Power Management Integrated Circuits
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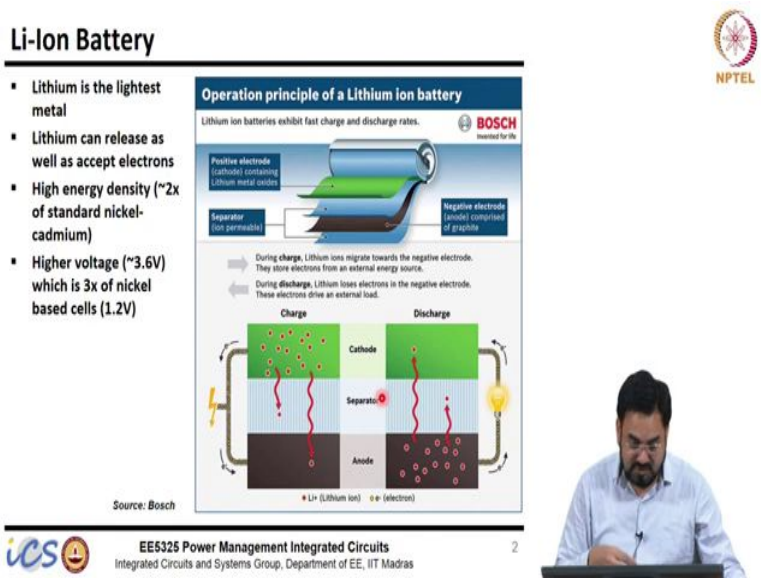
Lecture – 102
Li-Ion Battery and its Charging Phases



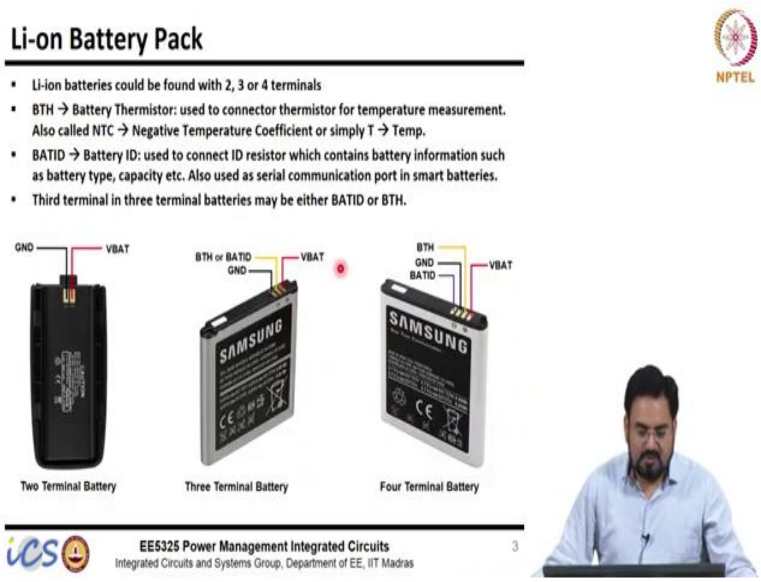
Even though I will be specifically talking about lithium-ion battery charger but the concept is applicable to any other batteries. Most of our handling devices or portable devices are using lithium-ion batteries. Even electric vehicles these days are using lithium-ion batteries, so this is more popular.

So, lithium is the lightest metal that is one of the main reasons it is used in a battery. And lithium can release as well as accept electrons and that is why it can be charged and discharged. So, it has quite a high density, almost 2x of your standard nickel-cadmium battery, you would have seen those cylindrical batteries 1.5 volts batteries which are used in remote controlled toys.

And the voltage here is 3.6 volt which is almost 3x of nickel based cells. So, your nickel-based cells are 1.2 volts and some cells are 1.5 volts. So, that is another advantage: you get a higher voltage, higher power density, and then it is very light.

During the charge phase, your lithium ion migrates towards the negative electrode and they store electrons from an external energy source, so you have plugged in your charger. So, these lithium ions will move this side. They will move back to the other side or from anode to cathode side during the discharge phase and they will release the electron and that is how the current flows from your battery to load. And when the battery is fully discharged again, you will find it in this state(left hand side). And then again you have to charge back in order to use the battery again.

