Week 4 : BMS Design Requirements

Week 3 focused on requirement 1 of BMS which is sensing and high-voltage control. Week 4 will focus on the other requirements (4); which are:

- Protection
- Interface
- Performance management
- Diagnostics

#1 BMS requirement : Protection

BMS must provide monitoring and control to protect in two (2) different ways:

i Protect the battery pack cells from out-of-tolerance ambient conditions.
ii Protect 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.
- It is important to isolate the damage caused by short circuit in the cell so that it does not propagate to other cells in the battery pack.

N.B: voltage is often considered as driving force, while current is the result of that force. Electrocution is primarily caused by electric current through the body. While voltage is the driving force that create current, it is the current itself that causes harm.

*** What to protect against**

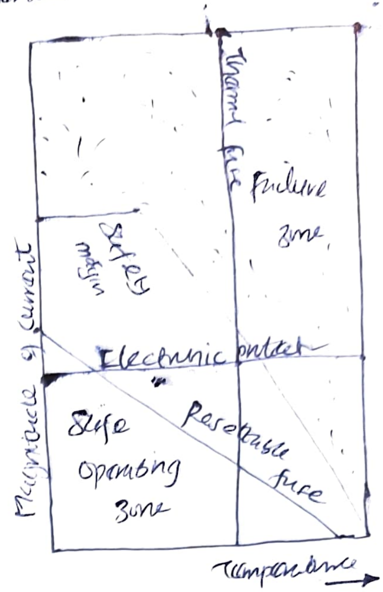
Different applications and different cell chemistries require different degrees of protection

- 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:

i Excessive current during charging or discharging
ii Possibility of and a response to a short circuit must be considered
iii overvoltage & under voltage
iv Think of high ambient temperature and overheating
v Ground fault / loss of isolation
vi Abuse to battery pack

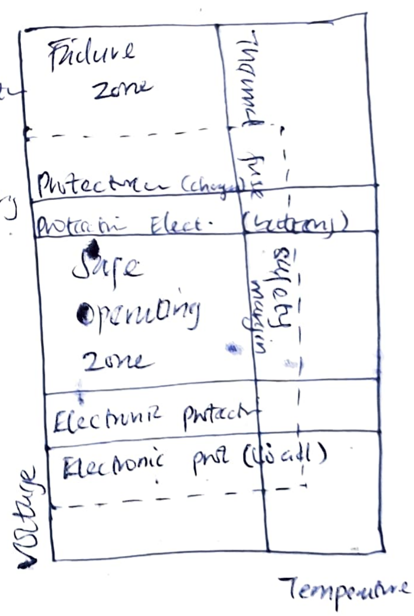
* Overcurrent / Over-temperature Protection

We should also consider what happens if protection mechanism itself fails. Whenever possible, redundant protection (fall back) paths should be implemented



- The "dotted region" is the unsafe region of operation of battery pack in terms of temperature and current magnitude
- Anywhere aside the region is technically an acceptable point at which the battery can be operated.
- However, leaving a safety margin in design is essential which is the "safe operating zone" in the diagram
- The safe region might include a thermal fuse, so that whenever the temperature increases beyond the fuse set point temperature, it trips.
- A resettable fuse is characterized by the diagonal line that is a function of both current and temperature.
- Before it reaches failure zone, 2 safety mechanism has completely tripped or damaged.

* Overvoltage / Over-temperature Protection



As shown in the diagram, the thermal fuse can protect against over temperature. Different kinds of electronic protection can protect against overvoltage and undervoltage.

- The most likely cause leading to overvoltage is when charging the battery pack, when plugged into a charger. The charging system might have its own overvoltage circuitry or software based undervoltage detection.

Examples of protection devices include:

- Thermal fuse: Opens contactors when temperature is above some limiting temperature

$$T > T_{limit}$$

- Conventional fuse: it operates when it heats up internally, and an internal element vaporizes basically.
- Active fault detection: BMS monitoring for fault conditions

* Fault detection / Tolerance

In addition to protecting the battery pack for environmental conditions that compose safety hazards, we also need to be able to build into our design the ability to detect operational faults, withstand, and rectify faults when possible

- Static-front BMS uses processors having dual CPUs cores. These cores execute the same instructions at slightly different time offsets and then compare the result of the instruction against each other.
- In a master-slave BMS, the slave systems can often detect cells faults without any additional input processing by the master.

