Week 3: BMS Sensing & High voltage Control

#1 Introduction and BMS functionality

BMS is an embedded system made from purpose-built electronics combined with purpose-built software or processing to enable a specific application. It has a large number of electronic components on a circuit board.

The electronics of the battery management system generates heat that must be managed by the thermal management system of the vehicle. So, the circuit board of BMS is housed in a metal case using **thermally conductive paste** so that there's good thermal conductivity but bad electronic conductivity between the components on the circuit board and the metal casing.

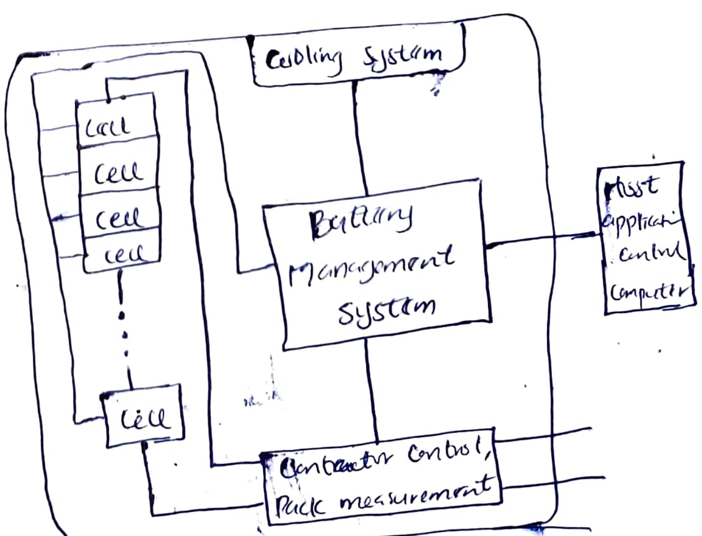
* Why do we need BMS?

A BMS has the following priorities:

- Safety: protects safety of the operator of the host application; detects unsafe operating conditions and responds
- Protect the pack (battery) itself especially if the host application fails in some way and is beginning to cause abuse to the battery pack. In many cases, the battery pack has authority to detect these conditions and to disconnect from the load.
- Prolongs life of battery as long as possible under normal operating conditions. It is done generally by informing the host application what is the maximum power that can be drawn from the battery pack or that can be sunk.
- Maintain battery pack in a state in which it can fulfill its functional design requirements. In automotive application, it may be required that under every circumstance, retain enough reserve in the battery pack
- Performance: BMS informs the host-application how to make the best use of the battery pack right now. (e.g power limits), control charger, e.t.c

* General BMS Functionality

- BMS is interconnected with all battery-pack components and with host-application control computer
- Functionality can be broken down into several categories:
  1. Sensing and high-voltage control
     - measure voltage, current, temperature
     - control contactors using pre-charging
     - Ground fault detection or isolation fault
     - thermal management



2. Protect against
- protection against overcharge, over-discharge, over-current, short-circuit and extreme temperature

3. Interface
- It might have to do with computing remaining range in an electric vehicle
- Communication with host-computer
- Data reporting and reporting

4. Performance management
- estimation of SoC of the battery cells, estimating power limits
- how much energy available and balancing/equalization of the cells

5. Diagnostics
- detecting abuse of the battery pack by the host-application
- determining SoH and SOL (state of life) estimation.

* The issue of cost
There is a cost associated with battery management, so not all applications implement all features.(functionality)

Rule of thumb (not mathematically derived but based on experience of experts) : Your battery is "cheap enough" if you cannot remember when you replaced it last.
Literally, inexpensive batteries really don't need to last very long. but large expensive batteries need to last as long as physically possible.

- Larger battery packs represent greater investment and motivate better battery management, even if there is an associated cost.
- This specialization focuses on large (e.g vehicular, grid) battery packs although the methods are quite general for consumer (laptop or phone) batteries.
  electronics

* Summary
1. A BMS is an embedded system that protects safety host-application operator, protect battery from abuse, prolong battery life, maintains battery in a functional state, and inform host application how to make the best use of the pack right now.

2. The BMS functional requirement fall into (5) general categories.
   i Sensing, high-voltage control
   ii Protection
   iii Interface
   iv Performance management
   v Diagnostics.

#2 Reasons for modular Design

BMS for large application usually involve batteries from which there will be a high power demand. High-power battery deliver high voltage, high current, or both.

- High power demand is met by maximizing the voltage of the battery pack. But the chemistry of individual battery cells is going to limit the maximum voltage. So for high-voltage packs, we must stack cell in series:

$$V_{pack} = n_s \cdot V_{cell}$$

- Cell construction places limits on cell current, so for high-current packs, we must wire cells in parallel:

$$i_{pack} = n_p \cdot i_{cell}$$

- Similarly, capacity in ampere hours scale as: $Q_{pack} = n_p \cdot Q_{cell}$

- Therefore, total pack energy and power can be computed as:

$$E_{pack} = n_s \cdot n_p \cdot Q_{cell} \cdot V_{cell}$$

$$P_{pack} = n_s \cdot n_p \cdot i_{cell} \cdot V_{cell}$$

To meet energy/power specifications, the product of n_s and n_p must meet some criteria, but the individual values of n_s and n_p are flexible.
series parallel

* Series & Parallel Cells

To chose the number of cells in series & parallel, the choice is usually made by economic factors and by safety factors.