So, during these charge and discharge phases, some of the ions are trapped, and based on that they have a limited charge and discharge cycles maybe 1000 cycles or so, after that your battery will be dead. That is why you cannot have an unlimited number of charge and discharge cycles. There are other reliability factors like your battery is heated too much and all those, so that will reduce the life of your battery as well. So, a lot of protection is involved there in the battery in order to make sure that battery life is extended.



If you look at a lithium ion battery pack, even though from the outside it looks like just a battery nut there is very little small PCB inside which contains some circuitry and I will mention what exactly those are. But, if you look at the battery of the old days, we used to have only two terminal batteries: one terminal is Vdd which we call VBAT and another terminal is ground. VBAT is nothing but battery voltage.

Nowadays, you will find either three terminal or four terminal batteries. So, what is the third terminal here? So, the third terminal is BTH or BATID. BTH is your battery thermistor. As I mentioned, batteries cannot sustain very high temperatures. So, there are some reliability reasons and safety reasons also there is a risk of explosion as well at high temperature. So, you have to limit when you are charging and most of the time the battery will get heated up when you are charging.

There is a thermistor connected between this terminal to the ground and you can monitor that voltage and that voltage will be mostly inversely proportional to temperature. So, when the temperature increases that voltage will go down then you will compare with the reference and you can basically either stop charging or reduce the charging current based on your temperature limit. So, let us say the maximum temperature you want to stop charging is 150 degrees or so. So, beyond 150 degrees you do not want to even charge at all. You can completely stop the charging, but let us say when you exceed 100 degrees Celsius or so. You can start reducing the current so that the temperature will not rise that much. You can maintain a temperature below whatever maximum limit is by simply reducing the charging current. So, that is why this thermistor is used which is connected at BTH and that is what the third terminal does.

And in some cases, instead of a thermistor, this third terminal can be used as BATID which is battery ID. So, this is again used to connect an ID resistor which contains the battery information such as battery type, capacity etcetera used as a serial and it can also be used at serial communication port.

When a battery is plugged in if this is being used as BATID. So, your phone or any device can read the voltage across the battery. So, let us say a constant current is being sourced in that resistor and you can determine the value of the resistor by measuring IR voltage across the resistor. And based on that value of the resistor you can find the type of battery, voltage, all the chemistry, and capacity. All that information can be found from that resistor value.

It comes from the battery standard, there will be a table of your R_{ID} and if your R_{ID} lies between in this range. So, this will be all the details of the battery, what is the capacity and all those. So, let us say if it is a 1000 milliampere-hour battery then R_{ID} maybe let us say 1 kiloohm. If it is a 2000 milliampere-hour then R_{ID} could be 2 kiloohms or so.

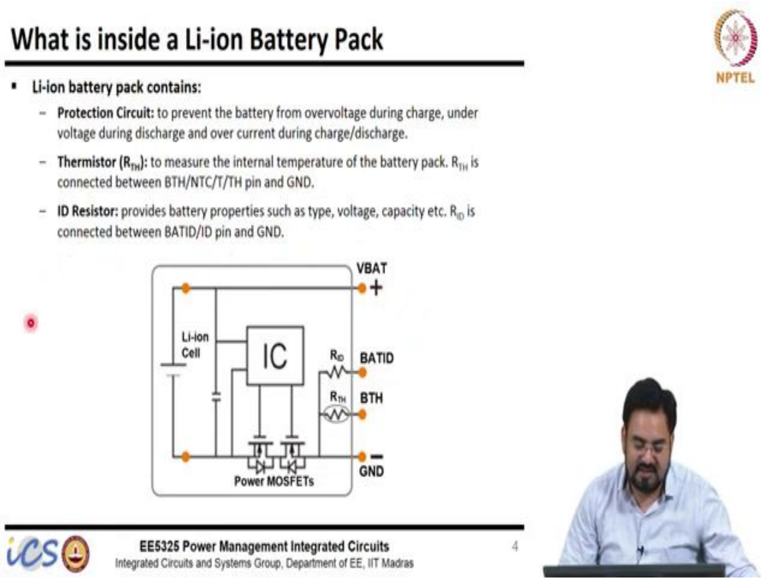
If it is being used as a serial communication port, then it is a single communication and there is no clock. So, it is a non-synchronous protocol. In that case, your battery can communicate with the host or your cell phone. So, from that, it can provide all the information, so whatever information you are getting from R_{ID} you can get that same information digitally, so this battery will have its own controller and it can communicate with the host.

