Electrochemical Energy Storage
Prof. Subhasish Basu Majumder
Department of Materials Science Centre
Indian Institute of Technology, Kharagpur

Module - 05
Characteristics of commercial lithium ion cells
Lecture - 21
Principle of Operation of Commercial Cells: viz. C - NMC, C - NCA etc.

Welcome to my course Electrochemical Energy Storage. And we are in module number-5, Characteristics of commercial lithium ion cells. So, this is lecture number-21 where Principle of Operation of Commercial Cells. You know that already we talked about graphite NMC or graphite NCA kind of cells, so that I will explain.

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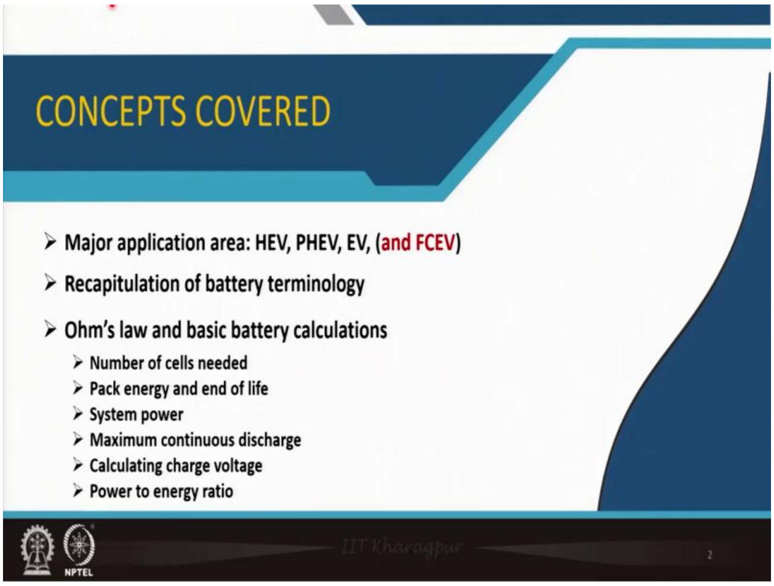

Now, in this particular lecture, we will talk about just introduce the major application area which is coming up in automobile sector, hybrid electric vehicles, then plug in hybrid electric vehicles and electric vehicles, so there lithium ion battery will be used in huge quantity, so that first I will introduce.

Then we will recapitulate certain battery terminology. And then finally, we will talk about basic battery calculations that is helpful for you to construct a battery pack in that way. So that will include that how many cells that actually you need to make a battery pack depending on the voltage requirement and capacity requirement. Then how to estimate the pack energy and end of life of the battery, then system power then maximum continuous discharge, how to calculate the charge voltage, what is power to energy ratio. So, those things will be talked about.

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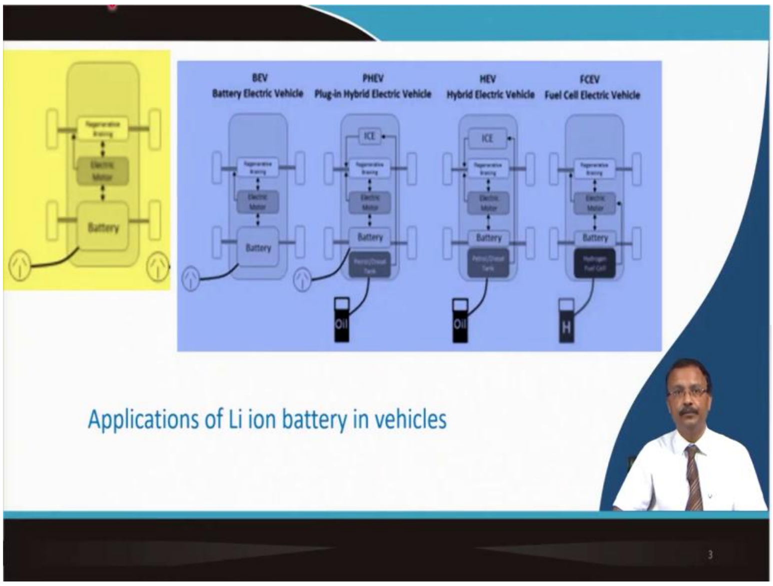

Now, if you see this application areas, this is electric vehicles already some company they have commercialized it. So, it is already there in the market. So, we call it is a battery driven electric vehicles. And in some cases, you have the fuel combustion normal fossil fuel.

And you have the battery as a backup. Whenever you need the battery power in conjunction with this fuel, then you use this plug in electric vehicle where the battery needs electrical power for recharging. And from the oil pump also, you need to fill your gas tank. Other concept is hybrid electric vehicle where the energy that you gain while you break the car which is run by fossil fuel, so that energy is used to recharge the battery. And the battery power you can use whenever it is needed.

