**Electrical Machines**
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**Module 1**
**Lecture 1**
**Single Phase and Three-Phase AC Circuits, Magnetic Circuit**

Let us try to see whether we can measure reactive power in a three-phased system directly, balanced system. I am talking about balanced system.

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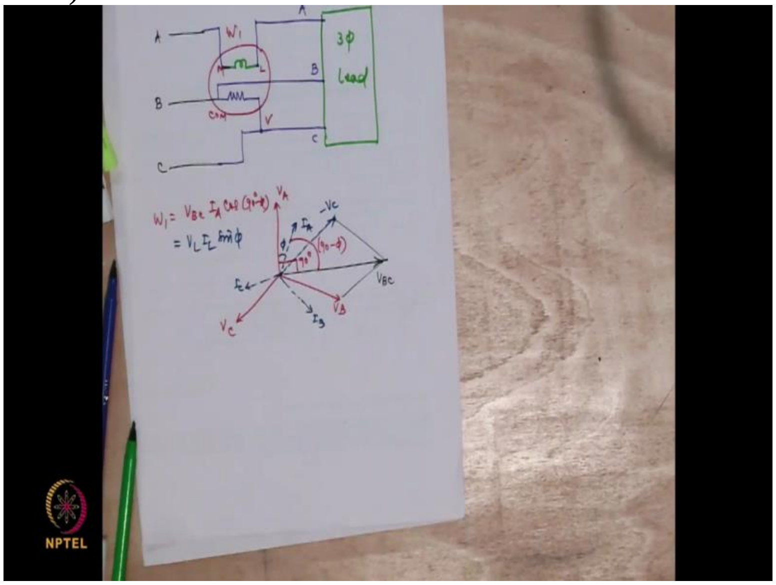


So, let us say reactive power we want to measure in a three-phase balanced system. So, let us say I have the three-phase conductors like this and here is my three-phase load. I am not really showing whether it is Delta connected or star connected, it does not matter. So, I am having a three-phase load. If I connect a wattmeter somewhat like this, we will be able to measure the reactive power. Let us try to see whether it is really true eventually.

If I connect a wattmeter like this, here is my current coil and here is my potential coil. So what I am trying to do is I should have shown this like this. This is going to the load, this will come in series and go back to the load. So, this is A, this is B, and the third phase C is directly going to the load and here is my potential coil. So, this is my wattmeter there. So I am showing this as the wattmeter.

So, I am showing this as M, this as L and this is a common point. It is supposed to be common, but I have not made it common; please note that and this is V. If I am having A phase here, B phase here, and C phase here and let us say my A phase current is somewhere here, B phase current is somewhere here and C phase current is somewhere here. So, I am showing this as $I_A$, $I_B$ and $I_C$.

And these are of course $V_A$, $V_B$ and $V_C$. Let me take the power factor angle. Please note, it is a lagging power factor angle. So, this is some phi I am having as the power factor angle. What I am applying to my voltage coil or potential coil is $V_{BC}$. So, I should essentially write this as - this is C, so, let me take this on the other side, this is $-V_C$. So, I can write this as $V_{BC}$. So, what I have done is to apply $V_{BC}$ to the potential coil. Whereas $I_A$ is the current that is flowing through the current coil.

This is $90^0$ clearly. I hope you understand, this is $90^0$. So, what I am having as the angular difference between $I_A$ and $V_{BC}$ is $90^0 - \phi$. So, I am going to get essentially $V_{BC}$ multiplied by $I_A$ multiplied by cos of $90^0 - \phi$ as the reading what I get out of my wattmeter. So, I should say if I call this as $W_1$, $W_1 = V_{BR} I_A \cos(90^0 - \phi)$. So, I can write this as $V_L I_L \sin\phi$. So, what I get is not really the reactive power, it is $\frac{1}{\sqrt{3}}$ times the reactive power.

So, whatever I get from the wattmeter reading, I have to multiply that by $\sqrt{3}$. Then I will get the overall reactive power of the system. I want you guys to verify whether this works for leading load as well. And I also want you guys to verify whether it will work for star connected as well as delta connected load. Although I have shown that as a black box, I have taken as though $I_A$ is $I_L$. Please check it out once. That is all I would say.

That I am leaving it as homework for you guys. Please check it out whether you are able to get the same kind of expression for leading load. The second one is for star as well as delta connections. So, for three-phase circuits recalling. So, we will not revisit three-phase again until we go over to three-phase transformer and three-phase induction motor.

