Fundamentals of Electric Vehicles: Technology and Economics
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Lecture No. 25
Technology and Economics

So, welcome and we will start looking at some other concepts, which are very crucial to understand and use a battery. I have already defined what is called state of health SOH, second is state of charge and self discharge. What we like to understand that, if I have if you are given a battery, how do you estimate what is the state of health. How do you figure out what is the state of charge? So, we are going to get into a little bit of detail because this is crucial to actually design the battery and use it in electric vehicles or anywhere else.

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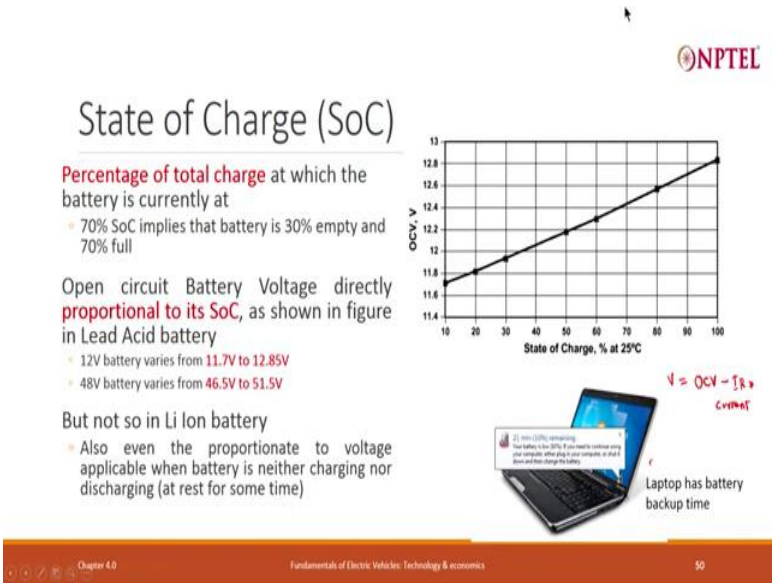

So, state of charge is just a percentage of total charge available at any particular time, it will keep on varying. State of charge of 70 percent means 70 percent battery is still there, 30 percent is full. So, many of you may have noticed that sometimes you have a laptop a sign comes up, the sign says it is a 21 minutes that is a 10 percent remaining, this is the state of charge. A laptop is estimating the state of charge and is displaying that. Now, if I look at how do I measure the state of charge, what is the mechanism.

Now, open circuit voltage for a lead acid battery, not for a lithium ion battery is a function of state of charge. So, I can measure what is called open circuit voltage, what is the open circuit voltage when the battery is not being used, you get an open circuit voltage when the current is 0 or nearly 0, you get an open circuit voltage. Because if there is a certain current the actual

voltage will be less than the open circuit voltage, it is open circuit voltage minus the internal resistance minus the current.

So, the voltage at any point is OCV minus the internal resistance multiplied by the current. So, it will depend on the current, if the current is 0 you get the voltage as open circuit voltage. For a lead acid battery it is linearly, state of charge is linearly proportional to open circuit voltage. So, just measure the open circuit voltage you know the state of charge. And for a 12 volt battery for example, open circuit voltage may vary from 11.7 volt, this is what is shown here to 12.85 volt.

12.85 volt means it is 100 percent, nearly 100 percent state of charge and 11.7 volt means it is 10 percent state of charge. For a 48 volt battery similarly, a full battery may be 51.5 when it is close to 10 percent it is 46.5 or 0. But this linearity relationship is not there, you can measure open circuit voltage that is very important. If it is part of the battery, there will be a BMS which will measure the voltage, convert it into numbers and store it or even can transmit it through a CAN interface that a battery may have.

That will give you the voltage, but what will be the state of charge? For lithium ion battery it is not linearly proportional.

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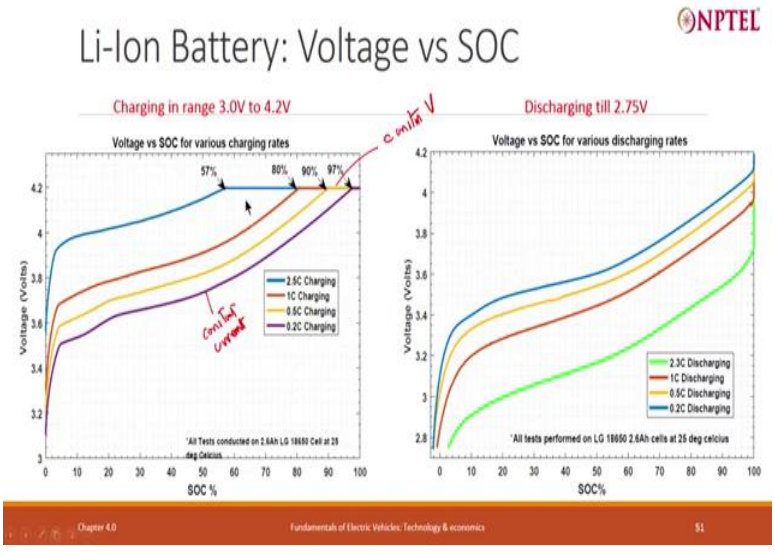

