Fundamentals of Electric Vehicles: Technology and Economics
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Lecture 1: EV Motors and Controllers

So, good morning everybody, this is a section where we will discuss about motors and controllers which is like the engine of the electric vehicle. And pretty much the entire performance of the electric vehicle is determined by how the motor and controller are going to perform. Let us get started with this, very broadly this chapter is broken into about nine sections. We will initially understand some fundamental physics that is underlying the motor.

There are many different phenomena that combine to act together to make the motor function the way we want it to. We will cover all of that in the first section at a very fundamental level and from there on we will move to discussing concepts like power, efficiency and power itself, though we use power as an abbreviation to define a motor, it is a 1 kilowatt motor or a 3 hp motor, it is an inadequate description, really the motor has to be specified by separately specifying what its torque is and what its speed is.

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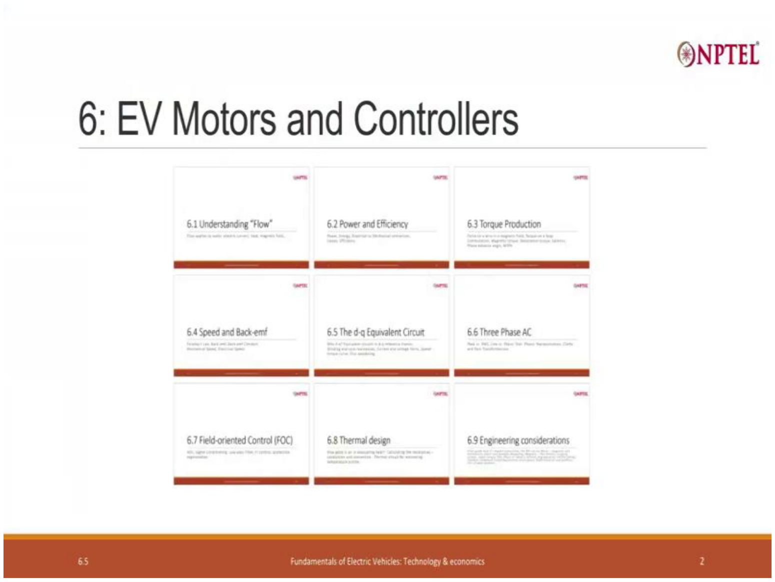

So, we will, and the product of the two is of course, power. So we will go into what contributes to the torque developed by the motor, how does speed get delivered by the motor. And we will develop a very simple framework which is called the DQ frame to analyze the physics of the motor which enables the performance of the motor. And then we will go on to applying this concept when we supply AC current or alternating current. And learn how to control the motor in such a manner that it performs according to our expectations.

And last but not the least will be the thermal aspects of it because finally the upper bound, the envelope of the performance, not only in the case of a motor or a controller but almost everything engineering is defined by the thermal aspects and how it is handled, how the temperature is controlled. And then before concluding we will discuss some important engineering considerations like material selection and other things. This is the broad overview.

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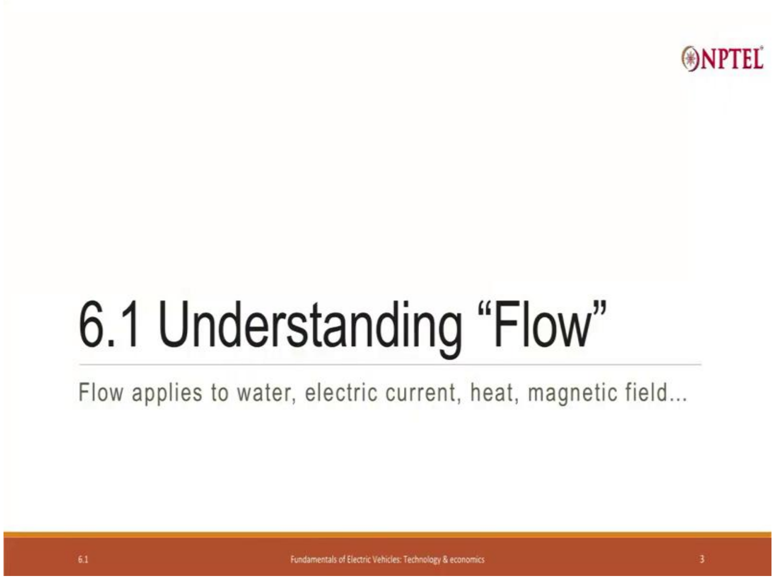