And the final one is fuel cell electric vehicle. So, that is we are not that much interested for that fuel cell electric vehicle for this particular applications. So, I am not going into details of it. So, these are the major application areas of the battery that we are talking about.

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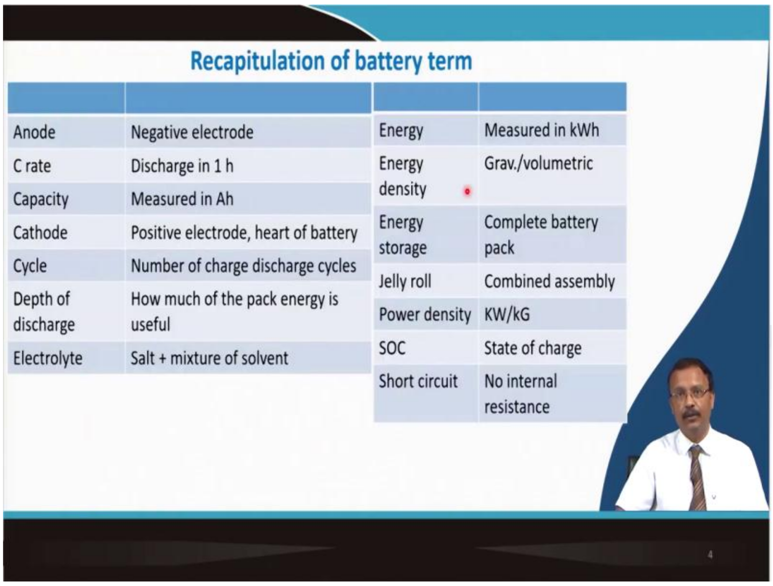

Now, some battery term that is important and you need to remember this that what is what. This anode or cathode that has limited usefulness in battery technology. So, usually anode is negative electrode, and cathode so called is positive electrode. So, they change their function while charge and discharge.

The C rate is important that once you charge your battery if you can charge it in 1 hour, that means, you are charging your battery at 1 C rate and if you can charge it say in 6 minute, then your battery charging rate is 10 C. So, if you discharge it in 1 hour, then you are discharging your requirement of current is 1 C. So, C rate is very important.

Then capacity usually that is measured in ampere hour. During discharge what you do you apply or you drain a constant current, and you measure the fall in voltage because you know that the voltage will change depending on the lithium ion insertion during discharge what is happening lithium ion is inserted in the positive electrode material. So, voltage is continuously falling.

So, that part the time if you calculate and you know the current of the discharge. So, that is nothing but the charge that is stored in the battery. So, in ampere hour, we actually note the capacity of the battery. The heart of the battery is cathode because its capacity actually control the total battery capacity, so that is positive electrode.

Number of cycles is how many times you can charge and discharge of the battery before its original capacity falls down to 85 percent. So, that is the cyclability that number is important usually for a good cell at least 500 cycles, it should withstand.

So, if you are starting with 100 ampere hour or it should be 85 ampere hour, and by the time 500 times you can cycle it. Depth of discharge is how much of the pack energy is useful. Electrolyte you know that still commercial cells use salt and mixture of solvent.

Energy usually is measured in kilowatt hour. Energy density can be either gravimetric or volumetric. Energy storage is complete battery pack what is the energy stored. It is not only cell, but the total battery pack how it is constructed we will talk about it in the forth coming lectures. Already you know the jelly roll, this is the combined assembly of the anode, cathode, tab, and your separator, either you stack it or you form a roll and put it in a cylindrical cell, so that is jelly roll.

Power density is important, it is actually kilo watt of power per kg of the battery. State of charge is important, what state or state of discharge that is important characteristics of the battery. And short circuit of the battery is very important. So, basically if there is no resistance due to the formation of lithium dendrite or several other things, so that we call it is a short circuited battery.

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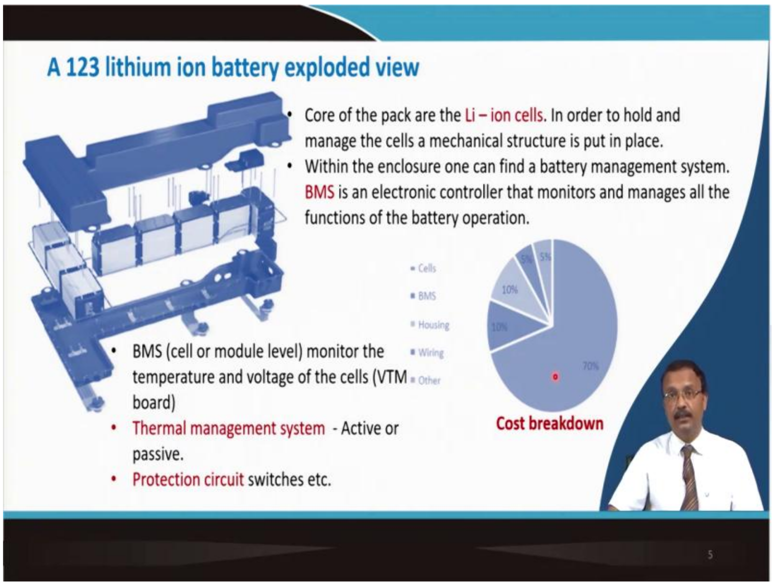

So, this company A 123, I believe now it is sold to some other company. So, if you go to their site, you will find that lithium ion battery actually this is a exploded view. So, there are several battery module to form this pack. And this whole pack is within this enclosure.

