Electrical Machines

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Lecture 14: Electromechanical Energy Conversion- I

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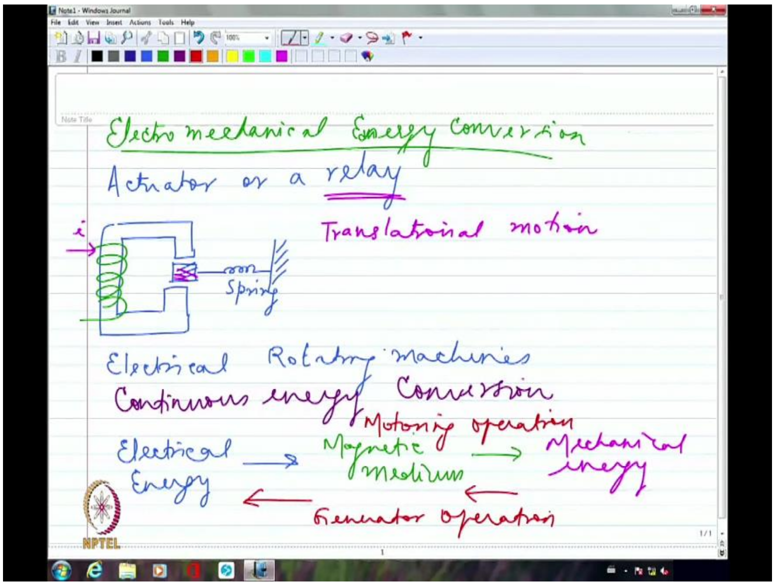

So, we are starting on the next topic which is actually electromechanical energy conversion. So far what we have seen in terms of electrical machines is transformer which is basically a static machine, there is no rotation, there is no movement involved and that is the reason why the air gap was very less and when the air gap is less the magnetizing current is also normally less, that is what we talked about earlier.

So compared to a transformer if we look at any other moving mechanism which is a rotating machine or translational machine, all those things are going to definitely have some amount of air gap between the stationary part and the rotating part. So that is going to definitely ask for more amount of current, if flux has to flow through the air gap also it will require more current. So as a rule any moving mechanism is going to demand more amount of magnetizing current as a rule.

So we are going to look at actually if you look at electrical to mechanical energy conversion, one of the examples is an actuator or a relay. What do we mean by an actuator? If let us say I have a structure like this, I am just going to arbitrarily take a structure which is somewhat like this and I want some other piece to come and close this gap and this gap is normally a lot this is not going to be closed at all. If I want this to be closed only on some instigation, some stimulation, I do not want it to close otherwise. So I am going to have a moving part which is also probably made up of iron and it is probably going to be connected to a fixed frame somewhere through a spring, this is not an inductance because as an electrical engineer we always think it is an inductance.

Let us say it is not an inductor it is a spring, the spring is holding probably this piece of iron at some point which is away from this particular C shaped magnet. So if I actually have a coil around this C shaped magnet and if I pass probably a current i through this, only when I pass a current the C shaped iron piece is going to get magnetized and it will attract this piece of iron. If I may say this is also made up of iron that is going to be attracted. So if it has to be attracted the current should be strong enough to nullify the action of a spring and it has to dominate over the spring's mechanism, only then it will be able to pull it. So this is generally known as an actuator.

The actuator is a mechanism which may have a translational movement depending upon how much current you are passing through, another mechanism which is creating a magnetic field. So this is essentially an electromagnetic actuation mechanism. This is also sometimes called as a relay; a relay typically is used for some protective features in a power system. For example, if I have a power system which is supposed to be carrying 1000 A of current, if the current goes more than 1000 A say it goes to 1200 A, then immediately a protection system should act because it should sense that there is some overload somewhere. Something has been short-circuited probably, so the current drawn is heavy. The current drawn is heavy and I have to make sure that somehow the circuit is cleared, so unless the fault is cleared I cannot activate again that particular load.

So the moment it senses over current, it should immediately open up some switch, so that is what happens in our homes also. In terms of many circuit breakers you might have seen in the mains box, the circuit breakers generally act as soon as maybe there is an over current. So if there is a short-circuit signs in any of the rooms or any of the loads, then immediately it will open out. So what happens there is also generally a relay or actuator mechanism, the moment the current goes beyond a particular value immediately the magnetic pull becomes quite a lot because of which some switch is opened or some switch is closed, that is what happens.

