Electrical Machines - I
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Lecture - 11
Core Loss - Eddy Current Loss

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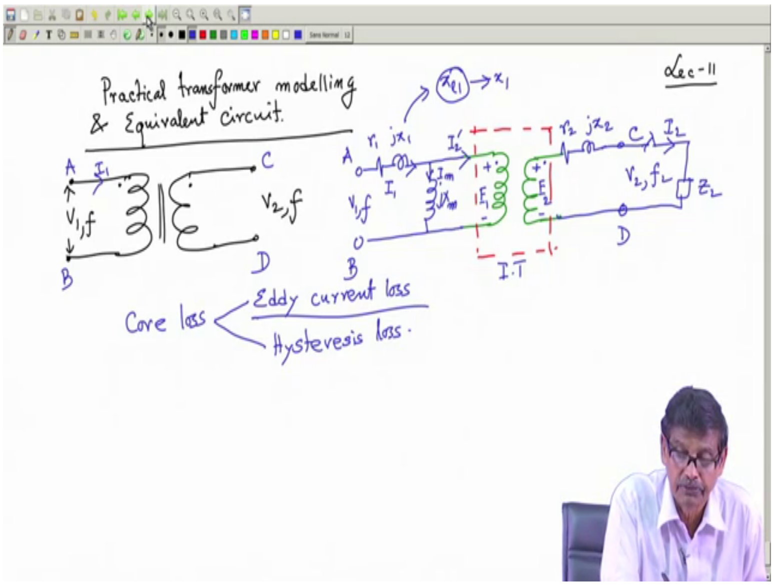

Welcome to lecture 11 on Electrical Machines-I and we have started discussing about modeling a practical transformer. Earlier we started with ideal transformer which means that windings has got no resistances, leakage flux is negligibly small, there is no core loss and then it was so easy only thing when you connect a load on the secondary side there will be a reflected current and that will decides the decide the primary current. Similarly we found out what will be the equivalent circuit refer to the source side that is primary side and to the refer to the load side or secondary side.

Then we started discussing about practical transformer. I first told that let us first assume that only there exists finite magnetizing current, it is not fully practical transformer, but only a transformer having a finite magnetizing current, then that can be taken in to account by connecting a an external considering an external resistance to be connected across the primary side of the ideal transformer xm we called it magnetizing reactance.

Then we considered resistance as well as leakage flux and finally, last time we obtained the equivalent circuit of a practical transformer as, this is suppose the practical transformer where you apply voltage V 1 and frequency f, then these are the terminal voltages you get at the terminal V 2 and f same frequency voltage and these are dots and. So, with respect to this two terminals which are available to me I can model it as an ideal transformer ok. For example, you will model it by an ideal transformer like this, we will assume this is the ideal transformer and that is this is ideal transformer.

And then you have connected some resistance and leakage reactance of primary and here is your magnetizing reactance jxm and then here also the secondary winding resistance r 2 and j x 2 and this is r 1 jx 1. To simplified matter I am using now a I am replacing xl 1. So, which is leakage reactance standing for I will simply write it by x 1 in order to always writing l.

So, x 1 x 2 small letters I have used because there values are small leakage flux is small and this portion is ideal transformer. And this voltage mind you these are the two terminals if you call it A B the terminals of the practical transformer C D, then here is your a, here is your B, here is your C, here is your D and within the transformer it can be then thought of as if there is an ideal transformer with this external parameters I have connected.

And then we have seen how to this is V 1 f 1 and this is V 2 f 2 what is this voltage? This is your E 1 and this is your E 2 mind you there is now distinction between E 2 and V 2 similarly with E 1 and V 1 these two are dots. And if you connect load here, then this current is I 2 feather current this is z 2 and if this ideal transformer we know if it carries current I 2 coming out from the dot, immediately on the primary of the ideal transformer this is the primary of the idea I 2 dash 2 will come and this is magnetizing current I m.

Magnetizing current is produced by E 1 and then to this the this current is the total current which will be this current. Because we I cannot go inside the practical transformer to see all this things this things are not there in fact, it is my way of modeling so, that everything matches it predicts correctly. So, this is I 1 this is I 2 dashed this is I m and this is your I 2 and then we drew the feather diagram which I am not once again drawing.

