Electrical Machines.
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Lecture 7
Transformer Equivalent Circuit Parameter Determination.

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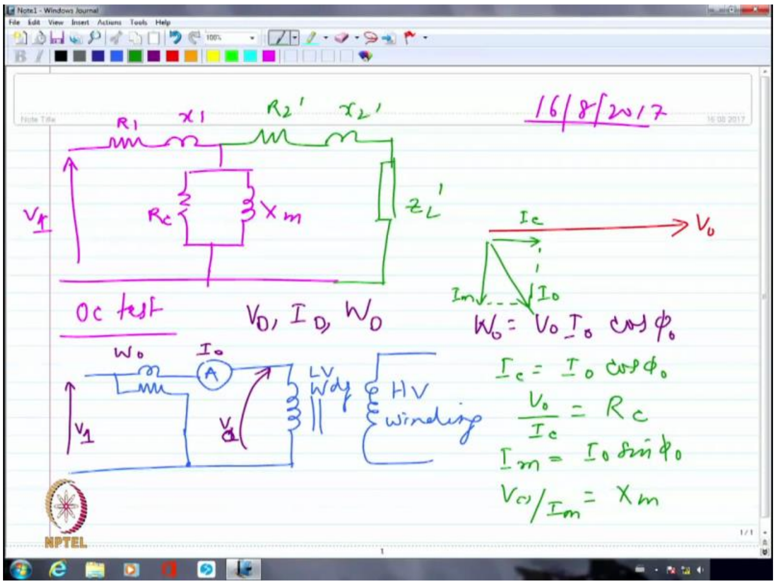

So, let us start off with what we had left off in the last class, BH loop, yes. So, we were looking at open circuit test and short-circuit test. If you may recall, we had drawn the equivalent circuit, overall equivalent circuit of the transformer, we also drew the phasor diagram. We said this is R_C, this is X_m and here is V_1, what we are applying. So, now this is R_2', this is X_2' and then this is what is our load, which we are calling as Z_L'.

We wanted to first of all determine all the parameters of this equivalent circuit which actually can be done by two tests. We said that actually loading the transformer is going to be difficult because we would end up wasting a huge amount of power and it will be very difficult for us to actually find the load which can withstand the rated current or rated power. That is the reason why we would like to determine the parameters, if it is possible by creating situations like applying rated voltage without really passing rated current.

And second situation applying or passing rated current, whereas applying only a fraction of the rated voltage. So, we are not really loading the transformer to the fullest extent, neither by the current, or nor by the voltage, that is what we are trying to do. So, in this case we initially talked about OC test. So, in OC test, what we said was that we are going to have the transformer connected through a wattmeter, and a ammeter. So, this is actually applying the voltage to the winding which will be the low voltage winding.

We are going to call this as LV winding, whereas the winding which is actually open circuited, that is going to be HV winding. So, now we will also measure the voltage what is applied here, so, we are going to call this voltage as V_1, whatever is applied is V_1. So, what I get as the reading will be V_1, I_1 and maybe W_1. Rather I name these as V_0, I_0 and W_0 to specify that this is no-load condition.

So, I am going to show this as I_0 and this has W_0 and of course the voltage applied here is rated voltage. And it may be very difficult for me to find the rated voltage if I am choosing the high-voltage winding which is to be excited. That is the reason I am trying to conduct this test by applying the voltage on the low voltage side, just for logistics reason. So, this is what we are doing and then we got basically W_0 equal to $W_0 = V_0 I_0 \cos\phi_0$. So, I should be able to get exactly what is $\cos\phi_0$ or the no-load power factor.

From which and from the phasor diagram we drew earlier, if this is V_0, I am going to have actually this as I_C and this as I_m and the addition of these two, I am going to get as I_0. So, I am looking at $I_c = I_0 \cos\phi_0$. And we can say $\frac{V_0}{I_C} = R_C$, And I am going to have similarly I_m or the magnetising current is going to be $I_0 \sin\phi_0$. So, I am going to write $\frac{V_0}{I_m} = X_m$ is equal to Xm.

