**Basic Electrical Technology**
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**Lecture - 20**
# The Practical Transformer

Hello everybody, in the last session we were discussing about the power transformer. We saw that the power transformer could be used for many applications one of them being isolation, power is for step up or step down and the third one is for impedance matching. in the case of isolation transformers the turns ratio is normally kept at 1 is to 1 and the primary side circuit is galvanically isolated from the secondary side circuit meaning there is no electrical connection between the primary side circuit and the secondary side circuit the only connection is through the medium of the core of the transformer which is magnetically coupled.

In the applications where you want to do step up or step down; apart from achieving isolation you can also try to achieve compatibility between the voltages in the currents on two sides of the circuit. So, if the primary side of the circuit is at one voltage and the secondary side of the circuit is at another voltage and to achieve compatibility between these two circuits one would use either a step up that is primary is at a lower voltage secondary is at a higher voltage or a step down primary is at a higher voltage and secondary is at a still lower voltage. Correspondingly the currents will be of the reverse auto, meaning; if the primary voltage is higher current will be lower compared to the secondary and if the primary voltage is lower primary current will be higher compared with respect to the secondary.

Then the third application that we saw that we could put the transformer to good use was in impedance matching. We saw that a real impedance on the secondary side will reflect itself on the primary side as the impedance divided by the turns ratio square or an impedance on the primary side will reflect itself on the secondary side as the impedance into the turns ratio square.
Let us just see one more example on the impedance conversion from the primary to the secondary before going further into the aspects of the transformer the aspects of practical transformers.

We have a transformer circuit; we have a primary and we have a secondary, there is a core and the secondary winding, we have an impedance which could be like that or to make it a bit more complex we could have one more impedance like this like a phi network, on the primary side we could have an impedance like this and then of course the source.

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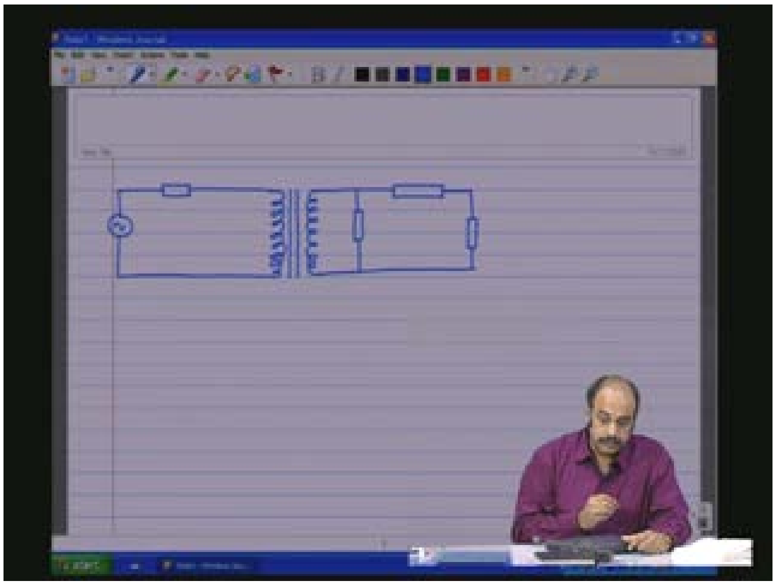

Now this is called let us say Z 1 Z 2 Z 3 and Z 4, this the turns ratio 1 is to n and dot polarities indicating that this portion of the winding is this portion of the winding is having the same case as this portion of the terminal of the winding. This is the primary side (Refer Slide Time: 5:16) we call this one as e g, let there be a current i 1 and there can be a current i 2 through Z 2, a current i 3 through Z 3 which will be the same current which is flowing through Z 4 also.

Now if you want to reflect everything on to the primary side all the things get transformed on to the primary side. Let me also indicate the voltages across each. We have a voltage across Z 2 and let us tell it is e 2, there is a voltage across Z 3 and that is e 3, there is a voltage across Z 4 and that is e 4.

Now, now for reflecting I am going to redraw the portion of the circuit. Of course the primary impedance the primary side impedance will still remain in the primary side without any change and the secondary side impedances can now be put in this let us say black box within this and that would be the reflected impedances reflected impedances and then we have a transformer that is perfectly ideal. So let us do the reflection one by one and see what happens.

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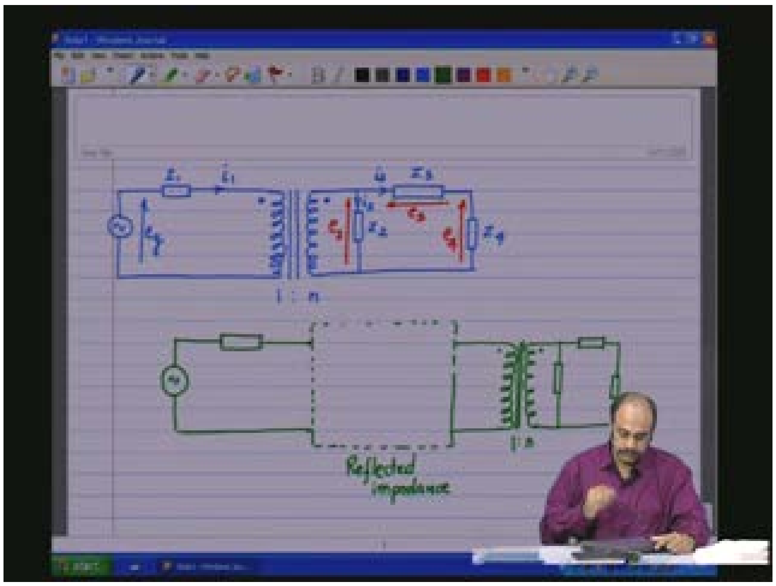


Now to start with we have the impedance on the secondary side which is like this 1 is to n, this is the dot polarity and to start with let us just make a connection between these two: this is Z 1, this is Z 2, this is Z 3, this is Z 4 (Refer Slide Time: 8:05). Now we want to make the impedance conversions from secondary side to the primary side which means you have to divide by n square.

So the first Z 2 will be transferred to the primary side. They can be transferred just as such. So Z 2 is removed from there and it will come in here parallel across…….. now it would have a value Z 2 by n square, it will have a voltage which is e 2 by n that will be the voltage which will be flowing and then the current through that………….. you see the current through that is i 2 and the current that same current transfers on to the primary side which would be n i 2. So as such every parameter associated with that is transferred on to the primary side.

Now let us transfer the Z 3. Z 3 is removed, it is now replaced with a short and then on this side let us make some space for Z 3 and we have Z 3 but it is having a value by n square. Now the current through Z 3 was i 3 and reflected on to the primary side the current through this should be n i 3, this still remains i 1. The voltage across Z 3 was e 3 and reflected on to the primary side it is e 3 by n. Every parameter associated with Z 3 is reflected in this manner.

Now we remove Z 4 from the secondary side and include it on the primary side. Now it is Z 4 by n square whatever the turns ratio. A current of i 3 was flowing through that and the same guarantee n i 3 flows through this. Of course now there is no current which is flowing here, this current will be equal to 0, this current is equal to 0 let us say an ideal transformer.