So, let us start with the flow. The simplest flow which we all see daily in our lives which we can therefore easily visualize is the flow of water. I will use that as an example to start with but then move on, move on to discussing various other flows like flow of heat, flow of magnetism, flow of flux and things like that. The thing about flow is that there is always a quantity that is flowing and there is a cause which causes the quantity to flow. The, the cause that creates the flow can be called in generic terms as the field or the forcing parameter and what is flowing is then the current that is flowing.

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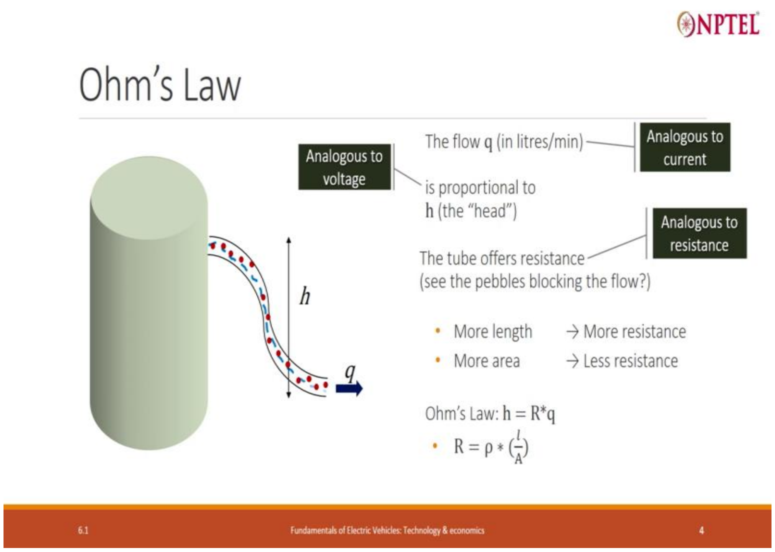

In the simplest example that we will discuss, I have shown a water tank. It could be the water tank at the top of the roof of your house and there are pipes through which the water is flowing, it reaches the tap where when you open the water flows out. The, when you open the tap water will flow out at a certain rate, you can measure that. If I keep a bucket of 20 liters and it takes 5 minutes for it to fill up then I can say that water is flowing at the rate of 4 liters a minute.

So how, how fast this water is flowing or how much volume per unit time is the water flowing depends really upon the pressure that it is getting which in fluid terms is called the head, means the height. The greater the height more the pressure will be. But the height alone does not fully define what the flow is and because it is flowing through some pipes I have just depicted that there are some stones and pebbles along the way but even without all of that just the material of the pipe, the walls they will offer some resistance to the flow, they will try to oppose the flow.

And so whatever flow we get is the result of overcoming this resistance. And just to give you an analogy with electricity the flow of water is like the flow of current, the head is very similar to the voltage that is applied, say from a battery. And the medium through which the current is flowing, the conductor will offer a resistance to the flow of current. And these three quantities are related by means of a simple law that you are all already familiar with Ohm's law, but I am just repeating it to refresh our memory and also I will be applying the same law in many contexts where you may not be so familiar.

And the Ohm's law says that the head is equal to the resistance multiplied by the flow, or voltage is equal to resistance multiplied by the current. So, resistance is really the constant of proportionality which gives the link between the forcing field and what is flowing, in generic terms. And this resistance actually depends on two broad kind of parameters, one is the material parameter and other is the geometry parameter. The geometry can be described by its length, the area of cross section.

