# Fundamentals of Electric vehicles: Technology & Economics

**Professor Ashok Jhunjhunwala**
**Institute Professor**
**Indian Institute of Technology, Madras**

**Lecture - 76**

**Course Summary**

Let me spend a few minutes looking at what all we did in this course. We started by saying electric vehicle is going to happen; going to happen faster than we think. Primary reason, it is 4 times more energy-efficient, it is non-polluting.

Economic viability is a concern, but it is, the gap is being filled every day. We can use smart techniques like swapping to make things move faster. We talked about how do you need to really design the vehicle which are energy efficient so that they consume less energy. And if they consume less energy, means battery size goes down. And if battery size goes down, things become more economically viable.

So remember that you tend to do energy-efficient petrol cars for the operation cost of the vehicle to go down. But for electric vehicles, you do energy efficient so that the capital cost can come down. Then, we came up with this interesting swapping technique by which you can convert the fixed cost of battery into a variable cost and that would help.

We got into a introduction of what kind of things are possible for charging, charging infrastructure, swapping, what consists of batteries, the materials for the battery, and introduce the concept of recycling. Introduce the concept at that time itself in Chapter 1, how do you really figure out cost of usage of something which is high upfront cost and low continuous cost?

The depreciation, interest rate, we get into what is called life of the battery and number of cycles et cetera, we introduced all of that. After doing a large introduction, we took a step back and sort of say, let us go to the fundamentals of a vehicle.

Movement, it is, after all, mechanical movement. What is the velocity at which it is moving? What is the acceleration that it is taking? What is the weight of the vehicle? What kind of road do we have? Based on that, can we calculate the first, the torque requirement? The motor has to give the torque at different speed. Vehicle may move at different speed, all the way from 10, 15 kilometer per hour to 100 kilometer per hour, 150 kilometer per hour. What is the torque and speed and what is the power requirement. Peak power requirement, peak torque requirement, and then we computed what is called the energy required.

Energy required basically till how much fuel I need to have or how much battery do I need to have. So we talked about all these things and we gave examples of what does it take for two-wheeler, three-wheeler, four-wheeler, trucks; we actually went through this completely in detail.

Something that is now I think taught in a automotive course or a mechanical engineering course, but I think for electric vehicle, all of us get need to know. So that is what we did in Chapter 2. Then we saw, said okay, we have decided to make electric vehicles.

In Chapter 3, we discussed, what are the subsystems which are common to electric vehicles and petrol vehicles and what are new subsystems. What goes out, what stays, what comes in? We went into the details of each of the subsystem, specifically, we said the most important thing that we will require is a battery, which is energy container.

Instead of fuel tank, we said that the motor and controller which is like your engine of a vehicle, equivalent to engine of a vehicle. We said that a VCU may be required; voltage control unit, which will manage all this. We said that we will require several DC-DC converters because not everything is runs on the same voltage.

We talked about various peripherals, what happens to the peripherals. Air conditioner will remain as air conditioner, except that it is now going to be electrically driven in a hydraulic driven. Power steering and breaks, again instead of a hydraulic driven, we said it will become electrically driven. We defined all this. We defined that there will be a software will be required.

And then, we also sort of said, the very important thing that will require is a charger. Because without the charger, batteries cannot be charged and we talked about the charger will be important component. There we introduced the term of on-board charger and off-board charger there.

After defining all the subsystems, we started sort of saying, let us look at the main subsystems in detail. And we went into the first thing that we take out into is battery cells because the cells which has to be put together to make a battery.

We started trying to understand what are the characteristics of cell. Each cell is a container can be a container of electricity; it can be charged-discharged. And we found that it can be charged-discharged only finite number of times; that is its life; life cycle. We then found out that this charging-discharging for each cell will depend on the temperature used for charging, and temperature used for discharging.

And that temperature dependence, we started looking into it. We then found that the life cycle of this cell is also depend on the rate of charging and rate of discharging. The C-rate, we defined the concept of C-rate and we went into the dependence. And finally, we sort of said the battery life will depend on the depth of this charge, how much you never fully charge, never fully empty; you leave part of the energy always there; that is, leave that much at the bottom, do not fully charge, leave it little empty so that you can run it more efficiently.