Now what is the voltage across this?

The voltage across this Z 4 impedance was e 4 and it is nothing but e 4 by n. You see the impedances all have been shifted, transferred to the primary side and after shifting, it is followed by a transformer of ratio 1 is to n and there is the secondary voltage across that. This is how the impedance from the secondary side can be transferred to the primary side.

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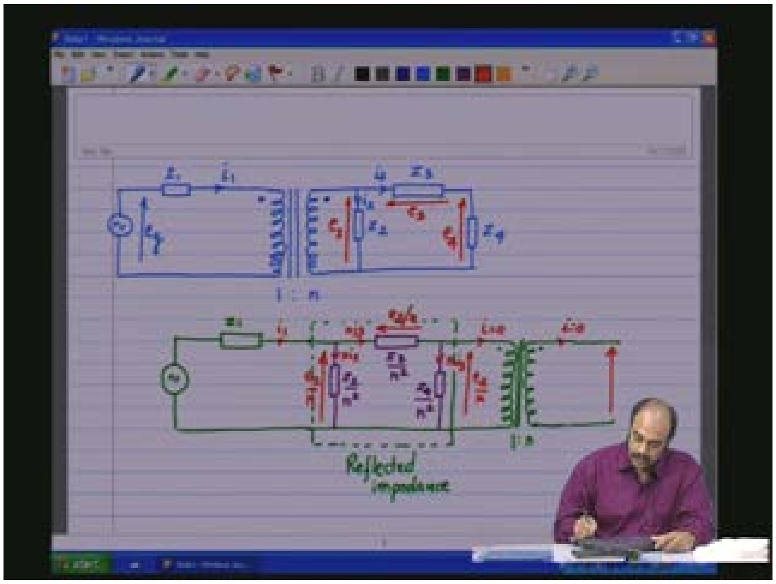

We could also look at the impedance being transferred from the primary to the secondary side also. Let us take a similar simple circuit. That is we take the same. let me copy this so that it becomes easier for you to understand. This is the circuit that we have been discussing. Let me paste it here. This is 1 is to n. Now let us transfer this impedance on to the secondary side.

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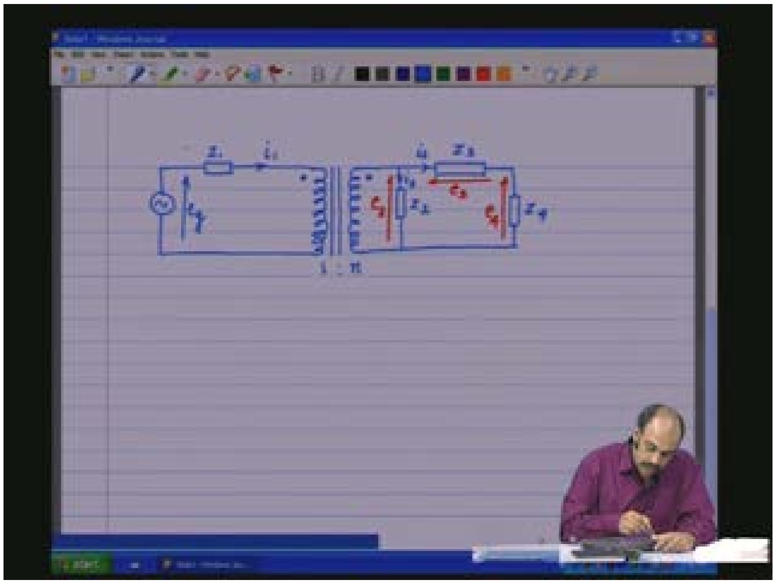

So what do you get?

You get…… there is an e g, core secondary windings and there is impedance which is shifted from the primary to the secondary and the rest remains the same. The secondary side impedance remain the same along with the parameters. So you have Z 2 Z 3 Z 4. Now Z 1 is shifted here so that becomes N square Z 1. Remember that when you shift from secondary to the primary it is divided by n square where 1 is to n is the turns ratio of the secondary winding number of turns to the primary winding number of turns n square Z 1 and the current through the current through the reflected impedance on the secondary side, primary side it was i 1 and therefore on the secondary side it is i 1 by n and what is the voltage across Z 1? Here the voltage across the Z 1 was e 1 and here it would be e 1 into n; all parameters now shifted to the secondary side.

Now e g could probably also be shifted to the secondary side by multiplying e g by the turns ratio n which means the circuit will look like this. We have the transformer winding, dot polarity, core, secondary and let us have e g; now it is e g into n winding n square Z 1 the existing secondary impedances Z 2 Z 3 Z 4. You see now here you have i 1 is equal to 0. This would be the equivalence circuit as seen on the secondary side and we saw here the equivalent circuit here as seen on the primary side.

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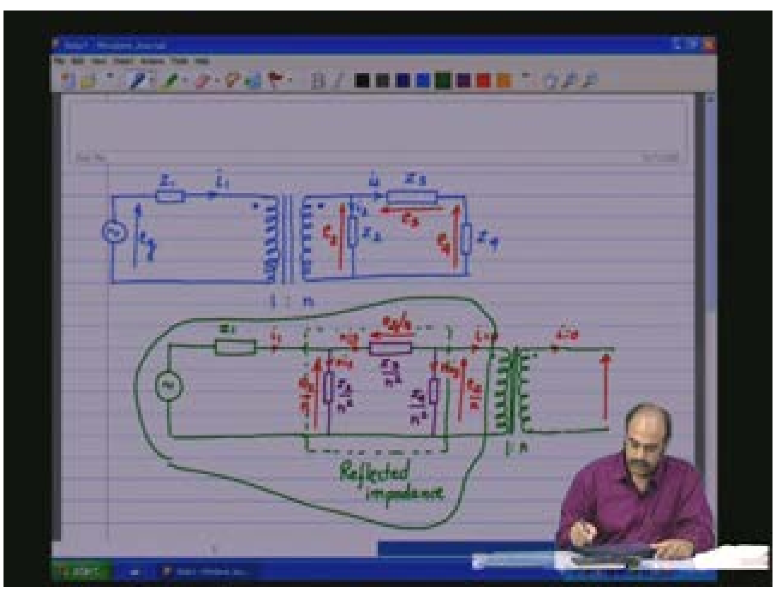

In this way one may choose to reflect impedance either from the secondary to the primary or primary to the secondary for purpose of doing the analysis depending upon the convenience of the circuits.

