Electrical Machines.
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Lecture 6
Transformer Equivalent Circuit and Methods of Reducing Leakage.

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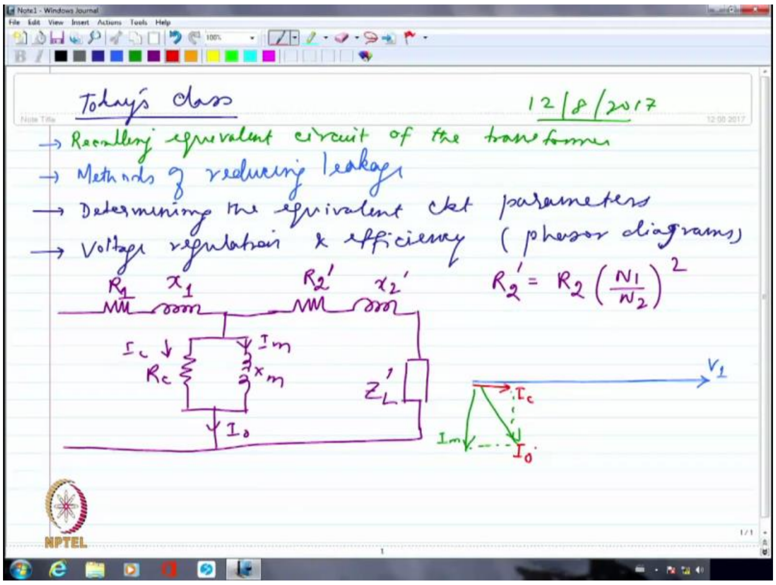

So, we will start off with equivalent circuit. Recalling equivalent circuit of the transformer that is the first thing we are going to do. The second thing what we are planning to do is methods of reducing leakage, then the third thing that we are going to look at is determining the equivalent circuit parameters of the transformer by open circuit and short-circuit test. we will also look at the load test.

Then we will look at actually voltage regulation and efficiency along with phasor diagrams also, because some phasor diagrams will be needed for the calculation of the voltage regulation, not for efficiency but definitely for voltage regulation we will need that. When we draw the equivalent circuit of a transformer, we are going to first of all consider the resistance of the primary winding, then the leakage reactance of the primary winding as well.

The leakage reactance is essentially due to some portion of the magnetic field lines, so we have some portion of the magnetic field lines which are linking only with the primary winding which we call as the primary leakage and we have some portions of the magnetic field lines which link only with the secondary of the field winding, which we call as the secondary leakage. So, we said also that the core is not ideal due to which we do have some core loss component of resistance, this is a fictitious resistance, not really the core resistance as such.

So, this is essentially an equivalent resistance that we can estimate based on how much is the loss that is taking place in the form of hysteresis losses and Eddy current losses. And normally this core loss is going to be smaller because of which if I look at the two portions of the no-load current, one which we call as I_C, which is corresponding to core loss component of current, And one more which we actually take it as the X_m, Which is corresponding to I_m, if I may call this as I_m, together it makes up for I_o, which is actually the no-load current.

And this actually if I look at, this is going to have a very bad power factor because the magnetising current will dominate over the core loss component of current. The magnetising current is reactive in nature and the core loss component of current is real and because core loss component of current is very small, invariably the power factor will be pretty bad for a transformer under no-load condition.

Then we said that on the secondary side, we have R_2, which is actually the resistance of the secondary winding itself but we wanted to transfer it over to the primary side, so we call that as R_2', where I can write $R_2' = R_2(\frac{N_1}{N_2})^2$, where R_2 is going to be the inherent resistance of the secondary winding but I want to visualize this from the primary side. So, I am multiplying by the $(\frac{N_1}{N_2})^2$. So, now that I have transferred, I can definitely connect it together.

That is why I was not connecting it together earlier but now they are electrically connected, there is no problem, And then I am going to have X_2', which is the leakage reactance of the secondary winding which is transferred over again to the primary side with the help of turn’s ratio. Now, finally I am going to have a load, a load if I connect it directly, I would have called that as Z_L, now I am going to call that as Z_L' because I am transferring it over to the primary side again.

Let me probably try to give you a little feel for the phasor diagram as well here, because we will be definitely again drawing the phasor diagram in greater detail but let me try to give a feel for the phasor diagram. So, let us say this is my voltage which I am applying for the transformer. So, that is the voltage that I am applying on the primary side of the transformer. Now, I can draw I_C along the voltage axis.

Very clearly I am not drawing anything to scale, because of course our currents and voltages can be compared in different, they are like apples and oranges, I cannot compare them but when I draw the load current, it is very difficult for me to draw the no-load current as 100^{th} or 150^{th}, so I am just drawing it approximately, that is it, not to scale. So, this is the I_C. Now I am going to have maybe I_m somewhat like this, the magnetising current is somewhat like this.

Now, when I add them together I_C and I_m, I add them together, I am going to get what is known as the no-load current. So, let me call this as I_o, this is what is the no-load current.

Student: (())(7:14).

Professor: Yes, in the primary side. This is V_1, here I am applying V_1.

Student: (())(7:25).

