Basic Electrical Technology
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Lecture - 18
Transformer Basics Part - II

Hello everybody, in the last session we were discussing about the transformer and in this session we shall continue our discussion on the transformer, its principles of action and also the features of the device. We shall focus first in this session on an ideal transformer. We were discussing in the last class about the hysteresis loop and when the operating point traverses around the hysteresis loop there is some amount of energy that goes unrecovered and that energy is the loss that happens every cycle on the hysteresis loss.

Now the hysteresis loss we saw was proportional to the frequency of operation and the flux density and also the volume of the core. There is one more type of loss in the core called the Eddy current losses. The Eddy current losses are occurring by virtue of the ampere's circuit law that we had discussed and we saw that if we have a transformer core let me draw an isolatory three dimensional view of a transformer core, this is a transformer core (Refer Slide Time: 2:48) so the windings are in this pattern as seen here and so on.

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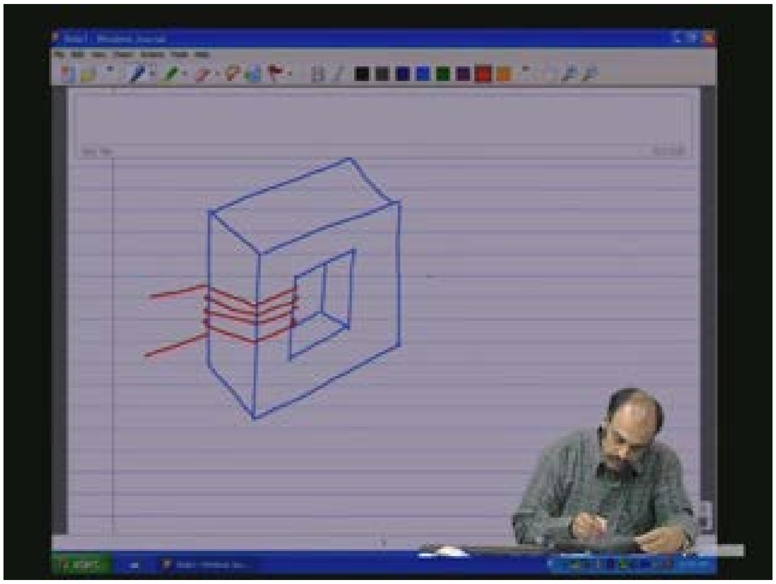

So this could be the primary and then you could have the secondary wound in this fashion and so on. Now we are interested in a cross section of the core as shown here. Now, in this cross section of the core because there is a primary current flowing there is a flux which is setup, a magnetomotive force which is setup in a particular direction let us say it is in this direction (Refer Slide Time: 4:15). Now this magnetomotive force is going to flow in a direction which is orthogonal to this cross section area which we have shown as hashed and this let us say is the flux.

Now by Ampere circuit of law if we have a flux or a H field there is going to be a current in a loop or if there is a current around the flux then there will be a flux in an orthogonal area. So we (…………….05:00) have a current which will be around like a loop around the flux lines. Now these currents which I am showing in blue these currents are called the Eddy currents these are called the Eddy currents. these currents are flowing in the solid mass of the core and as if the mass of the core is highly conductive then these currents could be quite high because the resistance will be very low and the i square loss is consequent because it is dependent on the square of the i which will be very high quite considerable and these Eddy current losses are not desirable because they are again the energy which is lost and not recoverable and cannot be transferred to the other port which is the secondary.

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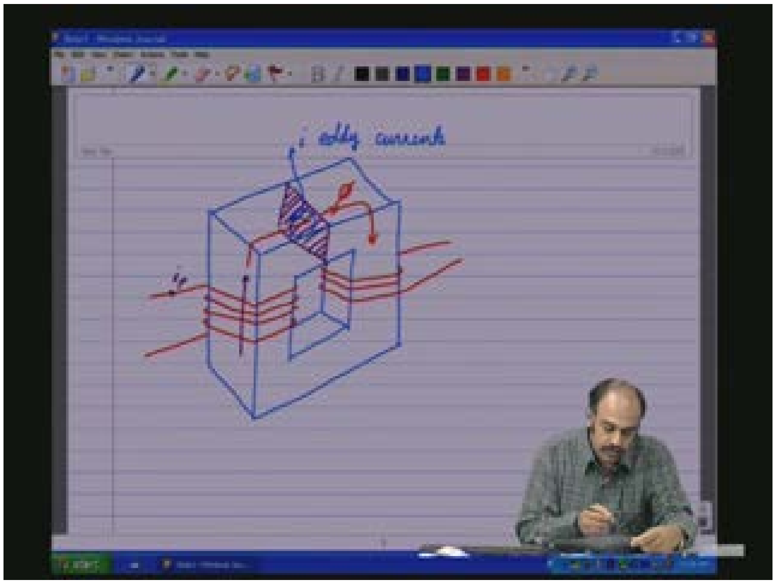

Therefore, these Eddy current losses need to be reduced. So, to reduce the eddy current losses what is generally done is to increase the resistance of the path where the current can circulate. So to increase the resistance of the path what is done is have laminations, what is done is to have laminations like that and so on. Now these laminations will make the cross section area in such a manner so they will be like this the cross section areas and the currents will flow only in within these areas (Refer Slide Time: 7:48). So what basically happens is for the direction of the current flow here the rho ℓ by A is reduced rho ℓ by A is the resistivity of the material; the resistivity of the material increases because there cross sectional area for the flow of current here is reduced and the length is also the length is reduced but still the resistivity is increased. So, once the resistivity increases the resistance for this cross sectional area for this lamination here will be much higher than for the solid mass which has a much higher cross sectional area.

Likewise, each of these current loops here the Eddy currents will see a higher resistance due to the fact that laminations have been introduced and these will see higher resistivity and as a result the induced current will be lesser because the induced voltage divided by the resistance is going to be lesser and as a result the i square losses are going to be contained much lesser than with the solid mass. So this way the Eddy current losses can be reduced and that is why in the power transformer you will see that the core is laminated and not one solid piece. Or otherwise, if the core if the core is made up of a highly resistive material like ferrite then the use of laminations is not warranted, one need not use the laminated core, they could use one solid piece of core material because the resistivity of the core material itself is high which will reduce the Eddy current losses.