* Standards

There are different international safety standards. For example, if designing for

i Passengers cars having maximum gross vehicle mass up to 3500kg fall under ISO26262:2011

ii Electric motorcycles fall under ISO/PAS 19695:2015 (similar to ISO26262).

iii Larger trucks over 3500kg, such as Ford F250, 350, Chevy Silverado 2500, as well as semis, buses) fall under IEC61508

Since there are different safety standards, it makes it difficult to have one universal BMS that can apply to any applications.
- Use different "safety integrity levels" (SILs), evaluated in different ways
- Very difficult to design to all these standards simultaneously.

40% of codes written in BMS are for safety standards.

* Summary

1. It is critical to protect battery pack operator and pack itself
2. Good design practice to require multiple protections to fail before pack itself fails
3. Redundancy of sensing and processing enables fault detection
4. Standards ~~design~~ informs best-practices designs, robust fault-tolerant implementations.

#2 How BMS interface with other System Components

* Requirement 3: Interface

The interface includes communication, charger control, data recording for diagnostic purposes, and auxiliary task such as range estimation.

- Communication via CAN bus

Control Area Network (CAN) bus is exclusively ISO standard for on board vehicle communications. In automotive application, it is the universal way of communicating between electronic components in the vehicle.

CAN is designed to provide robust communications between two processors in a very demanding and harsh automotive environment; where there are high levels of electrical noise. The CAN bus uses 2 wires and communicates in a serial fashion, one bit at a time between the two processors.

It is designed to network intelligent sensors and actuators and processors together and it is able to operate at two rates simultaneously.

i. **High Speed** (eg 1 million bits per seconds or one million Baud): used for critical operations such as engine management, vehicle stability, and motion control. things that are performance-critical and safety-critical.

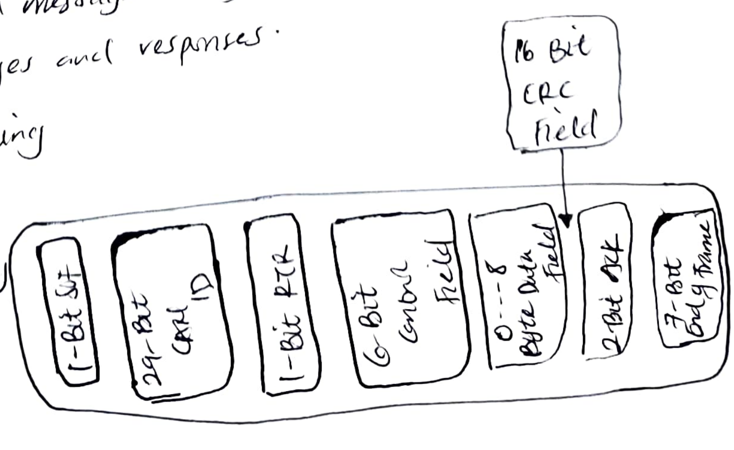
ii. **Low Speed** (eg 100 K Baud): Simple switching and control of lighting, windows, mirror adjustments and instrument displays where safety & performance aren't critical.

* Format of CAN-bus packet

The CAN bus protocol defines how to transmit information between two different entities connected on the bus in the following ways:

- Gives method to address the messages to a specific destination device connected to the bus
- Defines the data format to be used in the message
- Defines the transmission speed of the high-speed and low-speed aspects of the protocol.
- Defines priority settings for a message being transmitted on the bus and it also defines sequencing of messages and responses.
- Error detection and handling
- Control signal

- Data frames are transmitted sequentially over the bus



RTR = Remote Transmission Request

29-bit identifier for the address of the recipient of the message. 6-bit control field describes what the message is all about. The main part of the message is a data field with the information that has to be transmitted across the wire, across the bus from the transmitter to the intended recipient.