It is like even in a fuel tank. You do not take out the last bit of petrol and you do not try to fill it over brim because then it can spill. In this case, there is no spilling but basically, it impacts the life of the battery.

Having done that we then went into, okay, these are the cells that we have, we went into two parts. How do you build from the cell to the complete battery pack? What is involved? What is the configuration? How do you go about doing it? What are the different types of cells available? We went into what are the cell chemistry that is available today.

What are the cell chemistry that will come tomorrow? How does each of this impact the different parameter, charge-discharge cycle, the voltage, and the current, the temperature dependence, the DOD dependence, the rate of charging-discharging dependent? And all the time we are also talking about cost, cost, cost.

We talked about cylindrical cells, we talked about prismatic cells, we talked about the pouch cells; all three kinds of cells and how do we put them together. We also talked about the battery materials that we do not have these battery materials and we have to import these battery materials. And we talked about that how these battery materials can be recovered by using recycling.

We then looked at again the economics of the whole cells and battery. It is a fairly elaborate chapter, went into details. And then Dr. Kaushal came in and started looking at once again, cell-to-pack in great detail.

He first started sort of saying, well, you need to really understand how do you do mechanical packaging. You need to understand vibrations, you need to understand, what are the materials that are used to hold the cells together; are they going to bend, will there be stresses developing? And if they do, what does it do to the pack. Remember, if there are stresses, the joints between cells and the joints between what is called busbar and the cell, will all become loose and that can create a huge disaster.

So the mechanical aspect, if the vehicle is vibrating, what happens to the cells and the pack? After looking at it in somewhat comprehensive manner, the mechanical aspect, he went to the next most important aspect, the thermal. Probably the most important aspect, especially in India.

How much heat is generated? Where is that heat going as it is used, as it is charged, as it is discharged? What happens to that heat? Is that heat going to just increase the temperature of all the cells? If it increases the temperature of all the cells, the life is going to go for a toss.

What do you do? How do you do thermal design? How do you see hotspots do not develop? He went into detail how to compute this, how to simulate them, and figure out how to carry out thermal design; if cooling has to be done, what kind of cooling is to be done. For a very small pack, you may just let the environment cool it. For a larger pack, you start looking at both air cooling, liquid cooling.

Then he went into the electrical design. How do you design the pack electrically? How do you ensure that every electrical path from every cell to the terminus is in such a manner that nowhere extra resistances are found? Why is it important? Because currents can be 100 amperes and even a couple of milliohms resistance will completely change the characteristics of the battery.

Each cell, the difference between 90 percent charge and 90 percent empty is only, is less than a volt 0.8, 0.9 volt. 100 ampere, 0.2; 2 milliohms is already 0.2 volt. If you make a error of that kind, you are already making like 25-30 percent of capacity. You think that you have lost, we do not know what has happened.

So he went into electrical design, and then he finally went into BMS, the battery management system. So crucial, so crucial for ensuring first, first safety; number two, ensuring the cells are balanced, ensuring that cells have maximum life. And if put together, this whole battery pack, most people make the biggest mistake of thinking that it is just assembling of cell, and I think he must have given you a favor what all effort is required.

And if the design becomes far more complicated in Indian condition, where the temperatures can go up to 48 degree centigrade. So what do you, what happens when you do design it properly and not design it properly? With the same cells that therefore meaning same cost, you can get a pack whose life is 200 cycles, another pack which is close to 2000 cycles. That is the kind of difference that you can make.

And if you have gone through my calculations on what does it mean in terms of interest and depreciation, you can see how the whole thing gets immensely, immensely makes go or not go for electric vehicles.

After that, came Chapter 6 which Khanna, for practice at IIT Madras took it up. And he has got into details starting from basic physics, starting from the fact that you must understand flow when you want to understand the motors and controllers.