- For safety: overall battery pack voltage to be less than 100V DC
  $V \leq 100V$ (sometimes $\leq 50V$). This factor turns out to be a little bit arbitary. It is possible to have safety hazard at lower voltages or still even to be relatively safe at higher voltage depending on the environmental conditions.
  - National Fire Protection Association (NFPA) recommend voltage limit of 50V DC historically but value raised to 100V DC more recently
- The power electronics required for operating at voltage larger than about 600V is quite expensive. Hence, to minimize power electronics cost, most applications require voltage $\leq 600V$. This consideration limit n_s
- For efficiency, you want to minimize current to reduce i^2R losses due to wiring (and want to use thin higher R wire to reduce copper costs). In order to reduce resistance, we need for thicker wire with more strands on the wiring.
  → this consideration limit numbers of cells in parallels (n_p)

So, packs often designed using modules having voltage ≤ 100V, which are then wired in series for a high-voltage pack. • Building a battery pack for vehicle application, cells tends to be wired in series more than they're wired in parallel.

e.g "2P3S" pack / modules

↳ i.e 2 cell in parallel, 3 cells in series

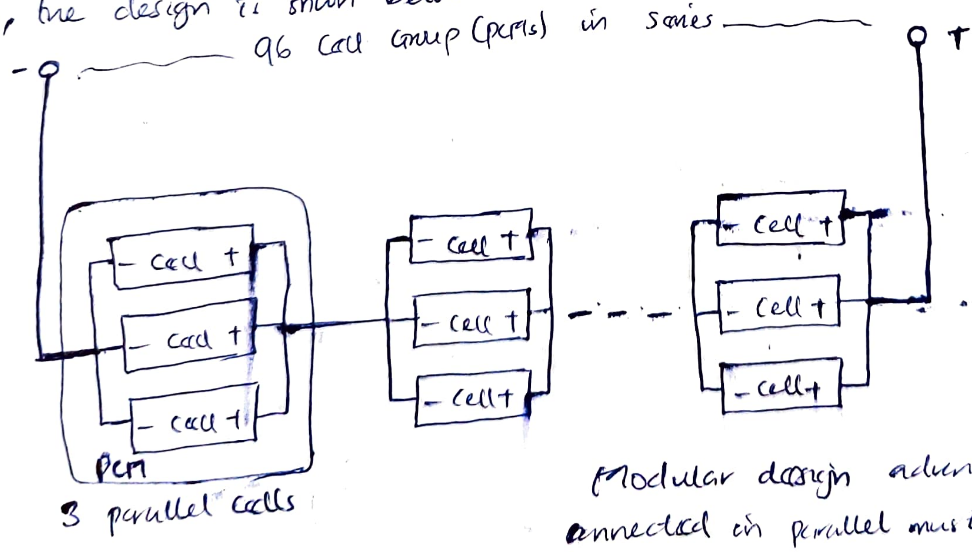
* Example of Nissan Leaf

- Most automotive battery packs manufactured from identical modules (e.g, Leaf pack comprises 48 "2S2P" modules)
- Smaller modules are easier to handle by humans or robots assembling the battery
- Individual module can be tested before integrating them into the pack
- Ideally, the overall battery pack design would be made from multiple instances of the same module design and ideally the same module could be used in different battery packs, to reduce non recurring ~~eng~~ engineering costs (NRE) costs, to design the battery module would be amortized over many products.

* Design of Modules

- Design Extreme 1: Parallel-cell modules (PCM)

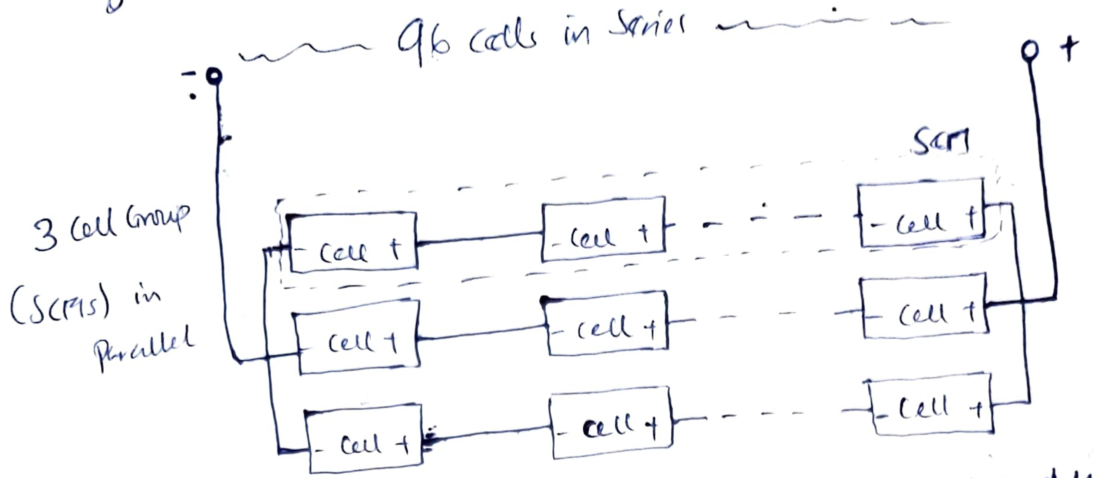
Suppose that I need 3 cells in parallel and a battery pack of 96 cells in series overall, the design is shown below.



Modular design advantage: Battery cells connected in parallel must maintain the same voltage electrically & physically because of KVL Kirchoff's voltage law. Hence, we need to measure one voltage per every three cells which reduces the cost of voltage sensing & BM algorithms.

For the same reason, the individual cells inside of these PCMs will self-equalize or self-balance because they must maintain the same voltage overall.

- Design extreme 2: Series cell modules (SCM)



In this case, 96 cells are connected in series to make 1 module called a series cell module or SCM. Three (3) of the SCMs are connected in parallel but only at the higher voltage terminals, not individual cell voltage terminals.

- The complexities; it is required to measure the voltages of all cells, which is true of any case for Lithium-ion BMS. In this case 3 × 96 = 288 cells are to be measured because they could potentially all be different whereas in PCM approach each module of three cells will have guaranteed the same voltage by KVL.

- In SCM approach, individual cells will tend not to balance each other automatically and some additional requirements for balancing circuitry.

- There is one advantage of SCM approach in some application. Building a modular battery pack out of SCMs allows to have same overall battery bus voltage with different capacity depending on how many SCMs installed in the application.

Most battery packs are some combination & compromise between both extremes (PCMs or SCMs). For example: 18-cell "3P6S" module: Module power & energy) with approximately 18x that of a single cell (but not quite, in practice).