So, I have got the parameters which are corresponding to the parallel parameters. That is whatever is my R_C and X_m, that is it, these two are determined based on my no-load test or open circuit test. I am not loading the transformer, I have kept the secondary on open circuit, that is the reason this is known as no-load test or open circuit test. Incidentally the same circuit can be used for determining BH loop but with a little bit of modification.

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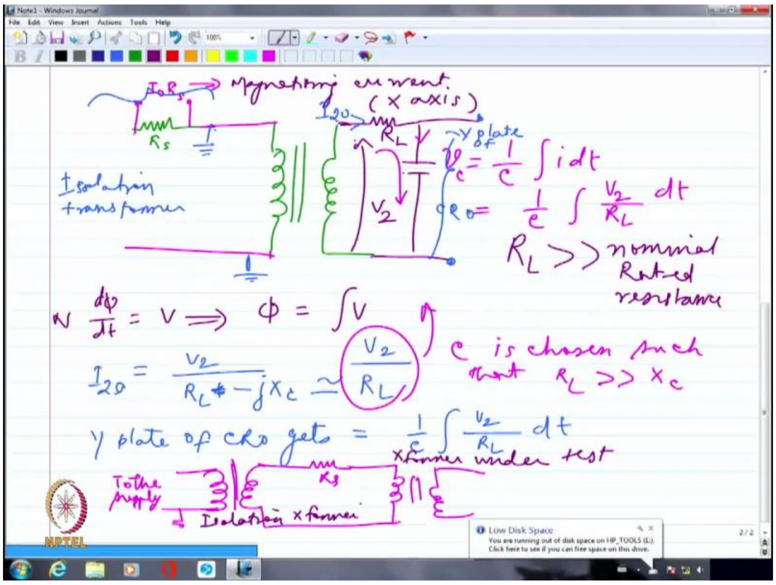

So, we are actually looking at the transformer under open circuit conditions. So, I am still showing the transformer under open circuit, the secondary is on open circuit. The primary is applied with the normal magnetising current because it is our open circuit, let me put the small resistance in series with the primary winding, so that the drop in the series resistance will be, whatever the series resistance, let me call that as R_S. So, R_S multiplied by I_m, whatever is the magnetising current or the no-load current, that will be the drop across the series resistance.

So, if I may call this as R_S, I am going to look at the drop across this as I_0Rs, that is going to be the drop. So, what I get there is the voltage, the voltage is actually giving me the no-load current multiplied by the series resistance. And this series resistance is known to me. Let us say I am able to measure this with the help of you know a multimeter or whatever and I know the values, so I can say I_0Rs is a series resistance. I_0R_S is the drop.

Now this is connected to the primary side and on the secondary side I would like to get the measure of the flux if I can, because if I get the flux and if I get the magnetising current or the no-load current, I am going to neglect the core loss component of current. I am assuming that the entire current that is flowing is approximately the magnetising current, Because I will not be able to segregate the two components of current you know physically or experimentally.

I can do it theoretically, but I cannot do it actually physically or experimentally. So, what I am assuming is the no-load current that is passing through the transformer is same as that of the magnetising current, approximation, that is what I am doing. Now, this voltage drop I_0R_S

will tell me what is actually the magnetising current quantity. So, this will obviously go to the x-axis of the plotting of V vs H, if I want to plot, I will give this to the x-axis or X plate of the CRO. That is what we were doing if you may recall.

This will go to the X plates of the CRO. So, I will put the CRO in XY plot mode. Now what I want is the flux, the flux has to go to the Y plate. So, to actually give the flux value directly, rather than that I can say normally $\frac{d\phi}{dt}$ is voltage, this we know, $N\frac{d\phi}{dt}$, maybe let me write that like that. So, I can indirectly say if I want flux, I should be able to integrate the voltage. If I integrate the voltage, I should be able to get actually whatever is my flux.

So, instead of getting the voltage integrated, what I am going to do is to connect first of all a resistance and put a capacitor here. Let's say if I do it, what is going to happen? Now, the current, the voltage is V_2, let me say it is V_2, I am applying some voltage V_1 on the primary side, V_2 is induced on the secondary side and it is on no load, so hardly there is any drop, the entire voltage is coming up. This resistance is going to be a very large value, let me call that as R_L.