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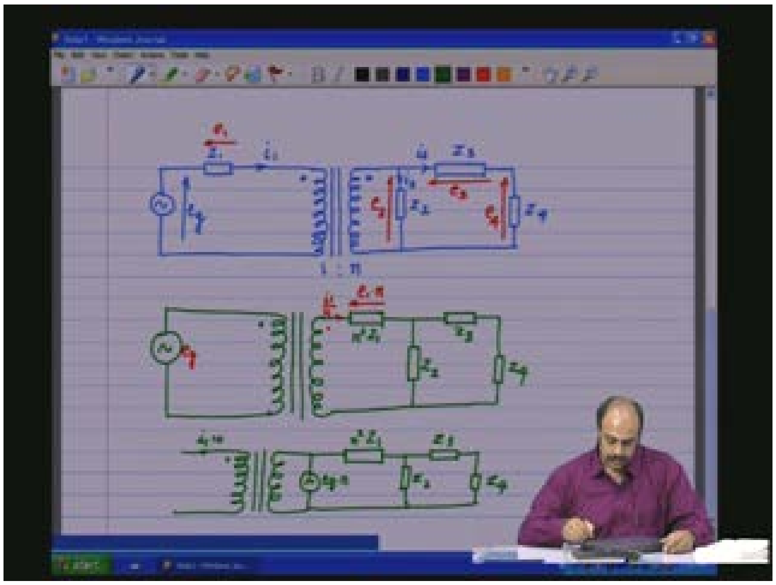

Now we would like to see we would like to see the transformer till now had losses to contend with that is due to hysteresis and Eddy currents. This we are calling it as core losses. Now from this aspect let us see an ideal transformer an ideal transformer means what characteristics.

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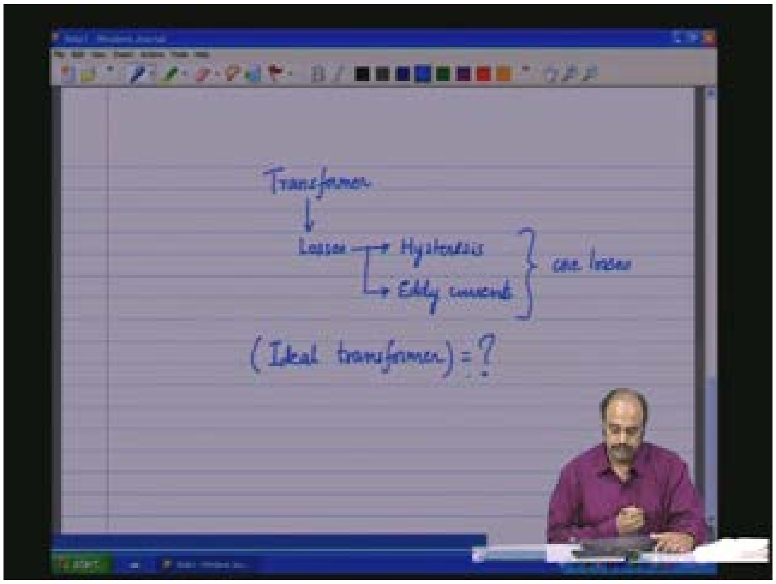


Firstly let us take the BH loop. So we have this BH loop plotted on to an orthogonal axis, vertical axis being the B, the horizontal axis being the H, this is NI by L ℓ m NI is ℓ mf the motive force and this is flux per unit area. So in that And we have seen before that this results in a curve which….. and the area covered within the area covered within the BH loop in a in a cycle is the energy that goes off as hysteresis loss because that is unrecoverable which implies that if this loop is narrower and narrower that is we tend towards we tend towards the loop which is like that.

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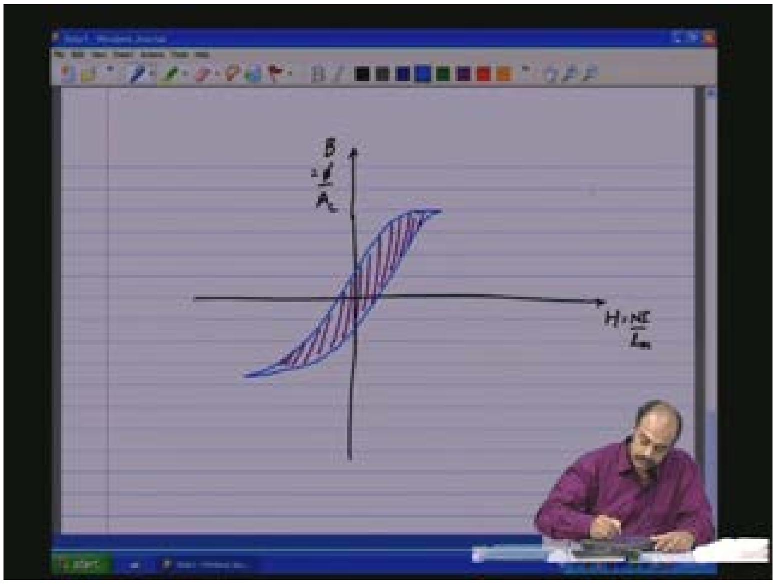

Let it tend towards this becoming narrower and narrower and in the limit let it become just a line length which means the area within this loop is almost zero or in the ideal case the area within the loop is zero then there is no hysteresis loss, hysteresis loss becomes zero. Here hysteresis loss is equal to 0.

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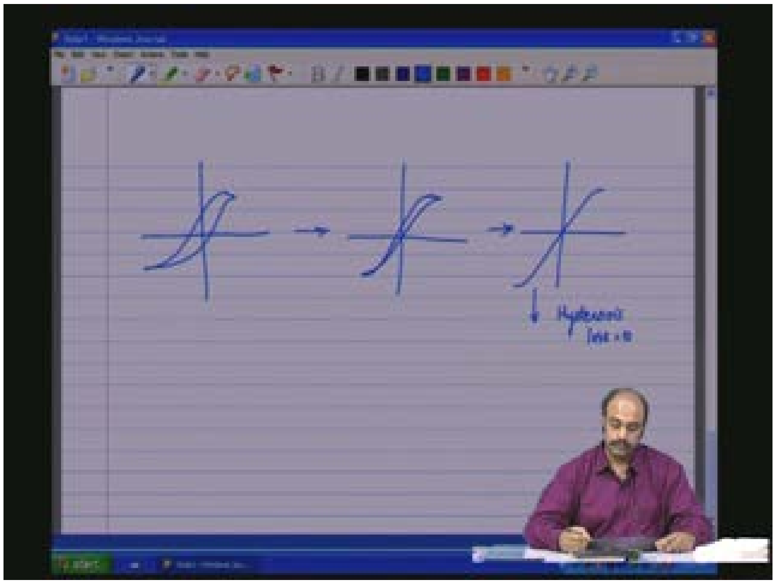

We also need to look at the slope of this (Refer Slide Time: 20:33) this slope it means that if I want the slope tells you how much amount of motive force NI by ℓ m, how much amount of current I have to pass on the primary of the coil to obtain a flux phi 1 by A for a given core.

