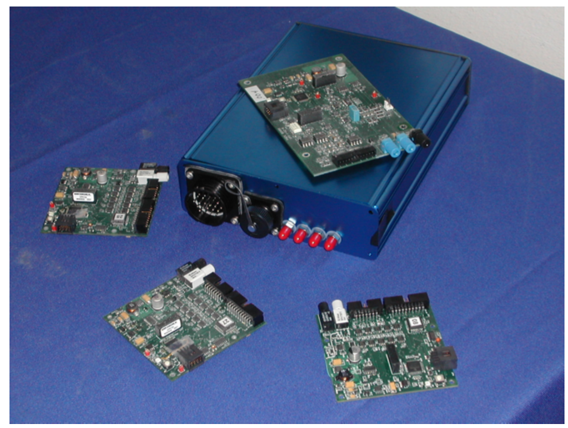
Battery-Management-System Requirements

1.1: Introduction and BMS functionality



- This course investigates the proper management and control of battery packs, usually comprising many cells.
- The methods and algorithms we discuss would typically be implemented by a battery-management system or BMS.
- A BMS is an embedded system (purpose-built electronics plus processing to enable a specific application).
  - Protects the safety of the battery operated device's operator. Detects unsafe operating conditions and responds.
  - Protects cells of battery from damage in abuse/failure cases.
  - Prolongs life of battery (normal operating cases).
  - Maintains battery in a state in which it can fulfill its functional design requirements.
  - Informs the application controller how to make the best use of the pack **right now** (*e.g.*, power limits), control charger, etc.
- There is a cost associated with battery management, so not all applications implement all features.
  - Your battery is "cheap enough" if you cannot remember the last time you replaced it.

- Larger battery packs represent greater investment, and motivate better battery management.
- This course will focus on large (*e.g.*, vehicular) battery packs although the methods we discuss are quite general.

■ Vehicular applications include:

- Hybrid-Electric Vehicle (HEV): Motive power provided by battery plus at least one other source (*e.g.*, gasoline engine). Essentially zero all-electric vehicle range.
- Plug-in Hybrid-Electric Vehicle (PHEV): Larger battery than HEV allows some all-electric range under certain operating conditions.
- Extended-Range Electric Vehicle (E-REV): Larger battery than PHEV allows some all-electric range under full-load conditions.
- Electric Vehicle (EV), a.k.a. Battery-Electric Vehicle (BEV): Battery provides only motive power.

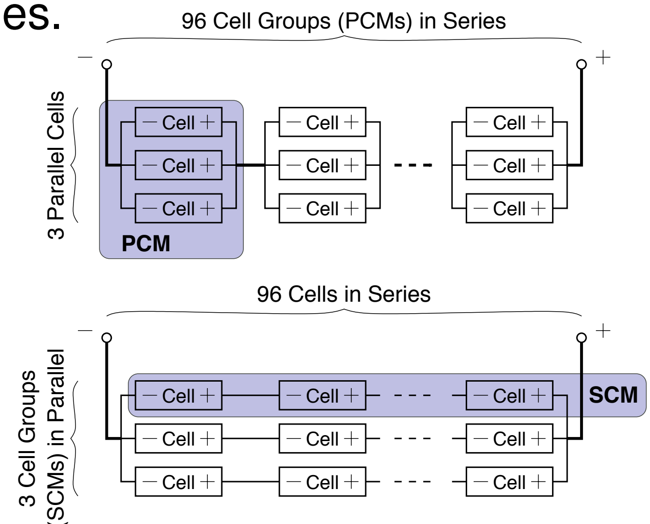
■ All of these vehicle types employ battery packs that are "large," "high voltage," and "high current."

- Some distinctions in design, which we will detail when necessary.
- Commonalities more significant than differences; when distinctions aren't important, we refer to the whole class as xEV.

■ Another large-scale application that justifies advanced battery management is for grid-storage and backup.

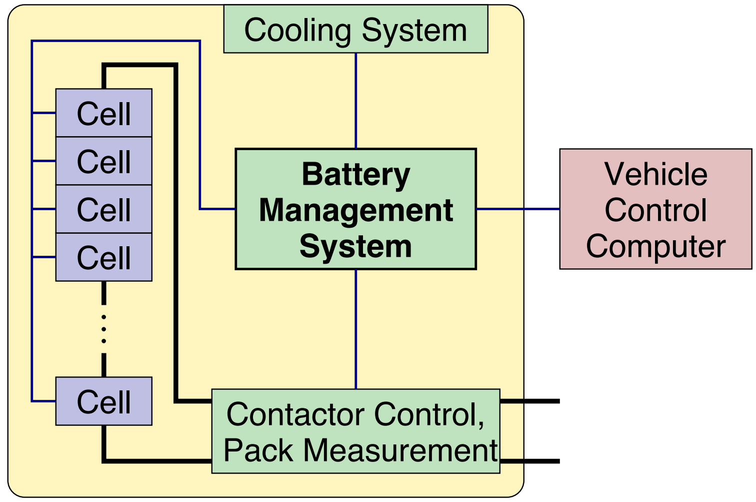
Battery pack topology

- High-power battery packs deliver high voltage, high current, or both.
- Chemistry of individual cells fixes their voltage range, so for high voltage packs, we must stack cells in series: $V_{\text{pack}} = N_s \cdot V_{\text{cell}}$.
- Cell construction places limits on cell current, so for high current packs, we must wire cells in parallel: $I_{\text{pack}} = N_p \cdot I_{\text{cell}}$.
- The series/parallel design is generally determined by economic and safety factors—modules are usually kept less than 50 V for safety, and packs are kept less than 600 V because power electronics begin to get very expensive at higher voltages.
- Generally want to minimize current to keep wire diameter small and reduce resistive I^2R wiring losses.
- Modules also minimize NRE, create reusable design. Extremes:
  - Parallel-cell modules (PCM),
  - Series-cell modules (SCM).



- We can design battery packs and BMS for either—most often use something in between these extremes.
- *e.g.*, a "3P6S" module has 18 cells: 3 in parallel and 6 in series.
  - Module power and energy are both approximately $18\times$ that of a single cell (but not quite, in practice, as we shall find).
- Cells in a module are welded/screwed to a common PCB having local BMS electronics for voltage measurement and cell balancing control—minimizes nightmare of individual wires to hundreds of cells.

BMS Functionality



- BMS is interconnected with all battery-pack components and with vehicle control computer.
- Functionality can be broken down into several categories:

1. Sensing and high-voltage control:
   - Measure voltage, current, temperature; control contactor, pre-charge; ground-fault detection, thermal management.
2. Protection against:
   - Over-charge, over-discharge, over-current, short circuit, extreme temperatures.
3. Interface:
   - Range estimation, communications, data recording, reporting.
4. Performance management:
   - State-of-charge (SOC) estimation, power-limit computation, balance/equalize cells.
5. Diagnostics:
   - Abuse detection, state-of-health (SOH) estimation, state-of-life (SOL) estimation.

