Basic Electrical Technology
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Lecture - 21
The Practical Transformer – II

In the last class we discussed about the practicals practical transformer. We looked at the features of the ideal transformer. We saw that the ideal transformer required features like infinite permeability, infinite saturation flux density, hysteresis loop area should be zero, resistivity of the core material should be infinite and of course the resistivity of the coil at the winding that is coiled around the core should also be zero so that there are no copper or core losses in the core.

Now we saw that the practical transformer has all of these features which are not which are finite and therefore they there will exist core losses and there would also exist a finite permeability and because of this we included in the equivalent circuit of the transform of the ideal transformer extra two elements: one element called the R c which represents the core losses, another element called the X m which represents the magnetizing inductance which means the current needed to magnetize the transformer. In the case of the ideal transformer there was no current needed to generate the flux.

So today we will go ahead and introduced introduce the other non-idealities, other imperfections to the ideal transformer and see how the overall equivalent circuit will look like. So till now we have an ideal transformer. So we have 1 is to n and to this ideal transformer we have put a resistance R c in parallel and also an inductance which gives an inductive reactance X m. So, to the primary we connect a source an AC source e g and the induced emf is e 1. There is a current i 0 flowing and through the core loss component there is a current I c flowing and through the magnetizing inductance there is a current I m flowing and through the ideal transformer i is equal to 0 if there is no load connected across the secondary and what you have here is e 2.

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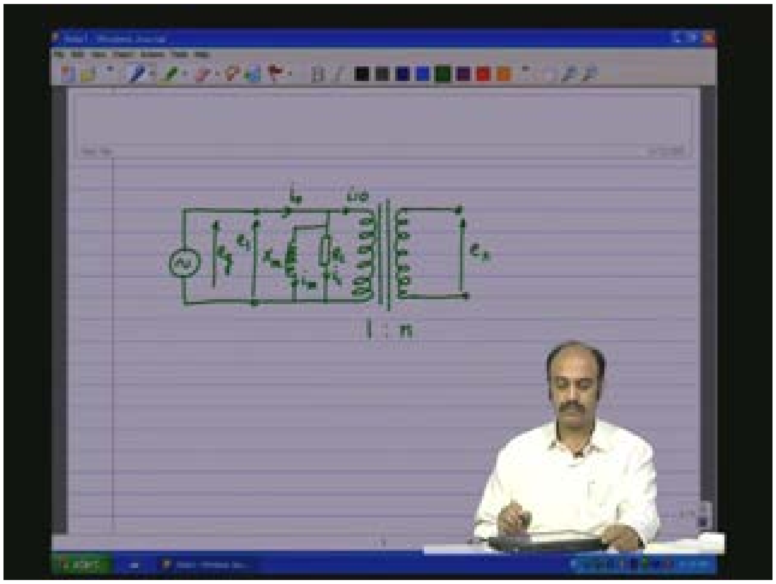

Now at this point let us formulise some notations. We have been interchangeably using upper case for the voltages, lower cases for the voltages, upper cases for the currents and lower cases without without being very consistent till now. But actually we have actually the lower cases where e 1 e 2 e g i 0 i m so on would imply instantaneous values. values So the instantaneous values you draw the vector diagram and if we if we are drawing the phasor diagram we said that the values of the vector represents rms values the routine square value or the effective values of the quantities.

So we shall use the notation with upper case for effective values; i 0 for the rms values, I c for the rms values, I m for the rms magnetizing current, e 1 has the rms value of the effective value of the induced emf, e g effective value of the applied generated voltage at generator voltage. Therefore e 1 e 2 e g I 0 I c I m so on they would represent the rms or effective values. So, from now on as we are going to draw phasor diagram in almost all the circuits that we will be discussing in future, we will try to use these upper case notations for the rms and the effective values and therefore the diagram would be phasor diagram and if we use the instantaneous value then those diagrams would be called the vector diagram.

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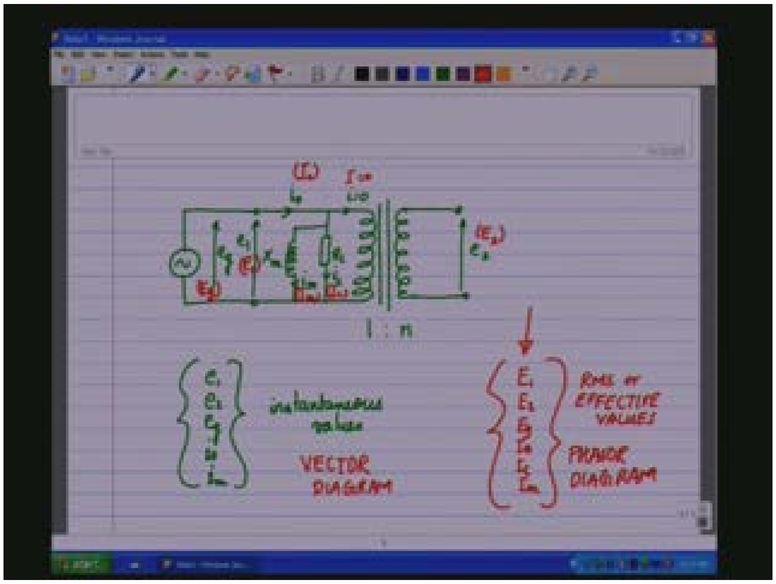

Coming back to the transformer we have the transformer the ideal transformer, this is the ideal transformer (Refer Slide Time: 8:00) and to the ideal transformer we have attached two components: the core loss component and the magnetizing inductance component or the magnetizing reactance component which indicates two non-idealities: one is the loss, that is there exists a finite hysteresis loop area and their exists eddy current losses which means finite resistivity and the other one is the X m which draw some magnetizing current which means to setup a to setup a flux in the core some amount of magnetizing current has to been drawn from the source and it is a reactive power that is being drawn from the source and therefore the magnetizing reactance except.

Now we shall introduce a few other non-idealities what is called the leakage component in the transformer. So, to understand this let us first take again an ideal transformer and the ideal transformer on the core on our normal rectangular core…………….. let me show the rectangular core like that (Refer Slide Time: 9:35) and we have the primary windings as shown, we also have the secondary windings wound on the same core as shown like this. This is the primary and the secondary. We have N 1 number of turns in the primary and we have N 2 number of turns of the secondary.

