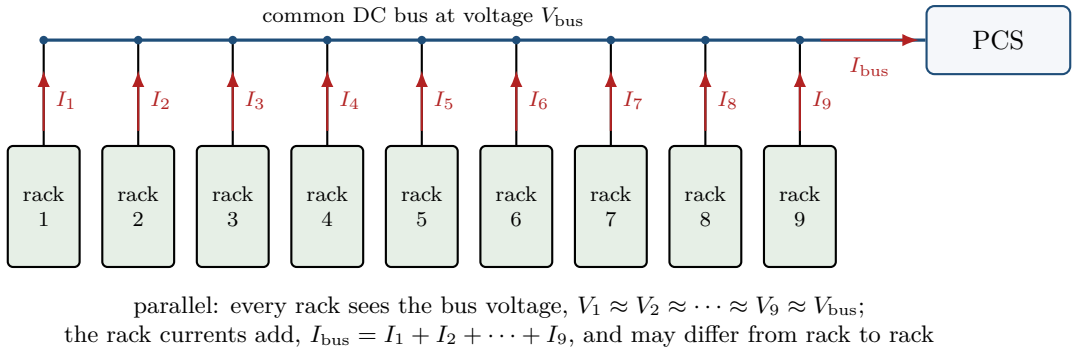


Figure 1.5: The nine racks of the reference container in parallel on a common DC bus, during discharge. Each rack is a series string of 396 cells; the bus current into the PCS is the sum of the rack currents.

current, a fraction of a volt to a few volts. The rack currents need not be equal. A rack whose cells are at a slightly different state of charge, or whose internal resistance is slightly higher, settles at a different current while sharing the common voltage. If the bus current is 900 A and the racks were identical, each would carry 100 A; in practice the nine currents spread around that value, for instance between 95 and 105 A (illustrative), and that spread is itself informative about the racks.

Capacity adds in parallel. Each rack supplies its own part of the bus current and drains its own 300 Ah, so nine racks in parallel can supply

$$9 \times 300\,\text{Ah} = 2{,}700\,\text{Ah}$$

to the bus, at the rack voltage. The voltage does not increase: the container has the voltage of one rack.

1.4.2 Series and parallel compared

Table 1.2 sets the two kinds of connection side by side. Each row is one electrical quantity; the two middle columns say what happens to that quantity when N identical units are connected in series or in parallel, and the last column gives the reference container's instance of each.

Table 1.2: Series and parallel connection of N identical units.

Quantity	Series	Parallel	Reference container
Voltage	adds: $N\,V$	same: V	396 cells in series give $\approx$ 1,267 V; nine racks in parallel stay at that voltage
Current	same through every unit	adds: $\sum I$	100 A in a rack is 100 A in each of its cells; the bus current is the sum of nine rack currents
Capacity (Ah)	same: C	adds: $N\,C$	a rack has 300 Ah; the container 2,700 Ah
Energy (Wh)	adds: $N\,E$	adds: $N\,E$	380 kWh per rack; 3.42 MWh per container

The table is worth memorizing, because most of the reasoning about measurements in the later chapters starts from it. A cell voltage is one term of a sum; a rack current is the current

of 396 cells; a bus current is a sum of nine rack currents; and only energy adds under both connections.

Principle 1.1. *In series, voltages add and the current is common; in parallel, currents and capacities add and the voltage is common. Energy adds in both.*

1.4.3 The whole container

The container is nine racks of 396 cells, so it holds

$$9 \times 396 = 3{,}564$$

cells. Its energy is nine times the energy of one rack,

$$E_{\text{container}} \approx 9 \times 380\,\text{kWh} \approx 3{,}420\,\text{kWh} \approx 3.42\,\text{MWh}, \tag{1.8}$$

and the same number follows from the cells, $3{,}564 \times 0.96\,\text{kWh} \approx 3{,}421\,\text{kWh}$, or from the bus, $1{,}267\,\text{V} \times 2{,}700\,\text{Ah} \approx 3{,}421\,\text{kWh}$. The three routes agree because they are the same product of a voltage and a charge, grouped differently.

Figure 1.6 draws the architecture as a ladder. Each box in the top row is one level of the hierarchy with its count of cells, its nominal voltage, its capacity and its energy; the label on each arrow says how many units of the level on the left make one unit of the level on the right, and how they are connected. The bottom row is the end of the chain, the PCS and the grid. Reading from left to right, the voltage grows only through the series steps and the capacity only through the parallel step, while the energy grows at every step.