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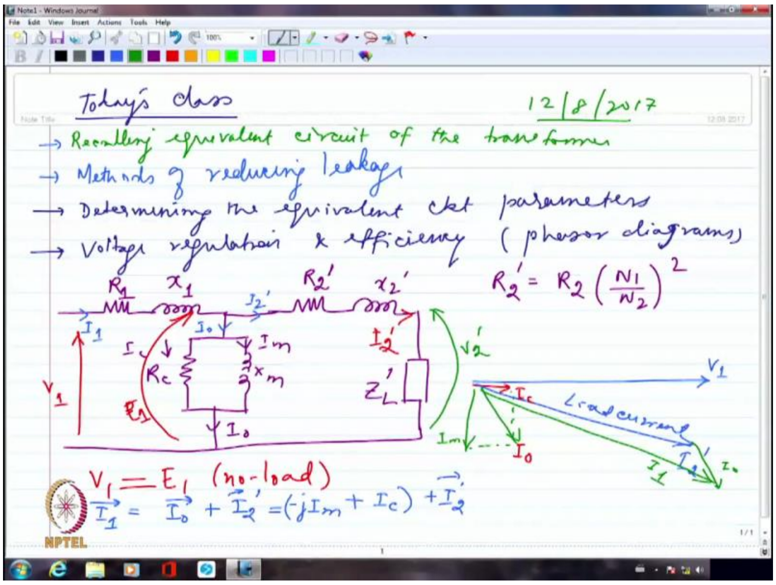

Professor: You are right, there is no doubt that I_C cannot be exactly in phase with V_1 because you have some drop that is taking place in R_1 and X_1. R_1, let us try to look at some of the values. If I am talking about a 2.2 kVA, 220 volts by 110 volts transformer, I told you that the primary current, rated current is about 10 A. What I am going to get as a no-load current is only 0.2 or 0.3 A. And these resistances and reactance's if I look at it in a transformer, the reactance, the leakage reactance will be really small, I cannot exaggerate this further.

That is because I don't have any air gap. In a rotating machine I have air gap, so obviously there will be huge amount of flux probably leaking into the air gap space, whereas there is no air gap here, because air gap is very minimal, the leakage will be very small. So, the leakage reactance typically of a transformer will be, if I look at in terms of voltages drop, then voltage drop will be only about 2 percent or 3 percent, nothing more than that.

Totally put together, the voltage drop in R_1 and X_1 as well as $R_2^{'}$ and $X_2^{'}$ put together will be only less than 5 percent that is under full load current condition. 10 A when it is flowing for a 2.2 kVA transformer, out of 220 volts if I try to find out how much is the drop that is taking place in (R_1+ $R_2^{'}$)+ j (X_1 + $X_2^{'}$) x10 A will give me a drop of only about less than 11 volts, 10 volts or 9 volts or something, it is going to be so low.

That is the case even when full load current is flowing. So, if lesser current is flowing, which is 2 percent of the current, who cares. So, the drop is really small during no-load condition. So, I can neglect that drop across R_1 and X_1, I can say that V_1 and E_1, if I may call this as E_1, capital E_1, so I can say $V_1 = E_1$ under no-load condition. That is the reason why I couldn't care less in terms of whatever is the phase shift that may exist between I_C and V_1, it is hardly anything.

So, I am just taking that both of them are in phase. Now, I have this as the no-load current. Once I got this as the no-load current, let us say I have connected the load now, when I connect the load, I am going to have definitely a secondary current. So, the secondary current, let me call that as probably $I_2^{'}$. I should not call that as I_2 because I have transferred it over to the primary side, so I cannot call it as I_2 anymore, I have to call it as $I_2^{'}$.

So, I will have some $I_2^{'}$ and $I_2^{'}$ phase angle depends upon what kind of load I have connected. If I have connected highly inductive load, I am going to have $I_2^{'}$ probably lagging behind V_1 or E_1 for that matter, by a very large angle. If I am connecting a unity power factor load, the current will be along I_C itself, if I am assuming that I am probably connecting some kind of lagging power factor load, I should not fact show it much longer than what I have shown because the load current will be very high as compared to the no-load current.

The no-load current is only less than 5%, then I should show the length of this particular current $I_2^{'}$ as almost 20 times or 25 times whatever is my no-load current, which right now I am not able to show, so I am assuming that you guys understand basically the constraints that the reason I have shown this as the load current. So, this is going to be actually my load current, this is the load current.

If I have the load current here, then I can add this current which is actually my I_o and this is $I_2^{'}$, these two added together will make up for I1. So, I should say I_1 vectorially is equal to $I_o + I_2^{'}$. And I_o is actually equal to I_m, That should be $(-jI_m + I_C)$, that is what is I_o actually, because it is lagging behind, So, I should say $(I_C - jI_m)$ is the overall no-load current. And no-load current added to $I_2^{'}$, that is what is going to give me the total primary current.

So, now I should be able to draw finally the overall current, So, I should actually draw I_o which is probably I will show it like this, I hope that I am showing it in the correct angle. So, this is I_o, so now both of them added together, I should have this as I_1, this is the overall I_1. So, if I draw the power factor, actually speaking the load current power factor I have taken that as the angle between V_1 and $I_2^{'}$, which is not accurate.

