Basic Electrical Technology
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Lecture - 22
The Practical Transformer: Part – III

In this class we continue with our on-going discussion on the practical transformer. In the last session we evolved the complete equivalent circuit of a practical transformer with all the imperfections put in that. Starting from the equivalent circuit of the transformer let us see how we obtain the phasor diagram and then we will have a discussion on per unit values or the per unit impedances which are very important from the transform from understanding the various features of the transformers and following that we will look at some simplifying assumptions that we make on the equivalent circuit so that we will be able to obtain the various impedances of the equivalent circuit from actual measurements.

So, starting from the equivalent circuit of the transformer which we have evolved in the last class we have a source E g and this is where the terminals of the practical transformer begins, there is first a resistance R 1 which represents the winding resistance of the primary coil and then you have a reactance the leakage reactance due to the leakage flux, this is followed by the leakage sorry the magnetizing reactance and the core loss component the magnetizing reactance and the core loss component which is now connected to the ideal transformer like this. There is a core with ideal characteristics, the secondary of the ideal transformer which is connected to the leakage reactance on the secondary side due to the leakage flux in the secondary ampere-turns this is followed by resistance R 2 which is the winding resistance of the secondary coil, this goes to the secondary terminals and to the secondary terminals we have the load and this is where the secondary terminals are (Refer Slide Time: 4:14).

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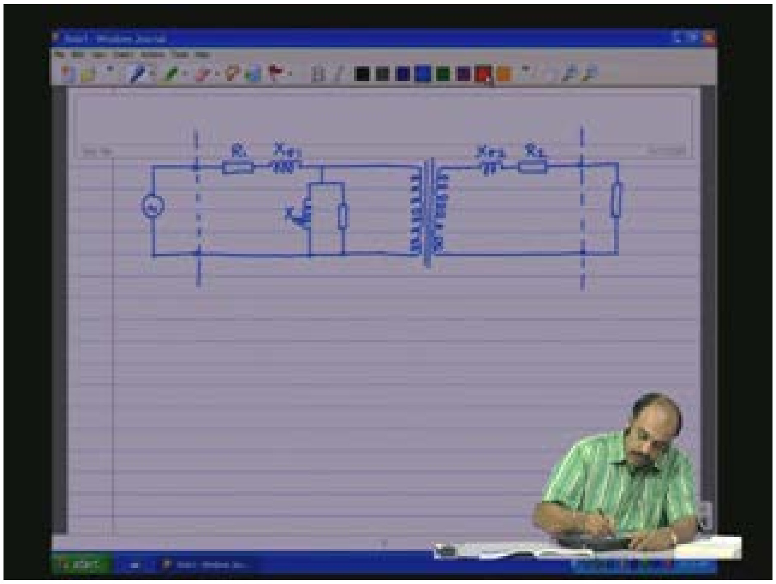

So this is E 1 and of course this is E g the generated voltage, this is the secondary terminal voltage E 2. Now here we have, let me introduce the dot polarities the dot polarities; this is 1 is to n, this is induced emf due to the mutual flux on the secondary side, induced emf on the primary side due to the mutual flux; there is of course a mutual flux which links two coils primary and the secondary, there is a current here I p and there is a secondary current I two. now there is a current here I 0 which gets split up into two components: I m the magnetizing current, I c the core loss component through R c and there is I 1 the current drawn from the source the primary terminal current and of course there are voltage drops across each of the components E R 1 E sigma 1 and there is a current in this direction we have E sigma 2 and the voltage across this. So this is the practical transformer.

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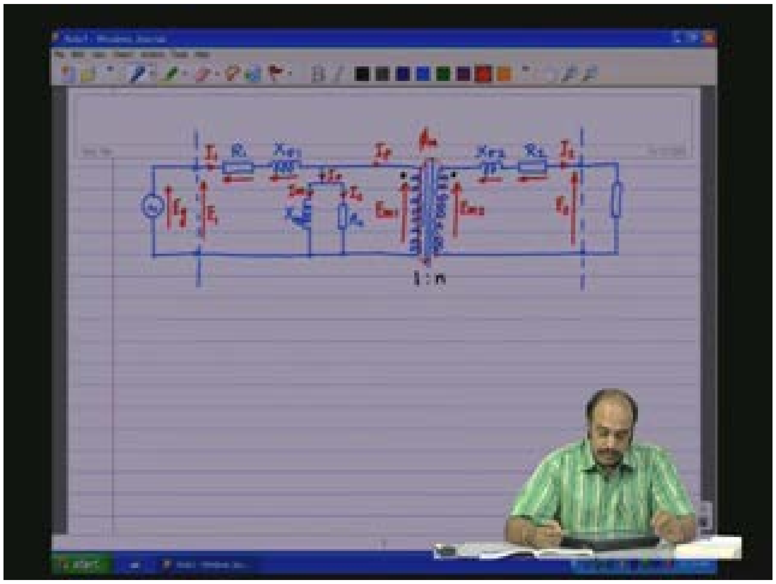

Now let us draw the phasor diagram for this practical transformer. It looks pretty complex but it is not actually so difficult to draw the phasor diagram. In fact we have imparts around the phasor diagram. We have drawn the phasor diagram for the ideal transformer portion, we have drawn the phasor diagram for the ideal transformer plus the core loss and magnetizing component portion, now we have to input these two. So let us start from the phasor diagram with the ideal components. We shall first of all have the two axes which is the x and the y axis which are called the alpha beta axis in the spatial coordinates.