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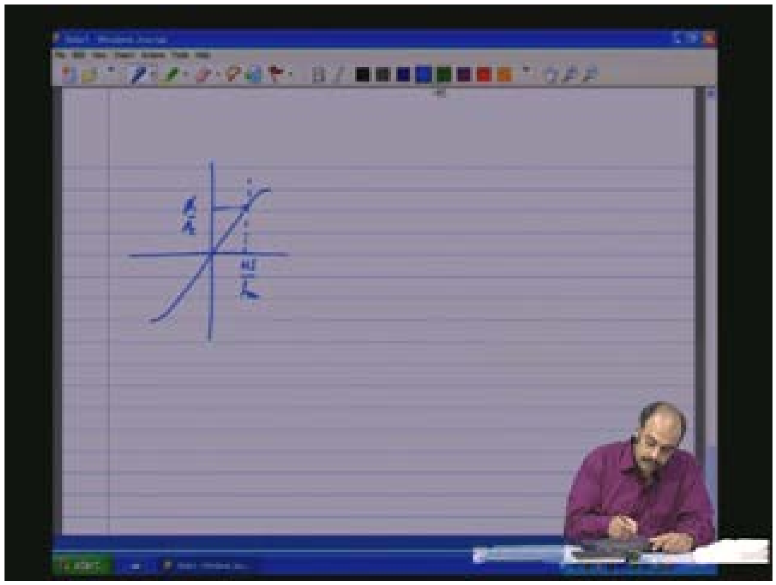

Now if this slope is made steeper then it implies that to get the same flux phi 1 I need to pass lesser current; if this were i 1 this will be i 2 by ℓ m and so on if the slope keeps on becoming higher and higher which means the permeability is improving because this slope is nothing but mu the permeability is going towards infinity, so in the limit this will tend to this will tend to this is almost vertical like that which means this has a mu Z (( )) (00:21:58) which is tending towards infinity this being the BH curve, this is the B and this is the H.

So what it implies; to obtain a flux phi m or pi m the current needed is negligibly small or (( )) (00:22:24) small or in the ideal case zero. So that is one another point of ideality where mu tends to infinity.

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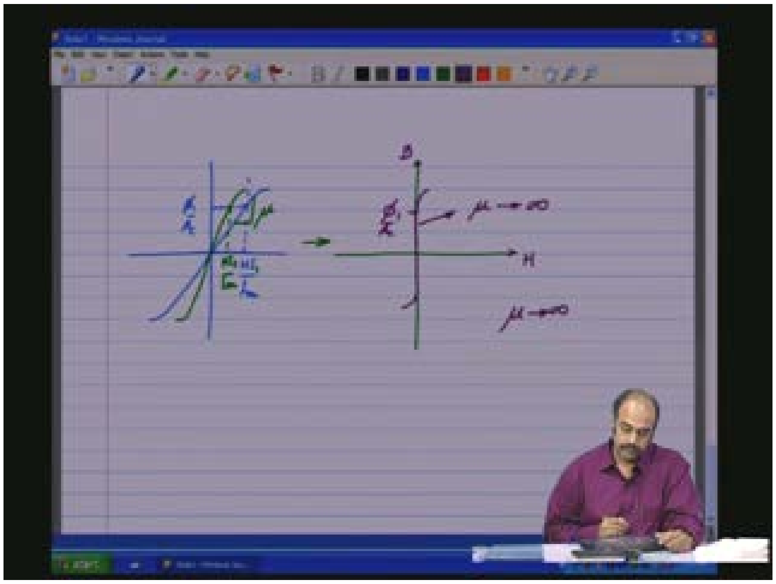


Now there is another point of ideality that one could note the same BH curve. You have the H and you have the B. We saw that let us say this is the BH curve. After certain level of B it saturates B sat, it loses its magnetism lose its magnetisation properties beyond which it does n't act like a magnetic material.

Now if this B sat starts tending to infinity, if B sat tends to infinity and we will land up with a magnetisation curve which is the vertical axis itself. So a magnetisation which is a vertical axis implies B sat is infinity, mu tends to infinity, permeability tends to infinity, hysteresis loss tends to 0 all these are important features of an ideal transformer. Note that all these would be features of ideal transformer something that we expect it to have.

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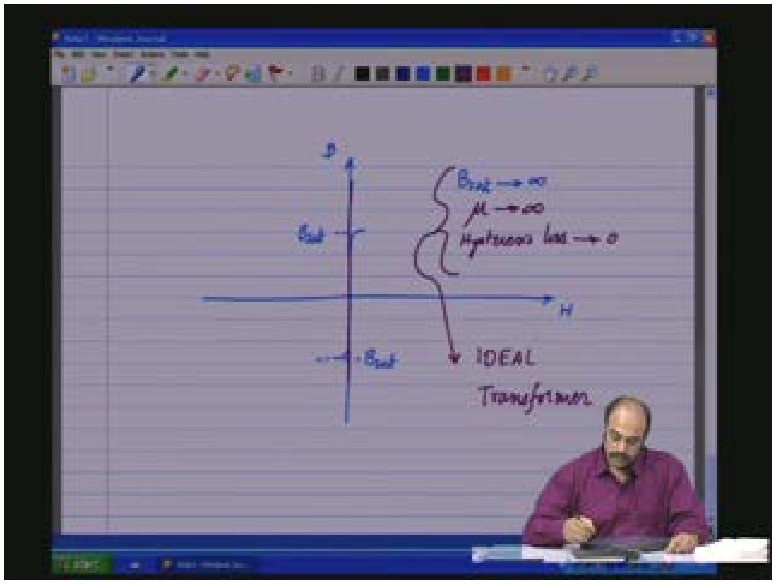


One more feature that is expected of the ideal transformer is that there should not be eddy current losses; losses should also tend to 0 which means the resistivity of the core material………. because if there is a flux flowing in the core material there is going to be currents around the flow of the floods in an orthogonal plane. So if the resistivity of the orthogonal plane is increased then that eddy current is going to be reduced and that resistivity becomes infinite and the eddy currents will also tend to 0. So the resistivity of the core material of core material should tend to infinity. This implies this implies the eddy currents tend to 0 which means eddy current losses due to I eddy square R core will tend to 0. So in an ideal transformer the resistivity of the core material should also tend to infinity.

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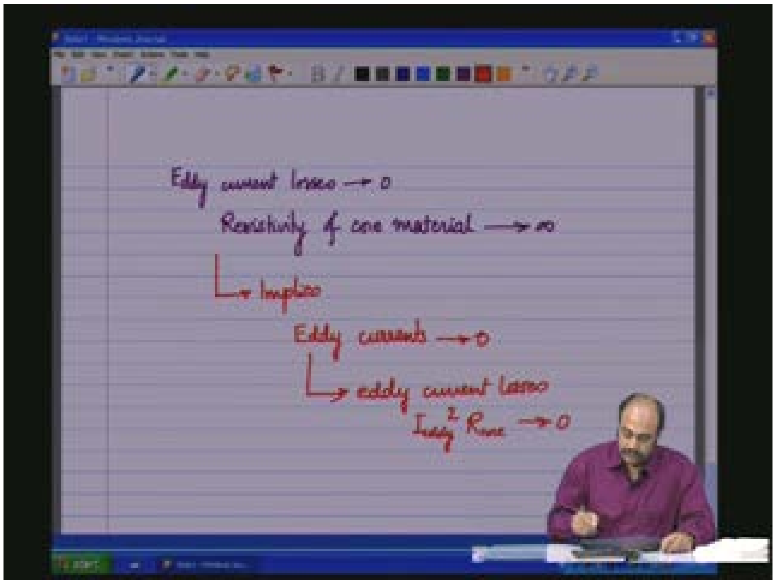


So, for an ideal transformer the following features exist for them. One is the permeability mu tends to infinity which makes the BH curve slope at 90 degrees that is along the vertical axis. second B sat the saturation flux density tends to infinity meaning the core never saturates whatever may be the current that you apply or whatever may be the motive force. Then third there is no hysteresis loop; the area of the hysteresis loop is 0 which implies hysteresis loss tends to 0. Then fourth resistivity of the core material of the core material should tend towards infinity, this implies eddy current losses are 0.