Whereas the inherent quality of the material which is given here by the symbol called rho, is called the resistivity. Sometimes it is convenient to use the reciprocal of rho and call it the conductivity, that defines the quality of the material. So when I write an equation like this where I am using a term called R the resistance, we must remember that behind this R there is, the material is playing a part and the geometry is also playing a part. And this will, the reason of why this is important will become obvious in future slides.

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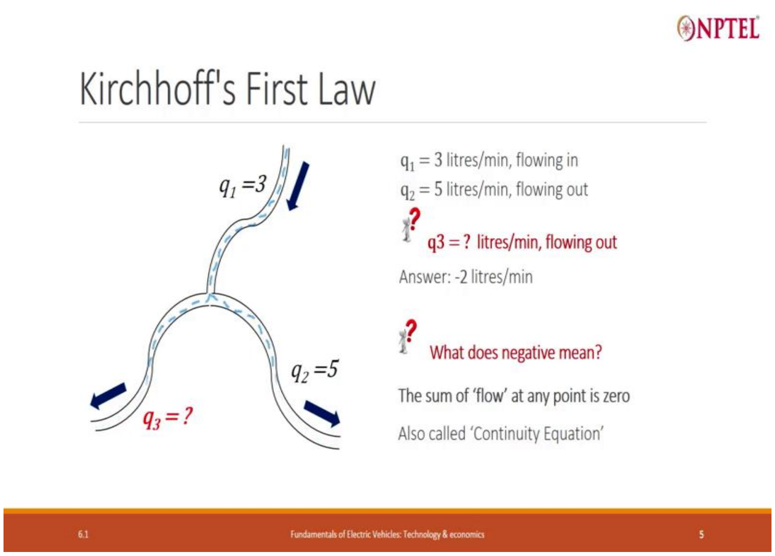

Now, having, there are only three laws that govern all flows, the first that we have seen is Ohm's law. The next is what is called Kirchhoff's First law, it is just a way of saying mass is conserved, which means whatever is flowing has to flow out, whatever is flowing in has to flow out, it cannot disappear nor can you create new material that will start flowing. So here you are seeing that there is a tube that is branching off into two. Water is flowing in at the rate of 3 liters per minute and it is branching off.

I know that one of the branches water is flowing out at the rate of 5 liters per minute. And the question is, how much is the water flowing out of the other tube? So, we know that the total amount of water flowing in has to flow out, so inflow is equal to outflow that is all Kirchhoff's first law says. So if 3 is flowing in, that means that q2 plus q3 must be equal to 3. But we already know that q2 is equal to 5, so if we do this arithmetic we will get that q3 is negative 2 liters, and what does negative mean in this context?

It means the water is flowing in, so the sign actually indicates whether it is flowing in or flowing out. So if I represent the flow rate with a sign plus or minus depending upon whether it is flowing in or flowing out and if I add up all the flows with the sign then it, the sum will be 0. So this is what Kirchhoff's first law says and in fluid mechanics the same thing is called continuity equation.

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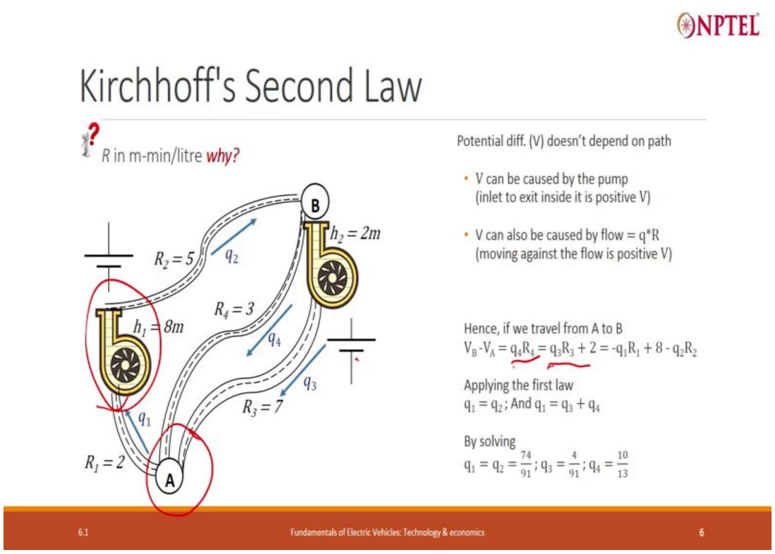

And then we come to Kirchhoff's second law which actually is nothing but a different way of expressing conservation of energy. So for example, if I am in a hilly terrain, I am running from one place to another, point A to point B, now point B is let us say 10 meters higher than point A. So when I run from point A to point B, the elevation that I have gained is 10 meters.