Now let us take the ideal transformer portion. Now if you look at the ideal transformer portion the primary voltage is E m 1, the secondary voltage is E m 2, the dot polarities are shown here, E m 1 and E m 2 will be in-phase. Therefore, we have E m 1 E m 2 both of them are in-phase and let me draw that portion on this curve. Then the secondary current I 2 will be in-phase with the primary current I p.

Now as the as it is stepped down from the way we have drawn here because E m 2 is less than E m 1 the current I 2 will be higher than I p therefore the current will be lagging and this would be I 2 and I p will be somewhere here let us say, they both will be in-phase and the flux phi 1 is going to be 90 degrees lagging the induced voltages because induced voltage is equal to n d phi by dt we know we have seen that before from the Faraday's laws of electromagnetism.

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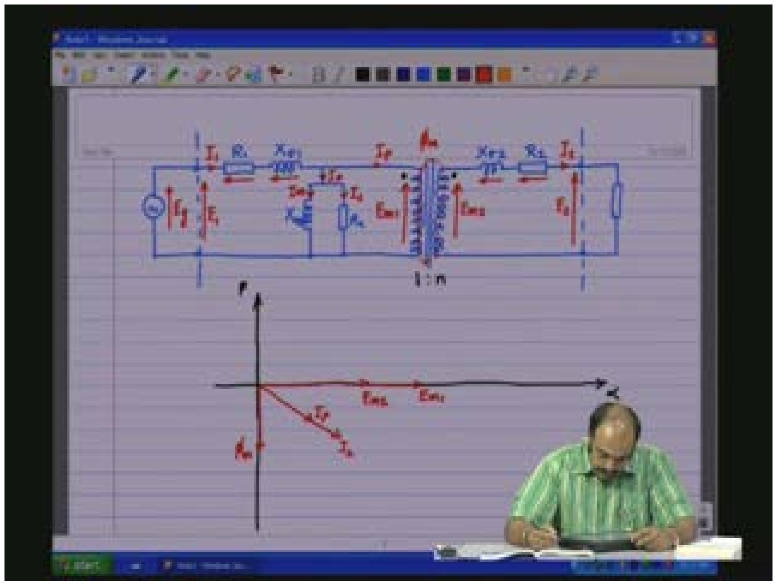

Now, I p I 2 is going to lag the induced voltage E m 2 by the amount of lag which is produced by all the reactances the impedance put together that is the leakage, R 2 and the load impedances put together. Now this would be the portion of the phasor diagram that we have obtained for the ideal.

Now, on including the core loss component or the magnetizing component we know that E m 1 and the voltage across R c will be in-phase because I c is the core loss component which will be in-phase with E m 1 and I m is the magnetizing component which is be which will be 90 degrees lagging with respect to E m 1. Now the magnetizing component is going to have a much higher impedance with respect to the core loss component. So let us let us put the core loss component of the current I c like that (Refer Slide Time: 11:04) and let me put the magnetizing portion of the current I m here and I 0 is as shown here this is I 0. So we see that I 0 which is the resultant of I m and I c and that is lagging E m 1.

Now the current I 1 is the vectorial sum of I p and I 0; the vectorial sum of I p and I 0 will be I 1. So I p is here so let us draw the parallelogram that is we draw the parallelogram for…… so this is I 1 that is I p plus I 0 will be I 1. So this is the primary current I 1 at the terminal, I 2 is the secondary terminal current.

Now what is E 1 the terminal voltage E 1?

Terminal voltage E 1 terminal voltage E 1 is the voltage across this terminal which is E m 1 plus the voltage across the leakage reactance plus the voltages across the winding resistance R 1 of the primary all these are vectorially added to obtain E 1. So we have E m 1 here so to E m 1 we add let us say I R 1, now I R 1 will be in phase with I I 1. now let us now draw parallel to I 1 so I will say this is the I 1 direction so along this I 1 direction we have we have a voltage which is I 1 R 1 and 90 degrees rotated which is J omega L sigma 1 into I 1 that is 90 degrees, this is 90 degrees.

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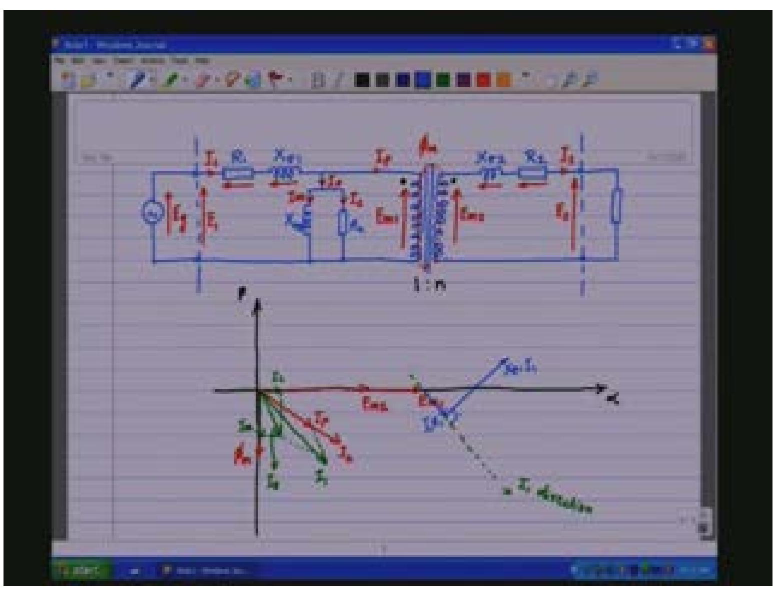

So E m 1 this is E m 1 plus X sigma 1 I 1 plus I 1 R 1 all put together will give you the vector E 1 the phasor E 1 in this case because we are talking of rms quantities. So this would be the E 1 phasor. Now we need to know what is the E 2 phasor. We know that in the secondary side E m 2 is along this, this is the E m 2. Now E m 2……….. look at the directions at an instant because the current is flowing in this direction; E m 2 minus the drop across the secondary leakage reactance minus the drop across secondary winding resistance I R 2 is going to be E 2.