And this enclosure design is depending on your application. So, the core of the pack is there are lithium ion cells. So, there are several lithium ion cells in each of this module. So, in order to hold and manage the cells, the mechanical structure is put in place. So, these enclosures are important.

Within the enclosure, one can find a battery management system which I will be separately talking about that what is their function, what exactly they do, so that battery management system this is basically an electronic controller that monitors and manage all the functions of battery applications. The very first lecture in the first module I remembered that we have talked about the BMS very short. So, the BMS cell or module level they monitor the temperature and voltage of the cell, so through a VTM board.

And there are thermal management system. And as you will be able to see I will describe that this thermal management system could be active type or passive type. And also there are protection circuit when there is some problem so that switch off the battery. So, the whole thing is important.

So far we are only talking about electrode material, separator material, electrolyte. And actual battery pack if you see that constitutes all those things plus several other things like BMS is required, thermal management is required, protection circuit is required, charging circuit of the battery, charge protection circuit. So, many things are required.

So, now if you do a cost breakdown, then you can see that the cell, then BMS then housing, then varying and other. So, all constitutes part of it. And only you can see that the 70 percent this cost is your cell and allied materials that you can that you are using.

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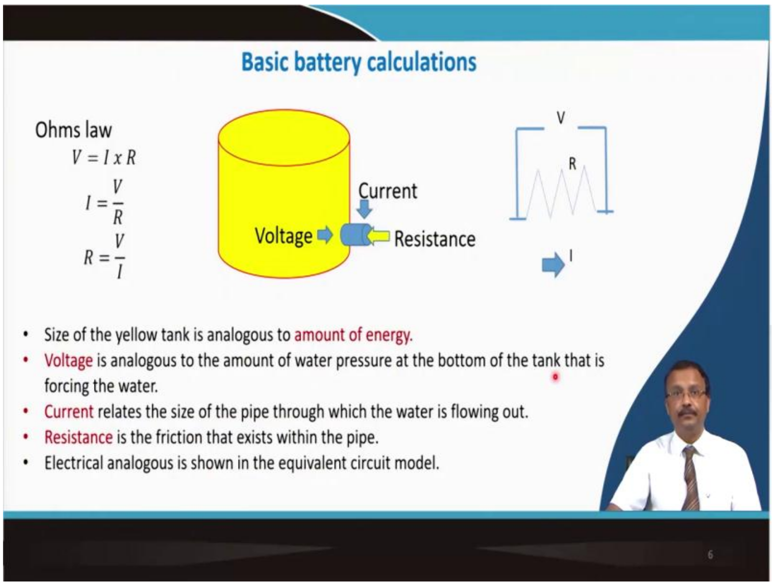

So, we can have some basic battery calculation based on Ohms law. All of you know that V equal to I into R. So, I can calculate I that is V by R. And I can calculate the resistance of the battery which is V by I. So, you can see this yellow tank that is analog analogous to the amount of energy that the battery stores.

$$V = I\,x\,R$$

$$I = \frac{V}{R}$$

$$R = \frac{V}{I}$$

So, as if you can see there is lot there is a big tank and filled up with water. So, when I am talking about voltage that is analogous to the amount of water pressure at the bottom of the tank. So, you know that if I have a filled water tank, then this pressure is more. So, the voltage is more, so that is the amount of pressure at the bottom of the tank that is forcing the water out.

The current that relates the size of the pipe. So, you can see a pipe is attached here through which the water is flowing out, so that current is related to this pipe. And resistance is basically the friction within the pipe. If you have a big pipe diameter, then the resistance will be low.

And lot of current can flow right. So, again we can draw a electrical analogous that is shown in this equivalent circuit model. So, we are applying the voltage across a resistance and current is flowing, and your battery is working. So, that is the main concern.