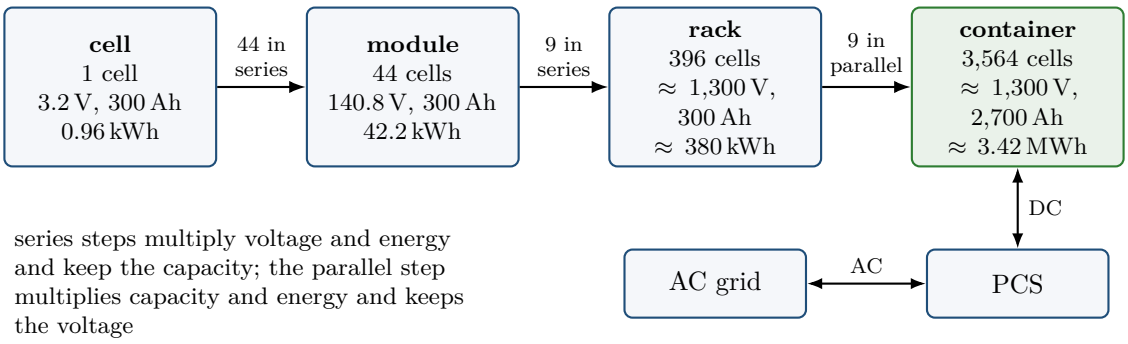


Figure 1.6: The architecture of the reference container, from one cell to the grid. Voltages are rounded: the nominal rack voltage is $396 \times 3.2 = 1{,}267\,\text{V}$ and measured rack voltages lie between about 1,250 and 1,350 V.

Written as a chain, the architecture is

$$\text{cell } (\approx 3.2\,\text{V}, \approx 300\,\text{Ah}) \xrightarrow{44 \text{ in series}} \text{module} \xrightarrow{9 \text{ in series}} \text{rack } (396 \text{ cells}, \approx 1{,}300\,\text{V}, \approx 300\,\text{Ah}, \approx 380\,\text{kWh})$$
$$\xrightarrow{9 \text{ in parallel}} \text{container } (3{,}564 \text{ cells}, \approx 1{,}300\,\text{V}, \approx 2{,}700\,\text{Ah}, \approx 3.42\,\text{MWh}) \to \text{PCS} \to \text{grid}.$$

Every cell voltage in the reference record belongs to one position in this ladder, every rack voltage and rack current to one of the nine strings, and every bus or PCS quantity to the top of it.

1.5 Current, charge and state of charge

The current flowing through a string says how much charge has left or entered every one of its cells. This section defines charge and its units, writes the charge balance that turns a current record into a charge record, defines the state of charge, and explains how the reported state of charge of the reference record is produced.

1.5.1 Current as a flow of charge

Electric charge is measured in coulombs (unit symbol C, set upright, not to be confused with the capacity C in italic). Current is the rate at which charge flows past a point, and one ampere is one coulomb per second,

$$1\,\mathrm{A} = 1\,\mathrm{C/s}.$$

The coulomb is a small unit for a battery, so engineers count charge in ampere-hours: one ampere flowing for one hour, or $1\,\mathrm{Ah} = 1\,\mathrm{A} \times 3{,}600\,\mathrm{s} = 3{,}600\,\mathrm{C}$. The capacity of one cell of the reference container is then $300 \times 3{,}600 = 1.08 \times 10^6\,\mathrm{C}$.

Because the 396 cells of a rack are in series, a rack current of 100 A means that 100 C of charge passes through each of the 396 cells every second. The rack-current channel of the reference record is therefore not the current of one component but the common current of 396 cells, and it is the only direct record of how much charge each of them has moved.

1.5.2 Counting charge

Charge moved is current accumulated over time. A rack of 300 Ah cells delivering 100 A for one hour has delivered 100 Ah, which is

$$\frac{100\,\mathrm{Ah}}{300\,\mathrm{Ah}} = \frac{1}{3} \approx 33\,\%$$

of its nominal capacity. For a current that varies, the accumulation is an integral. With $Q(t)$ the charge stored in a cell at time t and the current positive on discharge,

$$Q(t) = Q(0) - \int_0^t I(\tau)\,\mathrm{d}\tau. \tag{1.9}$$

Discharge ($I > 0$) lowers the stored charge and charge ($I < 0$) raises it. A telemetry record does not contain the continuous current but samples of it, I_k at intervals Δt, and the integral becomes a running sum,

$$Q_k = Q_{k-1} - I_k\,\Delta t. \tag{1.10}$$

With one-second samples, $\Delta t = 1/3{,}600\,\mathrm{h}$, so a sample of 100 A removes $100/3{,}600 \approx 0.028\,\mathrm{Ah}$. As an illustrative sequence, a rack that discharges at 150 A for 30 minutes and then charges at 60 A ($I = -60\,\mathrm{A}$) for 20 minutes changes its stored charge by

$$-150\,\mathrm{A} \times 0.5\,\mathrm{h} + 60\,\mathrm{A} \times \tfrac{1}{3}\,\mathrm{h} = -75\,\mathrm{Ah} + 20\,\mathrm{Ah} = -55\,\mathrm{Ah}.$$

Equation (1.9) is the *charge balance*: the charge stored changes only by the charge that crosses the terminals. It is one of the four relations on which the rest of the book is built.