Now let us take the current I 2 and from the tip of E m 2 let us draw an axis which is parallel to I 2. So this is I 2 and let us have an axis which is parallel to I 2. So we have an axis which is parallel to I 2 and this is called the I 2 direction. Therefore, along this I 2 direction from here we have minus R 2 I 2, so this would be the plus R 2 I 2 therefore we have to go in the minus direction, this is R 2 I 2 and this is minus R 2 I 2 direction (Refer Slide Time: 17:19) and minus this that is from this direction taking 90 degrees anti-clockwise would be the plus J sigma 2 direction of the voltage drop we are now subtracting that and therefore we have X sigma 2 I 2. So E m 2 minus I 2 R 2 minus sigma X sigma 2 I 2 and that is going to give you E 2, so this would be E 2, so this would be the phasor diagram of this complete of this complete equivalent circuit of the transformer.

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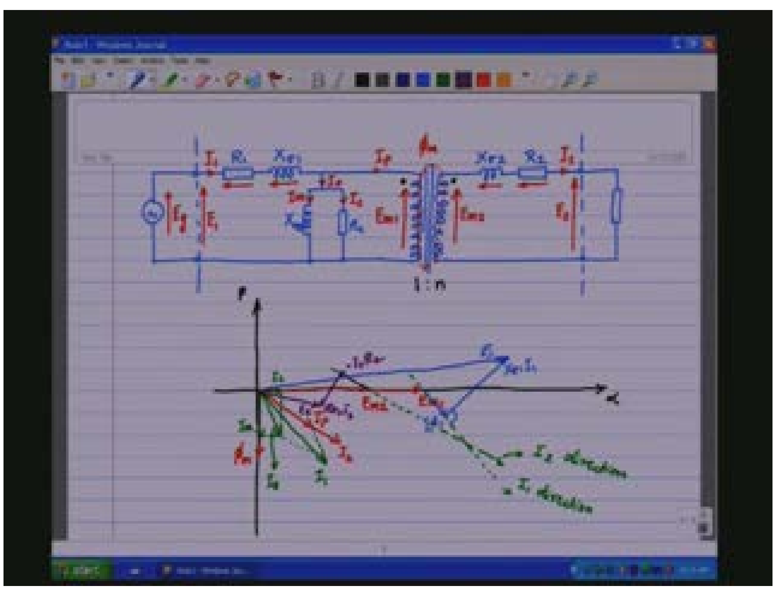

Though in the completed form the phasor diagram looks complex but it is not so, you can start from the idealized transformer which is how we evolve this circuit and then the core loss component or the magnetizing component and then follow it up with the leakage components and the winding resistance component that we added to get the complete phasor diagram of the transformer.

Now, because we will be using this quite frequently I am going to copy that, let us go to the next topic. the next topic we want to discuss is on the per unit values the per unit values. Normally it is advantageous to normalize the various parameters in the transformer that is you have the resistances, the impedances, the voltages, the currents all these could be normalized with respect to some base value and we have what is known as the per unit values that is you have the maximum value as 1 in terms of the per unit values or percent values that is the maximum can be 100.

Thus, if any value is 80 percent then we say that it is 0.8 times the base value so that would give you a platform for comparison of the various transformers and of various ratings. now in the case of the per unit values the nominal voltage nominal voltage of the transformer that is E 1 nominal is considered as the base voltage for the primary and E 2 nominal that is whatever that is the rated has a base voltage for the secondary; this is for the primary and this is for the secondary.

The VA rating nominal VA n which is the nominal VA rating the apparent power rating of the transformer VA rating is considered as the base apparent power and therefore from this the nominal current is nothing but the VA nominal by E 1 nominal if it is a primary, this would be taken as the base current for the primary and the base impedance Z n the nominal impedance is if it is for the primary side E 1 square by VA nominal, if it is for the secondary side that is if we say this is Z 1 n and Z 2 nominal the base impedance of the secondary side would be E 2 n square by VA nominal. These could be taken as the base values to obtain base values to obtain the per unit values of the transformers. Let us illustrate this with a simple example

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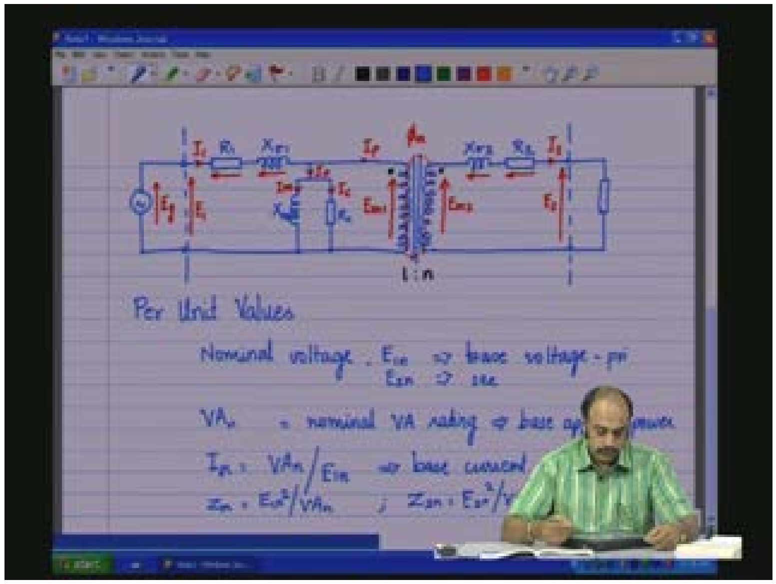