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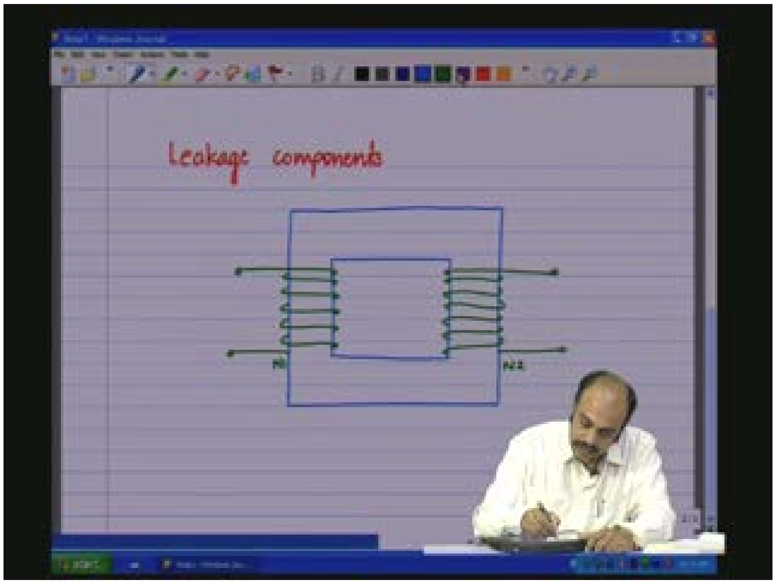

Now to this we shall attach a generator to the primary which is having an effective value e g and there is an induced voltage with an effective value e 1 across the coil. This being an ideal transformer if there is no load connected here and if there is a generator which is applied even with i is equal to 0 even with I 1 which is equal to 0 there is going to be a flux generated in the core and that flux generated in the core is something like that so we have the flux that gets generated in the core.

Now if there is no load here I 2 is equal to 0. Now there is a flux generated in the core and it is going to link with the secondary which is going to generate a secondary induced emf. Now this flux phi 1 m let us say during no load let us say 1 m 0 now this flux phi 1 m 0 is generated because a voltage source is generator is attached to the primary and as i is equal to 0 there is no ampere-turns, n i is 0 so there is no ampere turns to generate flux in the air and therefore all the flux is only in the core because the permeability is infinite in the ideal case and therefore all these flux linked to the secondary and it is going to produce a voltage at the secondary which is equal to 4.44 f N 2 phi 1 m 0. This is the amount of voltage that is going to get introduced or induced in the secondary across the secondary windings.

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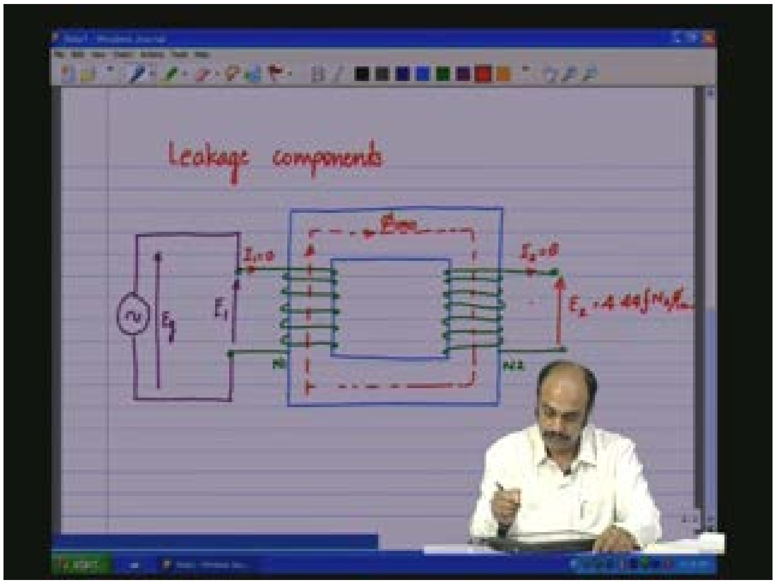

Now, on the application of the secondary load a whole lot things changes. the moment we apply the secondary load there is going to be a secondary current I 2, there is going to be a primary current I 1 which is not zero and these will induce a complex set of fluxes which interact each other and let us see what happens.

So first let us introduce a load. Let me now introduce a load on the secondary side. Now because a load on the secondary side has been introduced as Z 2 there is going to be a secondary current which is not zero and as a consequence there is also going to be a primary current which is at zero. So the flux is here or now N 1 I 1 is going to generate phi 1 m, this is generated by N 1 I 1. But there is also a possibility that some of the fluxes just loop back through the air like that; some of the flux is going to go through the core and some of the flux is going to look back through the air because now there is a finite NI which can drive the flux through the air which has a lower permeability.

Now this flux we will call it as the leakage flux which is not linking with the secondary, let us call that one as phi sigma 1. So in actuality N 1 I 1 N 1 I 1 is producing flux phi 1 but this phi 1 is this phi 1 is having two components phi 1 m and phi sigma 1. The phi 1 m component is called the mutual mutual component which links with the secondary winding, it is flowing through the core and links with the secondary winding, phi sigma 1 is called the leakage component and this does not link with the secondary.

Now because there is a flux phi 1 m flowing through the secondary there is going to be an induced emf in the secondary and that is going to be e 2 and that is driving a current I 2 through the low. now there is an ampere turns N 2 I 2 N 2 I 2 due to the fact that there is current flowing in this winding and this N 2 I 2 is going to give you an opposing flux in the core reason being that in the primary the power is flowing into the core and in the secondary the power is flowing out of the core. So we have an opposing flux which is flowing in the core material as shown like this (Refer Slide Time: 17:55); it is flowing in the opposite direction, this is an opposing flux N 2 I 2. Now this flux we call it as phi 2 m due to N 2 I 2. But phi 2 m is the flux that flows through the core links with the primary also. But this also produces ampere turns which pushes some flux through through the air yeah and it has a path something like that and this is called phi sigma 2 and this is the leakage component of the flux due to N 2 I 2 ampere turns and this phi sigma 2 does not link with the primary only phi 2 m links with the primary. Therefore we can from this simplify the flux pattern slightly by rewriting our transformer with its primary and secondary windings.

