Electrical Machines
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Lecture 5
Transformers -AMP -Turn Balance, Ideal and Practical Transformers

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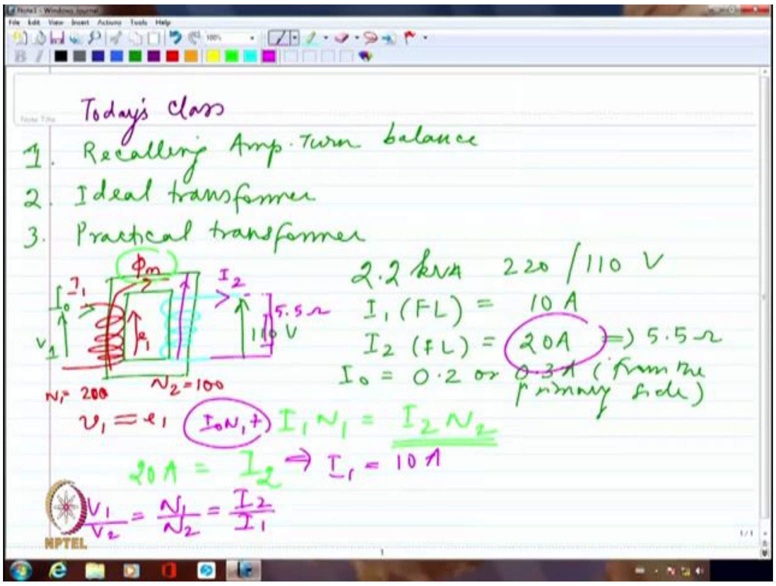

We had been discussing basic transformer action, we actually said that when I am having a transformer which is represented basically by a ferromagnetic core and on one side I have the primary winding and on the other side I have the secondary winding, and in the primary winding I am connecting a voltage source which is having a value of V_1, this may draw a very small current which I am calling as I_0 that is the no load current.

That is the no load current which is establishing the flux in the core and the core is made up of ferromagnetic material the permeability is high because of the which I_0 is going to be low, let's take for example some practical values, let's say I am going to take a 2.2 KVA transformer 220 by 110 V. So the primary side current full load current or rated current will be 2200 divided by 220 which is about 10 A and secondary current, full-load will be 110 divided by 20 A, 2200 divided by 110 which will be 20 A, so I should say in all probability I should be connecting a load of 5.5 Ω on the secondary side, 110 divided by 5.5 will give me 20 A of current.

So, if I am looking at the no load condition, no load condition current will be of the order of 0.2 or 0.3 A nothing more than that from the primary side I am talking about the primary side. So, from the primary side this is all will be the current. When this flux is established, I am going to have the secondary voltage which will be induced across this winding which will amount to 110 V on open circuit condition.

Now I am going to connect the load here, like this. So, this is 5.5 Ω I am connecting 5.5 Ω load, so what is going to happen is, a current will flow here which will be corresponding to I_2, which we wrote as 20 A if am connecting 5.5 Ω. So this 20 A will create definitely a flux in the core, it is not going to keep quiet, it is going to create a flux in the core but this flux in the core should oppose the original flux, if it had been aiding the original flux that will go to extremely large values and $\frac{d\phi}{dt}$ will also reach literally infinity.

So obviously by Lenz's law this has to oppose the original flux. The original flux was in this direction. It was actually going like this, this is what was ϕ_m or the mutual flux between the primary and secondary coils. Now the new flux that has come up will oppose this and because the ampere turns off this new flux will be quite high. Originally, I had only 0.2 A of current with N_1, whatever be the number of turns N_1 be.

Let us say maybe I had 200 turns here and 100 turns here, so N_1 equal to 200, N_2 equal to 100 and just taking it like this. So, I am going to have an ampere turn which is way too high as compared to the original ampere turn, so it will essentially kill that. If that is being killed the entire transformer action will cease to exist, so what is going to happen is, if the transformer action ceases to exist, I would have had definitely an e_1 induced here as well that e_1 will also collapse.

If e_1 collapses I will have definitely a huge current that will be flowing into the primary winding because originally what was running was V_1 minus e_1 divided by the resistance of the primary coil that is what was actually making the current go, Originally V_1 was equal to e_1 especially under no load condition there is no drop also because the current was only 0.3 ampere.

So the drop was negligible, so I was having basically V_1 is equal to e_1 but now if the flux collapses even for a fraction of a microsecond or millisecond I am going to have definitely the emf also collapsing huge current will flow, so that current what is being established in the primary will be rather gushing into such a value in such a way that you are going to have the ampere turns created by the secondary will be completely balanced by the ampere turns that have come up in the primary suddenly.