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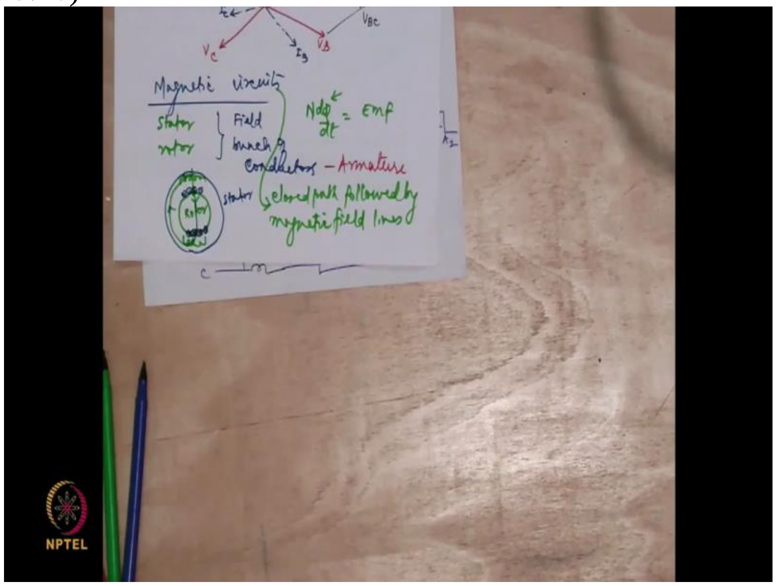


The next topic that we are going to venture into is magnetic circuits. What is the necessity for studying about magnetic circuits. In fact, electrical machines we are studying because there are huge number of applications. I do not think I need to elaborate on that. All of you guys know that if machines are not there, we are not going to be able to get any electricity and you know that literally we are our you know it is as good as breathing, electricity.

Without electricity, we will all be completely without anything. Even for a few days if your mobile does not work, it is a big problem. For charging, you need electricity for sure. Even your battery indirectly is you know electricity basically. Maybe you charge it using your mobile charger which is definitely coming from the grid. Similarly, many of our day to day you know work that we do, commuting these days, slowly we are moving to electric vehicle. Then we have basically you know the motors which are used in pumping water, you have you know in RO system, again you pump water.

If you look at, you know mixer grinder, without motor, it will not work. Lawnmower, it has motor. Fans, AC, you name it. Everywhere you have motors. Paper mills, textile mills, printing presses, any, sugar mill, cement mill, anything you talk about everything is going to have, all those industries have motors. So, machines have become definitely an essential part of our life. So, we are trying to look at how it works and whether we can improve any of its efficiency, whether we can conserve some energy, all these things we look at as research areas which are aligned or which are connected to the machines.

If you look at most of the machines, they are all made up of ferromagnetic material. It gives much more magnetic strength compared to what you have in a non-magnetic material. In a magnetic material, when you apply let us say 1 A of current, if I apply 1 A of current in a coil which is wound around a wooden piece, I will get probably X as the flux density or flux. Whereas if I am winding a coil, again passing the same 1 ampere of current in a coil which is wound around an iron core I am going to get maybe 1000 times or 4000 times more than what I got in the case of wood.

So, if I have higher magnetic field, obviously the electrical to mechanical energy conversion that takes place in the case of a motor or mechanical to electrical energy conversion that takes place in the case of generator, it happens through magnetic via media. So, if I have a large amount of magnetic field strength, the efficiency of this conversion would be far better as compared to what I would have gotten without that kind of a ferromagnetic material.

So, I am looking at how much torque is produced in the case of a motor or how much power is produced, electrical power is produced in the case of a generator. I would be able to say that torque per unit volume will be definitely much higher in the case of a machine made up of a ferromagnetic material as compared to if I had made the same machine with wood or a non-magnetic material. So, we are always looking at how a ferromagnetic material behaves when I apply a current.

And when I apply a current, what is the kind of fluxes produced, how exactly it passes through the machine, in what part it travels and so on and so forth we would like to analyze. And that’s what we are going to do in magnetic circuits. So, magnetic circuits essentially lay the foundation for analyzing the magnetic functioning or how electromagnetic behavior of the ferromagnetic material is. That’s what we are going to look at in this particular section.

If you look at any electrical machine, I am going to have two portions. One is a stator, the other one is a rotor. All of you know the basic principle of electromechanical energy conversion. I am sure you guys have studied about Faraday’s law of induction where if I have a variation in the flux, the rate of change of flux multiplied by the number of turns actually gives me ultimately whatever is the EMF induced. So $N\frac{d\phi}{dt}$ is actually giving me the EMF induced in any electromechanical system.