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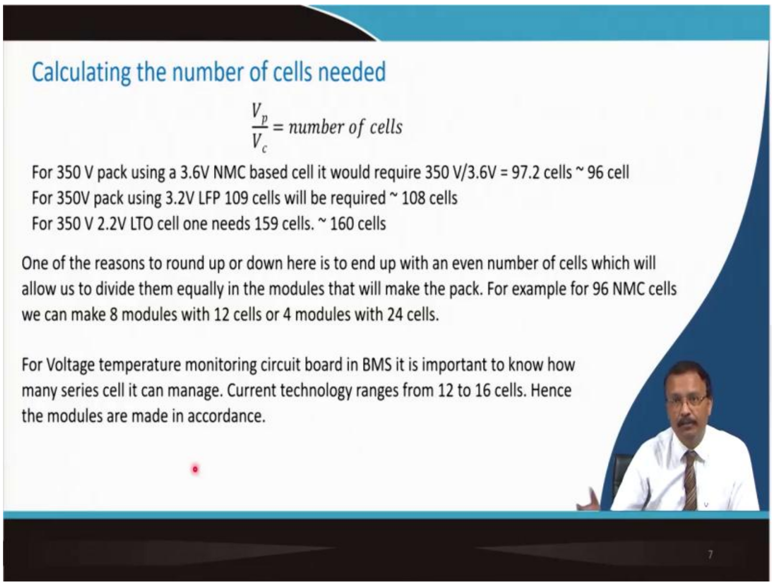

Now, it is important for you to calculate the number of cells that is needed. So, let us assume this V p is the pack voltage, and V c that is the voltage of individual cell. So, pack voltage and individual cell voltage, if you divide this then you will get number of cells.

$$\frac{Vp}{Vc} = number\ of\ cells$$

So, if you are using a 350 volt pack and using a 3.6 volt NMC based cell, NMC you know that one-third of nickel, one-third of manganese and one-third of cobalt layered structured material in usually graphite as the negative electrode, so that would require 350 by 3.6 that means, about 97.2 cells. So, cannot break the cell, but usually you take the nearest even number. So, 97, I will not take I will take 96.

Now, for 350 volt pack if I use a 3.2 volt LFP because if you change the chemistry then you compromise the voltage right. So, then I will be needing you say 109 cells right. Again I will take the nearest even number 108. Now, if you go for a LTO based cell, you know the LTO is having their voltage limit as 1.5 volt as a negative electrode, so that will reduce the voltage requirement to 2.2 volt. So, there you will be needing 159 cells. So, either you take 158 or you can take 160.

So, the reason for this rounding up or down, this is to end up with a even number of cells which will allow us to divide them equally in the modules right to make a matrix, so that will be easier to make the module or the pack of the battery. So, if you have 96 NMC cell, then we can make 8 modules smaller one, and each will contain 12 cells or 4 modules with 24 cells. So, we will divide that. So, that is useful, so that one part you have separated it is not all in a same place not all the eggs in a same basket, so that is useful for certain advantages.

For voltage temperature monitoring circuit board in a BMS, it is important to know that how many series cells it can manage because BMS is actually managing the cell performance. So, unlimited number of cells if that is in series like 16, 8. So, BMS cannot manage it if you make it 32.

So, current technology ranges to 12 to 16 cells. So, you will have to break the number of required cells into different modules, so that individual BMS can control their temperature, their state of health, their state of charge and stuff like that the temperature. So, the modules are made in accordance, so that must be clear to you.

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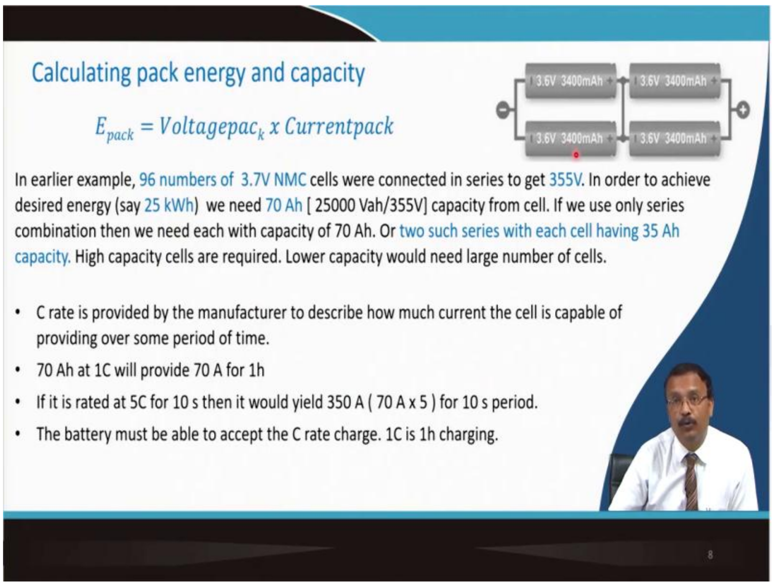

$$E_{pack} = Voltage_{pack}\ x\ Current_{pack}$$

Now, the pack energy and capacity that also is important. So, the pack energy is the voltage pack into current of the pack, so that voltage of the pack and current of the pack that will give you the energy. So, in last example, I cited 96 numbers of 3.7 volt NMC cells that were connected in series to get 355 volt.