I should take it as V2 dash and I2, I have to look at what is $V_2^{'}$, it is what is available here, this is $V_2^{'}$, I hope you understand. This should be $V_2^{'}$, so I have several drops, first I am applying $V_1 - R_1 + j(X_1)I_1 = E_1$ will give me E1. So, this E1 is going to be now passed onto the secondary side, which I may call that as E_2, if I am not taking the turn's ratio into account, but if I am taking the turn's ratio into account, E_1 and $E_2^{'}$ are the same, there are one and the same because they are following the turn's ratio.

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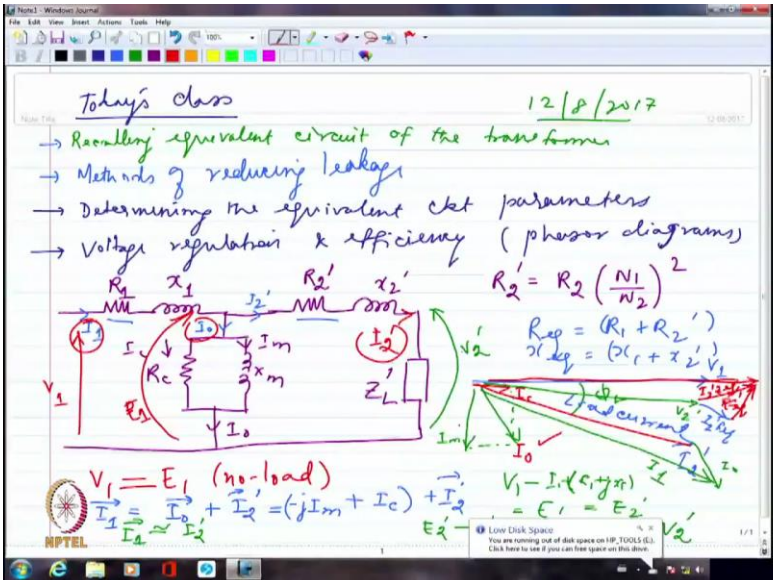

Now $E_2^{'}$ will be passed onto the load after getting dropped in this R_2 and $X_2^{'}$. So, I should say $E_2^{'} - I_2(R_2^{'} + jX_2^{'})$. So, I should be able to write this saying that V_1 minus I1 plus, rather $I_1(R_1 + j X_1)$, this will be E_1, which is also equal to $E_2^{'}$, But I should also write $E_2^{'} - I_2^{'}(R_2^{'} + jX_2^{'}) = V_2^{'}$.

So, there are two drops clearly, voltage drops, we are considering mainly the series portion because that is where the voltage is dropped. So, if I draw the power factor, approximately I can say maybe this is the power factor of the load, but that is approximation because I have taken directly the angle between V_1 and $I_2^{'}$.

Actually, I should have taken $V_2^{'}$ and $I_2^{'}$, but the saving grace is $(R_2^{'} + jX_2^{'})$ is small because of which, although there is a drop these two are in phase with each other, that is fine definitely there is a phase angle. So, let us probably try to account for it. So, if I have let me say probably $V_2^{'}$ it somewhere here, I am just going to arbitrarily drop $V_2^{'}$, it is not really exactly correct, maybe this is $V_2^{'}$, the length should not be so much. Ok So, it will erase the whole thing, or it will not erase at all.

So, this is what is $V_2^{'}$. This $V_2^{'}$ to that, I have to add what, first of all $I_2^{'}$ multiplied by…

Student: (())(17:15).

Professor: Exactly, no-load is open circuit. No-load and open circuit are synonymous with each other, they are synonymous with each other. So, to $V_2^{'}$. I have to add first of all $I_2^{'}(R_2^{'} + jX_2^{'})$, that is the first thing I have to do, then I have to add $I_1(R_1 + jX_1)$, if I add both of them, then I should get V_1, am I So, rather than doing that, let me assume, although I have written all these fully, I can say I_1 is approximately equal to $I_2^{'}$.

No harm in writing that after all because the no-load current is really small. So, as an approximation, what I am going to do is to $V_2^{'}$. I am going to add first of all $I_2^{'}(R_1 + R_2^{'})$ directly. So, this is $I_2^{'}$, so I can write this as maybe $I_2^{'}$ multiplied by R_{eq}, where $R_{eq} = R_1 + R_2^{'}$. So, I am going to have essentially $R_{eq} = R_1 + R_2^{'}$, similarly $X_{eq} = X_1 + X_2^{'}$. Overall series resistance of the transformer and overall series reactance of the transformer. So, I can take it like that. So, what I am doing is to $V_2^{'}$. I am adding first of all the drop in the resistance, two resistances. So, I am going to take the drop in R_1, take the drop in $R_2^{'}$, that I am going to multiply by the resistance and after all the current multiplied by resistance will be in phase with the current itself.

So, I have taken this in phase with this, these 2 are in phase. And to this I have to actually draw a perpendicular, so I have to take it like this, if I draw a perpendicular, that perpendicular is indicating that the resistance drop and inductance drop will be at right angles to each other, I hope you understand, the current and the resistance drop will be in phase with each other, and the current and the inductive drop will be perpendicular to each other.

So, once I write this as $I_2^{'}X_{eq}$, then I have to just extend this, and then say this is what is V_1, this entire red line is V_1, not the original blue line. This entire red line is V_1. So, I can draw the phasor diagram indicating separately R_1 and $R_2^{'}$ drop and X_1 and $X_2^{'}$ drop, rather than that I have put both of them together, so that I look at the overall terminal voltage vis-à-vis whatever is the voltage that is applied from the primary side.

