Basic Electrical Technology
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Lecture - 17
Transformer Basics

Hello everybody, in the last session we had discussed about electromagnetism towards the end of the session and we carry it on this session also to understand the basics of the transformer. So today's topic would be the basic principle of the transformer, transformer basics.

Transformer as we said is an electromagnetic device. There is part of the energy which is a part of the portion of the transformer which is associated with the electric domain and there is another part of the transformer which is associated with the magnetic domain. Energy flows across the domain from the electric to the magnetic, magnetic to back again to the electric. There is absolutely no connection between one port of the transformer and the other port of the transformer. The connection or the interconnection energy wise is only through the magnetic domain.

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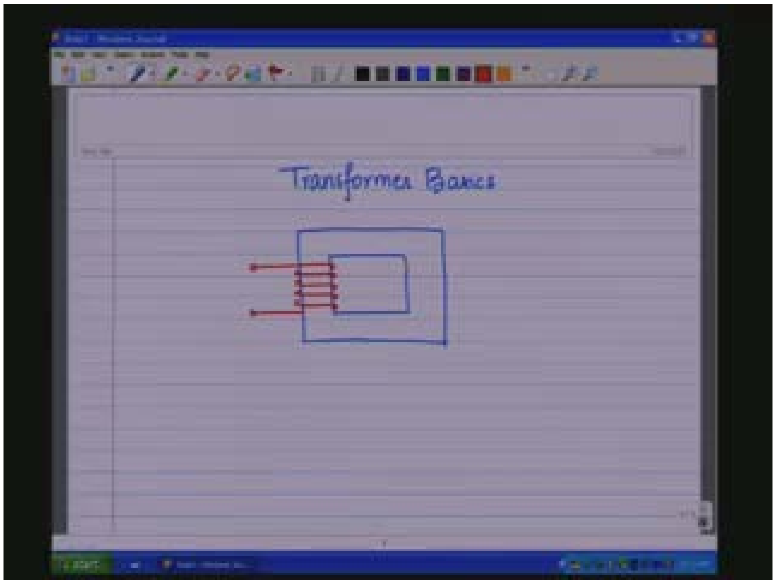

We saw that a transformer consists of a core and on the core we have some windings. So we have two windings: one for the primary one for the primary and another for the secondary. So this is the transformer winding (Refer Slide Time: 3:24). So we have the primary primary port or the primary side port which has its two variables the potential variable, the voltage e primary and the current i primary. Then on the secondary side we have of course the e secondary, the voltage across the secondary terminals and the current through the secondary winding if there is a load collected, if there is no load collected i s is equal to 0.

Now you see that the primary side electric circuit, secondary side electric circuit whatever is going to be there is not physically connected, the only transfer of energy can occur is through this magnetic domain the core here the core and we saw here that primarily we will be using Faraday's laws of Faraday's law of electromagnetism which is voltage v across the coil induced across that coil will be equal to N the winding number of windings in the coil into d phi by dt. This is called the Faraday's law of electromagnetism magnetism this law is the one which is going to be extensively used to derive various other relationships.

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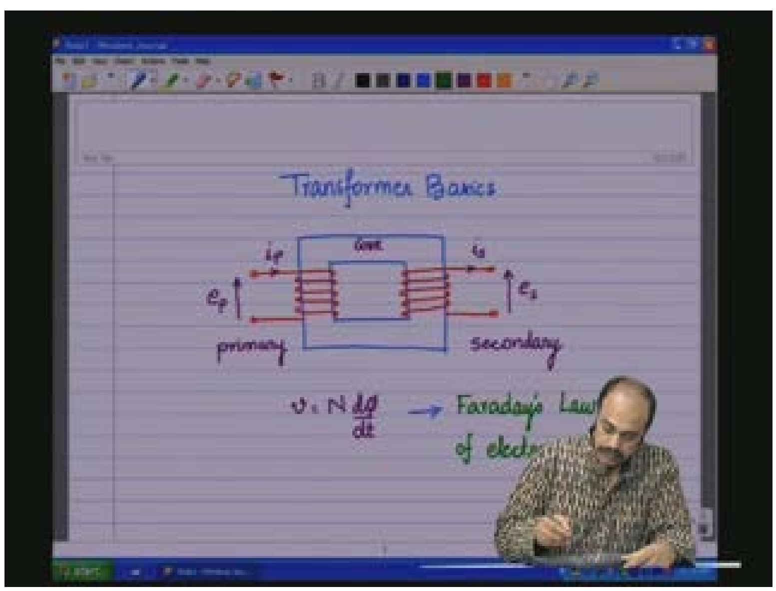

Now let us let us take this figure here. So I have marked this figure. I am going to copy that, go to the next page and we will paste that and then use this figure.

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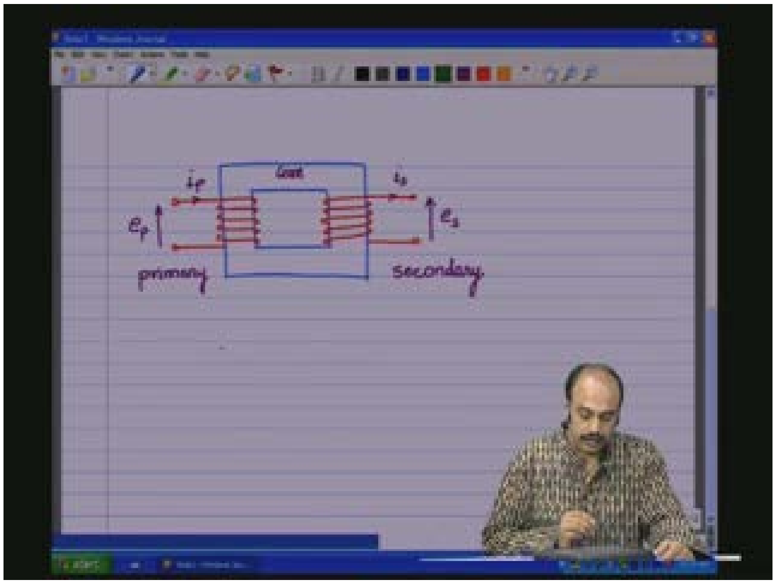