And there is a standard called MIPI BIF which is a MIPI standard battery interface and this is mainly used for that. So, that single terminal can provide all the information and there is a complete MIPI BIF controller inside the battery. And that is called the smart battery. When you are charging the battery, it can tell you what current it is being charged at. It can even tell you what voltage it has charged too. So, all that information can be provided by the battery itself, so a lot of things that are currently being done by the cell phone can be done by the battery.

Another purpose of that would be like it can identify itself through that digital communication port, so each battery will have its own unique ID. So, it can be used for authentication purposes. So, when that unique ID can be verified by the phone and we will know whether it is a genuine battery or it is a duplicate battery. So, a lot of duplicate batteries are there in the market and those batteries are not reliable. I mean most of the time the risk of explosion is with those batteries.

Let us say the real battery is capable of charging at some 4 amperes or so. I am saying this because these days you have fast charges, so those fast chargers can charge the battery at a very high current. So, but you need a real battery in order to charge at 4 amps but let us say you have a duplicate battery that cannot accept 4 amps, I mean from the outside it will look the same but inside the chemistry is completely different. If you charge the same battery with 4 amps it may explode. In order to avoid those kinds of situations, a cell phone detects it is a fake battery or it is a duplicate battery through this digital communication port. The cell phone will ping this battery over this phone and ask can you send me your UID? the battery will send the unique ID and it will see whether that unique ID is real or not or whether the battery can communicate or not. It is quite possible that the battery may not be able to communicate because those are cheaper batteries and they will not put the whole controller maybe MIPI BIF obviously.

When the cell phone does not get any answer from the battery it will imagine that it is not real. So, it may either not charge the battery at all or it will charge with a very low current. So, just to make sure that there is no risk of explosion or damaging your cell phone. In some cases, you may have a separate BATID and this is a four terminal battery, so that is also quite possible. You may have a 1 BATID port and 1 BTH which connects the thermistor.



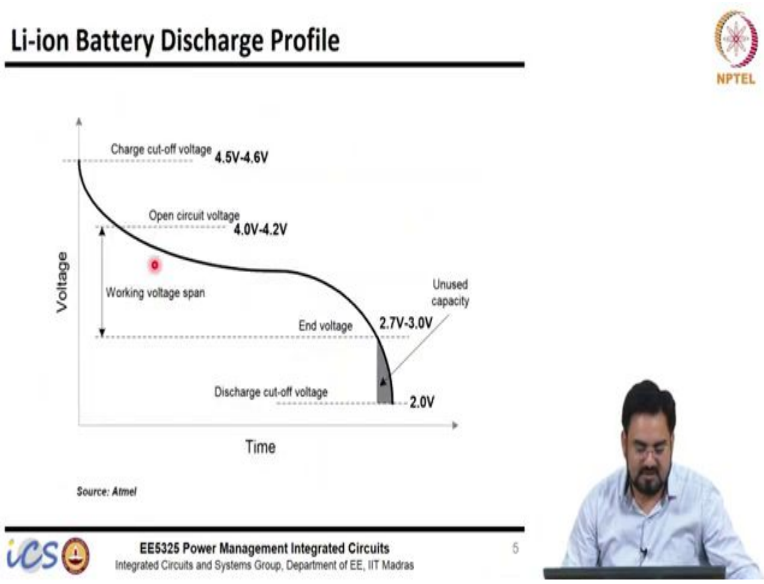
So, let us see what is inside this lithium ion battery pack. You have a protection circuit to prevent the battery from overvoltage during charge. This battery has a specified maximum voltage and if you charge beyond that then there is a risk of battery explosion or damaging the battery itself. So, we cannot charge beyond a certain limit.