Followed by a checksum that's used to detect whether there have been any transmission errors in the message and the checksum is often called a cyclic redundancy check or a CRC check.

The next field is a two-bit acknowledgement field that's used to acknowledge correct receipt of a message. And finally, the message concludes with a seven-bit end of frame or EOF, which is combined with the one-bit start of frame puts bookends on the message, so that the recipient knows that the entire message has been received correctly.

* Charger Control

Battery packs are charged in two ways:

1. **Random**: Charge delivered is unpredictable pattern; e.g. regenerative braking. Regenerative braking is used for only a portion of the overall braking needs, but it does help to increase efficiency.

2. **Plug-in**: for EV/PHEV/E-REV
In this application, it's possible to communicate directly from the battery pack through the host application to the charger, to control the charger's output current or power more directly. The routine of plug-in charging often follows what we call a constant power, constant voltage mode.
Lithium ion cells can safely accept much faster charging when they are warm than when they are cold. Some BMS implement heating that activates when the vehicle is being charged, when it's plugged in. The heating system is powered directly from the grid, so battery energy is not wasted in order to activate these heaters.

* What limits Fast Charging?

The most passenger vehicle of moderate size require between 200-300 Wh per mile traveled. The battery pack must be between 60-90 kWh of capacity.

- For 300 mile range, the battery pack must be between... If we're to charge the entire battery pack in 3 minutes which is roughly the time it takes to fill a gasoline tank of a standard automobile, then it would require a power transfer at the rate of about 1.8 MW
- In the US and household standard circuit, electrical power is provided at 110V AC, 15A or 1.5 kW and charging at this rate is termed level one charging. Level 1 service charges pack in 40-60h

- Domestic 30A, 220V or 6.6kW "Level 2" service charges pack in 10-15 hrs

Since most people don't drive 300 miles every day, Level 2 charging is generally considered sufficient for most vehicle applications.

- DC "Level 3" (CHAdeMO) fast charging, 500V, 125A can provide up to 80% charge in 30min
- Tesla "Level 3" fast charging for model S can provide 50% charge in 20min

Hence, the limit to how quickly we charge a battery pack is not truly limited to the battery chemistry. Instead, it's the electrical service to which the battery pack is connected.

The battery can also limit charge rates at high SOC and low temperature. So, present research on fast charging is concentrating on how can we accelerate the final 20 percent of charge and how can it be safely charged in low temperatures.

* Log book Function

For warrantee and diagnostic purposes, BMS must store a log a permanent record of unusual or abuse events. This record should include a description of what the abuse was:

- Abuse type: measurement out of tolerance, voltage, current, or temperature
- Duration and magnitude of abuse

It can also store diagnostic information that is ~~regarding~~ not directly related to any unusual event, but it could be useful in determining how the battery pack has been used over time.

- Number of charge/discharge cycles completed
- SOH estimates at beginning of each driving cycle

It can store the record in nonvolatile memory (e.g. flash memory) used in solid state drives in laptop or on a USB thumb drive.

* Range estimation

The most approach requires the BMS to compute an estimate of the present remaining range of the vehicle based on the amount of energy remaining in the LIB pack.

This is heavily influenced by environmental factors:

- Vehicle characteristics
- Terrains
- Are there a lot of hills, a lot of wind?

#3 BMS Requirement 4: Performance Management

The performance includes estimating SOC, power-limit computations, and having an ability to balance or equalize cells in a battery pack. Battery applications need to know two battery quantities:

- How much **energy** is available in the battery pack
- How much **power** is available in the immediate future

Knowing how much energy available is most important for applications such as EV:

- How far I can drive

Power is the rate of energy used. Knowledge of power available in the immediate future is most important for application like **hybrid electric vehicles**.

- tells whether I can accept to recharge energy quickly or whether I can provide energy quickly to accelerate.

Both power and energy are important for application such as **E-REV / PHEV** because they need to know how far they can drive also how quickly they can accelerate and decelerate.