And to me, it was great learning that whether you are talking about a simple water flow or any liquid flow, any fluid flow; or you are talking about electrical flow, electrical power, power flow, currents; or you are talking about magnetic flows because motors come to electromagnetic device; or you are talking about heat flow, they all flows and flow is somewhat abstract quantity. But they are governed by very similar equations. The physical phenomenon is different but to understand the flow, pretty much the same thing.

For example, if a voltage is created, current will flow; if a pressure is created, liquid will flow; if temperature gradient is created, temperature heat will flow; and if for magnetic, if you create the magnetic field associated with the flow is the magnetic field, when the sources of magnets are put in. The very fact that there is wires which broke, when current flows, magnetism comes in that is one, a mechanical movement gives another movement of magnetism and that results into the flow.

He integrated the four flow and he said that at least three of the four flows will be required in motor design. All the time, you have to worry about heat, you have to worry about, of course, the electrical current, and you have to worry about the magnetism. And based on that, he started trying to from fundamentals according to how is motor designed, what does it really get involved, and went all the way into in somewhat detail, probably a little bit too much of detail into a motor design.

He also got into controller design, briefly, but got into controller design. Controller design particularly for the modern efficient motors, and I think he took example of PMSM, Permanent Magnet Synchronous Motor; which is today dominating the electric vehicles. Essentially, came out of power electronics and power electronics, it came from the power electronics, understanding creating MOSFETs, creating IGBT which will switch voltage and currents and that becomes a crucial part.

How do you go about doing it from given power supply, a power supply comes from a battery, how do you really give the appropriate signals to the motor such that the motor does a desired job. Linked all these things to the performance of the motor, whether it is a speed or the torque produced, power consumed, peak power all these parameters were linked.

Then in Chapter 7, I came back and started talking about chargers. What kind of chargers are required? On-board charger, public chargers, bulk chargers. Went into detail of that, what are the standards evolving because that is where the standards becomes very important because somebody else will put the chargers, somebody else will make the vehicle; the two must interface.

We talked about not only in for current’s movement but also for communication; the importance of communication in these chargers. And we built, went into what it does to set up charger infrastructure, home chargers, as well as public chargers; and we went into economics of chargers also. I think, were pretty much therefore covered.

The Chapter 8, which will be done subsequently, one hour only is on the new area which is emerging. Can I monitor the vehicle, electric vehicle, and monitor it remotely? Today it is possible. You can monitor the battery; every cell in the battery can be monitored. A battery may consist of 400 cells and every cell, you monitoring the pressure, the temperature, the voltage, and current at every instant when it is being driven. And figure out what is happening to these cells. Because the cells are very problematic things. If you do not, if they are not managed well, they can get into trouble.

What does it tell us? It often tells us, well, these are not behaving that well, battery is not behaving, maybe battery designed has to be tuned. Sometimes, it tells us well in advance that this is what is likely to happen if a correction is possible, do that. Not while just the vehicle is running, but also during charging.

Similarly, it can monitor the motors and the controllers. What is happening to the motor, is too much heat getting generated? Is the torque to high? Is it consuming more energy than it should have? Is it giving you a smooth drive or not? Use all of this data and the data from the chargers. How is the charger charging? What is the best way charging? Remember that the way you charge will impact the life of the battery.

So can you monitor all this, learn from this data, do analytics, and figure out how do you make electric vehicles behave better for the consumer. That will be the last chapter. I hope you enjoy the course. There are lots and lots of assignments, they have tried to give you assignments. All that I can say, your exam is going to be very much like your assignments.

If you have done all your assignments well, exam will not be a surprise. But if you not done all your assignment yourself, every problem there, well, then you have not done it, you are to get the, take the consequence.

Please go through the chapters again, one good part of the NPTEL is that you can go through the lectures again. Try to understand that. The PPTs of this will also be provided to you and there will be a few corrections in PPT and few corrections in lectures. When you have reviewed the lectures, you have seen once in a while, we have made some small mistake while recording the lecture; small mistake. Sometime for example a milliwatt is said, told as watt.

I will put some slides together which will be corrections. It will be, corrections can be in the slides, correction can be in the lecture that I will put together and provide to you. Best wishes, thank you.