So, I can have a constant flux, but I can just move a conductor. If I move a conductor, the conductor will face varying magnetic field. So, I can do it that way to generate electricity or I can simply have a stationary conductor, but I am going to probably provide with an alternating current like I do in a transformer. That will also give me induced EMF but that is not going to give me mechanical to electrical energy conversion.

I hope you understand because I am providing electricity in the form of alternating current, I am also reaping ultimately electricity in the form of alternating current. So I am not doing electrical to mechanical energy conversion in the transformer case. Whereas in a rotating machine, invariably, what I am going to do is, to probably have a constant value of magnetism and then I am going to move a conductor, or, I am going to have a conductor which is stationary and then move a magnetic pole continuously, rotate it.

Then it will induce electricity. So, I need mainly two things for this purpose. One is I should be able to have a bunch of conductors in which electricity will be induced and the second thing is I will need a magnetism producing system which we call as the field system. So, we have stator and rotor are the 2 portions in an electrical machine where they may be accommodating, one will be accommodating field which will produce magnetism, the other one may be accommodating the bunch of conductors in which electricity is produced which we call as armature.

I can have the stator housing the field and rotor housing the armature or I can have it the other way around also. I can have stator housing the armature and rotor housing the field. Either way is possible. Invariably, depending upon the convenience of the design, we do it one way or the other. But either way, it will work, that’s not a problem. And when I have stator and rotor. I am definitely going to have probably the stator as the outer periphery.

This need not be always true. There are fans, electric vehicle some of them will have stator at the inner periphery and rotor at the outer periphery also. There are some mechanisms like that. But whatever we normally see in the laboratories, see in the industries, normally the stator is outer periphery and rotor is going to be in the inner periphery. So, I am going to have a rotor somewhere inside. So, I call this as the rotor, and this is going to be my stator.

Please note that the rotor gets its name because it is going to rotate, and it cannot rotate unless there is an air gap between the stator and rotor. So, whether I like it or not, in any rotating machine, I have to have air gap between stator and rotor. Whereas, that is absent in a transformer, because there is nothing rotating there. So there is no air gap between primary and secondary. The primary is equivalent to the stator you can say if you want to and the secondary is equivalent to the rotor or vice versa.

So, you have two independent windings there also. So if I am having the air gap, clearly it is not going to pass the magnetic field lines as well as the ferromagnetic material. The ferromagnetic material generally have something called permeability which is a very high value for them. It is a material property and it is going to allow the magnetic field lines to pass through them very easily.

Whereas, the non-magnetic materials like air or wood or any of them will not allow the magnetic field lines to pass through so easily which means if I have to have probably the magnetism produced in the coils here in the stator and ultimately, I have to induce electricity in the conductors here. These are all dot and maybe these are all cross for example. So, I am inducing electricity in the rotor conductors.

From the stator, the flux has to flow through the rotor conductors and then it should complete the path. So that means it has to necessarily pass through air. When we have the magnetic field lines passing through both iron as well as air we call that as a composite path and when we talk about magnetic circuit; the magnetic circuit is defined as the closed path followed by the magnetic field lines. Magnetic field lines are the same as the flux path that we are showing.

So magnetic circuit is essentially defined as the closed path followed by the magnetic field lines. Please note that just like how a current cannot flow in an open circuit this is also always a closed path. You will have a complete path; you know it will be a complete closed-circuit basically. So, I would say that in this case, maybe the magnetic field line will pass through this, pass through these conductors, pass through the rotor and complete itself like this.

This may be the magnetic circuit path basically. So, I am going to have to actually pass the magnetic field lines through the air gap. That means I have to forcefully push it through the air gap which means I will require more current to produce a higher strength of the magnetic field as compared to what I would require in the case of a transformer.

In the transformer, there is no air, there is no air gap because of which, I do not have to do this tough job of pushing the magnetic field lines through the air gap whereas in the case of an electrical rotating machine I have to push it through the air gap which means I will require more strength of the current generally.