1.5.3 State of charge

The *state of charge* expresses the stored charge as a fraction of the usable capacity,

$$\mathrm{SOC} = \frac{\text{charge currently available}}{\text{usable charge capacity}} = \frac{Q}{C}. \tag{1.11}$$

An SOC of 100 % means full and 50 % half full. An SOC of 0 % means the defined lower operating limit, not a cell emptied of all its chemical content: the cell is never discharged that far, and 0 % marks the point at which operation stops. A rack with 150 Ah remaining of 300 Ah is at

$$\mathrm{SOC} = \frac{150\,\mathrm{Ah}}{300\,\mathrm{Ah}} = 50\,\%,$$

and a full rack that delivers 100 A for one hour ends at $(300 - 100)/300 \approx 66.7\,\%$.

Dividing the charge balance (1.9) by the capacity gives the state of charge as a function of time,

$$\mathrm{SOC}(t) = \mathrm{SOC}(t_0) - \frac{1}{C}\int_{t_0}^{t} I(\tau)\,\mathrm{d}\tau, \tag{1.12}$$

which says that the state of charge at any time is its value at a starting time minus the charge delivered since then, expressed as a fraction of the capacity.

1.5.4 Coulomb counting and the reported state of charge

The state of charge is generally not measured. There is no SOC sensor in a cell: no instrument reads the charge stored inside it. The sensors on a battery measure voltage, current and temperature, and the state of charge must be estimated from them. The BMS estimates it, and the most common method is *coulomb counting*, which is equation (1.12) computed in real time: start from a known value, integrate the measured current, and divide by an assumed capacity. Many BMSs also reset the count when the battery reaches a recognizable condition, such as full charge or a long rest; between resets the reported value is a function of the measured current alone.

In the reference record the reported state of charge is produced essentially this way: the BMS integrates the same rack-current measurement that appears in the record and divides by an assumed capacity. The SOC channel is therefore not an independent measurement of the true stored charge. It is partly a calculation based on another sensor, and it inherits that sensor's errors and the assumptions of the calculation:

- *A current offset accumulates.* If the current sensor reads 1 A high (illustrative), the computed charge drifts by 24 Ah per day, which is $24/300 = 8\,\%$ of state of charge per day.
- *A capacity error scales every change.* If the true capacity has fallen to 285 Ah (illustrative) and the BMS still assumes 300 Ah, a 100 Ah discharge is reported as a drop of 33.3 % when the true drop is $100/285 = 35.1\,\%$.
- *An initial error persists.* Equation (1.12) carries $\mathrm{SOC}(t_0)$ forward unchanged; an error in it is never corrected by the integral.

The practical consequence is a rule for analysis. Comparing the reported SOC with a charge balance computed from the same rack current tests only whether the arithmetic was done; agreement is guaranteed by construction and says nothing about the battery or the current sensor. To learn something about the true stored charge, the analysis needs a measurement that the integral did not use, such as the cell voltage at rest.

Principle 1.2. *A reported state of charge is a derived channel, not a measurement: it is an integral of the measured current divided by an assumed capacity, and it cannot independently confirm a model driven by the same current.*

1.6 Supervision, heat and the grid interface

The cells, strings and racks store the energy; three further parts make the machine work. This section describes the battery management system and why it measures every cell, the battery as a thermal system, and the power conversion system, and then assembles the complete picture and outlines where the following chapters go.

1.6.1 The battery management system

The *battery management system* is the computer and control system that supervises the battery. It works as a loop: its inputs are the readings of the cell-voltage, current and temperature sensors; it compares them with limits and computes estimates; and its outputs are alarms, operating limits sent to the PCS, and commands that open or close the contactors. In the reference container the BMS reads 396 cell voltages and 216 temperatures in each rack, together with the rack voltage and rack current. It monitors cell voltages, rack voltage, current, temperatures and the state of charge, manages *balancing* (equalizing the charge of the cells in a string, typically by bleeding a small current from the cells that are fuller than the rest), and protects against overvoltage, undervoltage, overheating and overcurrent. Table 1.3 lists the typical protective functions; each row gives the condition guarded against, the measurement that reveals it, and the typical response.

Table 1.3: Typical protective functions of a BMS.

Condition	Measurement	Typical response
Overvoltage	any cell voltage above its upper limit	reduce or stop charging; open the rack contactor if it persists
Undervoltage	any cell voltage below its lower limit	reduce or stop discharging; open the contactor if it persists
Overheating	any temperature above its limit	reduce the allowed current; stop operation at a higher threshold
Overcurrent	rack current above its rating	limit the current through the PCS; open the contactor on a fault
Imbalance	spread of cell voltages in a string	balance the cells

Two features of the table matter for what follows. Every protective function acts on the most extreme cell or sensor, not on an average; and the BMS's outputs (limits, contactor states, the reported state of charge) appear in the reference record beside the measurements, so an analysis of the record must keep track of which channels were measured and which were computed or decided by the BMS.

