Fundamentals of Electric Vehicles: Technology and Economics
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Lecture - 49
Power and Efficiency

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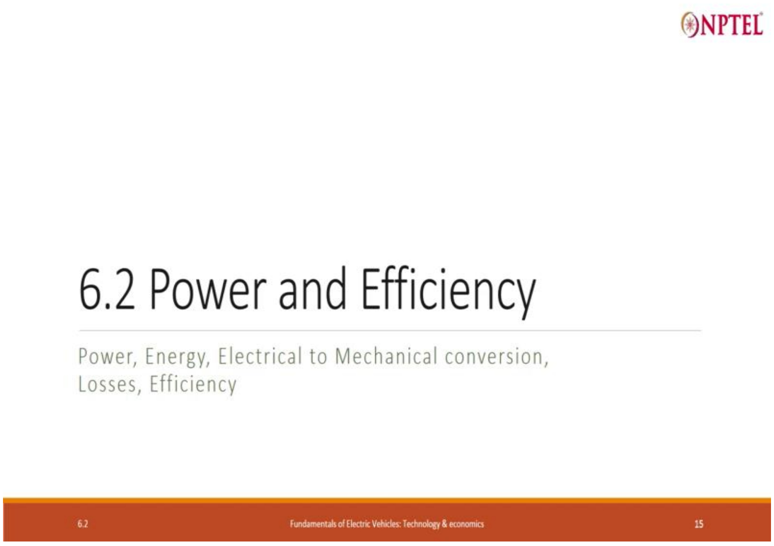

So in the, in this chapter, we will be covering about the idea of power. I had already alluded that the product of the force and the flow is a measure of the power. But in the case of a motor what does it mean and what really is the change, transformation of the power that is happening? These are the points that we will be looking into.

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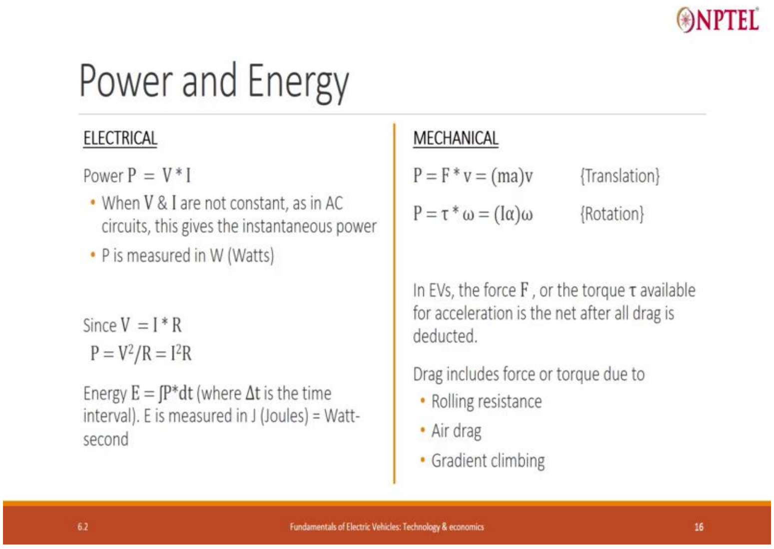

What happens in a motor is that we are supplying it with a certain voltage, therefore, it is drawing some current. And as a consequence, the power being supplied to the motor is the product of the voltage and the current, which is measured in watts. And we already know that from Ohm's law, V is equal to I R.

So I can alternatively express power as I squared R or V squared by R, they are all equally valid ways of expressing what the power is. And if I add up the power at every slice of time, the total energy can be obtained in a given interval of time. So that is measured in joules, which is watts multiplied by seconds, watt second.

You have in earlier lessons used a much larger unit of energy, which is 3600 watt seconds, abbreviated as watt-hour. But essentially, power multiplied by time in whatever units is a measure of the energy.

But what happens to the motor when I, when it takes in this power? What it does is it delivers mechanical power. The mechanical power could be in the form of rotation of the shaft, in which case the power is expressed as torque multiplied by the angular speed. Or it can be expressed as the force acting on the vehicle multiplied by its velocity. And force itself can be expressed as mass into acceleration or torque can be expressed as moment of inertia into angular acceleration. These are the different ways in which the mechanical power can be expressed.