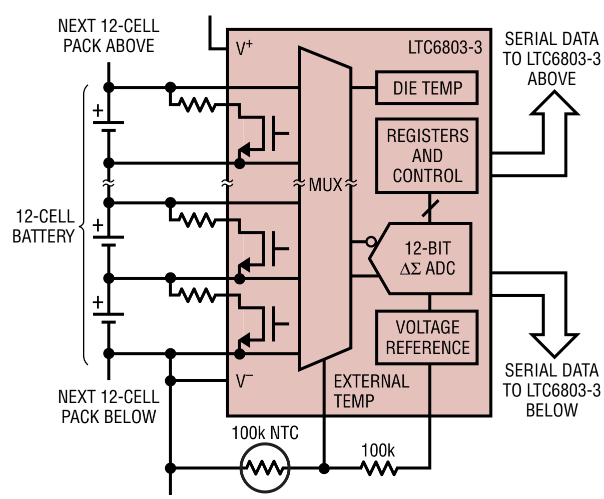
- In this chapter, we address some of the more basic (but still important) design considerations; later chapters will develop performance management and diagnostic topics in detail.

1.2: Requirements 1a–c: Sensing

1a. Battery-pack sensing: Voltage

- All cell voltages are measured in a lithium-ion pack:
  - Indicator of relative balance of cells.
  - Input to most SOC and SOH estimation algorithms.
- It's also a safety issue:
  - Overcharging a lithium-ion cell can lead to "thermal runaway," so we can't skip measuring any voltages.

- Special chipsets are made to aid high-voltage BMS design.
  - Low-cost "dumb" measurement chips used in modules, proximate to cells; high-cost computational processing in distant master unit.
  - Special chips implement difficult task of highly accurate A2D voltage sensing with high common-mode rejection and fast response in high-EMI, high-heat, high-vibration environments.
  - Can often be placed in parallel for redundant fault-tolerant designs.
- A number of vendors make chipsets, including: Analog Devices, Atmel, Intersil, Maxim, O2Micro, Texas Instruments.
- We consider a specific example (LTC6803) designed in Colorado Springs by Linear Technology.



- Monitors up to 12 cells in series in a module, 120 cells in a pack.
- Has built-in isolated communications between daisy-chained parts.
- Supports internal or external cell equalization circuitry.
- Can be powered by module itself, or externally.
- Measures up to four temperatures (with some external circuitry).

■ Points to be considered in a design:

- How many cells can each IC monitor?
- How many cells total can be monitored?
- Does it support passive/active balancing?
- What is the measurement accuracy?
- How many temperature measurements can be made?
- How many wires to communicate from IC to IC?
- What is chipset availability and cost, per cell?

1b. Battery-pack sensing: Temperature

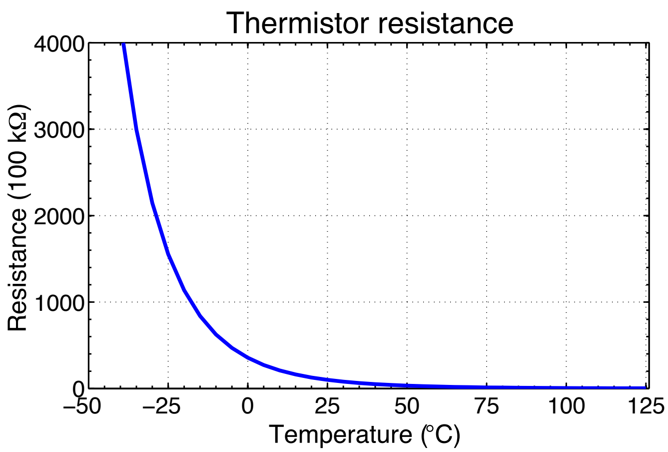
■ Battery pack operational characteristics and cell degradation rates are very strong functions of temperature.

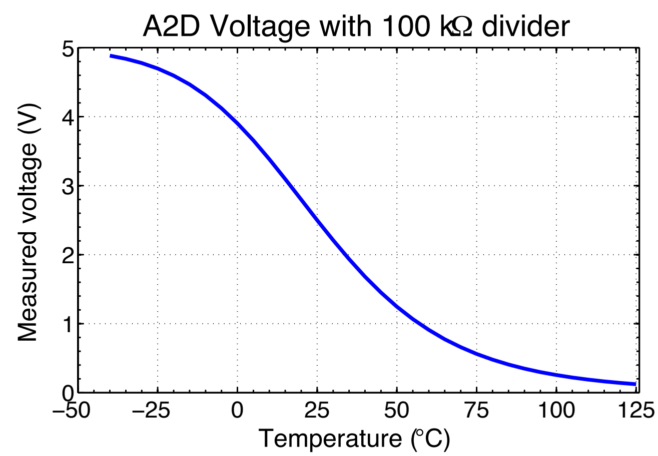
- Don't charge at low temperature; control thermal management systems to keep temperature in "safe" region.
- Unexpected temperature changes can indicate cell failure or impending safety concern.

■ Ideally, we measure each cell's internal temperature. But,

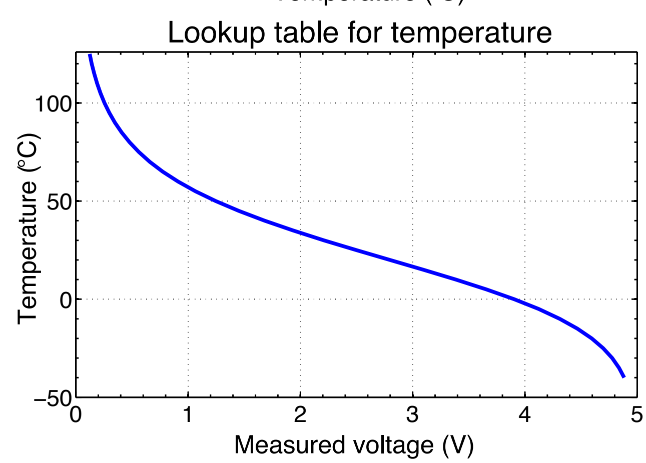
- With accurate pack thermal model, can place sensors external to one or more cells per module and calibrate internal temperatures.

- To measure temperature, must produce a voltage signal indicative of the temperature, which is then measured via an A2D circuit.
  - Thermocouple directly produces a (very small) voltage, which can be amplified and measured — needs “cold junction compensation.” Probably best suited for lab tests.
  - Thermistor (NTC/PTC) easier to use in products. Resistance changes significantly with temperature.
- Thermistor can be used in Wheatstone bridge, if resistances are calibrated. Or, using a voltage divider.
- Thermistor data sheet gives resistance as a function of temperature.
- In one example, we have the plotted relationship. If we put this thermistor in lower leg of voltage divider, with a 5 V source, we get:



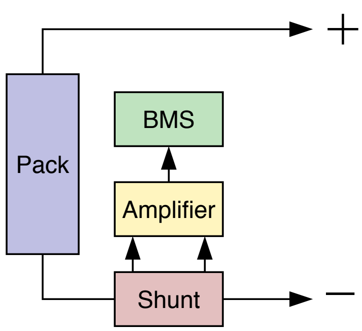


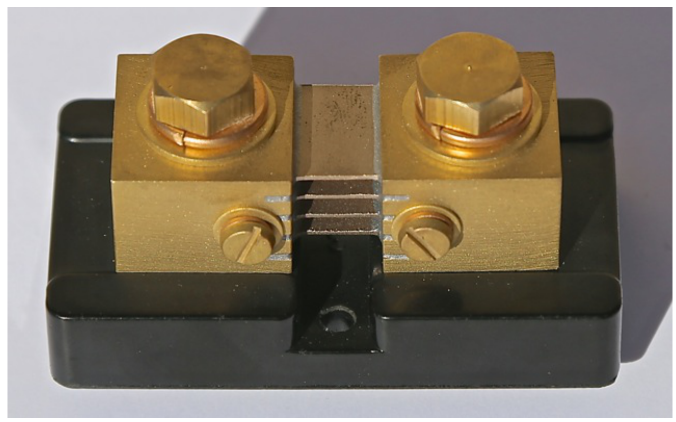
- In software, we want to convert a measured voltage into the thermistor temperature.
- So, we create an “inverse” table of temperature as a function of voltage: use in table lookup.