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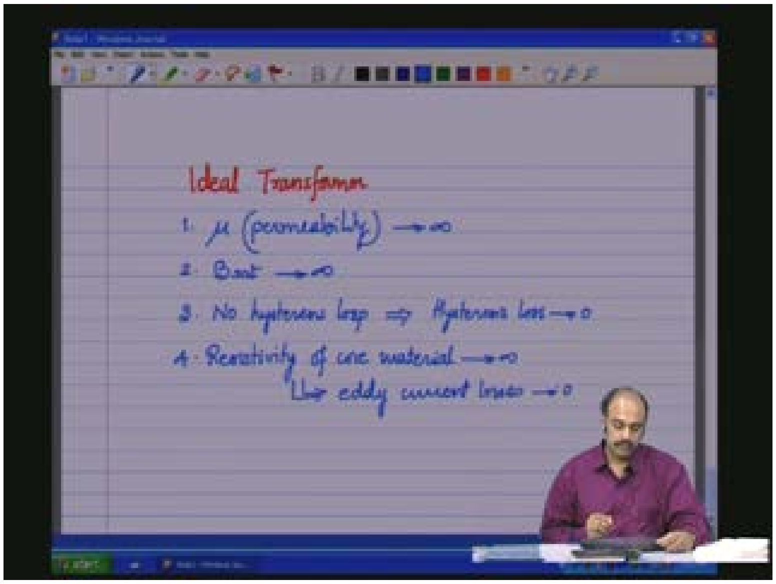


Further there is a fifth one which is on the coil; the coil which is wound on the core should have zero resistance. So the coils in the winding resistance should tend to zero meaning the copper that is…….. normally copper is wound on the core but copper has a finite resistance therefore if there is a winding or finite number of turns the resistance is also finite and therefore there is going to be i square or i square or loss. So the coil is winding resistance if it is tending to 0 there is no copper loss, the copper loss is i square into R winding will also tend to 0. This would be an ideal transformer with absolutely no loss. So whatever energy is given to the primary the same energy goes out through the secondary port.

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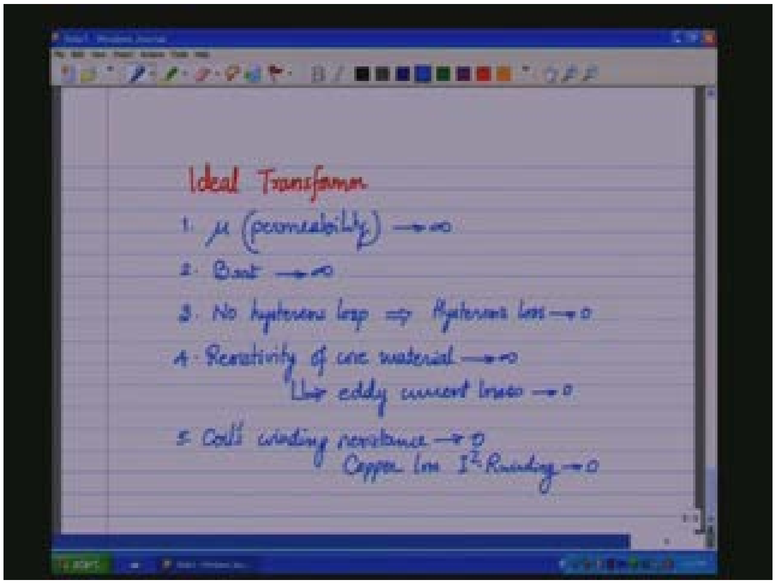


In other words, if there is no load on the secondary if there is a voltage applied on the primary there is no current flowing through the primary winding, zero current is sufficient to setup flux in the primary and the flux in the core and the flux that is setup in the core which is the motive force setup in the core will induce an emf on the secondary according to the turns ratio and the secondary voltage is developed with zero energy being lost in the hysteresis or the eddy current or the copper loss that would be the feature of an ideal transformer.

Now, the practical transformer……….. because we cannot expect to obtain or get or make an ideal transformer the practical transformer the practical transformer will have a finite mu; mu or the permeability is finite which is not infinity. The B sat the saturation flux density is not infinity but a very finite value. And as I said CRGO has around 1.2 tesla, CRNGO Cold Rolled Non-Grain Oriented silicon steel has 1 tesla ferrites 0.3 tesla so on. So it is a finite value which means beyond this value the core will saturate and will not behave as a magnetic material; the loss of electromagnetism will not hold good.

Then the third point there is a hysteresis loop. Hysteresis loop is not zero or non-existent it is a finite area which means there is a finite hysteresis loss. And the fourth the resistivity of the core material is not infinite but is finite which means there is some finite eddy current loss and fifth the coil that are wound on the core is normally copper or aluminium which has some finite resistance and therefore the coil or winding resistance is non-zero which means there is going to be a finite copper loss. So, a practical transformer has all these to varying degrees depending upon the type of materials used and depending upon the type of the windings used in the way it is designed.

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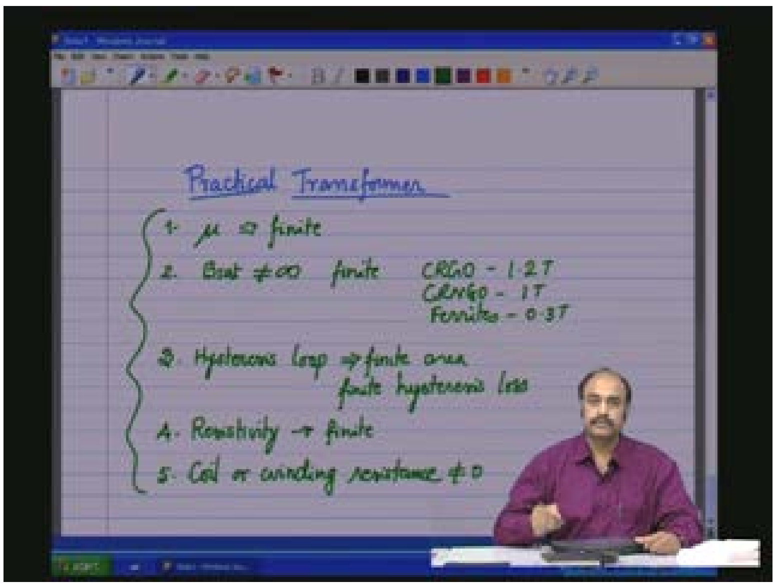


Now how do we represent a practical transformer electrically?
Because an ideal transformer we know has a symbol like that with a turns ratio. This is an ideal transformer ideal transformer (Refer Slide Time: 33:28). What would be the equivalent circuit for a practical transformer that will be the focus of the discussion in the forthcoming dialogue.

Now let us start with the ideal transformer and one by one let us introduce the non-ideality and how does it reflect electrically on the equivalent circuit we shall discuss and see the effect of the that particular non-ideality on the equivalent circuit.