1.6.2 Why every cell is measured

A rack is only as healthy as its weakest cells, and an aggregate measurement hides a weak cell. Consider a rack in which 395 cells sit at 3.35 V and one cell sits at 2.80 V. The rack voltage is

$$395 \times 3.35\,\mathrm{V} + 2.80\,\mathrm{V} = 1{,}323.25\,\mathrm{V} + 2.80\,\mathrm{V} = 1{,}326.05\,\mathrm{V},$$

while a rack of 396 cells all at 3.35 V would read $396 \times 3.35 = 1{,}326.60\,\mathrm{V}$. The low cell lowers the rack voltage by 0.55 V, or 0.04 %, and the average cell voltage from 3.3500 V to $1{,}326.05/396 \approx 3.3486\,\mathrm{V}$. A rack voltage of 1,326 V lies in the middle of the normal range of 1,250 to 1,350 V, and the 0.55 V shift is far smaller than the change that the state of charge produces in the course of a day.

Figure 1.7 shows the example. The left panel plots the voltage of each cell against its position in the string, from 1 to 396: the blue points form a flat line at 3.35 V and the single red point, placed at position 200 for illustration, sits at 2.80 V. The right panel plots the string voltage, the sum of the 396 cell voltages, for a rack with all cells normal (blue bar) and for the rack with the one low cell (red bar), on an axis that starts at zero. The deviation that is obvious in the left panel is invisible in the right one.

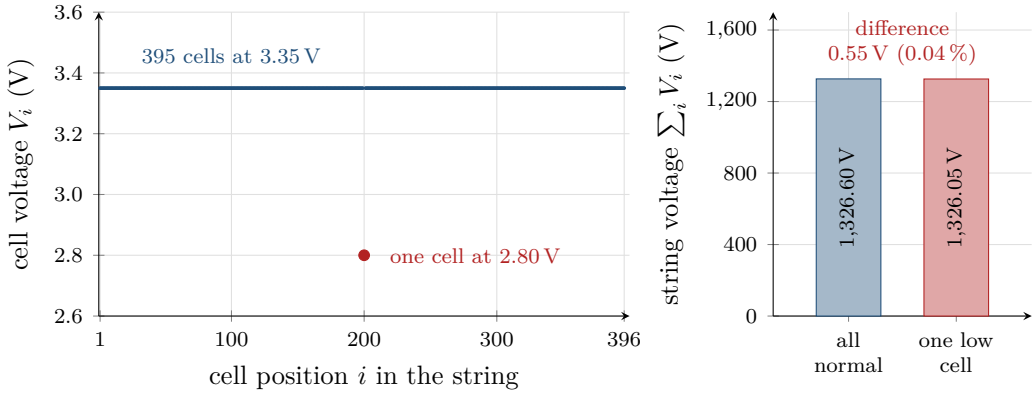


Figure 1.7: The dilution of one abnormal cell in a string sum. Left: cell voltages of a 396-cell rack with 395 cells at 3.35 V and one at 2.80 V. Right: the string voltage, equation (1.4), with and without the low cell. Values are illustrative; the position of the low cell does not affect the sum.

The reason is arithmetic. In a sum of 396 comparable terms, any one term contributes about $1/396 \approx 0.25\,\%$ of the total, so even a large change in one cell is a small change in the sum. The problem disappears in the aggregate and in the average. Yet the low cell is the one that determines what the rack can do. Because all 396 cells carry the same current (Section 1.3.2), the BMS must stop the discharge of the whole rack when the lowest cell reaches its lower voltage limit, even though the other 395 still hold usable charge. The usable capacity of the rack is set by its weakest cell, while the rack voltage and the rack average look normal. This is why the BMS measures every cell, and why an analysis that uses only rack-level channels can miss the condition that limits the rack.

Principle 1.3. *An aggregate can look normal while one cell limits the system: a single cell contributes about* $1/396$ *of a rack's voltage, so its deviation is diluted in the rack sum and in the rack average, but it alone can end a discharge.*

1.6.3 The battery as a thermal system

A battery is also a thermal system. Current flowing through a cell meets an internal resistance R, and the electrical energy lost in that resistance becomes heat at the rate

$$P_{\text{heat}} = I^2 R. \tag{1.13}$$

The heat depends on the square of the current, so it is the same on charge and on discharge, and doubling the current quadruples it. The chain of cause and effect is

$$\text{current} \rightarrow \text{resistive loss} \rightarrow \text{heat} \rightarrow \text{temperature rise} \rightarrow \text{cooling removes heat.}$$

The temperature is set by the balance between the heat generated and the heat removed. In its most primitive form, the heat stored in the battery changes at the rate at which heat is

generated minus the rate at which it is removed,

$$C_{\text{th}} \frac{\mathrm{d}T}{\mathrm{d}t} = I^2 R - \dot{Q}_{\text{cool}}, \tag{1.14}$$

where C_{th} is the thermal capacitance (the heat needed to raise the temperature by one kelvin) and $\dot{Q}_{\text{cool}}$ the rate of heat removal by the cooling system. When the two terms on the right are equal the temperature is steady; when generation exceeds removal it rises.