What is really happening in a motor is that electrical power is getting converted into mechanical power. And when I am using the equation with torque or force, what I am talking about is the torque or force that is available for acceleration, which is after all the drag components are deducted from it. And you are already familiar with all the drags, so I will not go into that in detail.

There is rolling resistance, there is air drag, and there is a drag associated with climbing a gradient. After all of this, whatever is the residual torque that is available, that is what contributes to the acceleration.

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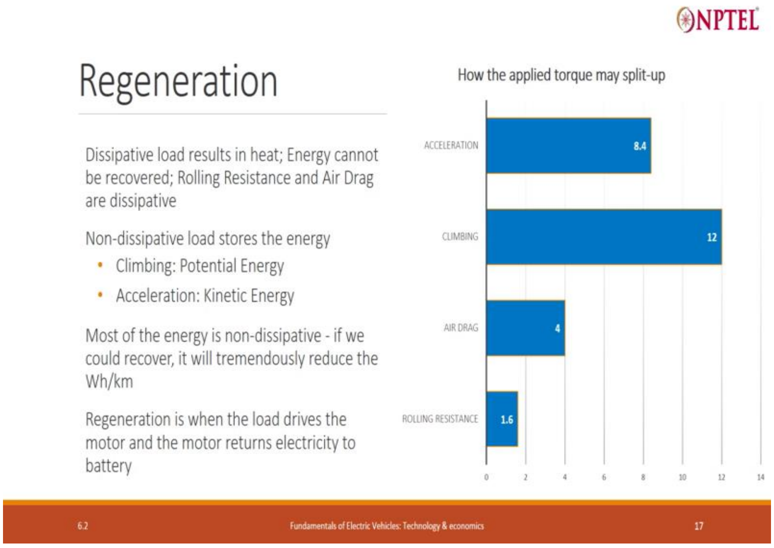

Now, we come to a very important concept. If I take a snapshot of a, say a truck, which is going up a flyover at some moderate speed. The motor is delivering some torque. In this case, it is 24, 25, 26; 26 Newton meters of torque is getting delivered by the motor. And there are many claimants to the torque. There are many different things associated with the movement of the vehicle, which are all consuming some part of the torque or the other.

There is rolling resistance, which is typically very small and the vehicle is not going very fast. So air drag is not very high but it is definitely more than the rolling resistance. Climbing requires a lot of torque. So a very significant part of the torque is consumed in the, by the claiming action. And then, whatever is left beyond that results in acceleration of the vehicle and that is the last claimant the torque.

Now, if you look at the different loads, we are seeing that there are broadly 4 loads. The air drag and rolling resistance are what are called dissipative loads, which means they consume energy and immediately convert them into heat. And once something is converted into heat, I cannot recover it, I cannot recover back that energy.

But the energy that is consumed in climbing is not dissipated as heat. It actually results in elevation of the vehicle to a higher level. So it is in some sense, stored in the vehicle as potential energy. And likewise, the acceleration is resulting in a higher speed of the vehicle and this increased velocity is stored in the vehicle as kinetic energy.

And proof that this energy is stored is that if I now switch off the motor, I do not need to spend any energy to roll back down the hill. The vehicle will convert its potential energy and move back. Same way, if I am traveling at a high speed after having accelerated, if I switch off the motor, the vehicle will continue to move off its own momentum for a long distance before it can, it comes to a stop. So the energy can be recovered.

Only thing is if I try to recover the energy by just switching off the motor, then the dynamics of the vehicle will cause the movement. The vehicle as well as the terrain will result in a motion, which may not be to my liking. It may be moving too fast or it may be moving too slow.

So I want to recover the energy but keep the motion in control. And the normal way it is done is that I will let the vehicle drive the motor and let the motor, in turn, generate electricity rather than consume electricity and put that electricity back in the battery, which I can then draw whenever I need in the manner I need. This reversal of torque, it is not reversal of motion; it is not the vehicle is running in the reverse direction or the motor is rotating in the reverse direction. It is the torque that is getting reversed.

Instead of motor driving the vehicle, the vehicle is driving the motor. This is called regeneration and as you can see, a significant part of the torque is actually amenable for regeneration. And if we can achieve that to any reasonable degree, it will significantly bring down the consumption of energy from the battery source.