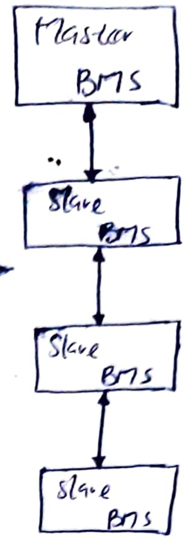
* Battery Architecture

A modular battery pack suggests a hierarchical master-slave BMS design as well. For example, we might have some of the electronics dedicated most directly to managing individual cells that are located inside of the module of cells they manage.

- One "slave" BMS unit is associated with each module
  - module's cells welded/bolted to slave PCB, minimizing wiring and wiring losses.
  - Slave BMS has all of the electronics for measuring voltages, for measuring temperature, and for balancing the individuals cells.

There is commonly a single master unit for every battery pack and the master unit does the supervisory control of everything overall.

- Master measures pack current, control contactors
- Communicates with slave via daisy-chain or star architecture
  - daisy-chain architecture tends to be the most popular to reduce wiring. as shown



* BMS Slave role

- measure voltage of every cell within the module
- measure temperature: to connect to off board thermistors to be able to do that.
  - from algorithmic point of view, we'd love to measure temperature of every single cell independently, instead, most battery packs use only one or two temperature sensors per module. Thus, using some kind of interpolation or extrapolation method to estimate the temperature of the other cells on the module.
- Balance the amount of energy stored in every cell within the module
  - Each battery has different efficiency, self-discharging rates and so on. because of that, it is required to equalize the level of charge in individual cells. either by draining charge out of cells that have more energy than others or by moving charge from cells having more energy to other cells.
- Communicate all of the information that it measures and collects back to the master so that algorithm can process this information in the master unit. It can use a serial bus where the master can communicate over a daisy-chain bus to the individual addressable components or to all of the components at the same time using a broadcast message.

* BMS Master role

- controls the contactor of the high-current switches that connect the battery cells of the battery pack to the load and also disconnect the battery pack from the load.
- monitors the battery pack current and measuring isolation between high-voltage battery pack and the chassis of the load.
- Communicate with BMS slaves using a serial communication bus and it also communicate with the host-application.
- The master BMS controls the thermal management

* Slave Design Reusability

One important benefit of a master-slave design is that many aspects of the design can be reused from one application to another. We don't have to redesign the electronics starting from zero-scratch whenever we build a new BMS for a new application.

- It is possible to reuse a slave design, assuming electronics used are flexible in terms of number of cells monitored, physical sizes matches or fit into different package required by different applications.
  - While electronics design may be reusable in most cases, it can be necessary to redesign the circuit board (PCB) footprint to fit in different applications.
  - For high volume production, it is good to optimize the slave design for that particular application in order to save cost.
- Different cell chemistry need different voltage and temperature ranges, but these can often be accomodated via simple software changes. It turns out that 5 volts voltage range is pretty common, so it's quite easy to design the slave electronics to be able to handle any lithium-ion chemistry presently on the market.

* Master Design Reusability

It is often more difficult to reuse the master design. The master needs to be more flexible

- different applications require different number or types of contactors
- types of current sensors used
- ways to connect the battery pack charger and different types of thermal management system

It is possible to reuse the design of a master and a BMS but this can be accomplished only by incorporating quite a lot of flexibility using additional analog inputs & output and digital inputs & output than might be required in a special purpose design.

* Summary

1. For high energy or high power, we need to configure cells in parallel & series in high capacity battery packs.
2. Safety and cost limit numbers of cell in series; losses vs cost give tradeoff for number of cells in parallel.
3. Modular design has advantages in handling, testing, and reduced NRE cost
4. Modular pack design also motivates master/slave topology for BMS
   - Slave handle voltage/temperature measurement & balancing
   - master handles current/isolation sensing, contactor control, and thermal management

#3 Cell voltage Sensing

* Battery-pack voltage sensing

If lithium ion battery cells were overcharge by mistake, it could lead to thermal runaway. Thermal runaway happens when heat builds up in a cell which causes the separator to melt, causing an internal short circuit and further heat buildup and the reaction becomes self-sustaining.

At the most basic level, voltage is measured using a circuit that is known as an analog-to-digital converter (ADC, A/D, A-D, A2D, or A-to-D). An analog-to-digital converter samples the voltage level at its input and converts the voltage level into a binary pattern of ones and zeros inside of a special purpose integrated circuit or inside of a microcontroller having a built-in ADC

There are several common ADC architectures; for example,

- A direct-conversion or flash ADC uses a bank of comparators and fixed reference voltages, outputs code of closest reference (fast, expensive). This technology is the fastest of all the ADC methods and it's essentially instantaneous.
- Successive approximation: it guesses at what the voltage might be then output voltage corresponding to that guess using its digital-to-analog converter. It then uses a single comparator to see whether the voltage produced by the guess is above or below the voltage at the input that it's trying to measure. It is a somewhat slow approach because of the need to repeatedly make the guesses, but it is very inexpensive approach to implement. Summarily, successive approximation compares input to output from DAC (digital-to-analog converter) and uses feedback to modify DAC signal, resolving input to desired accuracy (slow, inexpensive).
- Delta-Sigma ($\Delta\Sigma$): it is ~~ap~~ adopted in many applications. It's known as a sigma-delta or sometimes as a delta-sigma approach. The method is somewhat similar to successive approximation approach, because it guesses what the voltage is and produces a voltage at its output corresponding to that guess. It uses a one-1 bit flash analog-to-digital converter which requires only a single comparator to encode that difference between the approximation and the input trying to measure. It uses oversampled 1-bit flash ADC to encode difference (Δ) between approximation and input, sums (Σ) differences and filters to give final high-resolution result at desired slower sample rate (very popular).

Regardless of the methods used for ADC, each of these is usually implemented on a specialized integrated circuit (IC), because of the need to precisely match all of the resistance and capacitances and all of the components involved in making the circuit.

* Resolution of an ADC

When designing a BMS, analog-to-digital converter for the design must be selected and there are several criteria one should be aware of. The first is the resolution of the converter.