So, I am essentially going to have I_1, originally it was I_0, now I am going to have I_1 and I am going to have essentially I_1N_1 is equal to I_2N_2. I_2N_2 was the new ampere turns that were created because of the load current and I_1N_1 is the current where the primary has essentially drawn excessive amount of current to make sure that I_2N_2 is nullified. So I_1N_1 and I_2N_2 are equal to each other but in opposite directions because of which I am going to have only the original flux which was phi m that will prevail, that will be maintained.

So, the transformer action is maintained because of the mutual flux which was originally established with the help of the no load current. After that whatever is the current drawn due to load being included that will always be nullified by whatever is the current that is drawn from the primary to make sure that the ampere turn is quelled completely that is what is going to be happening.

So, if I look at the values, I am going to have 20 A as the secondary side current. So corresponding primary side current will be 10 A if I look at the total current of the primary side, I should have this 10 A added to the 0.3 or 0.2 ampere with their respect to power factors as well. So definitely it will not be even 10.2 or 10.3, it will be $(10)^2 + (0.2)^2$ along with their own power factor angles and so on and so forth that is what will be the total current and the total current definitely will be very close to 10.

So, I can literally neglect I_0 that is the reason why, if I have to be really accurate I should say I_2, I_1N_1+I_0N1 as well, I should have said this but I am essentially neglecting this because when I add I_0 and I_1 along with their phase angles the overall current what I get will be almost equal to I_1 itself, it is not going to be any different from that of I_1 which we will see eventually when we are drawing the phaser diagram.

So, the ampere turn balance essentially is the major underlying principle of transformer action we will revisit this for every kind of transformer that we are going to talk about. So, we have seen basically that the transformer is going to follow $\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$ this is a relationship that is going to be followed by the transformer.

Let us start off with ideal transformer action and then let us go over to the actual practical transformer.

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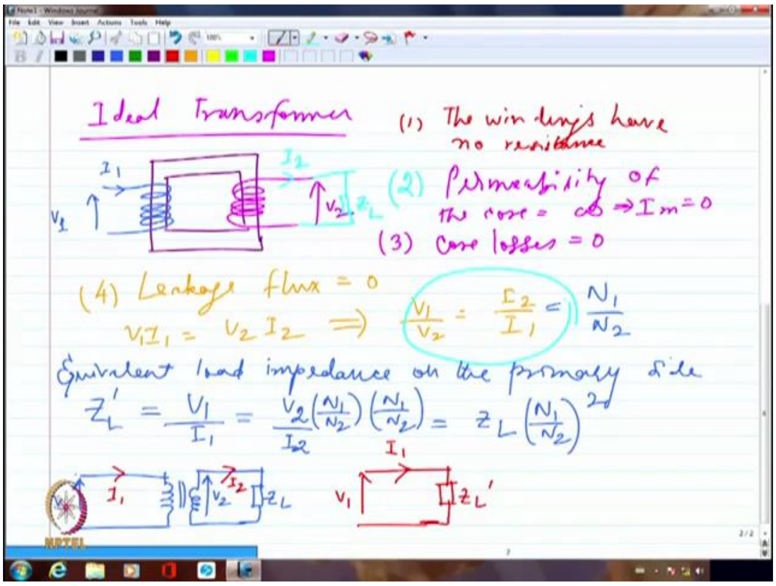

So, in an ideal transformer, I am going to again specify that by a core and then I am going to have one winding here which is the primary and am going to apply voltage of V_1 here and I_1 is flowing here after the load is connected of course and I am going to have the secondary winding here and I am going to have V_2 as a terminal voltage. I have still not shown the load. So, we are going to have basically in an ideal transformer we are going to neglect a few things.

What are all the exemptions that we are going to make is, because obviously practical transformer will differ from this. So, the first and foremost assumption we are going to make is the windings have no resistance. So, we are going to assume that the conductors are ideal, so I am not going to have any voltage drop inside those winding resistances. The resistances are assumed to be 0. So, I am going to assume that the windings have no resistance.

The second assumption that I am going to make is that if I want to establish a flux in the transformer, I will require literally 0 current, if the permeability is infinity. So, I am going to assume that the permeability is infinity. So, permeability of the core is infinity. Third assumption that I am going to make is that the core is not going to have any losses, so if I say permeability is infinity very clearly, I am going to have the magnetizing current equal to 0, this is implied.

I am not going to draw any current to magnetize the core or establish the flux. So, I am assuming that magnetizing current is 0. The third assumption I am making is the core losses are 0. I am not going to have any losses in the core and the last assumption that I am going to make is, whatever is the flux established that is going to completely confined itself to the core that means nothing is going to flow through the air surrounding it, so whatever flux links with the primary will always linked with the secondary.