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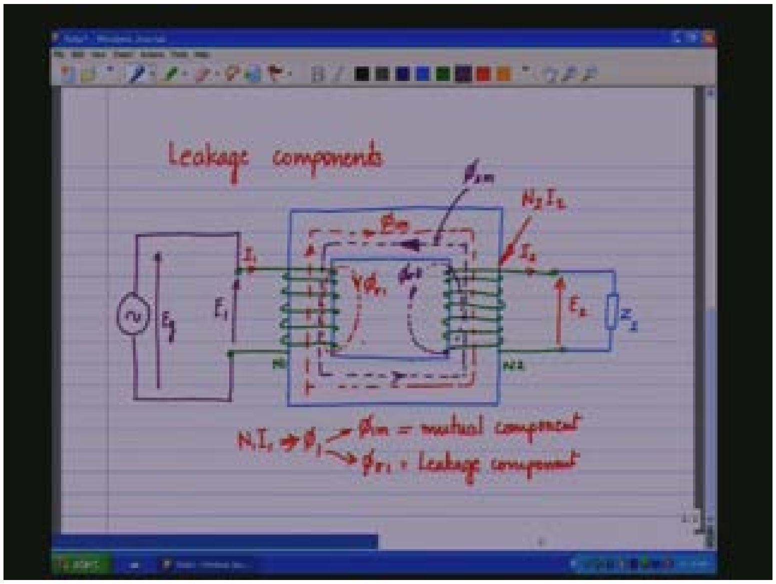

Leakage components

$N_1 I_1 \to \phi_1 \begin{cases} \phi_{1m} = \text{mutual component} \\ \phi_{\sigma 1} = \text{Leakage component} \end{cases}$

This the primary winding (Refer Slide Time: 19:42), this is the secondary winding which is connected to the load Z 2 which is connected to the load Z 2, there is a current I 2 which is flowing here, there is a current I 1 which is flowing here and there is a voltage source with effective value e g, also induced value e 1 e g equal to e 1 which is………….. now this is having N 1 turns and this is having a N 2 turns.

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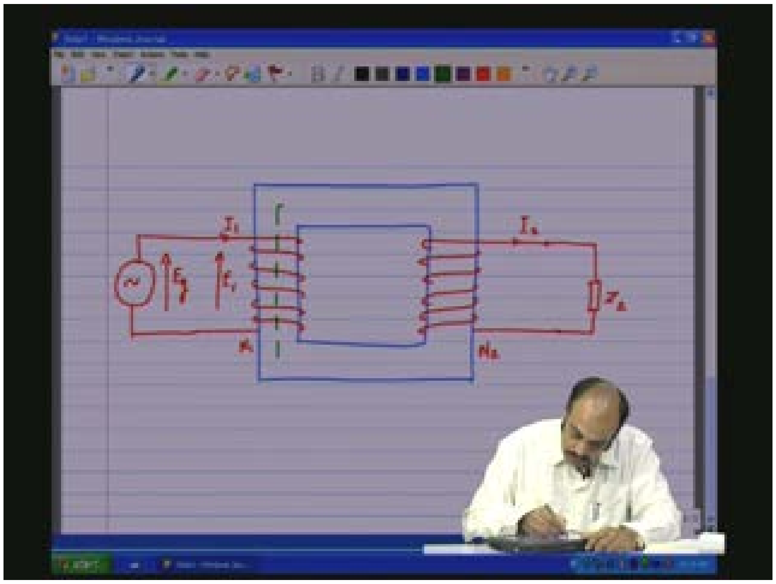

Here let us have the equivalent flux in the core which is which is flowing like this and we shall call that as phi m. the equivalent flux in the core, see we have phi 1 flowing in one direction phi 2 flowing in the opposite direction the equivalent flux phi 1 m minus phi 2 m vectorially would give you phi m and this is called the mutual flux let us say. And in the primary we saw that N 1 I 1 is producing flux phi 1 which has two components phi 1 m and phi 2 m sorry phi 1 m and phi sigma 1 phi 1 m is the mutual component and phi sigma 1 is the leakage component there is a leakage component here (Refer Slide Time: 21:31).

So we have a leakage component of the flux phi sigma 1 and likewise on the secondary on the secondary for N 2 I 2 ampere turns phi 2 is produced and this has two components phi 2 m and phi sigma 2 the leakage component. So the leakage component is not linking with the primary and that is what we are going to show here this is phi sigma 2. So we have three fluxes: the primary leakage flux, the secondary leakage flux and the mutual flux which links both the coils together. So if we look at even the induced voltages at the primary and the secondary now the secondary induced voltage is composed of two components, the voltage due to the mutual flux which links the primary and the secondary phi m which is 4.44 N 2 f phi m that is one component which is due to this flux and then varies as we call this one let us say e 2 just e 2 e 2 due to the mutual flux, then there is the other component which is due to the leakage flux here phi sigma 2 which is also linking the N 2 piles and that would be let us say E sigma………… let me just rename this as E mutual on the secondary side E leakage sigma on the secondary side the voltage across the leakage voltage induced due to the leakage flux which is 4.44 into N 2 f phi sigma 2.