So, that is what I have taken have the overall the drop that takes place within the transformer. So, let me again recall the phasor diagram step-by-step because I have made a little bit of modification here and there, first of all we drew a voltage which is the applied voltage V_1, from there we first drew the no-load current. So, the no-load current has two components, one is core loss component of current, which is in phase with the voltage, the other one is the magnetising current, which is at 90^0.

Although it does not look like 90^0 in the figure I have drawn but it should be exactly at 90^0. When we add these two, we are getting the no-load current. So, I_o is a no-load current, where we are adding to I_m and I_C, both of them. So, I_o is the no-load current. Once I get I_o, my no-load phasor diagram is done almost. After that I have to include the load or take the load into account. The load current that is flowing his $I_2^{'}$. Actual load current flowing is I_2, I have taken it with the help of turn's ratio to the primary side and I am calling that as $I_2^{'}$.

Now, this $I_2^{'}$ and I_o added together will give me I_1. So, I should have taken into consideration, when I take the drop through R_2 and $X_2^{'}$, only $I_2^{'}$, whereas when I take the drop in R_1 and X_1, I should have taken I_1, which will include the no-load current as well, but a no-load current is only less than 5 percent of the full load current. So, it is if I neglect it, so I am taking up an approximation $I_1 = I_2^{'}$.

So, now what I am doing is I_1 or $I_2^{'}$ I take into consideration and I take all the drops that are taking place in the series parameters, like R_1, $R_2^{'}$, X_1, $X_2^{'}$. So, $R_1 + R_2^{'}$ I am calling as R_{eq} and the drop in that R_{eq} will be in phase with the current. So, what I have as the current, I can just take parallel to that $I_2^{'} R_{eq}$, and then perpendicular to that will be X_{eq} drop. So, I have taken $I_2^{'} X_{eq}$.

When I add these two, actually I can drop a vector here which is $I_2^{'} Z_{eq}$, if I may call it as that. So, I could have drawn a vector here which will actually show me as $I_2^{'} Z_{eq}$. If I feel like I can show it. Now, $V_2^{'}$ plus whatever is the drop that has taken place in the impedances within the transformer, series impedances within the transformer, these two added together gives rise to V_1. So, that is what is actually my V_1.

So, if you actually look at it in a transformer, between V_1 and $V_2^{'}$, the phase angle will be really small, normally. So that is the reason it is all right sometimes to start off the phasor diagram assuming that V_1 and $V_2^{'}$ are at the same phase and you start drawing the phasor diagram and then as and when you get more parameters, you try to make small little amends, that is what we do. The phasor diagram of the transformer

Student: Ma'am I_2 and its equivalent should not be inductive?

Professor: It cannot be completely inductive, it will be resistance plus inductive, but it will be reactive, yes.

Student: (())(25:13).

Professor: It is not at 90^0. No, see please remember that this is voltage, whereas this is current, $I_2^{'}$ or I_1, these are currents, currents should lag behind the voltage, which is happening.

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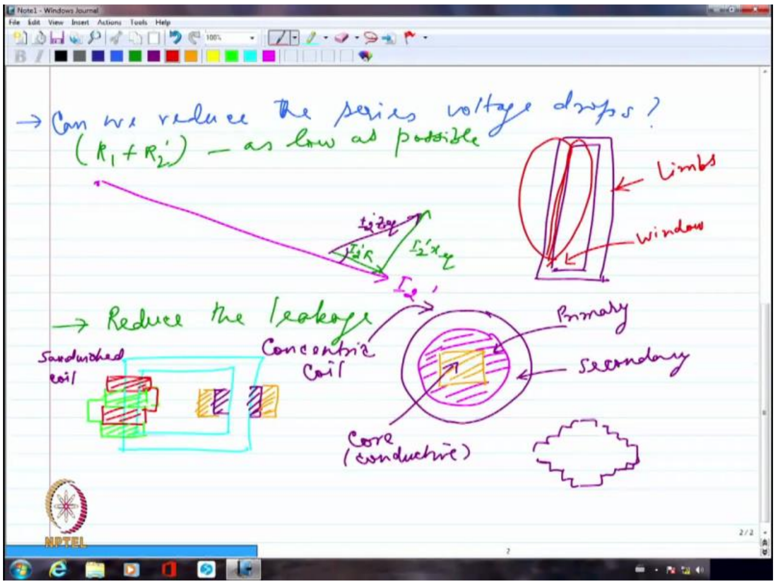

Look at them individually, this is, let me probably draw this portion slightly expanded it here. This was my I_2, What I drew as $I_2^{'}R2$ let us say I draw like this, $I_2^{'}X_2$ is like this, so this is $I_2^{'}R$, this is $I_2^{'}X$, of course equivalent. Now, when I look at this, this is $I_2^{'}Z$ equivalent. Now look at the phase angle between this and the current. You get back now the current is lagging. I hope I have made myself clear.

Student: (())(26:29).