So first let us introduce the effect of effect of core losses effect of core losses. Now the transformer an ideal transformer is shown in this manner; there is a core and then the secondary winding. Now there is a source on the primary side an AC source and that is called e g. Now this source is connected to the ideal transformer. So, under normal ideal conditions when the output on the secondary side is open there is no load connected, this current i 2 is equal to 0 i 2 will be equal to 0 and therefore i 1 will be equal to 0 which means even zero current is sufficient to provide or infinitesimally small current negligibly small current is sufficient to provide the required ampere-turns or the magnetomotive force to setup a flux in the core which gets linked to the secondary to produce e 2 to produced e 2. This is the primary induced voltage.

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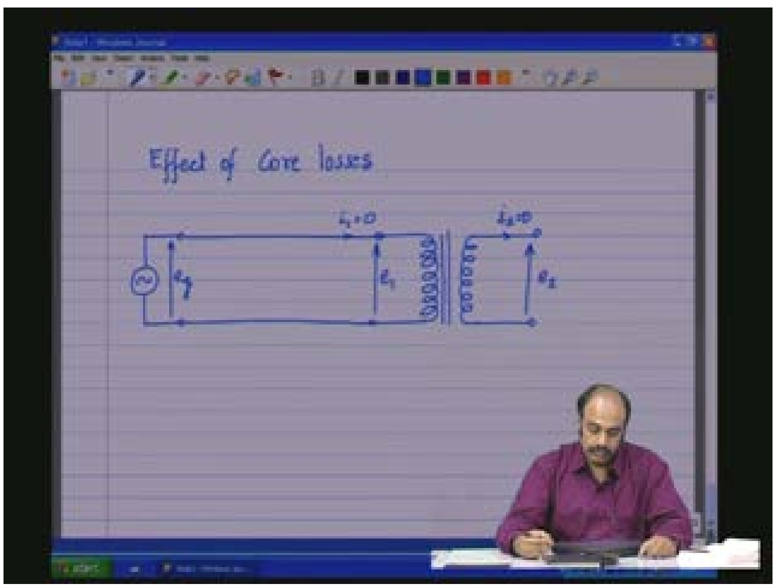


But in a practical transformer we said that there is core losses one of the non-idealities we are introducing. Now if there is core losses even when there is no load connected across the secondary terminals the hysteresis loop is going to be traversed; every cycle the hysteresis loop is going to be traversed and for every traversal at the hysteresis loop the area covered by the hysteresis loop that portion that amount of energy is going to be unrecoverable so that energy gets lost which means that much amount of energy has to be supplied by the source which means the source current will have some current i 0 even under no load conditions whatever that is.

Now that current is not going through the ideal transformer so it has to go through some lossy element. So we put in a lossy element here (Refer Slide Time: 38:04) and let us call that one as R c is a core loss component and the current that is going to flow through this is whole i 0 itself which flows through this and provides the i square or i 0 square R c as a core loss equivalent core loss component.

Now additionally let us also introduce the finite permeance finite permeance non-ideality or finite permeability non-ideality which means mu is finite. So what does it imply is mu is finite and the slope is not 90 degree the slope is not finite which means the BH curve is not along the vertical axis it is going to be slightly away from the vertical axis as denoted by the permeability which means that there is some amount of current needed to setup the required flux there is some amount of current needed to setup the required flux there is some amount of current highly needed to setup the required flux phi, this is phi, this is phi, phi and the B where B is nothing but phi by A and H is nothing but N i by L so we could also have a phi I curve which means a finite current is needed to setup the flux which means that current is also to be drawn from the source you know under normal condition that current is also to be drawn and diverted to the flux producing device or flux producing component of the equivalent circuit and i 1 should still continue to be zero because this ideal transformer is not going to take any current to setup the flux which means from here I am going to have one more component and let us call that one as X m (Refer Slide Time: 40:54) so this i 0 which is drawn from the supply is going split into two components: one is i m and the other is i c; i c is that component of i 0 which produces the core losses, i m is that component of i 0 which produces the magnetic flux in the core flux in the core such that it can be linked to the secondary and such that it can be linked to the secondary and have an induction on the secondary side. Hence, these two non-idealities result in such an equivalent circuit.

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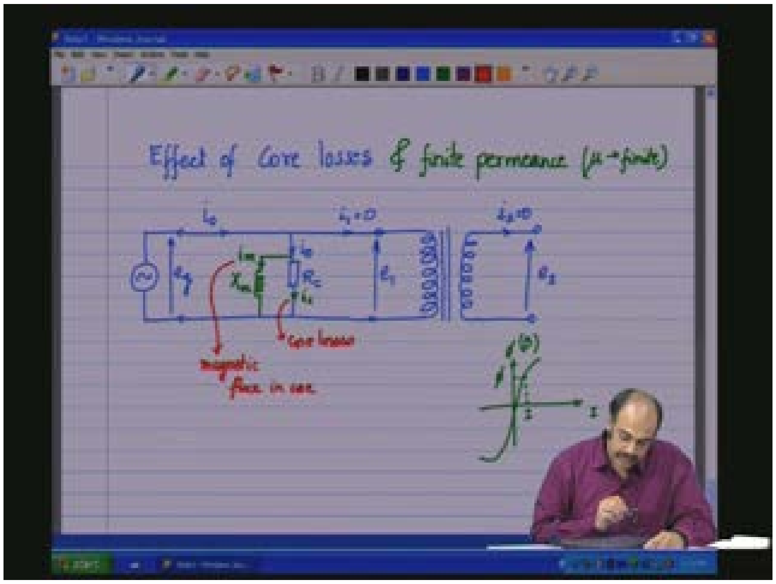


How do we measure this?

You see that ic is producing a loss in R c i square i c square R c so the voltage across R c and even will be in-phase which means i c will be in-phase with e 1 and e 1 is same as e g, i m is the flux producing component which will lag which is passing through an inductor inductive reactance and therefore i will lag 90 degrees whatever the voltage across the device. So, if we look at the phasor diagram it should look like this. So let us first take this to the next page and we go the next page, we paste.

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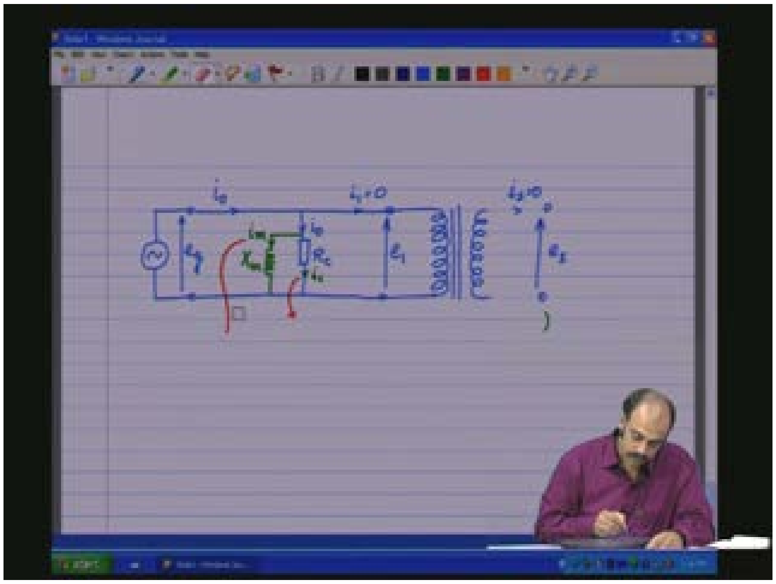

So, so if we if we have let us say the spatial coordinates and along this axis I have e g which is same as e 1 and along that is i c and 90 degrees lagging will be i m which in fact produces phi m the flux and the resultant of i c and i m will be i o by Kirchoff's current law. This is i 0 (Refer Slide Time: 44:32). This is how it would look like.