So, leakage is 0. I don't have any leakage at all, if I assume that there is no resistance and there are no core losses very clearly I am going to have whatever is the input power is equal to the output power, so I should be able to write basically $V_1I_1 = V_2I_2$. So this is one way of saying V_1 by V_2 equal to I_2 by I_1 but definitely it is not as enlightening as what we talked about in the case of ampere turn values because the transfer must normally have, as high efficiency as 98% or 99% in many cases which means I can say almost all the input power is converted into output power.

So, which means the assumptions what we have made as resistance is negligible or very small is true, no doubt but it is not 0, definitely it is not 0, that is the reason why you are getting the efficiency to be 98% or 99% otherwise you should have had the efficiency to be hundred percent, Now let us say I have connected a resistance here or impedance, let me call this as Z_L, so I have connected a load impedance of Z_L.

When I connect the load impedance of Z_L. This is going to probably draw a current of let us say I_2, Now I can say the power on the secondary side is V_2I_2 whatever is $\cos\phi_2$, if I say Z_2 is purely resistive I can directly say V_2I_2 is the power and V_2I_2 equal to V_1I_1 if I neglect all the losses from which I can definitely say this is true. Now I would like to represent this Z_L on the primary side or I want to transfer the impedance from the secondary side to the primary side.

So, if I want to find out what is the equivalent load impedance on the primary side, so I want to transfer the impedance, so I have to see how I do it. So, I want to see what is the load on the primary side? For that what I have to do is, let me call that as Z_L' probably because Z_L is the actual impedance connected on the secondary side, Z_L' is the equivalent impedance. I am visualizing from the primary side that should be equal to $\frac{V_1}{I_1}$. Only then I will call it as the equivalent impedance as I visualize from the primary side.

But V_1, we wrote already $\frac{V_1}{V_2} = \frac{N_1}{N_2}$, so I should be able to write this $V_1 = V_2\frac{N_1}{N_2}$ And similarly I can write this I_1 in terms of I_2, so I should be able to write this as $I_1 = \frac{I_2}{(\frac{N_1}{N_2})}$, so I can say

$I_2(\frac{N_1}{N_2})$ I am taking it here now $\frac{V_2}{I_2}$ is actually my Z_L. That is what we wrote earlier, $\frac{V_2}{I_2} = Z_L$, so I should be able to write $Z_L(\frac{N_1}{N_2})^2 = Z_L'$. So if I represent the load impedance connected on the secondary side of the transformer from the primary side, I have visualized from the primary side, I have to essentially multiply that by the turns ratio square and to whichever side I am transferring it that number of turns should come in the numerator, the other one should come in the denominator, you can remember it that way.

Basically we are looking at the impedance being transferred from one side to the other side to whichever side the destination side should be coming on the numerator, the number of turns of the destination side should come on the numerator and from where I am transferring should come on the denominator, so I should have $(\frac{N_1}{N_2})^2$ as the transfer parameter when I am trying to transfer the impedance from the secondary side into the primary side.

So I should be able to draw it somewhat like this, if this is my primary side, this is what was V_1, originally I had one winding here, another winding here and here is V_2 and I had connected Z_L here this is what was the representation of the transformer. Now I should be able to write this directly as though I just have V_1 applied here, I don't have to represent them by two different windings and so on and so forth.

I can simply draw an impedance here which is Z_L' and I am going to have a current of I_1 flowing here, whereas here of course it was I_2 and here it was I_1, this is how it was, so we have just represented this by a single circuit and this is definitely easier for applying KVL, KCl and so on that the reason we wanted eliminate this magnetically coupled representation.

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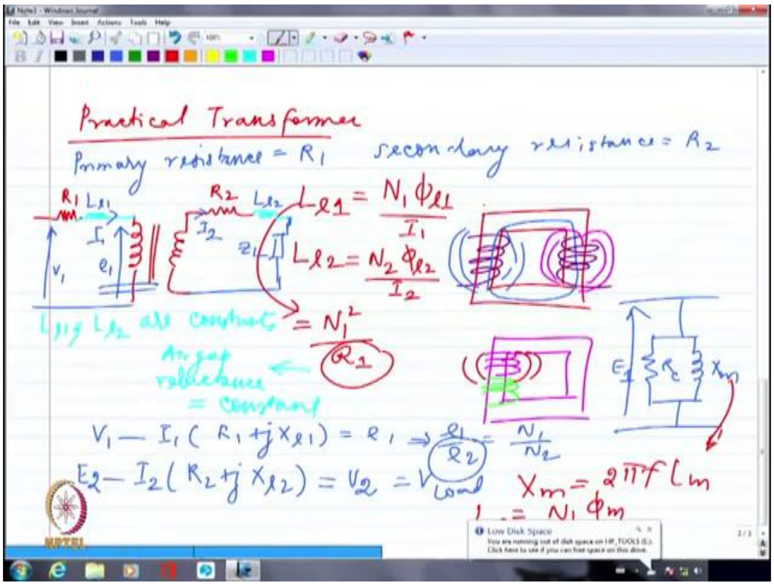

Now, let us try to take a look at a practical transformer. We said we are neglecting the resistance in the primary and secondary windings. The first and foremost thing we are going to do is to include, so let us say primary winding resistance, let me take that as some R_1 and secondary resistance I am going to take as R_2. So, I have taken both the resistances. Now the next thing that we need to consider is, so let me look at the transformer again. I have here is the winding and I have a resistance here which is R_1.