1c. Battery-pack sensing: Current

- Battery pack current measurements are required:
  - To ensure safety.
  - To log abuse conditions.
  - By most state-of-charge and state-of-health algorithms.
- There are two basic sensing methods: Shunt and Hall effect.
- Shunt sensor is low-value (*e.g.*, 0.1 mΩ) high-precision resistor in series with battery pack, usually at low-voltage end.
- Current computed by measuring voltage drop: $I = V_{\text{shunt}}/R_{\text{shunt}}$.

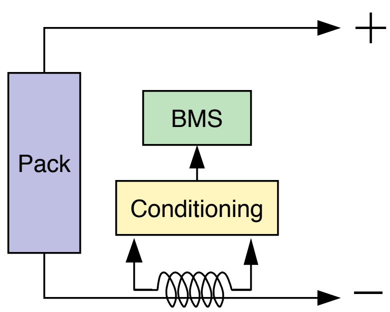




- Some comments on current-sensing shunts:
  - Power and sense connections must be made separately: four-wire voltage measurement via a Kelvin connection.
  - Current shunts have no offset at zero current, regardless of temperature, so they are good to avoid drift in coulomb counting (but, offset might still be introduced by measurement electronics).
  - Current shunts are not isolated from the pack. If BMS must be isolated from pack, extra circuitry is required.

- Resistance of current shunt changes with temperature, so temperature must be measured and resistance calibrated.
- The shunt itself introduces some energy losses, and generates heat that must be dissipated.
- The sensor produces a tiny signal that must be amplified—any wiring must be protected from EMI.

■ Hall-effect sensors measure magnetic field generated by current flowing in a wire.

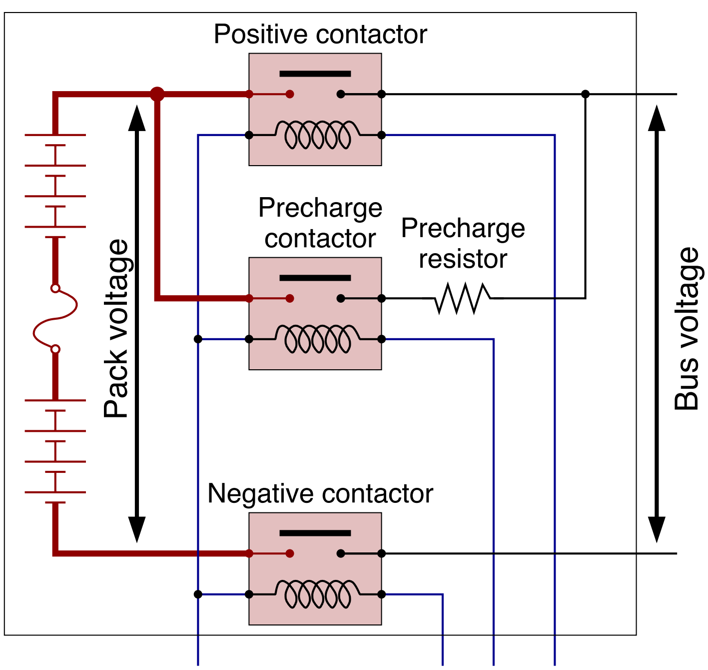


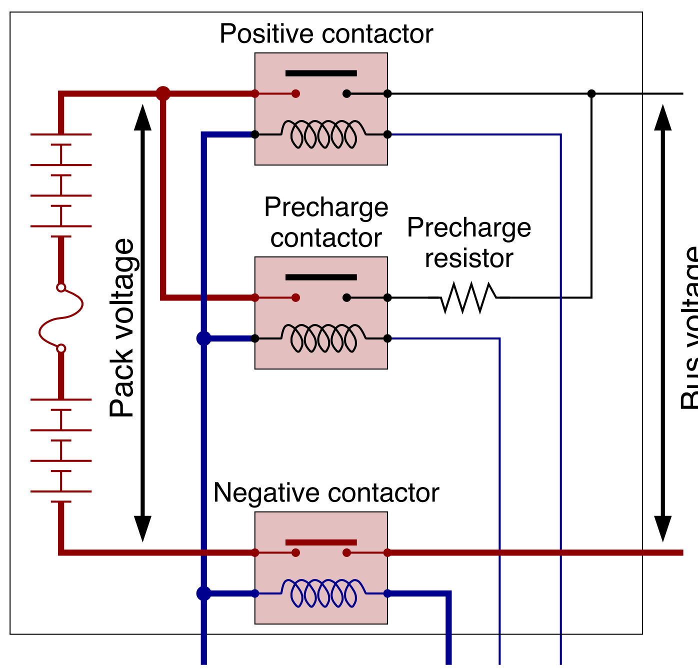
■ Some comments on Hall-effect sensors:

- Hall-effect sensors are isolated from the pack current and therefore no special isolation circuitry is needed.
- Feedback circuitry is needed to guard against sensor magnetic hysteresis. Sensors come prepackaged with this circuitry.
- Even so, Hall-effect sensors suffer from offset at zero current, which changes with temperature.
  - Even if "zeroed" at room temperature, they will report a small current when there isn't one as they change temperature.
  - Frequent calibration is necessary, and may be possible in some applications (*e.g.*, HEV if it it known that there is zero current.)

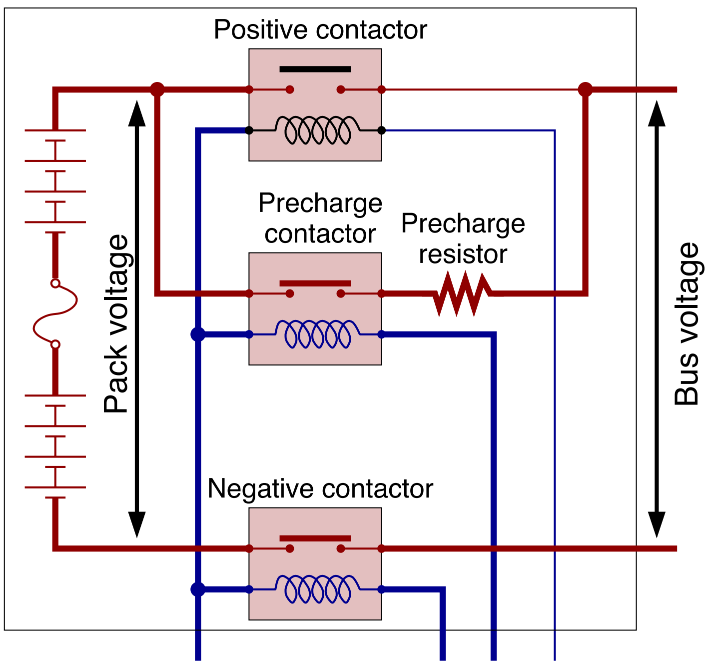
1.3: Requirement 1d: High-voltage contactor control