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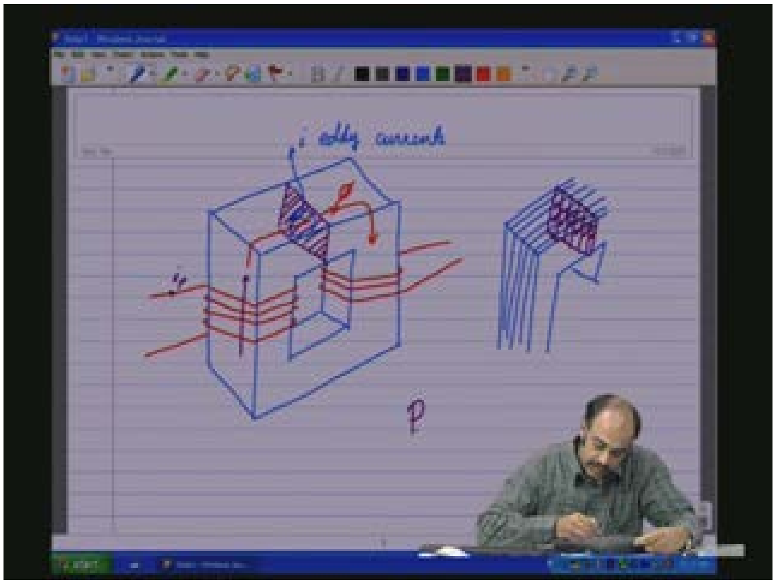

There is an empirical relationship for the eddy current power loss which is proportional to the flux maximum flux density square and frequency square. However, the frequency higher is going to be the eddy current losses and higher the flux density maximum flux density of the core higher is also going to be the eddy current losses because the current that is going to be induced will be directly proportional to the flux density and therefore you will have the i induce will be also proportional to the amplitude of the flux density and therefore the loss is going to be proportional to i square times or B n square times hence the terms square of B m.

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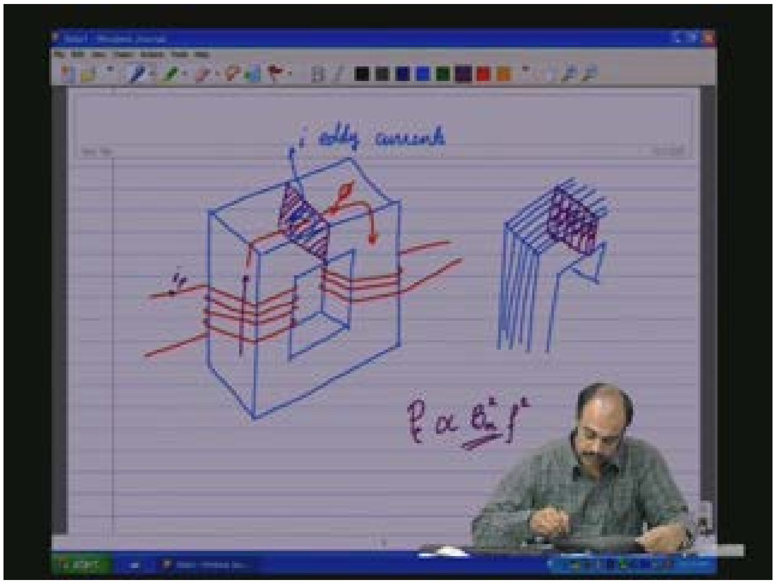

So we have the core losses which are composed of hysteresis loss plus the Eddy current loss. The hysteresis loss plus the Eddy current loss together form the core loss and as currents are flowing through the copper coil there is going to be some finite resistance associated with the copper coil which is wound on the transformer core the primary and the secondary and there is going to be an i square R or copper loss associated and that is called the copper loss associated with the copper coil which is wound on the core due to the fact that there is current flowing through it and due to the fact that there is a finite resistance associated with the coil and that is the copper loss.

So, core loss plus copper loss will be the total losses in the transformer; will be the total losses in the transformer P loss. So, if we have a transformer with a primary and a secondary and if there is a P input, P 0 will be equal to P input minus P loss which is the core losses and the copper loss put together what comes out here.

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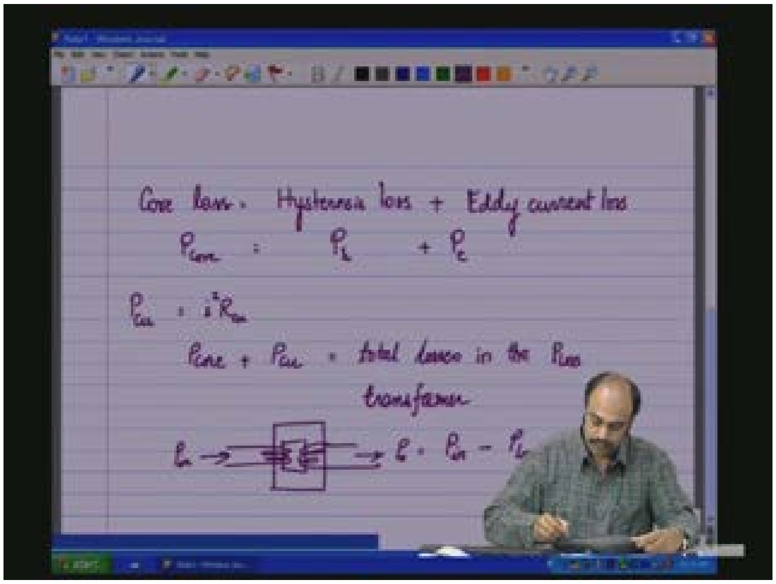

Now there is one more important feature in the case of the transformer that we need to be careful about while designing, is the volt second balance the volt second balance, this actually comes from the Faraday's laws law of electromagnetism and what does Faraday's law of electromagnetic magnetism state; it says that the induced voltage e is equal to N the number of terms in the core dphi by dt into dphi by dt where phi is the flux in the core that is if we have if we have a core of N terms winding on the core and then if we apply a voltage e there is going to be a flux setup due to the fact that there is current flowing and the rate of change of flux into N is going to induce the same voltage e here.

now this voltage e which is equal to N dphi by dt or N A c dB by dt where phi is equal to B into A because flux density B is flux by the area of cross section of the core so N A c db by dt and therefore the flux is given by 1 by N A c integral of e dt. Now N and A c are constants and therefore B is proportional to integral of edt. This is the volts (refer Slide Time: 15:15) and this is the second. That is what is known as the volt second balance meaning this integral integrant or integration should not have a waveform that is continually increasing meaning e should not be a DC value, if e is a DC constant value, then on integrating this would be the constant into t which means it is a continuously increasing value and after sometime the flux density for the particular core for every core or every type of core material there is a value of flux density beyond which the flux density will not increase. That is why we say the core has saturated and it loses its electromagnetic property.