So, let us say the battery's maximum voltage is 4.6 volt when fully charged. If you charge it even a few 10's of millivolt higher it will be at risk actually. So, that is very important we cannot overcharge the battery, there is a circuit which will detect the voltage if it is overcharged then it will completely cut off.

You cannot over discharge also. So, there is a minimum specified voltage below which you will not allow your battery to discharge. The problem is if it goes below that voltage then in order to bring it back to that voltage, it may take forever to charge that battery because when the battery is fully discharged you cannot charge that battery with a high current. Because if we charge with a high current then again there is a risk of damaging that battery.

So, that is why this protection IC will not allow to charge or discharge of a battery beyond a certain limit. And it can have an over current protection also, so if you are charging more than the specified current then that can also be detected and it will cut off the charger.

You have a thermistor just like I said you have a BTH terminal that connects this thermistor with the ground which monitors your battery temperature and then the Id resistor is connected between BATID and this ground. And if you have BATID as I mentioned if this is being used for serial communication then you may have another IC or that IC may integrate both the controller as well as protection everything, so there will be a complete transmitter receiver for that serial communication.

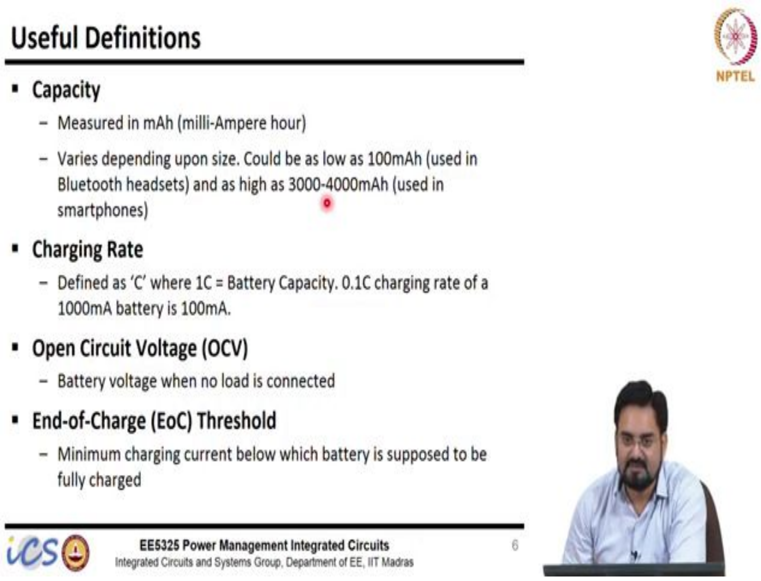


So, if you look at a lithium ion battery discharge profile this is how it looks like. So, typically your voltage will fall in the range of 3.3 to 3.6 volt. And when it is fully charged it may be 4.5 to 4.6 volt and this is your charge cut off voltage which I was mentioning. And then when your battery is fully discharged, then it can be somewhere between 2.7 to 3 volt.

Below which it is the unused capacity because you can see the voltage drops very quickly here and this region is mostly flat. So, your working voltage span is mostly this because here also you can see the voltage is discharging very fast. So, maybe within a few minutes if you connect the battery it will fall to this voltage.

But most of the time it will remain within this range which is mostly this flat curve remains 3.3 to 3.6 volt. When it goes below 3 volts you mostly cut off, and this is the point where you say your battery's charge has gone to 0 percent. But if it goes below 2 volts then you completely discharge the cut off then your protection IC will kick in. But this portion is taken care of inside the phone charger itself, the phone will not allow the battery to discharge below this.

So, let us say you keep your cell phone for a month or so, and due to some reason, your battery is being discharged and goes below this level. Then that protection IC will cut off that battery completely, so it will be a completely open circuit by opening this FET then your voltage will remain at 2 volts.