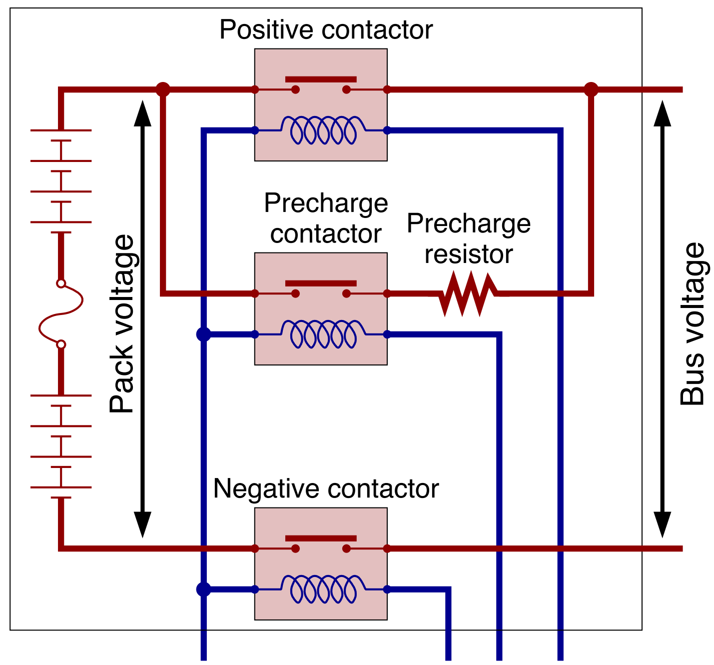
- High-voltage battery packs are designed to be completely isolated from chassis ground, for safety reasons.
  - If you were to touch chassis ground and any point in the battery pack, you should be completely safe.
- Similarly, when not in use, the battery pack internal high-voltage bus is completely disconnected from the load at both terminals.
  - This requires two high-current capable relays or "contactors."
  - The load is often capacitive, so if both contactors were simultaneously closed, a huge amount of current would instantly flow, potentially welding the contactors closed or blowing a fuse.
  - So, a third "pre-charge" contactor is used.
- Pack initially at rest; then negative contactor activated.
  - Connects "–" terminal of the load to "–" terminal of battery pack





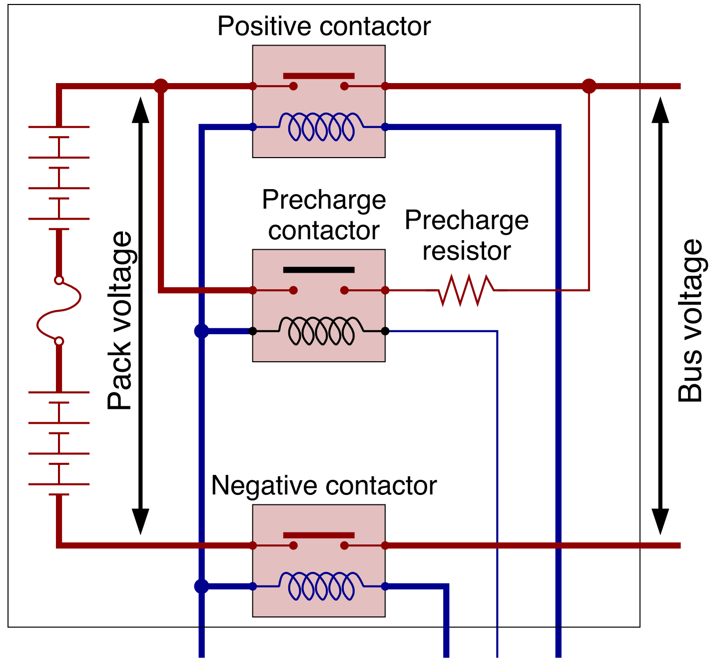
- Precharge contactor activated next.
  - The precharge resistor limits current flow, and the pack charges up the capacitive load (relatively slowly).
  - Precharge resistor temperature is monitored—if too high, load may have short circuit fault and pack disconnects.
  - Bus voltage and pack voltage are monitored—requires high-impedance voltage dividers and isolated op-amps.
  - If bus and pack voltages don't converge after a specified interval, load may have short-circuit fault: pack disconnects.





- Main contactor is activated when bus and pack voltages converge.

- If bus and pack voltages become "close enough" "quickly enough," then BMS closes/ activates the main "+" terminal contactor.
  - Load is now directly connected to pack through low-resistance path.
  - Precharge contactor is disconnected/ opened/ deactivated.

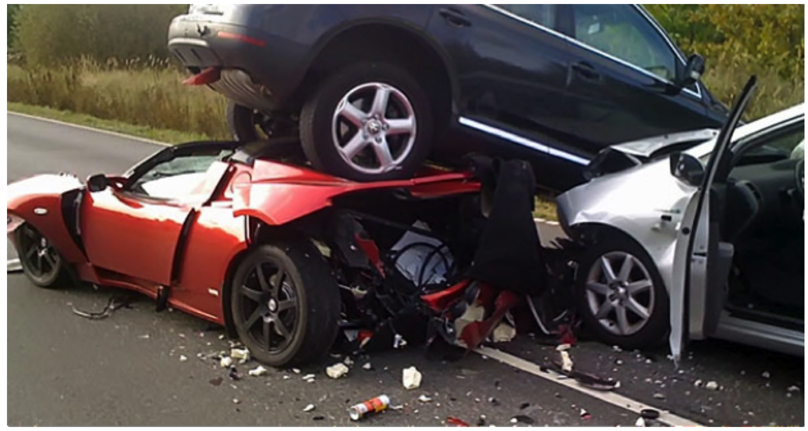


- Procedure to follow on pack shutdown is not as clear.
  - Abrupt disconnection may cause arcing/welding, but capacitive load probably stores enough energy to prevent this.
  - Activating precharge path prior to main contactor disconnect probably wise—still have a current path to prevent welding of main contactor, but could possibly blow precharge resistor.
  - Again, capacitive load probably saves resistor too.

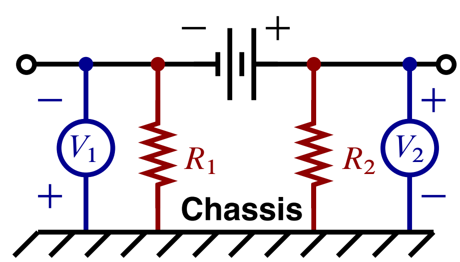
1.4: Requirements 1e–f: Isolation sensing and thermal control

1e. Isolation sensing

- Isolation sensing detects presence of a ground fault.
- Primary concern is safety: Is it safe to touch a battery terminal and chassis ground at the same time?



- Battery "should" be completely isolated from chassis ground, so "should" be no problem.
- FMVSS says isolation is sufficient if less than 2 mA of current will flow when connecting chassis ground to either the positive or negative terminal of the battery pack via a direct short.
- In the circuit diagram, paths between the battery and chassis ground are drawn as red resistors; ideally these have infinite value.