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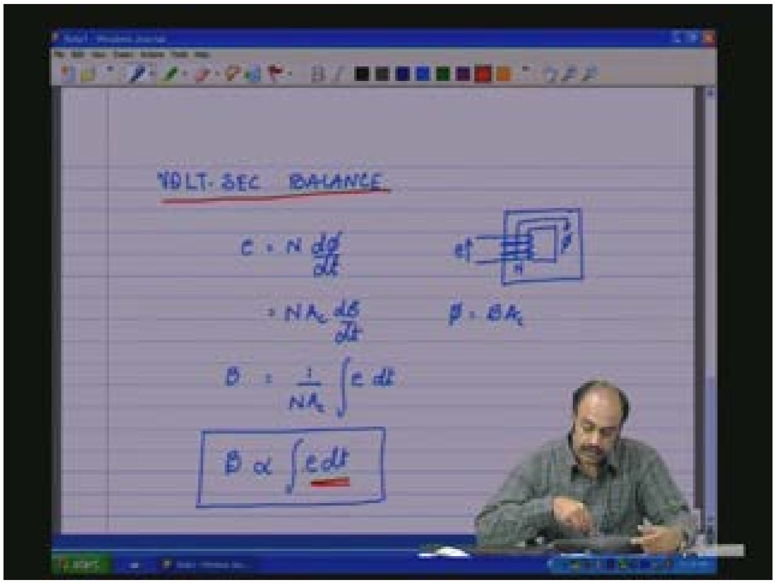

Thus, if the if this value here integral of edt is continuously increasing then a time approaches when the value goes beyond the flux density permitted for the core and the core will saturate, it loses its electromagnetic property and it will just be a plain short circuit. Therefore it is essential that for the particular core this volt second; integral of e dt is nothing but the area under the voltage curve, the area under the voltage curve should not go beyond a value whatever is permissible for that core whatever the flux density that is permissible for the core, this is the volt second balance.

If, for example; we have e is a constant V V constant of amplitude V then integral of Vdt is going to be V into t and this has an amp waveform and this keeps on increasing beyond a particular value where we have B sac; beyond that particular value the flux core will saturate and it loses its magnetic properties. If V were e were sinusoidal V m sin omega t then this would result in V m cos omega t by omega as this one and this is divided by omega 2pi f and therefore this value has a sinusoidal character but the peak values are always V m by omega and the design value of V m by omega should be such that this does not exceed B sat of the core. In such a case the core will not saturate and it will have it will retain its magnetic properties; this is the volt second balance which one need to be conscious about while designing.

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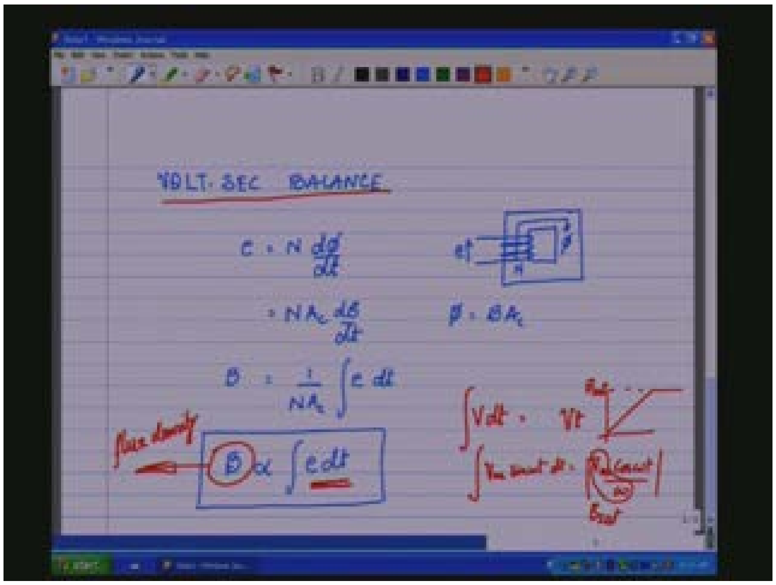

Now, for sinusoidal waveforms, again from the Faraday's law of electromagnetism we have e which is equal to N A c dB by dt. Let us draw the BH curve; we have H and B, let us draw the approximate BH curve. This is the BH curve (Refer Slide Time: 19:27). Now, if you see that beyond this particular value of flux this we call it as B sat, beyond that value of flux the core saturates, beyond this value of flux density minus B sat the core saturates so you have to operate at a slightly safer value. Let us say that we do not allow for saturation and that the flux is allowed to swing only between some plus B m to minus B m which is less than B sat. Then the whole swing of the BH loop is like that. So that will be the BH loop that will be traversed if the flux within the core were B m that is it swings from minus B m to plus B m and plus B m to minus B m and so on.

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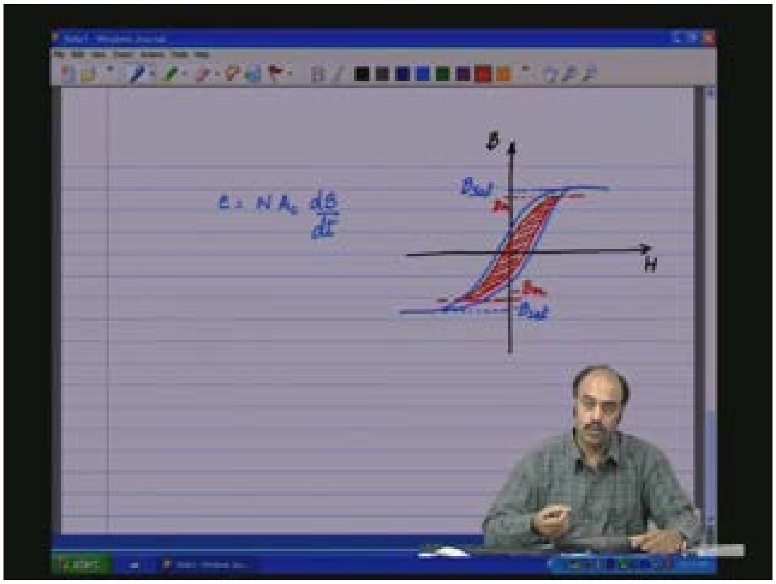

Now, going from minus B m to plus B m takes half a cycle and again from plus B m to minus B m takes another half a cycle. So one full cycle means minus B m to plus B m plus B m to minus B m is one full cycle. So let us take any one of the half cycle which is the flux density swinging from minus B m to plus B m or plus B m to minus B m in a time span of T by 2.

So we have integral e dt which is equal to N A c B N A c B and the B has swung from minus B m to plus B m that is a total swing of 2B m in that time in that time of 0 to T by 2. So let me multiply throughout by 1 by T by 2 and here also 1 by T by 2. This portion (Refer Slide Time: 22:35) is nothing but the average voltage e average across the coil and this is 2 by T N A c and the flux that is swung from minus B m to plus B m is 2B m in a span of T by 2 which is 2B m. So 1 by T is nothing but the frequency so we use 2 N A c sorry this 2 and 2 becomes 4 N A c frequency into B m this is average.

