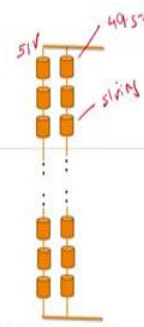


Fundamentals of Electric Vehicles Technology & Economics
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Lecture No. 28
Introduction

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NPTEL

Building mSnP battery pack



Cells can be connected **in series** to form a **STRING**

- 14 cells connected in series to form 48V battery
- 20 cells in series for 72V battery
- 100 cells in series for 365V battery
- 200 cells in series for 730V battery

Strings can be connected in parallel to increase capacity

- Two 14S2P strings with 15 Ah cells would be of 48V * 2 * 15 Ah capacity or 1.5 kWh capacity
- Any capacity can be built

But a concern: if strings do not have exactly **same voltage** (will mostly not be so), current will flow from one string to another for balancing

- This will happen continuously while charging or discharging and even when IDLE
- not good for battery

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First, let me look at mSnP, m in series first and then n in parallel. As I told you this configuration is not preferred configuration, this is what it shows you first put 14 or what m cells in series, you put another m cell in series and this you call it a string, each one of them is a string and then you put multiple strings in parallel and that gives you the n strings in parallel, it will give you mSnP. 14 cells if you connect it in series will give you 48 volt so it becomes 48 volts, if you put 20 cells in series it will give you close to 72 volts. So, that is how the battery packs are designed.


Of course, as I told you this is not the best way, we will come to that in a few minutes. 100 cells in series will you 365 volt, 200 cells in series will give you 730 volts. Strings can be connected in parallel to increase capacity. So, if I use 14S into 2P of 15 cell, I get 48 volt, this 14 series means 48 volt into 2 in parallel each is 15 Ah capacity so I get you multiply this 96 into 15 ampere hours is 1.5 kilowatt hour capacity, any capacity can be built.

Any voltage, any current can be built using something like that, but there is a concern. I put 14 of them in series, let us say cells have slightly different voltage at any time at any time during charge or discharge. Suppose, the voltage of this together works out to be at any time 50, 51 volt, and for this it works to 49.5 volt. What will happen? String voltage of the two strings are different and you connect them in parallel, immediately a current will start flowing

like this because the voltage has to be same, this is internal current, not external, this is called balancing. And every time we charge or discharge the voltages of number of cells in series will not be same.

So, a lot of balancing required, a lot of this balancing actually hurts, you are actually discharging and charging the cells, the cell life goes down unless cells are exactly the same voltage. Even if you take the cells at the time of manufacturing measure, if they are exactly the same after some usage as SOH becomes from 100 percent to 99 percent, the voltage will not remain same. And the current will keep on for flowing from one string to another. This will happen continuously while charging and discharging, even when idle you will keep on trying to balance and not good for battery so this mechanism mSnP is not used.

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Building nPmS battery pack

Cells can be connected **in parallel to form MODULES**

- Four 15 Ah cells give a module of 60 Ah
- Eight 15 Ah cell give a module of 120 Ah
- Sixteen 15 Ah cell give a module of 240 Ah

Modules can now be connected in series to make a battery of higher voltage

- If we connect 14 modules of 60 Ah (four 15 Ah cells in parallel) in series, we get a pack of 4P14S: voltage is 51V and is 60 Ah
 - Capacity = 51V x 60 Ah = 3.06 kWh
- If we connect 14 modules of 120 Ah (eight 15 Ah cells in parallel) in series
 - Pack is 8P14S and capacity is 51V x 120 Ah or 6.12 kWh

No major balancing issue here: Auto-balancing between cells in a module all the time

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What is used is something like this. You first create a module, this is a module, put n series cells in parallel and then you connect them. So, this is a module, first you connect the module and then you put module into series, you put four cells in parallel of 15 Ah, you get 60 Ah. 8 will give you 120Ah, 16 will give you 240Ah, so you get a module of different Ah. Now you connect them in series to make battery fire voltage.

You put 14 modules of 60 Ah you will get 4P14S 51 volt 60 ampere hour, capacity is 3.06. If we connect 14 modules of 120 ampere hour in series you will get 8P14S or 6.12 kilowatt, this is the way nPmS and this the only way the right way of designing it. No major balancing issue, of course, you can say here the within a module there may balancing. What if the cells

are of not same voltage? Well, this is the reason the cells in parallel has to be carefully chosen, they are exactly similar kind.