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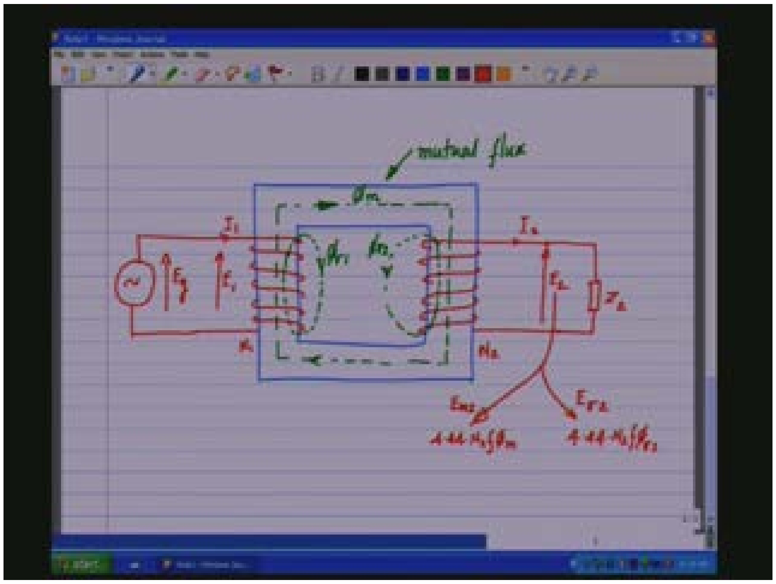

Now of course these two fluxes are not necessarily in-phase and therefore these two voltages are also not in-phase so it is vectorially they will add up to obtain the e 2 across the secondary. Likewise, the primary side also you have two components which are producing the induced emf: one component 4.44 N 1 now f into phi m this is the voltage that is induced due to the mutual flux flowing in the core which links both the primary and the secondary and the other component which is 4.44 N 1 f phi sigma 1 this is the voltage induced due to the leakage component of the flux which is linking only N 1 and not N 2. So these are the voltages that get induced due to the various fluxes.

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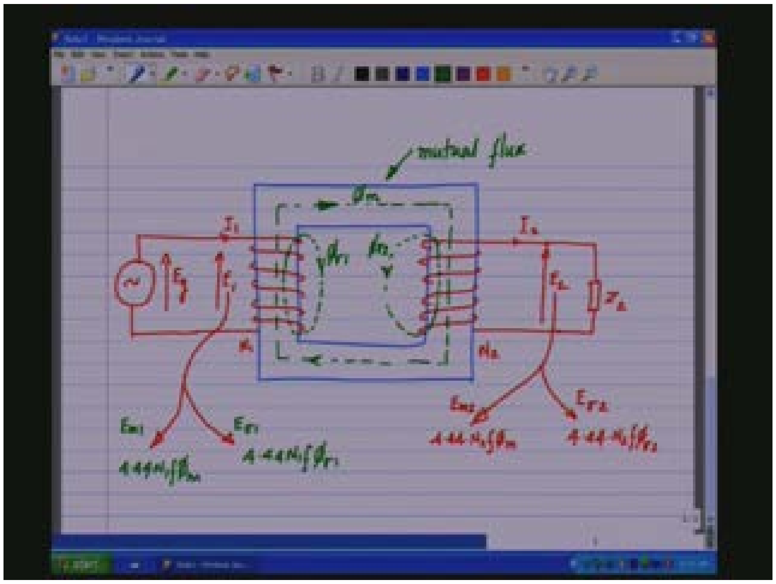

Now we can reconstruct our constructive equivalent circuit by up by probably looking at these voltages. We know that e 1 is the vectorial sum of the induced emf em 1 and e sigma 1 which is the leakage component. Likewise, in the secondary also it is the vectorial sum of E m 2 and E sigma 2 the leakage component.

So how does it look in the equivalent way?

So what we can do this flux here which is phi 1 (Refer Slide Time: 26:44) which is containing both the mutual and the leakage can be split into two windings: one which links with the secondary that will be the ideal transformer or rather which does not link to the secondary but still there is a flux, so we shall reconstruct it in this manner.

Let us have the transformer here and let us have this windings primary and the secondary as shown here (Refer Slide Time: 27:40). Now this has N 1 and N 2. Now here there is a current which is flowing through this coil and this N 1 I 1 is going to produce flux phi m in the core. So let us say this is an ideal transformer which means that all the flux is flowing. Now let us have a virtual coil here also N 1 turns, of course the flux is not flowing through the air so there is going to be a flux here equivalently let us say flowing through the air due to the fact that there is a current flowing through this coil and this coil the same current flowing through this coil and that coil and that is going to induce an emf which is E sigma 1 due to the leakage flux phi sigma 1 because a current I 1 is flowing through the coil. So this is an equivalent coil which is just producing the leakage factors that is it is producing the leakage flux this is producing the voltage which is being induced due to the leakage flux E sigma 1 and this is producing E m 1 the primary side induced emf due to the mutual flux which is linking both the primary and the secondary coils and this flux of course is called phi m mutual flux.

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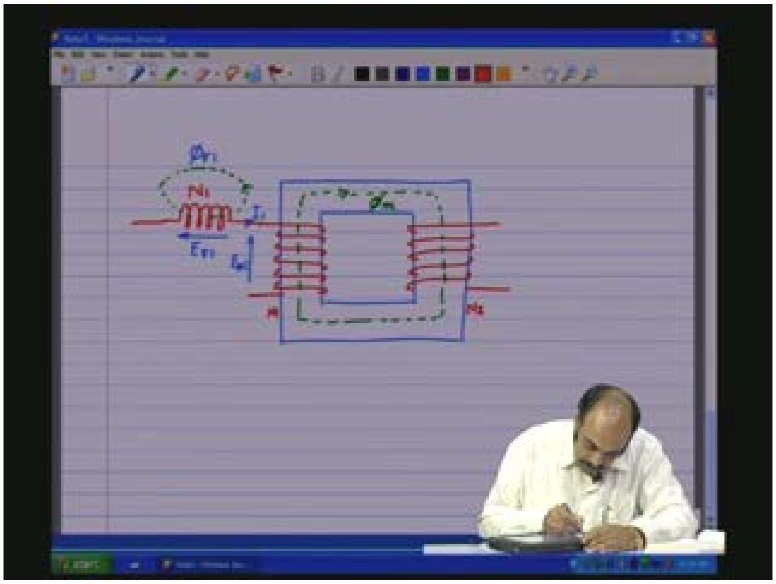

Therefore, if I compute the primary portion of the circuit you have generated so that is the generator here which has an effective value of the e g. Now, similarly on the secondary side there was a flux due to a current I 2 flowing in the N 2 coil which produced a flux phi sigma 2 and this flux phi sigma 2 will produce E sigma 2 as the will produce E sigma 2 as the induced emf due to the leakage flux and we have E m 2 an induced emf across the coil due to the mutual flux and on completing the circuit here we have the load Z 2 and this would be the terminals of your transformer, this is going to be e 2 (Refer Slide Time: 31:34) and this is of course e 1.