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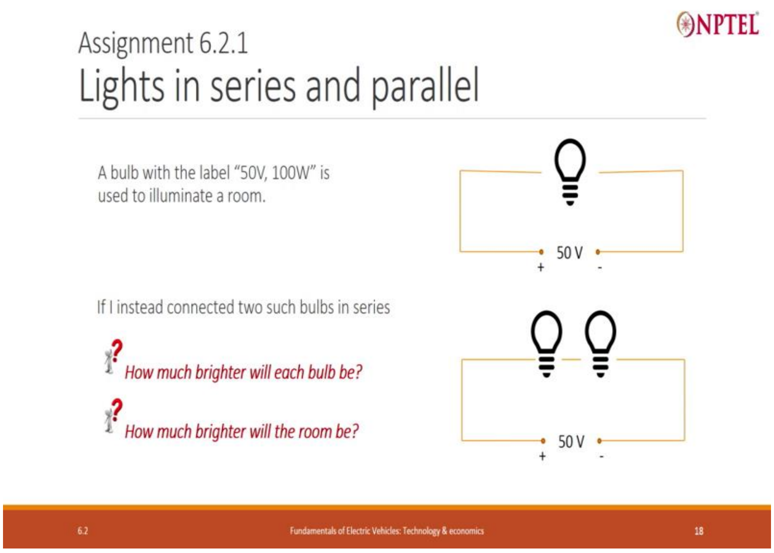

So now, here is an assignment based on what you know about power, what you know about resistance, electricity, series, parallel everything. There is a bulb on it, it is embossed.

Normally, all the bulbs have some label embossed on it, which says it is a 50 Volt, 100 watts bulb. And I have connected it with a 50 Volt power source and it is illuminating my room.

I want to make the room brighter. So what I do is I get two bulbs and I connect them in series. How much brighter will each room be? And as a result, how much brighter will the, will each bulb be and as a result, how much brighter will the room overall be?

This is something I want you to work out. The answer is a little counter-intuitive. The question is simple, I am not saying it is complicated to work out. But work it out carefully, do not jump to conclusions.

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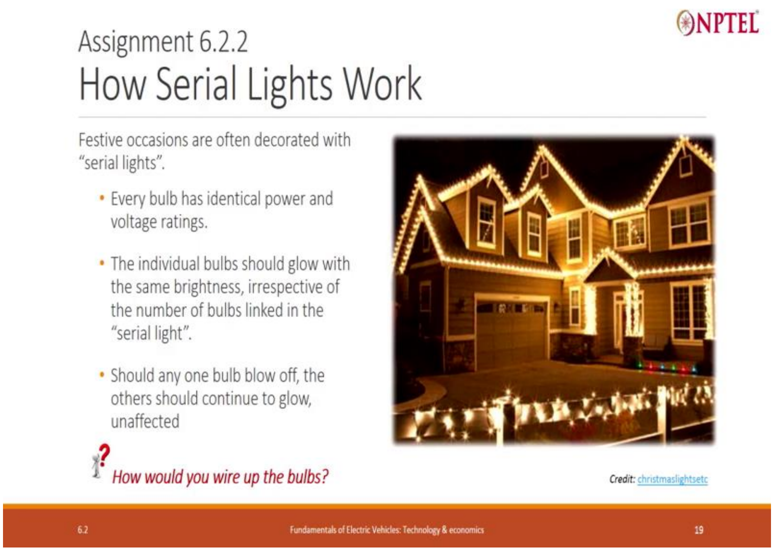

The next assignment is about what we have all seen and it is called as serial lights. On festive occasions, we decorate our homes, temples are decorated, streets are decorated with what are called serial lights.

Now, somebody has come to me with the requirement that they want serial lights to be put in their house. The requirement is that all the bulbs are identical. They should all glow equally brightly. And whether I connect 100 bulbs, 200 bulbs , or 1000 bulbs the brightness of each bulb should remain unchanged.

This is what we want of a serial light. I do not want to add more bulbs and find that everything is becoming dimmer. That is not a nice way to connect it. And when I connect so many bulbs, maybe 1 bulb will glow, somewhere else there will be a loose connection, another bulb will not glow. Even if one or two of these bulbs do not glow, all the others must continue to glow unaffected. It should not be that, just because one bulb has a problem, everything becomes dark, I do not want that. How should I connect the bulbs so that I satisfy these conditions? Remember, they are called serial lights. Again, the answer is sort of counter-intuitive. Figure it out.