This R_L is going to be a very large value. What I mean by large, again large and small relative. If I say it is a 2.2 kVA 220 by 110 V transformer, repeatedly whatever we had used earlier, I am just using it again. 5.5 Ω is my normal secondary resistance, if I want the secondary current to be at rated value, but instead of 5.5 Ω if I use maybe 200 Ω or 300 Ω, I would call that is a very high resistance compared to the nominal resistance.

So, I am going to look at a resistance which is way too high as compared to the nominal or rated resistance that I may connect, such that the rated current flows through the transformer. So, R_L is going to be much higher than the nominal rated resistance of the transformer. Not resistance of the winding of the transformer, I am talking about resistance which I will connect as the load resistance normally. So, instead of 5.5 Ω, I may end up connecting 200-300 Ω, very large resistance.

Now, I have a capacitance also, so if I try to look at what is the current that is flowing here. Let me call this as some I_{20} because it is still considered to be no-load. If I had connected 5.5 Ω, I would have gotten maybe 20 A. Now that I am connecting 300 Ω, the current will be negligible literally. So, I am calling that as I_{20} because it is at almost 0 load. So, $I_{20} = \frac{V_2}{R_L - jX_c}$.

If I choose the capacitance is such a way that R_L is much higher than X_C, I can definitely choose the capacitance, it is $\frac{1}{\omega_C}$ after all. So, if I try to look at the overall impedance, it will be $\sqrt{(R_L)^2 + (X_C)^2}$. If X_C is really small, you know, I can say $\sqrt{(R_L)^2 + (X_C)^2}$ is approximately equal to R_L itself. So, I am going to choose the capacitance is such a way that this impedance is almost equal to R_L.

So, I am going to have this as my I_{20}. So, I should say that C is chosen such that R_L is much higher than X_C. So, because of which I can say the current is mainly dependent upon R_L only, nothing else. So, I can substitute this here, if I try to look at what is the current that is flowing here, please remember CRO terminals what I have is like voltmeter terminals. So, obviously there is hardly any current going into the CRO.

So, the entire current that is flowing here has to flow only through the capacitance. So, I am having the current to be $\frac{V_2}{R_L}$, so the current through the capacitor will also be $\frac{V_2}{R_L}$, but the voltage across the capacitance will be $\frac{1}{C}\int i.dt$, that is what is the voltage across the capacitance, which will be $\frac{1}{C}\int \frac{V_2}{R_L}.dt$.

So, we are integrating the voltage indirectly by passing the current through a capacitor. So, what I am getting as the capacitor voltage, which I am plotting in the Y axis of the CRO is a measure of flux, of course it has some multiplication factor like $\frac{1}{R_C}$. I do have definitely a multiplication factor, no doubt, but it is a measure of flux. So, what actually I am going to get across the Y plate, so this is going to go across the Y plate of CRO, this terminal will be connected to Y plate, that will go to the Y plate of CRO.

So, what I am getting across the Y plate of the CRO I can write it as Y plate of CRO gets basically $\frac{1}{C}\int \frac{V_2}{R_L}.dt$, this is what is coming. Which is actually equal to $\frac{\phi}{N}$, because $N\frac{d\phi}{dt} = V$. So, obviously if I am only looking at voltage, it is $\frac{V}{N} = \frac{d\phi}{dt}$. So, $\phi = \int \frac{V}{N}dt$.

So, I am getting a measure of flux, I am not saying it is exactly flux per unit area, flux per whatever unit turn, I am not saying that at all. I am basically saying that I am getting a measure of flux, as simple as that, that is all. So, what we do in the BH loop experiment is to send this to X plate and send this to Y plate. So, this goes to Y plate and this goes to X plate. So, what I am getting in the X plate is not really H and not even I_m in amperes, it is rather I_m multiplied by whatever is the series resistance I have got.

That is the reason why if I want really in amperes, whatever is the magnetising current, I have to divide it by R_s, R_s I have measured, so it is not a big deal. So, what I am getting is not directly I_m in amperes, I am rather getting I_m multiplied it by Rs in volts. So, ultimately, I have to scale everything to get the hysteresis loss. So, this is essentially the principle behind BH loop. But I hope you understand the principle behind the experiment.