Now consider a transformer which is rated for 250 KVA transformer which has a primary voltage of 4160 volts to a secondary voltage of 480 volts and it is a 50 hertz operation. So this is the primary and this is the secondary ready (Refer Slide Time: 23:31). So now the question is we need to calculate base impedance calculate base impedance.

Now on the primary side, first let us take the primary side, so, on the primary side the base impedance is E 1 n square by VA n which is 4160 is the rating of the primary square divided by 250 into 1000 VA which is 69 ohms. Now, on secondary side the base impedance for the secondary side Z 2 n is secondary nominal voltage square VA nominal which is 480 square by 250 kilo VA which is around 0.92 ohms. So this becomes the per unit sorry this becomes the base impedance. So, any impedance value divided by the base impedance will give you the per unit impedance.

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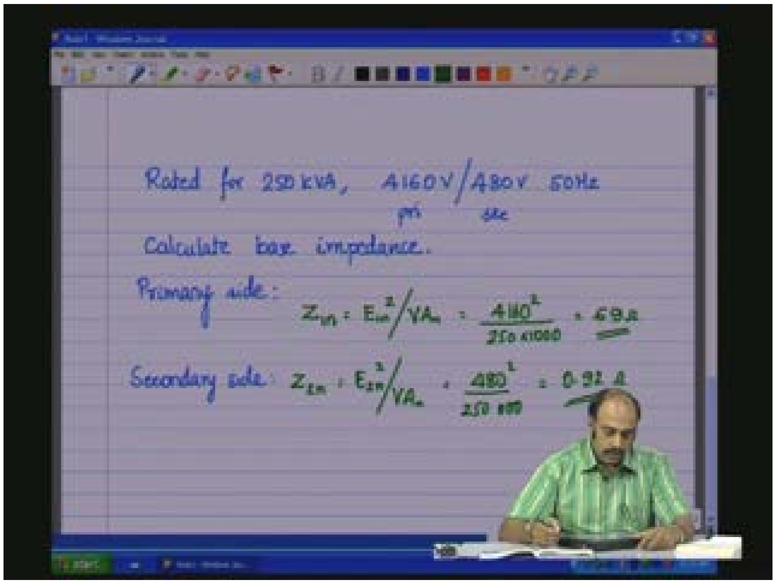

Now the advantages of the per unit values are many. Actually if you see the relative values of the reactances the core the core loss component, the magnetizing component, the leakage component, the winding component so the relative values of these with respect to different ratings of the transformer all these comparisons can be made very well with the per unit values at the normalized values. Now, to give you an idea let us say we have these parameters in the circuit that is this equivalent circuit has these following parameters R 1 R 2 these are the winding resistances of the coils and we have X sigma 1 X sigma 2 the leakage reactances, X m this is the magnetizing reactance, R c this is the core loss resistance, i 0 which is the no load current which is drawn from the primary source.

Now for these circuit elements what are the per unit values; what are the PU or the per unit values?

Now these per unit values are also dependent upon the VA rating of the transformer. But for a very wide range right from 1 KVA to 100 mega VA the per unit value change is not very much, the change in per unit value is a very small fraction. However, we can have typical values of these per unit values which will give us an idea of the order of the reactances on the resistances of the typical transformers of that particular rating. So we have the per unit values for let us say 1

KVA to 250 KVA and 1 MVA that is 1 mega volt amp to 100 mega volt amp; for these two ranges the per unit values are given like this. So, for R 1 and R 2 the per unit values range from 0.009 to 0.005 that is it is 0.009 at around 1 KVA, 0.005 at around 250 KVA and one could do a interpolation linear interpolation for different other VAs in between and these values vary from 0.005 to 0.002; the per unit values are dimensionless quantities.

You see actually the variation is not much from 0.009 to 0.005 for 250 KVA variation and for around 100 MVA variation also 0.005 to 0.002 and the leakage reactances have the per unit values of 0.008 to 0.025 the per unit value at around 1 KVA is 0.008 and at around 250 KVA is 0.025 and 0.03 at around 1 MVA and 0.06 at around 100 MVA and for magnetizing reactance it is around 20 to 30 and for the higher range it is around 50 to 200. For the case of the core loss component it is around 20 to 50 in the 1 to 250 KVA range and it is around 100 to 500 in the 1 MVA to 100 MVA range. The no load current that is drawn from the primary source is varying 0.05 to 0.03 in the 1 to 250 KVA range and 0.02 to 0.005 in the 1 to 100 MVA range.