And while charging-discharging you have to make sure that different current does not flow through, that is the reason you actually connect them like this, you have to make sure that the resistance is not difference, if the resistance is different, you know, different current will flow, do not worry about it. If internal resistance is different, you apply the same voltage different current will flow. So, you have to worry about each and every of this, there is a self balancing and at time you can enable some more balancing which is okay otherwise land up in trouble.

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Cells to Module and Modules to Pack

- Multiple Cells packed in parallel to form a **Module**
 - Cells selected so that they are of same voltage (balanced)
 - Cells connected with a metal bar that conducts electricity
- Multiple Modules in series to form a battery **Pack**
- Battery Management System (**BMS**) a must to get optimal performance
 - Especially for Li Ion batteries

Cell equalisation during Charging

- Monitor voltages and temperature of each module and total pack current

If a module is over-charged (impacts life), equalise by

- Passive balancing:** bleed module with higher voltage through a resistor, so that it charges slower, or just drain it
- Active balancing:** stop charging module with higher voltage; instead, use its output to charge the rest of pack (using a DC-DC converter)

BMS could limit **temperature of each module if active cooling is done**


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So, basically cells to module and module to pack, so multiple cells packed in parallel to form module, cell selected so, that they are same voltage balanced cells connected with a metal bar that conducts electricity. So, the cells are put on a metal bar so that it does not give too much of resistance, it is conducted very easily. Multiple modules hooked into a series to form a pack and then there is a battery management system which will monitor the voltage of every module, the current of every module and temperature of every module.

And for lithium ion batteries, it will then try to work to get optimal performance. During charging if unequal current flows between multiple batteries, you will try to do what is called equalization, it monitors voltages and temperature of each module. If a module is not getting sufficiently charged, you bypass another module or you let more current flow into that module. If temperature of any module is going up, slow down, do not let it charge. If a module is overcharged as opposed to another, it impacts life.

And there is a two methods of balancing. I think probably Kaushal will cover that more. One is a passive balancing and another is active balancing. Passive balancing basically means bleed one module with higher voltage through a resistor so that some current flows into the next module. Active balancing stop charging a module of higher voltage and instead charge the other module at lower voltage. And then BMS has to worry all the time about temperature.


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Electrical Design

As **high currents** are involved, a **conductor is not zero voltage drop**

- Smallest resistance-difference between two electrical paths may result into differential voltage-drops: currents will flow more on one rather than the other creating imbalances
- For example if current enters battery as shown by the arrow
- Electrical Path to cell marked "a" is shorter than that for one marked "d"
- Cell imbalance will be created between cells **a** and **d**
- It happens more between modules, as current from one cell in a module to other is more as compared to that from another cell



A pack with continuous imbalance will quickly **deteriorate in Capacity**

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A very important component of electrical design, as high currents are involved a conductor is not a 0 voltage drop, that is the point that I am making. Smallest resistance different between two electrical paths may result into differential voltage drops, current will flow from one rather than or another rather than the other creating imbalance. So, a lot of imbalancing take place because electrical design is poor.


In fact a very interesting thing that I had come across there are let us say there is a metal plate to which all the cells are connected. This is then connected in series to another metal plate where four more cells are connected. And these two metal plates can even be same, it does not matter. You will think you have done it right, you have thick metal plate which you have connected, but look at here, this path from here to here is shorter path as opposed to here to here.

Shorter will have a smaller resistance, longer path will have a longer resistance because there is only single connection between these two, you have problem. So, the way to correct is that you will have multiple connections, you cannot have a single connection, then more or less

same amount of current will flow, same thing I am showing here, if a current enters here and supposed to be going here, the same thing the current is entering, if it goes through a it encounters resistance, it goes through d if your let us say inlet comes from one side inlet also has to come from a way by which all 4 gets equal.

And this is the kind of problem that you will get into it happens more between modules as current from one cell module to another is more as compared from one other cells more cells. A continuous imbalance deteriorates capacity, some of that can be corrected but a continuous imbalance deteriorates capacity.

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Failures in Battery Pack I

If a cell in nPmS pack

- One of n parallel cells may become **open circuit** – (n-1) cells in module continue to function
 - Module capacity goes down by $(1/n)$ Ah -- Battery will function with reduced capacity $(n-1)PmS$
- One of n parallel cells become **short circuit** – the full module has zero voltage
 - Battery voltage will be (m-a)S: the pack is now $nP(m-1)S$
 - Can continue to function **only if** the drive train functions at lower voltage: poor performance
 - **Repair will involve replacement of whole module – difficult (depends upon pack):**
 - Replacement of a cell is difficult

If a serial connection between module fails: battery fails

- Generally easier to repair – may require bus-bar replacement

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So, electrical design has to carefully done. I want to point out two more things and stop here. What if there are failures, what kind of failures happen? Suppose you have modules nPmS, n cells in parallel m in series and one of the n parallel cells become open circuit, what is open circuit? Suppose there are 4 of them now only 3 cells are in parallel, one of them is not there.