One word of caution in this experiment, when I connect this to H plate, and connect this to Y plate, please understand that the CRO will have in X plate, there will be two terminals, in Y plate also there will be two terminals. So, one of them will be grounded and the other terminal will be given to the signal or vice versa, we do not know. It is after all AC, so I do not even know whether I am going to ground this terminal or this terminal.

So, if I by chance ground this terminal for example, whereas this terminal of the transformer is grounded probably. It is as good as short-circuiting that particular complete you know the connection itself, the primary is short-circuited. So, I do not want that to happen, that is the reason why the CRO ground is anyways collected to the main ground of the laboratory, I can’t help it, that is done already, I can’t do anything. That is the reason why we use an isolation transformer here.

There will be an isolation transformer at this point. The isolation transformer, all it does is it will be a 1:1 transformer. So, what I will have is an isolation transformer in the input side like this and I am going to connect this to the supply. So, I know for sure that probably this side is grounded, it doesn’t matter. From here I will connect it to R_S and whatever I have to do and then I will connect it to this transformer. So, this is the transformer under test. So, this transformer will be transformer under test, whereas this transformer will be isolation transformer.

So, now after all the transformer under test and the transformer which is connected to the other side, they are not connected together. In terms of electrically they are not connected together. The primary and secondary of the isolation transformer are isolated from each other, there is no connection directly between the ground of the primary of the isolation transformer and the secondary of the isolation transformer. Now, I do not have to worry, all the grounds are separate.

So, I do not have to worry that something is really going wrong with the entire connection that will not happen. So, normally BH loop experiment will never be conducted without an isolation transformer. The isolation transformer is only meant for making sure that nothing is short-circuited inadvertently, without knowing some ground is connected to some other ground.

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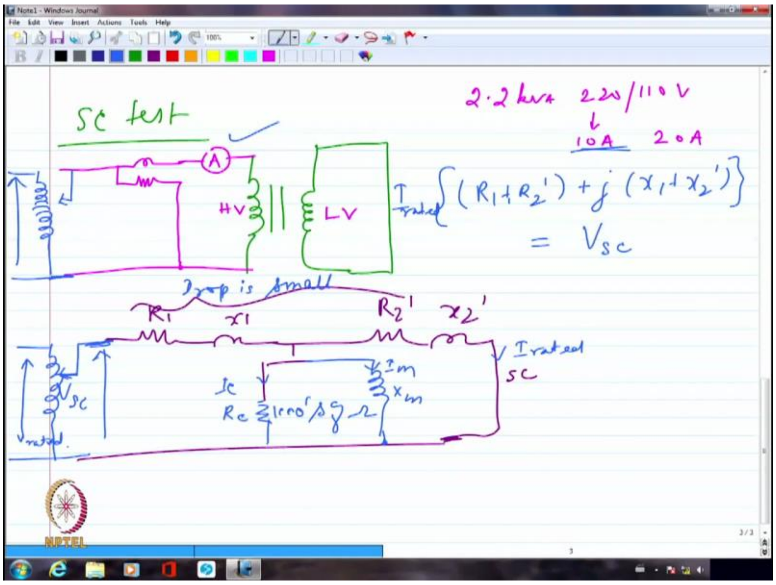

Professor: Auto transformer cannot be used as an isolation transformer. Auto transformer cannot be used as an isolation transformer because it has only one winding. The primary and secondary are not isolated. So, if I have a ground for primary, it is very much the ground for secondary also, I am not differentiating between them. So, auto transformer cannot be used as an isolation transformer.

So, let us try to look at the short-circuit test. So, in the short-circuit test, as the name indicates, I am having the transformer here and I am going to short-circuit the secondary. The secondary normally is chosen to be the low voltage winding in this case. So, I would try to apply the power supply from the high-voltage side, whereas this is LV. High-voltage winding will have lower current obviously. I want to pass rated current 220 by 110 V.