Now if you see here let us say that there is some voltage which is going to be applied here (Refer Slide Time: 6:38). So a voltage is applied here e p or the primary. This voltage source once it is applied is going to cause a current i p to flow through the primary coils. So once a current i p is flowing through the primary coil there is going to be a rate of change of flux induced within the core. That is e p will be, let me say that there are N 1 or N p number of turns connected terms on the primary coil and N s number of turns on the secondary coil. So e p will be N p d phi by dt. So the voltage e p which is across the coil which is applied from the source directly as there is no other impedances that should also be the voltage across the coil like Kirchhoff's voltage law and that is driving a current i p. Now this i p is setting up a magnetic field within the core and the field the flux inside the core is going to have a rate similar to the applied voltage. So, if the applied voltage is having a particular frequency, the frequency at which the flux is going to change will also be the same. So this d phi by dt is the rate of change of flux within the core. So there will be a flux which will be setup in the core so there will be a flux which is setup in the core and that has a d phi by dt that is what is causing the induction of the voltage across the coil.

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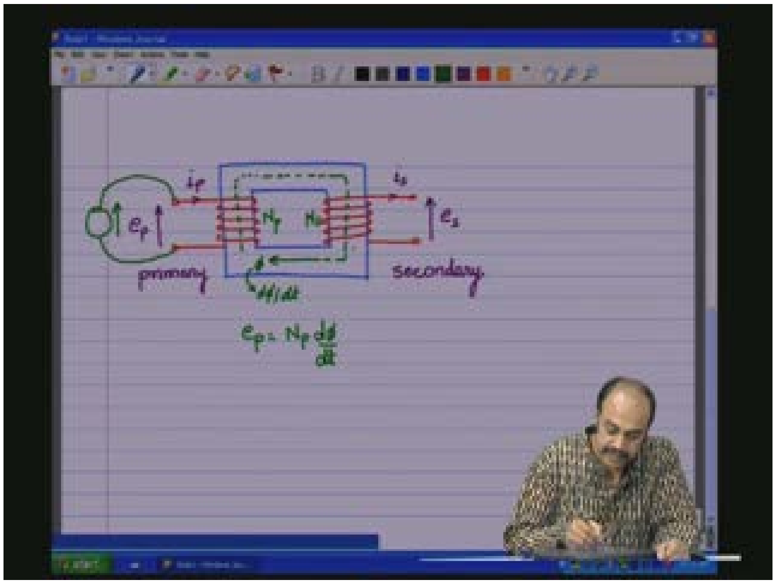

Now the same flux is linking the secondary also. Therefore, if we look at the secondary coil e s will be N s d phi by dt that is there is another coil here N s the same flux flowing through the coil so N s d phi by dt is going to cause a voltage e s to be induced across the secondary coil. All these by Faraday's law is it not? Both of these are by Faraday's law.

Now e secondary by e primary that is the voltage across the secondary divided by the voltage across the primary of the coil that is the ratio of the secondary voltage across the secondary port to the voltage across the primary port is equal to using using these two terms; you have N s by N p because d phi by dt is the same for both the coils because the same flux which is linking both the coils. This means that e secondary is N s by N p into e primary. So, if there is a primary voltage e p applied across the primary port then if N s is the secondary number of terms, N p is the primary number of terms then the secondary voltage induced across the secondary port e s will be the ratio of the terms N s by N p into e p. this is one of the major equations for the transformer operation.

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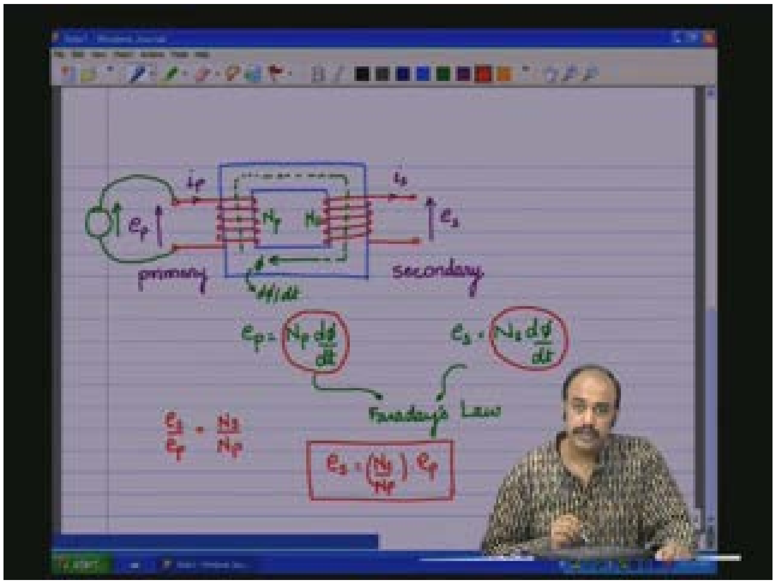

The primary the primary side here…… let me again use that. Now the primary here is containing N p number of turns and N s number of turns. Now the power at the primary is e p i p; the power at the secondary port is e s i s. Now we know that this is the transformer is lossless, there is no loss in the transformer in an ideal transformer. Of course a practical transformer will have some losses we will discuss about that later. But let us say an ideal transformer there is absolutely no loss, no accumulation of energy so whatever energy comes into this port will get transferred to the other port which means this should be equal to this in which case we can obtain the relationship between i p and i s. We know that e s is equal to N s by N p into e p. So, if you substitute for e s here we get e p into i p will be N s by N p into e p into i s. So this is e s.