So these are typical examples of translational motion or linear motion using electromagnet. But what we are going to concentrate mainly is on rotational mechanism and you should also realize that this kind of actuator or relay is a onetime process. Maybe if I need a protective feature once it will actually, again it has to be reset, may be another time when the fault happens it will again act. It is not a continuous energy conversion whereas generator or motor is a continuous energy conversion mechanism from electrical to mechanical or mechanical to electrical. We are going to have continuous energy mechanism taking place in rotational machines.

So what we are going to concentrate specifically is electrical rotating machines which will actually have continuous energy conversion mechanism. That is what we are going to look at in this particular course on the whole, until now what we talked about was only a static machine. Transformer is also very much a machine but it is a static machine. So what we are going to look at now from now on is rotational machines. So I can have actually on one side I can have electrical energy input and it is going to go through a magnetic via media because actually the magnetic medium is not going to contribute towards any energy directly, it is only serving as a conduit between the electrical energy and mechanical energy.

So if I am having electrical to mechanical energy conversion, I am going to have the mechanical output ultimately. Now this is going through magnetic via media, so we will call this as actually the motoring operation. When electrical energy is converted into mechanical energy we call that as motoring operation. On the other hand, if I am actually giving mechanical energy as the input and we are going to have ultimately electrical energy as the output through the magnetic via media again, we call this as the generator operation.

So we will be looking at both of them. Please understand that the same machine can work either as a motor or as a generator, only thing it requires is either electrical energy input or mechanical energy input but there should be a magnetic via media which will also be present for sure. So the magnetic via media, what we are actually looking for should be in the form of an electromagnet and we call that system as field system and where the electrical energy is given as input if is a motor or from where it is taken out as the output if it is a generator we call that portion as armature.

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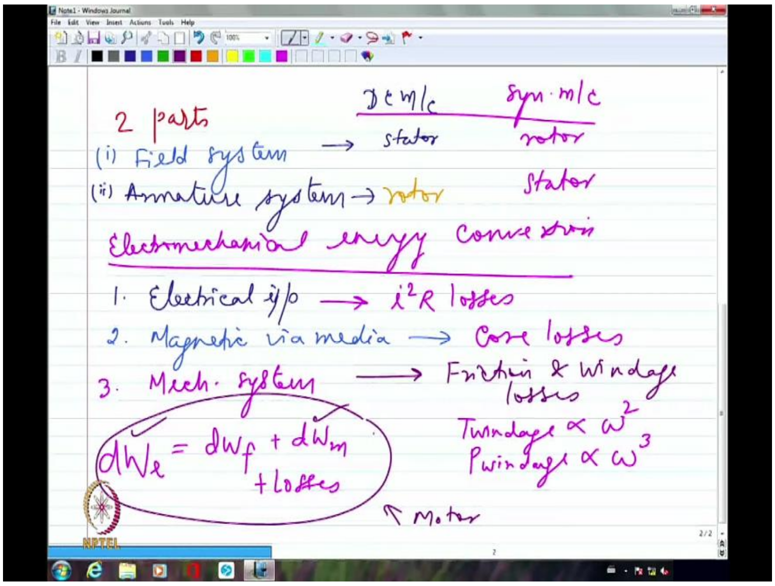

So specifically we are going to have two portions in the electrical machine, we are going to have one of them as field system the other one we call that as armature system. And when we are looking at filed system it can be actually the stationary portion or it can be the rotational portion, no problem. The same way armature could be stationary, armature could be rotating. It depends upon what kind of mechanism I have designed.

For example, if I am going to talk about DC machine, normally we will see the field system to be the stator, armature system to be the rotor. Whereas if I am looking at basically synchronous machines for example which we will be talking about towards the end of the course, the field will be housed in the rotor and armature will be housed in the stator. It does not matter even if it is the other way around, it would work but for convenience for logistics purpose generally we tend to arrange the two different systems in two different portions like this.

So it need not be the case that I have to have field in the stator or I have to have field in the rotor, in fact in some of the electrical machines that are there in our machines laboratory which is there in second block we have synchronous machines having the field system actually in the stator and the armature in the rotor and it still works, it is a laboratory so anything goes, it does not matter. We are not going to look at optimization of design and things like that, it is essentially to demonstrate that either way it will work, that is the reason it is like that as far as our electrical machines is concerned.