We got 20 A as the current on the low voltage side and on the high-voltage side it was only 10 A. So, high-voltage side if I energise and if I have to pass rated current, then I don't have to worry so much because I do not have to look for very high current value source, I do not have to look for that. So, I would always try to energize the high-voltage side when I am conducting the short-circuit test.

But, I have to keep an eye on how much is the current that is flowing because I do not want to exceed whatever is the rated current value. So, I have to continuously keep an eye on the ammeter. So, normally I will connect an ammeter in series in this case also. And of course, I would like to measure the power, so I would also connect a wattmeter very clearly. See, if I am talking about again 2.2 kVA 220 volts by 110 V transformer, corresponding to 220 volts I have only 10 A, as the rated current.

Whereas for this I have to look for a 20 A source if I want to push rated current through the winding. I am connecting the source on the HV side, so my source has to pump in only 10 A, not 20 A. So, I am always looking at lesser amount of value being applied, whether it is current or voltage from my source. So, in this case I am not going to apply rated voltage anyway, I am going to apply only rated current.

That is only present in the high-voltage side. So, I am using the high-voltage side for energising. Now, we have the equivalent circuit of the transformer as R_1, X_1 and of course $R_2^{'}$ and $X_2^{'}$, let me forget about the parallel values, doesn't matter. Now, here I have short-circuited, this is the short-circuit, I completely short-circuited this portion, which means the impedance that is limiting the current in the series path is $(R_1 + R_2^{'}) + j(X_1 + X_2^{'})$, that is all is limiting the current.

And if you look at $(R_1 + R_2^{'})$, I told you that they will be very small because I am not going to really let a huge amount of voltage drop within the transformer, I want to design the transformer well so that it doesn't eat away all the voltage that I am applying. So, $(R_1 + R_2^{'})$

is also going to be small and there is hardly any leakage because there is not much of air gap, so, the leakage reactance's are also going to be very small.

So, overall the drop that is taking place here, I would say the drop is generally small, unless I deliberately design a bad transformer which is generally not done. So, I would see that to pass rated current, now I want to pass only rated current, this is I_{rated}. So, in this case it is 10 A for example, so, I will have $I_{rated}\left((R_1 + R_2') + j(X_1 + X_2')\right)$, this is actually whatever is the voltage that I have to apply on short-circuit.

Under short-circuit conditions if I want to pass only rated current through the primary winding, I am reading it continuously and I do not want that to exceed the rated value, the impedances $(R_1 + R_2') + j(X_1 + X_2')$, so that multiplied by rated current should have been the applied voltage from the primary side, so that it will only actually you know put the rated value of current passing through the transformer windings, whether I look at the primary or secondary, if I limit the current to rated value, both of them will be limited to rated value.

So, I am going to have essentially the voltage applied during the short-circuit test to be much lower than the rated value of voltage. So, under short-circuit test, whatever is the voltage I apply, indirectly it gives me an indication of what are the internal impedances of the winding of the transformer, it gives me a feel for what is $R_1 + R_2'$, what is $X_1 + X_2'$.

So, if the voltage applied during short-circuit test is only 10 percent of the rated value, that means the voltage drop that is taking place within the transformer winding is only 10 percent of the rated voltage. If it is 5 percent, that means I have even lesser amount of impedance internally within the transformer, so the voltage drop becomes less.

Student: (())(27:29) Is the voltage drop in the transformer during SC test zero? And are the iron losses negligible during the SC test?

Professor: It is not 0, it is very small. See, if I am talking about R_C, I said basically that R_C is you know taken to be generally in such a way that it balances whatever is the hysteresis and eddy current loss. And I am going to have very low hysteresis and eddy current loss in a transformer, hysteresis loss I don't have much control but eddy current loss I am decreasing as much as possible. If I am decreasing the eddy current losses and hysteresis losses quite a bit, that means I_C is going to be really small.

If I_C is a small, R_C has to be quite a lot, $I_C^2R_C$, please note that I_C has more influence on the losses than R_C itself because R_C power 1, whereas I_C power 2. So, I_C I want to minimise, if I want to minimise I_C, R_C has to be increased quite a bit. So, R_C normally in a transformer will be like 1000 Ω, maybe more. So, the better the design of the transformer, R_C value will almost tend to infinity, it is not infinity, compared to the winding resistance it will be very high..