We have e p on both the sides we remove that and this results in i p by i s which is equal to N s by N p or i p is just equal to N s by N p into i s. This is the other relation that is the relation for the other variable the kinetic variable.

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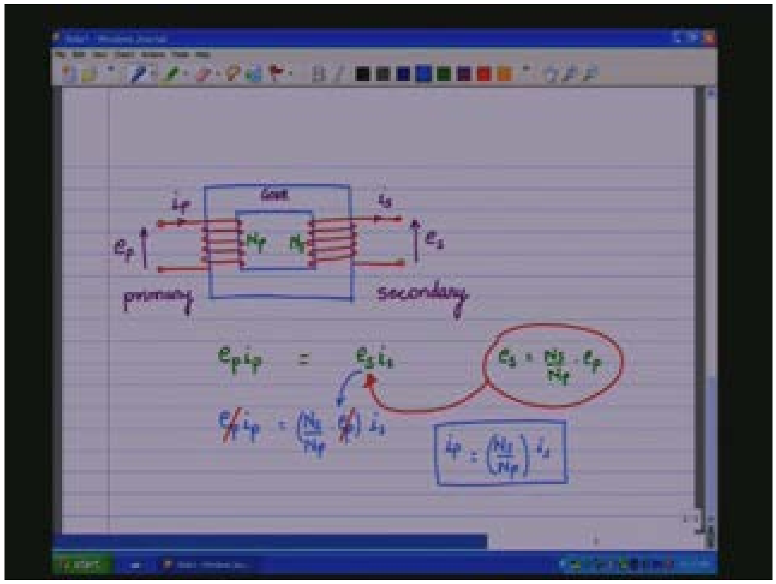

Thus, summarizing we have these two important relationships: e s by e p which is equal to N s by N p this is for the potential variable variables of the ports two ports, then i p by i s equals N s by N p this is for kinetic variables of the port or you could say this is the effort variables the flow variables of the ports.

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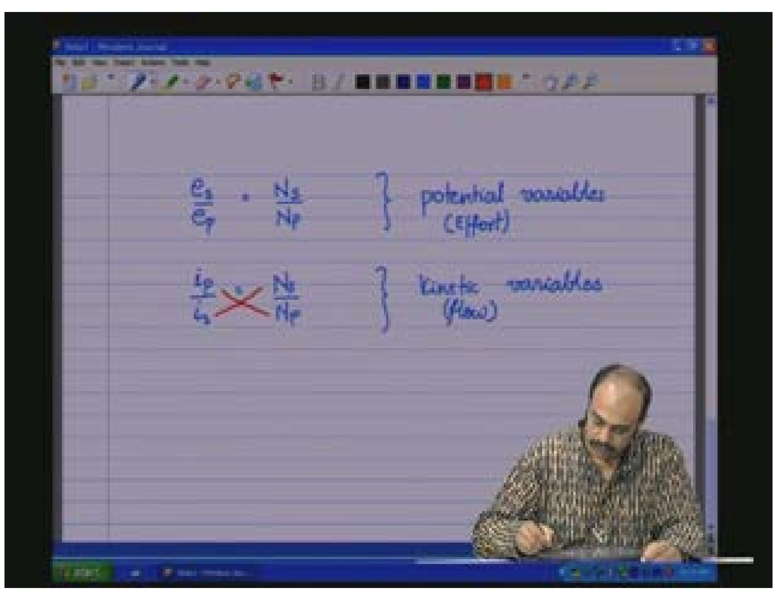

Note here the inverse proportionality e s by e p which is equal to N s by N p; e s is proportional to a proportionality to the turns the number of turns, the current is inversely proportional to the turns i p and N p, i s and N s so that the energy conservation is obeyed so that the power at the primary and the power at the secondary under ideal conditions will be the same.

Now, to understand a bit more further about the transformer on the magnetic there is one more law that one needs to understand about. Let us say there is a there is a conductor there is conductor, now this conductor is carrying a current. So this conductor is carrying a current I. So if this conductor is carrying a current I through it then it is going to generate a magnetic field around that so there will be a magnetic field around this conductor with some direction and this and this is called this law is called the Ampere's law.

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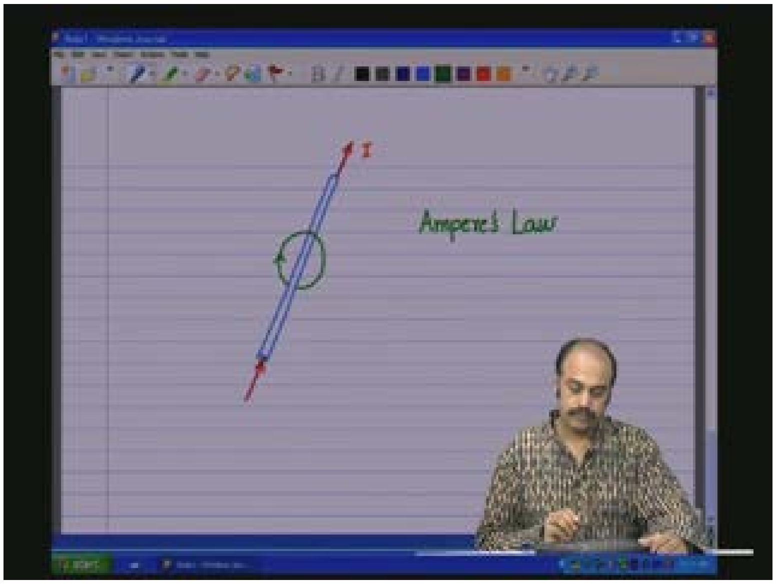

What does Ampere's law state?

If there is a current carrying conductor then that will create a magnetic field around the conductor as shown here, of some intensity H. H is the magnetic field intensity, this is in amps per meter. In other words, the converse is also true, meaning; if there is a magnetic field intensity around a conductor then there will exist a current which will flow through the conductor so the converse of the Ampere's law is also true. If there is a conductor current through the conductor it will generate a magnetic field intensity of H around the conductor. If there is a magnetic field intensity of H around the conductor then there will exist a current which will be flowing through the conductor so both the converse and the Ampere's law is valid.