Similarly, I have secondary here and I have a resistance of R_2 we have still not completed the circuit. Then I have the flux established as I told you earlier when we were discussing the magnetic circuit there will be definitely say thousands of lines that are flowing through the electromagnetic core. At least one or two will escape and they will go through the air gap path. So, if I am saying that I have probably this as a core and I have a got primary winding here and the secondary winding here. Although most of the flux will go like this may be, one or two of flux lines will go like this and go like this. These are leakage flux lines as far as the primary is concerned.

Similarly, I will have at least some flux lines go here like this and go here like this. So, these are going to be the leakage flux lines corresponding to the secondary. Practically, we would never ever construct the transformer like this the primary on one side and secondary on the other side. Even if I am saying that this is what is my core and I am going to have probably the primary here and one more secondary coming up here and so on. Still the lines of flux can go only through this it does not have to link the secondary who knows, in which case there will be still some amount of leakage flux.

But in general, what I can say is the leakage is invariably through the air path. It is hardly ever through the iron part it is going to be always through the air part, because it is through the air path definitely it is going to cause some self-induced EMF that self-induced EMF will account for some kind of inductive drop. So, I would always represent the voltage that is lost the self-induced EMF that is lost. In the form of leakage parameter, I would rather represent that by an inductance drop which is known as the leakage inductance drop or leakage reactance drop.

So, if I may call this leakage reactance for the primary as L_{l1} leakage similarly L_{l2} is the leakage corresponding to the secondary side. I can definitely say that this L_{l1} will be corresponding to the number of turns $\frac{N\phi}{I}$ is inductance. So, I can say this is $\frac{N_1\phi_{21}}{I_1}$ or small i_1.

Similarly, I should be able to say this as $\frac{N_1\phi_{22}}{I_1}$ or small i_2 instantaneously if I try to calculate. So this is going to be my leakage inductances one thing I want you to realize is I can represent the same thing by $\frac{N^2}{Reluctance}$ as well we derived one expression for inductance. So, I should be able to write this as $\frac{N_1^2}{R_1}$ of the primary air gap path.

Similarly, for the other case it will be $\frac{N_2^2}{R_2}$ where R2 will correspond to the secondary air gap reluctance path. And please remember that this reluctance is along the air gap, so that is not going to change. If the reluctance in the iron core we are considering the permeability keeps on changing, depending upon at what portion of the magnetisation characteristics we are operating the machine.

So, the permeability is not a constant in the case of the ferromagnetic core so inductance will not be a constant depending upon the magnetisation characteristic portion where we are operating. So, if I considered the air gap this is essentially air gap reluctance this is air gap reluctance. So, I am essentially going to have this as a constant this will not change. So, if I am assuming this to be a constant. I can say the leakage inductance is also fairly a constant, it is not going to change, the leakage inductance will not change in the case of a transformer.

So I would say that L_{l1} and L_{l2} they are not equal to each other. L_{l1}, L_{l2} they need not be equal to each other or constants as far as the transformer is concerned. So they can be represented as inductances which are coming in series with this winding. Similarly, I can put one more inductance in series on the other side.

Let me call this as L_{l1} and let me call this as L_{l2}, Now of course I will be applying a voltage V_1 here and I will be connecting a load Z_L here. Now whatever is available as V_1 I am going to say that if this is drawing a current of I_2, this may be a current corresponds to I_1 which will be actually governed by the turn's ratio. I_1 should be actually governed by the turn's ratio because $\frac{I_1}{I_2} = \frac{N_1}{N_2}$ .Now if this is I_1, I am going to have $V_1 - I_1(R_1 + jX_{l1})$ that is what is going to be available as V_1 here. So, what is available as the induced EMF which is actually giving me the relationship finally $\frac{e_1}{e_2} = \frac{N_1}{N_2}$. So even I am talking about as the available EMF across the winding, which will be actually inducing a secondary EMF. So I am going to write $\frac{e_1}{e_2} = \frac{N_1}{N_2}$. If I am writing in terms of even instantaneous voltages.

So, I would definitely have only e_1 available across the primary winding which will be instrumental in inducing a secondary EMF of e_2. So, the magnetic flux that is established in the core will correspond to e_1 and not correspond to V_1. V_1 is the applied voltage; e_1 is the voltage that is induced within the primary coil which will be linking with the secondary coil as well.