So, this will be some thousands of volts. Similarly, X_m is also essentially talking about what is the mutual inductance between the primary and secondary in one sense, because that is the one which is talking about the common flux that is existing between primary and secondary. So, if I do not have much of air gap, obviously the coupling between the primary and the secondary has to be pretty much intact. So, I am looking at this, actually this X_m value is an index of how permeable the core is.

So if the permeability of the course is pretty good, X_m will be a very high-value. So, higher the value of X_m and higher the value of R_C, I would say that the transformer is getting closer and closer towards the ideal transformer. So, normally this is I_C and this is I_m, which put together actually make up for my no-load current and the no-load current is less than 5 percent. So, I really do not have to take that into consideration, when 10 A is flowing through the primary winding, this may be 0.04.

So, 0.4 or 0.3, I do not have to worry so much to take that into account. That is the reason why I am neglecting it. So, this V_{sc} what I applied normally done through, it will be done through an auto transformer. So, I am going to show the auto transformer here and this is applied by only influencing or applying the voltage with respect to only a fraction of the total turns available in the total auto transformer winding.

So, this is where I apply 220 V or 230 V. So, I am going to apply V_{rated} probably at this point. Rated voltage is applied here, from there is a variac or auto transformer, from the auto transformer this is the variable jockey point which is going to probably be put at very minimum number of turns. So, what I will do is slowly increase the voltage applied by increasing the jockey position of the transformer or rotate, I have to rotate it and then make sure that I don't exceed the rated current.

So, I cannot really, directly apply this here, so let me show this here again, this will be connected to a variac like this. So, the earth point please note is the same. So, variac cannot isolate, it cannot isolate between the primary of the transformer under test and the power supply, it is not isolating, it is actually the same earth between both of them. So, I have to have the power supply connected here, that is where 220 V is connected.

Student: Why cannot we apply full voltage in SC test? Is isolation transformer required for OC and SC test?

Professor: If you are applying only less amount of voltage, where will the current come from?

Student: How do you know that this is the rated current?

Professor: See you have an ammeter connected. So, this ammeter you have to keep an eagle eye on that continuously.

Student: That you have to check?

Professor: Yes.

Student: Like that if you do the open circuit test (())(32:50).

Professor: You apply rated voltage.

Student: (())(32:52).

Professor: No, that is in BH loop. You will not have an isolation transformer in all the no-load tests, not at all. That is why I said that is another little diversion I have taken, let me go back to the previous slide. This is actually our no-load test. So, this is actually our no-load test. This is actually the BH loop, I think this is the no-load test. So, this is the open circuit test, where I have not shown any isolation transformer, what I could have shown is directly apply it through a variac and the variac in all probability will be connected to the top point, no isolation.

Open circuit test does not require an isolation but if I am plotting a BH loop, because I am connecting the power components directly to the CRO and CRO is meant only for electronics components, not meant for power components. I am mingling the two, I better take precautions.

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

Professor: You can use but why would you like to do it? Because isolation transformers are costlier, auto transformers are less costly and you do not need to separate the earth. Unless you have a requirement to separate the earth, you generally do not use an isolation transformer. In the laboratory we can do anything but if I try to go to an industry and ask for an isolation transformer for this kind of job, they will kick me out. So, I have to see what is done most economically.