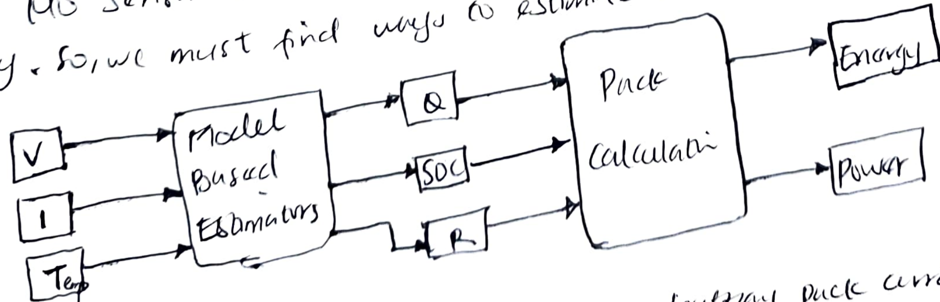
*** Why must we estimate energy & power**

It turns out that no sensor exists that's able to measure the available energy or power. Instead method is created to estimate the amount of energy and power.

- To estimate energy, we must know (at least) all cell state-of-charge **z_k** and capacities **Q_k**
- To estimate power, we must known (at least) all cell state-of-charge **z_k** and resistances **R_k**

*** Why must we estimate SOC, SOH ?**

No sensor exists that can measure state-of-charge or capacity or resistance directly. So, we must find ways to estimate the values!



The available input include cell voltages, battery pack current, and cell or module temperatures. Those basic measurement are used with computer models called algorithms to estimate capacity in state-of-charge and resistance.

* Quality of Estimates

There are both good and poor methods to produce estimates; poor methods are generally simpler to understand, code, and validate, but yield less-accurate results.

- Impacts of a poor estimator can be
  - Abrupt corrections when voltage or current limits exceeded leading to customer perception of poor drivability
  - Overcharge or overdischarge which damages cells
  - Compensating for uncertainty by overdesigning pack.

Kalman filters turns out to be the optimal way of estimating the internal state of some dynamic system when we have the ability to measure only the inputs and output of that system.

* Summary
- Application need to know battery available energy and power
- Can't measure; must estimate based on z_k, Q_k, R_k
- Can't measure; must be estimated using measured voltage, current, and temperature
- These also must be estimated using measured voltage, current, and temperature
- Kalman filter is the optimal way of estimating internal state.

#4 State of Charge

In Lithium battery, when discharging the electron leaves the negative electrode but when charging the electron moves from the positive to negative electrode.
When cell is fully charged, there will be a lot of lithium on the negative electrode.
So, SOC can be said to be physical quantity of how much lithium is present in the negative electrode particles. Or equivalently what is the concentration of lithium in the negative electrode particle of the battery cell

* What is physical basis for cell SOC?

The maximum theoretical concentration of lithium in electrode particle is $C_{s,max}$. C is for the solid particles of the electrode.
The concentration, s for the solid particles of the electrode.
The concentration of lithium in particle at time 'k' is $C_{s,avg,k}$
Average concentration of Lithium in particle

$$\theta_k = \frac{C_{s,avg,k}}{C_{s,max}}$$ stoichiometry of electrode (θ_k)

The stoichiometry is the number range between 0 and 1 and can be considered as a kind of an electrode state-of-charge.

- Electrode SOC is different from what is reported to user as a cell state-of-charge.
- Stoichiometry must remain between $\theta_{0\%} > 0$ and $\theta_{100\%} < 1$. So when a cell S.O.C is 0% stoichiometry for the electrode is actually a number bigger than 0.
- Cell SOC is (note: $\theta^{neg}_{0\%} < \theta^{neg}_{100\%}$, but $\theta^{pos}_{0\%} > \theta^{pos}_{100\%}$)

pos - positive electrode

$$z_k = \frac{(\theta^{neg}_k - \theta^{neg}_{0\%})}{(\theta^{neg}_{100\%} - \theta^{neg}_{0\%})} = \frac{(\theta^{pos}_k - \theta^{pos}_{0\%})}{(\theta^{pos}_{100\%} - \theta^{pos}_{0\%})}$$

*** How does SOC relate to cell voltage?**

Cell voltage depends on Li surface concentration on particles that contact positive and negative current collectors. If a sensor can measure average concentration directly, then we could be able to measure state-of-charge directly. No such sensor exist!