So, let us say I have first of all in electromechanical energy conversion systems, I am going to have mainly three portions being looked into, one is the electrical input. Whenever I am talking about an electrical input, that means I have certain voltage applied, there should be some current flowing, because of which there will be definitely some i^2R losses as well, so correspondingly the losses in electrical input system will be i^2R losses.

Similarly, if I look at the magnetic via media normally I may see that there is some increase in the field energy also. Electrical energy we know is $Vidt$ or $Eidt$, whereas if I am talking about field energy obviously it should be associated with inductance, so $\frac{1}{2}Li^2$ typically, that is what we are talking about as the energy that is associated with the field or magnetic field. But along with that I may have core losses what we talked about already in transformer that is due to the magnetic field and core losses generally will be associated with the machine only if I am talking about alternating currents. We already talked about this. Hysteresis loss and Eddy-current loss we will have only if there is alternating current, otherwise we are not going to have those losses.

And the third type of subsystem which is the part of electromechanical energy conversion system is the mechanical system. So the mechanical system again will have the losses as actually friction and windage losses. These are the two losses that are going to be there normally with any mechanical system, friction I am sure all of you know. What is windage? Any idea, what is windage? Friction all of you know, what is windage?

Windage is associated with wind, so if I am running the machine in vacuum I will not face this problem. But unfortunately we do not run the machine in vacuum we always run it in an environment which is probably filled with air. So when the machine is rotating it has to definitely displace the air, surrounding air. So that air is going to offer some resistance to the movement of the machine, that particular loss encountered because of the presence of air or wind, surrounding wind that is known as windage and this will be more if the machine is trying to rotate faster because it has to displace the wind more, so it is like fan. When you have the fan rotating much faster you see that more and more wind you get.

So generally you are going to see that this particular windage is always dependent upon the speed at which the machine is rotating. If it is rotating at lower speed the windage losses faced by the machine will be smaller, if it is rotating at a higher speed you will see that the windage losses are more. And in general empirically the expression we can say the windage loss is actually proportional to, if I write it in the form of torque, so T windage I am saying, the loss torque associated with windage.

Normally we talk about the losses in the form of watts but here I am talking about it in the form of torque. So the windage loss is proportional to ω^2 or $(speed)^2$ so I should say power associated with windage or the power loss associated with windage will be proportional to omega cube because T*ω is what is the power, so I can say that T corresponding to windage will be proportional to ω^2 or the power corresponding to windage will be proportional to ω^3.

Student: Where is the velocity of the wind?

Professor: Where is the velocity of the wind? It is let us say I am just having you know in a room I am rotating the machine. The wind is really not, we are not expecting it to move just like that. It is almost still because of which you will get ω, directly whatever is the rotating speed that will become ω as to calculate whatever is your loss torque or the power. If you are for example looking at an elevator which is probably going in say a tower which is having a huge height like 112 floors, so it is going to go through the entire height in a fraction of maybe a minute, so which means it has to tear through the wind column and then go.

So very you know it will be very realistic to model that as you know a wind windage kind of torque because it will be proportional to the velocity square, at what velocity it is going because frictional losses will not be directly proportional to whatever is the velocity square. So we are essentially looking at two components, one is like a static friction. In fact, friction itself we will looking at different things, viscous friction will be proportional to ω, static friction will not be dependent upon ω at all. The third static friction is the initial frictional component which will be required to move, give the initial momentum and the third component is windage.

So you will have essentially there are three components if you want to really do the air-splitting completely for all the frictional quantities.

Leakage flux in the case of the magnetic field, see in the magnetic field if you are talking about leakage flux, that will be actually counted as the voltage drop more than any power loss. It will not be counted into the power loss; we are talking mainly about the real power losses. Whereas if you are talking about iron loss that is clearly real power loss because it will contribute to heating whereas leakage flux is not going to contribute towards heating, it will only go into voltage drop.

Okay, so normally we should write if it is a motoring mechanism dW_e which is the electrical power input for a short duration, that should be equal to whatever is the increase in the field energy plus whatever is going to be increase in the mechanical energy plus of course losses. I have to include all the losses and this is true for a motor because we are giving electrical energy as the input. If I am writing this for the generator I have to write $dw_e=dw_f+ dw_m+$ losses because in the case of generator what I am giving as the input is mechanical energy and what I am getting as the output is electrical energy.