So, suddenly he this is happening only in one module, other modules have full capacity, but this one module capacity has gone by 3 by 4 of the original one, overall pack capacity will go down by 3 by 4 because when the current flows, the current if you try to flow more, if all of them are getting charged by 1 C, this will start getting charged by 1.33 C, that will destroy the pack completely. Overall capacity itself goes down, because though other cells have capacity, capacity will not be utilized. So, open circuit basically immediately means, in any module one cell is all.

Supposed there is a short circuit one of them parallel cells, all the cells in parallel will get short circuit. So, you see the voltage will go down by 3.7 volt, which basically means, the voltage has gone down, your motor etc everything has been designed to operate at certain voltage, now they will get differential voltage. But still short circuit is better than open circuit, open circuit hurts you much more. So, drive train will get poor performance, but one can do that and these are to be monitored, the BMS has to monitor if anything like this has happened.

Now replacement will involve taking out the module, and these are all module which are welded together, very difficult to take out the modules. So, replacement of module may be sometime possible, replacement of cell is not possible. Now, when you do the design itself, you have to worry about what will I do if I have to replace? How difficult will it be? You cannot think about it later.

So in the design time, you can sort of say these things I will only connect through screws, so that they can be taken out, I will connect even even the bus bar that I will connect through screws, so I can open up and take this out. If a serial connection between module fails, battery fails, it does not go through. But it is generally easier to repair, it may require some bus bar replacement.

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Failures in Battery Pack II

Failure in BMS: **replace BMS**

MOSFET in BMS heated: **design issue**

Temperature sensor failure: detect and replace

- Risky: failure to detect rapid heating and cutting-off (BMS function) may take cells to meltdown

Cell **capacity deterioration:** Battery Pack Capacity deterioration

- Unbalanced cells in modules: Battery Pack Capacity deterioration

Incorrect SoH or SoC estimation

- BMS may cut-off battery (and thereby vehicle cut-off) even when charge is not low
- Wrong display of charge remaining

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What happens if a BMS fails, that is more easy to detect and it does fail, BMS fails more often, but easy, just to replace BMS recalibrate everything you are worried about again SOC and all those things. But the other problem that you often find that you have to switch in

current, switch off current, and for that use MOSFETs. And MOSFET is a heat dissipating device and if a MOSFET is getting and you are supposed to remove that, if a MOSFET is getting overheated, you will see the temperature, it is a design issue, if one MOSFET is getting heated compared to the others, you have to worry about it, you have to shut down that MOSFET otherwise, the MOSFET is likely to fail.

Temperature sensor failure, there are lots of temperature sensors, every module temperature is going to be sensed, every MOSFET temperature is going to sense and you find some time these temperature sensors not well not very good quality, in which case, they will give you all kinds of results and you will end up doing something totally different from what you were supposed to do. Sometime the sensor will fail, some time sensor will give you a wrong temperature and you have to detect it otherwise, these are dangerous because it can result in too many down.

You think that there is nothing wrong in the sensor but it is getting heated up is one of the most risky thing. Cell capacity deterioration that is another thing that happens and largely it is unbalanced cell in modules, battery pack capacity deteriorates. Incorrect SoC and SoH estimation. What are the important thing, we had a battery with incorrect and the drivers will complain saying, sir it was showing 40 percent SoC and suddenly my vehicle got cut off.

For a long time we thought something was wrong in vehicle. Something was wrong in display, actually we found out later on it was SoC, SoH estimation mistake, it can result into a problem.

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To Sum up

We have looked at Conceptual Design of Battery Pack so far .

- Not looked carefully at Mechanical Design (**bulging, pressure, vibration hurts life**), Thermal design (**high temperature hurts**) and BMS design (getting the best out of cells and Safety)
- Even the electrical Design was **minimally** dealt with

Cell selection is critical in price and performance

- Cost issue** will be examined more in next section
- Cell performance in terms of **life-cycles** and impact of charging-discharging rate, operation temperature, depth of discharge on life-cycles is important

But **Pack-design also impacts** battery life-cycle

- Cell-imbalance** has highest impact
- Pressure on cells, Vibration, cell temperature difference, differential currents impact life-cycles
- Inaccurate** determination of SoH and SoC impacts vehicle performance

So, to sum up, we have looked at a conceptual design of a battery pack so far. Not so carefully at what will be the mechanical design which will stop the bulging, the pressure, how will vibration be tackled, not a thermal design, they are basically done electrical design and you have not done the BMS design. This is what Doctor. Kaushal will actually do in his set of lectures, get into a depth of each of these things. This is what a battery pack design will be. The simple configuration of putting them in series and parallel is fairly easy, everybody can do it.