In order to achieve the desired energy like 25 kilowatt hour, we need 70 ampere hour because this is coming from 25 kilowatt hour. So, that means, volt ampere hour divided by 355. So, we need 70 ampere hour capacity from the cell. Now, if you use only series combination, then we need with a capacity of 70 ampere hour; or I can divide into two, two such series each with having 35 ampere hour capacity, then that will give me the required capacity which is needed.

So, eventually high power sorry high capacity cells are required; if you have lower capacity that would need large number of cell. So, nowadays this cylindrical configuration that actually is having lower capacity because in a small place you are packing. So, you can get 3.4 ampere hour capacity and 3.6 volt. So, you can calculate what is the energy of each individual cell. So, there are various configuration that is possible to achieve the desired capacity level.

Now, here the C rate is provided by the manufacturer. So, manufacturer will tell you that what C rate is required to charge this battery and discharge the battery also. So, you cannot undefinitely increase the C rate and your battery will be dead. So, 70 ampere hour at 1 C will provide 70 ampere current for 1 hour.

Now, if it is rated 5 C for 10 second, then it would yield 350 ampere, that means, 70 ampere into 5 for a 10 second period. So, for 10 second period, you can discharge it at pretty high rate for your application.

For complicated application, this is important because you are driving a car, you need a battery which can give you lot of energy, so that you can drive long, but at the same time you need power also. If you want to drive in a upslope, then you need to accelerate or you need power to cross this. And when you are in down slope, then you can using the power. So, sometimes in a fraction of second you need more power, so that is dependent on the cell that you are using.

And the battery must be able to accept the C rate charge at least 1 C that is 1 hour charging because if you are driving a car, then you will have to charge it when the battery gets discharged. So, 1 hour is minimum in a charging station for you to wait right. Usually you if you full when you fill your tank with gasoline, you spend 5 to 10 minutes, but here 1 hour is 1 C rate, and that is one of the problems that you cannot charge it or discharge this battery at high rate it is like 10 C rate is equivalent to 6 minute.

But 10 C rate, your battery will be dead unless you have a very different chemistry. In my last module lecture I described that by putting a combination of super capacitor in the battery, it is possible for you to increase the power density. So, existing chemistry if you are using with the normal diffusion limited electrode, then it is extremely difficult to achieve a 10 C charging capability. So, you must you will have to think other alternates.

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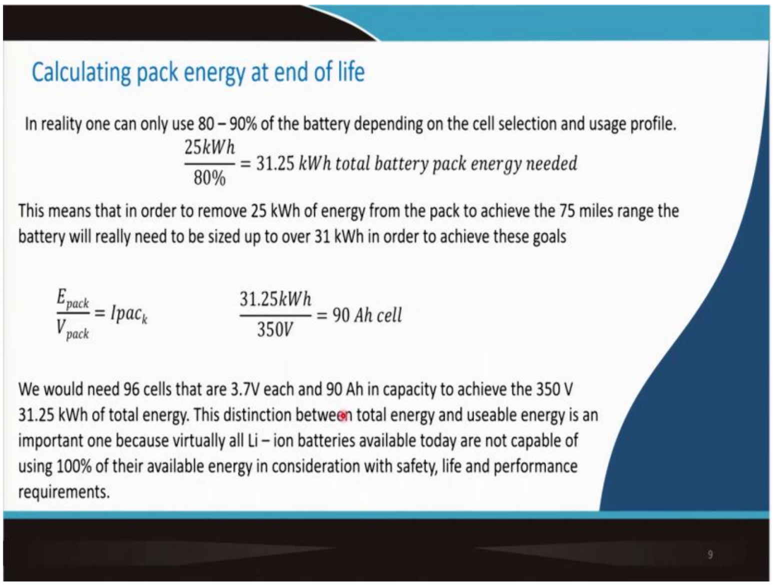

So, pack energy and end of life also can be calculated. In reality 80 to 90 percent of the battery depending on the cell selection and using uses profile, one can use 80 to 90 percent of it. So, if you have a 25 kilowatt hour energy 80 percent of that is 31.25 kilowatt total kilowatt hour. So, this much pack energy is needed. So, your application demands 25 kilowatt hour, but your battery since you can use 80 to 90 percent of it you cannot drain it fully. So, you will have to have a higher pack.

So, that what that means? that means that in order to remove this 25 kilowatt of energy from the pack and to achieve the driving of 75 mile range, the battery will really need to be sized over 31 kilowatt hour in order to achieve these goals. That means you have space limited you will have to put the battery in your car.

So, at least 75 mile you should drive before you actually recharge your battery. So, a larger pack means it is a problem right, you are losing your space. So, therefore, the high capacity cells are important. And we need to continuously work on the battery chemistry.

And so far anywhere you will see any website all this NMC, NCA, graphite LFP, LMO, these are the material. And this material you cannot give you we need to work on new chemistry. So, this E pack and if you divide with V pack, then you can get the I pack one. So, you can have 31.25 kilowatt hour energy and 350 volt. So, 90 ampere hour cell you will be needed.