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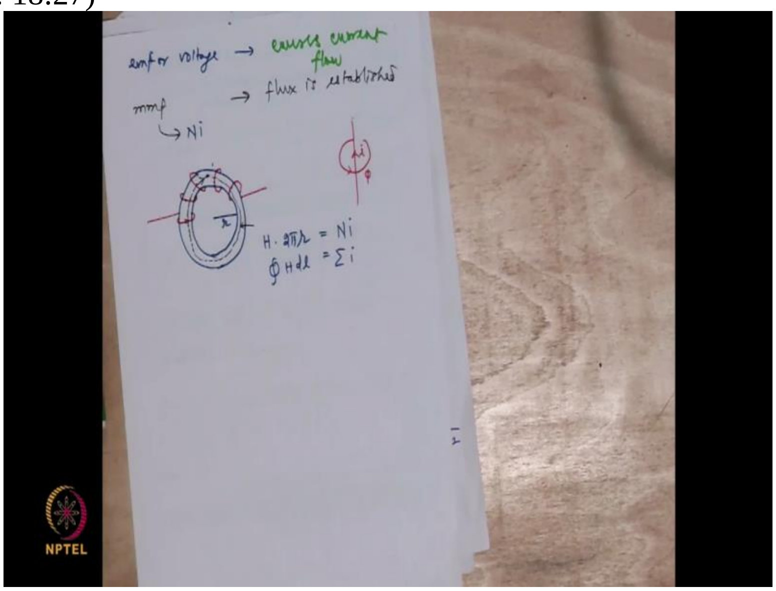


Just like in an electrical circuit, how we say that EMF or voltage causes current flow" I can say the same way in a magnetic circuit, I am going to have MMF causing the flux. The flux is established because of MMF. What we mean by MMF is if I am passing a current through a coil, let us take probably an example, maybe I have a ring like this. And I am going to probably wind the conductor like this. So, it is just you know wound around like this.

I will just show a few turns and then from here it is coming out. So, I should show as though from here, this is again getting out ultimately. So, if I have so many turns like this, all of you know that thumb rule basically that if I am having probably a current in this direction, my finger show direction of the flux lines. So, if I am going to have for example, a current flowing in this direction, I should show the flux lines will be in this direction basically.

So, this is the flux line or magnetic field lines whereas this is the current direction. The same way I should be able to say here also, if my current is flowing like this right, so I am going to have the flux lines produced in this particular direction. That will be a closed path clearly. So, I should complete it. I cannot leave it halfway through. So, this is how it is. It should be a circle of course I am showing it in different way.

But this is essentially the magnetic field line that is the way it is produced. Now if I am saying that along the flux path how many times the current is being linked. So, I should say, it is encountering the current once here, once here, once here, once here and one more time here. So, 5 times, it is actually encountering the current along the flux path. So, if I call this as the magnetic field line, how many times the magnetic field line is encountering the current that is actually known as the MMF.

That is the product of how many times the current is big encountered multiplied by the current magnitude itself that is what is MMF. In one sense, I can directly correlate that to the number of turns, how many times it has been wound around. So, the number of turns multiplied by the current magnitude itself is generally known as the MMF. So, in this particular case, I can directly write this as NI. This can also be correlated by Ampere's Law.

Because Ampere's Law essentially says that the magnetic field intensity, the integral of magnetic field intensity along the closed path will be equal to the total current you know linked with that contour. So, I should be able to say in this case if I say that this is the radius R, I can say basically 2πR is the length of this magnetic path multiplied by H which is the magnetic field intensity should be equal to whatever is the number of turns times I.

What actually Ampere's Law says is $\oint Hdl$. The same thing we have written it now after integrating and after adding all the currents. How many times the closed path or close contour is being linked with the same current, that is what we have written. So, if we have an MMF of NI or if I pass a current of I, if I have only one turn, then I am going to definitely have less amount of MMF. If I have 10 turns, definitely I am going to have a higher amount of MMF.

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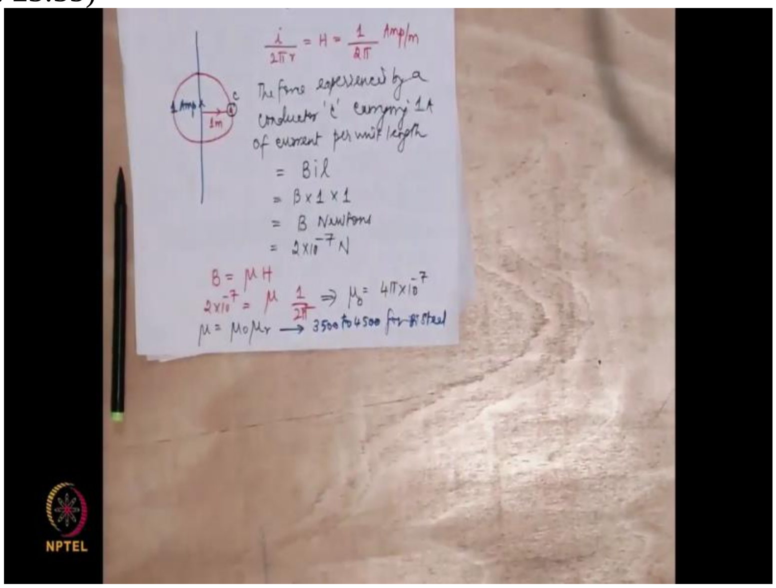