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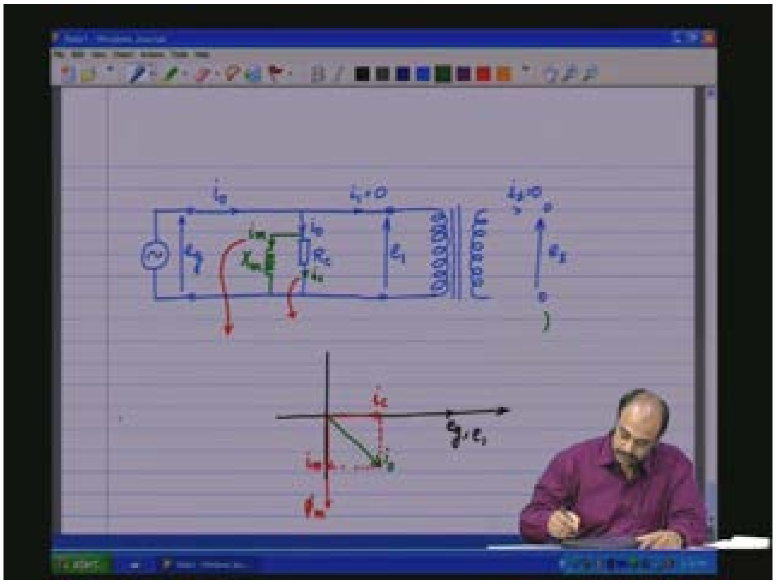

Now i 0 into e 1 i 0 into e 1 is the VA that is drawn from the source. So VA drawn from the source will i 0 into e 1. i c into e 1 is the active power that is the last component which is drawn from the source and i m into e 1 is the reactive power that is drawn from the source for setting up the magnetic flux in the core. So this will be let us say a reactive power Q, this will be an active power P this is drawn from the source and this is going to be the root of P square plus Q square let us say.

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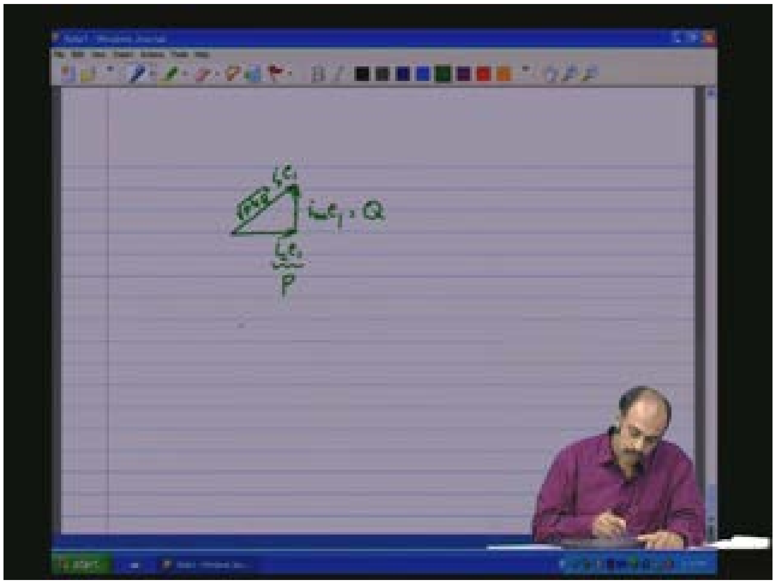

So R m and X m can be found out from this and this. So P the power the active power is nothing but e 1 square by sorry we use R c, R c is nothing but e 1 square by R c and Q reactive power is nothing but e 1 square across the same inductance divided by X m. Therefore, you have R c which is equal to e 1 square by P and you have X m which is equal to e 1 square by Q. Hence, measuring the active and the reactive power or measuring i 0 and e g voltage capturing it on the oscilloscope and then computing the P and the Q that is the active power component which is watts, the reactive power component which is V AR and this of course is a V A one can compute R c which is the core loss component and X m which is the magnetising impedance or the magnetizing reactance component of the transformer under no load conditions meaning when the secondary side is open circuited there is no load connected across the two secondary terminals.

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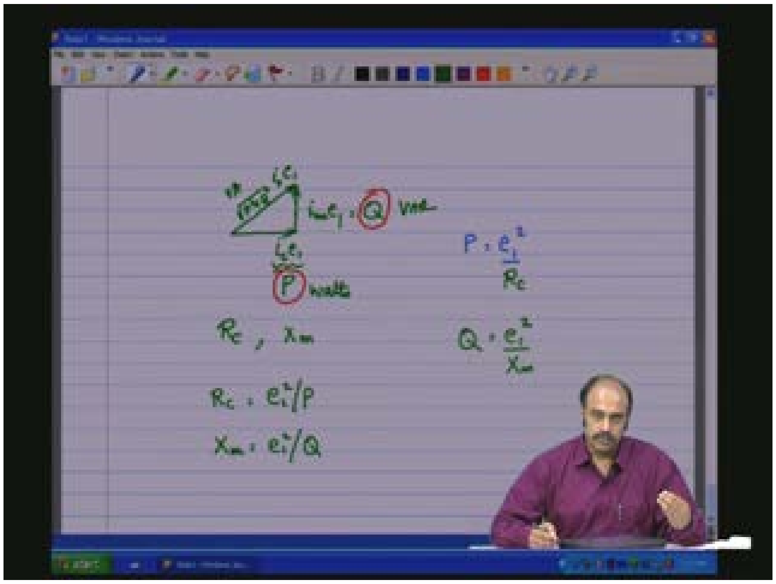


Now let us let us do a small example for this particular case of non-ideality where we have introduced a finite permeability and we have also introduced the core loss components into the transformer into the ideal transformer. So the equivalent circuit is now composed of an ideal transformer plus some added components in parallel; one is the last component R c and another is the magnetizing component X m which is basically an inductance ℓ m.

Let us say we have a transformer and at no load at no load it draws current i 0 which is equal to 5 amps. The primary is connected to e g is 230 volts 50 hertz and from the watt metre test that is by connecting watt meters the active power that is power loss or the iron loss or the core loss the power loss component in the core is 200 watts let us say. Now this information is given let us find out what is the apparent power apparent power that is the VA.

Now VA we saw we said in the previous…… this is nothing but i 0 into e 1 is i 0 into e 1 which is phi into 230 volts. This is the VA. Now we know that the P P in this is the active power here which is 200 is watts given then what is Q? Q is root of VA square minus P square which will be root of 5 into 230 square minus 200 square so we have the Q.