So, what is there for linear for lithium ion battery? And this is a very important learning, open circuit voltage or voltage versus state of charge. Voltage versus state of charge depends on, it is different for charging and different for discharging. For example, during charging time, and it will depend on the amount of current. If I am charging at 0.2C, then this is the curve. Now,

this of course, will depend on the kind of cells that you use and kind of battery that you use. But it is a typical curve like this.

So, you can, when you design the battery, actually the designer will measure this, the voltage versus current. Now, you want the open circuit voltage, so you want current to be negligible, very small, during charging time, extremely low current, nearly 0 current. So, if there is nearly 0 current, this factor will be nearly 0. So the voltage that you are going to measure is open circuit voltage.

And that time you measure the voltage and the relationship between the voltage and state of charges given out here. So, if you look at it, when the you are doing a 0.2 C if it is a very, very low rate of charging, the voltage will start at a very low voltage, will keep on increasing. And even, you have not, if you have come to close to 5 percent state of charge, and you have already the voltage is 3.5 volts. Now, it is going to increase somewhat linearly not linearly linearly, it will go up, it will go up with 0.2 C, it will go up to 97 percent state of charge.

So nearly full, it is not full yet. This part of the curve you actually try to charge it using what is called constant current. So in the charger, the voltage is continuously varied, the voltage is applied, for example, in the beginning you may apply for a cell if you are charging close to 3.5 volt, and you will find out what is the current. If the current is less than 0.2 C, you will increase the voltage slightly, if the current is more than 0.2 C you decrease the voltage. So you increase decrease voltage and a charger can do that more or less automatically so that you track the voltage and you keep on charging.

This is a constant current charging, in the sense the current imply is a fixed amount 0.2 C. So, depending on the size of the battery, you take 0.2 C and do this, this is what will happen to the cell voltage. When it reaches nearly 97 percent state of charge, then you will see very little very little the voltage is almost constant between 97 to 100 percent. It is very close to 4.2, it may be 4.195. And now from 4.195 to 4.2 you do not want the voltage to ever exceed 4.2.

So, you do not (incre) keep on charging with constant current, but you clamp the voltage, it is called constant voltage charging, this part is a constant voltage charging, this is a constant voltage charging, we will come to that, whereas is this part is constant current charging. So, you do this at 0.2 C and you take this plot. So, this is the plot that will give you voltage

versus state of charge. And you can use that you can measure the voltage and then estimate what the state of charge is.

If the state of charge on the other hand increases 2.5 C, you get a different curve. The curve is not, so it depends on the rate of charge you are doing. So, then you get a curve like this. Your voltage is voltage is higher with 50 percent current because your open circuit voltage open circuit voltage.

If I look at it, if I go back to this, the voltage that we are measuring is open circuit voltage minus IR into the current. So the current is larger, your actual voltage is going to less than open circuit voltage, more the current more the current you will see the actual voltage has to be higher, actually the voltage has to be higher for the same SOC.

Here for 0.5 C this is for a specific cell, but you can take another cell, the trend is like this. You will see in this case it goes up to 90 percent and reaches already point, it reaches 4.2 volt, now you cannot charge it anymore. Well you can charge but you have to do what is called constant current charge, you keep the voltage fixed, the current will reduce smaller and smaller and smaller negligible current will actually flow.

If on the other end you charge it 1C, you see the curve is like this and it goes up to 80 percent and then it stops and from here onwards, you have to charge it at a very low current to get there. If you do something like 2.5 C for the particular cell, you see that very quickly, when the 5 percent state of charge is there itself the voltage has reached close to 3.9 volts or 3.95 volt and from here onwards it charges slowly, but it hits at 57 percent state of charge itself, it hits the top.