The cell voltage depends on the concentration of lithium at the surface of the particles in the electrode, and particular, at the surface of the particle in direct contact with the negative current collector.

SOC depends on average concentration of lithium and voltage depends on surface concentration at one point. Not a direct relationship between SOC and voltage. No immediate direct correspondents between cell voltage and cell state-of-charge.

- Changing temperature, which changes voltage doesn't change SOC
- Resting a cell, which changes voltage doesn't change SOC
- Entire current profile vs net current which changes voltage but not SOC

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.

- voltage useful as an indirect indicator of SOC and very helpful in SOC estimation. but not a good independent predictor of state of charge.

*** How does SOC relate to cell current?**

SOC is related to cell current via

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

eta

η - colombic efficiency $\simeq 1$ but ≤ 1

Q = cell total capacity in As (Coulombs)

cell current:

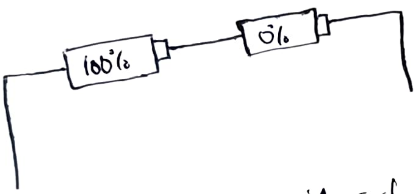
+ve on discharge

-ve on charge

NB: Q measures number of vacancies in the electrode crystal structure between $\theta_{0\%}$ and $\theta_{100\%}$ that could hold lithium; it is not a function of temperature, rate, etc. It is different from a discharge capacity what is commonly put on a data sheet for a battery cell.

- The equation is not very good for estimating SOC and yet is actually an exact representation of state of charge of the battery cell.
- Estimating SOC via this integral equation is called **"Coulomb Counting"**. It suffers very serious inaccuracies when we can't measure current perfectly or not knowing coulombic efficiency or no perfect estimate of the total charge capacity.
- Coulombs counting should never be used in a battery management system as primary state of charge estimation method.

* Battery pack SOC



- Should "Pack SOC" be 0% because we cannot discharge? NO
- Should "pack SOC" be 100% because we cannot charge? NO
- Should "pack SOC" be the average of the two 50%? NO

The term "pack SOC" is ill-defined and should never be used.
The battery pack should not end up in the situation as drawn above. Hence, balance the cell.

- Why might we even want to know "pack SOC"?
  - Setpoint control: Average SOC of all cells might work.
  - Fuel gauge: Distance to empty kind of calculation or a fuel gauged kind of calculation.

* Summary

- SOC has a real physical basis that can be connected directly to cell electrochemistry.
- If we know average Li concentration in either electrode, then

$$z_k = \left(\theta_k^{neg} - \theta_{0\%}^{neg}\right) / \left(\theta_{100\%}^{neg} - \theta_{0\%}^{neg}\right) = \left(\theta_k^{pos} - \theta_{0\%}^{pos}\right) / \left(\theta_{100\%}^{pos} - \theta_{0\%}^{pos}\right)$$

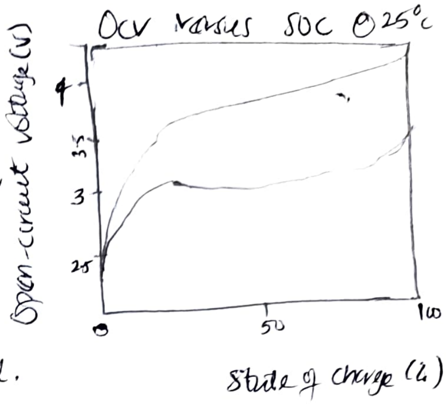
- Pack SOC doesn't make sense and should not be used.