So obviously, e_1 will be less than V_1 and it will be essentially because of the drop that occurs in the leakage reactance and the resistance of primary winding. Now this is essentially the voltage that is available in the secondary e_2. So, from e_2 again I should have $I_2(R_2 + jX_{l2})$ and rest of what is available will be the terminal voltage. So, I am going to have the terminal voltage V_2 or what is available across the load, this is also V_{Load}. The same voltage is V_{Load}.

V_{Load} clearly is less than V_2. So, I have two sets of drops voltage drops, one is in the primary resistance in the leakage reactance, another one is secondary resistance and leakage reactance. Only after both this drop whatever is available goes to the load how much ever negligible it may be but when we actually calculate this for thousands of amperes of current, although the resistance may be only 0.1 Ω or 0.01 Ω, still it adds up and it comes to somewhat not such a negligible value so we have to take care of that.

Now that we have said that this e_1, which is corresponding to the flux, established that flux is the one which causes the core losses and the flux, is established because of the magnetising current, which have flown even under no-load condition. So, I have to represent them as well. So those will be represented just like what we did in the case of magnetic circuit analysis for sinusoidal excitation.

So please recall that and for that how we represented was to have a resistance and the magnetising reactance which would come parallel with each other for whatever is the voltage that is coming up across this and a voltage that is coming up in this case is e_1 and not V_1 that is not V_1 that is e_1 because the flux is established the mutual flux is established corresponding to the self-induced EMF within the primary coil which is linking with the secondary coil as well.

The leakage definitely does not link with the secondary coil so I have to necessarily subtract R_1 and X_{l1} drop before I really say that this is what is established in the EMF in the primary, which is linking with the secondary. So this value of voltage will be e_1. This resistance what I am showing as RC is a fictitious resistance, you cannot put a multi-meter and measure the core resistance and say that is what RC is no, not at all. This is essentially due to hysteresis losses and Eddy current losses that take place within the core so if that is so many watts, X watts or Y watts.

We are essentially trying to negotiate or ultimately arrive at some value of resistance, which would representing this amount of loss. So this is the fictitious resistance and similarly this reactance is also a fictitious reactance.

So if I say this $X_m = 2\pi f L_m$. That is what I would say as X_m. Now L_m can also be represented by $\frac{N_1 \phi_m}{I_m}$. I hope you understand I can definitely write this as because this was the original flux established when magnetising current itself was flowing. It is not after I_2 or I_1 have come into picture. So, I should be able to write this $L_m = \frac{N_1 \phi_m}{I_m}$ or the magnetising current.

And this magnetising current what I am drawing to establish the flux depends heavily upon in what portion of magnetisation characteristic I am working on or the machine is working on. So, obviously this L_m will not be a constant for any voltage or any frequency I can’t say it will be a constant, it is difficult to say that it will be a constant unless I specify a particular operating point, if I say this is the operating point, at which I am going to operate my transformer upon.

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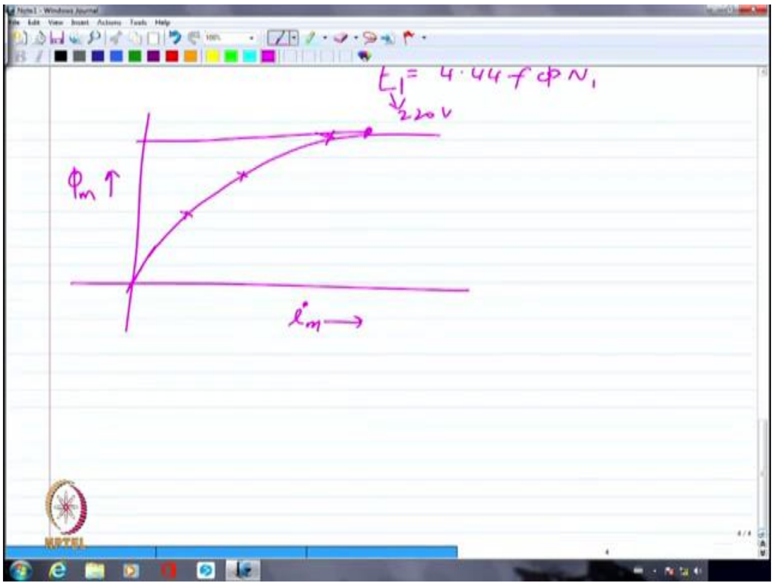

Let us try to look at again the magnetisation characteristic and establish this. Let us say this is my magnetisation characteristics. I am not throwing the entire hysteresis loop I am only showing the magnetisation characteristic and I am saying that this is I_m and this is ϕ_m .

I can operate it here I can operate it here I can operate it here. Very clearly, the inductance values will be different in different points. I can’t say it will be the same, but invariably what we are actually doing is to operate this at the rated voltage and at rated frequency. ϕ_m is the mutual flux, which is linking both primary and secondary, which is confining itself to the core, it is just confining itself to the core.