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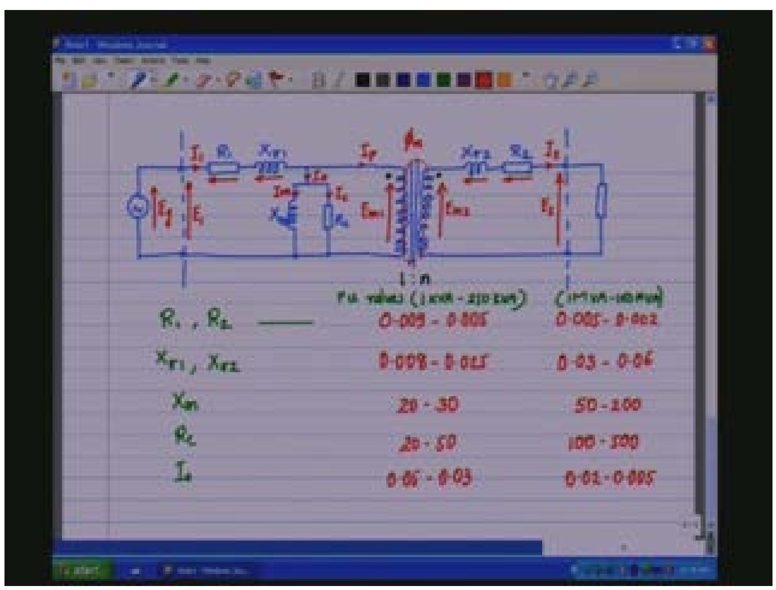

This is a very useful table which you can use for comparing various rating transformers. For example let us take a transformer; paste, (Refer Slide Time: 32:18) let us take a transformer and try to evaluate from the per unit values the order of magnitude of the various parameters that is the reactances and the resistances in the equivalent circuit of the transformer.

Again take let us say the rating of the transformer is 250 KVA with the primary to the secondary voltage ratio of 4160 volts to 480 volts 50 hertz distribution transformer transformer. Now for this let us try to for this transformer let us try to find the various values of the reactances from the per unit values of the previous table. Now first let us find out the base impedances. Now Z 1 n base which is which is nothing but 4160 square by 250 VA which is 69 ohms and Z 2 n that is the baseless turn of the secondary side is 480 square by 250 KVA which is 0.92 ohms, these are the base impedances.

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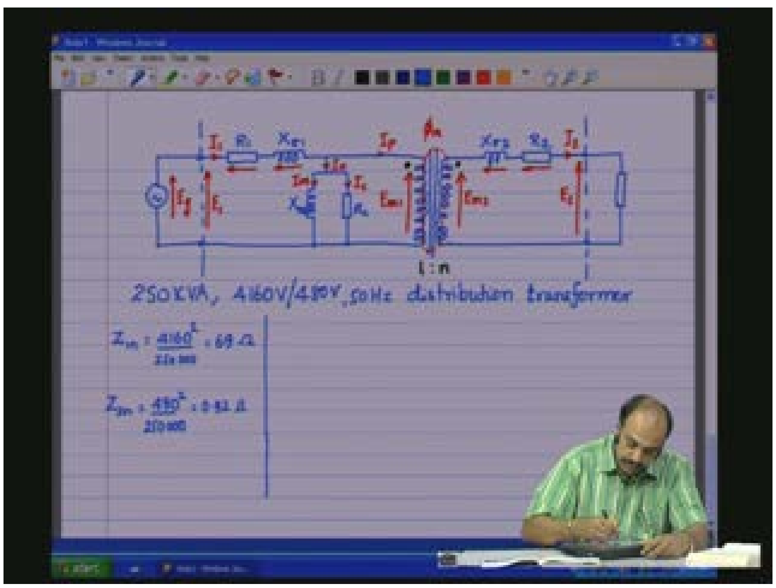

Now using these impedances we now evaluate the various components as given in the table in the previous table. So now R 1 we look at the table and we are talking of the 250 KVA transformer and therefore let us take these values for consideration. So R 1 and R 2 the per unit value is 0.005. So R 1 is 0.005 into…….. on the primary side the base impedance is 69 ohms which is 0.35 ohms, R 2 is again 0.005 and the base impedance of the secondary side is 0.92 which gives you 4.6 milliohms.

Now the leakage reactance X sigma 1, now if you look at X sigma 1 the per unit value 0.025 for a 250 KVA transformer is 0.025 into the base impedance for the primary side which is 69 will give you 1.7 ohms and X sigma 2 secondary side leakage reactance is having 0.025 into the base impedance on the secondary side which gives you 23 milliohms.

Now X n the magnetizing reactance, so the magnetizing reactance has a per unit value of 30 which is 30 into on the primary side 69 ohms is the base impedance which gives you 2070 ohms or roughly about 2 kilo ohms and R c R c has a value of 50 so it is 50 into 69 which is 3450 ohms so approximately 3.5 kilo ohms. Now this is the real impedance values that is the order of magnitude or approximate values of the real impedance values of the transformer which we can now write here that this is now having a value of 0.35 ohms, having a value of 1.7 ohms, this is around 2 kilo ohms, this is around 3.5 kilo ohms, and this we found it as around 23 milliohms, this is 4.6 milliohms, so this has a voltage of 4160 volts to on the secondary side approximately 480 volts. This is the turns ratio n which is equal to 480 by 4160.