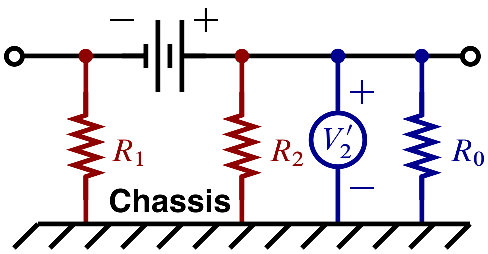


- The "isolation resistance" R_i is the lesser of R_1 and R_2. So, R_i must be greater than $V_b/0.002 = 500V_b$.
- For the BMS to sense whether the pack is sufficiently isolated from the chassis, it must somehow measure R_i.
- To do so, we measure V_1 and V_2 using a high-impedance measurement circuit, $\geq 10\,\text{M}\Omega$.
  - This breaks strict isolation, but not enough to worry about.
  - Note polarity of voltmeters—both V_1 and V_2 are positive.

- R_1 and R_2 form a voltage divider. We want to find the smaller of the two resistances. So if $V_2 > V_1$ find R_1, else find R_2.
- Note also that $I_1 = I_2$ so $V_1/R_1 = V_2/R_2$. We'll use this identity.

Fault on low side: Find R_1

- If the fault is on the low side, we want to solve for R_1.
- We insert a known (large) resistance R_0 between the battery and chassis ground, via a transistor switch, as shown.



- This again breaks strict isolation, but not enough to worry about if R_0 is "big enough" (*i.e.*, $\gg 500V_b$).
- We measure V_2'. Note that by KCL, $\dfrac{V_b - V_2'}{R_1} = \dfrac{V_2'}{R_2} + \dfrac{V_2'}{R_0}$.
- Substitute $V_b = V_1 + V_2$ and $R_2 = R_1(V_2/V_1)$,

$$\frac{(V_1 + V_2) - V_2'}{R_1} = \frac{V_2'}{R_2} + \frac{V_2'}{R_0}$$

$$= \frac{V_2'(V_1/V_2)}{R_1} + \frac{V_2'}{R_0}.$$

- Solve for R_1

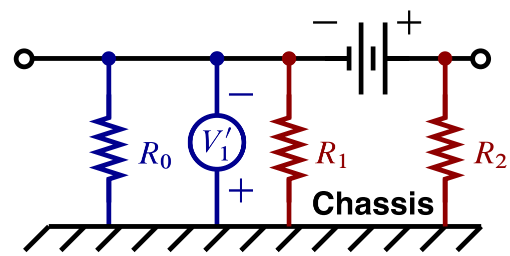
$$\frac{(V_1 + V_2) - V_2' - V_2'(V_1/V_2)}{R_1} = \frac{V_2'}{R_0}$$

$$R_1 = \frac{R_0}{V_2'}(V_1 + V_2 - V_2' - V_2'(V_1/V_2))$$

$$= \frac{R_0}{V_2'}\left(1 + \frac{V_1}{V_2}\right)\left(V_2 - V_2'\right).$$

- Isolation is deemed sufficient if $R_i > V_b/0.002$ or $R_2 > 500V_b$.

Fault on high side: Find R_2



- Procedure is similar if $V_1 > V_2$ except now we want to find R_2.
- Configure as shown, measure V_1'.
- By KCL,

$$\frac{V_b - V_1'}{R_2} = \frac{V_1'}{R_1} + \frac{V_1'}{R_0}.$$

- Substitute $V_b = V_1 + V_2$ and $R_1 = R_2(V_1/V_2)$

$$\frac{V_1 + V_2 - V_1'}{R_2} = \frac{V_1'(V_2/V_1)}{R_2} + \frac{V_1'}{R_0}$$

$$\frac{V_1 + V_2 - V_1' - V_1'(V_2/V_1)}{R_2} = \frac{V_1'}{R_0}.$$

- Solve for R_2

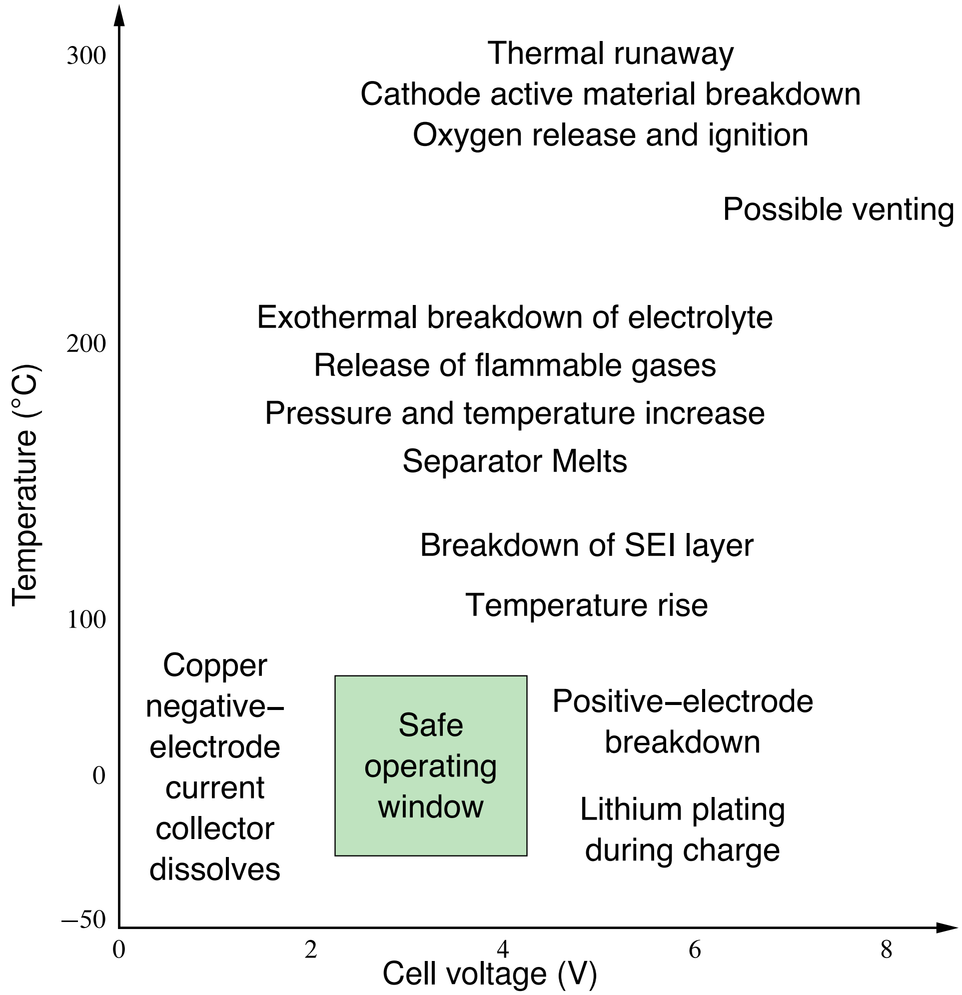
$$R_2 = \frac{R_0}{V_1'}(V_1 + V_2 - V_1' - V_1'(V_2/V_1))$$

$$= \frac{R_0}{V_1'}\left(1 + \frac{V_2}{V_1}\right)\left(V_1 - V_1'\right).$$

- Again, isolation is considered sufficient if $R_i > V_b/0.002$ or $R_2 > 500V_b$.

1f. Thermal control

- Will not go into detailed thermal management control strategy.
- Generally, Li-ion cells last longest if maintained in temperature band from about 10 °C to 40 °C during use.
- Air cooling may be sufficient, especially for EV.