Now what we have done is we have brought out the leakage fluxes and that component of the reactance which is which is actually the voltages that are induced due to the leakage fluxes out on both the primary side and the secondary side and therefore and therefore here you have X sigma 1 the leakage reactance on the primary side which is equal to E sigma 1 by I 1 E sigma 1 by I 1 and on the secondary side the leakage reactance is equal to E sigma 2 by I 2.

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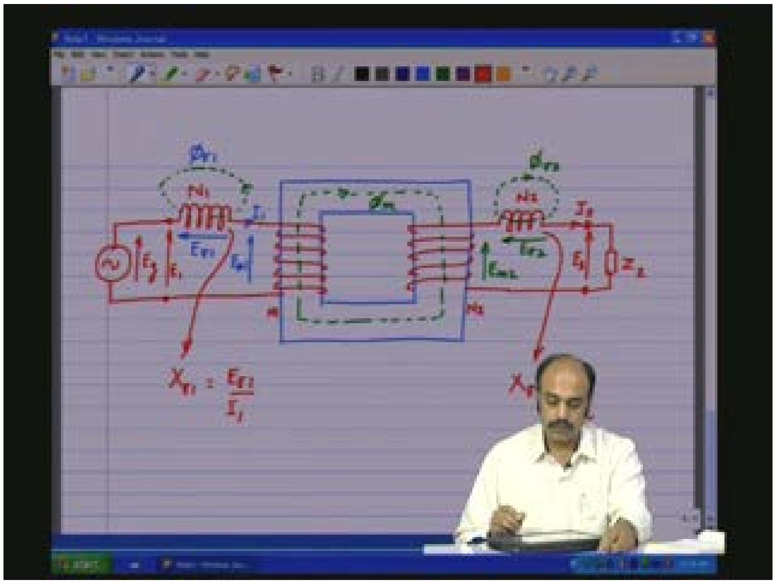

Now there is one more non-ideality to add and that is the winding resistances. So, the windings the coils which are wound on the core here they are physical wires made of copper or aluminium and therefore they have finite resistances. but depending upon the length of the wire the value of the resistance can be fixed or measured and that is going to be in series with the coil and the coil themselves in the ideal transformer can be assumed to be having zero winding resistance which means we bring out here the resistance of the coil we bring out here the resistance of the coil and say that this is R 1 and then we bring out the resistance of the coil the secondary side and that we call it as R 2.

So R 2 is the coil resistance of the N 2 turns, R 1 is the coil resistance of the N 1 turns. Now this transformer here we said was ideal. but if this transformer this portion of the transformer this is now consider to have the imperfections of the core loss and the magnetizing inductance then the equivalent circuit what we discussed in the last class would come into place in this portion. So the entire equivalent circuit can be written in the following manner.

So we have a source with generator voltage e g and this source is connected to the terminals of the transformer and this would be e 1 the terminals of the transformer (Refer Slide Time: 35:38). Now from their primary side terminals if we go you have first R 1 the winding resistance and then we have an inductance which is going to give an inductive reactance L sigma 1 the leakage inductive reactance on the primary side and then further going down we have two components that we discussed in the last class which is the core loss component and the magnetizing inductance component core loss component and the magnetizing inductance component X m and R c and this goes into the primary of the ideal transformer the ideal transformer. The secondary of the ideal transformer contains the leakage reactance of the secondary, this is followed by the resistance of the secondary coil N 2 terms and that gets terminated as the secondary terminals and there we have the load across the secondary terminals so this would be our secondary.

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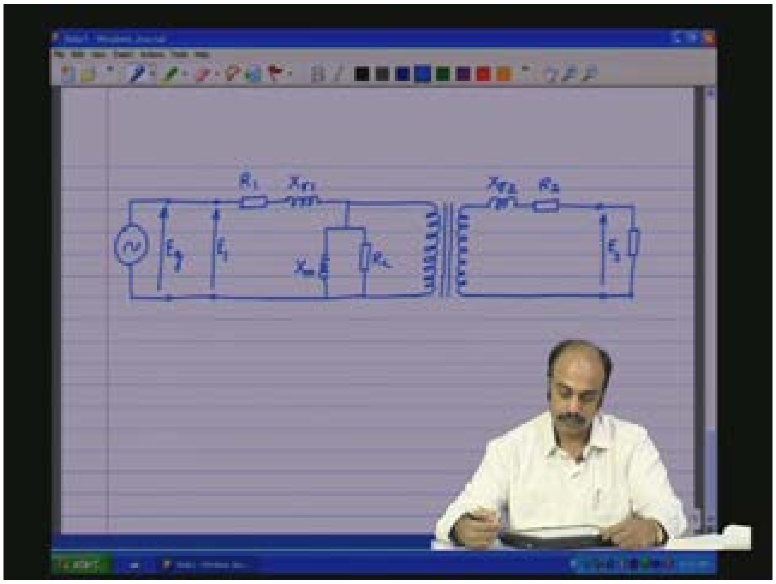

So if you see here 1 2 3 4 this is the practical transformer. So, if I draw this red enclosure here the practical transformer which has terminals 1 2 3 4 this portion is an ideal transformer so the practical transformer is composed of the ideal transformer plus non-idealities which are represented in terms of circuit elements that is the leakage reactances X sigma 1 and X sigma 2, magnetizing reactance X m, core loss resistance R c, primary side coil winding resistance R 1, secondary side coil winding resistance R 2 so this would be a practical transformer. And actually to you what will be available is the terminals 1 2 3 4 and everything else is a black box and all these are embedded inside the transformer which are not available to you as physical quantities. However, the values of these can be obtained through some measurements which we will discuss much later. But for now this would be the complete equivalent circuit of the practical transformer. So then we have to define the currents.