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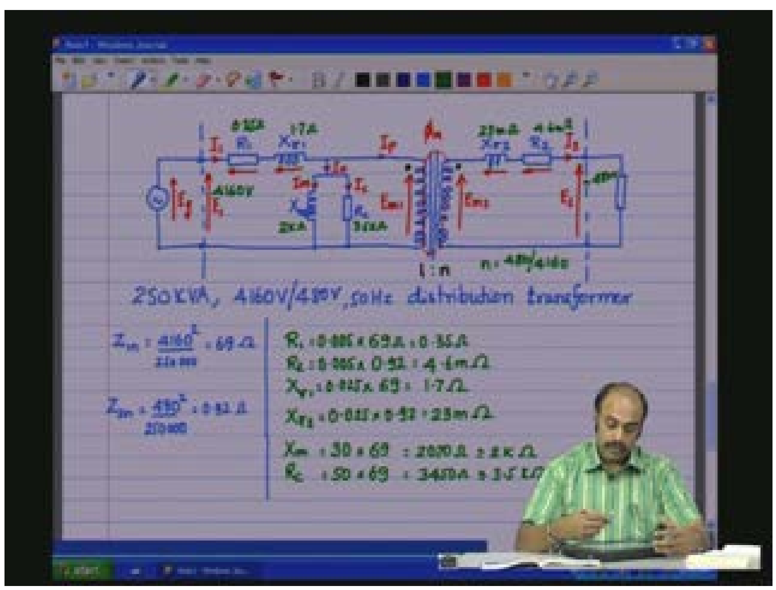

So this way given a rating of the transformer, this is the power rating of the transformer looking at the table of per unit values one can obtain the order of values of the various resistances and the reactances of the transformer and this will give you comparison between various transformers from various manufacturers of the same rating.

Now, the next point we would like to discuss is the equivalent circuit itself. Now you see that this equivalent circuit the complete equivalent circuit can be simplified under certain operating conditions. We have two major operating conditions: one is under open circuit condition and the second is under loaded condition loaded condition this is considered as no load operation. So under no load the secondary load here the secondary load is removed, the secondary is open circuit. Under loaded condition the load is connected across the secondary terminals.

Now let us take the case of open circuit condition which is no load. So, under no load some of the parameters may vanish. So there is no I 2 which means I 2 becomes 0. So, if I 2 becomes 0, this being an ideal transformer I p becomes 0 so only what is drawn from the primary source I 0. Now as I 2 is 0 the presence of this leakage reactance and the winding resistance is not needed and as in these winding resistances the leakage reactance is very small the I 0 into the impedance drop will be very small compared to the voltage which is applied these can be neglected that is R 1 and X sigma 1 can be neglected which means the equivalent circuit under no load condition could be simplified as this just the magnetizing loss component followed by the ideal transformer with the secondary just open circuited, dot polarities 1 is to n and this of course is E 1 or E g; so you have X m R c I c I m I 0 there is no current flowing through any of these I p equal to 0 and I 2 equal to 0, this is E 2.

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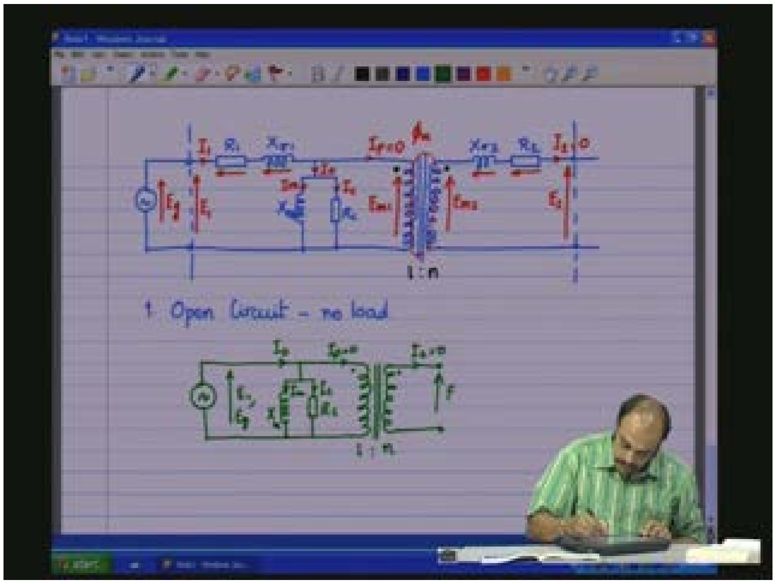

This is how the equivalent circuit would reduce to under no load conditions. Now if you look at the condition under load there is going to be I 2 flowing under full load condition. So, if you look at the full load condition let us go to the next page (Refer Slide Time: 43:06) I 2 is going to flow through it the full rated I 2, I p is going to be I 2 into n, I 0 is going to be a very small percentage of I p that is I 0 is going to be very very less compared to I p and therefore I 0 can be neglected which means X m and R c can be neglected under full load conditions. Therefore, under the full load conditions we have E g R 1 X sigma 1 the ideal transformer secondary side X sigma 2 R 2 and Z 2 whatever the load is going to be or we will call it as Z L instead of Z 2 so we call it as Z L, this is1 is to n.

In fact everything can be taken on to the primary side by the conversion and then we can make the following modifications. We remove this transformer here, we put the transformer on this side (Refer Slide Time: 45:13) so here I 2 is equal to 0, this also I p is equal to 0 and we join it here. Now these values would be by n square by n square divided by n square this would be the impedance that one would see which means the resistance the impedance as seen from the source Z 1 equivalent as seen from the primary side would be equal to R 1 plus R 2 by n square that is the resistance resistance component plus X sigma 1 plus X sigma 2 by n square that is the reactive component as far as the transformer impedances are concerned internal impedances as concerned plus Z L by n square that is the load component so this is the load component of the transform.