There are some useful definitions that you need to remember when you work on these charging circuits. So, capacity is one thing. Battery capacity is always measured in milliampere hour. 1 ampere hour or 1000 milliampere hour which means if you draw from that battery constantly 1 amp current then it will last for one hour. If it is a 3000 milliampere hour then you can draw constantly 3 amp for 1 hour or 1 amp for 3 hours. So, that is why capacity is always measured in milliampere hour not in watt actually, a watt is different. Watt is then you have to multiply with the voltage and that voltage is not constant here.

So, it could be as low as 100 milliampere hour. If you see your old days cell phones which had black and white screens, they will have a very small battery. So, capacity is only 100 milliampere hour and the power consumption of those phones is not so huge even 100 milliampere battery will last for 2 to 3 days. If you look at your Bluetooth headset or your smartwatch, you cannot put a bigger battery there. So, as you increase the milliampere hour, then your battery size also increases. And when you go like 3000 or 4000 milliampere hour you will see a very big battery used on the phone.

If you measure with the voltage level then you are not actually measuring the capacity. The capacity is always measured in milliampere hour. It is like a coulomb count. Current into time is the charge. So, it is always storing the charge, so you have to measure the capacity in the charge, voltage level will not give you a real number. It may give you maybe some number, but that will not be accurate if you want to accurately measure the capacity then milliampere hour is the only way to measure. Let us say you have a new cell phone, the battery may be lasting for a day or so. And the charging time will also be high in a new battery. After a year you will see your battery will be charged quickly and it will discharge quickly.

When the battery gets older, the capacity of the battery itself starts reducing. So, if you have a 1000 milliampere hour capacity battery after a year only 500 milliampere hour capacity would be left. In reality, the 100 percent battery for an older battery is only 500 milliampere hour and 1000 milliampere hour for a new battery. Even though they might be the same battery. And this happens mainly because of the aging factor and that is why we say it has 1000 cycles of charge discharge. Because what happens after 1000 cycles of charge and discharge, the capacity is almost 0 and your battery will not last even for a few minutes.

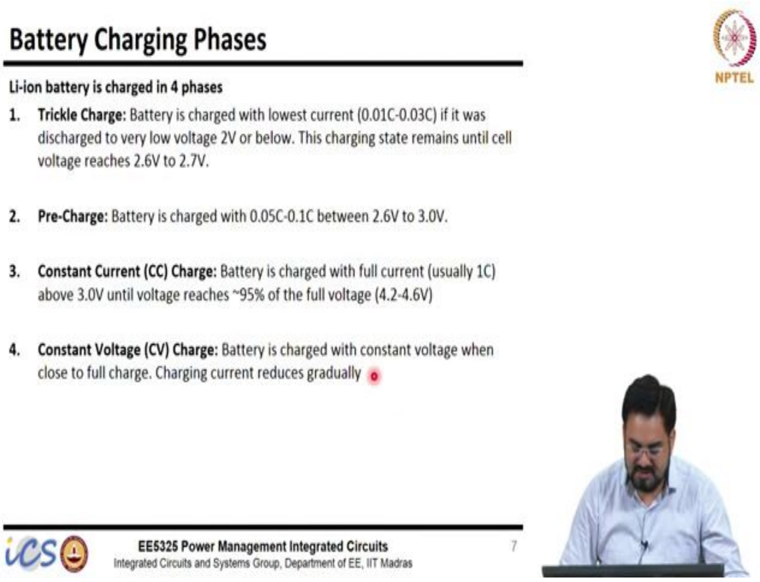
So, in reality, the old phone should show only 50 percent capacity when it is fully charged, not 100 percent. So, this is the one thing we have not very accurately done in most cell phones and may need to be done especially in the case of electric vehicles.

In electric vehicles, let us say after a few years your battery's capacity is reduced. And initially when you started with a new car and a new battery, let us say in one charge it was going 100 kilometers. After a year it is able to go only 50 kilometers. So, in the capacity, it should show only 50 percent so that you know that it will only go 50 kilometers not 100 kilometers, just like your petrol tank. If a full tank is filled then you know that depending upon mileage you know the number of kilometers you are getting but if your tank is half only then you can guess, how far it will go? But in the case of an electric vehicle, in both cases, it is showing 100 percent then it is very difficult.