#5 Available Energy and Power

* Cell total Energy Estimate

- Energy is an ability to do work, measured in Wh or kWh
- Cell total energy equal to

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



- The equation is not a function of the magnitude of current used to withdraw that energy. Not a function of temperature or rate.
  - It is impossible to get as much energy out of a cold battery cell, as it is to get out of a warm battery cell.
- The equation above shows how to compute how much energy physically present, but it does not tell how to extract all of that energy. And that is why power estimates is needed in addition to energy estimates.
- Power estimates tell how quickly energy can be extracted at a point in time.

* Cell available power estimate

Power limits state maximum rate at which energy is moved out of the battery cell or out of the battery cell, without exceeding electronics design limits or some battery electro chemical design limits.

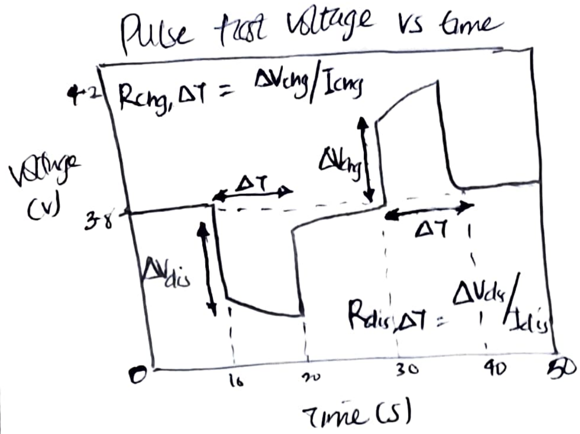
Dis/charging cell at too high a power level, the rate of degradation will be accelerated. This will lead to a premature battery pack failure.

Power is **instantaneous** quantity: $P = IV$ in W or kW

When power limits is computed, there is an immediate challenge. Estimate must provide **moving-window** power limits.

- Calculate to enforce design limits (e.g on cell voltage and current), predictive over ΔT second future time horizon → in order of 10 or 20 secs
- Update at a faster rate than once every ΔT seconds

Hybrid pulse power characterization (HPPC): Simple and commonly used approach for power estimates. It is based on performing a very simple test on a battery cell in the laboratory

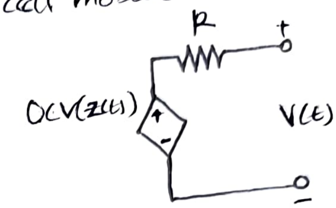


Once the calibration test is performed and have calculated resistance at different states of charge set points, different temperature, and have store these value in a table, then real time can be used to compute available power estimates.

*** HPPC discharge Power**

For HPPC discharge power, assume simplified cell model

$$v(t) = OCV(z(t)) - i(t)R$$



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

When HPPC method is used to compute the amount of discharge power, we assumed we are concerned only with keeping the cell terminal voltage between some V_{min} and V_{max} limits.

- For discharge power, set $R = R_{dis,\Delta T}$ and clamp $v(t) = V_{min}$

$$P_{dis} = v(t)\, i(t) = V_{min}\left(\frac{OCV(z(t)) - V_{min}}{R_{dis,\Delta T}}\right)$$

*** HPPC Charge Power**

Using same simplified cell model

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

N.B! This quantity is −ve
can multiply by −1 (take absolute value) if need to report as positive value

For charge power, set $R = R_{chg,\Delta T}$ and $v(t) = V_{max}$

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

HPPC method in general uses a very simplified cell model that does not include all of the effect occurring inside the cell. Hence, the equations above are not perfectly accurate on a dynamic scenarios for real battery cell.
- It is a common practice to derate the estimates produced by these equations by multiplying the computed power value by some factor slightly less than 1.