Now, to get an idea of the direction we use the thumb to point. Let me draw this, so we have the right hand, we have the thumb, this is the wrist. Now let the thumb point in the direction of the current.

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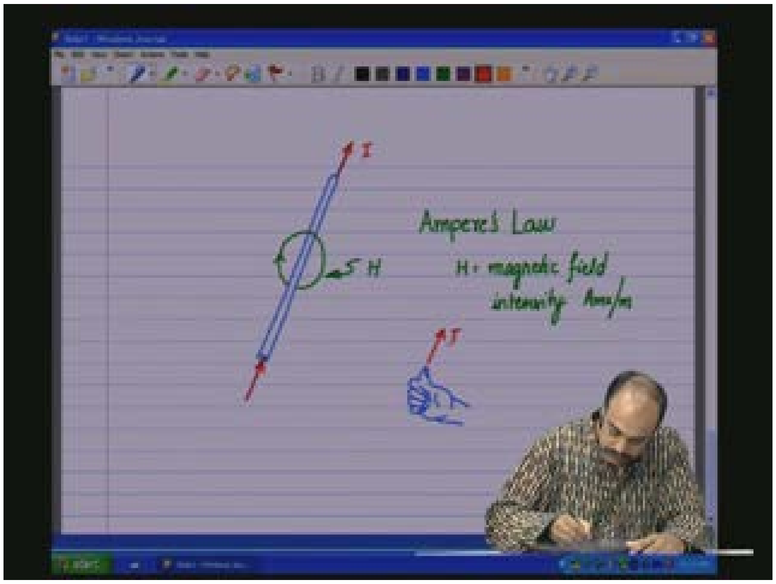

Assume that a current is flowing out of the picture towards the camera. The thumb is pointing in the direction of the current and the fingers are folded as shown here.

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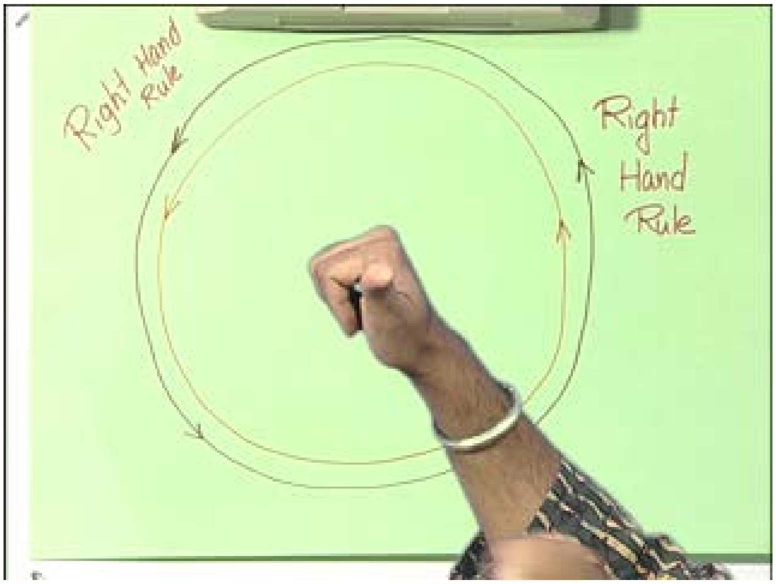

Allow the allow the flux lines, you see the flux lines which are orthogonal in an orthogonal plane to which the current is flowing, the fingers point in the direction which direction in which the flux is going to flow. So as the fingers are pointing here for a current flow in this direction you will see the anti-clockwise direction of the field lines, this is the right hand row.

Now normatically we can state the Ampere's law as integral of H dot dℓ 0 to ℓ m which is the magnetic path length is equal to mmf or amp turns N into I. This is in ampere turns. This is the units. This is the mathematical statement of Ampere's law.

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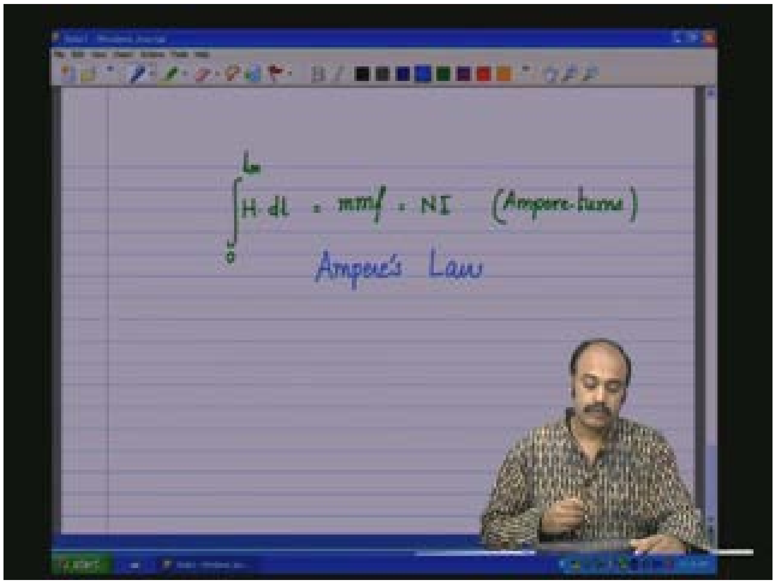

What does it mean?

Again coming back to the conductor we have this conductor and through the conductor we are going to pass current I and let us say I have number of conductors number of such similar conductors so on each having the same current I and let that number be N, you have N such conductors. So, about these N conductors there is going to be a flux a magnetic field and that magnetic field H is also dependent on the path length the magnetic path length that is ℓ m. So, if you integrate H around the path then that is going to give you N into I ampere turns or the magnetomotive force. If m is 1 then integral of the magnetic field intensity around the path length is going to give you the current I.