So, because of which it does not account for the leakage, the leakage is eliminated, I_m is the magnetising current drawn by the transformer even under no-load condition to establish the flux. So initially, I am just applying a voltage V_1. The transformer primary winding is energised, when it is energised it is going to establish a flux, that flux established is ϕ_m that is confining itself to the core and the secondary winding is linked with that flux because of which you are going to get a voltage V_2 induced.

So, ϕ_m essentially is not because I_1 or I_2, it is because of I_m and that is persistent that is not going to be killed, Because I_2 was trying to kill it and I_1 bounce back to protect it. So, you are having ϕ_m all the time and that is essentially the mutual flux which is linking both the primary and secondary.

Now, depending upon the operating point because I am talking about the mutual flux which is established in the ferromagnetic core, I have to take the magnetisation characteristic of the ferromagnetic core, and if I am looking at different operating points the inductance L_m will be different no doubt but if I am following basically this particular operating point of let us say it is 220 V transformer this equation $E_1 = 4.44f\phi N_1$.

Very clearly for a given voltage, under given frequency my flux is fixed it cannot change because it is essentially $\phi = \frac{E_1}{4.44fN_1}$ .It is setting stone once that is setting stone I know for sure that I am going to operate at some particular operating point nothing else.

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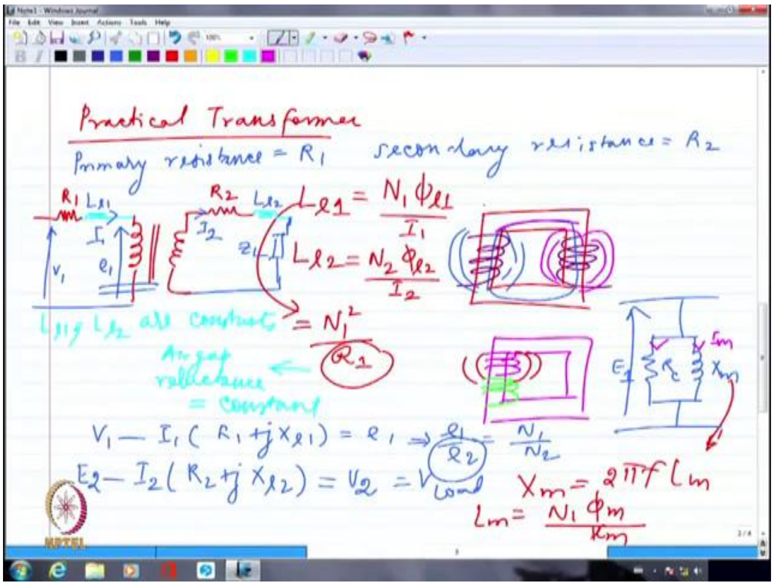

You got the point that $X_m = 2\pi fL_m$. Basically, we are establishing a flux in the core so in the core we are establishing a flux. To establish a flux in the core we need some current called magnetising current if the permeability is not infinity. So, you need some amount of current and that current flowing through the coil wound around the core is establishing the flux. This can be represented by an inductance that is what we said in the sinusoidal excitation when we were discussing because the current is slightly lagging and we should be able to say that, it will flow through essentially an inductance.

So, we are representing the magnetising current the flowing path by an inductance. This inductance we are calling as the magnetising inductance or X_m or $2\pi fL_m$ is the magnetising reactance which is X_m. So, we are going back to the original discussion or I want you to refer back to the original discussion what we did for a ferromagnetic core having an equivalent circuit of resistance in parallel with an inductance.

The resistance is representing the core losses the inductance is representing the current carried to establish a flux, yeah, I_m is almost same as I_0, I am going to come to that I_m is almost same as I_0 remember that I have also shown one more parallel path. The parallel path is definitely not talking about only inductive current it is talking about the resistive current. So, when I add the resistive current correspondent to core losses with that of the inductive current which is magnetising current, I get the total I naught.

So, under no-load condition itself I will have definitely core losses that is represented by RC. I will also have the flux established that is represented by X_m. So, I have two portions of the no-load current one is in phase or real component and the other one is going to be the perpendicular component.

So, I will have a two component definitely for the no-load condition itself.