If I now run back to point A the elevation I lose is the same 10 meters. Now, this does not depend upon the path I take, I may run up like this and I may run down by some other path.

Irrespective of the path I take, the height difference depends on the starting point and the final point, it does not depend on the path. This is what Kirchhoff's second law says. It is just another way of saying that gravity is a field where energy is conserved.

So, I have shown you a circuit where water is flowing across many pipes, there are also some pumps which create extra head, extra pressure to make the water circulate. So in this context the pump can be thought of as a battery which causes the flow of water. And the exit side I am using the symbol there is positive and at the place where the water is entering is like the negative terminal of a battery.

And what Kirchhoff's law tells me is that in any circuit the potential difference from, between one point and another will be the same irrespective of the path that we travel to measure the potential difference. And there are two ways in which the potential difference can be caused. One is the product of the flow and the resistance and the other is just the battery or the pump or whatever is causing the field.

There are two ways and the sign convention that we normally follow is that if I am travelling against the flow then it is like traveling uphill and I am gaining in potential. Likewise, if I am travelling inside a pump or a battery from the inlet side to the exit side that is again considered positive and the converse of it is negative. So, using these two simple rules we can choose any path that we like and compute the potential difference.

Now, the question is I want to know how much is the water flow in each of the pipes? As you can see there are 1, 2, 3, 4, 5, 4, 4 there are 4 pipes, each of them is having a flow q1, q2, q3, q4 and I want to be able to compute that. So, before we get into that I just want you to take a moment to reflect, what is the unit of resistance? We are familiar that in electricity it is voltage per ampere and it is denoted by ohms. In the case of water flow, it would be head divided by flow rate and we have already agreed that we will use liters per minute for the flow rate.

So the unit of resistance in the case of water flow will be meters per liter per minute which can be expressed as meter minute per liter that would be the units. So, all the resistance is given here are in that unit. Now, if we decide to travel from A to B, any two points I can choose, it is just convenient for me to choose the two points that are mark there. I find that I can get from point A to point B through three different paths.

I can go by the middle path or I can go by the path on the right or I can go by the path on the left and what Kirchhoff's law tells me is that no matter which path I take the potential difference will be the same. So, if I use this knowledge then if I take the middle path going from A to B, I am travelling against the flow so the potential difference will be a gain of q4 into R4, that is what I have written here.

And next if I take the path on the right, again traveling from A to B, then I am initially going against the flow of current. The potential gain is q3 into R3. And then I am traveling from the inlet side of the pump to the exit side of the pump where a head difference of 2 meters is being created. So, the potential difference there will be this. And if I take the path on the left likewise it is negative q1 R1 because I am traveling along the flow, downstream I am flowing.

And then I am going, encountering a plus 8 and then the flow is again downstream, it is minus q2 R2. So all of these have to be equal, this is what Kirchhoff's second law tells me but it is also true that the first law is valid. So if I apply the first law over here, then I know that the inflow is q1 and the outflow is q2 they have to be equal. Likewise I can apply the first law at the point A the outflow is q1 and the inflow is q3 plus q4 they also have to be equal.

So using this set of relationships if I were to solve it, I will let you solve it, I am not going to solve it, but here is what you will get if you solve it correctly, you will know what is q1, what is q2, what is q3 and what is q4. So, this is the broad idea behind how we solve for circuits using just three laws, the first is Ohm's law, the second is Kirchhoff's first law which is just conservation of mass and Kirchhoff's second law which is conservation of energy.