Professor: We are neglecting when finally we drew the voltage drop, we didn't neglect it initially, that is why we wrote very clearly I_C, I_m, some of that is no-load current, then that no-load current be added to I_2' and we said that that was I_1, but finally when I was writing the drop, I could have written I_1R_1, I_1X_1+I_2 R_2, I_2X_2. All these things added together will give me that total voltage drop, but it is actually hair-splitting, you do not really need so much of hair-splitting.

So, we will try to work out maybe one problem at least, right from the parameter estimation of a transformer until voltage regulation and efficiency calculation. So, that will give you a feel for what kind of values we are getting, if we neglect it heavens are not falling, that is what it means. So, engineering approximations are always done so that finally what you obtain as experimental values somewhat coincide with the actual calculated values, then you say your assumptions are okay.

So, we are not going to do as accurate calculations as a mathematician does, definitely not. So having said that, now we have to go and take a look at first of all whether we would be able to get these values, that is R_1, R2 dash, X1 and X2 dash and similarly the values of Rc and Xm at least to a good accurate extent, that is acceptable accuracy, whether we will be able to get them experimentally, that is one thing we will have to do.

Second thing we also know now that the voltage drops that are taking place in R1, R_2', X_1, X_2' are uncalled for but we have to live with them. Can we minimise them? So, these are the two questions that we are going to answer in the next few minutes. So, first thing is whether we can decrease, can we reduce the voltage, the series voltage drops, that is the first question that we are going to answer. If we want to reduce the voltage drop, R_1 and R_2' first of all have to be decreased.

The maximum we can do is to use a material which is of very low resistivity. That is why we normally use copper coils although copper is more expensive. Most of the transformers use only copper coils, But sometimes when we buy it from the grey market, what they do is already used copper in any old motor or something, they take it out, just beat it up again so that it looks good copper, it looks like good copper and then they put it up and invariably you find that the transformer fails within it few days.

So, generally, at least in the laboratory when we buy, we make sure that we test it properly, all the parameters of the transformer and only when we know it is fairly good we release the payment, that is what we do. And we try to order it from fairly renowned industries. So, this resistance being low is important to make sure that the performance index of the transformer, like efficiency and voltage regulation, that is the voltage drop should be contained within a particular limit, so these things should be done.

Student: What happens if copper (())(30:35) is there?

Professor: If you use it, see, basically gets oxidised definitely and when it gets oxidised, unless you remove the Oxidation portion, the resistance will not be decreased. What these people do is…

Student: (())(30:53) what about the other surface?

Professor: Everywhere, you are taking into account when you actually choose a wire for a particular gauge thickness. You are going to assume that the entire cross-sectional area is occupied by the current. So, if the outer shell is not occupied by the current, because it is highly resistive, then you are overheating the inner core, which is not good. So, generally it is not it is not a good idea to choose a wire whose thickness is less than what you anticipate at the current limit.

So, generally you go with the consideration that you will give a factor of safety of 1.25 or 1.5. So, if I expect that 15 A of current has to flow through my copper coil, I would say what is the amount of current density the copper can withstand, and I will put generally 1.5 times 15 as the factor of safety and then I will choose correspondingly depending upon the current intensity what is the area of cross-section I have to choose for the wire, that is how we choose.

So first of all R_1 and $R_2^{'}$ should be as low as possible. So, this will be ensured by choosing a good quality copper wire normally. The second thing we would like to do is very clearly to reduce the leakage. So, to reduce the leakage flux, what we are going to do normally is to put the primary and secondary as much as possible sandwiched in the same limb. So, if I say that this is what is the transformer’s core. I may put actually primary here, let us say this is the primary coil.

Then I may put a secondary coil right beneath that, again I will put the primary here, then I will put the secondary once again here. Similarly, I will put it on the next limb also, so I am going to have the primary and secondary, primary, secondary sandwiched continuously. And of course I have to connect these two in series. I will have to connect these two in series, similarly I have to connect these two in series. So, I have to necessarily connect them, no doubt, because all the turns have to come in series, only then I am going to get N times voltage per turn equal to the overall voltage, so I have to connect them in series but I will have essentially primary and secondary sandwiched in one particular limb itself and the next limb also.

Student: (())(34:08).

Professor: We can do that also, that is another way, concentric coil, we call them as concentric coils. So, this is in case both of them are of comparable voltage. If both primary and secondary are of comparable voltage, the comparable voltage thing will come up when I want only isolation to be established, maybe I have a 220 V system, another 220 V system, I don’t want the earths to be coming together.

So, I will have one primary 220 V, one secondary 220 V, from the primary I may supply the voltage, from the secondary side I make connected to some motor or load or rectifier or whatever. So, I want isolation very clearly between the primary and secondary, in which case they will be of the same voltage rating. So, I can put them like this, whereas, so I would call this as sandwiched, this is sandwiched coil. Whereas, I may have something called concentric coil.

Concentric coil is what just now told so I will have probably my primary here. It is wound around the limb and the secondary is going to be probably around that as well. So, I am showing something like the cross-section or longitudinal section,

So, if I say that this is my core. I am going to have one coil like this, so this is all occupied by the coil let us say. This may be primary, and I will have the secondary around this.

So, this is actually my primary coil probably and this is going to be the secondary coil, and this is going to be the core. So, this is what is concentric coil.