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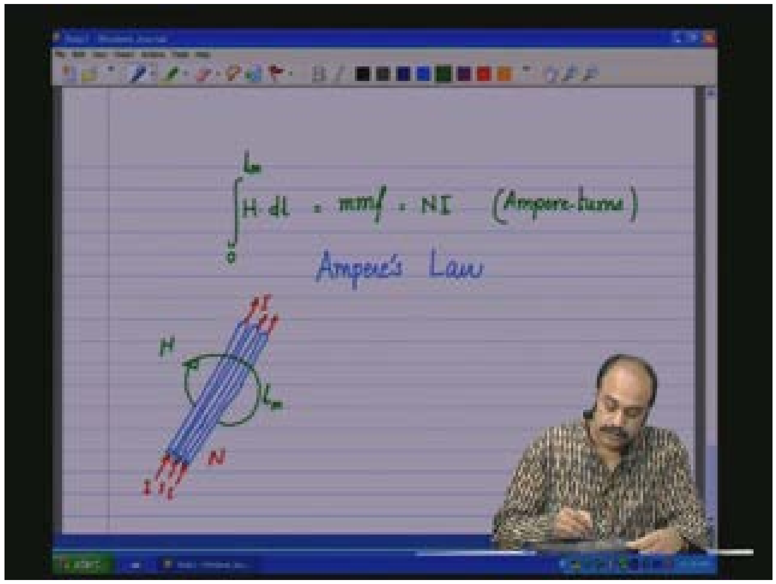

Now this is the implication of the Ampere's law. You have a current I and if there are N such conductors all carrying the same current then NI would be the magnetomotive force which is going to derive the flux in the magnetic material around the conductor. This means that if you have a coil, let us have a coil, let me draw the coil, so this is……………… (Refer Slide Time: 26:19) like that and the current goes through like this goes through the coil and then comes out here the current I.

Now, if you take this portion let us say this coil portion here you will see that there is………… this portion here (Refer Slide Time: 27:01) you will see that there are two conductors carrying current I which means there will be there will be a magnetic field like this. So, if there are two or if there is N such conductors each carrying current I in this coil and that is causing a feel may feel field of intensity H being created and on integrating this H around this magnetic path length l m will give you NI depending upon how many turns you have put. this is the principle in which NI that the magnetomotive force is created.

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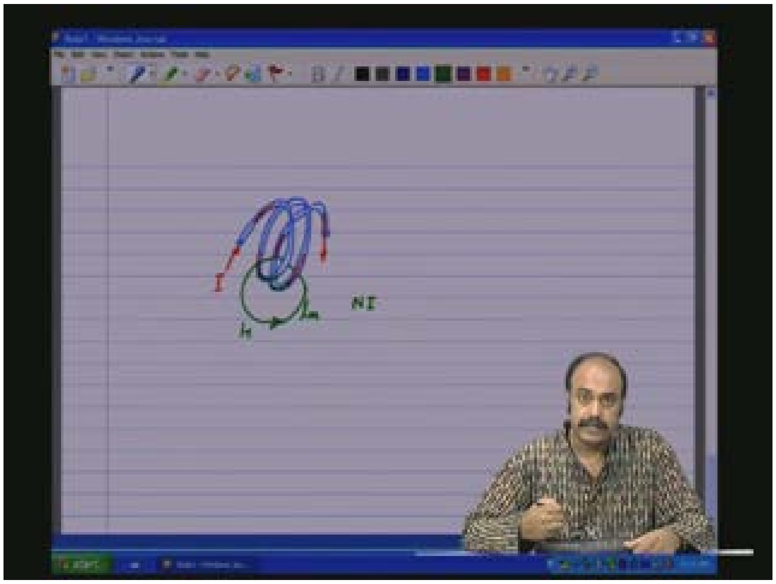

There is one more term that you need to be familiar with which is the flux density and that is having a symbol B. So, from the Ampere's law we saw that 0 to ℓ m H dot dℓ is equal to NI which is mmf or the magnetomotive force. If H were uniform throughout the path length then H integral of path length will be NI or the mmf or H into ℓ m is equal to NI. The magnetic field intensity H is equal to NI mmf by the magnetic path length ℓ m; this is having units of amps per meter.

Now as I was saying here B is the flux density there is a magnetic flux phi per unit cross sect per area unit area or cross section area of the core that is cross section area through which the flux is flowing. So, if we have the cross section area of the core and flux is flowing in this direction through the core this cross section area which is orthogonal to the flow of the flux is AC. So flux per unit area this is having units of Tesla flux per unit area or Weber's per unit area is Tesla. Flux has a unit of Weber's Weber's per meter square is Tesla named after the famous Scientist Tesla who contributed……………………………….. so B and H; B is flux density, H is the field intensity which is basically the motive force for generating the flow of flux. However, these two are related.

Ideally if we plot B and H there should be a linear straight line B and H this is how it would be vacuum of free space, this is flux per unit area, this is mmf NI by path length Amps per meter, this is Tesla or Weber's per meter square. Now this slope here (Refer Slide Time: 31:59) delta B delta H is mu mu is equal to delta B by delta H and it is linear it is B by H. This means flux density B is equal to mu H. However, the flux in the core is not linearly related to the magnetomotive force as shown in the previous graph. It exhibits a hysteresis nature.