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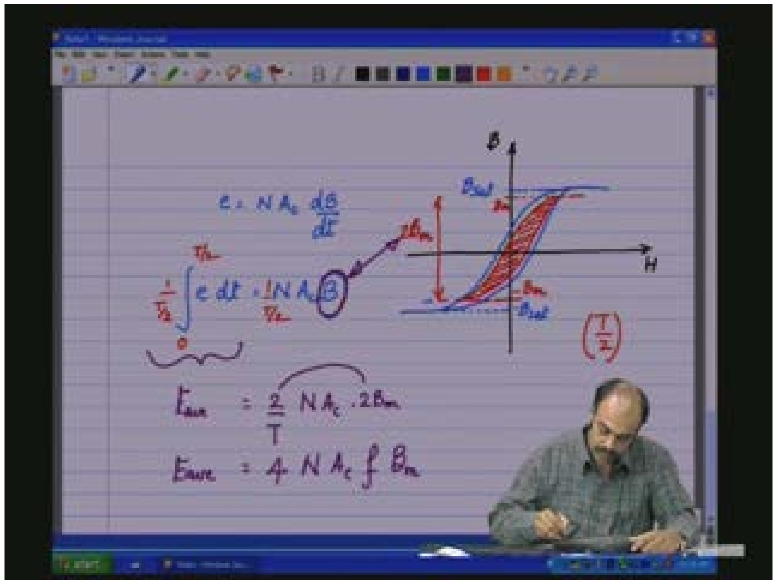

We would like to express everything in terms of the effective value or the RMS value in sinusoidal analysis. Therefore, we use the relationship that we that we obtained few classes ago when dealing with sinusoidal waveform; the RMS value divided by the average value is 1.11 and therefore RMS value is equal to 1.11 into average value. Therefore, using that relationship here if we need to have the RMS value that will be equal to 1.11 average value which is equal to 1.11 into 4 N A c f B m or we have the voltage across the coil E RMS is equal to 4.44 N A c f B m. This is a pretty important voltage equation for the transformer or the voltage across a coil when we are talking of sinusoids.

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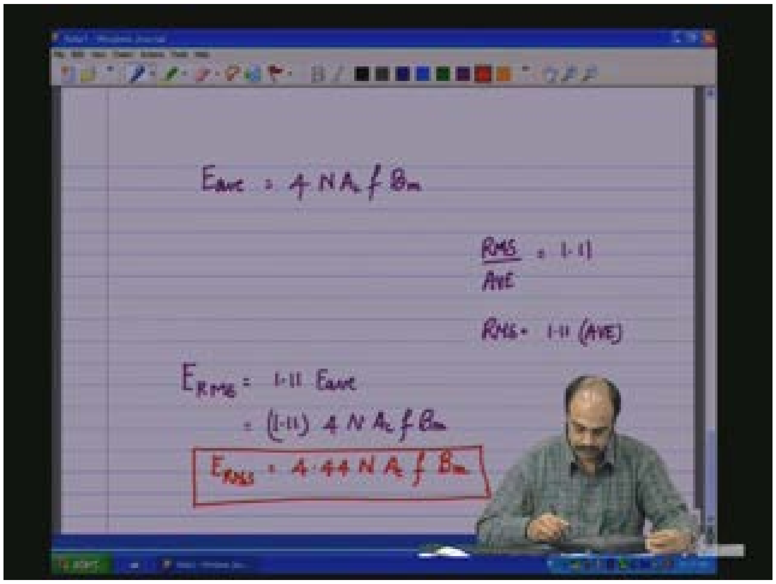

Now looking at this equation the voltage E if we do not put any subscript here as RMS or average or peak if a subscript is not used then it automatically means the effective value or the RMS value is given by 4.44 N A c f B m. Now, meaning of this equation we see that the voltage that is induced is proportional to the number of terms and there is the frequency dependence which comes in the frequency of the applied voltage and this is the maximum allowable flux density flux density max allowed.

Note here for various materials I can give the approximate figures; for ferrites ferrite materials B sat is around 0.3 Tesla so B m should be less than 0.3 Tesla should be around 0.25 Tesla; for CRGO this means cold rolled grain oriented silicon steel B sat is around 1.2 tesla and normally B m is chosen around 1 tesla so that it is less than the B sat value and still retains the magnetic properties for cold rolled non-grain oriented CRNGO cold rolled non-grain oriented silicon steel for this B sat is around 1 tesla and B m is not only chosen around 0.8 to 0.9 tesla.

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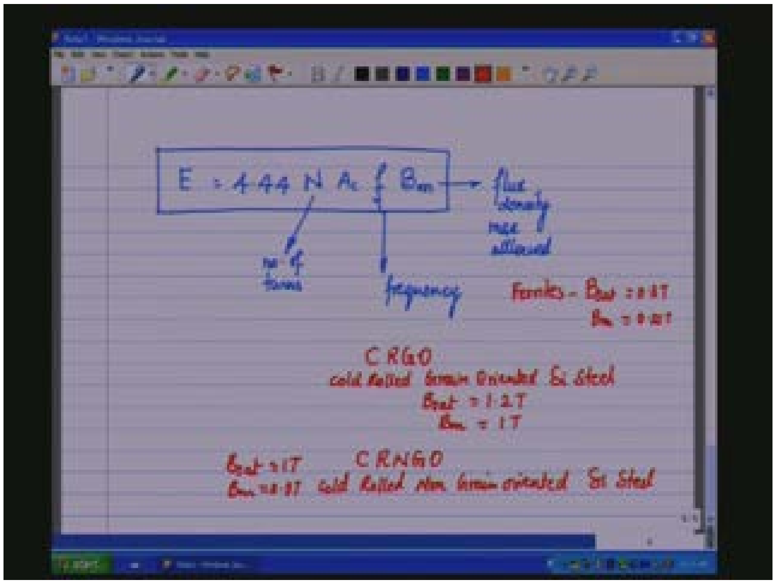

Like that for different materials different B sat they are the inherent property of the magnetic material different B sats are available and the operating flux swings the flux density swing should be less than the B sat value. So, that is the value that has to be used for used in the design equation there.

Now look at a slightly different formation of the equation with this and this brought together on one side (Refer Slide Time: 28:58). In that case we have E by f which is equal to 4.44 N Ac B m. So for a core, for a transformer design this is a constant and once the core is chosen this is a constant and once the core is chosen and the number of terms are fixed the flux density in the core the maximum operating flux density in the core is also fixed which means this figure is a constant. This voltage by f V by f E by f being a constant also means or implies that volt second is a constant. So one has to design for a volt second product in the case of the transformer such that the flux in the core does not exceed the maximum flux density in the core B m does not exceed B sat for that core that is the important conclusion that you should draw from this particular modified equation here.