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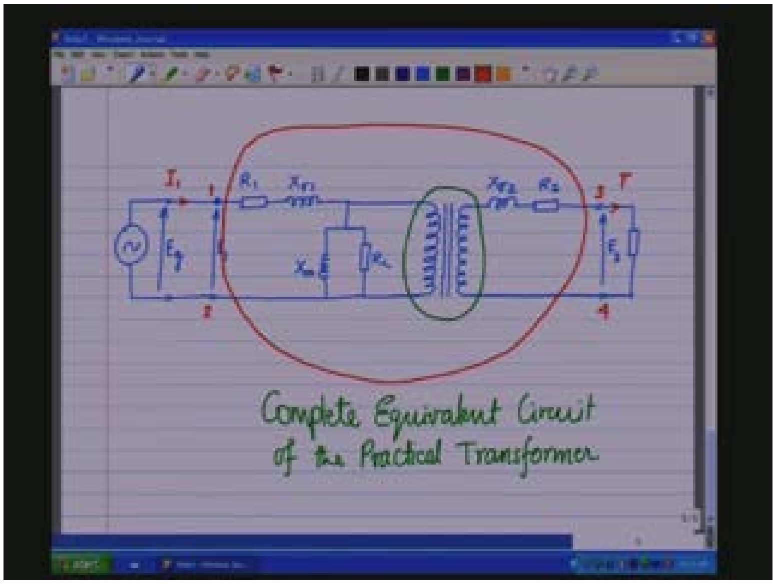

Complete Equivalent Circuit of the Practical Transformer

So we are taking a current from a source we are taking the current from the source we will call it as I 1 and there is a current flowing in the secondary it is called I 2. So now I 1 flows through the primary reach into the transformer, it gets split here as I 0 and it goes through here as I p ideal I primary ideal and on the secondary side you have the current I 2 which is flowing through and here you have I n the magnetizing component, I c the core loss component of the current and voltages-wise this voltage will be E m 1, this voltage is E sigma 1 and this voltage is e 1 which is across the terminals of the transformer. Likewise, this voltage is E m 2 and this voltage is E sigma 2 and there is a voltage here which is I 1 R 1, there is a voltage here which is I 2 R 2 which defines completely the equivalent circuit of the practical transformer.

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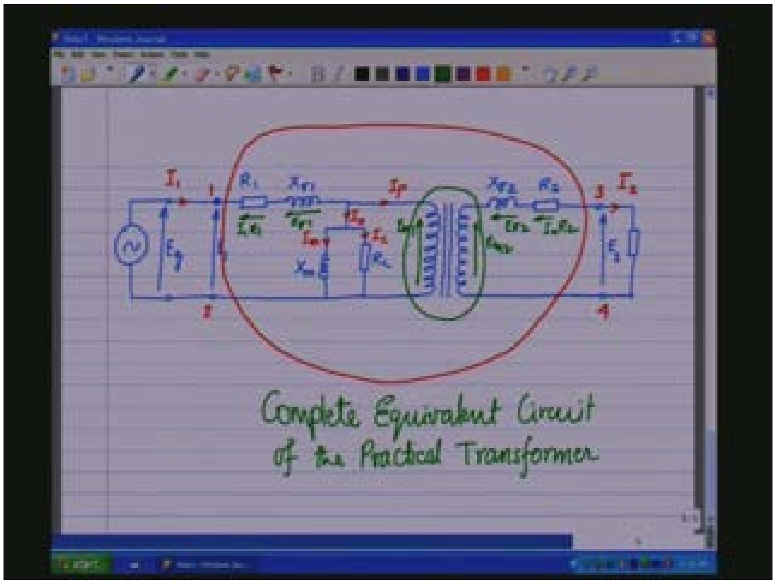

Complete Equivalent Circuit of the Practical Transformer

Now let us take simple example to consolidate what we have done till now.

the secondary winding of a transformer The secondary winding of the transformer has 180 turns. So, under load meaning when the secondary side is connected to a load Z 2, under loaded condition the secondary current I 2 effective value always effective value is 18 amps. The phi m which is a mutual flux is 20 milliwebers, the secondary leakage flux phi sigma 2 is 0 sorry is given to be let us say 3 milliweber and the frequency of the generator is 50 hertz that is we are applying a 50 hertz frequency. Now these are the specifications given for a particular transformer. Let us find first the voltage induced voltage induced in the secondary by the leakage flux as a first step.

let me So what is the voltage induced in the secondary?

We know that E sigma 2 E sigma 2 is given by 4.44 N 2 into frequency into flux sigma 2 phi sigma 2 which is 4.44 into 180 turns into 50 hertz into 3 milliwebers which 0.003 webers so that would be 119.9 volts or approximately 120 volts. So, 120 volts is induced due to the secondary leakage.

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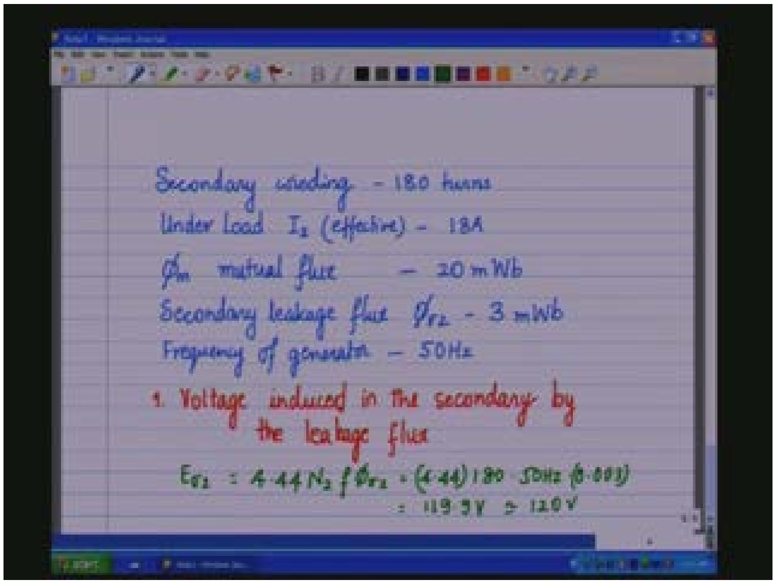

Secondary winding - 180 turns

Under Load I_2 (effective) - 18A

ϕ_m mutual flux - 20 mWb

Secondary leakage flux $\phi_{\sigma 2}$ - 3 mWb

Frequency of generator - 50Hz

1. Voltage induced in the secondary by the leakage flux

$$E_{\sigma 2} = 4.44 N_2 f \phi_{\sigma 2} = (4.44) 180 \; 50Hz \; (0.003)$$
$$= 119.9V \simeq 120V$$