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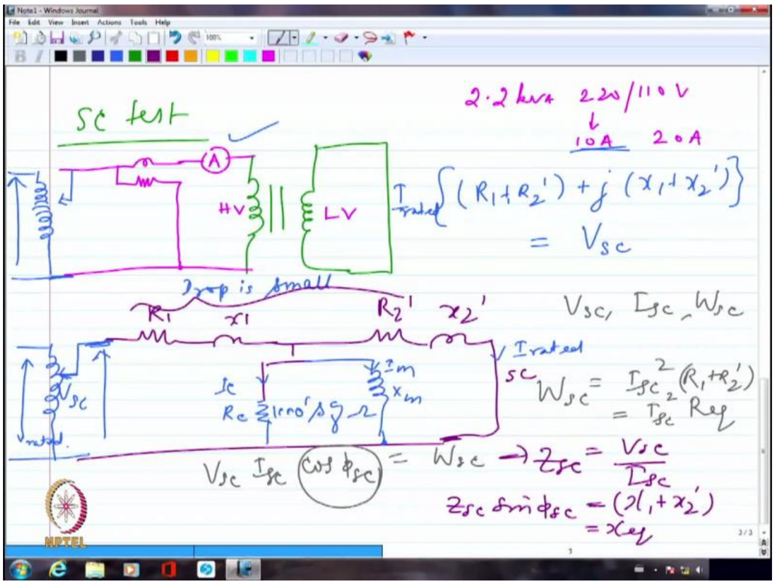

So, let us look at now the short circuit test calculations. So, I am going to have V_{sc}, I_{sc} and W_{sc}. W_{sc} will give me only the real power quantity, which will be very clearly $I_{SC}^2(R_1+R_2^{'})$. Only two resistances are there and only they can dissipate real power. So, what I get actually as W_{SC} will be $I_{SC}^2(R_1+R_2^{'})$, and from here I should be able to get what is the value of R_1 and $R_2^{'}$.

Generally it is very difficult to separate out R_1 and $R_2^{'}$, similarly it is very difficult to separate out X_1 and $X_2^{'}$, most of the times we take it as what we get as the total resistance divided by 2, we will take as R_1, similarly total resistance divided by 2 we will take it as $R_2^{'}$, which is okay for all practical purposes. If I had measured the resistance already of the primary winding at the insufficient stage, then it is different.

Otherwise R_1 and $R_2^{'}$, similarly X_1 and $X_2^{'}$, it would be very difficult to segregate. I would only get the total value, so I may call this as R_{eq} . I may call this as R_{eq}. Similarly, I can say that $W_{SC} = V_{SC} I_{SC} \cos\phi_{SC}$, from which I know what is $\cos\phi_{SC}$. Once I have $\cos\phi_{SC}$, I can directly get the impedance from V_{SC} and I_{SC}, it is a series circuit mind you unlike open circuit test.

In open circuit test it was a parallel equivalent circuit, so we were trying to look at the currents being divided, here the voltage is getting divided between R and X. So, I can say basically in this case as $Z_{SC} = \frac{V_{SC}}{I_{SC}}$, so I can say $Z_{SC} \sin\phi_{SC} = X_1 + X_2^{'}$, which I may call as X_{eq}. So, I have got X_{eq} and R_{eq} of my transformer windings, which will account for the series parameters in the equivalent circuit.

Once I have these, that is R_{eq}, X_{eq} and the no-load losses, I should be able to assist the performance of the transformer under different load conditions whatever I imagine, not a problem, because I know the parameters of the transformer. If I had to load the transformer, the same 220 by 110, 2.2 kVA transformer, how much of power I would have wasted up because I should load it probably for first 2200 W, then I have to do it for maybe 1100 W, 1000 W and so on and so forth.

And then I will have to see how I am getting the voltage at the terminal and what is the kind of efficiency or the wattmeter reading that I am getting. So, it would definitely entail a huge amount of loss. Which actually I would be dissipating in the external resistance. And at least it is 2.2 kVA I can manage the show, if it is 400 MW, I really had it. So, I cannot really expect to be loading a 400 MVA transformer with the help of a proper resistance and things like that.