Now if I say that I am just taking a current carrying conductor of infinite length and let us say it is carrying a current of 1 A and I am looking at what is the magnetic field intensity around this at a distance of say 1 meter. I should be able to write that as, please remember, if it is only one conductor it is as good as only one turn. There is no other turn. It is encountering it only once. So, it is as good as one turn.

So, I should be able to write this as you know whatever is the current, that is $\frac{1A}{2\pi r}$. This will be my H. And I is 1, R is also 1, so I should be able to write this as $\frac{1}{2\pi}$. And $\frac{1}{2\pi}$, I should have written as $Amp/m$. This is what is my magnetic field intensity experienced by anything that is placed at a distance of 1 m away from that infinitely long conductor. I am assuming that the return path of the conductor is very far away.

So that is not having any influence on the magnetic field intensity. Let's say at this point, I am going to place another conductor C, and let's say the conductor is carrying 1 A of current. What is the force experienced by that particular conductor? I want to first of all get that. So, the force experienced by a conductor C carrying 1 A of current per unit length. I want to calculate it per unit length of C, will be B*il* basically. That is what you write normally.

Here I am talking about unit length, I do not know B, I have to calculate. I is 1 A, L is 1 m because per unit length I am calculating. So this will be essentially B Newtons but in the SI units, if you look at the definition of ampere, it would say the ampere is a current carried by 2 infinitely long conductors placed in vacuum, if the force between them happens to be $2\times10^{-7}\,\mathrm{N}$ if they are 1 m apart and the force is calculated per meter length.

This is how in SI units' ampere is defined. So, by that definition, we can say this should be equal to $2\times10^{-7}\,\mathrm{N}$. Because we have taken very long conductor initially, then we have placed the second conductor which is also carrying 1 ampere of current and we have placed them apart by 1 meter so I should say that this is the force that we are getting between these 2 conductors. But we have a relationship if you may recall, $B = \mu H$.

H is the cause, magnetic field intensity is the cause and B is the effect. The 2 are related by a material property called permeability which is mu and we have taken basically that we have placed a conductor probably in air or vacuum or whatever. And the moment we say the force is $2\times10^{-7}$, we have to assume that it is probably placed in a non-magnetic material. That is how ampere is defined in SI units.

So, I should say from this that $2\times10^{-7}$ equal to $\mu\frac{1}{2\pi}$. I am just substituting the values what we got from which I should be able to say $\mu_0 = 4\times10^{-7}$. We will have to come up with the units for this. Let us try to take a look at what the units are. Now this is known as the permeability of free space or air or a non-magnetic material basically.

So, this will be used time and again in all your magnetic circuit calculations. So, we are going to have essentially the magnetic circuit calculation continuously encountering this mu value and we call this as mu naught normally, indicating that it is essential the permeability of air or free space. Whenever we are looking at any other you know magnetic material, we are going to have the actual permeability of a magnetic material to be $\mu = \mu_0\mu_r$, where $\mu_r$ is known as the relative permeability and the relative permeability is going to be generally, you know, a few hundreds to few thousands depending upon what kind of material I am looking at.

For example, for silicon steel and steel and so on, it will be about 3500 to 4500. Whatever we use in the transformers many of them are going to have this $\mu_r$ value to be almost 3500 to 4500 for steel and silicon steel. Now let us try to arrive at the unit for $\mu$.