So, we need 96 cells that are 37, 3.7 volt each, and 90 ampere hour in capacity to achieve the 350 volt 31.25 kilowatt hour of total energy. You can work it out. This distinction between the total energy and usable energy is an important one because virtually all lithium ion batteries available today are not capable of using 100 percent of their available energy in consideration with safety, life and performance. If you deep discharge, there are lot of problems.

For example, you know that in case of this lithium manganese oxide based positive electrode material certainly you can have more discharge capacity if you can deep discharge it below 3 volt level. But once you try to discharge it below 3 volt level, then all kinds of problem this manganese oxide m into dissolution etcetera will come in picture, capacity will not be that great because of the Jahn-Teller distortion and then actually that will be a block for you.

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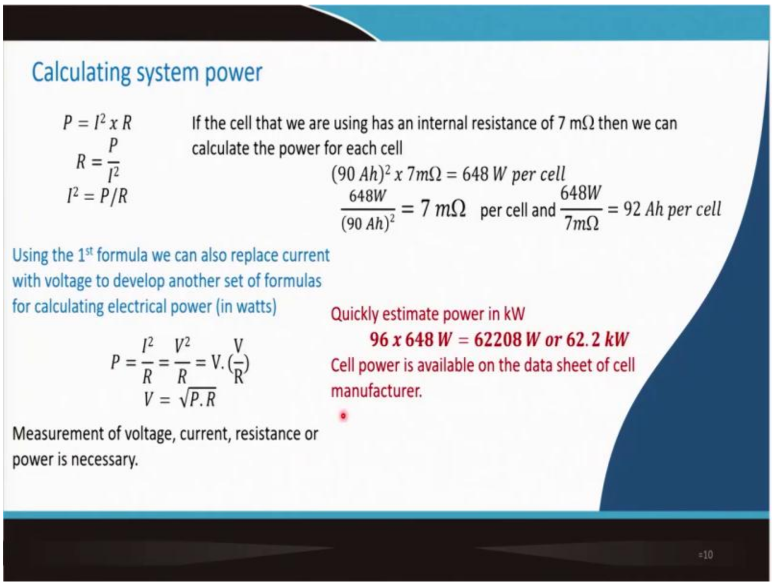

$$P = I^2 \; x \; R$$

$$R = \frac{P}{I^2}$$

$$I^2 = P/R$$

So, system power you can calculate the power is I square into R, R is P by I square. And I square equal to P by R. So, if the cell that we are using has an internal resistance of say 7 milli Ohm, then we can calculate the power of each cell. So, 90 ampere hour square into 7 milli Ohm, so that means, 648 watt per cell. So, 648 watt per cell, I divide with this 90 ampere hour whole square. So, I will get the resistance about 7 milli Ohm per cell. And 648 watt by 7 Ohm, that means, 92 ampere hour per cell.

So, using the same the first formula, we can also replace current with voltage to develop another set of formula for calculating the electric power in watt. So, this power is I square by R that means V square by R that means, V into V by R. So, V is root over of power into resistance.

$$P = I^2R \; = \frac{V^2}{R} = \text{V}.\;(\frac{\text{V}}{\text{R}})$$

$$V = \sqrt{P.R}$$

So, measurement of voltage, current, resistance or power, this is necessary. So, you can quickly estimate the power in kilowatt, this 96 numbers into this 648 watt, so that means, 62.2 kilowatt. So, cell power is available on the data sheet of the cell manufacturer. But if you have this data with you, you can quickly calculate the system power by using this simple formula.

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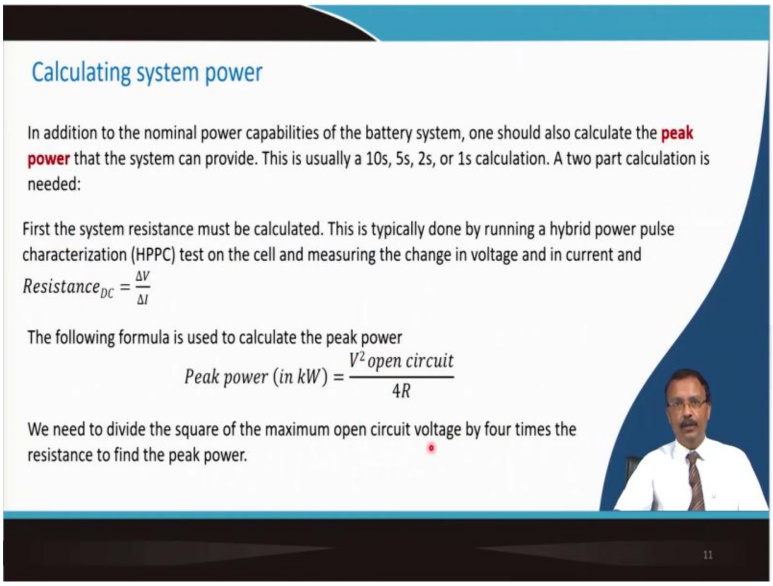