Electrical design is somewhat tough, but because you do not understand 200 amperes, if it was 1 ampere the problem would not be so serious. A milli ohm resistors will only give you a millivolt difference. So, electrical design we dealt with minimally you may deal a little bit, but more carefully as mechanical, thermal and BMS design you look at. Cell selection itself is critical in price and performance, cost issue will be actually looked at very carefully in the next section, cell performance and life cycles and impact of charging, discharging rate.

Operation temperature, depth of discharge all of these will have impact on life cycles. All of this will have impact on cells that is the next section we will look at what is the battery cost, usage cost that I have been talking about right from there. The pack design also impacts the battery life, cell imbalance has highest impact on battery life, pressure on cells, vibration, cell temperature differences, differential currents impact life cycles of the battery.

Inaccurate determination of SoC and SoH of course hurts the bad vehicle performance, after some time starts hurting the battery performance. So, this is what we have to summarize this and what we will do next, is there some questions fairly simple questions.

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Assignment 4.6

1. Need a 15 kWh battery with nominal voltage at 350V. The cells that one has is 3.65V, 14 Ah Li Ion cells. How will one use cells to build the best configuration for the battery? What will be the battery voltage when its SoC is 100% and voltage when it is 0% SoC?
2. Need a 0.5 kWh battery at 48V. What cells will I use? What would be the configuration?

I will not go through the questions well, let me quickly look at it. Battery pack of 15 kilowatt hour with a nominal voltage of 350 volt, your cells are 3.65, 14 Ah configure what will be the battery voltage at 0 percent and at 100 percent. Need a 0.5 kilowatt hour battery of 48 volt, what is cells that are used? What would be the configuration?

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Assignment 4.6 (contd)

3. A battery pack of 375V, 200Ah is to be made to power a luxury car. One battery pack is made with 3.65V, 4Ah, 21700 Cylindrical cells and another pack uses 3.65V, 50Ah prismatic cells.
 - a. Suggest nPmS configuration for each case to achieve the pack requirements.
 - b. Find the total number of cells in both cases.
 - c. A cell in module of n parallel cells fails in open during operation. Find the resultant nominal pack voltage in V, pack capacity (Ah) for both the packs.
4. A Battery pack of configuration 2P14S is made with 3.65V, 13Ah Li Ion cells to power a two wheeler. The pack is used in field for some time and has undergone 5% degradation. The pack operation is limited from 10% SoC to 90% SoC level to improve life.
 - a. Indicate the SoH (%) of this battery pack and DoD of operation.
 - b. What is the nominal voltage of pack and the capacity in kWh.
 - c. What is the usable capacity (kWh) of battery pack at current level of SoH.

A battery pack of 375 volt, 200 ampere hour is to emit to power a luxury car. One battery pack is made with 3.65 volt, 4 Ah, 21700 single cell, and other with prismatic cell. Suggest nPmS configuration for each case, find the total number of cells in each cases. A cell involved module of n parallel cell fails, find the resultant nominal pack voltage in V and ampere hour for both the packs. You will find some interesting results.

A battery pack of 2PN14Sn is made using 13 Ah lithium ion cell to power a two wheeler, the pack is used in the field for some time and has undergone 5 percent degradation. So, SoH is 95 percent. The pack operation is limited between 10 percent to 90 percent SoC. Indicate the SoH percentage of this battery pack and DoD of operation, I have already given you the answer. What is the nominal voltage of the pack and the capacity in kilowatt hour? What is the usable capacity of the battery pack at the current level of SoH?

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Assignment 4.6 (contd)

5. True or False
 - a) Packs made with cylindrical cells need right pressure to be applied on cells to avoid bulging.
 - b) nPmS configuration implies first make series of m cells and then attach n such series in parallel.
 - c) In a module of 4 parallel cells of 3.65V, 4Ah each one cell fails in open. The resultant capacity of module is then reduced to 12Ah.
 - d) SoH of a battery pack is the SoH of the strongest cell in the pack.
 - e) SoC estimation is independent of SoH estimation.

And there are various true and false please answer that and you will then come to the next section, which I will do next class.