As an illustration, take a rack whose 396 cells and connections add up to a resistance of $R = 0.2\,\Omega$ (illustrative; about $0.5\,\text{m}\Omega$ per cell). At a rack current of 111 A the heat generated is $111^2 \times 0.2 \approx 2{,}460\,\text{W}$, about 2.5 kW; at 222 A it is about 9.9 kW. With an illustrative thermal capacitance of $C_{\text{th}} = 2 \times 10^6\,\text{J/K}$ and no cooling, 2.46 kW raises the rack temperature at $2{,}460/(2 \times 10^6) \approx 1.2 \times 10^{-3}\,\text{K/s}$, about 4.4 K per hour. The analysis of the reference record uses a rack-level balance of exactly the form of equation (1.14), with the heat generation tied to the measured rack current and the rack temperatures as the measured response; the chapter on thermal behavior develops it.

1.6.4 The power conversion system

The battery is DC and the grid is AC, and the PCS converts in both directions: from DC to AC during discharge and from AC to DC during charge. It also controls how much power goes in or out, by setting the current it draws from or pushes into the DC bus. On the DC side the power is the product of the bus voltage and the bus current,

$$P_{\text{DC}} \approx V_{\text{bus}}\, I_{\text{bus}}. \tag{1.15}$$

With $V_{\text{bus}} = 1{,}300\,\text{V}$ and $I_{\text{bus}} = 1{,}000\,\text{A}$,

$$P_{\text{DC}} \approx 1{,}300\,\text{V} \times 1{,}000\,\text{A} = 1.3 \times 10^6\,\text{W} = 1.3\,\text{MW}.$$

If the nine racks share that current equally, each carries about $1{,}000/9 \approx 111\,\text{A}$ and delivers about $1{,}300 \times 111 \approx 144\,\text{kW}$. At 1.3 MW the container's 3.42 MWh would last about $3.42/1.3 \approx 2.6$ hours, ignoring losses and state-of-charge limits. The AC power delivered to the grid is slightly less than P_{DC}, by the losses in the converter.

Equation (1.15) is how an ordinary current measurement becomes a grid-scale power flow. A thousand amperes on the bus at 1,300 V is more than a megawatt, and a 1 % error in the current measurement, 10 A, is an error of 13 kW in power and, by equation (1.9), of 10 Ah per hour in the charge balance of the bus.

1.6.5 The complete picture

Figure 1.8 assembles the machine. The top row is the chain grid, PCS and DC bus, with the AC and DC sides of the converter labeled. Below the bus hang the nine racks, each connected through its own line carrying its current I_r; the bus current I_{bus} flows into the PCS. The dashed lines from rack 1 open it up at the bottom of the figure: a row of cells, of which five are drawn (V_1, V_2, V_3, V_{395} and V_{396}, here indexing cells), joined in series and carrying the single rack current I_1. The brace under the cells gives the rack voltage as their sum, and the note on the right states the two rules that hold inside and between racks.

Read from top to bottom, the figure states the facts to keep:

1. The grid is AC; the PCS converts between AC and DC and sets the power.
2. The DC side is a common bus to which racks 1 to 9 connect in parallel.
3. Inside a rack, 396 cells are connected in series.