It can be in square shape, it can be in circular shape, it depends upon how the laminations you have designed, It depends upon very clearly the laminations you have designed because if I have all the laminations of the same shape and same size, then it is going to be square, if rather than that I am progressively reducing the overall thickness or overall width, then it will look as though it is triangular or it can approximate itself to something like I can have it this way basically.

So, I can have something like this, I am just showing approximately. So, similarly the other side also it can go like this. So, I can approximate it to a circle, I can do this also, so it depends. Now, please note that the core is also conductive, or it is metallic. And the primary and secondary coils, definitely they are made up of copper, they are also conductive, we will put insulation around them, no doubt.

If the primary is of low voltage rating, then I will put primary inside and secondary outside, because, if the secondary is of 400 kV and primary is of 15 kV, 15 kV will require only less insulation, whereas 400 kV will require thicker insulation. And because I require thicker insulation, very clearly that coil turns will probably be of higher diameter, because it will be really thick, it will be very difficult to wind it into a smaller diameter coil.

So, one thing is because of the inherent diameter I will get for the coil, as the voltage rating increases, I will have thicker insulation, so the diameter of the coil will become larger and larger. Whereas, one more reason is because the core is also metallic, I need to make sure that the breakdown strength of the insulation is good enough to withstand the voltage, the coil making a puncture onto the insulation and reaching out for the current into the core.

So, the core and the coil are separated only by the insulation. If the voltage the strength, $\frac{dV}{dt}$ if I am talking about or $\frac{dV}{dX}$, where the centimetre, I am talking about the thickness of the insulation, if that exceeds the insulation strength, then the insulation will be punctured. Higher the voltage I will require higher as the separation distance. So, if it is lower voltage rating, I can put it closer to the core, whereas if it is larger voltage rating, I better put it away from the core.

So, larger voltage rated winding will be placed in the outer concentric circle, whereas lower voltage rated coil will be placed in the inner concentric circle. So, this is one of the ways of decreasing again leakage reactance. So sandwiched coils and concentric coils, these are two ways of reducing leakage reactance. One more generally that is done is we try to make, we never make the core broader and thicker, we try to make them thinner and longer like this, I am sorry for the bad drawing.

This is how we make it so that the air path really becomes longer, this is the air path, if I am saying that the flux is having a path like this, it is going through the window, so we call this as the window, and these are limbs. Limbs of the core and the window of the core. The window is generally made thinner and longer, that makes essentially the length of the air gap path really increased. The length increases, we said $\frac{L}{\mu A}$ is the overall reluctance. So, the reluctance is going to increase further and further.

If the reluctance increases further and further, the number of lines that are escaping into the air gap will decrease. The number of lines escaping into air gap decreases, the leakage decreases. The total number of lines that are confining themselves to the core will be increased correspondingly. So, three ways of reducing the leakage is one is to increase the length of the window, the second is to have sandwiched coil, the third one is to have concentric coil and the fourth one is shell type construction. We looked at shell type and core type.

Core type construction always enhances air surrounding air more, where it makes it more. Whereas in shell type construction, mostly it is surrounded by iron. So, hardly anything escapes into air. So, shell type construction generally enhances or reduces the leakage quite a bit. So, these are four ways of reducing the leakage in the case of a transformer, fine? Now that we have seen the importance of R_1, $R_2^{'}$ reduction and X_1, $X_2^{'}$ reduction, let's try to see how to estimate the parameters or equivalent circuit parameters of the transformer.

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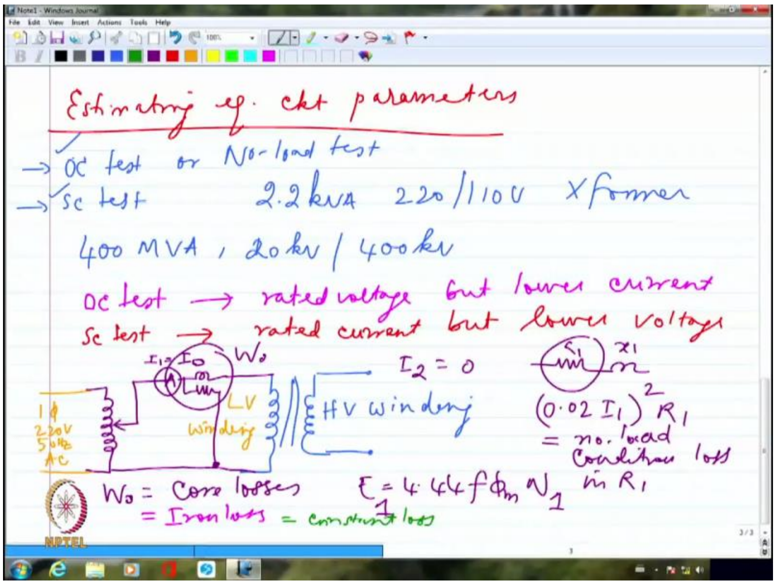

So, let us try to look at two tests that are commonly conducted in a transformer to ascertain the equivalent circuit parameters of the transformer. So, one of them is open circuit test or no load test, the other one is short-circuit test. Rather than doing this, we could have simply loaded the transformer, let us say I have a 2.2 kVA, 220, again let us take the same parameter what we had taken, at 220 by 110 V transformer.

