Fundamentals of Electric Vehicles: Technology and Economics
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Lecture 2: EV Motors and Controllers

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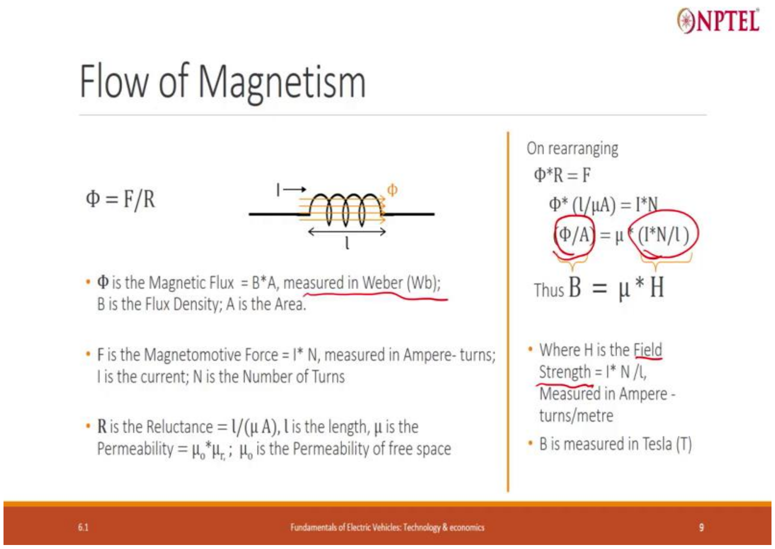

So next, let us come to magnetism. We are less familiar with magnetism and the flow associated with magnetism than we are with water or electricity. But it has the same form, same structure and one important difference, we will come to that. So, when current flows through a coil and the coil has N turns, a magnetic flux is the flow that is caused by this.

The thing that is flowing is magnetic flux and the forcing function which is causing the flow is the current going through the turns in the coil. So that we denote by the term F and the flux that is flowing is denoted normally by the Greek alphabet phi. And the magnetomotive force F is nothing but the current multiplied by the number of turns. And this flux is flowing through a medium just like we saw water flowing through a pipe, or current flowing through a wire.

Here it is flowing through a medium, that medium may just be air, or it could be paper, or I could keep a soft magnetic item like electro steel and that will offer some opposition to the flow of magnetic flux. We do not call it resistance, there is a slightly different name for it, it is called reluctance. So, the same Ohm’s law, phi is equal to F by R, here phi is the magnetic flux, F is the magnetomotive force and R is the reluctance.

And just like we had conductivity which is a property of the material and then length and area which is geometry of the material, same way reluctance depends upon the permeability which is very similar to conductivity and the geometry of the material defined by the length and area. And normally rather than just talk about the permeability of the material in isolation the common habit is to compare it with that of vacuum, compare the permeability of the material with the permeability of vacuum and say that this material is three times as permeable as vacuum.

Something else is hundred times more permeable than vacuum or free space. So that is called the relative permeability, just like you have relative density in the case of density which is compared with water, here you have relative permeability which is taken by comparing it with that of free space. Now again, I want to remove the messy geometry from the equation, I do not want l and A.

So, I will take this equation Ohm's law, phi into R is equal to F. R is l by mu A, I will take the A together with the phi and I will take the l to the right hand side, then I get this, like current density, this is the flux density whose units are Weber, no, the flux is in Weber. This is, flux density is measured in Weber per meter squared, there is a separate term for it, it is called Tesla, Weber per meter squared is Tesla and this is ampere turns per meter, F is measured in ampere turns because it is I into N and this entity that we have by dividing it with N is called the ampere turns per meter and that is called the field strength.

So, the flux density is equal to mu times field strength. In this equation again we have removed all the geometry factors there is no l there is no A, only material property comes. So if I plot B versus H what I get is just a property of the material which is unaffected by the geometry. So, let us go and plot this. We will be, we expect to get a graph like what we got for the conductivity when we drew for electricity.