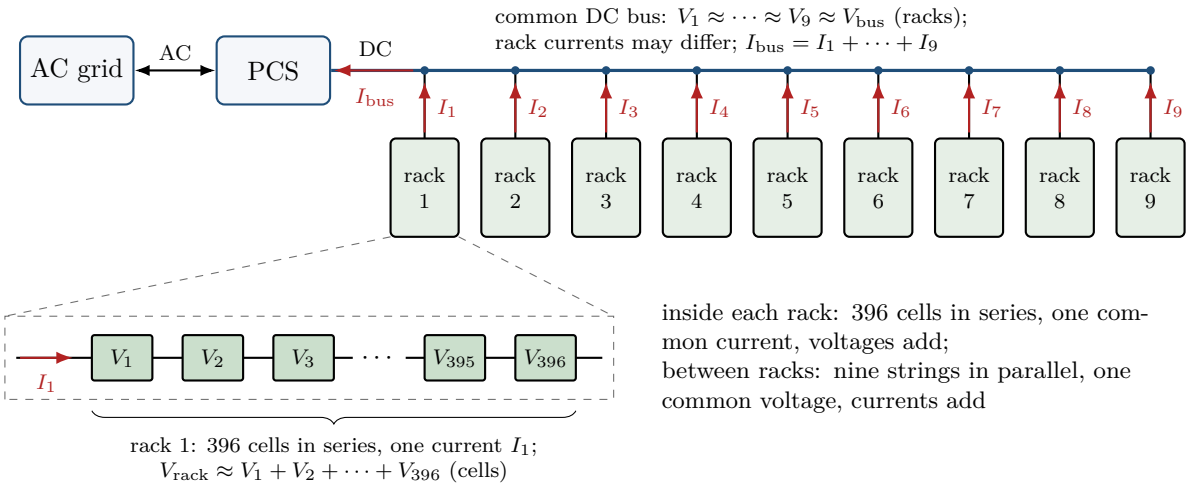


Figure 1.8: The complete picture of the reference container: grid, PCS, common DC bus, nine racks in parallel, and inside each rack 396 cells in series. Arrows show the direction of current during discharge.

4. The same current flows through every cell of a rack.
5. The rack voltage is approximately the sum of its cell voltages, $V_1 + \cdots + V_{396}$.
6. The rack voltages are approximately the same, because the racks share the bus.
7. The rack currents can differ from one another.
8. The total current is the sum of the rack currents, $I_{\text{bus}} = I_1 + \cdots + I_9$.

Every channel of the reference record attaches to one place in this picture: a cell voltage to one box in the bottom row, a rack current to one vertical line, a rack voltage to one rack, a temperature to a location inside a rack, the reported state of charge to the BMS's integral of a rack current, and the power to the PCS.

1.6.6 What the following chapters add

This chapter has described the machine; the following chapters describe what happens inside it and what its measurements can reveal. The electrical quantities used here (voltage, current, charge, power, energy) and their units are defined carefully in Chapter 2. Chapter 3 opens the cell: its chemistry, the relation between open-circuit voltage and state of charge, and why that relation is nearly flat for LFP, which is the imperfection of the water-tank analogy. Chapter 4 introduces internal resistance and the circuit model of a cell, which explains why the terminal voltage V differs from the open-circuit voltage U whenever current flows. Chapter 5 describes the BMS and the hardware in detail, Chapter 6 the thermal behavior, Chapter 7 degradation, Chapter 8 faults, and Chapter 9 what the sensors measure directly versus what must be inferred.

Four relations organize that work, and each has appeared in this chapter in its simplest form: the charge balance, equation (1.9); the rack or string voltage identity, equation (1.4); a per-cell electrical model relating each cell's voltage to its current and state, of which equation (1.2) is the crudest version; and the heat balance, equation (1.14). The question the book works toward is: given these measurements and these physical laws, what can be known about the battery, and what is fundamentally unidentifiable?

1.7 What to retain

Definition 1.1 (Battery energy storage system)**.** A battery energy storage system is a power converter and a supervisory system around a large array of low-voltage cells, in which series connection builds the voltage (396 cells, about 1,300 V per rack) and parallel connection builds the current, capacity and energy (nine racks, 2,700 Ah, 3.42 MWh). Within a series string every cell carries the same current, so one current measurement and one integral describe the charge of 396 cells, and the reported state of charge is that integral, not an independent measurement.

Table 1.4 lists the chapter's objects, the relation or value that defines each in the reference container, and the subsection in which it is introduced.

Table 1.4: The objects of this chapter.

Object	Relation or value	Subsection
BESS	grid $\leftrightarrow$ PCS $\leftrightarrow$ battery; charging and discharging as energy conversion	1.1.1, 1.1.2
Cell	$V_{\text{cell}} \approx 3.2\,\text{V}$, $C \approx 300\,\text{Ah}$	1.2.1
Energy	$E \approx V\,C = 960\,\text{Wh}$ per cell	1.2.2
Power and energy	$E = P\,t$; MW for how fast, MWh for how much	1.2.3
Series string	$V_{\text{series}} = \sum_i V_i$; common current	1.3.1, 1.3.2
Rack	396 cells; $\approx 1{,}267\,\text{V}$ nominal, 300 Ah, 380 kWh	1.3.3, 1.3.4
Parallel bus	$V_r \approx V_{\text{bus}}$; $I_{\text{bus}} = \sum_r I_r$	1.4.1
Container	3,564 cells, 2,700 Ah, 3.42 MWh	1.4.3
Charge balance	$Q(t) = Q(0) - \int I\,\mathrm{d}t$	1.5.2
State of charge	$\text{SOC} = Q/C$; coulomb counting	1.5.3, 1.5.4
BMS	measures, estimates, protects, balances	1.6.1
Dilution of one cell	one cell is $\approx 1/396$ of the rack voltage	1.6.2
Heat balance	$C_{\text{th}}\,\mathrm{d}T/\mathrm{d}t = I^2R - \dot{Q}_{\text{cool}}$	1.6.3
PCS power	$P_{\text{DC}} \approx V_{\text{bus}}\,I_{\text{bus}} = 1.3\,\text{MW}$ at 1,300 V, 1,000 A	1.6.4

1.8 Exercises

Exercise 1.1. An illustrative container uses cells of 3.2 V and 280 Ah, with 52 cells per module, eight modules per rack connected in series, and ten racks in parallel. Compute (a) the energy of one cell; (b) the number of cells in a rack, and the rack's nominal voltage, capacity and energy; (c) the number of cells in the container, the capacity available at the DC bus, and the container's energy. Check the last answer by two of the three routes of Section 1.4.3.