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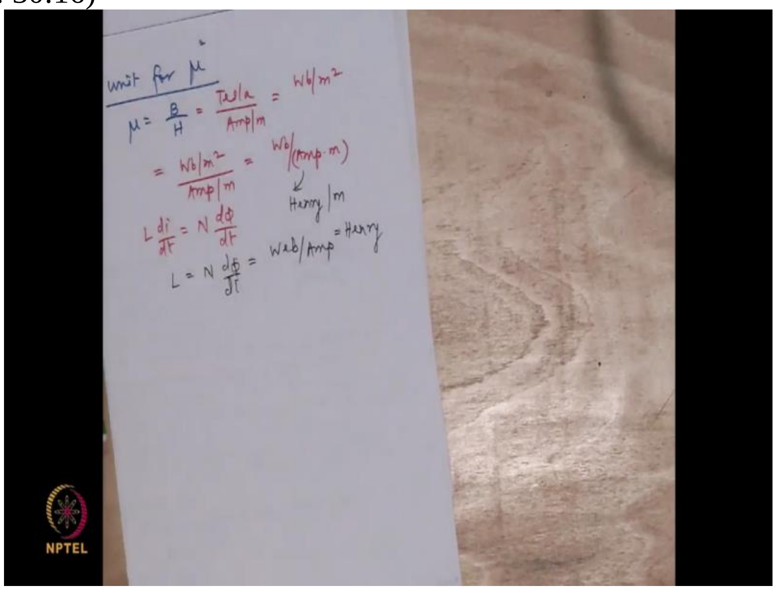


So, let us try to look at the unit for, we said that $\mu = \frac{B}{H}$. B is flux density which means either it should be expressed in Tesla or $Wb/m^2$ and this will be basically H is $AmpTurn/m$, because we wrote; H is actually if you look at the calculation what we have done, we have done $\frac{N1}{2\pi r}$, that is what we did. So, we should write this as ampere turn.

Turns do not have any dimension. So, we should be able to write this as ampere per meter. So, I can write actually this as the unit for $\mu$ as $\frac{Wb/m^2}{Amp/m}$. So, I should be able to say this as $Wb/Amp\ m$. The whole thing comes in the denominator. I can also look at it a little differently. I can say that if I look at $L\frac{di}{dt} = N\frac{d\phi}{dt}$, this is a you know relationship expressed in the form of Faraday's law but when we look at it in terms of electrical circuit because we always refer to the magnetism that is occurring associated with the alternating current by including a fictitious quantity called inductance.

So, the inductance comes into picture to represent the magnetism that is taking place or that is coming into picture because of a current passing through a conductor. So, from here, I should be able to say that $N\frac{d\phi}{di}$. So, I should be able to say this as you know this is, N does not have anything as the dimension, so $Wb/A$ .So, $Wb/A$ is Henry. So inductance is here normally measured in Henry.

So, this is essentially Weber per ampere which is Henry. So, from here, I should be able to write this as Henry per meter. So, the permeability has the unit of Henry per meter. So, you can actually look at it from the equivalence of $L\frac{di}{dt} = N\frac{d\phi}{di}$.

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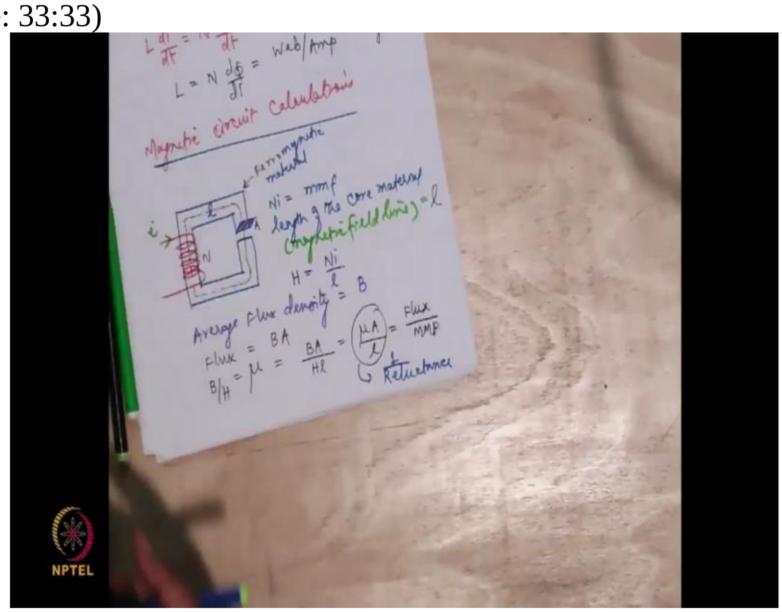


So, if I am having a magnetic circuit somewhat like this, let me probably draw this like a transformer. So, I am going to take a core which is like a transformer core. But I am going to introduce a small air gap in between. So, I have introduced a small air gap in between and if I am going to have the turns wound around this limb only let us say and let us say there are some N number of turns and I am going to pass the current I through this.