Now, only one thing is now left for the which exists in a practical transformer, but we have not taken note of that that is called the core loss; core loss. And core loss has two components; one is called eddy current loss; eddy current loss and the other is called hysteresis loss. We will first see why there will be eddy current loss and why there will be hysteresis loss? We try to understand on what factors this losses depend and then how to take that loss into account by incorporating a resistance in this equivalent circuit? That is the goal because after all something becoming the as I told you this core of the transformer will become hot, whenever there will be a changing magnetic field perpendicular to the area of cross section exists in the core.

So, this will be the topic of study today. So, first we take the case of eddy current loss that is what we will do. First we will understand the eddy current loss, then we will try to impose it on a; mind you in a transformer the this was the case.

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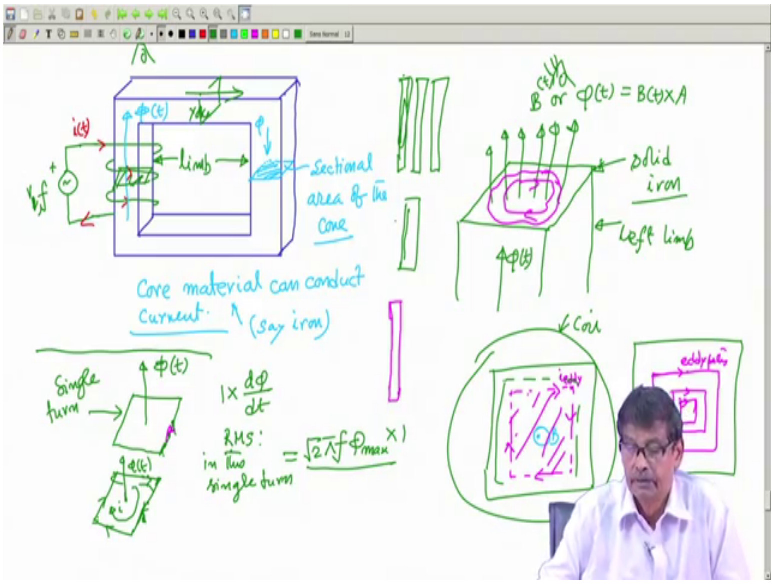

Here is the magnetic material and this material has got a you know a depth in three dimension I am trying to draw, this is the core material and there will be coils here it goes like this I am so, sorry. Anyway I will take, this one I will take it.

So, this is the coil and here we are connecting an AC source that is the thing. Secondary coil I am not drawing to begin with. [FL] If this is excited from an AC voltage source V 1 with frequency f then we know there will be current drawn from the supply which will be flowing like this. Of course, this current will be time varying time varying current lagging the approximately the voltage by 90 degree and so on.

But none the less there will be fluxes produced in the core that is phi t that two will be time varying ok. And the cross sectional area of the core is a rectangle that is the this areas, this is the area and this area let us assume is constant throughout the core. So, flux will be flowing perpendicular to the area any area you consider that flux is crossing perpendicular to that area, this is called core area sectional area of the core this is the thing.

Mind you core is a say ferromagnetic material made of iron and it is solid like this and this core material is also conducting. Core material can conduct electricity because iron not a good material like your copper, but it also carries current it can allow current to flow core material can conduct current ok. Core material means say iron say iron or ferromagnetic material. So, they are good conductor of electricity.

Now, if you look at this cross sectional area the left hand column, I will draw it separately in this way. This is the sectional area and here is the this side I am drawing understand this is the thing. What I told through this flux lines are coming now, may flux lines see these are B or phi. B is also function of time because phi t is after all B t into the cross sectional area A this is the cross sectional area.

Now, so, there is a time varying flux sometimes flux will go left hand side incidentally, the this vertical part of this core material they are called limb. This is also limb and this horizontal portions are called yoke. So, in the limbs this is left limb, left limb I have drawn and this winding I am not drawing it is there. So, I have cut it and trying to figure out what is happening how flux limbs are flowing perpendicular to this cross sectional area. So, this area is here I have the sectional area, got the idea. So, this is this.