Exercise 1.2. The reference container discharges at 1.3 MW with a bus voltage of 1,300 V. (a) Compute the bus current and, assuming the racks share it equally, the current in one rack and in one cell. (b) What fraction of a rack's 300 Ah is delivered in 30 minutes? (c) Ignoring losses, how long can the container sustain 1.3 MW from an SOC of 90 % down to 10 %? (d) With the illustrative rack resistance $R = 0.2\,\Omega$ of Section 1.6.3, compute the heat generated in one rack at this operating point, and at twice the power with the same bus voltage.

Exercise 1.3. A rack with $C = 300\,\text{Ah}$ starts at $\text{SOC} = 80\,\%$. It discharges at 120 A for 45 minutes, rests for 15 minutes, and then charges at 90 A ($I = -90\,\text{A}$) for 40 minutes. (a) Use equation (1.12) to compute the state of charge at the end of each phase. (b) The current sensor reads 1.5 A too high throughout the 100 minutes, including the rest. What error does this

introduce in the reported state of charge at the end? (c) The true capacity is 270 Ah while the BMS assumes 300 Ah. Starting from a true SOC of 80 %, compute the true SOC at the end of the discharge phase and compare it with the reported value. (d) Explain why comparing the reported SOC with an independent analyst's integral of the same rack current would reveal neither error.

Exercise 1.4. A rack of 396 cells has 395 cells at 3.30 V and one cell at a voltage V_{low}. (a) Compute the rack voltage for $V_{\text{low}} = 3.30\,\text{V}$ and for $V_{\text{low}} = 2.70\,\text{V}$, and the percentage difference. (b) Show that no single cell, at any voltage between 0 and 3.30 V, can lower the rack voltage by more than about 0.25 %. (c) If the rack-voltage sensor has an illustrative accuracy of ± 0.5 %, can the rack voltage alone reveal the low cell? (d) The BMS stops discharge when any cell reaches 2.50 V. If the low cell stays 0.60 V below the others throughout a discharge (a simplification), at what voltage are the other 395 cells when the discharge stops, and what does this imply for the usable capacity of the rack?

1.9 Connection to the TERRA framework

The architecture of this chapter maps directly onto a conservation graph, and the mapping already shows which questions the reference record can answer.

- **Charge conservation on a rack node.** The charge balance, equation (1.9), is an accumulator: the rack is a node whose stored charge changes only by the current on the edge that connects it to the bus. The DC bus is a node with no storage, and the current rule of equation (1.7), $I_{\text{bus}} = \sum_r I_r$, is its conservation law.

- **The series string is an edge with one flow.** The common current of Section 1.3.2 means that a rack is an edge whose single flow, I_r, passes through 396 cell components. One measured flow drives 396 component models at once, which is why the rack-current sensor is the most consequential measurement in the graph.

- **The string voltage identity is a redundancy relation.** Equation (1.4) relates two independent sets of sensors, the rack-voltage sensor and the 396 cell-voltage sensors, through a physical identity. Because both sides are measured, its residual is a test of the sensors and of the connections between cells and terminals, not a definition.

- **Measured versus derived channels.** The reported state of charge of Section 1.5.4 is computed from the same rack current that drives the charge balance. A conservation boundary with no independent measurement crossing it gives an identity, not a test: fitting the charge balance to the reported SOC confirms the BMS's arithmetic and leaves the true capacity undetermined.

- **The heat balance is an energy-conservation node.** Equation (1.14) is a thermal node with storage C_{th}, an input edge I^2R tied to the electrical flow, and an output edge $\dot{Q}_{\text{cool}}$ to the cooling system; the rack temperatures are the measured states.

- **A fault is a hypothesis with a signature.** The low cell of Figure 1.7 changes the rack voltage by 0.04 %, which a normal model of the rack can absorb into its state of charge or its sensor noise. At the cell node the same fault is a 0.55 V departure. A fault is detectable only where its signature lies outside what the normal model can explain, which is why the graph must carry the cells and not just the racks.

In summary, a battery energy storage system is a graph of a few thousand cell components on nine series edges joined at one bus node, with a converter at its boundary and a thermal

node beside each rack. Its two connection rules are conservation laws, its reported state of charge is a derived channel rather than a measurement, and the dilution of one cell in a sum of 396 is the first instance of the book's central question: which properties of the battery the available measurements can and cannot determine. The next chapter, Chapter 2, defines the electrical quantities used here with their units and the relations between them.