This will definitely create the magnetic field lines. So, the magnetic field lines probably I can look at it this way that it is going to go around like this and it will go through the air gap also forcefully, there is no other way because it will try to confine itself as much as possible to the ferromagnetic material. If I say that this core is made up of ferromagnetic material, because of its permeability being quite high, the magnetic field line I have shown only one, but there will be definitely multiple number of lines and they those things will confine themselves as much as possible to the ferromagnetic material because the permeability of the ferromagnetic material is pretty much high.

Now I can say that NI is the total MMF available, magneto-motive force available which is going to contribute towards producing the magnetic field lines. Now if I look at the overall length of the magnetic circuit, the length of the magnetic circuit actually corresponds to what is the length of the magnetic field line.

So that means I have to say, probably I have to look at the complete circumference of this particular core and if I say the average circumference is L, so I should say length of the core material or I would say on the other hand it is the magnetic field line is equal to L here. This is L So I should be able to say in this case that the magnetic field intensity $\frac{NI}{l}$. Let us say I probably have a rectangular cross-section for this core.

Let me call this area of cross-section of this core as A. Through this A, continuously I will be having huge number of flux lines flowing. If I say that the average flux density that is created in the core is equal to B, then I am going to say that the overall flux equal to $B \times A$, where A is the area of cross-section of the core. and I can say that $\frac{B}{H} = \mu$. In which case, I should be able to write this as, you know, $\frac{BA}{Hl} = \frac{\mu A}{l}$.

This is equal to on the whole $\frac{BA}{H\,/} = \frac{Flux}{MMF}$. It is very similar to the relationship between voltage and current in an electrical circuit. So, we are going to say that if I compare an electrical circuit with that of a magnetic circuit, MMF will be very analogous to whatever is the voltage source in an electrical circuit. Flux will be analogous to whatever is your current in an electrical circuit.

So that means the ratio of the voltage to current which we call as resistance or impedance in an electrical circuit. We will similarly call the ratio of MMF to flux as the reluctance. So, this ratio whatever we have got here is going to be $\frac{1}{reluc\tan ce}$ or reciprocal of reluctance.

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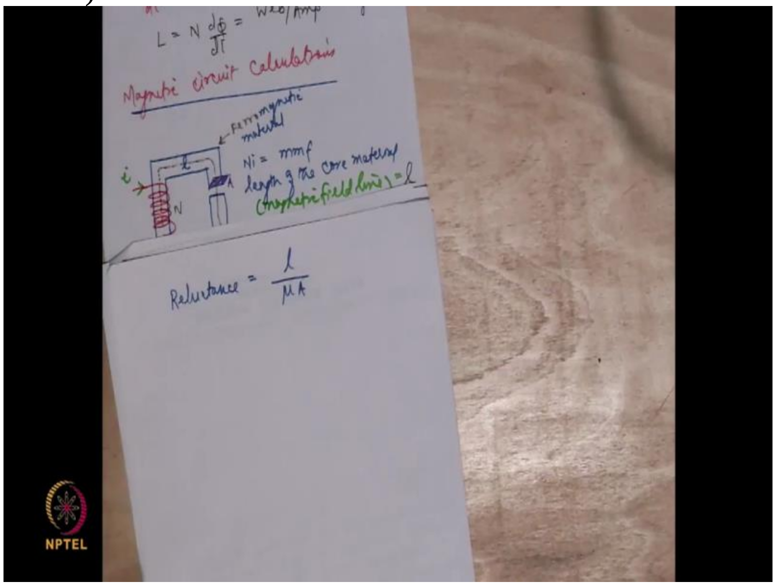


So, we can say basically that the reluctance in a magnetic circuit is equal to $\frac{/}{\mu A}$. What I have done is, to neglect the air gap very clearly I should have taken the air gap effect in this case. I am going to include that that is why I included the air gap in the first place.

Student: (())(39:50) We get the relation $\mu = \frac{B}{H}$

Professor: See, $\mu = \frac{B}{H}$ we are not deriving at all completely. We have not derived it, we have assumed that there is a cause and there is an effect and ultimately the effect depends upon the material property and the material property is permeability.

So we are just going ahead with the relationship that H and B are directly proportional to each other as long as the material property is a constant, which is not a constant in the case of iron, which we will come to but we are essentially assuming that the cause and effect, the cause is the current that is flowing, the effect is the magnetic field created or magnetic flux created.

The two are directly related to each other, directly proportional to each other, we are assuming that. I am not really deriving that and we are saying that when you have both of them directly proportional to each other, the proportionality constant happens to be $\mu$. That is all we are assuming.