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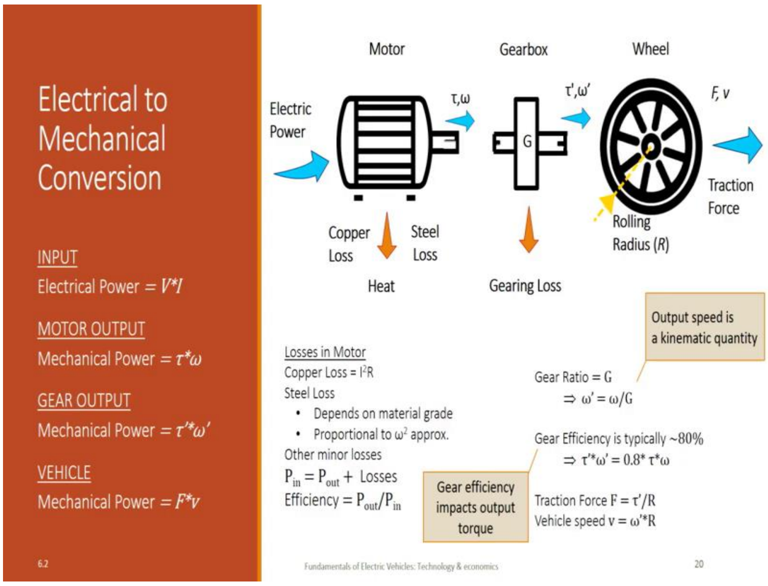

Now, let us look at electrical to mechanical power conversion in a motor at a black-box level. We are still not opening up the motor, from an outer view, let us see what is happening to the power. We are supplying the motor with electric power and the power that is being supplied is voltage into the current.

As a result, as you can see in the graphic, the shaft is rotating. Typically, it rotates very fast and it is able to deliver torque. The product of the torque and angular speed is the mechanical power. Now, normally I want much more torque at a much slower speed. So I introduce what is called a gearbox, which can be described as a speed reducer or it can be described as a torque multiplier before I can connect it to the vehicle.

So what happens to the torque and angular speed tau and omega of the motor is that the gearbox converts it into a new pair of torque and speed, tau prime, and omega prime, in a certain ratio G, which defines the gearbox. So that ratio G is the gear ratio. And then, I am able to connect it to the wheel of the vehicle.

And this omega prime, when it connects to the wheel whose radius is R the rotation causes the vehicle to have a angular, have a linear speed, which is equal to omega times R. And the force acting on the vehicle causing it to move is tau prime divided by R. So this is the sequence of power conversion that happens when a motor is used to drive a vehicle. Is this clear? If there are any questions, please ask me because we will now get in a little more detail of this.

So I am connecting the output shaft of the gearbox to the wheel. So the angular speed of the shaft omega prime multiplied by the radius of the wheel will cause the translational speed, V, of the vehicle. Likewise, the torque that is getting applied divided by the radius will cause the translational force, which is called the traction force that is causing the vehicle to move.

Now, this simple picture gets messed up because there is leakage of power all along in every step. Firstly, in the motor, current is flowing through the copper wires, which have some resistance. We try to design it in such a way that the resistance is as small as possible, but still, there is a loss. And as you already know, that loss will be equal to I square into R, where R is the resistance of the windings.

In addition, we have seen that steel is getting magnetized and demagnetized and that is leading to a hysteresis loss. There are also other losses, for example, there is something called eddy current loss, which is more significant than hysteresis. And, that is actually proportional to the square of the speed.

See, hysteresis, if you remember, every cycle there is a certain quantity of loss. So the more the number of cycles, more the losses. So it is proportional to omega, hysteresis is proportional to omega. Eddy current is a current that is circulated by the action of what is called Faraday's law.

Because the flux is changing, there is a circulatory current that is set up and the magnitude of this is proportional to the frequency. The magnitude of the loss in one cycle is proportional to the frequency. The total loss is in turn proportional to the frequency. Therefore, the overall energy loss on account of energy current, of eddy current is proportional to omega squared, and that is a more significant contributor to it.