The resolution of an ADC is the smallest change in the input signal that can be measured. It's the step size between consecutive converter output codes in voltage. Consider an ADC that has M-bits as its output, that is, it has 2 to the power M 2^M output codes. If these codes happen to be distributed evenly over the entire input range, then the range of input from the lowest voltage to the highest voltage called EFSR where FSR means full-scale range. If evenly distributed, the resolution:

$$\frac{E_{FSR}}{(2^M - 1)}$$

For example, consider a converter (ADC) which has input range of 0V to 5V and has 16 bits of precision, the resolution Q is

$$Q = (5V - 0V) / 2^{16} - 1 = 76 \mu V$$

microvolts

Resolution of 76 μV is a common value

The smallest change to output corresponds to a single bit change on the least significant bit position of the output. So the resolution of an analog to digital converter is often called the LSB voltage → Least significant bit voltage of the converter.

* Accuracy of an ADC

Another consideration when choosing ADC is its accuracy. The accuracy of an ADC has to do with the absolute difference between the reported value and the true value. The differences might arise due to several causes

i. Inaccuracy of quantization: unmeasurable part of true voltage and unmeasurable part has magnitude that is less than one-half of this resolution
→ unmeasurable value between $\pm \frac{Q}{2}$

ii. **Offset error:** Offset is a constant difference; a constant bias between the ideal measured value and the reported measured value that spans the entire measurement range of the converter. Offset can be caused by biases in the electronics, either internal or external to the converter

- Gain error : The third source of inaccuracy of the converter is gain error. If the actual conversion process has different slope in input/output relationship of an ideal conversion process, there is a gain error in the conversion. The gain error is usually expressed as a percent (%)
- Nonlinear error : It is any departure from the actual and ideal step width in the conversion. It is often expressed on the number of analog to digital (ADC) converter counts.

* Other ADC considerations

i Temperature:
The offset and gain & non-linear errors are all functions of temperature.

ii Timing jitter:
It is when the absolute time difference between samples made by the converters is not exactly constant

iii Aliasing:
- This is not so much a function of the converter itself, as it is a function of the fact that we look at a continuous time signal that only snapshot at discrete points in time, not at every single point in time. In control theory and signal processing, Nyquist sampling theorem states that the sample rate should be at least twice the highest frequency in the input signal.
- Otherwise, high-frequency inputs will be alised as low-frequency signals on the sampled signal.

One factor to our advantage when designing a sample radius, that battery cells have long time constants and they are quite slow devices. We don't need to sample the amp of volt ages at a very high rate due to the dynamics of the battery cells themselves. However, it might be more important to sample the input voltage quickly if the external load has some very fast time constants.

In automotive application, the battery pack is connected to a device called an inverter that drives the motor. The inverter has power electronics inside of it that often have switching frequencies in tens of kilohertz. BMS algorithms help to mitigate the effect of noise from the inverter and still provide good estimates of state of charge and SoH.

* Chipsets

Because high power battery packs usually comprise many battery cells and series, it's not efficient to use discrete A/D components to measure all of the voltages and all the cells. Instead, there are different integrated circuits (IC) or chipsets for the specific purpose of aiding high-voltage BMS design.

- Special chipsets are made to aid high-voltage BMS design
  - Low-cost "dumb" measurement chips used in modules or slave units close to the battery cells which transmit voltage measurements to a master unit and the master unit does all processing for SOC & SOH estimation.
  - Special chips implement difficult task of highly accurate A2D voltage sensing with high common-mode rejection and fast response in high-EMI (electromagnetic interference), high-heat and high-vibration environment.
  - These chips are also often designed so that they can be placed in parallel for redundant and fault-tolerant design. If different chips that are expected to provide exactly the same voltage measurement produce different measurement, hence one of these chips is faulty.
  - The master unit then inform the application that there is a fault in the BMS that must be investigated and repaired.
- Multiple vendors make chipsets to perform their voltage measurements (e.g Analog Devices, Maxim, Texas Instruments).

* Example Chipset: LTC6811

LTC6811 designed by Analog Devices (formerly Linear Technology). Each of the integrated circuits, each of the 6811 parts is capable of monitoring up to 12 cells in series in a module. Multiple of this chipset can be placed in series in a daisy-chained slave architecture, so that overall, 100s of cells in series in a battery pack can be monitored.

In order to facilitate the connection of measurements from one slave to another, this chip has built-in isolated electronics for communication between the parts. It is very highly noise immune that allows for very robust communication in noisy environments.

This chip also supports both internal and external cell equalization circuitry either using passive balancing or connected to an active balancing solution. The chipset can be powered by the battery module itself.

This chip is able to measure up to five (5) temperatures directly. It can also be configured with some external circuitry to measure more temperature than that is required.

* Selecting a chipset
- How many cells are wired in series in the battery pack compared to how many cells each integrated circuit is able to monitor?
- How many cells in total can be monitored using however, many number of chips?
- Whether the chipset supports passive/active balancing?
- What is the measurement accuracy?

- must be able to measure a sufficient number of temperatures for inputs to the BMS algorithms.
- In order to minimize overall system cost, you need to minimize the number of wires needed to communicate from one integrated circuit (IC) to another in between different slave units to the master BMS. How many wire to communicate from IC to IC?
- What is the chipset availability and cost, per cell?

* Summary

1. All battery cell voltages on a lithium-ion battery pack must be monitored continously during operation
2. This is done using an analog-to-digital converter, generally built into an IC
3. Resolution and accuracy are A2D features that must be considered in design.
4. Special chipsets are available from several silicon vendors to monitor high capacity battery packs. eg LTC 6811

#4 Temperature Sensing

Battery cell operational characteristics and cell degradation rates depend very strongly on temperature. For example, electrical resistance of a battery often quite low at warm temperature and quite high at cold temperature. We can get more power out of the battery cell at warm-temperature because of the lower resistance than we can at cold temperature.

The rate of degradation is a strong function of temperature. Battery cells tends to degrade much more rapidly at warm temperature than they do at cold temperatures. When BMS is controlling the thermal management system, it needs to know the temperature of the battery cells in order to do so properly.