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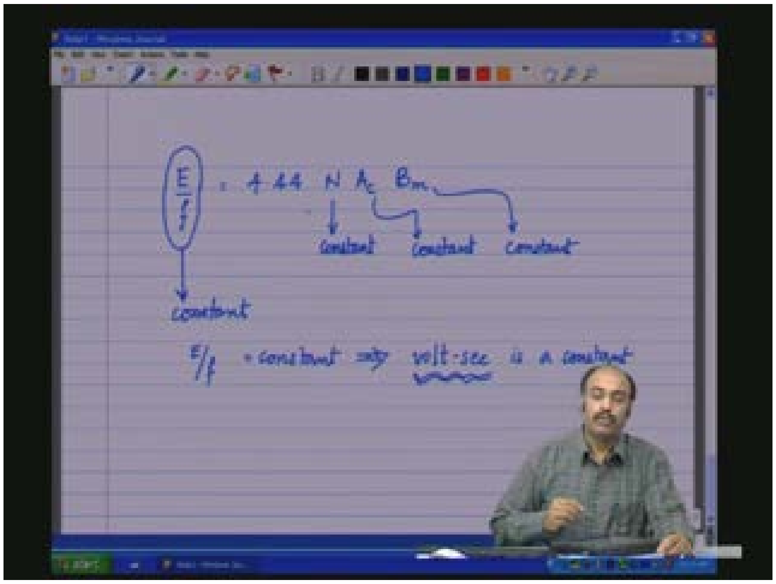

Now we have the transformer and we have been representing this transformer in this fashion. We draw a square core and then we have the windings which are written like that, this is the primary and this is the secondary, this is N 1 number of turns and this is N 2 number of turns, this is N 2 number of turns N p number of terms or N s number of terms depending upon…………..

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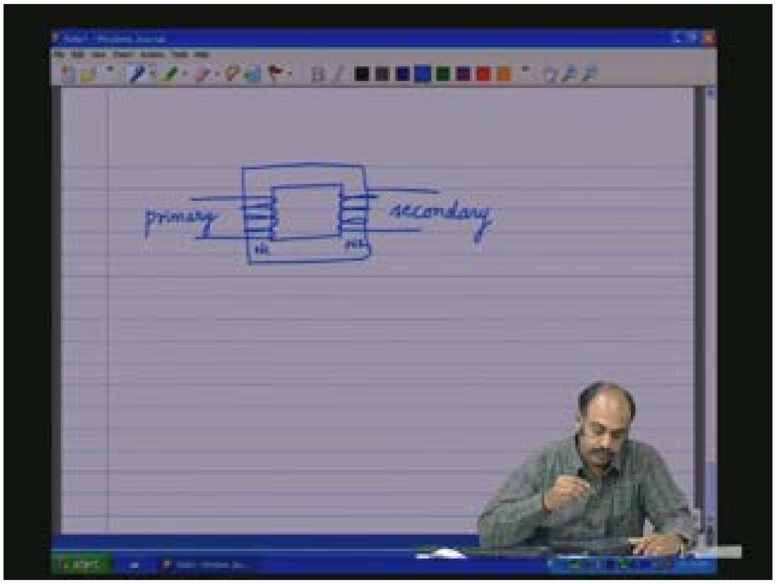

Now we shall represent this as an electrical symbol. We have an electrical symbol associated with this which will be used now in the circuit diagrams that is it is written in this form; there are two coins like that and then there are two parallel lines which are drawn in between to show that these two are coupled with a core inside in between, this is the primary or e 1 (Refer Slide Time: 32:31), this is the secondary or e 2, there is a primary current or i 1, secondary current or i 2, this is the and there is a N 1 is to N 2 number of turns in the primary number of turns in the secondary. This is how a transformer is represented as a component in an electrical circuit.

Now here we have less number of turns here and more number of turns on the secondary side, this would in general imply that the primary voltage is smaller and the secondary voltage is larger and it is a step up transformer; that would be a step up transformer. If the symbol is written in this fashion as shown here with the primary voltage more than the secondary voltage and consequently the primary number of turns being more than the secondary number of turns now here you have N 1 less than N 2 and here you have N 1 greater than N 2 which means e 2 the secondary voltage is less than the primary voltage and such a transformer is called a step down transformer step down transformer.

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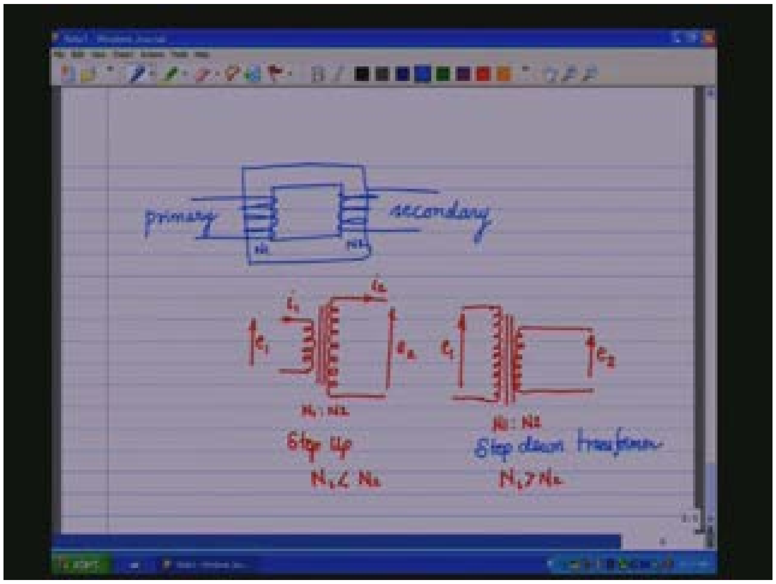

And if one writes a symbol with equal number of turns has shown here then such a transformer is a one is to one transformer, this is the primary e 1, this is the secondary e 2, primary current i 1, secondary current i 2; it is a one is to one transformer, the secondary voltage e 2 is the same as the secondary current secondary volt primary voltage e 1. The main function here is that galvanical galvanically the primary portion of the circuit and the secondary portion of the circuit are isolated meaning there is absolutely no contact between the primary portion of the circuit and the secondary portion of the circuit. For such applications where one uses a transformer just for the purpose of isolation galvanic isolation between one part of the circuit and the other part of the circuit then such a transformer is called an isolation transformer.