And then, there are some other losses, which are proportional to omega to the power 1.5. So it is a little bit messy and nonlinear. But very broadly, we can assume that the steel loss is proportional to omega squared. And then, there are other minor losses. There is something called magnet loss, there is something called windage loss, which is nothing but the air drag inside the motor where the rotor is rotating against overcoming some air drag, all of that.

So all of them, together cause a certain loss of power, and finally, what is left is what comes out as mechanical power. So the P out that is indicated there is the mechanical power and what we are supplying is P in. The output mechanical power is always less than what we have supplied and the ratio between them is called efficiency. This is as far as the motor efficiency is concerned but that is not the end of the story. Next, let us look at the gearbox.

The input speed omega is getting converted into an output speed, which is omega prime and the ratio between the two speeds is given by the gear ratio. This is based on the geometry, size of the gear, and things like that of the different machine gears. So anything, which just depends on geometry is described as a kinematic quantity.

But there is also an efficiency associated with the gearbox. It could be as good as 90 percent but it is conservative to assume that it is lower and predict things on that basis. It depends on a number of factors, depends upon the alignment, the precision of manufacture and friction, the lubrication a number of things.

The impact of this efficiency is that the output power of the gearbox, which is tau prime into omega prime, will be lower than tau into omega. But as we already know, omega prime is not affected by efficiency, it is only coming from geometry relations. So the effect of efficiency is entirely on the torque. The torque is the entity that is affected by the efficiency of the gearbox. And so, we will find that the traction force on the vehicle is lower than what we expect on account of the efficiency of the gearbox.

Student: Where does this loss (()) (16:34) go? Does it get converted to heat?

Professor: Yes, the gearbox will get hotter. So there is not a very strict rule. Some rule that many people use is that every pair of machine gears is 5 percent. And normally, this will be a 2-stage gearbox that will be like 5 plus 5, 10 percent. But if there are any misalignments and other things or wear and tear, then it could be worse.

So as I described, the traction force is applied, is affected by the loss in torque, which comes because of the efficiency of the gearbox. And yes, efficiency of the gearbox is something that we often overlook. We are focused on motor and things like that. But gear does play a very important part in the overall efficiency, that is what I want to point out here.

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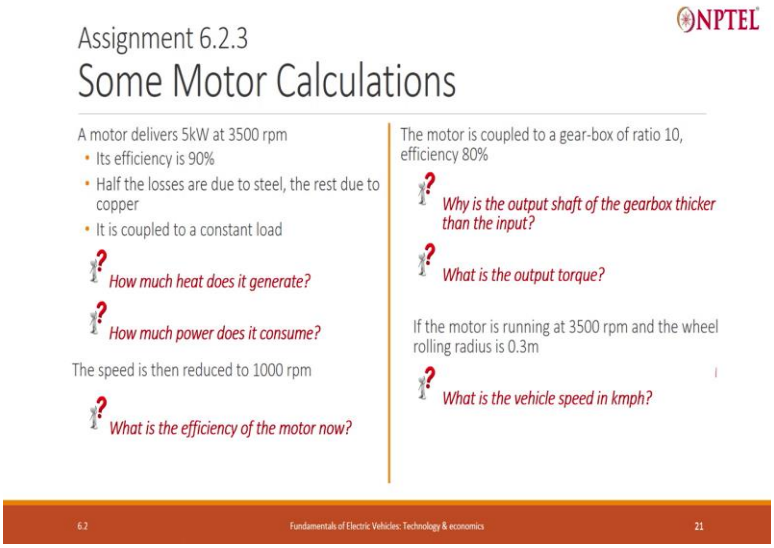

So we had a very simple overview, almost commonsensical. And all that we have said is that Power in is equal to Power out, and Power out is equal to the useful mechanical power plus losses. But just by knowing this, you will be surprised that actually you can get a lot of insights about the motor and that is what this assignment is about.

If you do this assignment, you will be surprised how much you already know about the motor, even before we have opened up the motor. So here, we are talking about a motor, which is delivering 5 kilowatt at 3500 rpm and its efficiency is 90 percent. Half the losses are due to steel, half the losses are due to copper. And it is coupled to a constant load.

Remember, it is not a vehicle. A vehicle is normally not a constant load. As it moves, air drag, many things will change, it may go up a gradient; so you cannot really measure a motor by putting it on a vehicle. We have some equipment in the lab, typically, it is called a dynamometer, to which we couple, where we can control all these things and then measure the performance of the motor alone.