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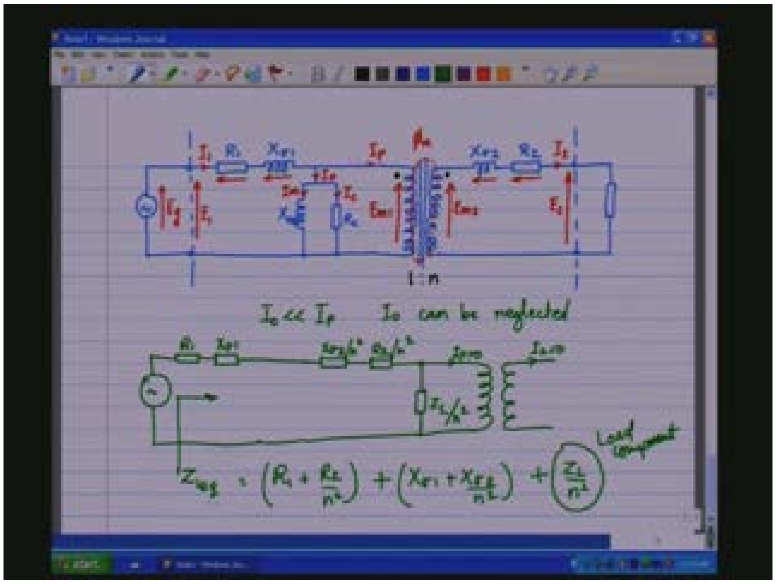

Hence, it just reduces to R plus j X p that would be the equivalent resistance of the transformer. And now we should attempt or obtain the parameters the various parameters of the equivalent circuit. So, if from the measurable quantities we are able to obtain the various parameters of the equivalent circuit then our analysis then our discussion on the transformer would be complete.

So, going back to the equivalent circuit going back to the equivalent circuit (Refer Slide Time: 47:51) we perform two tests on the transformer: one test is called the open circuit test. We said that when we are doing the open circuit test the secondary side is open which means I 2 is 0 which means I p is also 0; this implies that I do not need these reactances under open circuit conditions, we just saw that these become very negligible. Therefore, under open circuit condition this becomes the equivalent circuit that we will be looking at, I p will not exist and this will not exist.

Now what are the things that we can measure?

Under the open circuit test we measure E 1, E 1 is measurable with a voltmeter connected across the terminals of the transformer, E 2 is measureable with a voltmeter connected across the terminals of the secondary of the transformer of the practical transformer then we can also measure I 0, I 0 can be measured by connecting an ammeter in series that is we connect an ammeter we connect an ammeter in series to measure I 0 this is an ammeter which connects……… now the voltage here is measured with a voltmeter. We also connect a voltmeter here to measure E 2 or let me use the following symbols and an ammeter, a voltmeter and a voltmeter.

Then we could one more thing we could measure the active power that is taken from the source by connecting a wattmeter by connecting a wattmeter by connecting a wattmeter at the primary side, this measures the active power that is taken from the source. So we will be obtaining P which is obtained by connecting a wattmeter. So you need two voltmeters: one ammeter and one wattmeter to do the experiment which is the open circuit test.

Hence, once you have this the VA is given by E 1 into I 0. E 1 into I 0 is the VA which is drawn from the source and the reactive power VAR given by root of VA square minus P square where P is the active power measured in the wattmeter and based on this we can obtain R c which is equal to E 1 square by P and we can obtain X m which is E 1 square by Q and we can obtain n which is E 2 by E 1. So, based on these measurements these parameters are obtained. these measurements could be taken Around five readings can be taken for these measurements and an average of that found that and that could be used for making the calculation here to improve the accuracy of the measurements.

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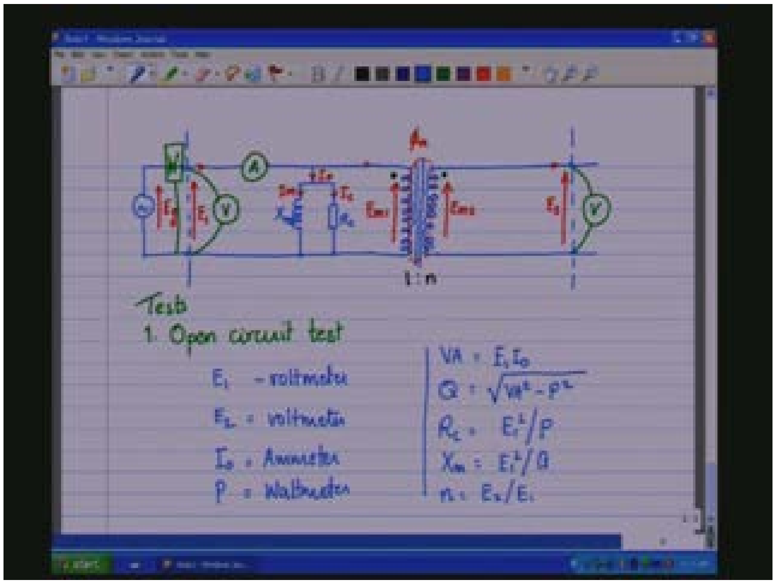

Thus, now we have obtained the core loss component the X m which is the magnetizing component and the turns ratio from the open circuit test. We now perform the next test which is the short circuit test. In the short circuit test what is done is the secondary is short circuited. Since the secondary is short circuited we do not apply the full nominal voltage to the primary; the voltage E g that is applied is a very small amount. In fact, it can be applied through a variable voltage source or an autotransformer; you just keep increasing the voltage till the rated current flows through other nominal current flows through the secondary and take the measurements at that time, the measurements can be taken quickly so that the transformer does not heat up. Therefore, under the short circuit condition we see that the I p will be much higher than the I 0 and therefore they can be neglected so these portions will vanish as they are negligible and we can do one more thing as I was saying; these impedances can be transferred on to this side which means which means that we remove this (Refer Slide Time: 55:02) and transfer them on to the primary. So we include and then a short here I p is equal to 0 I 2 equal to 0. So, as this is equal to 0 this ideal transformer could also be removed so equivalently we have just this portion as the equivalent circuit now. This would be X sigma 2 by n square, this is R 2 by n square.