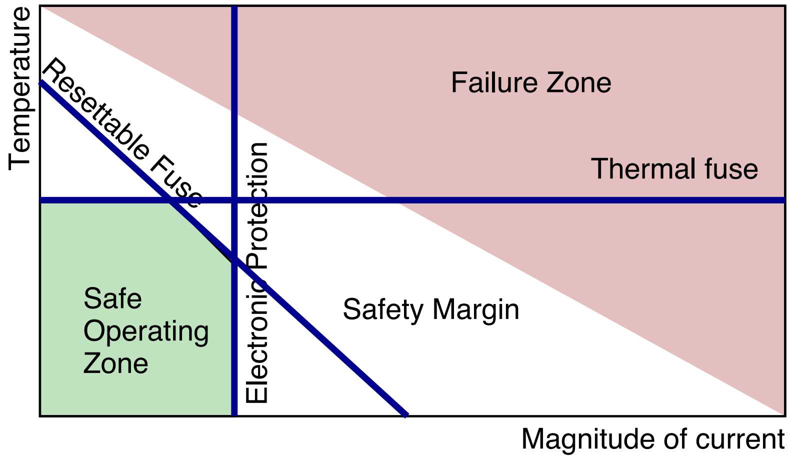
- Liquid/evaporative cooling may be necessary for some aggressive HEV/PHEV/E-REV applications.
- Heating may be necessary in some cases to avoid charging at low temperatures—high risk for cell damage if pack is charged below about 0 °C.
- May also want to measure input/output temperature of coolant for use with battery pack thermal model.

1.5: Requirements 2 and 3: Protection and interface

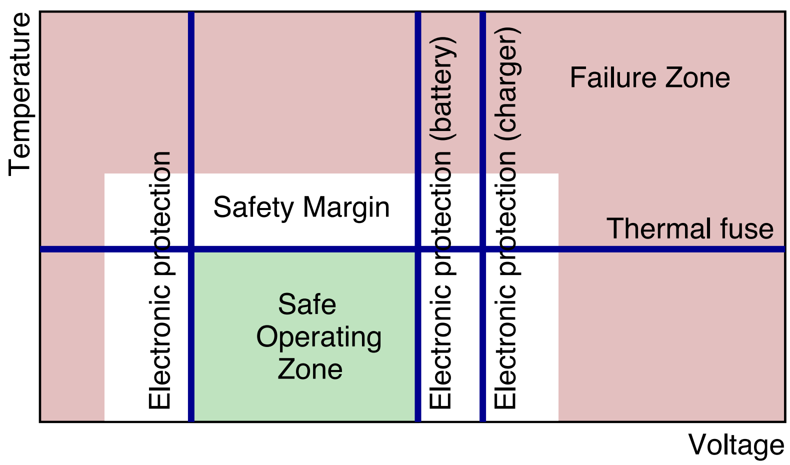
2. Protection

- BMS must provide monitoring and control to protect:
  - Cells from out-of-tolerance ambient operating conditions.
  - User from consequences of battery failures.
- High-energy storage batteries can be very dangerous:
  - If energy is released in an uncontrolled way (short circuit, physical damage), can have catastrophic consequences;
  - In a short circuit, hundreds of amperes can develop in microseconds; protection circuitry must act quickly.
- Different applications and different cell chemistries require different degrees of protection.
  - Failure in a lithium-ion cell can be very serious: explosion/fire.
  - Protection is indispensable in automotive environment.
- Protection must address following undesirable events or conditions:
  - Excessive current during charging or discharging;
  - Short circuit;
  - Over voltage and under voltage;
  - High ambient temperature, overheating;
  - Loss of isolation;
  - Abuse.
- When possible, fallback protection paths should be implemented

- Red = cell-manufacturer specified region where cells will most likely be subject to permanent damage;
- Anywhere else "okay" but need margin of error;
- Generally design to limit cell's operating conditions to smaller "safe" region, shown here in green;
- Safety devices are then specified to constrain cells to safe region.
- White = safety margin.



- Similar for voltage limits:
- But, each protection device added into main current path increases battery impedance, reducing power delivered to load.



- Examples of protection devices include:
  - Thermal fuse: Opens contactor when $T > T_{\text{limit}}$.
  - Conventional fuse: May not act quickly enough;
  - Active fault detection: BMS monitoring for fault conditions.

3a. Charger control

- Battery packs are charged in two ways:

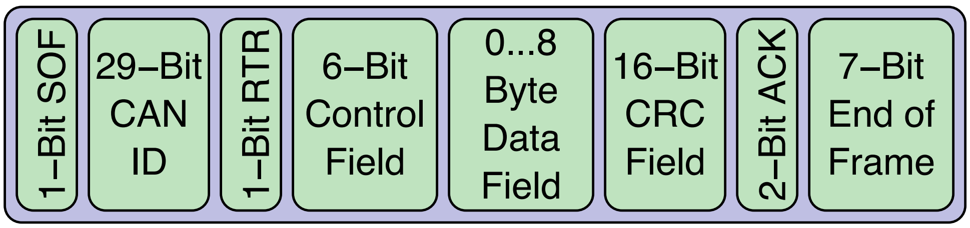
- Random charging: Charge is delivered in random unpredictable patterns; *e.g.*, regenerative braking
  - Controlled by providing inverter power limits.
- Plug-in charging: EV/PHEV/E-REV have plug-in modes:
  - Control charger current, voltage, pack equalization;
  - Often do CC/CV but more exotic methods possible;
  - Most Li-Ion cells should not be charged at low temperatures, so heating systems may be required.

- Small print: Passenger vehicles require approx. 200–300 Wh/mile.
  - For 300 mile range, 60–90 kWh capacity, charge in 3 minutes requires a rate of 1.8 MW!
  - Domestic 15 A, 110 V or 1.5 kW service charges pack in 40–60 h
  - Domestic 30 A, 220 V or 6.6 kW service charges pack in 10–15 h

3b. Communication via CAN bus

- Control Area Network (CAN) bus is industry ISO standard for on-board vehicle communications.
- Designed to provide robust communications in the very harsh automotive operating environments with high levels of electrical noise.
- Two-wire serial bus designed to network intelligent sensors and actuators; can operate at two rates:
  - High speed (1M Baud): Used for critical operations such as engine management, vehicle stability, motion control;
  - Low speed (100 kBaud): Simple switching and control of lighting, windows, mirror adjustments, and instrument displays (etc.).

- The protocol defines the following:
  - Method of addressing the devices connected to the bus;
  - Transmission speed and priority settings;
  - Transmission sequence;
  - Error detection and handling;
  - Control signals.



- Data frames are transmitted sequentially over the bus.

3c. Log book function

- For warrantee and diagnostic purposes, BMS must store a log of atypical/abuse events
  - Abuse type: out of tolerance, voltage, current, temperature
  - Duration and magnitude of abuse
- Can also store diagnostic information regarding
  - Number of charge/discharge cycles completed
  - SOH estimates at beginning of each driving cycle;
  - And much more. . .
- Data stored in memory in a “history chip” (*e.g.*, FLASH memory) and downloaded when required.
  - A “silicon serial number” chip can help.