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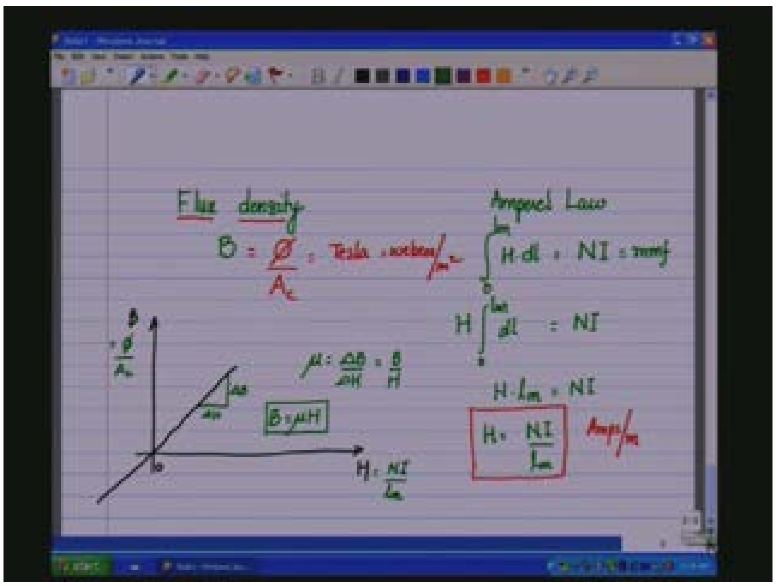

Let us say we have a graph four quadrant graph x and y axis and let us say the x axis is the H magnetic field intensity, the y axis is B which is the flux density which is equal to phi by Ac and this is equal to NI by ℓ m.

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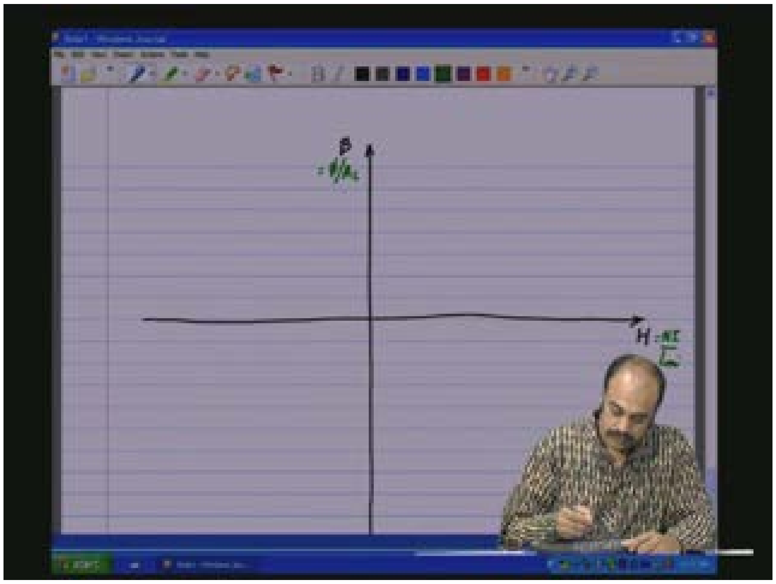

So, in actuality you will see that let us say we start with a virgin specimen a new specimen; as the field intensity increases as the magnetomotive force increases the flux in the core will increase, flux keeps on increasing as you increase the magnetomotive force in the X direction. But you see that it loses its linearity and gradually it starts to saturate. So, beyond a particular value of magnetic field intensity the flux in the core will not increase any further. Then let us bring back let us bring back the magnetic field intensity towards zero. So, as we start bringing it towards zero we will see that it does not come back along the same path it exhibits hysteresis. So when the magnetic field intensity is zero there is some remnant flux which is in the core. So, to meet that zero you have to give a cohesive force here, you have to give a cohesive force in the negative direction that is you have to give a negative flux indent intensity or negative mmf in the other direction then the flux is totally removed. So when you start giving H in the negative direction this continues further then beyond a particular value flux does not go any further it saturates. Then when we bring back the field intensity again in the positive direction this starts again exhibiting the hysteresis there is a remnant flux when H is 0. To make them flux zero you have to apply a positive H and then this will swing in this manner.

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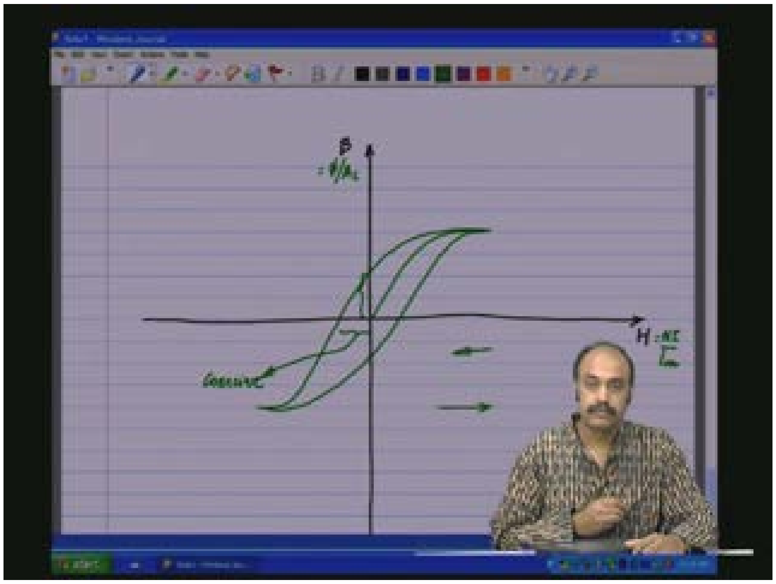

So, a virgin specimen starts with zero and then from there on it exhibits this kind of a hysteresis curve so all magnetic materials will exhibit this kind of a hysteresis curve called the BH loop. So the magnetomotive force which is proportional to the magnetic field intensity is not linearly related to the flux in the core or the flux density d in the core; it is related by this kind of a graph which exhibits hysteresis and this is called the BH curve or the BH loop.