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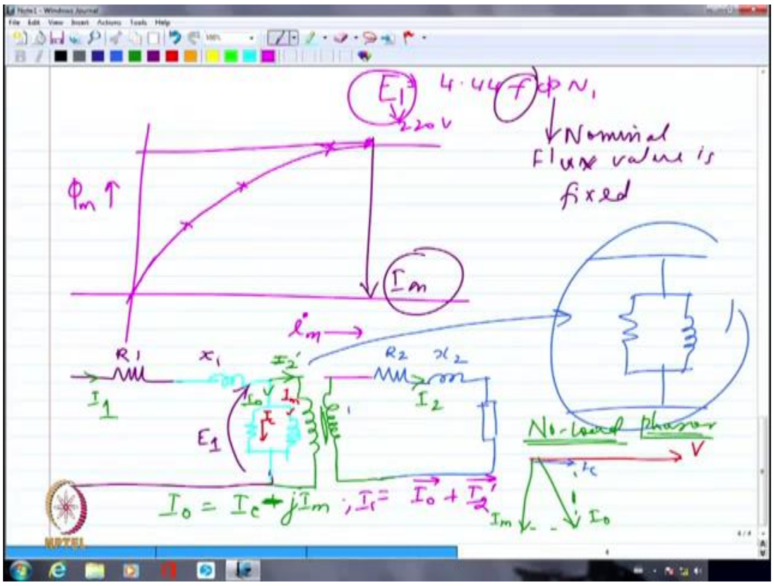

So, we said that the voltage rating of a transformer is fixed and similarly the frequency of a transformer is fixed, so this flux value is fixed. I would say rather than saying then flux value is fixed nominal flux value is fixed, because we say nominal voltage is this nominal frequency is this, and nominal flux value is fixed. If nominal flux value is fixed, I will have that magnetising current also fixed and the operating point is fixed which means that inductance is fixed.

So at rated condition or rated operating condition, we are going to have L_m value as a fixed value it will not be changing, but if I try to plot L_m for different values of voltages clearly the operating point is changing because $E_1 = 4.44f\phi N_1$, will definitely change if I change the voltage.

So, if I try to plot what is the magnetising reactance for different values of applied voltages it would not be a constant it would be a changing but for a given rating of the transformer for a given operating point of the transformer L_m will be a constant. Now we can draw the equivalent circuit as R_1, which is the primary winding resistance, let me write this as small X_1, which will, actually corresponds to the leakage reactance of the transformer primary winding.

So rather than writing capital X_{l1} and so on I am writing this as small X_1, and I am going to have primary winding here. Obviously, the resistances is spread out throughout the primary winding. Similarly, the leakage is not lumped in one place, but I am just lumping it so that it is easier for me to analyse the transformer.

The resistance R_1 is the lumped resistance of the primary winding so I am lumping it together so that it is easy for me to analyse the whole that's it. So, this is primary winding resistance now what is available here is V_1.

Now there is iron core here and then I am going to have secondary winding here. Now I am going to have secondary winding resistance secondary winding leakage reactance. That is X_2 and then here is the load. Now this portion I am going to represent by what we drew as the equivalent circuit of our ferromagnetic core.

So, I have to fix this portion in the middle, but I am assuming that I am exciting the transformer from the primary side and I am connecting the load on the secondary side. So, I should show even this parallel component whatever I am showing in the primary side itself.

Although you can show it on either side not a problem but I am showing it on the primary side so I would rather erase this portion I would erase this portion and I would show it as though I am connecting basically one resistance and one inductance here. and now I will show the primary winding as an ideal primary winding.

And similarly, secondary winding let me show as an ideal secondary winding with the core in between. So, what I am trying to do is, to lump the non-idealities of the transformer in the form of resistance, inductance in series and the core losses and the magnetising current requirement of the core to establish the flux and to feed the losses as R_C and X_m. Again, on the primary side itself.

And what is left over in the form of primary winding which is shown here is the idealised form of primary winding as simple as that. Now I can transfer these things to the other side R_2 and X_2 and Z_L, I should be able to transfer over to the primary side.

If you want to show it on the other side, you have to again say that $R_c\left(\frac{N_2}{N_1}\right)^2 . \left(\frac{N_2}{N_1}\right)^2$ has to be multiplied for each of the parameters, but normally we show it on the primary side because of the fact that we assume that excitation is always coming from the primary side and the load is always connected on the secondary side. This is our assumption as simple as that. yeah

So, in the parallel circuit if I try to look at that current I am going to have something as the core loss component of current, fictitious again see basically I am saying that maybe the hysteresis loss is something like hundred watts in a 2.2 kW transformer kVA transformer. Let us say it is as 100 watts. Now what I have to write is this 100watts should be equal to $I_c^2R_c$. I am going to have certain flux established because of his magnetising current so that should also be whatever is my reluctance of the entire core I calculate so on.

I should have N_1 times I_m divided by the flux is the reluctance of the core that is how it should come up. So now this is I_m and this is I_C please note that one is resistive current and one is inductive current, so if I show this as a the voltage applied to a transformer for example I am going to have actually, whatever is my I_C somewhat like this, which will be in phase because it is resistive current.