And whatever is the increase in the field energy that is just incidental, I am not intending to really do it but it is just incidental. I am not going to really strive hard to increase the field energy, what I want is actually conversion from mechanical energy to electrical energy or electrical energy to mechanical energy. I am not interested in increasing the field energy but if the air gap is decreasing, maybe the flux will increase due to which maybe my field energy will increase or decrease that is just incidental. It is not really going to cause specifically intentionally any increase in field energy at all.

What I am worried specifically about are these two and I would like to minimize the losses as much as possible, right. So let us try to first of all see with this background in mind whether we would be able to get an expression for electrical to mechanical energy conversion process, whether we would be able to get an expression for force or torque. How do we really go about doing it? That is what we are going to in this particular chapter, we are essentially trying to look at how electrical to mechanical or mechanical to electrical energy conversion takes place and whether we can get an expression for the torque or force so that we would be able to utilize it later.

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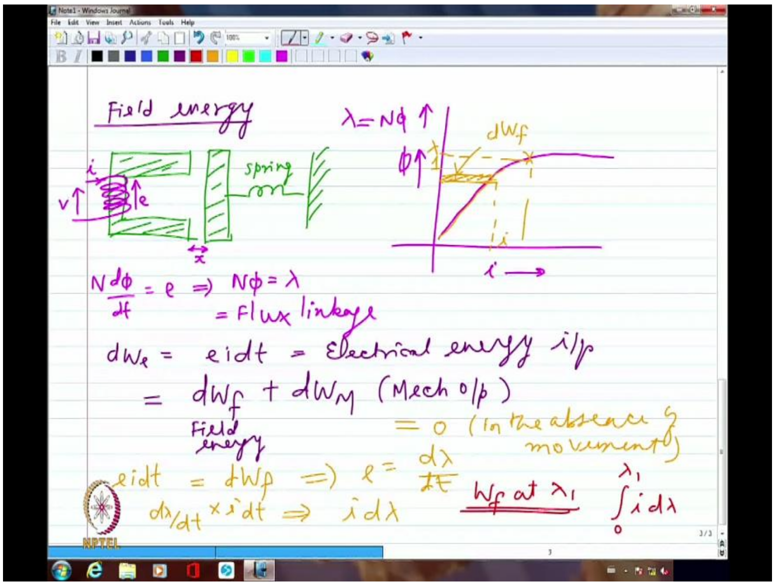

So let me first of all take the same mechanism. So we are first of all going to understand very clearly what is field energy. We have still not gotten clearly what is the field energy, we know $\frac{1}{2}Li^2$, that is all. But how are we really going to quantify it? That is what we want to check it out, okay. So for this let me again take the same mechanism as what probably I drew earlier, I am drawing more like a C here and then maybe I have one more piece here. There are two pieces, both of them are made up of say magnetic or Ferro-magnetic material.

And let us say this is connected to a frame which is a fixed frame through a spring, fine. Now I am going to have a coil wound around here which is going to be passed with the current i, fine. And when actually I am applying a voltage V, probably I will have a current i depending upon what is the resistance and what is the inductance. If it is DC for example, I can say $\frac{V}{R} = i$ directly. If it is AC I am going to have definitely an inductance drop also and there will be an induced EMF e on the other side, that is the induced EMF.

Now let us say the distance is something like x, this is the distance x I am having as the air gap, okay. Now when actually the current was not flowing, still maybe I was having the distance of x and when the current is flowing, if the current is not strong enough I am definitely going to have still that distance maintained as x because the spring is going to hold it at that particular place whether we like it or not.

So, if I try to actually plot, as I increase the current, how my flux is increasing or I may write $N\phi$ how that is increasing. Either ways it is fine, N is number of turns, so I am just multiplying the flux by the number of turns and I am calling that quantity as λ because we normally write $N\frac{d\phi}{dt} = e$. So, I am going to write $N\phi$ as λ and I call this as flux linkage. How many times this flux is linking with you know the total magnetic path? So, this I am calling as $N\phi$.

So, if I plot this, we know basically that I am going to have as I increase the current it will increase, and it will reach some saturation. This is what is our magnetization characteristics normally. If I am talking about x being larger and larger, the distance is larger and larger, very clearly it is approximating itself to larger and larger air gap and the air gap reluctance will dominate over whatever is the reluctance of the iron path. So it will become more and more linear.