If I have to conduct the test on this transformer and ascertain when I load it to the fullest extent, how the transformer is really performing. That will give me a clear picture of how it is behaving when I load it to the fullest extent or when I load it with inductive load, when I load it with capacitive load, I can definitely conduct the test, but the transformers normally we use in the power stations or industries, they are all of the rating of thousands of MVA or at least hundreds of MVA.

For example what we use in a power station which is generating 400 MVA power, it will be a 400 MVA transformer with probably 15 KV or 20 KV / 400 KV. This is the kind of thing that we are going to see in a power station. And if I have to test this transformer directly by loading it, it will be really a monumental task. First of all, how will I find the load which will carry whatever is 400 MVA divided by 400 KV, that much of current.

So, I have to essentially get load which will actually carry so much of current and it will dissipate so much of power, then I should be able to cool it. So, it is going to be really difficult for me to test such a transformer by loading it actually and it will be a huge wastage of power. So, rather than doing that, if I can do something like create such kind of condition which will be equivalent to loading it fully without actually loading it.

And that is what we do in these two tests. In open circuit test and short-circuit tests, we are essentially creating situations such that the transformer is put through such an operating condition which will emulate the normal loading condition, although not simultaneously. What I mean is in open circuit test you will apply rated voltage but lower current. And in the other test which is short-circuit test, you will apply rated current but lower voltage. This is what we do in these two tests.

Student: What is the rated voltage, V1 or E1?

Professor: V_1, because E_1 is internal to the transformer, which we cannot measure. And after all the difference between V_1 and E_1 is not too much. That is the reason we always go by engineering approximations again, that is the reason. So, if we subject it to 220 V on the primary side, or 110 volts on the secondary side, I call that as rated voltage, it is being subjected to rated voltage. Similarly, if we pass 20 A on the secondary side or 10 A from the primary side, I call it as the transform is being subjected to rated current.

And that is what we do during short-circuit test and open circuit test respectively. So, in open circuit test, as the name indicates, we are going to keep the secondary open, so let us say this is my transformer, and then I am going to keep this open circuited and here is my core. And invariably the open circuited portion will correspond to high-voltage side. The open circuited winding will be HV winding, whereas this will be LV winding, LV corresponds to low voltage winding, the other one is high-voltage winding.

So if I am having instead of 220 by 110, if I think of $\frac{22\text{kV}}{110\text{V}}$, even it can be like that, if it is that way, then invariably I will try to apply 110 V because that kind of source is easily available for me, 22 kV will be difficult for me to get, so always I will try to choose the low voltage winding to be energised in the case of the open circuit test because I am looking at applying rated voltage.

So, the rated voltage has to be corresponding to either low voltage or high voltage but logistically it will be easy for me to apply the voltage on the low voltage side rather than high-voltage side because high voltages are not common, high-voltage sources are not common. So, now what I am going to do is to apply, so normally what we do in the laboratory is to apply it through a variac or auto transformer, we will study about auto transformer a little bit later but let us say I am having this as single phase 220 V, 50 hertz AC, this is what is available.

Now, I am going to connect this to something called as an auto transformer, auto transformer is like an inductor, iron core inductor, nothing else, I just have a larger number of coils. That is bound in an iron core. Now, I am applying this entire voltage to that coil, now if I tap only 4 number of turns, I will get only half the voltage, halve the number of turns, if I tap the 100 percent number of turns, I will get complete voltage, if I choose only 75 percent of turns, I will get only 75 percent of voltage.

It is as good as potential divider but without resistive loss, that is all, I don’t have any resistive loss and it works because of highly inductive nature of this iron cored coil. So, from here I am going to apply this voltage to the low voltage winding through an ammeter and through a wattmeter. So, this wattmeter is connected in between the primary coil and the input source. Now, please note that there is no current flowing on the secondary side, so I_2 is 0.

So, what I am having as I_1 here will be equal to I_o, that is actually the no-load current itself, nothing more than that. So, what I am getting in the open circuit test is only no-load current and as we know the no-load current of a transformer is really small because of the no-load losses been decreased and also the permeability of the core being very high. So, I can say that if even if I consider the series resistance of the transformer which I may say R_1 and X_1, the series resistance loss is going to be really small.

Let's take the quantities, if I say that at 100 percent load, I am going to have $I_1^2R_1$ to be 100 watts let us say. When I am having only 5 percent of the current or 2 percent of the current flowing, the current is going to be only 0.02 I_1 for example and I have to see what is the loss at this condition, it will be $0.02\,I_1^2R_1$. This will be the no-load condition series resistance loss.

So, if I try to look at this, this is 0.0004, which means it is less than, not even 4 percent, it is 0.04 percent, 0.04 percent of what I would have incurred in R_1 as the loss under full load conditions. So, originally if it was 100 watts, now I will have only 0.04 watts as the loss, am I Which means it is going to be really small, so I can afford to neglect it. So, under no-load condition we take it that the series parameters hardly ever play a role in the voltage drop as well as in the power loss.

So, the series parameters that we can even consider is R_1 and X_1 because R_2 and X_2 don't even have any role to play, it is not even carrying any current. So, R_1 and X_1, both of them hardly play a role because of the fact that I am not going to have a good amount of current flowing through the transformer under open circuit or no-load condition. So, I can say in general that in open circuit test what we get as the wattmeter reading.