So, you can 2.5 C is a fast charging. So, first important point that I want to make fast charging does not charge the battery full, it can only charge in this case 57.6 percent that is all that it will charge. For something, some other cell you may be able to charge up to 70 percent 75 percent, so that will depend on cell to cell. So, this is what you can charge. This is the voltage versus SOC. Now, this is a charging side, whereas discharging, discharging also has a very peculiar cuvre.

And these curves, well, manufacturers can give you a little bit but actually if you design the battery, you measure it, you actually use that then in the battery. Now, if you look at it, if you discharge it slowly, let us say 0.2 C, your voltage will immediately increase at and your, so it

is falling from here, so it is falling from here with 100 percent charge it will start falling like this and by the time your state of charge goes to 10 percent the voltage goes to 3.4.

On the other end at 1C charging, it will go to 10 percent it will go to 3.2 and something like 2.5 C charging the only 10 percent state of charge is left at close to 2.9. So, this and if you see again here, so you can only very quickly to fall to 3.6 volts, if you try to discharge at 2.5 C and then it will charge. Now these are extremely important when you design batteries. What do you do? So, maximum amount of charge is actually located out here.

If you see fast charge cannot be done at over 57 percent. So most of the measurements are done using what is called open circuit voltage or nearly 0 current. So, these curves are important, how the the relationship between state of charge and voltage. So, it is possible for you to measure state of charge at any time. If you want to take just a state of charge without talking about what is the state of charge is a reflection of how much the battery is charged, then the current has to be negligible.

As soon as you start using higher current, you will see a state of charge showing a difference, that you will have to take into account. But in reality state of charge has to be always measured as if it is open circuit, that will tell you the amount of energy that battery has at any particular time.

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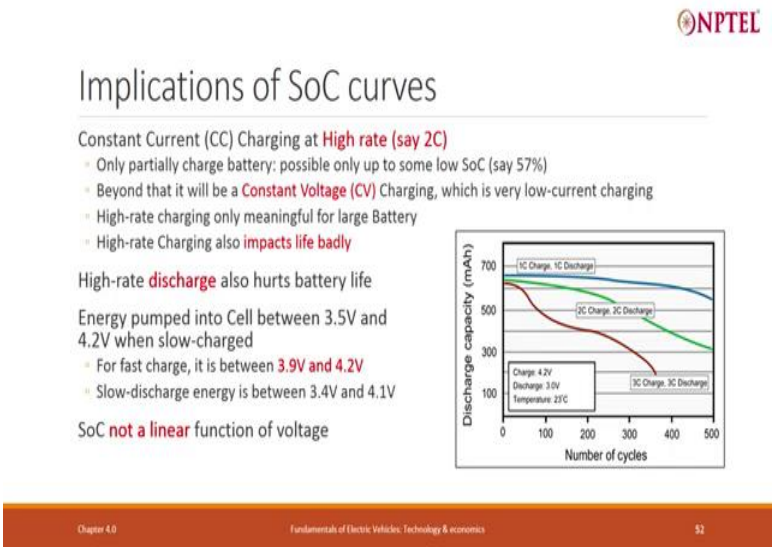

Now what is the implication of state of charge? As I told you, constant current charging at high-rate can go up to only 57 percent. Beyond that is a constant voltage charging, which is a low current charging. Now remember there are high rate charging only meaningful for large

battery. High-rate charging also impacts the life of the battery. Why, because only 57 percent of the battery capacity is usable. If you take a 1 kilowatt hour battery, and you charge it fast, only, you get 570 watts maximum. So, you are really wasting most of the battery.

But on the other end it is a 100 kilowatt, maybe 57 kilowatt is not bad. High-rate of discharge also hurts the battery life. Now again you see 1C charge discharge is something like this, 2C it is already becoming like this. 3C almost destroys. Of course there are batteries which can charge a discharge at 3C. But any 3C discharge will hurt the battery compared to low charging. Energy pumped into the cell between 3.5 and 4.2 when slow charged in that that is what you see here. If pumping into cell is between 3.5 volt close to this to 4.2.

But for fast charge, it is between 3.9 and 4.2. So, voltage is changing only very limited extent. Slow discharge energy is between 3.4 and 4.1. SOC is not a linear function of voltage and actual SOC is always the open circuit SOC. So, you charge or discharge at nearly 0 current and that is what you take as open circuit voltage and use that to calculate SOC. Anything else that you do, your SOC will not be will not be accurate. So, this voltage method of state of charge, voltage versus SOC is a very problematic thing.

If you see it is voltage versus SOC depends on the charging discharging and the rate at which you are charging, discharging. So, voltage versus SOC method is not used in lithium ion batteries for estimating state of charge. We will come to what is used then for the state of charge measurement.