There are **exception** to the general rule that degradation happens most quickly at warm temperature. For example, at very cold temperatures, there can be extremely rapid degradation if we attempt to charge a battery cell. **Lithium-plating** can happen at very quickly degrades the cell and even result in a safety situation.

- So it's common not to charge lithium-ion battery cells when the temperature is colder than 0°C
- Unexpected temperature changes can indicate cell failure or impending safety concern.

In an ideal situation, we measure each cell's internal temperature, but,
- inserting temperature sensor into the packaging is not really feasible. So it is mounted external to some of the cells. Since temperature difference across a well-designed battery module are relatively small, only a few temperature sensors placed at strategic locations in the battery model or pack and a thermal model is used to **interpolate** and **extrapolate** among these measurement to come up with estimates of temperature at every cell location

* How to measure temperature: **Thermocouple**

There is no circuit that can directly measure temperature. Instead, temperature is converted into voltage related to that temperature and the voltage is measured using an analog-to-digital converter.

1. One method to produce a voltage proportional to temperature is to use a **thermocouple** which comprises 2 dissimilar metals in contact with each other and acts as a miniature battery. A chemical reaction is happening at the surface of this bimetal barrier that produces a small voltage.
   - The voltage produces by the thermocouple varies with temperature in proportion to the temperature difference between the thermocouple

- The thermocouple voltage is very small in order of microvolt but it can be amplified and measured and the temperature can be computed from this measurement
- A design challenge when using thermocouples is that there must be a calibrated reference temperature against which compared with the measured temperature. Some ICs can generate the reference temperature internally but otherwise, there is a need for external calibrated temperature source which is not feasible on a BMS.
- Overall, thermocouples are best suited for laboratory testing when all necessary temperature references and equipment on hand. They are not suited for production of BMS design

* How to measure temperature: Thermistor

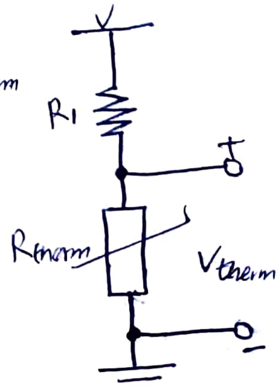
A thermistor is a special kind of resistor. All resistors have value that changes somewhat with respect to temperature but most resistor designs are done such that the temperature variation is minimized. ~~Thermistor~~ is designed to maximize the change in resistance as a function of temperature. There are two (2) varieties:

1. Negative temperature coefficient (NTC) thermistors have resistance that varies inversely with temperature. $R \propto \frac{1}{Temp}$
2. Positive temperature coefficient (PTC) thermistors have resistance that varies proportionally with temperature. $R \propto Temp$

So if measure thermistor resistance, temperature measurement could be inferred. But resistance can't be measured directly with an electric circuit; only voltage can be measured directly using ADC analog-to-digital converter. Hence, the resistance is somehow converted into a voltage that's measurable.

* Voltage-divider Circuit

A way of converting resistance into a measurable voltage and a common way to do it is using a circuit known as a voltage-divider circuit



- In the circuit, the top resistor R_1 has resistance the does not vary appreciably with temperature, but the lower resistor R_{therm} has value that is designed to vary significantly with temperature
- The circuit is supplied with a constant known voltage, V at the top of the circuit and the analog-to-digital converter measures the voltage drop across the thermistor
- $i = \frac{V}{(R_1 + R_{therm})}$ $\qquad V_{therm} = \frac{R_{therm}}{R_1 + R_{therm}} \times V$

- The value of R_1 is designed to limit power loss through the circuit and provide a useful measurement range for V_{therm}. The value of R_1 is designed to be relatively high in order to minimize the current. The value of R_1 is similar to the thermistor resistance at some reference temperature 25°C

*** Voltage - divider analysis**

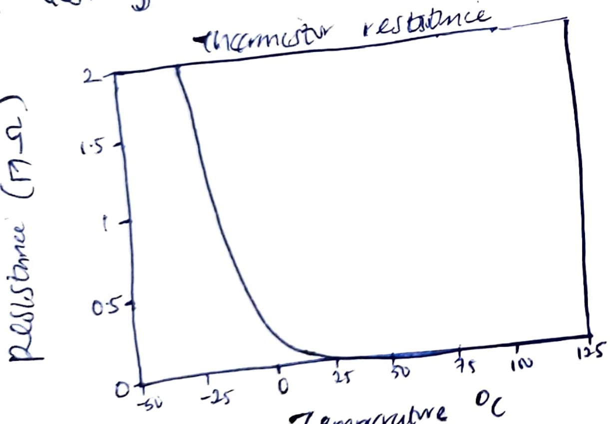
$$R_{therm} = \frac{V_{therm}}{V - V_{therm}} \times R_1$$

The data sheet that documents the specifications of the thermistor will give an equation that relates the resistance of the component to temperature

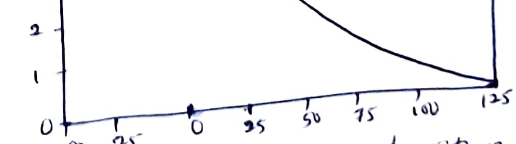
$$R_{therm} = R_0 \exp\left(\beta\left(\frac{1}{273.15 + T} - \frac{1}{273.15 + T_0}\right)\right)$$

where T is temperature being measured, R_0 is resistance at reference temperature T_0; temperature converted from Celsius to Kelvin by adding 273.15, β is a device parameter.

*** Voltage-divider + thermistor example**



Thermistor resistance for an NTC device having $R_0 = 100\,k\Omega$ at $T_0 = 25°C$ and $\beta = 4282$



The second plot show what the measured voltage would be at the analog-to-digital converter if we use the thermistor in a voltage divider circuit

if $V = 5V$, $R_1 = 100k\Omega$, V_{therm} varies with temperature

* Summary

1. To preserve battery health, it is important to monitor and control cell temperature

2. Usually to expensive to measure all temperature; instead measure module temperature and use thermal model to extrapolate to cells in modules.

3. No mechanism that allows to measure temperature directly. Instead, it is converted into a voltage and voltage is measured using ADC
   - can use thermocouple with amplifier
   - Use thermistor plus voltage-divider circuit (most commonly).