So this is some kind of a setup where I can put a constant load, which does not depend upon the speed and things like that. The question, first question is how much heat does it generate? These are all not trick questions, they are very straight forward but you have to focus on what the questions are and answer them.

How much heat does this motor generate? How much power does it consume? I have said that it delivers. It delivers means the useful output, mechanical output is 5 kilowatt. And the question is how much does it consume?

Now, I am reducing the speed to 1000 rpm from 3500. What will be the efficiency of the motor now? Just to give you a hint, when I am running it initially at 3500 rpm, half the loss is copper, half the loss is speed. Then I am reducing the speed, I am not reducing the load, and you will see in subsequent lessons why this is so.

The copper loss depends upon the current and the current depends upon the torque, which is the load. Since I am not reducing the load, the copper loss will remain unchanged. And we already discussed that steel loss is proportional to the square of the speed, approximately. So the other half, which is a steel loss will be reduced by a factor which is square of the speed. Square of the speed, in this case, is something like 12. So less than a tenth it will reduce.

So we are going to have a significantly lower steel loss but the copper loss will not be changed, which means the total loss, the sum of the copper, and steel losses is going to be much lowered. So will the motor be more efficient now or less efficient? That is the question. Compute the efficiency and tell me.

The next part of this question is that we are coupling this motor to a gearbox, whose ratio is 10. In this case, I have said, both are equal at 3500 rpm. But the computation that I am asking you to do is what will happen when the speed reduces to 1000 rpm.

Student: (()) (21:08)

Professor: It is, there is no general answer to it because like I told you, the question is, is copper loss normally higher or the steel loss higher? They both different on different thing, depend on different things. The copper loss depends upon the load, the steel loss depends on the speed.

If I am going at high speed with very low torque, which means I am cruising on the highway at a high speed, then steel loss is very significant compared to copper. But if I am climbing up a hill at low speed but with a high torque, then the copper loss is much higher than the steel. So it depends on the operating condition, am I operating in a high torque, low-speed condition, or am I operating in a low torque, high-speed condition. Depending on that the weightage of the two different loss components will change.

Student: (()) (22:01)

Professor: Considering it to be? Brushless. Yes. The, apart from the copper and steel losses, I told you that there are other minor losses. Windage will be there, there is something called magnet loss. If there are brushes, they will also contribute to an additional loss. We will generally consider brushless, yes.

So now, we will come to the next part of the question. I am taking this motor and coupling it to a gearbox. I am not putting in the vehicle, everything is done in a lab. I am connecting it to a gearbox. And the gearbox I know, has an efficiency of 80 percent, let us say.

One question, I do not know if you recollect, in the graphic in the previous slide, the output shaft of the gearbox was a little bit fatter than the input shaft. And the question is why is the output shaft thicker.

And one reason why you should also try to answer the question is tomorrow if you find a gearbox lying on a table and you want to know which is the input and which is the output, the easiest way to figure it out not by rotating and seeing gear ratio and things like that. You just see which side the shaft is thinner and you know that is the input. But why is it so, that is a question? And if I were to couple this motor with a gearbox of ratio 10 and efficiency of 80 percent, what will be the output torque?

Student: (()) (23:38)

Professor: In electric vehicles, we always prefer to run the shaft at a high speed and do a gear reduction of the speed and multiply the torque. The reason for that is much of the expense in terms of magnet and copper and everything associated with the motor is related to the torque.

If I can build a motor that is low on torque and compensate by making it run at a high speed, then my motor will be more economical. And by just putting a gearbox, I can then multiply the torque. So that is the normal architecture that is preferred.

So we do not build a motor that delivers high torque at low speed and then step up the speed; that is not cost-effective way of doing things. So that is why we always have a reduction gearbox, which will reduce the speed and multiply the torque. Fine?

Student: (()) (24:40)

Professor: Yes. In the case of an electric vehicle is what we are talking about. We are not talking about in general gearboxes in the world. But in an electric vehicle, if I am using a gearbox, then the output shaft is thicker than the input. And I want you to figure out why it is so, and also calculate what the output torque of the gearbox is.

And if this motor is running at 3500 rpm and after connecting with the gearbox as described above, if I connect the output shaft to a wheel whose radius is 0.3 meters, what will be the speed of the vehicle?