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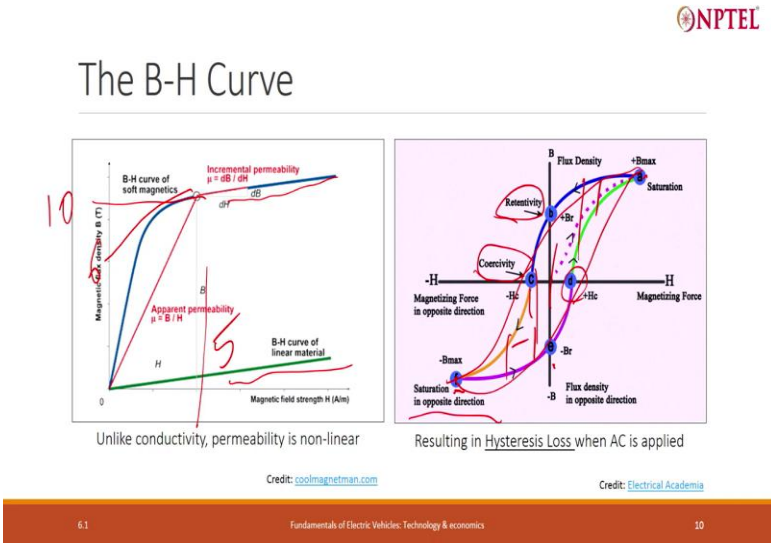

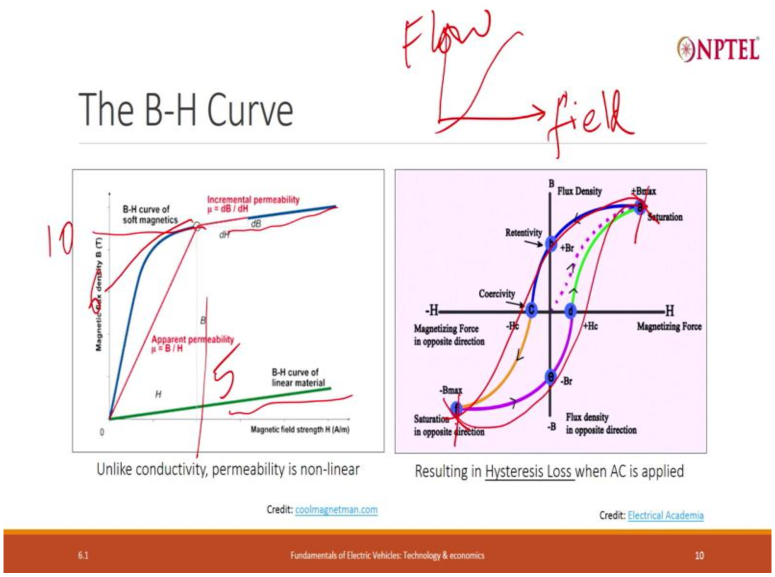

But there is a difference, there is a catch. If I take some material like paper which has a very poor conductivity it has a very low slope, there are no surprises there. But when I take a material like soft iron the slope is very high that means its permeability is very high, its permeability is probably hundred times better than that of paper. But that is only up to a certain point, as I slowly start increasing the magnetic field strength, more and more flux will start building up in the material and then it suddenly stops building up any more flux.

You can think of the material like a sponge, when I am pouring water into it, it just soaks up the water, but after a point it is just full of water, then if I pour any more water it does not soak, it just allows it to pass through, that is called saturation, no more flux can build up in it. Its ability to soak up any more flux is no longer there. And at that point you will see that the slope is the same as that of paper or wood. So, what started off as a very permeable material after some buildup of flux has become as bad as a non magnetic material.

So, this non-linear behavior is because of saturation and this saturation is something very important we will encounter it again and again in different phenomena and it will significantly affect how the motor behaves. The first consequence of this is that when I take, let us say I have a coil some n number of turns I am passing some current and I am increasing the current gradually, so the ampere turns per meter is increasing, I have gone up to a value of 5, 5 not phi, 5 and it has reached a value of 10 beyond this it is not going to increase, the magnetic flux density.

Now, I say okay it is not increasing anymore let me bring it back to 0. So what do I do? I reduce the current but when I reduce the current it does not come back in the same path instead it comes like this. So when the current is completely switched off there is still some magnetic flux remaining in the iron. So I took a piece of iron, I connected it in this magnetic circuit increased the current, it became magnetized to an extent of 10 Tesla.

And now I have switched off the current but it is still having some Tesla remaining, probably there is some 6 Tesla remaining and that is called the retentivity. It has retained some magnetism, if I now take out that magnet after switching off the current and take it near some iron filings it will attract them, it is a weak magnet but it is still magnetized, if I want to completely demagnetize it I have to now pass a negative current.