Now let us put the second question. What is the value of secondary leakage reactance? So secondary leakage reactance is given by the voltage induced due to the secondary leakage reactance divided by I 2. If you go back you see that the secondary leakage in the reactance X equal to the E sigma 2 by I 2 which is equal to…………………

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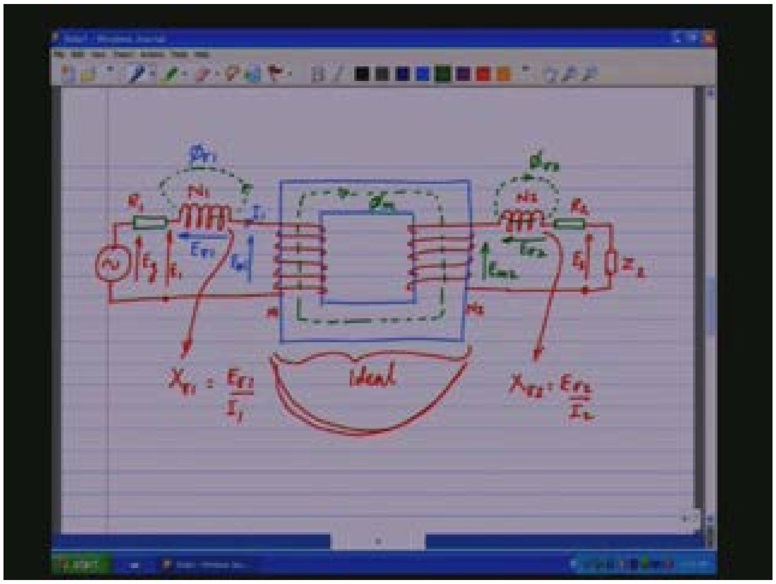

And we obtained E sigma to be around 119.9 volts divided by what is given is around 18 amps which is flowing through the secondary and this is around 6.66 ohms.

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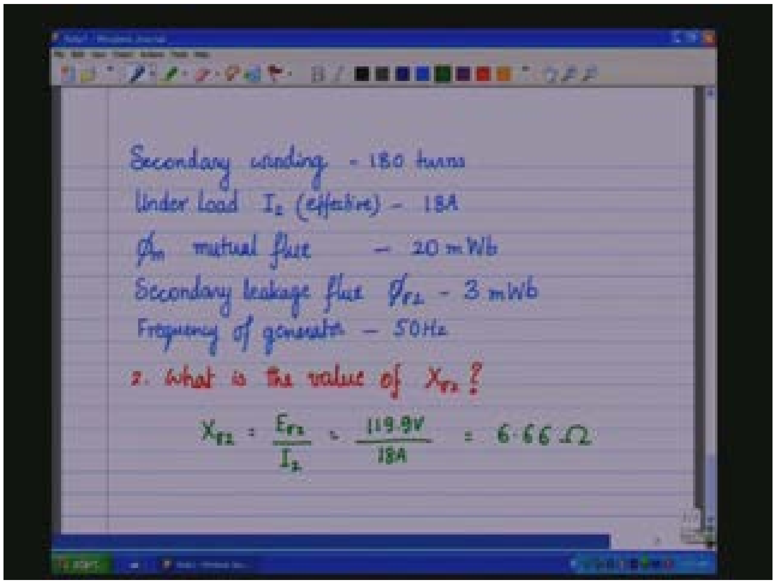

Secondary winding - 180 turns

Under Load I_2 (effective) - 18A

ϕ_m mutual flux - 20 mWb

Secondary leakage flux $\phi_{\sigma 2}$ - 3 mWb

Frequency of generator - 50Hz

2. What is the value of $X_{\sigma 2}$?

$$X_{\sigma 2} = \frac{E_{\sigma 2}}{I_2} = \frac{119.9V}{18A} = 6.66\,\Omega$$

Let me put a third question to the same problem. What is the voltage induced at the mutual flux; what is E m 2 the voltage induced by the mutual flux phi m. So E m 2 is equal to 4.44 into N 2 into f into phi m and this is 4.44 into 180 turns into 50 hertz into 5 m which is 20 milliwebers 0.02 webers and this is 799.16 volts or approximately 800 volts. Just give you a feel for the number what you go what you want to do when you start calculating. Of course we will take a few more examples later on.

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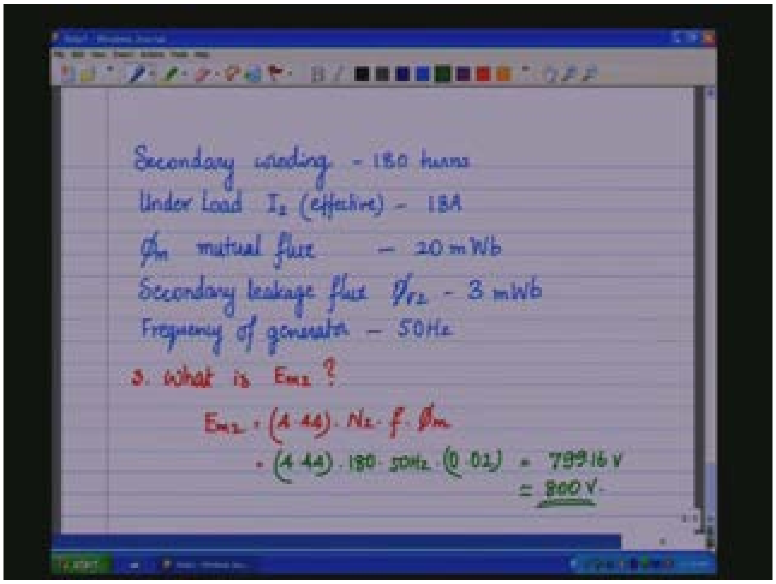