Chapter 2

Electrical quantities: voltage, current, power, energy, ampere-hours, C-rate and state of charge

2.1 Three quantities at two terminals

Seen from outside, a battery is first a two-terminal device. Whatever happens inside the cells, the rest of the system meets the battery at a positive and a negative terminal, and at those terminals three quantities can be asked about: the voltage across them, the current through them, and the power that the two together carry. Everything else this book discusses (charge, energy, capacity, state of charge, heat, aging) is either built from these three or inferred from them. The question of this chapter is

which electrical quantities describe a battery at its terminals, how they are related, and which of them are measured rather than computed.

The chapter defines each quantity in turn, works every relation through with the numbers of the reference container, and ends by reading the channels of the reference record with those definitions in hand.

Jargon: volt, ampere, coulomb, ampere-hour, watt, watt-hour, C-rate, coulomb counting

The *coulomb* (symbol C) is the SI unit of electric charge. The *volt* (V) is the unit of voltage: one volt is one joule of energy per coulomb of charge. The *ampere* (A) is the unit of current: one ampere is one coulomb per second. The *ampere-hour* (Ah) is the charge moved by a current of one ampere flowing for one hour, so 1 Ah = 3600 coulombs; battery capacities are stated in ampere-hours. The *watt* (W) is the unit of power, one joule per second, and the *watt-hour* (Wh) is the energy transferred by one watt in one hour, 1 Wh = 3600 joules; the kilowatt-hour (kWh) and megawatt-hour (MWh) are 10^3 and 10^6 watt-hours. The *C-rate* is a current divided by the battery's capacity in ampere-hours, written with a suffix C: a 300 Ah cell discharged at 150 A runs at "0.5C". *Coulomb counting* is the estimation of state of charge by integrating the measured current over time and dividing by an assumed capacity. The letter C therefore does three jobs in this field: the unit coulomb (upright C), the capacity C (italic, in Ah), and the C-rate suffix. The context always says which is meant.

Key idea

A battery is described at its terminals by voltage, current and their product, power. Charge and energy are the time integrals of current and power, and state of charge is a charge integral divided by an assumed capacity: it is computed from the current, not measured.

This section defines voltage and current, the two quantities a sensor can read directly at the terminals of a rack.

2.1.1 Voltage

Voltage, measured in volts, is the electrical potential difference between two points. Physically it says how strongly charge is pushed through a circuit connected between those points: one volt means that each coulomb moved from the higher to the lower potential gives up one joule of energy. That definition, energy per unit charge, is the one to keep, because it is what later turns ampere-hours into watt-hours. A single cell of the reference container has a voltage of about 3.2 V. The value is not fixed: it depends on how full the cell is and on the current flowing, which are the subjects of Chapters 3 and 4. For this chapter 3.2 V is the nominal value.

Cells connected in series, positive terminal of one to the negative of the next, add their voltages. A rack of the reference container is a series string of 396 cells, so its voltage is the sum

$$V_{\text{rack}} = V_1 + V_2 + \cdots + V_{396} = \sum_{i=1}^{396} V_i, \tag{2.1}$$

where V_i is the voltage of cell i. With every cell at its nominal value this gives

$$V_{\text{rack}} \approx 396 \times 3.2\,\text{V} = 1267.2\,\text{V} \approx 1267\,\text{V}.$$

The reference record shows rack voltages between about 1250 V and 1350 V, which brackets the nominal value: the cells sit above 3.2 V when the rack is full or being charged and below it when the rack is nearly empty or delivering a large current. Equation (2.1) is an identity of the circuit, not an approximation, and it will matter later that the record contains both sides of it: a rack voltage channel and 396 cell voltage channels.

2.1.2 Current

Current, measured in amperes, is the rate at which charge flows past a point of the circuit. If Q is the charge that has passed,

$$I = \frac{\mathrm{d}Q}{\mathrm{d}t}, \qquad 1\,\text{A} = 1 \text{ coulomb per second}. \tag{2.2}$$

Read backwards, equation (2.2) says that charge is accumulated current. With a constant current the charge moved in an interval Δt is simply

$$\Delta Q = I\,\Delta t, \tag{2.3}$$

so a current of 100 A flowing for one hour moves 100 Ah, and for two hours 200 Ah. When the current varies, the product is replaced by an integral,

$$\Delta Q = \int_{t_0}^{t_1} I(t)\,\mathrm{d}t, \tag{2.4}$$

which is the area under the current trace between t_0 and t_1. With I in amperes and t in hours the area is in ampere-hours; with t in seconds it is in coulombs, and 1 Ah = 3600 coulombs converts between the two.

END OF THE PREVIEW

Battery Energy Storage Systems

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