If I have a larger air gap I am going to have more and more linear characteristics, if I have smaller air gap I am going to have more and more non-linear characteristic because of the iron coming into picture and whose reluctance is dominating I have to look at it. So if the air gap is smaller I am going to have highly non-linear magnetization characteristics like what we saw in the case of transformer. This is how it is going to be. What I am giving as the electrical energy input let me try to see.

That will be $eidt$ because I am misusing the i^2R losses, I do not want to take that into account at all, i^2R losses are not going towards any energy conversion, it is just dissipated in the form of heat. So what comes out as the induced emf e essentially is towards the inductance, it is going towards the inductance of the coil. So, I am writing $eidt$ as the electrical energy input.

If I just neglect all the other losses in mechanical form or core losses and so on, I should have $dw_e=dw_f$ we wrote this earlier plus dw_M. I am neglecting the losses, so I am not writing the losses at all. So this is actually the mechanical output and this is the field energy or increase in the field energy. I have not really mentioned about any movement so far because I have not really sufficiently pumped in you know enough amount of current. So it was not able to attract the other piece of iron, so there was no movement at all. So if I look at how much is the mechanical energy output when there is no movement, this will be zero in the absence of movement.

So, whatever I supplied the entire thing went towards increasing the field energy, that is what it is indicating, right. If I do not see any mechanical output whatever I have given as the input of electrical energy which was eidt that entire thing has gone towards actually creating you know only the field energy. So, if I am saying that I should say eidt incidentally becomes my dw_f and e is after all $\frac{d\lambda}{dt}$. So, I should be able to write this will be $\frac{d\lambda}{dt}$ idt.

So, this will give me essentially $i\,d\lambda$, so $i\,d\lambda$ in the absence of any movement gives me directly whatever is the field energy that has been accumulated for a small duration dt. So just to tell that graphically if I am looking at a particular value of i and if I am looking at a small variation in λ, this strip actually gives me the area under the strip you know in the left side of the curve which is the magnetization characteristics. This is going to give me what is dw_f.

So, the field energy is given by the expression $\int_0^{\lambda_1} i.d\lambda$ provided I do not see any movement at a particular position of maybe the entire magnetic circuit. I should be able to say if I get i $\int_0^{\lambda_1} i.d\lambda$, I will be able to get the field energy.

So for example, if I am looking at a particular λ value here maybe this λ is let us say λ_1, I should be able to get w_f at λ_1 flux linkage, for this magnetization characteristic will be zero to λ_1 $id\lambda$. That is what will give me what is the field energy associated with that particular magnetic circuit when it reaches the flux linkage of λ_1.

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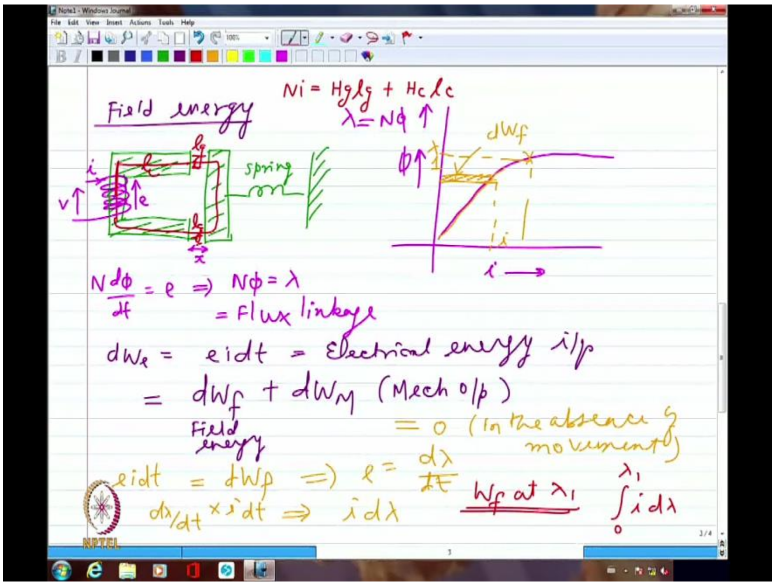

So this I can again express it in the terms of magnetic circuits, magnetic circuit quantity. I have two specific magnetic field intensities, let us say associated with the core and associated with the air gap. Let us try to look at the magnetic circuit again. These magnetic field lines are going to flow like this, flow like this and then flow like this and come back. If I take the average length I should say l_c is higher because l_c consists of all this length and all this length and all this length and this length as well. All that corresponds to ferro-magnetic core, the gap length are only this much. This is l_g this is also another l_g, that is it.