In reality, the measurement should be just like you measure the fuel in the petrol tank, even though your petrol tank measurement which is shown is not very accurate, but still, it will tell you whether it is half full or full 100 percent full, but in case of when they show the battery level, they will just look when it is fully charged or fully discharged or mid charge that is it. They will not show what the real capacity is. But this is really important and eventually, it will come up and it will start measuring the real capacity which is left in the battery based on that it will show the level.

The charging rate is defined as C where 1C means whatever the capacity of the battery is. So, let us say it is a 3000 milliampere hour battery, so when I say 1C that means 3 ampere hour. When you are charging at a full rate you will say you will charge at 3 amp. If it is a 5000 milliampere hour battery then 1C is 5 ampere. When I say 0.1C charging rate that means one 10th of that. So, 1000 milliampere hour battery if you are charging at 0.1C then you will say you are charging at 100 milliamperes.

Open circuit voltage is nothing but the voltage across the battery when nothing is connected to the battery. So, your battery is completely disconnected from the load and you measure the voltage. End of charge threshold, so this is a minimum charging current below which battery is supposed to be fully charged.



So, there are different charging phases in the battery and this is really important if you are designing a battery charger. You need to know these things otherwise your charger will not work at all, or even if you are able to charge the battery then it will damage the battery completely, so these phases are really important.

Trickle charge trickle charge is a battery charge with the minimum current which is 0.01C and 0.01C is 1 percent of your full capacity. If it is a 1000 milliampere hour then you can say 10 milliamps to 30 milliamps only. If it was discharged to 2 volts or below that is what I mentioned that you do not allow the voltage to go below 2 volts. But if it is allowed then you cannot charge with the high current then it may take forever to charge. You may be sitting half a day to get your battery to even come to the 3 volts where you can start charging with the full current. So, this charging state remains until the cell voltage reaches 2.6 to 2.7 volt. This is the minimum voltage where you can start charging with a higher current. When say higher, it means higher than 1 to 3 percent.

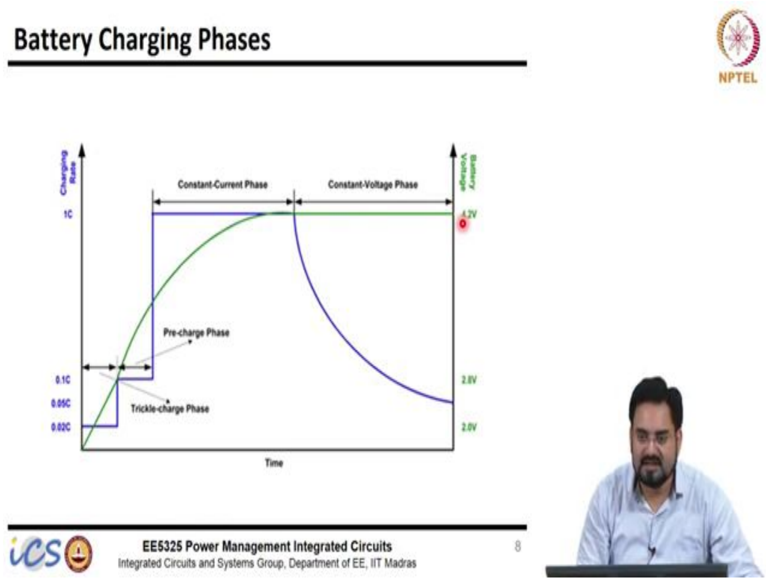
Then the next level is 5 to 10 percent. So, now from here, you can move to the next level which is the pre charge phase. So, most of the time your battery or your cell phone does not allow your battery to discharge below this volt. This will be your 0 percent actually. So, from 0 percent when you charge, you will be starting from pre charge and not from trickle charge. But due to some reason just as I mentioned if you keep your phone for a month or so unused then due to leakages it may go down. And then when you connect the charger, then you have to wait for a very long time in order to get to the pre charge phase. And then after that, your battery will start charging quickly. So, 0.1C between 2.6 to 3 volt.