In addition to the normal power cable capabilities, the battery system one should also calculate the peak power. So, peak power that the system can provide. So, usually as I have told the peak power is for 10 second, or 5 second, or 2 second, or 1 second calculation. So, a two part of calculation is needed. First the system resistance you must calculate this is it typically done by a Hybrid Power Pulse Characteristics HPPC.

$$Resistance_{DC} = \frac{\Delta V}{\Delta I}$$

So, I will try to explain it more when we will talk about the BMS. So, this is done on the cell and measured the change in voltage and current and also resistance. So, the resistance, the DC resistance is this change in voltage by change in current. So, this formula is also used to calculate the peak power peak power if it is in kilowatt that is the value of voltage in open circuit condition divided by 4 times into the resistance.

$$Peak\ power\ (in\ kW) = \frac{V_{OCP}^2}{4R}$$

So, we need to divide the square of the maximum voltage open circuit voltage by 4 times of the resistance to find the peak power. I will try to formulate some problem. And please work out this thing because these are all very simple formula. And once I can set some problem, so that if you solve it then it will be little bit clear to you.

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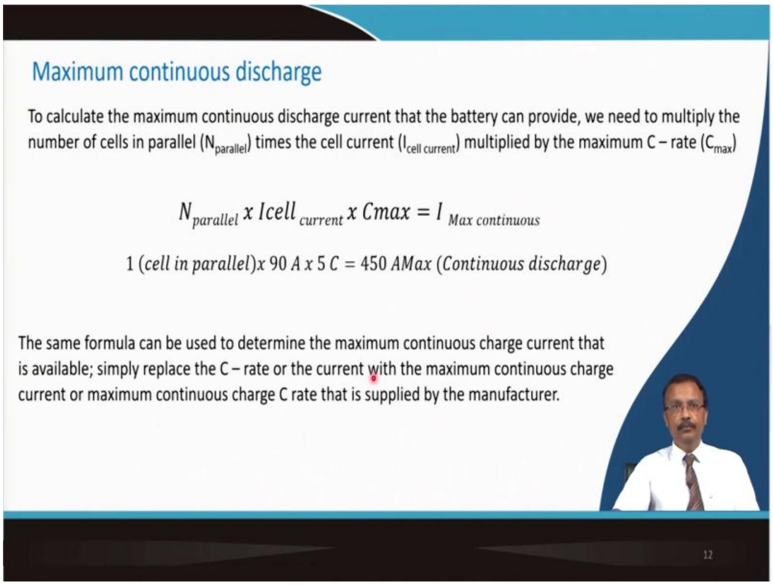

$$N_{parallel}\ x\ I_{cell\ current}\ x\ C_{max} = I_{max\ continuous}$$

So, now, it is important to know the maximum continuous discharge and to calculate this maximum continuous discharge that the battery can provide, what we need to do is to multiple the number of cells in parallel with the cell current and multiplied by the maximum C rate. So, parallel cell into the cell current into the C rate.

So, that will give you the continuous discharge current. So, if you have one cell in parallel, and 90 ampere you can get from their capacity 90 ampere hour, and then your maximum C rate is 5 C. So, 450 ampere maximum will be your continuous discharge right.

The same formula that you can use to determine the maximum continuous charge current as well, simply replace the C rate or the current with the maximum continuous charge current because usually the charge current is not same as discharge current. Charge is done at much lower C rate usually C by 2 to C by 5 rate it requires time for charging, and discharge you can do little bit higher rate, but the supplier specification must be adhered to.

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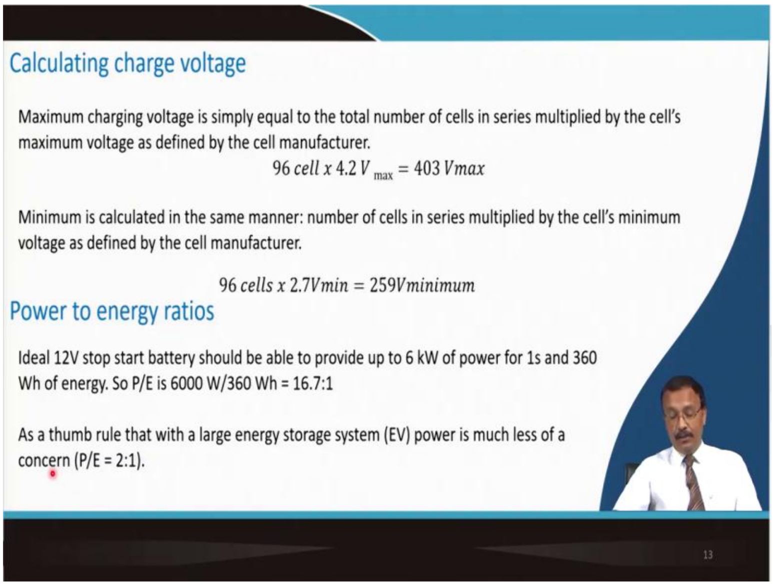

Charge voltage also can be calculated. The maximum charging voltage is simply equal to the total number of the cell that is in series multiply by the cell maximum voltage, and that is also you should do what has been defined by the cell manufacturer. So, 96 number cells into 4.2 volt max, so that means, 403 maximum voltage that is the charge voltage.