Now, the moment there is a time varying flux, we know that if you have a closed turn. Suppose a rectangular turn you imagine and there is a perpendicular to this there is a time varying flux phi t. Suppose a single turn you considered single turn of conducting material single turn and suppose you have a time varying flux perpendicular to its area.

Then there will be induced voltage in this turn, what will be the value of this induced voltage? Number of turns that is 1 suppose single turn into d phi dt and what you what will be the RMS voltage? RMS voltage in the single turn; in the single turn will be equal to root 2 pi f phi max instead of n 1 it is 1. See this turn is not this turn which makes the coil what I am telling, I am just considering a separate problem all together suppose there is a single turn like this and you have a induced volt flux which is crossing this as coil area in a perpendicular direction, then the induced voltage is n d phi dt and its RMS value will be just like a transformer and that value will be root of pi f phi max into 1.

And if this coil is closed; you first imagine as if this coil I have not they I have connected a switch suppose then across this coil 2 suppose it is opened that is let me do it like this suppose there a imagine there is a. So, there is a flux here. So, between this two terminals then and RMS voltage exist of this magnitude. Therefore, if the this turn is closed on to itself that is this is closed, then I will say there was an induced voltage and now this induced voltage will drive a current in this loop why not?

Because it has become a seat of mf as it happens in any turn in the primary and secondary coil and it is if it is closed then I will say this RMS voltage whatever is induced here that divided by the resistance of this turn will given the current. And that current 2 will be time varying AC current will be flowing what will be the direction of the current? If suppose phi t is going up and increasing then from Lenz's law, I know the direction of the induced current in this loop should be such that it will oppose this increase in flux that is it will be by it went on like this. So, this was my turn. So, the direction of the current has to be like this.

Who will drive this current? This induced voltage and the circuit is already closed if it is a closed loop and this current has to be like this so, that it can oppose the increase in phi 2 for which the induced voltage is there that was the cause. So, that will be the introduction of the current it will try to oppose the cause.

And if I want to know what will be the if the current flows here, then there will be power loss in this loop and that power loss will be I square into resistance of the path if you neglected inductance of this loop a single turn inductance is neglected. In fact, to be very correct I should say induced voltage divided by the impedance of the turn that decides the current, but I am telling neglect the inductance of this coil why? Because single turn inductance is proportional to n square and so on let us neglect.

So, that is this is a information which is true when you are studying transformer or not. The problem I have stated here a single rectangular turns and let us imagine there is a time varying flux going up and down crossing this coil, then there will be RMS voltage induced single turn that is why n is 1 and this voltage will drive a current, but direction of the current is you have to apply Lenz's law arguing that let us imagine that flux is suppose increasing in the upward direction, then the current induced in this loop that is this current must flow in this direction. So, that the it will try to oppose the very cause for which it is drew that is the Lenz's law.

[FL] With this background let us now come here in the transformer core what is happening. In the transformer core as I told you this it magnetizing current has produced this phi t here and imagine any section either here or there where not. And every section the same flux is crossing and it is a solid piece of iron suppose solid iron.

Now, the question is where this fits this thing here it is like this. If I simply draw this way try to understand first this is the suppose I am looking from the top, this thing I am looking from the top, this is the section the flux lines are coming out. So, flux lines are suppose I this is the direction of B, I have just shown one line B is coming out and if it is coming out and it is time varying doing going up and down.

Now, what you do, you consider a closed path like this. So, this closed path, I can imagine there is a single turn here through which there is a time varying flux like this therefore, in this path in this loop which I have considered there will be an induced voltage whose value will be root 2 pi f phi max enclosed by this area, not this full phi max.

If you consider a single loop like this, then you have to take this area and then calculate what is the phi max there into 1 and this switch is already closed you have nothing to do imagine any closed path through this time varying flux perpendicular to this area and there will be induced voltage and there will be if it is going up your eddy current loss direction of eddy current in the single path consider should be like this, because your B is coming out and it will go inside because of this induced. It will try to oppose that cause B was increasing upward direction. So, it will try to oppose the cause your and this current is called i eddy eddy current.