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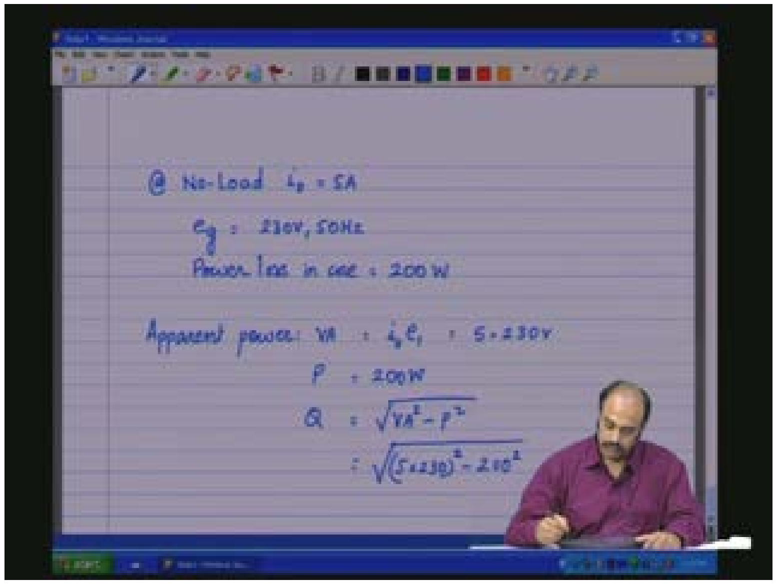


Once you have the Q and the P R c is given by e 1 square by P which is 230 square divided by 200 ohms X m the magnetizing impedance or the magnetizing reactance is given by e 1 square by Q which is equal to 230 square divided by root of 5 into 230 square minus 200 square that many ohms. So this gives R c and X m and this can now be utilized used to find what is i c.

Now i c is equal to e 1 by R c which is equal to 230 divided by 230 square into 200 which is equal to 200 by 230 amps and i m is equal to e m by X m which is 230 divided by 230 square root of 5 into 230 square minus 200 square amps. So this will give you the core loss component of the current and the magnetizing component of the current and one can plot the one can plot the phasor diagram and obtain and see that……….. let me do and see that if we have 230 volts this is e 1 or e g we are going to have i c and there is going to be i m and the resultant that is going to be 5 amps.

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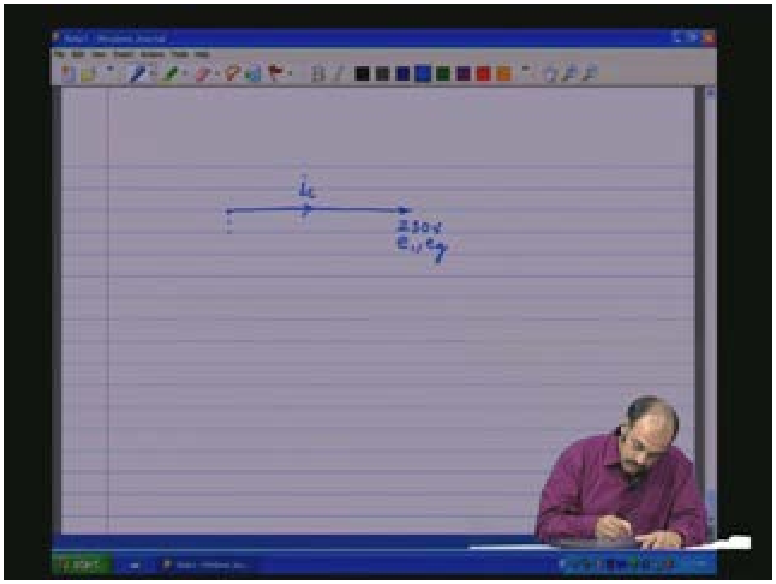


So if this is going to be less than if we look at this equation this is approximately less than an amp or around 0.8 or 0.9 amps so this approximately 1 amp and this will be slightly greater than 4 amps so that you get resultant 5 amps. So if you calculate this portion this should be around 4 amps and this should around 1 amp greater than 4 amps.

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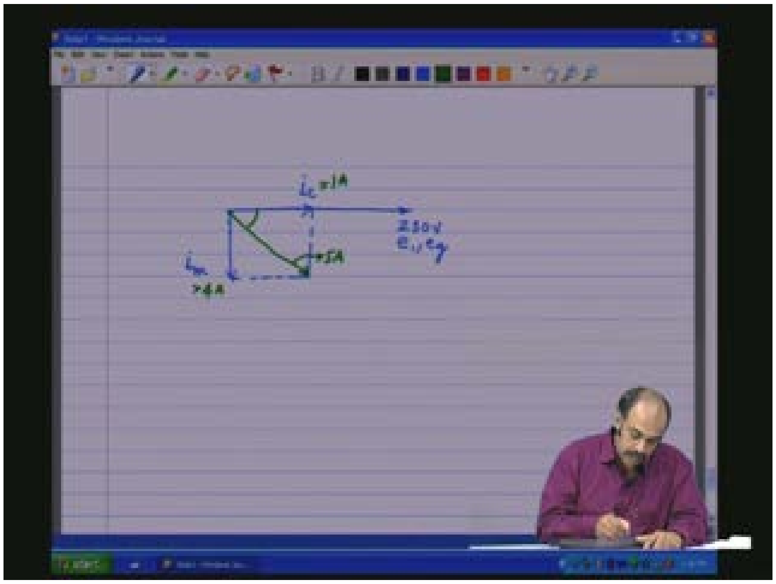

So this would be the vector diagram and this will be the angle i 0 by which the current lags the applied voltage e 1 or e g. So what we have done here is introduced two non-idealities: the loss component and the finite permeability component.

Now we also have to see that whatever ampere turns that the primary current is primary current is generating which is N 1 into i 1 is going to have a motive force within the core of the transformer. Now that is going to link to the secondary turns N 2 and generating a voltage e 2 and if there is a load on the secondary there is a current i 2 flowing in the secondary. Now, that secondary current is going to also produce a motive force within the core of the transformer which is N 2 i 2. Now N 1 and N 2 would be opposing in nature because on one side the power is entering the transformer and on the other side the power is leading the transformer and because of this opposing nature they cancel each other and there is an effective flux in the core.

Now all the ampere-turns or all the flux that is produced by the primary does not link all the windings on the secondary and all the ampere-turns or motive force generated by the secondary current i 1 which is N 2 i 2 is not going to link with the primary so there is going to be some flux which will not link with the other winding and that is called the leakage flux. So there is only a portion of the flux that actually links between the two coils and that is called the mutual flux. So we have the leakage flux and then mutual flux which results in actually lesser voltage being developed across the other windings in the core.

Now all the practical transformers will have some flux which does not link the other coils which are in the core path and they are called the leakage fluxes. And we will see how we try to incorporate the leakage flux component into the equivalent circuit model to have a much more complete picture of the transformer. Further we need to also include the copper loss component into the model. This we will see in the next session.

Thank you for now