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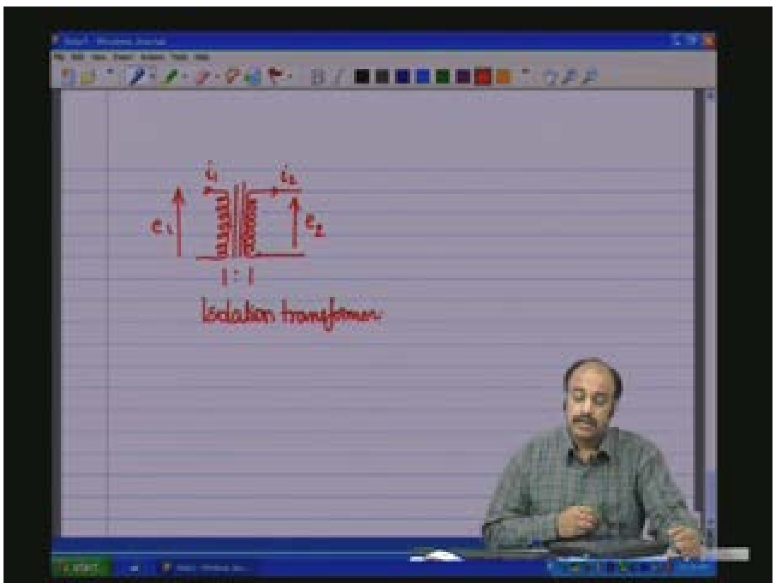

Of course a transformer can be used to perform more than one of these functions like it could be used for performing isolation plus step up, isolation plus step down so on and so forth.

Now, to complete a symbolic representation of the transformer in the electric circuits there is one more item that we need to add and that is we have the primary winding, secondary winding, they have two terminals here, they have two terminals here (Refer Slide Time: 36:28) let us say this is e 1 and this is e 2 and we have a core in between, this is N 1 is to N 2. We also add a dot. This dot indicates that at the dot end the polarities on the two sides of the transformer that the primary side and the secondary side are in-phase. That is if the voltage is measured at this point with respect to the non-dot terminal and likewise on the secondary side the voltage measured on the dotted terminal with respect to the non-dotted terminal the voltages will be in-phase.

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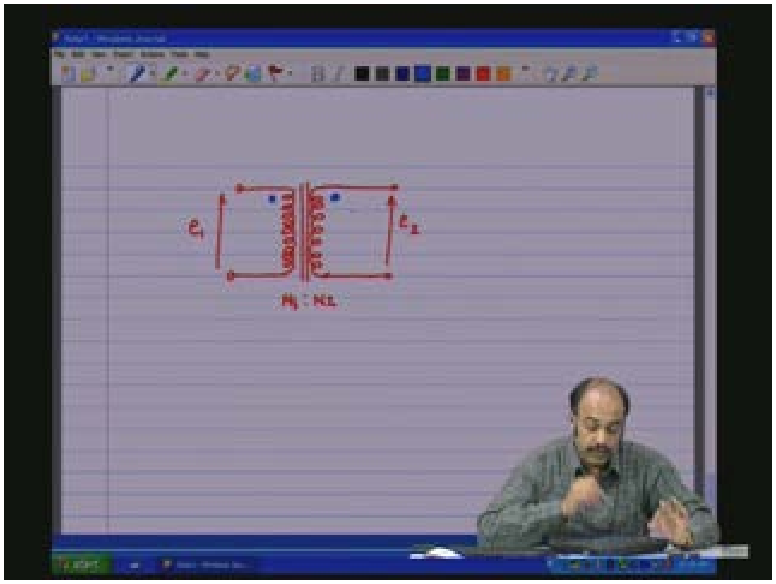

We have a transformer in this fashion and let me put the dots line this and let us call this terminal as A and this terminal as B, this terminal as C and this terminal as D. Now we are going to apply let us say some voltage across the terminal V AB. We now apply a voltage across the terminal V AB it is an AC voltage. Now how does the waveforms look across the primary and the secondary with respect to time.

Let us say V AB meaning we are measuring at A with respect to B and the other one is V CD we are measuring at C with respect to D. So if we had a waveform of this sort across V AB which is applied then the voltage V CD will be in-phase will be in-phase as shown.

Now if we have a dot polarity of this fashion which is depend which depends upon the winding sense, so instead of winding the secondary let us say which was clockwise in the previous case it now becomes anti-clockwise, the dot polarity is now in this form. Therefore, the secondary is no longer…… V CD is no longer like the case that we saw before, it is now…….. so when A is positive with respect to B it means that the dot portion will be positive with respect to the non-dot portion. So, if A is positive with the respective B, B will be positive with respect to C. So, in V CD C will be negative with respect to D. So we would see that there is a reversal of polarity and when A is going negative with respect to B, B is also going negative with respect to C. But see if D goes negative with respect to C, C goes positive with respect to D and that is what you have CV is positive during this time. So you see that there is a 180 degrees phase reversal. So dot polarities are crucial to indicate the phase relationship between the primary and the secondary. So the phase relationship between the primary and secondary are represented by the dots called the dot polarity. So the dotted portions are supposed to be in-phase and now these dot polarities can also be used for generating the phasor relationship to get the phasor diagram between the various parts of the circuit and including the transformer.

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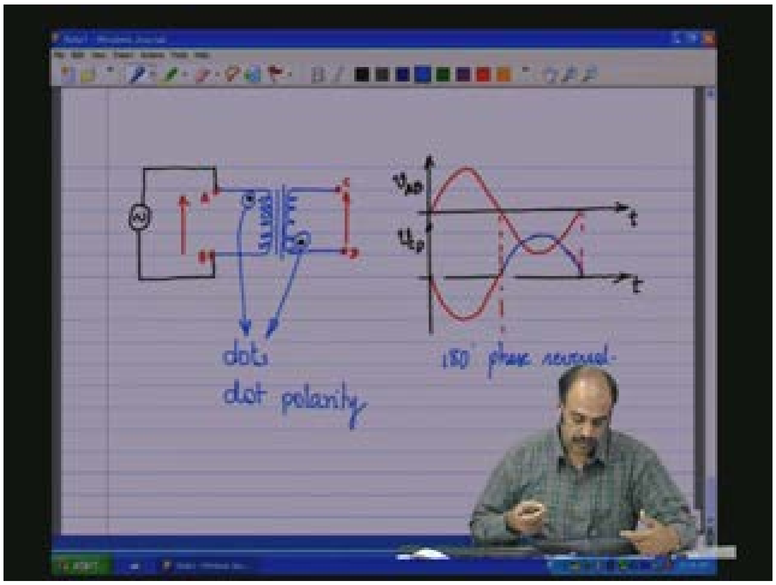

Let us draw the phasor relationship between the primaries and the secondary for any given dot polarity. So let us have a primary coil, let us have a secondary coil, there is a core and there is a primary we will we will we will keep it as e 1 consistent with the other, there is a primary voltage e 1 and there is a secondary voltage e 2, as of now there is no node connected here so let us now do that job of connecting a load across the secondary. This means there is going to be a current i 1, there is going to be a current i 2 in the secondary and this is N 1 is to N 2.