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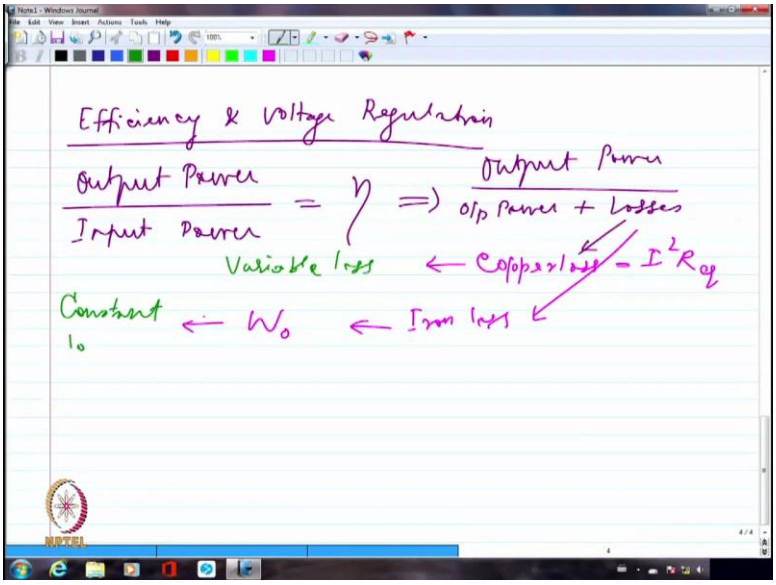

So, now that we have seen these two tests, let us try to now look at the two performance parameters of the transformer, one is efficiency and the next one is voltage regulation. So, if I am looking at efficiency. The efficiency is defined as in terms of power, real power. So, I have to say output power divided by input power, this is what is efficiency. Output power, maybe I am giving it to an induction motor, I am giving it to a resistive load, I am giving it to probably a heating unit, maybe I am giving it to whatever apparatus I am having.

I may be having some way of measuring it. So, I may be able to measure the output power, or I may say that I want an output power of maybe 250 W from this transformer. So, in which case how much should apply from the input side, I should have a fairly good idea. That is the reason why generally the parameter estimation of a transformer becomes extremely important, that tells you indirectly, internally how much the transformers are going to swallow and how much will you get at the output.

So, if I want so much of power output from the transformer, really how much should I be supplying, this is one thing. Second thing is if I know that out of the 250 W output of a transformer, maybe it is going to dissipate 20 W, to that extent the transformer will get heated up. So, am I providing adequate cooling for the transformer, will the transformer get overheated, because of which the surrounding components will also get overheated and ultimately it will result in a failure.

For example, in your PC you have that SMPS, that SMPS will always have a transformer inside. That transformer probably is going to carry only about 300 W of power, nothing more than that, but out of 300 W of power, maybe it will be dissipating 20-25 W and it is a pretty constrained space, there is hardly any space available. So, you might have to make sure that adequate cooling is being done. So, if adequate cooling or circulation of air is not available, I might have to fit a small fan.

That will consume more amount of electricity, that is different, but I have to make sure that nothing fails. So, we would say that the efficiency estimation becomes extremely important from these two viewpoints. How much is the input power I have to give and how much of the cooling that I have to make sure that is available for the apparatus that I am using. So, I can say this as output if I am able to measure, output power divided by output power plus losses.

So, what are the two losses? Losses will correspond to copper loss, which is actually I^2R loss, nothing else. So, I have to write this as $I^2 R_{eq}$, because I am rather putting together R_1 and $R_2^{'}$. I may not be a constant, are you getting my point, depending upon how much is the resistance I have connected on the secondary side, if I connect 5.5 Ω in the 2.2 kVA transformer, it will be supplying rated power of 2.2 kVA.

If I connect 10 Ω, then correspondingly I will have 1_1 A only instead of 20 A. So, the current is the variable one depending upon what kind of load I have connected. So, these copper losses are also known as the variable losses, these are variable losses, they are not constant loss, this is known as variable loss. The second kind of loss I have is iron loss or constant loss, which we already saw that that is corresponding to $I_c^2R_C$.

If I try to say it in terms of equivalent circuit, I can say that also that this will be equal to hysteresis loss plus eddy current loss or I can also say this is W_0, what I got as a no-load circuit, you know when I did no-load test, I got some W_0, I applied rated voltage at rated frequency, so hopefully the flux is at rated value. If the flux is at rated value, I should be able to get whatever is lost as the iron loss. So, this is actually the constant loss.

So, in the next class we will try to look at the actual efficiency expression and the variable load conditions, we will derive the conditions for maximum efficiency. One particular point I had forgotten which I have to mention in the next class as to why the wattmeter reading in no load test represents only iron losses, why the wattmeter reading in the short-circuit test represents only I square R losses or copper losses, why not the other way around.