So I am going to have the gap length to be really really small whereas the actual core length is going to be much larger. So the magnetic circuit length on the whole is l_c+l_g, maybe I can call this as $\frac{l_g}{2}$ and this is also $\frac{l_g}{2}$, together it becomes l_g. So, I should be able to write that, if I try to look at the MMF in this case this MMF will be Ni which will be $H_gl_g+H_cl_c$, this is what is the total MMF that is going to be associated with this magnetic circuit at this point in time.

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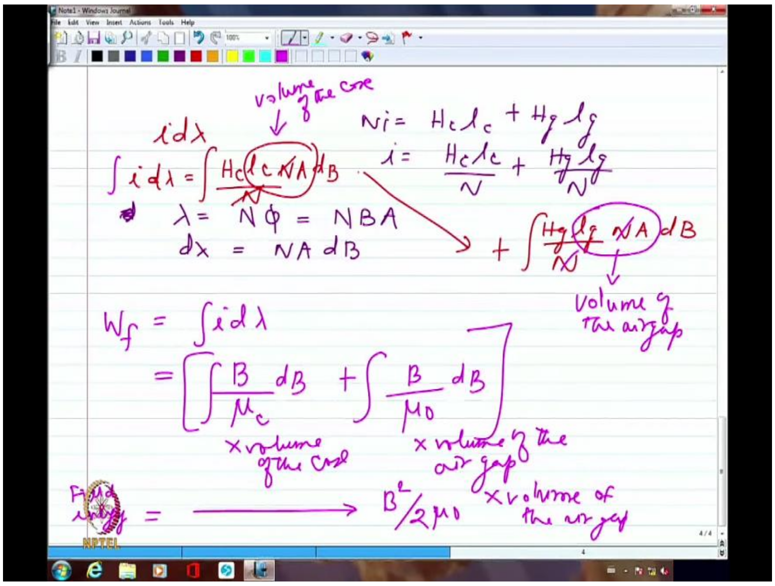

So, I should be able to, now I want to express $i.d\lambda$ in terms of magnetic circuit parameters, that is why I am going through this, okay. So, I can write basically i is equal to because I wrote already $Ni=H_cl_c+H_gl_g$, so I can write $i = \frac{H_C l_C}{N} + \frac{H_g l_g}{N}$. So, I should be able to substitute that i here, so that I do not have to write that i again. But let me write for $d\lambda$, first of all we wrote $\lambda = N\phi$. Let me write this as NBA where area is A is the area of cross-section of the core. I am neglecting fringing, so I am assuming that the area of cross-section is everywhere the same, okay.

So, this is A, so NBA so if I write $d\lambda$ if I assume that the area is a constant it is not having any deformation, NAdB. I should be able to write this, so let me write this $i\,d\lambda$ as first of all i is substituted with $\frac{H_C l_C}{N} d\lambda$ maybe this is NAdB. That is the first portion and another portion is going to be $\frac{H_g l_g}{N}$NAdB.

So, I should be able to write it like this. Let me assume maybe the flux density whatever I am looking at for the core I should be able to write, first of all let me cancel these and A into l c I can write as the volume of the core. And I should be able write similarly this N and this N are cancelled. A Multiplied by Ng, I should be able to write volume of the air gap.

So, I can say w_f which is equal to $\int id\lambda$ will be, in this case will be H_c whatever is the flux density B, divided by I can say probably μ of the core, μ of the core and I should be able to write multiplied by dB probably and or I can retain it as it is H_c but I have just replaced it by

$\frac{B}{\mu_c}$. And the next one I can write it as $\frac{B}{\mu_o}dB$. The whole thing multiplied by of course here I have to multiply this by volume of the core and I have to multiply this by the volume of the air gap.

Now I can definitely write this is $\frac{B^2}{\mu_o}$ when I am actually integrating it over the you know the entire region of the flux density, I should be able to write this as. $\frac{B^2}{2\mu_o} \times \text{volume of the air gap}$. Here I will get maybe $\frac{B^2}{2\mu_C}$ but please note μ_C is going to be much much higher as compared to μ_0. So the field energy associated with the air gap will be much higher as compared to the field energy associated with the iron core because to magnetize the air gap I will require much more amount of you know current and power to be pumped in as compared to what would have happened for the iron core.