Let us say negative 1. Only at this point the magnetic flux is completely flushed out. And the extent of negative field that I have to give to fully demagnetize the material is given by this entity called coercivity, I have to force the magnetism out by giving a negative magnetizing force and then if I further proceed in the negative direction it will get saturated in the opposite direction.

And I can repeat the cycle this will be the negative retentivity, this will be the positive value of the coercivity and then again it will saturate in the positive direction. So, what you see here is that it is travelling in one path coming back in another path, going forward in one path coming back in another path. And normally the product of the field parameter and the flow parameter is actually the power, like we plotted voltage versus current and the product of voltage and current is the power.

Likewise the product of B and H is somewhat like a measure of the power. The area under the B H curve is a measure of the total energy because the integral of power is the energy. The energy that it takes to move it from here to here is more than the energy that it, that it releases back when I come back from here to here. So, if I start from here and travel down this path by supplying some energy and then travel back and I recovered the energy the amount of energy I recover is lower than the amount of energy that I originally supplied.

How much lower? It is the difference between the two areas which is the area within that curve. So in every cycle I lose this energy like it is common with the normal AC current that we get at homes. If I am doing this 50 times every second, 50 times this area is the amount of energy that I will lose, so this loss is called hysteresis which happens when you have a AC current.

And our motors most of them run with AC current and the steel is getting magnetized and demagnetized as many times as the frequency is and this is a significant contributor to loss in a motor, it is a significant contributor to what is called the steel loss. There are other losses we will discuss about it later but this is one important component of the loss. So, in general I have a, this is the field whatever is forcing a flow I am calling it as the field and this is the flow, and the product of the two is the power.

For example, the field is the voltage and the flow is the current, product of voltage and current is the power. And the area under the flow versus field is the integral of the power which is the energy. So, in this B H curve when I am going from this point to this point, from this point here to this point here, this is the path I am traveling by and the area under that is the total energy associated with that path.

Now, when I come back from this point back to that point I am not taking the same path I am taking a different path. The energy associated with this path is different from the energy associated with the other path. So, when I complete a full loop, there is a net difference of energy and that is the hysteresis loss.

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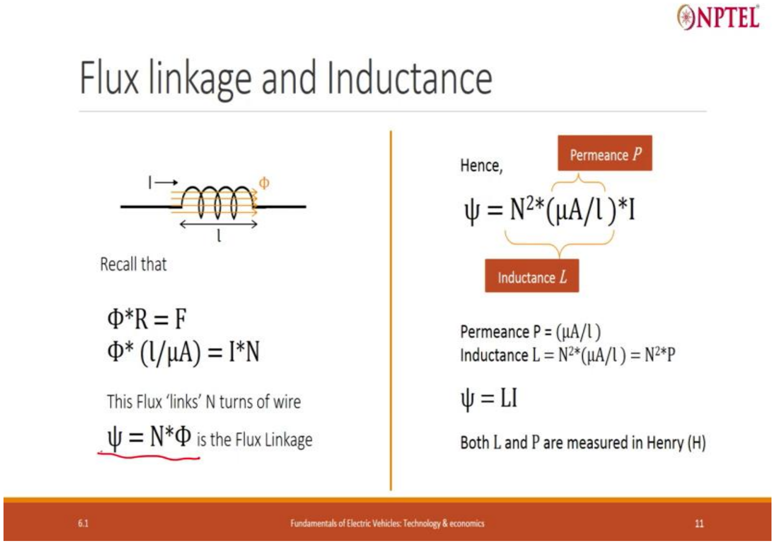

Now, there is a small twist to the idea of flux and this is very important because of something called Faraday's law which we will see later. It is not usually flux alone that is important, but the flux is flowing past N turns of a coil, so it is in some sense wrapping around the N turns. And we are interested in the total wrapping of the flux and that is called the flux linkage.

So, if a flux phi is flowing through the coil with N turns the flux linkage is phi multiplied by N and we denote that by the symbols psi. But we already know that phi into reluctance is the magnetomotive force. So, if I extend this instead substitute for phi by putting psi then what I get is N squared and what I have on the right hand side is the reciprocal of the reluctance.