#5 Battery pack Sensing: Current

Battery pack electrical current measurements are required:

- To monitor battery-pack safety in order to ensure that excessive amounts of current are not flowing.
- To log abuse conditions
- They are required by most SOC and SOH algorithms.

We cannot measure any physical quantities directly except for voltage. therefore, current also cannot be measured directly; it must be converted into voltage signal then measure via **A2D** converter. There are two (2) basic methods to do so:

1. Using a **resistive** shunt
2. Using a **Hall-effect** mechanism

* Shunt Current Sensor

A shunt is a low valued but high precision calibrated resistor in series with battery pack, usually at low-voltage end. (eg (0.1mΩ))

usually at the negative terminal of the battery pack, between the negative of the battery and the negative of the load.

- Current computed by measuring voltage drop!

$$I = V_{shunt}/R_{shunt}$$

- Since the shunt resistance must be small (to avoid large power losses due to i^2R_{shunt} heating), the voltage drop across the shunt will be small as well. So, the voltage is usually amplified before sensing and the calculation for current is adjusted accordingly.

• Shunt details

There are four (4) connection terminals on the shunt:

- One out of 2 large terminal on the top is connected to the negative terminal of the battery ~~pack~~ stack, the other to the output negative terminal of the battery pack.
- Battery pack current passing through these parallel plates produces the voltage drop to be measured
- The resistance between the two smaller screw terminals is calibrated, and the sensing leads are connected to these smaller terminals.

* Kelvin four-wire connection

Kelvin connection in shunt enables 4-wire voltage measurement. Essentially, no current is drawn by the analog to digital converter that's connected to the small screw terminals has no voltage drop over it.

We are truly measuring the voltage drop across only that calibrated resistance. If the voltage sensing wires are connected to the large terminals, voltage drop across the calibrated resistance + the voltage drop across the screw terminals in the connection is measured.

- Some comments on current-sensing shunts are:

i) To use a shunt sensor, use 4-wire connection, otherwise the measurements will all be wrong.

ii) Shunt sensor has no built in offset at zero current, so they are good to avoid drift in coulomb counting. (but amplifier or A2D circuitry may have offset)

iii) Current shunts are not electrically isolated from the pack: If BMS must be isolated from pack, extra circuitry is required.

iv) Design consideration: when using a shunt, we desire to have a very low shunt resistance to minimize power losses. Regardless of chosen resistor, there will be some power loss.

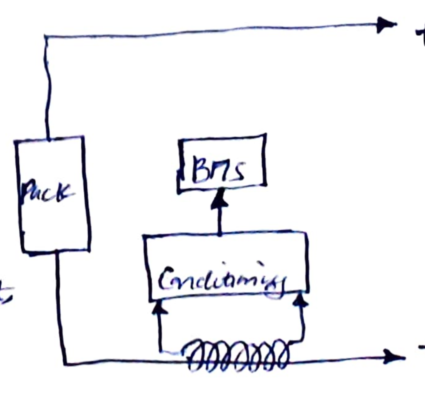
v) Heat generated via i^2R shunt losses must be dissipated.

vi) Amplification of shunt signal is necessary and the wiring must be shielded from Electromagnetic Interference.

* Hall-effect Current Sensing

It is based on a principle from electromagnetics which says if a coil of insulated wire is wrapped around a primary current carrying wire, the primary current carrying wire induces an electrical current in this coil.

- If a coil is wrapped around a primary current-carrying conductor, the electromagnetic field produced by the conductor induces a secondary current in the coil.
- Hall-effect sensors measure the induced current in the secondary coil and use that to infer what the amount of current passing through the primary wire.
- Main battery-pack current-carrying wire passes through the oval opening on the center of the sensor. Hence no direct electrical connection is made between the sensor and the high-voltage battery pack.



- Some comments on Hall-effect sensors are:

i) Hall sensor are electrically isolated from pack current so no special isolation circuitry is needed.

ii) Feedback circuitry is needed to guard against sensor magnetic hysteresis (sometimes packaged with sensor)

Hysteresis means that a current reading after charging a battery pack for a while will be different from current reading after discharging a battery pack for a while even though the current might be exactly the same at the moment in time.

causes the present measured voltage to be a function of instantaneous current going into primary and past current that went through primary current carrying wires.

iii) Hall-effect sensors suffer from offset at zero current, which changes with temperature

- Even if "zeroed" at room temperature, it will report incorrect current as they change temperature.
- So if Hall-effect current sensor is to be used, some kind of compensation is necessary. It is also necessary to estimate the DC bias and substract it from measurements in the algorithms.
- Because of the additional complexity to the algorithms and the uncertainty added to the estimates, the ~~tutor~~ personally do not prefer Hall-effect current sensors.

* Summary

i) Battery pack electrical current must be measured to monitor safety, log abuse, and inform SOC and SOH algorithms.

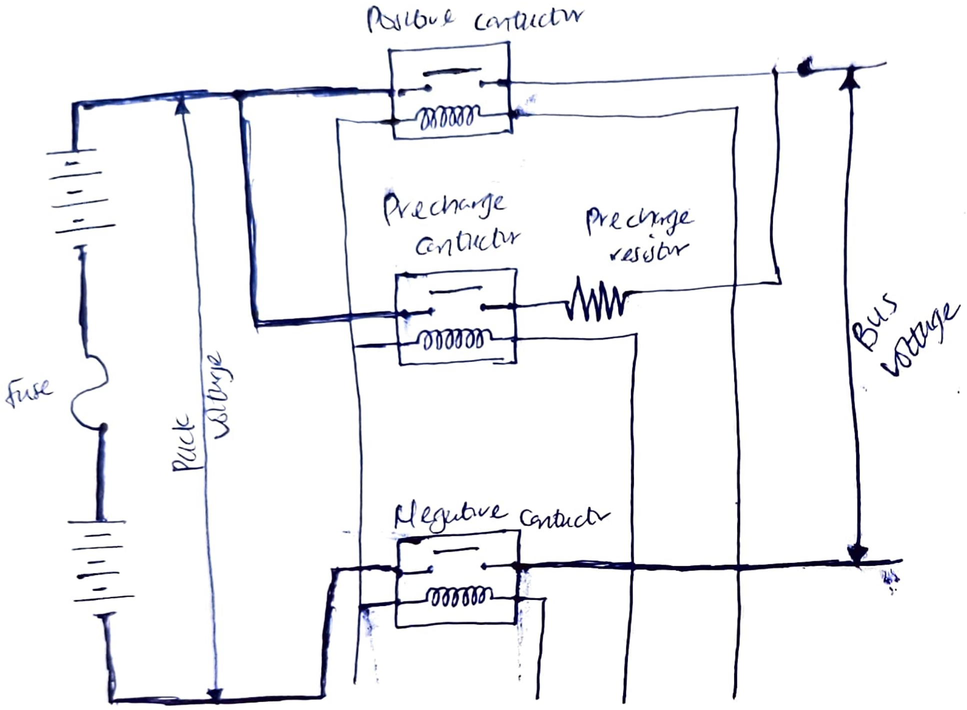
ii) Two methods may be used: either ~~current~~ shunt or Hall-effect sensor