And minimum is calculated in the same manner, the number of cells multiply by the cells minimum voltage that is defined by the cell manufacturers. So, this is the minimum voltage that you need 259 volt minimum. Now, power to energy ratio is important. So, consider a 12 volt start and stop battery which you use in a scooter that will be able to provide up to 6 kilowatt of power for 1 second, and 360 watt hour of energy.

So, you can calculate the P by E ratio is 6000 watt by 360 watt hour. So, about 16.7 is to 1. So, you can have a thumb rule that with large energy storage system which is required for electric vehicle power is much less of a concern. So, the P by E ratio is 2 is to 1 which is actually in true sense is not correct because we need high power density battery as we have the sophisticated cars will come into market. So, it needs to be improved.

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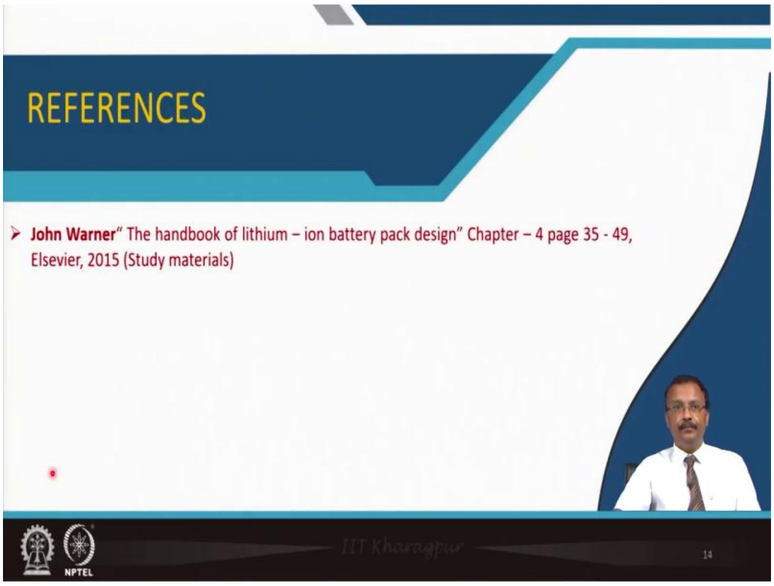

So, this particular part is actually covered from a book by John Warner, is a excellent book on lithium ion battery pack design. So, how step wise he has defined that how can build your own battery. And chapter 4 is important 35 to, 49 pages. So, this is your study material.

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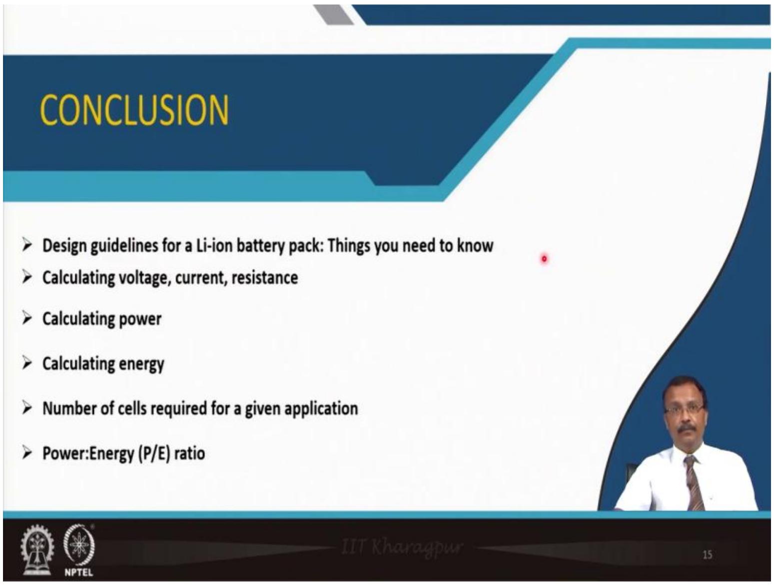

And in this particular lecture we have covered the design guidelines for a lithium-ion battery pack. And things you need to know calculating the voltage, current, resistance, then calculating the power, calculating the energy, number of cells required for a given application, and finally, power is to energy ratio.

Thank you for your attention.