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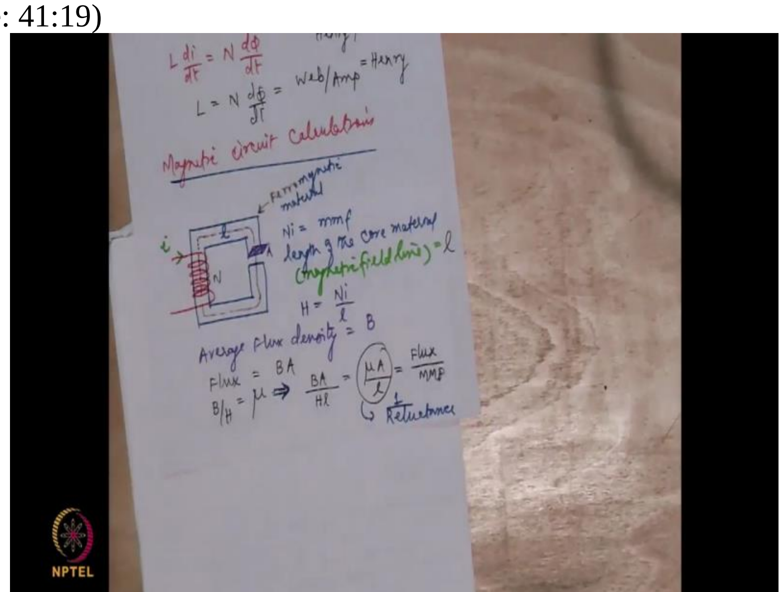


See, basically we are saying that BA, we are essentially writing basically that $\frac{B}{H} = \mu$. Now we are multiplying $\frac{B}{A}$ and we are multiplying $\frac{H}{l}$. We have just done it arbitrarily, assume that way. Then I have to write, $\mu$. On the top I have to multiply it by A and at the bottom I have to multiply it by L. That is all I am doing. So from here, I am writing this. I should have put just the arrow. I am not writing equal.

I am just multiplying $\mu$ by A and H by *l* and I am writing $B \times A$ = flux and $Hl = MMF$.

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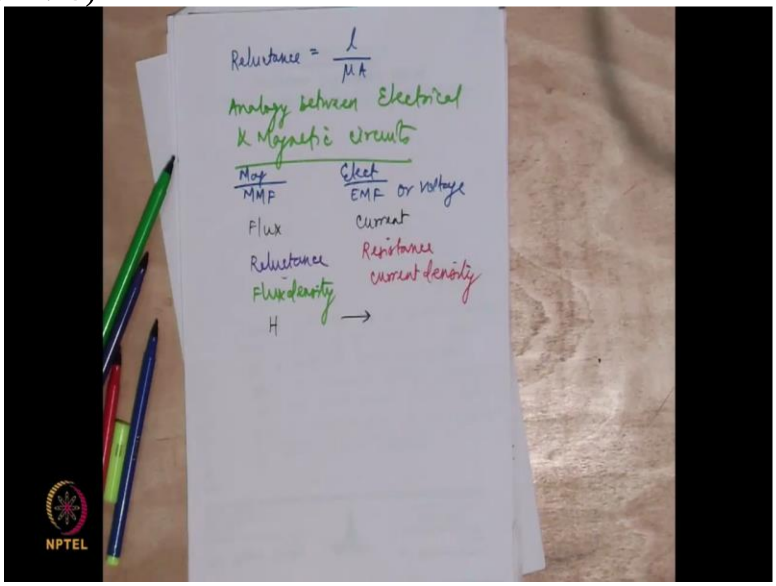


So we are essentially having we will continue with magnetic circuits further, but we are essentially having the analogy between electric and magnetic circuits as follows. So if I have MMF in the magnetic circuit, in the electric circuit, I have EMF or voltage. In the magnetic circuit, if I have flux, I am going to have in the electric circuit current and in the magnetic circuit if I call this as reluctance, I am going to call in the other case as impedance or resistance.

And if I say flux density B in the case of magnetic circuit, the same way I can call this as current density. Whereas the magnetic field intensity H does not have an equivalent quantity I would say in the electrical circuit. Magnetic field intensity which we call as MMF per unit length that does not have an equivalent quantity in the case of current electricity. So, we will probably deal with H a little differently as compared to what we deal with in the case of electric circuit. So, we will go on to magnetic circuit calculations with air gap and so on in the next class.