Then the constant current charge phase. This is the full current charge which happens here. So, the battery is charged with the full current which is usually 1C and 1C is nothing but your battery capacity. And we charge using 1C current until the voltage reaches 95 percent of the full voltage.

Then we enter the constant voltage charge. The reason is I cannot charge the battery to 100 percent with a full current, otherwise, you cannot accurately stop the charging at the maximum allowed voltage. So, you have to basically start reducing the current before that. So, after 95 percent, you know what is the maximum allowed voltage and you enter a constant voltage so that your battery voltage will be regulated. So, this constant voltage mode will automatically start reducing the current when the battery is charging up, when it is fully charged the current will be almost 0.

But if you keep in a constant current mode for 100 percent time then it is quite possible you can overcharge the battery and there is a risk of damaging it. Think about a regulator. So, your regulator is now starting, so when the regulator will stop charging the output capacitor. When it reaches the full voltage, so now it is 95 percent correct. You enter the constant voltage mode after 95 percent. Your feedback will be coming from your battery and you have a reference voltage. And the reference is telling that your feedback voltage will be the same as V_{ref} when the battery is at 4.6 volts. But when you entered into constant charge, let us say the battery was at 4.5 volts, 100 millivolts below full voltage. So, 100 millivolts more you have to charge now. So, your constant voltage regulator will automatically make sure that it will keep supplying the current until it goes to 4.6 volts, and then it will stop charging automatically because your feedback will not allow it to charge the output further.

So, your current will gradually start dropping. Even if there is no load when you start your LDO, there will be some current drawn from your power FET in order to charge that capacitor to the final voltage. But when it charges to the final voltage current will stop, that is how the capacitor is charged. The same thing happens here also, so you can imagine your battery is nothing but a very huge capacitor.



These are different phases. You can see here this is your trickle charge which is like 1 to 3 percent then when your voltage level reaches this point then you enter the pre charge which is 2.6 to 3 volt. This level is actually programmable. Some batteries may have a 2.7 volt and some may have a 3 volt. So, it is not really fixed, but most of the time the minimum could be 2.6 and the maximum could be 3.0, but it could be anywhere in between this.

It will remain in pre charge phase until this voltage. And then from here, it will take off and you enter into a full charge. It is a constant current phase and you can see where you are charging with 1C. In the old days, these batteries used to be charged with 1C only, but nowadays you have a fast charger. They can charge the battery with a much higher current. That is how you get fast charging.

This is battery voltage and this is your current. Look at the charge and discharge profile, most of the capacity is here. So, the voltage will be changing slowly. Think about if you have a big capacitor. In this range your capacitor value is small, but in the middle range, your capacitor value is 10 times more. So, even if you charge with the higher current your charging rate will not be that fast. The capacity is different in these cases. You can see here it is falling quickly, here falling quickly, but here it remains much flatter.

You can imagine that this battery has a maximum voltage of 4.2 volts. So, it is not necessary that all the batteries will have a 4.6 maximum voltage. There could be some batteries that may have 4.2 volts maximum voltage, but over time the batteries have improved and nowadays you can see 4.5 or 4.6 volts when they are fully charged. But a few years back those batteries were only having a maximum voltage of 4.2 volts. So, those are the improvements that are basically being done in the batteries to increase the voltage level. So that you can get more capacity and the battery will last longer.

As I mentioned you never know whether the battery is genuine or not. So, if it is a genuine battery you are using a genuine charger. Then all the protection circuitries are there. I mean there are a lot of low end phones which even though you call them smartphones they will give you all the features. But they do not have a genuine part inside. You do not know what charges are being used there? Whether all the protection is there or not?

Let us say, the battery does not have a thermistor at all. What will you do? It gets overheated and it may explode. So, the cheaper batteries will try to reduce the number of parts as much as possible because they are much cheaper compared to the original batteries. So, most of the time, there are very rare cases where you will find that genuine batteries have exploded.

And you do not know under what conditions, but most of the time risk is there when your battery is getting charged or if the battery is getting discharged with the high current and then again the same thing, it may get overheated and explode.