iii) Hall-effect sensor suffer from offset at zero current, which changes with temperature. Hysteresis also occur there-in. But it is still used in commercial products mostly because of their built in electrical isolation.

#6 High voltage Contactor Control

When a battery pack is not in use, its internal high-voltage bus must be completely disconnected from the load both +ve & -ve terminals. An on/off switch is needed known as **relay** or more often as a **contactor**. Both are high-current capable devices. A low voltage or low current signal activates the contactors, closing an internal switch that connects its main terminals.

Any practical battery management system for a high power application uses not two contactors, but three, where the 3rd contactor is known as **Pre-charge contactor**.



- Pack initially at rest: all contactors open
- Fuse is incorporated for safety reasons
- Coil is the control mechanism for the contactor. When the coil is activated, the contactor closes and vice versa.
- Thick line shows activated connections. Load is disconnected from the pack.

Step 1: close negative contactor

Step 2: close precharge contactor.

To close the precharge contactor, the right branch of its coil is activated. Then current flows from battery pack through the precharge resistor to the load. The battery pack current is limited by precharge resistor. Resistor temperature is monitored; if too high, load may have short circuit, pack disconnects.

Bus and pack voltages also monitored: if they don't converge quickly enough load may have short-circuit fault, pack disconnects.

If the precharge current doesn't approach zero quickly enough the load may have a short circuit and the pack should disconnect.

Step 3: Close positive contactor

If bus and pack voltages become "close enough", "quickly enough", then BMS closes/activates the main "+" terminal contactor.

Step 4: Open precharge contactor

As a final step, after the positive contactor is closed, the precharge contactor may be opened.

* Shutting down battery from Load

Procedure to follow on pack shutdown not as clear. Abrupt disconnect may cause arcing/welding of contactor. However, one possibility is to
- activate the precharge path in reversed order which it was started, giving current path to prevent welding, but might blow precharge resistor.

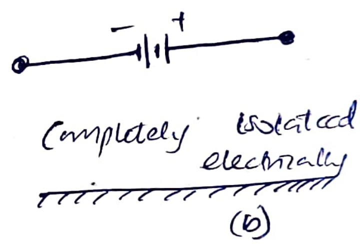
Most likely the battery pack can be disconnected from a capacitive load simply by opening all of the contacts.

* Summary

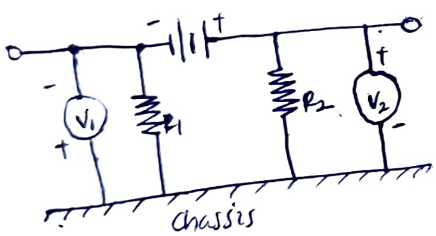
1. There is a need for care when connecting the battery pack to its load on power-up
2. For the common scenario of a capacitive load, a precharge path is needed to charge the load relatively slowly before the main contactor is closed.
3. This imposes the need for pack and bus-voltage monitoring, precharge-resistor temperature monitoring, as well as the use of three contactors.
4. The main purpose of a precharge resistor is to limit the initial surge of current (inrush current) that occurs when the capacitors in the system are first charged. It controls inrush current when connecting a power source to a load with capacitor, such as an inverter or motor controller

#7: How to Sense Electrical Isolation in a BMS

- Isolation sensing detects presence of a ground fault. Primary concern is safety, hence, is it safe to touch a battery terminal and chassis ground at the same time? The high voltage battery should be completely isolated from the chassis
- In standard vehicle, the positive terminal from the 12V battery is wired independently to everything in the vehicle that requires power and the ground of the 12V battery is wired directly to the chassis. This is done to eliminate the need for running ground wires to every component in the car, it saves wiring. 12V does not have sufficient potential to cause significant injury or harm.
- The Federal Motor Vehicle Safety Standard (FMVSS) says isolation is sufficient if less than 2mA of current will flow when connecting chassis ground to either the positive or negative terminal of the battery pack via a direct short. 2mA is less than or close to a lethal threshold.



* How to

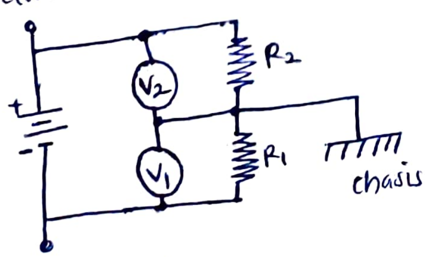


These resistors are only shown in circuit to model whatever resistance is actually present and ideally the resistance is infinite.

The "isolation resistance" R_i is the lesser of R_1 and R_2. So, R_i must be greater than $V_b/0.002 = 500V_b$. By Ohm's Law, the isolation resistance must be greater than the battery voltage divided by 2 milliamps.

For the BMS to sense whether the pack is sufficiently isolated from the chassis, it must somehow measure R_i. To do so, V_1 & V_2 using a high-impedance A2D $\geq 10M\Omega$ is measured.