Reciprocal of reluctance again has a term, it is called the permeance. But in this equation it is not just the permeance that I have but I am also having an N squared. If I multiply the permeance by N squared that is called the inductance. The difference between permeance and inductance is just a term N squared which is dimensionless, so the units of both of them is Henry H. And the important relationship psi is equal to l into I comes from this.

So, psi equal to l into I is just another form of Ohm's law that is what I want you all to appreciate. And this psi is very important because the rate of change of psi results in production of voltage that is Faraday's law, we will look at that in greater detail subsequently, but I am just giving you a preview of that, why we are interested in psi is because psi is the thing that defines the voltage.

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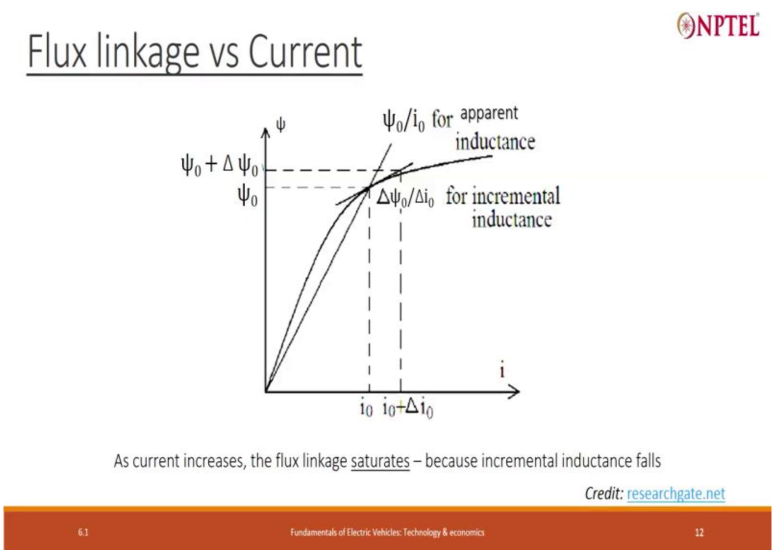

Now, we saw that psi is related to I and the constant of proportionality is l again when we want to compare how that relationship is we will plot psi versus I. And by now you will not be surprised, the relationship here also is not linear it is initially having a high slope and subsequently the slope tapers off and the phenomenon is called saturation.

Beyond a certain amount of current there is no further increase in the flux, therefore the flux linkage saturates and afterwards it is having a very poor inductance. The slope is a measure of the inductance, it starts off as a very good inductance and then as it saturates it becomes a very poor inductance. This again has important consequences in the way a motor functions, particularly in the torque, we will discuss that later.

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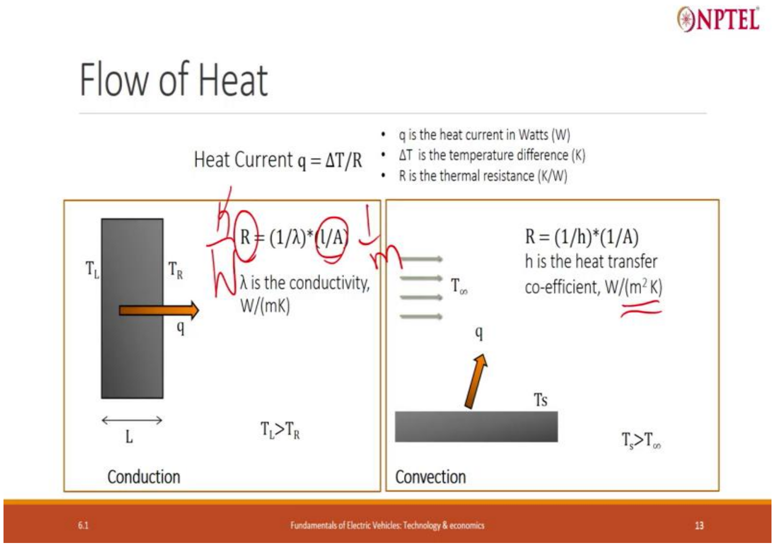

And lastly I come to flow of heat. Here again standard form of Ohm's law applies, what is flowing is heat denoted by q. What is causing the flow, the forcing function is the temperature difference delta T and the heat is flowing through some medium which offers resistance, thermal resistance in this case. So, q is measured in watts because it is the amount of energy that is flowing, heat energy that is flowing per second.