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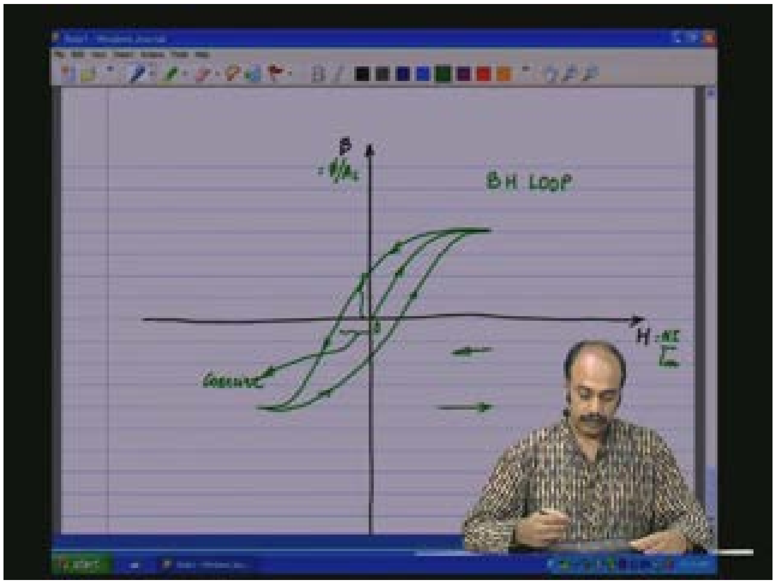

Now we have………. few equations we need to put it down. First one was you have the field intensity which is NI by ℓ m which is nothing but mmf, mmf is the ampere turns by ℓ m. Now the second is the flux density B which is given by the flux in the core for unit cross section area. then third the relationship between B and H in the linear region mu H. So B is equal to mu H in the linear region, mu is a constant, however, in a practical core mu is not constant as we saw that it exhibits hysteresis BH curve exhibits its hysteresis mu is varying from point to point so it depends upon the operating point; it is more or less linear close to the zero operating point. These three relations govern the operating principle of the transformer.

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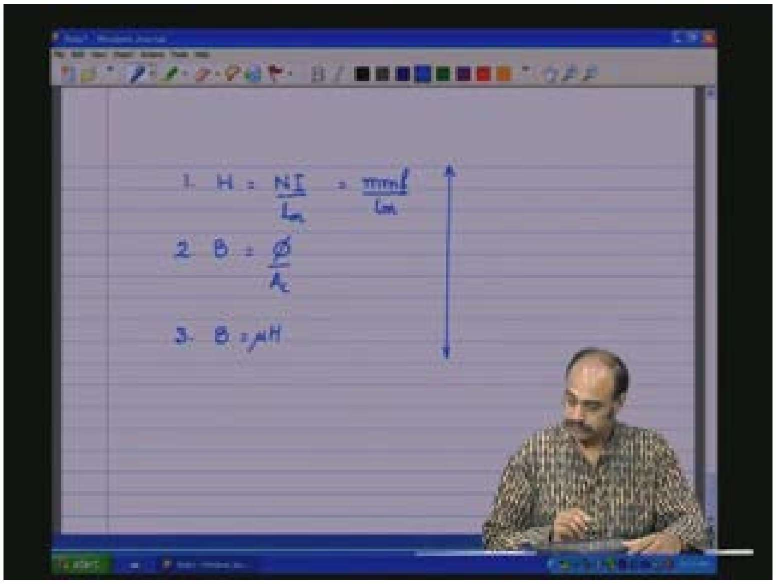

Now let us have a look at what happens inside the core of a practical transformer. In a practical transformer there is going to be some loss. What are the losses in the practical transformer? There are two types of losses in the core of the transformer. The losses in the core of the transformer one is called the hysteresis loss hysteresis loss, the other is called the eddy current loss; these are the two losses that occur within the transformer.

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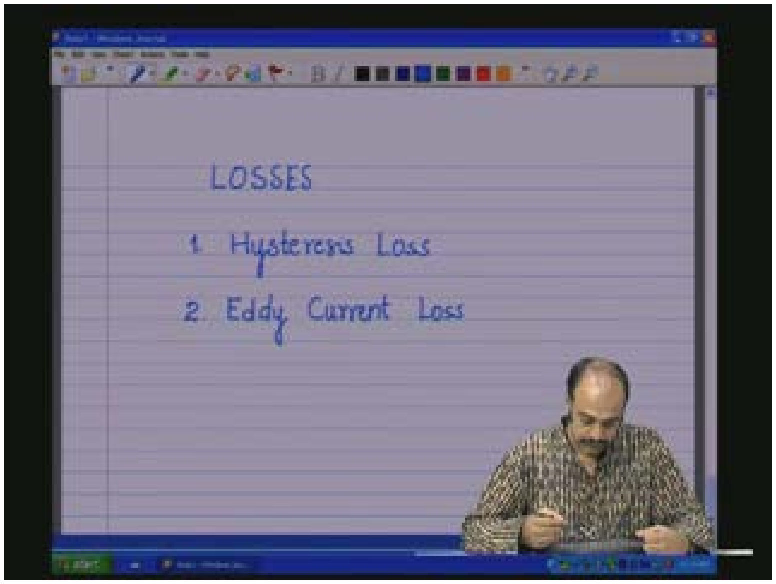

So, if you take this core material (Refer Slide Time: 40:24) so there is going to be input energy here going through into this port so e p i p and then there is going to be e s i s which comes out of the secondary port. But in between inside in the core there is one the hysteresis loss the hysteresis loss P h and the eddy current loss P e. Further there is going to be some finite resistance in the coil of the conductor and i square R is going to be lost i p square R p is going to be lost in the primary, i s square R s is going to be lost in the secondary. Now this occurs in the copper that is called the copper loss P cu. So what occurs at the secondary e s will be the primary power minus these losses which would be P h p e and P cu. So it will not be exactly same as the primary power what would you get at the secondary side, it would be less by an amount equivalent to the losses which are encountered like hysteresis loss, the eddy current losses and the core losses these are called the core losses and the copper loss.