Now, the big question is this thing does it happen to this selected so, called closed loop? No it will happened in all the possible suppose this is the cross sectional area, you can select a path like this, you can select a path like this are you getting these are paths of eddy current eddy paths.

You can select a path like this any closed path you imagine there will be induced voltage in that loop. You can figure out how much it will be and that divided by the resistance of this path will give me the current in this loop, next loop, next loop I mean therefore, this currents eddy currents will be I cannot avoid if it is a solid piece of iron and if we are claiming that it is a time varying field exist here perpendicular to this cross sectional area, then eddy currents will be flowing.

It is not in the coil induced voltage in the core and there will be eddy currents and because of that this each of this loop current, i square into r of this path i square into r of this path. So, if it is a solid piece of iron you will find it has become hot if you touch this one with your hand core material if you touch it will become hot.

Therefore, there will be power loss, where the power loss takes place in the transformer in the winding resistance coil resistances r 1 r 2 whenever they will carry current there will be power loss taking place that is incidentally called copper loss, that will come discuss in detail.

But what I am telling if you touch the core it will become hot why it will become hot? There is no electrical connection between the coil and the core which is made of say iron, solid iron the reason one of the reasons will be because of this, because through the sectional area a time varying flux exist and you choose any conceivable closed path there will be induced voltage and eddy currents. It may not be rectangular any arbitrary path loop now after looking at it if I say the path is like this will there be some eddy current like this? Yes it will be.

Now, we shall try to understand what should I do to reduce this loss. Now mathematics first physically I mean try to understand why this eddy current loss occurs because so much sectional area, so many area it looks like it will be very difficult to calculate the eddy current loss it is not. In fact, it is not so, easy you have to write field equation this that solve the current eddy currents I am try to estimate the eddy current power loss that we have to estimate.

But I can understand by apply a common sense that this eddy losses can be reduced if I instead of using a solid block of iron like this what I will do? I will use thin plates. Suppose I say there is a iron plates I am drawing it still thicker this is I will go to next page.

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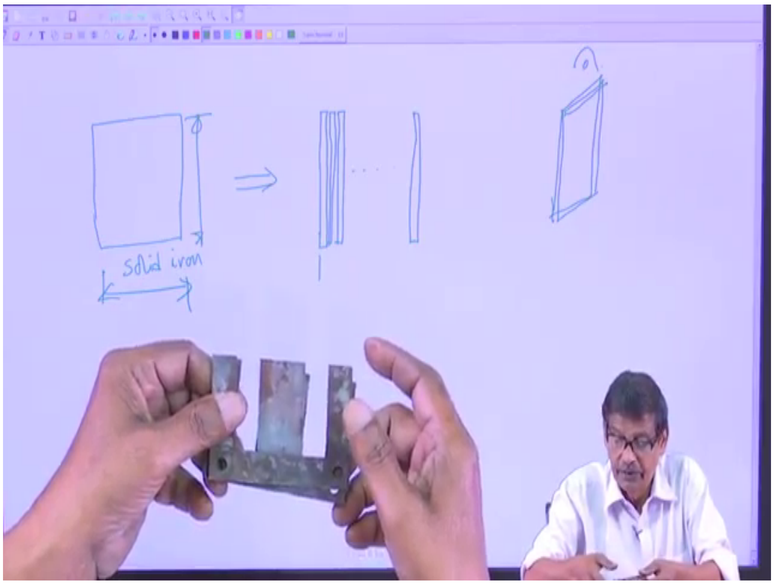

What I will do is this, this core material the this was the solid sectional area of the core this is solid iron. Instead of doing like this what I can do? I will take plates thinner plates and keep them side by side thin plates are you with me? That is the plates are like this you have you chop this thing with it cutting tools slices like your pages of book thickness of the book will be achieved.

So, you this is the width of this iron, this was the length whatever it is sectional area, the same sectional area can be realized by instead of using a solid block of iron thinner plates, that is you take one plate here, take another plate there and stack them together clam them to get I think you have got the idea.

So, the sectional area from the top if you look, it will look like this thin plates I will show you. Suppose this is a thinner plates like this magnetic circuit, there able to see no thinner plates. You iron plates and you put another like this I have brought only 2, you can put several such plates to have a height here that is the width of this magnetic circuit this portion.