And this simple set of three rules is applicable to a number of flows that we encounter in physics and we will be actually discussing as many as seven of them. We have already discussed water, very briefly I have touched upon how it is analogous to electricity, but we will move on and look at electricity in some more detail before which here is the first assignment for you to do.

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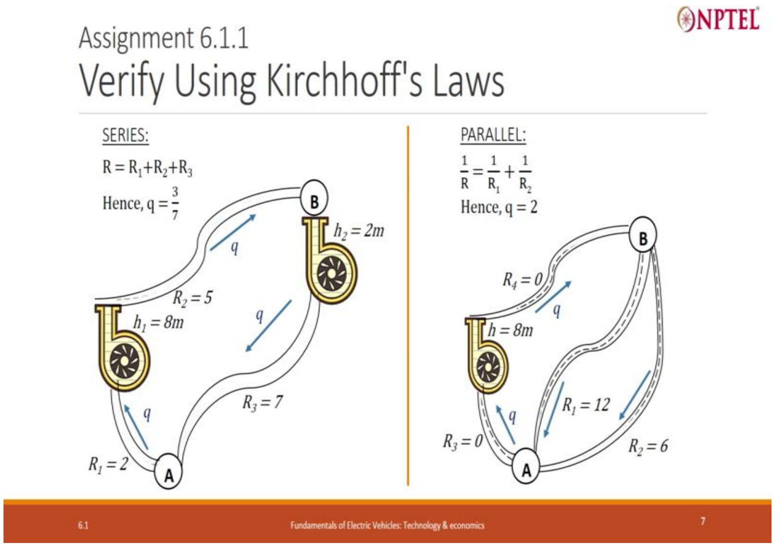

The, what you are seeing here is a circuit where there are two pumps, they are like two batteries and each is trying to force water in a direction opposed to the other. So, the two pumps as you can see are oppositely oriented and the pipes offer some resistance. And the same water is circulating through all of them, which means that the three pipes are in series.

And you will remember from what you have learnt in high school that when you have a number of resistances that are in series, then the total resistance is the sum of the resistances, but you do not have to remember that if you just know Ohm's law and Kirchhoff's first law and Kirchhoff's second law, then the same method that we used in the previous slide, you can adopt that to compute the flow and that is actually the way for you to verify that the total resistance is equal to R1 plus R2 plus R3.

So you can, you can derive this relationship without knowing this relationship if you know Ohm's law, Kirchhoff's law 1 and Kirchhoff's law 2. Likewise and of course, you will find that the flow is 3 by 7, 3 by 7 liters per minute. Likewise, what you see here are two pipes in parallel between the points A and B and they in turn are linked to a source that is pumping water and the link from the source and to the source is offering zero resistance.

So, now what is the flow q that is marked in the diagram, is the question. You can apply the formula for two resistances that are in parallel but even without knowing that using first principles from Kirchhoff's first law and second law you will be able to calculate the flow. And by doing that you will be able to verify that the relationship, that the total resistance is given by 1 by R is equal to 1 by R1 plus 1 by R2 holds true. And you will find that the water that is circulating is 2 liters per minute. So, this is something that you can work out.

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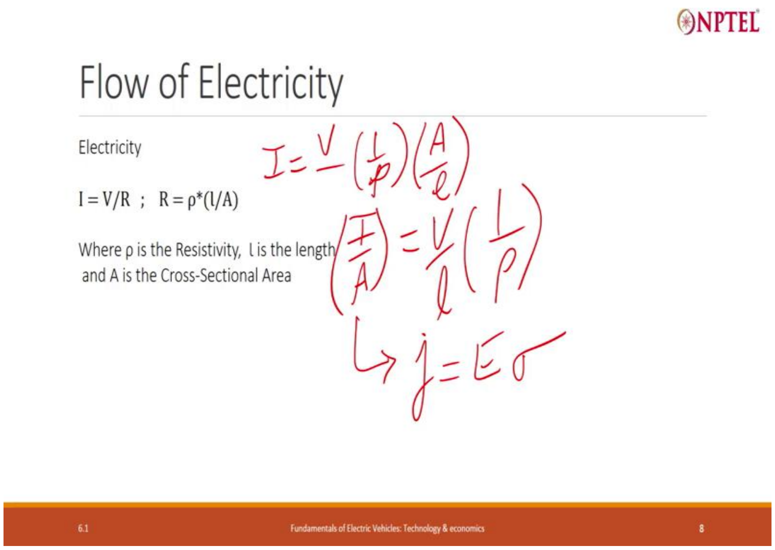