So, if I may call this as W_o, it will be basically only the core losses, it will not contribute to anything towards copper loss. Think about it again, I am applying rated voltage at rated frequency, so the flux will be at rated value, $E = 4.44f\phi_m$ into number of turns, this is what we wrote as the equation. So, if I am talking about E_1, this is N_1. So, if I look at the flux value, if I am applying rated voltage, whether it is from the primary side or secondary side, it doesn't matter.

The flux is going to be at rated value as long as the frequency and voltage are at rated value. So, if it is at rated value, then I am essentially looking at the overall magnetic circuit depicting a behaviour which is very similar to nominal operating conditions. So, under normal operating conditions, however the magnetic circuit may be, that is what is the behaviour depicted by the transformer under this condition.

So, if the flux is at rated value, the frequency is at rated value, the voltage is at rated value, I can say the core losses will be at rated value, whereas the copper losses are very minimal. So, whatever is the reading I am getting from the wattmeter I would call that as the rated core loss or no-load loss. The core loss incidentally is also called as iron loss and they may also be called as copper loss I mean constant loss.

Constant loss we call it because we assume that if the transformer is rated for 50 hertz and 400 V, it will always be operated at 400 V and 50 Hz, hardly ever we operate it at lower voltage, hardly ever we operate it at different frequency than what it is rated for. So, if we assume that as long as the voltage and frequency are kept as constant, the iron losses or core losses are constant, so we call them in constant losses.

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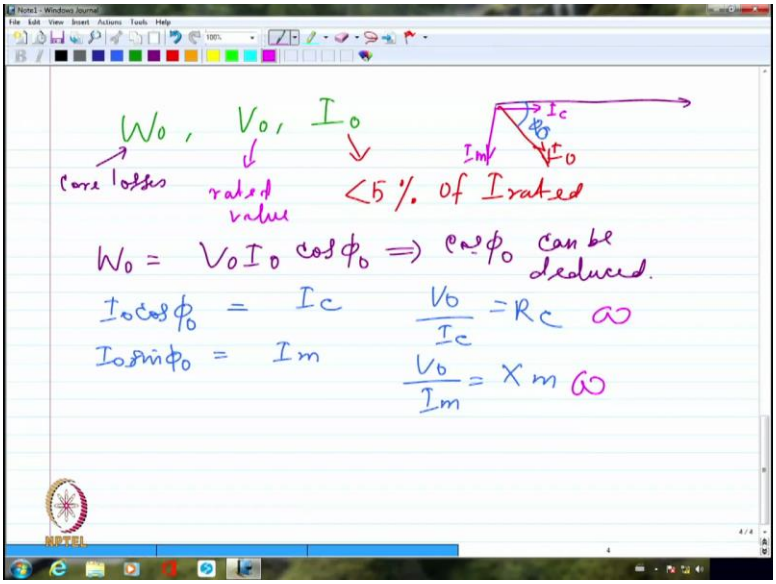

So, it is called as constant loss because voltage and frequency will be normally maintained as constant, that is the only reason. So, what we get out of the no-load test is we are going to get W_0, V_0 and I_0, these are the three readings that we are going to get. V_0 invariably will be rated value, I naught will be probably less than 5 percent of I_{rated}, if it is a well-designed transformer. And this is going to be core losses.

So, I should be able to get rest of the equivalent circuit parameters in the parallel circuit because the parallel circuit is the one which is talking so much about magnetism, the parallel portion of the equivalent circuit. So, I should be able to say $W_0 = V_0 I_0 \cos\phi_0$. So, $\cos\phi_0$ can be deduced. Once I have $\cos\phi_0$, I should be able to say, see, we drew the phasor diagram if you may recall, if this is V, I am going to have I_C along this and I am going to have to I_m along this. So, the resultant current what I get will be somewhere here.

Which is corresponding to I_0. And if I may say this is what is ϕ_o. If this is ϕ_o, I should be able to say that $I_0 \cos\phi_0 = I_c$ and $I_0 \sin\phi_0 = I_m$. Once I get this, I can say simply say $\frac{V_0}{I_m} = X_m$,

Because they are in parallel. So, I should be able to say $\frac{V_0}{I_C} = R_C$ and $\frac{V_0}{I_m} = X_m$. Had it been an ideal transformer, what would be the value of R_C and X_m?

If it had been an ideal transformer, how much will be X_m, infinity or 0? Sure, infinity? It has to be infinity because I_m has to be 0. I should be able to establish the flux without any current. If the permeability is infinity, without any MMF I should be able to establish flux within the core. So, for an ideal transformer, these two should be infinity, because I will not have any I_C, I will not have any I_m, I should not have any core losses, I should not have any requirement for the current for establishing the flux.

Student: In an ideal transformer, the core loss is 0, can R_C be 0?

Professor: If R_C is 0, I_C will be infinity. So, if I_C is infinity, the no-load current of the transformer will get to infinity. In a transformer if I am not connecting any load, if it is an ideal transformer, the no-load current should be 0, got it. So, I can’t have R_C to be 0 either. What you say is right, if R_C is 0 or if I_C is 0, should get core losses to be 0.

But although that is true if I have R_C to be 0, the no-load current will literally become infinity, they are in parallel, remember that, R_C and X_m are in parallel. So, if R_C is 0, I will have no-load current reaching infinity, which will not be the case, which should not be the case.