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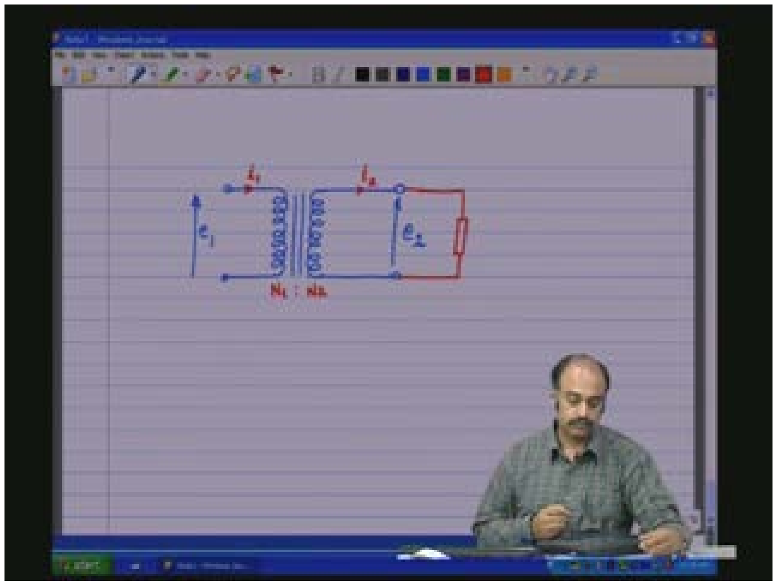

Now let us also have the dot polarities which means when the dot side is positive the dot side here is also positive. Note that here when the dot side is positive on the primary side this is secondary, the current is entering the dot and here the current is leading the dot; the current is entering the dot and this is positive, energy is put into the transformer; the dot side is positive current is leaving the dot and the energy is removed from the transformer so that is how the energy passes through the transformer, goes from the primary to the secondary side.

Now let us represent this as our conventional winding that we used to do before with a rectangular core. let us say we have a core as shown here (Refer Slide Time: 46:19), there are some windings so we have the primary side winding, we also have the secondary side winding, we are going to connect a source an AC source of frequency f across the primary which is going to result in voltage e 1 so the applied and the induced are going to balance each other and there is going to be a load resistance or an impedance here which is going to result in e 2. Let us say that

I mark the generated voltage and let me call that one as e g; under normal conditions e g will be same as e 1.

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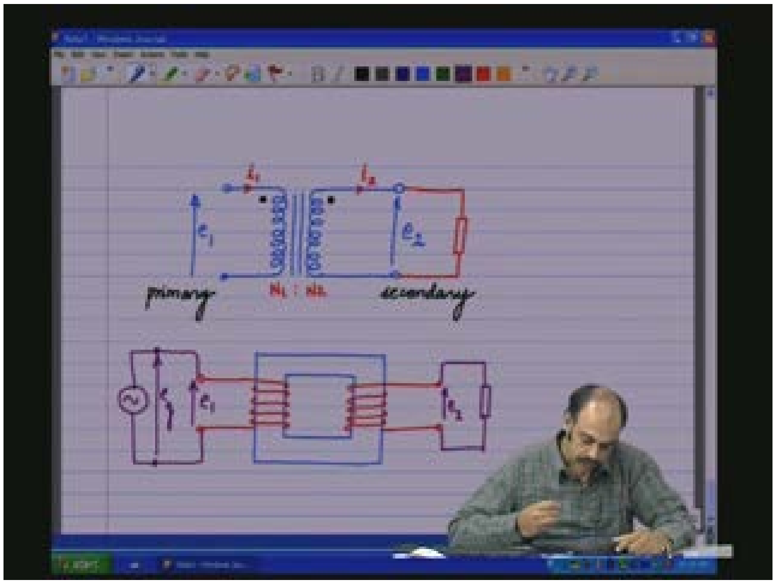

Now let us say there is i 1 and now there is an i 2 flowing through the load; this has N 1 number of turns and this has N 2 number of turns. So this current i 1 is flowing through N 1 initially when the load was not there let us say, initially load was not there this is open which means i 2 is 0 so the current flowing through N 1 generates a flux due to ampere turns N i and let us say this is N 1 i 1.

Now if the load is connected and this flux N 1 i 1 which is generated in the primary is linking the secondary and multiplied by N 2 a voltage e 2 is generated by the Faraday's law of electromagnetism and the moment you collect the load here e 2 divided by whatever the impedance Z 2 is going to result in a current flowing through the secondary circuit. Now this current is flowing through this coil which is going to provide at cancelling the motive force so a mmf is provided here, plus minus let us say here at a given instant, now a current flowing out of the dot let me put the dot the current is entering the dot or current is flowing out of the dot is going to create a cancelling mmf. So what happens, we are going to have a mmf which will cancel the earlier which will cancel the earlier mmf and this is N 2 i 2 and due to the cancelling effect the mmf was reduced. Reduction in the mmf means on this side the induced emf e 1 has reduced but the applied voltage e g is still the same the emf here even instead of being the same as e g has now reduced which means there is a voltage potential difference which will cause a very high current to flow. So the current is keep on increasing till the current i here goes back balances the cancellation due to this. So the current i 1 here will increase till N 1 i 1 balances the cancellation due to i 2 N 2 i 2 that occurred due to the presence of the load which means i 1 would have increased such that even now matches e g. So this would mean that there is there is a cancelling mmf provided by the primary N 1 i 1 dash such that this is cancelled out and what will remain would be N 1 i 1 under the case when there was no load and that would be the magnetising component of the flux.

So the flux in the core is going to be same as it was under roller condition whatever may be the load you may increase there will always be a cancelling ampere-turns that gets generated in the primary which will cancel out the load induced ampere-turns and thereby the flux in the core is always going to be constant whether it is no load or load at condition such that the volts (……..52:23) balance is maintained according to the previous equations that we saw which will make the transformer to operate in the magnetic zone.