* Computing battery-pack available power

HPPC cell discharge power is computed

$$P_{dis}^{cell\,j} = v_j(t)\,i_j(t) = V_{min}\,\frac{OCV(z_j(t)) - V_{min}}{R_{dis,\Delta T,j}}$$

Computing power in series multi-cell battery pack, still clamp $v(t) = V_{min}$

Using minimum limiting current, multiply by number of cells in series

$$P_{dis}^{pack} = \sum_{j=1}^{N_s} v_j(t)\,i_j(t) = N_s V_{min} \min_j \left(\frac{OCV(z_j(t)) - V_{min}}{R_{dis,\Delta T,j}} \right)$$

Similarly, for charge (power (charge) = -ve)

$$P_{chg}^{pack} = \sum_{j=1}^{N_s} v_j(t)\,i_j(t) = N_s V_{max} \max_j \left(\frac{OCV(z_j(t)) - V_{max}}{R_{chg,\Delta T,j}} \right)$$

* Computing battery-pack total energy

Recall that cell total energy is computed as

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

Every battery could have different charge capacity & total state of charge. In a battery, each cell may have different Q_j and $z_j(t)$. However, computing battery pack energy is a three-step process:

1. Determine minimum Ah to discharge any cell to z_{min}
   - start with generic SOC equation

$$z(t) = z(0) - \frac{\text{Ah discharged}}{Q}$$

   - Set $z(0) = z_j(t)$, $z(t) = z_{min}$, $Q = Q_j$, rearrange

$$\text{Ah discharged} = \min_j Q_j(z_j(t) - z_{min})$$

2. For many Ah discharged, compute resulting SOC of all cells

$$z_{low,j} = z_j(t) - \frac{\text{Ah discharged}}{Q_j}$$

3. Compute total battery discharge energy

$$E_{pack}(t) = \sum_{j=1}^{N_s} Q_j \int_{z_{low,j}}^{z_j(t)} OCV(\xi)\,d\xi$$

* Using lookup table for efficiency

The energy integration computation can be done and stored in a look-up table for essentially instant computation in real-time environment

- integrated OCV can be stored in look-up table (LUT) for instant "computation"

```
% code
Iv3Ref = cumtrapz(zRef, ocvVec);        cumtrapz, - trapezoidal cummulation

Iv2 = interp1(zRef, Iv3Ref, max(zmin, z));
%
```

* Summary

- Estimates of battery-pack power can now be computed over future time horizon and battery pack total energy by expanding on how we computed cell power and energy.

#7 Battery Requirement 5: Diagnostics

Diagnostics involve: Abuse detection, state-of-health (SOH) estimation, and state-of-life (SOL) estimation

* External abuse detection

BMS system is not in control of battery-pack destiny. It therefore provides guidance to host application regarding what are the maximum power limits of the battery pack and how much energy is available and so on. But the host application might choose to ignore those limits or might fail in some way that causes those limits to be violated - this might include a violation of voltage limit, current, power, or temperature limits.

BMS must detect and log external abuse.

All of the abuse conditions that are detected are logged for warranty and post mortem diagnostics.

* Internal failure detection

BMS must be able to detect & log failure of its own algorithms and components. This includes detecting voltage, current, temperature-sensor failures, failure of balancing system, contactor failure, thermal management system failure, loss of communication.

* State of Health (SOH)

BMS must be able to compute and report an estimate of the state of health of the cells of the battery pack. SOH is not defined quite so precisely. It is generally trying to quantify how much a cell has aged to that point in its life.

- Two (2) measurable indicators of SOH
  - i Capacity; which starts out at 100% and decreases by about 20-30% before we consider that cell to have reached its end of life (Capacity-fade)
  - ii Resistance of a battery starts from a certain value and might increase 50% to 100% over the lifetime of the battery cell. (power fade)
- Estimating R_k and Q_k as the pack operates will give indicators of life.

SOL (state of life) tries to predict how much life remains as a percentage or an absolute value in terms of calendar time.

N.B: State of Health (SOH) is an estimate while State of Life (SOL) is a prediction

ii) SOH uses past & current data to estimate a current condition of the cell. SOL attempts to predict what will happen with the cell in future

iii) Future rate of cell abuse and aging may differ from past so SOL tend to be quite inaccurate

Summary (Week)

BMS Requirement;

1. Sensing & high-voltage Control
2. Protection
3. Interface
4. Performance Management
   SOC, SOH, SOF $\longrightarrow$ State of function (power)
5. Diagnostics