- If we redraw the circuit (a), it becomes more clear that R_1 and R_2 form a voltage divider

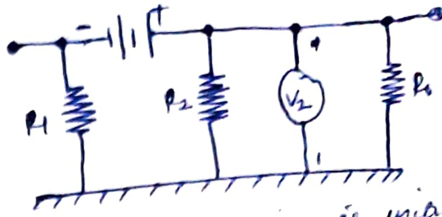


- Find the smaller of the two resistances:
  - In a voltage divider, the smaller voltage corresponds to the smaller resistor
  - So if $V_1 < V_2$ find R_1, else find R_2
  - $I_1 = I_2$; $\frac{V_1}{R_1} = \frac{V_2}{R_2}$

* Fault on low side : find R_1

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

This breaks strict isolation, but not enough to worry about if R_0 is "big enough" ie $R_0 >> 500 V_b$



Isolation resistance of initial measurement of V_1 < V_2

- Measure V_2'. KCL

$$\frac{V_b - V_2'}{R_1} = \frac{V_2'}{R_2} + \frac{V_2'}{R_0}$$

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

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

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

Combine terms that include R_1

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

Rearranging,

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

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

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

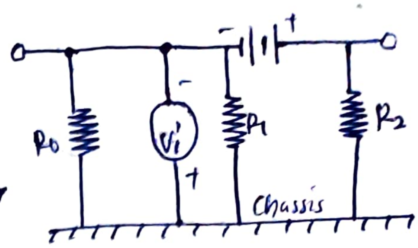
Upon calculation, it is concluded that battery pack is sufficiently isolated if this isolation resistance R_i is larger than 500 times the voltage of the battery.

Isolation is deemed sufficient if

$R_i > V_b / 0.002$ or $R_i > 500 V_b$

* Fault on high side: find R_2

Procedure is similar of the initial voltage measurements $V_1 > V_2$ except that we now find R_2



- To do so, insert a known large resistance R_0 between battery and chassis ground, via a transistor switch shown

- Voltage difference measurement; measure V_1'

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 $R_1 = R_2 (V_1/V_2)$

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

- Combine terms including R_2

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

- Rearranging

$$R_2 = \frac{R_0}{V_1'}\left(V_1 + V_2 - V_1' - V_1'(V_2/V_1)\right) = \frac{R_0}{V_1'}\left(1 + \frac{V_2}{V_1}\right)(V_1 - V_1')$$

$$R_2 = \frac{R_0}{V_1'}\left(1 + \frac{V_2}{V_1}\right)(V_1 - V_1')$$

Hence, Isolation is deemed sufficient if $R_i > V_b/0.002$ or $R_2 > 500V_b$

* Summary

i. In a vehicle application, we must maintain isolation between high-voltage battery pack and chassis of the vehicle

ii. Isolation is deemed sufficient if less than 2mA of current will flow if a direct short is placed between one terminal of the battery pack and the chassis

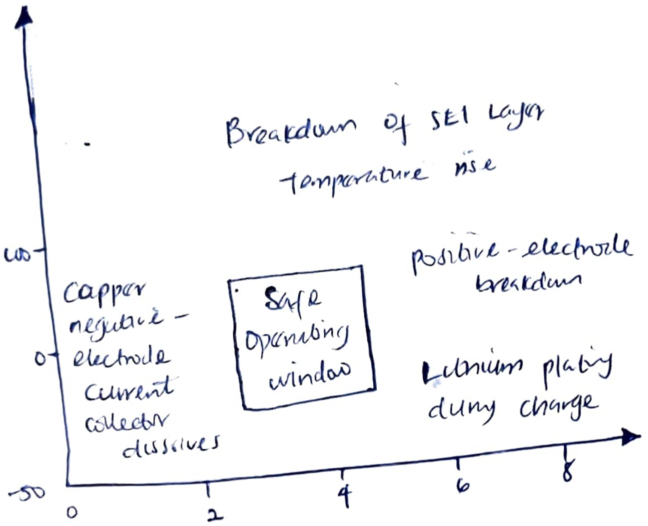
iii. Isolation is sufficient if $R_i > 500V_b$

#8 Thermal Control

The temperature of a battery-pack has some fairly significant impacts on safety as well as the lifetime of the battery pack. Generally, lithium-ion cells last longer if maintained in temperature band from about 10°C to 40°C during use.

Rule of thumb: a comfortable temperature for human is also comfortable for batteries.

It is important to keep uniform temperature across battery pack for uniform aging.



* Types of thermal management

There are two (2) different methods are commonly used to cool a battery-pack.

1. Air cooling may be sufficient especially for EV (low rates)
forced air cooling where fans direct air across the battery cells in order to cool them.

2. Liquid cooling; where some thermally conductive liquid is run through pipes and/or plate next to the cells to remove heat from them. Liquid cooling may be necessary for some aggressive P/HEV applications, or range and life extension.

- Electric vehicles generally need less cooling per cell than hybrid electric vehicles because electric vehicles are designed for energy applications for long-range application so each cell is discharged at a relatively low rate and therefore generates heat at a relatively low rate per cell.

- Heating may be necessary to avoid charging at low temperature - high risk of cell damage of pack is charged when cells below about 0°c. Biggest reason we might want to heat a battery-pack is to enable charging and it is done probably only when the battery pack of the vehicle is plugged in to the utilities grid. So we are not wasting battery-pack energy to heat the battery-pack.

- In some cases, battery-pack may be cooled below ambient temperature. Air cooling and liquid cooling exchange heat with the environment (hybrid) can be used. But instead, some kind of a refrigerant is possible to cool the battery-pack below the temperature of the environment ↳ it could be energy consuming from the battery-pack but using utility grid, it can be a good idea at stationary.

* Summary

1. It is important to keep battery-pack cells at a "comfortable" temperature to ensure safety and to extend life
2. Important to keep cells at a uniform temperature for consistent aging (also reduce need for many temperature sensors)
3. Present commercial systems use either air or liquid systems, and some reports indicate that range and life are negatively impacted by air systems.
4. Active heating and cooling while vehicle plugged in can extend life, shorten charge times.