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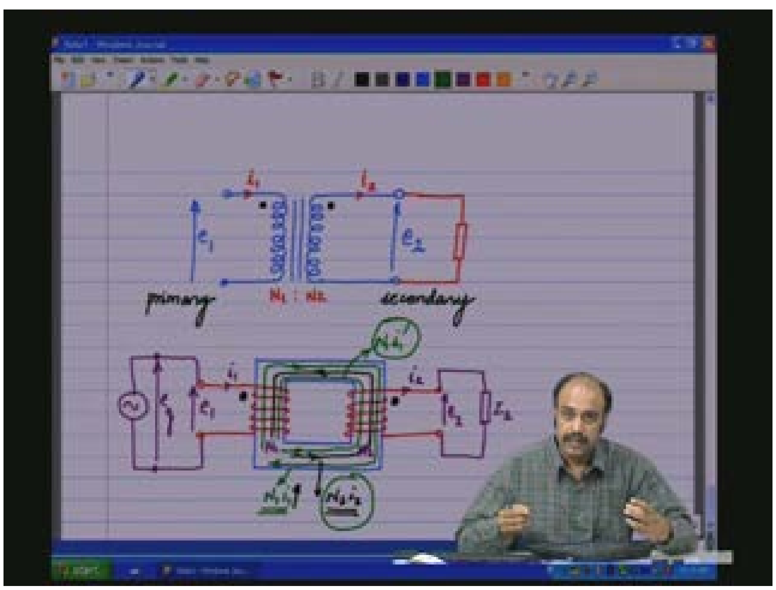

Now with this concept now we should be able to draw the phasor diagram. We have here the primary and the primary is connected primary is connected to a source voltage source I will still name it as e g as the generated voltage or the applied voltage, this is generator voltage which is apply and there is a induced voltage across the primary effectively even equals e g always at every instant of time.

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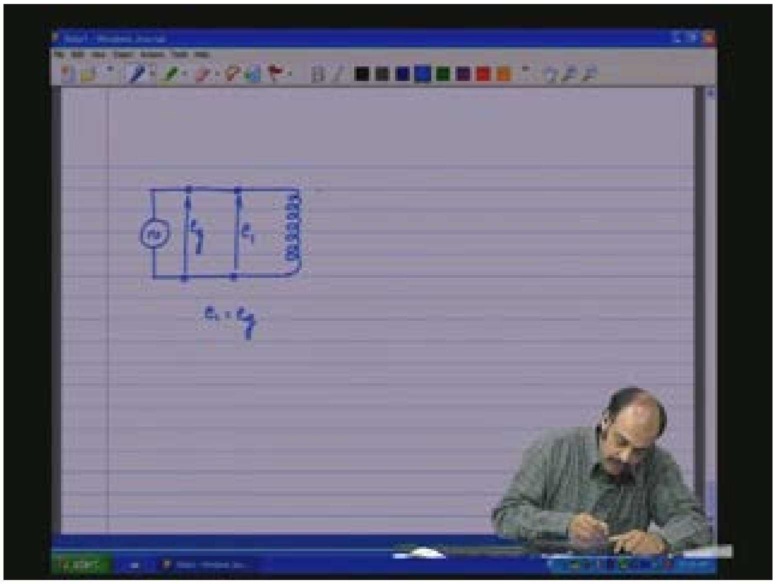

However, to distinguish between the generator voltage and the induced emf or the induced voltage let us have this distinction; and we have a core and then the secondary and the secondary is connected to a load and the load could be resistive or that is RL or RC or RLC any impedance Z too. Now there is a voltage across the secondary and we call that as V 2. Now the current through the primary we will call it as i 1, current through the secondary we call it as i 2, we have the dot polarities as shown here and this is N 1 is to N 2; this will complete the way the transformer looks.

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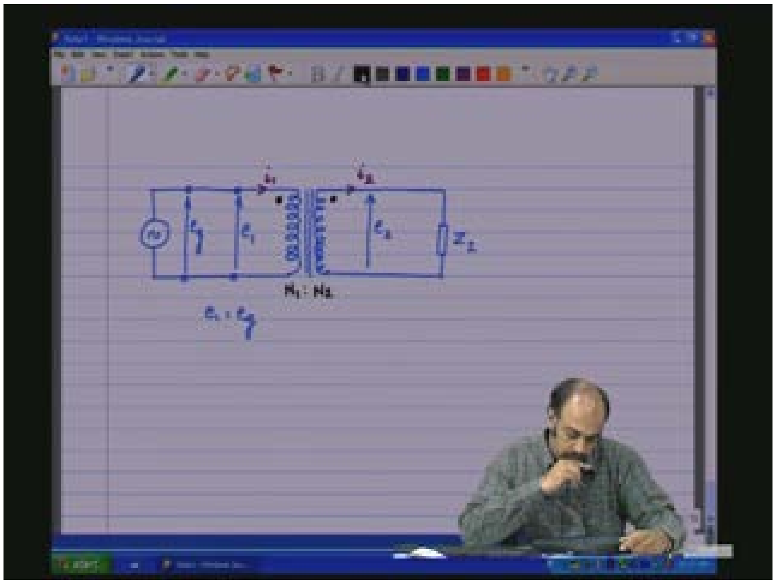

Now let us draw the phasor diagram for this transformer circuit. This is a spatial coordinate systems as I have been saying. We have seen quite a few times in the earlier classes or the earlier sessions while discussing the phasor diagrams with sinusoids, this is the alpha axis and this is the beta axis. So we need to choose some reference phasor along this direction and remember that phasor means same as the vectors except that the amplitudes are effective values or the rms values.

Now we shall choose the input voltage as the reference direction that is this would be the e g direction that we are choosing. Now, as e g and e 1 are one at the same this also means that we have e 1 in-phase with e g. Now, by the dot polarities let us say N 2 is, for the moment N 2 is less than N 1 which means it just steps down; e 2 is less than e 1. From the dot polarities we say that e 2 and e 1 are in-phase; exactly they follow each other by the dot polarities which mean e 2 is in-phase with e 1.

Now let us say that Z 2 is a lagging power factor node that is an inductive node which means i 2 has to lag e 2. So let us have i 2 lagging e 2 by some angle theta. What happens to i 1?

Now we see that N 2 is less than N 1, we know that e 2 by e 1 equals N 2 by N 1 so e 2 is N 2 by N 1 into e 1 which is less than e 1 and i 1 by i 2 equals N 2 by N 1 this is the inverse proportionality so N 2 by N 1 is less into i 2 sorry this is ya N 2 by N 1 is also equal to i 1 by i 2. So N 2 by N 1 is less and therefore i 1 will be less than i 2 whatever be the value of i 2. So i 1 will be less than i 2 in this case; e 2 will be less than e 1 in this case which means we will have i 1 here because by dot polarity i 1 and i 2 will be in phase because e 1 and e 2 are in-phase. So i 1 will have a vector in-phase with i 2.

Now what about the flux in the core?

The flux in the core will be lagging the voltage by 90 degrees. This is the flux phi m in the core. This is because we have V which is equal to N d phi by dt, there is a d phi coming which is N j phi m. So we see that the voltage vector is whatever the phi m vector direction rotated by 90 degrees because of the j and that is what it is that is what it means by this j operator so phi m should lag voltage by 90 degrees that is what it means so this would be the vector diagram of an ideal transformer.

In the next class we will see how a practical transformer will behave after having done few examples some examples in this case.