And I am going to have the other current as the inductor, so I should show may be my inductive current somewhat like this and drawing all big, big things really the currents are very small but never the less I am just showing it for the sake of it. Normally, the core loss of component of current will be much smaller than the magnetising current. The core loss component is smaller because of the fact that the Eddy current losses are minimise drastically by laminating the core. Hysteresis losses still exist, I can't eliminate but the Eddy current losses are minimised to a large extent because of the lamination process of the core.

So now, when I add them together. These two are added together so I am going to get this as I_0 that is my no-load current. So the no-load current of the transformer consist of two portions one will correspond to core loss component of current which is fictitious, and the other one is the magnetising current drawn by the transformer which I would not say is completely fictitious because you need that MMF definitely to establish the flux but only because you establish the flux the core loss is also happening.

So, if you measure it will definitely consist of both real portion as well as reactive portion, that's why the no-load current of the transformer will not lag behind the voltage exactly by 90° no way. It will definitely lag behind the voltage alright maybe by 80° may be by 75° not 90°. This is essentially because of the core losses is real it is happening you cannot negate it. So, this is the phasor diagram corresponding to no-load condition. This is the no-load phasor diagram.

Now I hope so that you at least got an idea of how really the transformer functioning is built up right from the no-load condition then you connect the load, then the current bounces back and that current what comes here so if I call this as I_2, I should say definitely there is no-load current here. There will be definitely I_2' or whatever is the reflected current from the secondary side into the primary. Now I_2' and I_0 together makes up for I_1. I_0 is really, really small that is why we were able to neglect it we wrote $V_1 I_1 = V_2 I_2$.

We are neglecting I_0 but if we want accuracy, I cannot neglect I_0, So, what we are having is essentially a load current on the secondary side that will have a reflection on the primary side. And the primary side reflection will have the same power factor as that of the load power factor. There is no difference because I have not included the no load current as yet.

No-load current definitely will have a poor factor because it consists of a magnetising current and it consists of a core loss component of current and core loss of component of current is minimised because I have already laminated the core, but the magnetising current is if I look at the comparison if I have 0.3 A as the overall current as the no-load current I may have 0.05 A probably as the core loss component of current.

Whereas almost closer to 0.28 or 0.25 or 0.27 or something as my magnetising component of current. So when I add them I have to say I_C is the real component of current so the no-load current will become $I_0 = I_c - jI_m$, please look at it a complex number again, I have the core loss component of current, which is in the real axis along the positive direction whereas magnetising current is in the imaginary axis along the negative direction this is my no-load current.

Now to this if I want to get what is actually I_1. I have to write I_1 will be equal to this I_0. I am writing this as a vector plus whatever is my I_2' this is also a vector both of them are vectors.

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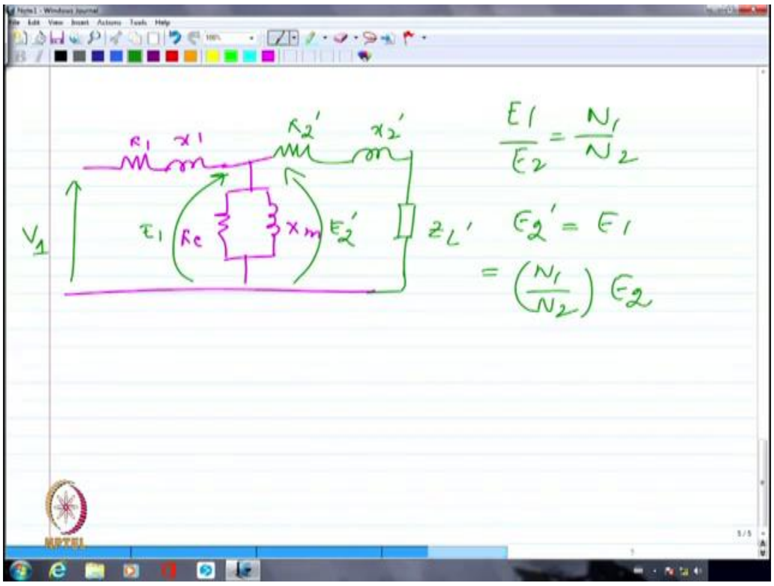

So, let me just finish by drawing the overall equivalent circuit from which we will start our discussion tomorrow, so I am going to have R_1. I am going to have X_1 and I am having here R_C and X_m, and on the secondary side I am going to have R_2', X_2' and Z_L'. What I am applying is V_1 what I am getting here is E_1; I can also call that as E_2'.

E_2' is actually $E_2\frac{N_1}{N_2}$. Everywhere you put the turn's ratio, basically what we have is $\frac{E_1}{E_2} = \frac{N_1}{N_2}$. So I am going to write as E_2' is actually same as E_1 both of them are the same, so how can I say that it is because it is $\frac{N_1}{N_2}E_2$. I am transferring over the secondary voltage onto the primary side so we will continue from this point onwards in tomorrow's class.