So, many thinner plates you use of small thicknesses and stack them together instead of using a solid iron. But then not only that also what you do that is very important step. You simply it is a solid iron you simply cut it in different pieces stag them together no not like that then what you have to do is you have to give a varnish coating to each plate give a varnish insulation paint it varnish insulation.

So, that each plate is electrically insulated from the next plate. Although they are side by side kept like this the one plate, this is another plates you place it, but between these two plates there will be no current can flow because this plate is insulated from this plate while you are putting. So, each plate has its own electrical identity, it is not dictated by the others.

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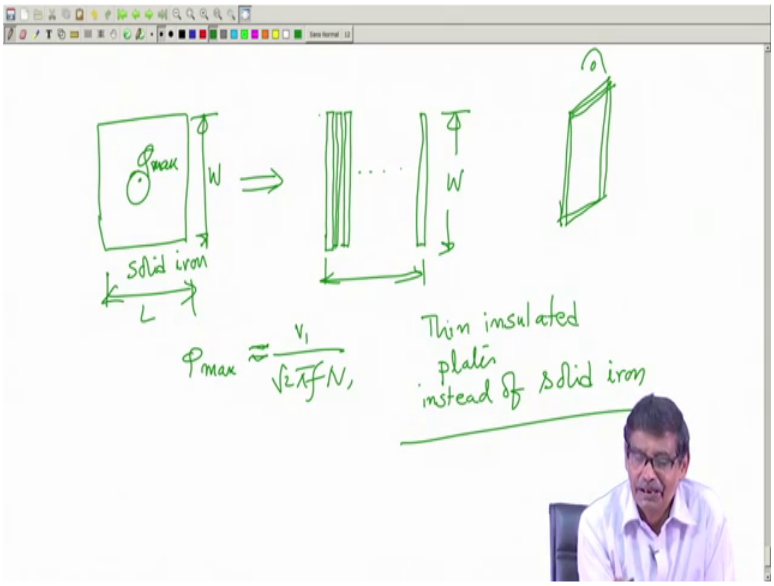

So, the these one this length and this is the width suppose this is the length, this is the width of this area, this is the width I can realize that one like this that area will be realized and I kept several thin plates together. And then where is your coil in this previous diagram if you see while where is the coil if I write like this the sectional view, where is the coil? Coil must be shown here this coil if you look from the top this is this one. So, coil was here is not coil. I think you have got the idea this coil this primary coil it should be shown around it creates flux like that.

Anyway; so, this will be the RMS induced voltage where that fellow has gone next page this was the thing. Therefore, the coil is here still total flux phi max is primarily decided as you know is V 1 by root 2 pi f N 1 is not approximately at least this is phi max if you give. So, phi max is perpendicular to the sectional area coil is here, which has created this phi max sin omega t and it was doing like this here also phi max was in this direction here also phi max in this direction ok.

Now, what is the motivation of using this number of plates? Motivation is if it is a solid piece of iron the area you can have many number of closed path as I told you and each one of them is carrying eddy current loss, eddy current loss will be created losses will be more.

So, by common sense then it looks like instead of using a solid block of iron I will now do it one this page so, that you appreciate the point. Instead of using a solid piece of iron if I use thinner plates like this, I am showing the gap larger so, that we understand the point. So, this is a plate and there is phi perpendicular to this there will be eddy currents now, but if you make thinner plates the eddy current paths or number of paths available will become less for each of the plates. Getting a plate is electrically insulated from the other. So, if you want to concentrate on a single plate you will see in this plate the eddy current loss will be less because of the thing.

Therefore we, will use cannot the two path actually (Refer Time: 35:24) law this plates to make a instead of using a solid iron better use thin plates thin insulated plates instead of solid iron it will lesser than thing very much because the each plate is electrically insulated from each other and eddy current will a.

In fact, if I say this thickness of each plate is. So, small you will not find any eddy path existing of course, that is not the case we will discuss it in the next class this is interesting and try to understand. My our goal will be to find out an approximate expression of this eddy current loss and what factors it depends.

Thank you.