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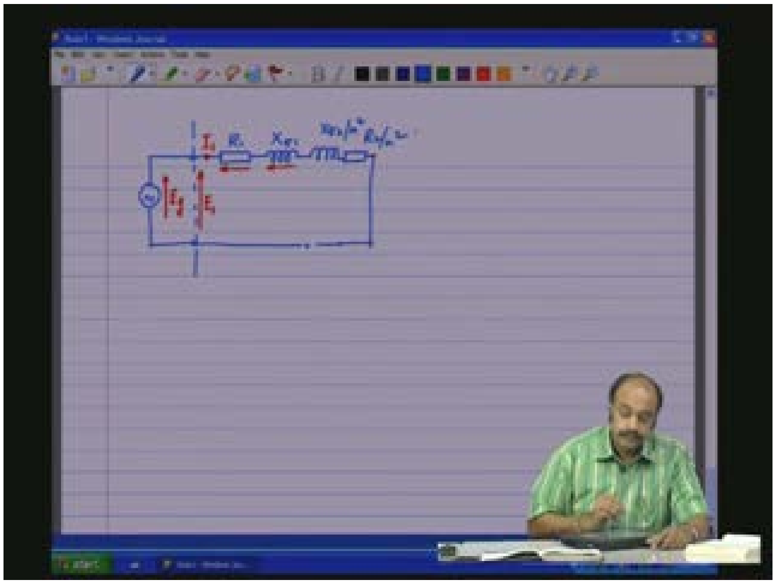

Therefore, you continue to keep the wattmeter here wattmeter, we continue to keep an ammeter keep the ammeter here, then we need an ammeter there and then we measure the voltage across the primary through a voltmeter, so we measure the voltage through the voltmeter across the primary. These are the changes that happen when you do a short circuiting of the secondary side so this is called the short circuit test. Here we are measuring E 1 with a voltmeter, we are measuring I 1 again with a voltmeter and we are measuring the active power which is drawn from the source again with the wattmeter.

Now these we can use to obtain the rest of the parameters. Now E s that is E 1 divided by I 1 the voltage across the primary divided by the short circuit current will give you Z p. So Z p is obtained. Now R p is obtained from the power that is measured in the short circuit condition by I 1 square. Well, I 1 square into R will be R p which is R 1 plus R 2 by n square and X p X primary side is given by root of Z p square minus R p square which is X sigma 1 plus X sigma 2 by n square so this is R p and. So R p gives you the total reflected primary total reflected winding resistances of both the primary and the secondary as seen from the primary side, X p gives the total leakage reactances of both the primary and the secondary side reflected on to the primary side as seen on the primary side so this gives you the leakage reactance and this gives you the equivalent winding resistances so the short circuit test can be used for finding these two parameters; as n is known one can also find out the other parameters, R 1 can be measured directly knowing the number of turns that are measured directly from a multimeter and R 2 can be found knowing n and these in this case we have to take this as an equivalent secondary leakage or the primary leakage as seen on the primary side.

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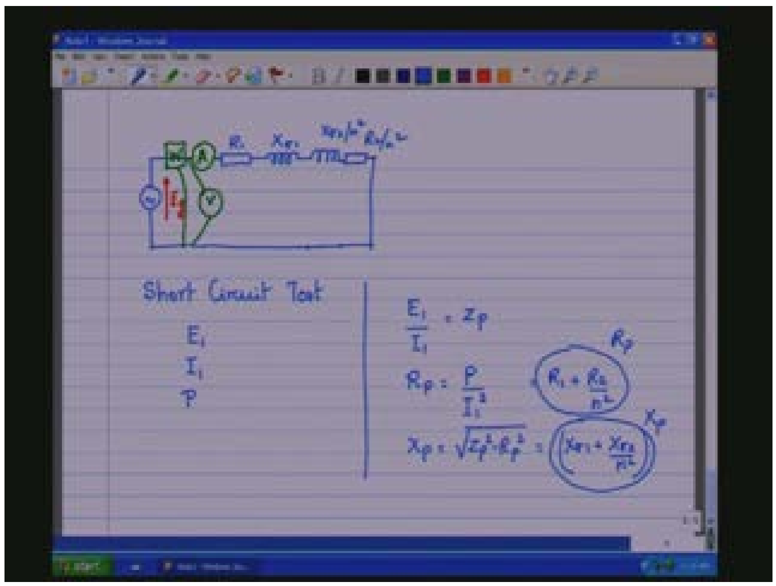

With this we know about the transformer equivalents or complete equivalent circuit, the phasor diagram, how to analyse it and then what are the parameters that come into the imperfect or the practical transformer. We also discussed about the per unit impedances which are used for comparing the various transformers of various ratings. And finally we have done two experiment which is the open circuit test and the short circuit test to obtain the parameters the parameters of the equivalent circuit of the transformer as explained before and these parameters can be plugged in from the measured quantities and they will give you the model of the transformer which can be used for further analysis with other circuits.

In the next class we will take up the concepts of DC motor and generator. Thank you for now.