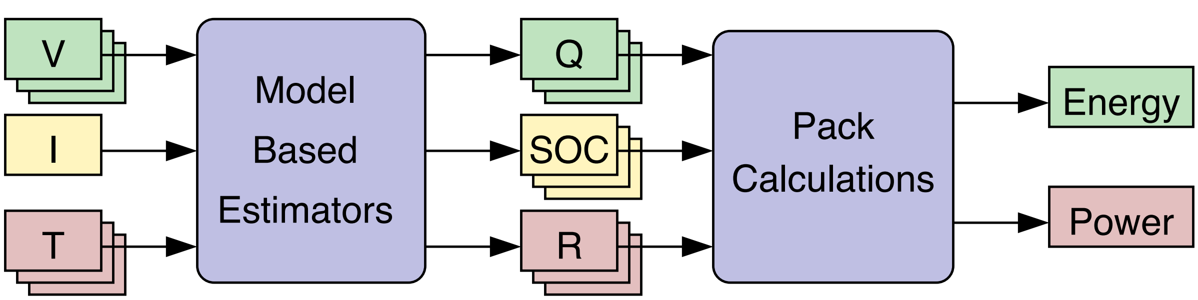
3d. Range estimation

- How far can I drive before pack energy is depleted?
- This is proportional to pack total energy but is heavily influenced by environmental factors:
  - What are the vehicle characteristics?
  - How is the vehicle being driven (gently/aggressively)?
  - Are there a lot of hills, a lot of wind?
  - Is it warm or cold out?
- At present, it appears that each OEM will have their own range-estimation algorithms.
- It is sufficient for the moment to produce the required inputs to those algorithms; esp. how much energy is in the pack.

1.6: Requirement 4a. State-of-charge estimation

What needs to be estimated, and why?

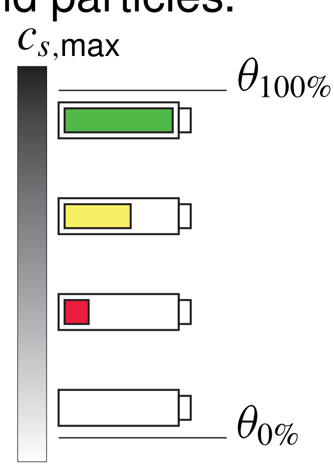
- xEVs need to know two battery quantities:
  - How much energy is available in the battery pack;
  - How much power is available in the immediate future.
- An estimate of energy is most important for EV:
  - Energy tells me how far I can drive.
- An estimate of power is most important for HEV:
  - Power tells me whether I can accelerate or accept braking charge.
- Both are important for E-REV/PHEV.
- To compute energy, we must know (at least) all cell states-of-charge z_k and capacities Q_k.
- To compute power, we must know (at least) all cell states-of-charge and resistances R_k.
- But, we cannot directly measure these parameters—we must estimate them as well.
- Available inputs include all cell voltages, pack current, and temperatures of cells or modules.



- We'll see that there are both good and poor methods to produce estimates: The poor methods are generally simpler to understand, code, and validate, but yield less accurate results.
- The impact of this can be:
  - Abrupt corrections when voltage or current limits exceeded, leading to customer perception of poor drivability, or
  - Over-charge or over-discharge, which damages cells, or
  - Compensating for uncertainty of estimates by over-designing pack.
- All of these have costs in dollars, weight and/or volume.
- A major premise of this course is that investing in good battery management and control algorithms and electronics capable of implementing the algorithms can reduce pack size and end up with a considerable net savings.

What really is state-of-charge (SOC)?

- Charging a cell moves lithium from the positive- to the negative-electrode of the cell; discharge does the opposite.
- Electrochemically, the cell state-of-charge (SOC) is related to average concentration of lithium in the negative-electrode solid particles.
- Define the present lithium concentration stoichiometry as $\theta = c_{s,\text{avg}}/c_{s,\text{max}}$.
- This stoichiometry is intended to remain between $\theta_{0\%}$ and $\theta_{100\%}$.
- Then, cell SOC is computed as: $z_k = (\theta - \theta_{0\%})/(\theta_{100\%} - \theta_{0\%})$.



- It is reasonable to wonder what is the coupling between SOC and cell voltage? Maybe I can infer SOC by measuring voltage?
- Cell voltage depends on temperature and electrode particle *surface* concentrations, but SOC depends on particle *average* concentrations.
  - Surface and average concentrations will not generally be the same.
- Furthermore,
  - Changing temperature changes cell voltage, but not average concentrations, so does not change SOC;
  - Resting a cell changes its voltage but not average concentrations, so does not change SOC;
  - History of cell usage changes steady-state surface concentration versus average concentration (hysteresis).
- In summary, SOC changes only due to passage of current, either charging or discharging the cell due to external circuitry, or due to self-discharge within the cell.
- So, we will find voltage useful as an indirect indicator of SOC, but not as a direct measurement of SOC.
- How about current? SOC is related to cell current via

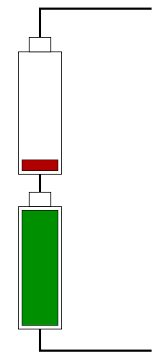
$$z(t) = z(0) - \frac{1}{Q}\int_0^t \eta i(\tau)\,\mathrm{d}\tau.$$

  - Cell current is positive on discharge, negative on charge.
  - η is cell coulombic efficiency ≈ 1 but ≤ 1.
  - Q is the cell total capacity in ampere seconds (coulombs).
- Note, total capacity Q is a measure of the number of locations in the electrode structure between $\theta_{0\%}$ and $\theta_{100\%}$ that could hold lithium.

- It is not a function of temperature, rate, etc.

■ Estimating SOC via this relationship is called "coulomb counting." We'll see in Chap. 3 that this method has some serious limitations.

■ One final point here when discussing SOC is the issue of "pack SOC."



■ Consider the picture to the right. What is the pack SOC?

- Should it be 0 % because we cannot discharge?
- Should it be 100 % because we cannot charge?
- Should it be the average of the two, 50 %?

■ The term "pack SOC" is ill-defined, and should not be used.

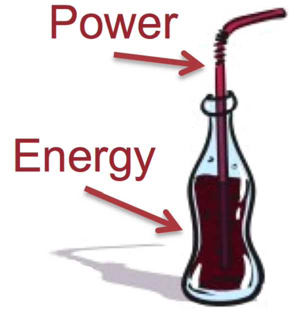
■ One issue this points out is the need for cell balancing—we'll look at this in Chap. 5.

■ Another is to bring up why "pack SOC" might even be something we desire to know.

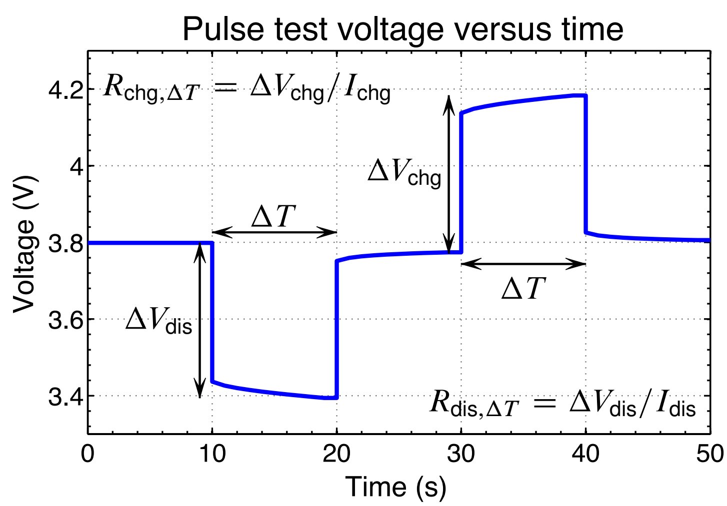
- Setpoint control: Average SOC might work for this;
- Fuel gauge: Real issue is battery pack energy.