The temperature difference can be measured in Kelvin or degree Celsius, The thermal resistance is the ratio between delta T and q, so its units will be Kelvin per watt. The simplest example of flow of heat is when it is flowing past a slab of some uniform area of length L. Heat always flows from higher temperature to lower temperature, just like current always flows from higher potential to lower potential.

So, the temperature on the left is higher than the temperature on the right. And the length of flow path is L, so we can represent the resistance using the familiar formula 1 by lambda into l by A where lambda is the conductivity, just as we had permeability and we had electrical conductivity, here we have thermal conductivity. And again from a dimensional examination of the terms involved, you know that the units of lambda will be watts per meter Kelvin because the dimension of this is 1 by meter and the dimension of this is Kelvin per watt.

So, watts per meter Kelvin will be the unit of lambda. So this is the phenomenon called conduction. There is another way in which heat flow happens, there is a hot surface and there is a colder fluid, typically air that is flowing. The important difference between conduction and convection is that there is no notion of length because the air is just all around it.

So it is not happening across any predefined length it is just circulation that is causing the heat transfer. So here the resistance will be expressed as instead of 1 by lambda I have a different parameter called 1 by H, where H is called the heat transfer coefficient, but instead of L by A, I have just 1 by A. So, what this tells is that, is that H has a different dimension compared to lambda there is an m squared instead of m. The dimension of length is absorbed in the heat transfer coefficient called H.

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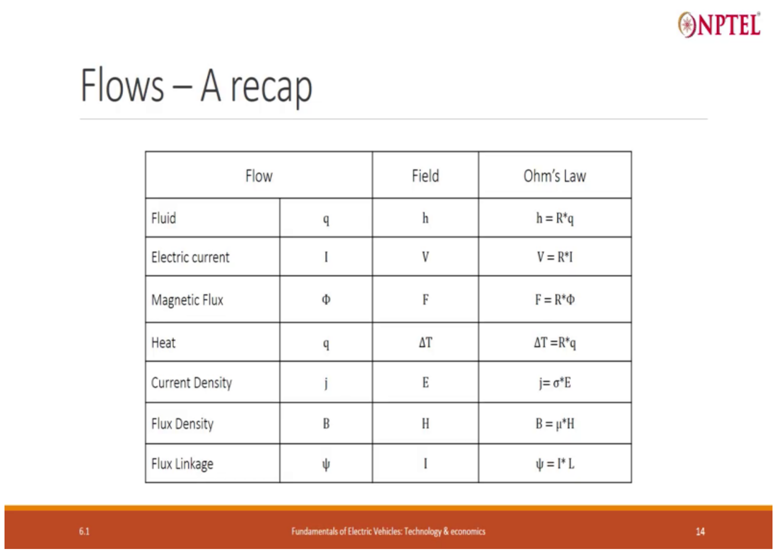

Flow		Field	Ohm's Law
Fluid	q	h	h = R*q
Electric current	I	V	V = R*I
Magnetic Flux	Φ	F	F = R*Φ
Heat	q	ΔT	ΔT =R*q
Current Density	j	E	j= σ*E
Flux Density	B	H	B = μ*H
Flux Linkage	ψ	I	ψ = I* L

So, with this we come to the end of discussion of different kinds of flows, all of these flows interplay in a motor and the interaction among them is the, is what gives us the final performance of the motor. So before we start going into the motor straight away I will give you a quick recap of all the flows that we have discussed. We have discussed as you can see 1, 2, 3, 4, 5, 6, 7, 7 flows. And in all of them there is a flow parameter and there is a field parameter.

The field parameter is what causes the flow and the flow parameter represents the thing that is flowing and the relationship between them is Ohm's law. And on top of that I can say that the thing that is flowing is conserved and that will be Kirchhoff's first law. And the field that is causing the flow is a conservative field which means the energy is conserved and that is

Kirchhoff's second law. That is all there is to all the physics that is related to the motor. Fine, is there any questions? I will be happy to take them. In thermal flow.

Student: (())(19:25).

Professor: q is in watts.

Student: q?

Professor: Yes. The thing that is flowing is heat. And whatever is flowing per unit time is what we are trying to measure like in the case of water it is liters per minute, is what we took as a unit of time, same way when we are talking about heat flow, the heat that is flowing is measured in joules per second and joules per second is nothing but watts.