Now, let us go into the flow of electricity in some detail. This is what is Ohm's law and as I told you the law is correct, it is useful in its own way but normally when I want to compare one material with another material, I have got copper and I have got aluminum, and I want to know which for example is a better conductor, then when I look at this I find that the copper is having a certain resistance.

And if I measure the aluminum it will, that wire will have a different resistance. Can I compare the two resistances and straight away say which is a better conductor as a material? Normally I cannot because the resistance depends not only on the material, it also depends on the geometry. So, I may have a very thin copper wire and I may have a very fat aluminum wire, and the aluminum wire will end up giving me lower resistance than copper.

If I were to conclude that therefore, aluminum is a better conductor that would be a mistake. So, when I want to compare different materials I like to remove the geometry from the picture, it is very messy. I will show you how I will do that. I have got I is equal to V by R so I can write it as, I is equal to V and R is equal to 1 by rho and there is an A and there is an l. I hope this is clear, I have just taken the reciprocal of R. Now what I will do is, I will take the A along with the I, I divided by A is equal to V divided by l into 1 by rho.

Now, I divided by A is the amount of current that is going, that is flowing per unit area, per square millimeter, per meter square, whatever units I choose and V by l is the voltage drop per unit length, per meter, or per centimeter, depending on the units I choose, I can call this as the current density because it tells me per unit area what is the current that is flowing j, and the voltage drop per unit length, I will call it as the field rather than the voltage and 1 by rho which is the resistance, resistivity 1 by rho of that is the conductivity.

Now the nice thing about this equation is that this allows me to compare different materials, I can take aluminum, I can take copper, I can take steel and compare and I will know which is a better conductor and which is not.

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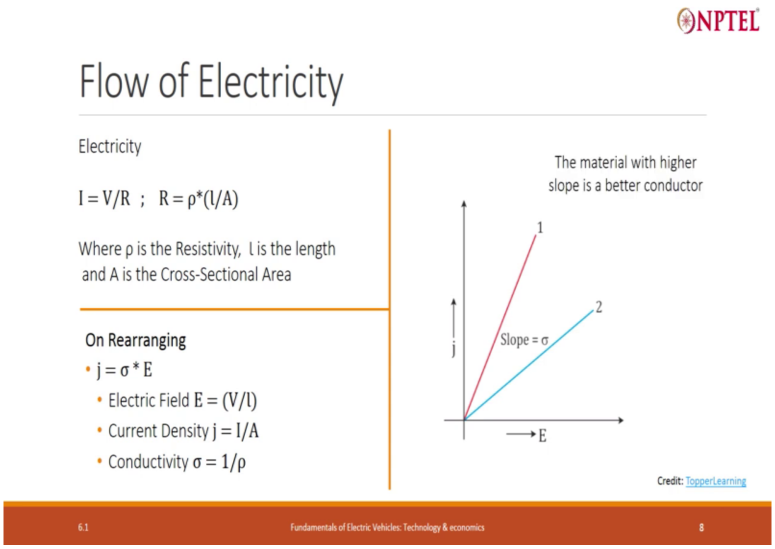

So, this is the rearranged form of the Ohm's law where I have taken the geometry away. The electric field is V by l, the current density is I by j and 1 by rho I am calling it the conductivity. Using this if I were to plot j versus E for two different materials, the slope is the conductivity. Whichever material has a higher slope, is a better conductor compared to the material with a lower slope. So, this is convenient when I want to compare material properties in terms of their conductivity. And we will be doing something like this for all the other flows that we will now be discussing.