Yes, you have to multiply by the volume also but if I look at the overall energy that is associated with the air gap although the volume is really small, generally the energy associated with the air gap is going to be outweighing whatever is the energy associated with the iron core. I agree that the iron core volume is high here, no doubt but because of the fact that the permeability is really small for the air gap as compared to a normal Ferro-magnetic core most of the times we tend to ignore which is not correct if we want correct calculations.

So there are two different kinds of approaches we take when we see that the energy stored in the iron portion is also fairly large. Whereas most of the times in many of the calculations we tend to ignore whatever is the energy stored in the iron portion if it is really negligible and most of the cases it happens to be negligible, that is the reason we neglect it, right. But we have got basically an expression that is $\frac{B^2}{2\mu_0}$ as the energy associated with the air gap provided I am already given the flux density and if I know the volume of the core I will multiply volume of the air gap, I will multiply this by the volume of the air gap.

So this is essentially the field energy associated with the air gap, $id\lambda$ is not really the expression for field energy all the time unless I am looking at the mechanical movement being zero, if it is zero yes, $id\lambda$ can be the expression for the field energy.

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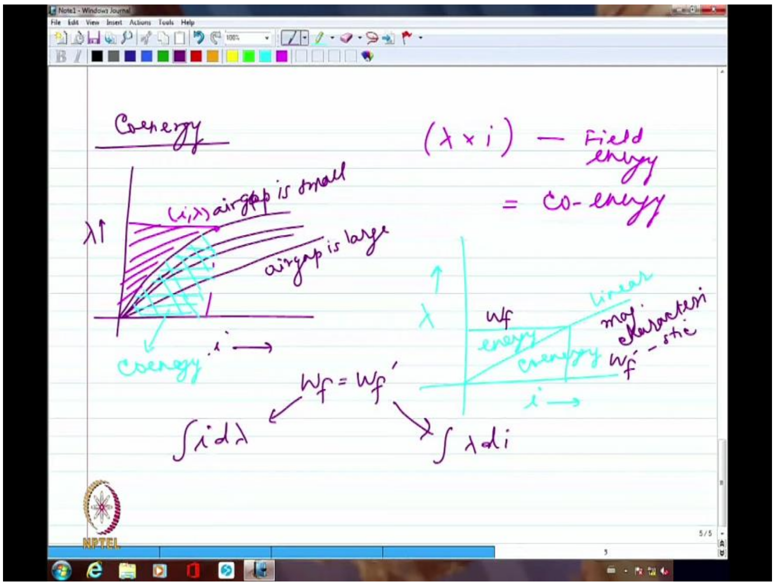

So now that we have got the expression for this field energy, I am going to introduce one more term called coenergy which does not have any physical significance because we are going to use that coenergy also. So let us try to look at what is coenergy. Once we understand field energy, coenergy and what is the electrical input it will be easy for us to derive the expression for the torque or force. That is the reason why I am first introducing these terms and I am exactly following the approach of P C Sen exactly. So please take a look at that if you are still having confusion, it will at least clarify matters to some extent.

So, let us say I am having a magnetization characteristic like this, this clearly indicates that I am drawing the magnetization characteristics for an iron core along with maybe some air gap. If it is only associated with a large amount of air gap it should have been linear. If I reduce the air gap further and further it will go further and further towards non-linearity. So this is air gap is large or primarily we are looking at the air gap, here the air gap is small. And what we are drawing is of course i vs λ, now I have completely switched to λ I am not writing ϕ because I am multiplying that by number of turns all the time.

So this is what is going to be you know the characteristics, whatever I get as field energy I am basically talking about this portion. For a given air gap I call this portion as the field energy okay, whereas whatever is left over so if I actually say λi. That is this is the point where we are going to write this is i, λ that is the point i, λ. So if I multiply i and λ together I get the complete area of the rectangle.

So, $(\lambda i - \text{field energy})$ I call as the coenergy. What I am trying to do is to actually find out the area of the rectangle λi and if $\lambda i - \text{field energy}$ which is actually area above the curve long with the λ axis, that whatever is left over I call that as the coenergy. So in this particular sense I am going to have essentially this portion completely as the coenergy, right.