1.7: Requirement 4b. Energy and power estimation

Cell total energy versus cell power



- Energy is an ability to do work, and is a total quantity measured in Wh or kWh.
- Power is rate at which energy can be moved without exceeding cell or electronics design limits, and is an instantaneous quantity $P = IV$ in W or kW.
- Dis/charging at too high a power level will accelerate cell degradation and lead to premature battery pack failure.
- We calculate cell power to enforce design limits (*e.g.*, on cell voltage and current), predictive over the next ΔT seconds, updating at a faster rate than once every ΔT seconds.
- We will talk later about advanced methods to compute cell power.

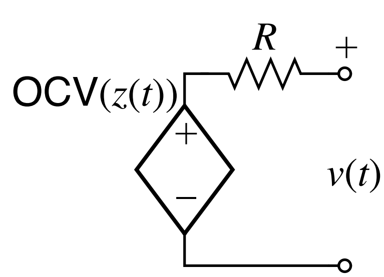


- In the meantime, we introduce a simple (and commonly used) approach.
- Run cell tests; tabulate cell resistance at different SOC and temperature setpoints.
- We assume a simplified cell model

$$v(t) = \text{OCV}(z(t)) - i(t)R,$$

or

$$i(t) = \frac{\text{OCV}(z(t)) - v(t)}{R}.$$



- To compute a power estimate, we first assume we are concerned only with keeping the terminal voltage between v_{min} and v_{max}.
- For discharge power, set $R = R_{\text{dis},\Delta T}$ and clamp $v(t) = v_{\text{min}}$. Then,

$$P_{\text{dis}} = v(t)i(t) = v_{\text{min}} \frac{\text{OCV}(z(t)) - v_{\text{min}}}{R_{\text{dis},\Delta T}}.$$

- For charge power, set $R = R_{\text{chg},\Delta T}$ and clamp $v(t) = v_{\text{max}}$. Then,

$$P_{\text{chg}} = v(t)i(t) = v_{\text{max}} \frac{\text{OCV}(z(t)) - v_{\text{max}}}{R_{\text{chg},\Delta T}}.$$

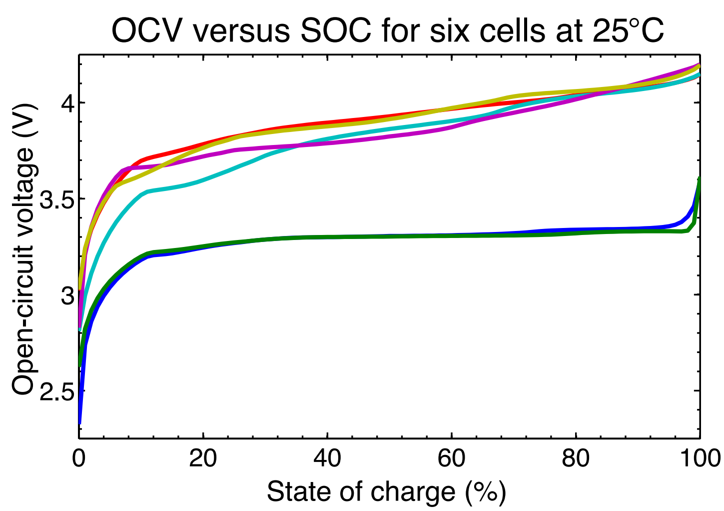
- Note that this quantity is negative. It is customary to report positive discharge and charge power, so we modify this last equation to compute instead

$$P_{\text{chg}} = v_{\text{max}} \frac{v_{\text{max}} - \text{OCV}(z(t))}{R_{\text{chg},\Delta T}}.$$

- We usually de-rate this estimate since the equations assume initial equilibrium condition.
- Cell total energy is equal to

$$E(t) = Q \int_{z_{\text{min}}}^{z(t)} \text{OCV}(\xi)\,\mathrm{d}\xi \approx Q V_{\text{nom}} \Delta z.$$

- Note: Total energy is not a function of temperature or rate.

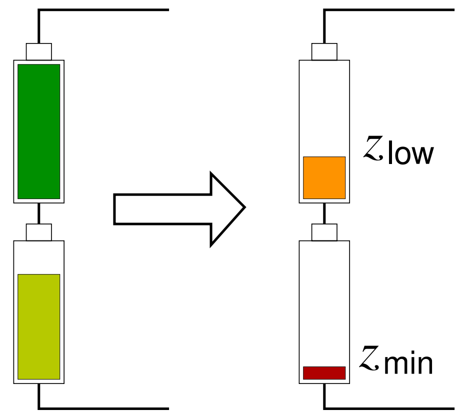


- However, it is impossible to get all that energy out at high rates and cold temperatures, which is why we need power estimates as well.

4d. Pack total energy and pack total power

- To compute pack power using the above approximate computation of cell power, simply multiply the lowest power value computed for any cell by the number of cells in the battery pack.
- To compute pack energy, first determine how many Ah will discharge the lowest cell to z_{min}.
- For this many Ah discharged, compute the resulting SOC of all cells:

$$z_{\text{low},k} = z_k(t) - \frac{\text{Ah discharged}}{Q_k}.$$



- Then, compute

$$E_{\text{pack}}(t) = \sum_k Q_k \int_{z_{\text{low},k}}^{z(t)} \text{OCV}(\xi)\, d\xi.$$

- Note: Integrated OCV is stored in table for instant computation.

5. Diagnostics

- The battery management system is generally required to report a “state-of-health” or SOH estimate for the battery pack.
- This is not a precisely defined term.
- Generally, it is a quantification of the cell aging processes.
- Two measurable indicators of cells are its present capacity and resistance. Over life,
  - Capacity decreases 20 % to 30 %: known as “capacity fade.”
  - Resistance increases 50 % to 100 %: known as “power fade.”

- Estimating R_k and Q_k as the pack operates will give indicators of life. We study this in Chap. 4.
- Some also define a "state-of-life" or SOL metric, which tries to predict how much life remains as a percentage or calendar time.
- The issue is that the future rate of cell abuse may not be the same as the past, so aging may accelerate or decelerate.
- It's more useful to know the state of the internal physical degradation mechanisms instead of only R_k and Q_k, as addressed in Chap. 7.

Where from here?

- The focus of the rest of the course is how to estimate the battery internal state, and how to control battery operation for optimal tradeoff between life and performance.
- All future discussion requires a more detailed understanding of how batteries work and how to represent that mathematically.
  - So, our next step is to review some helpful battery models.
- Note also that many/most of the methods we talk about are patented and owned by EV-related companies.
  - This is true even of methods commonly found in the literature—most have been developed by companies for their own use.
  - Strongly motivates research to develop methods that are sufficiently different from those that have been patented, so that they may be implemented freely (or, so that you may patent them!).
  - But, it also means that you may not use these methods commercially without license from the patent owner.