Secondary winding - 180 turns

Under Load I_2 (effective) - 18A

ϕ_m mutual flux - 20 mWb

Secondary leakage flux ϕ_{l2} - 3 mWb

Frequency of generator - 50Hz

3. What is E_{m2} ?

$$E_{m2} = (4.44) \cdot N_2 \cdot f \cdot \phi_m$$

$$= (4.44) \cdot 180 \cdot 50\text{Hz} \cdot (0.02) = 799.16\text{ V}$$

$$\simeq \underline{800\text{ V}}$$

Now the next topic that we need to have a look at is the issue of the power that is getting transferred. So the power that is getting transferred from the primary side to the secondary side is the VA the apparent power. The transformer has to be rated for the apparent power even though even though only the active component of the power is what is given to the load; the reactive component again flows back but still that component has to be handled by the transformer; reactive component emanates from the primary side goes through the transformer and also comes back to the primary side, it is regenerative of the reactive component but the transformer has to handle that power. So, if there is fully completely reactive load meaning if there is a reactive load of 1000 VAR and if there is a resistive load of 1000 watts in both the cases the transformer has to be rated for 1000 VA because that 1000 VA is what it has to handle and the heating value of the transformer is actually related to the apparent power because whether it is the reactive load or the active load the transformer has to undergo so many cycles which means so many traversals of the hysteresis loop and also the eddy currents in the transformer does not distinguish between the reactive load and the active load and therefore the heating in the transformer is related to the VA or the apparent power that is flowing through the transformer and therefore the name plates of the transformers are rated in terms of VA rather than watts, this is one issue.

Therefore, if you take an example let us say a name plate of transformer, so a transformer name plate, name plate of distribution transformer, it is a high power transformer transformer indicates that it is a 250 KVA transformer 50 hertz, primary has 4160 volts rated, secondary has 480 volts rate and this is the specification of the transformer.

So first one let us say what is the nominal primary and secondary currents?
So the nominal current of the primary that is I 1 is given by the VA VA rating divided by the nominal e 1 of the primary which is 250 into 1000 VA divided by 4160 volts which gives you 60 amps. Likewise, the nominal rating of the secondary is the VA rating which is the same for both the primary and secondary by the nominal secondary voltage e 2 whatever it is rated so that is 250 into 1000 VA divided by 480 volts which turns out to be 521 amps as a VA rating.

Now suppose for this transformer which is rated at 4160 volts we apply we apply instead just 2000 volts is applied 2000 volts is applied, under such conditions can it give the same VA rating that is the question.

Now if we take the transformer we are applying a voltage which is lesser than the primary which means the whole second is smaller for the same frequency which means the operating point in the BH curve is going to be a small so a smaller BH loop is going to be traversed and therefore the transformer is going to run cooler. However, if we have to get the same VA, if I have reduced the voltage to have the same VA if you reduce the voltage the current has to be increased proportionally to have the same VA which means the I square losses would increase by times and the windings may not be rated to handle the doubled or the increased current because the losses are going to be I square times and therefore the windings or the coil of the transformer which is on the core can handle only the nominal current for what it is rated which means 60 amps for the primary and 521 amps for the secondary.

Therefore, if I apply 2000 volts 2000 volts then the VA is 2000 volts into 60 amps which is 120 KVA. So, for a 250 KVA transformer if you are applying a lesser voltage do not expect that it will deliver the whole 250 KVA because it cannot handle the increased current because the windings will not be rated for the increased current and therefore you have to limit the current only to the nominal current which is the 60 amps and therefore the nominal current into the reduced voltage will give you the apparent power which is going to be considerably reduced with respect to the rated.

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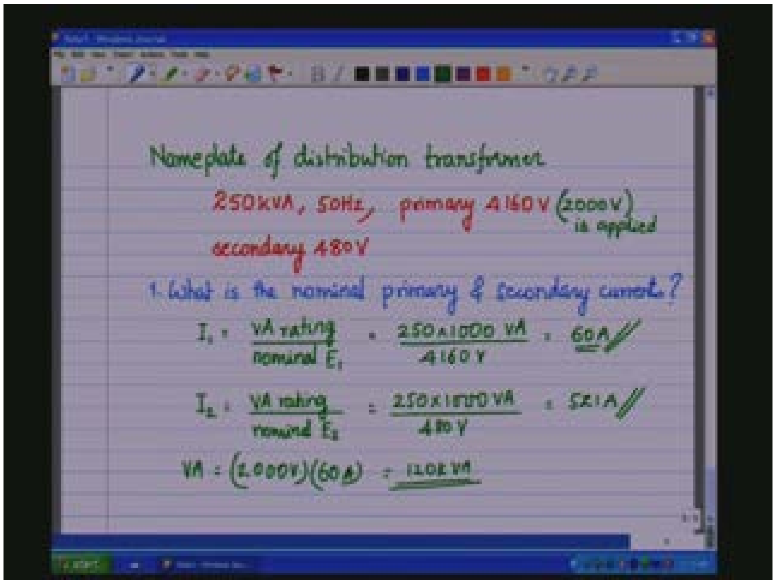

Nameplate of distribution transformer

250 kVA, 50Hz, primary 4160 V (2000 V is applied)

secondary 480 V

1. What is the nominal primary & secondary current?

$$I_1 = \frac{\text{VA rating}}{\text{nominal } E_1} = \frac{250 \times 1000\ \text{VA}}{4160\ \text{V}} = \underline{60\ \text{A}}$$

$$I_2 = \frac{\text{VA rating}}{\text{nominal } E_2} = \frac{250 \times 1000\ \text{VA}}{480\ \text{V}} = 521\ \text{A}$$

$$\text{VA} = (2000\ \text{V})(60\ \text{A}) = \underline{120\ \text{kVA}}$$

Now, having discussed the practical transformer and having developed complete equivalent circuit of the practical transformer which contains three reactances: the magnetizing reactance X m, the leakage reactance X sigma 1 and X sigma 2 the primary and the secondary leakage reactances and contains three resistances R c which is the core loss component, R 1 which is the winding resistance of the primary coil, R 2 which is the winding resistance of the secondary coil all these are put together along with the ideal transformer results in the practical transformer.

Now, to this practical transformer the various loads and voltages are applied and with a different power capacities. And in the next session we shall discuss about the impedances and the values of these practical components that we introduced in the practical transformer, how to obtain them and also about the per unit impedances which will give you much better understanding of the transformer. We shall discuss all these things in the next class.

Thank you.