Please note that whenever I am having non-linearity the coenergy is happens to be greater than the field energy, please note that this is kind of a convex curve so I am going to have this portion which is actually the coenergy, this coenergy. So coenergy happens to be greater than whatever is the field energy. Whereas if I have a linear graph like this, I am going to have basically this as the rectangle and this line whatever I got is actually the you know it is going to be dividing this area exactly into two halves because of which I will have energy whereas this is my coenergy and this is the plot of λ versus i, right and this is a linear curve linear magnetization characteristics.

What I have got is linear magnetization characteristics because of which I am going to have if I call this as w_f if I call this as w_f^1, so $w_f = w_f^1$ if I am talking about a linear magnetization characteristic. So we are deliberately introducing the terminology of coenergy so that we will be able to understand further a movement takes place will we be able to express force or torque in terms of coenergy or energy. That is what we want to check. That is the reason why I have introduced this particular terminology of co-energy.

There is no physical significance of co-energy, but you may try to write that as λdi, just like how you wrote $id\lambda$ in the absence of any movement. We wrote $\int id\lambda$ was actually the field energy, so I would be able to write $\int \lambda di$, that as the coenergy. So, I can write in the absence of any movement again $w_f = \int id\lambda$, $w_f^1 = \int \lambda di$, but we are not talking about any movement so far, fine. Now we are going to migrate to a case where there is a movement.

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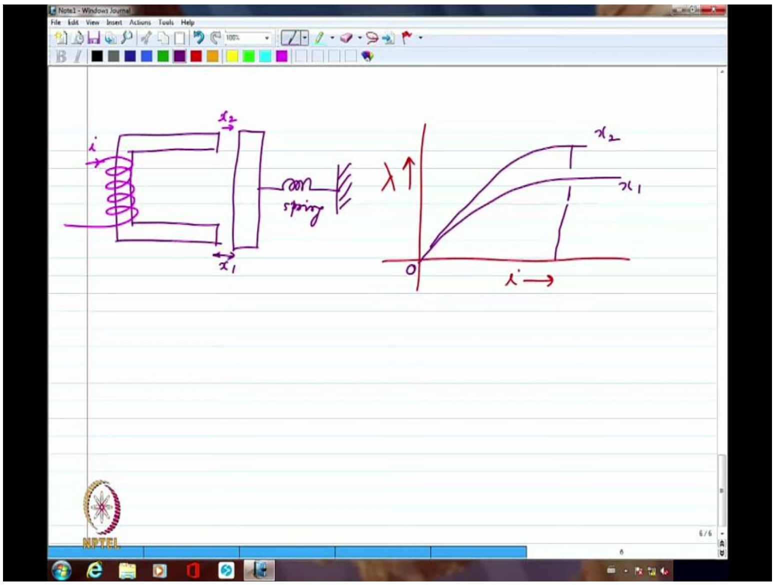

So let us say I take the same structure, so this is a C shaped magnet and I am going to have one more movable part. This movable part is still stationary because of a spring that is attaching it to a frame and let us say maybe I have this distance to be x_1, okay. Now I am going to pass a current here, so let us say I am going to pass a current here from i because of which some movement is taking place but still the spring is holding it pretty tightly. So from x_1 maybe it is moving to a distance of x_2 which is less than the original x_1, so it has been attracted, still it has not been hit the next one the actual C shaped magnet, so it is still in the process of moving. So I probably have this moving up to a distance x_2. Originally, it was x_1 now it is x_2, so it has moved slightly towards whatever is actually my C shaped frame C shaped magnet.

So if I try to actually draw, again the magnetization characteristics for these two distances. This is i this is λ; I am going to have actually the first magnetization characteristics probably like this. The second magnetization characteristics will be somewhat like this. So, this is corresponding to x_1 this is corresponding to x_2 because when the distance decreases, I should have definitely more magnetic field or more magnetic flux being there in the magnetic circuit for sure because the reluctance has decreased.

So this is what is going to be the case, so if I say this is O let me probably write you know at a particular current, at a particular current i. I am not changing the voltage so if I actually make the movement pretty slowly or the movement is happening very slowly, at every point the current would have reached its steady state value which is $\frac{V}{R}$ whatever is the resistance of the coil. Please understand definitely there will be transience in between because the inductance is changing, as your gap changes the inductance will change. So at every point you are going to have a transient response, you guys have studied RL circuit response. If inductance is changing the current will change but steady state current will be $\frac{V}{R}$.