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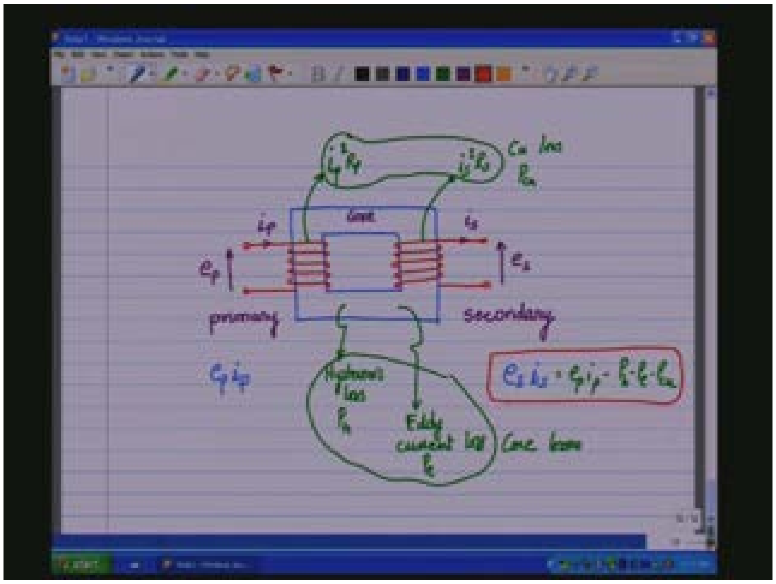

So keep this in mind that in a practical transformer the power output is going to be slightly lesser than the power input by an amount equal to the losses: the core losses and the copper loss; and the core losses composed of two main components: the hysteresis loss and the eddy current loss. Now let us see what these losses are.

First let us take up the hysteresis loss. In the core we saw that the BH curve exhibits a hysteresis curve or hysteresis loop, it is not linear in nature and the B the flux density B is given by mu H where mu is not a constant but it keeps changing based on the operating point and this is equal to mu H is NI by ℓ m. Therefore, I is equal to B ℓ m by N mu N this is one equation. The other equation………… so this equation is coming from Ampere's law Ampere's law; another equation as a result of the Faraday's law we have V is equal to N d phi by dt which is equal to N.

Now phi is nothing but BA c is it not?

So, if A c is constant it would be N Ac dB by dt this is the other equation which comes from the Faraday's law which comes from the Faraday's law.

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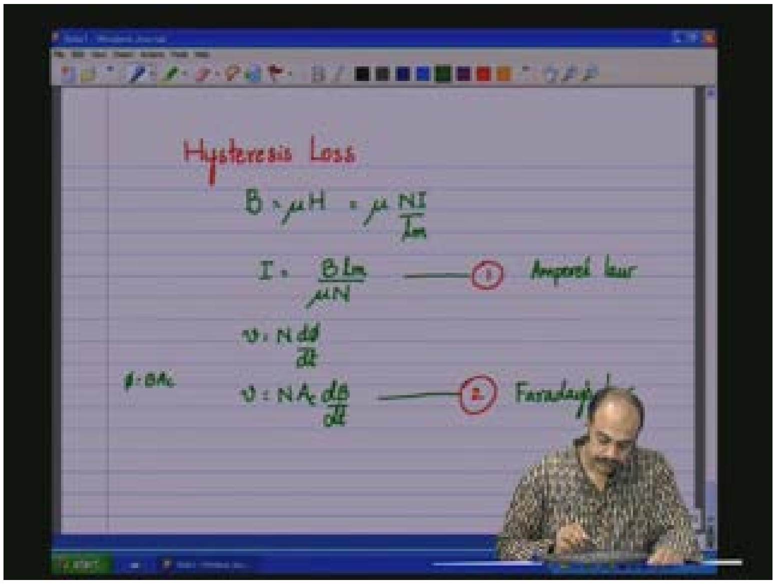

Now the instantaneous energy delta E instantaneous energy delta E is voltage into current into time delta t and this is this is given by voltage gain by the Faraday's law which is NA c dB by dt that is for this (Refer Slide Time: 46:58) then I is given from Ampere's law which is B ℓ m by mu N B ℓ m by mu N into dt, this is equation 1 and equation 2. This is the instantaneous energy. This is having units in joules instantaneous energy in the core.

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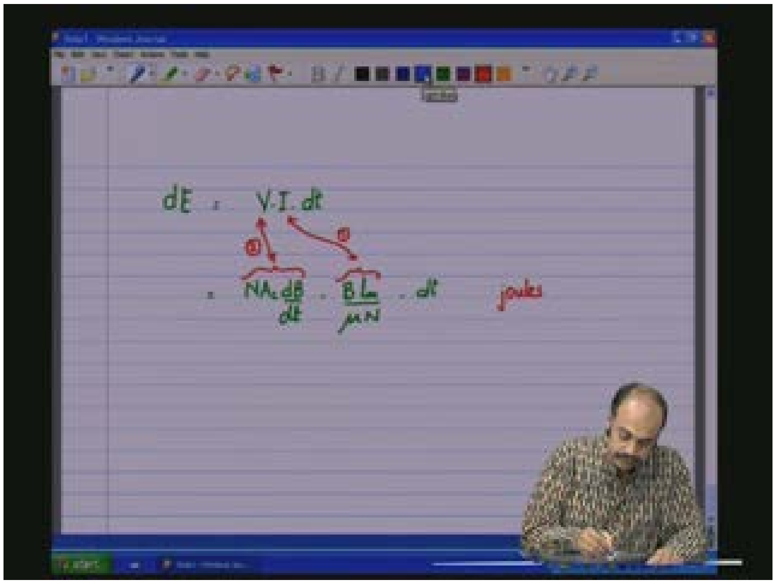

Now here A c and ℓ m magnetic path length and the cross section area together gives the core volume V c. This is core volume core volume this and of course we do not directly cancel like that but it effectively means that we now have N V c B dB by mu N so this N and this N also goes off and we have a very simple equation V c B by mu into dB, this is the instantaneous energy.

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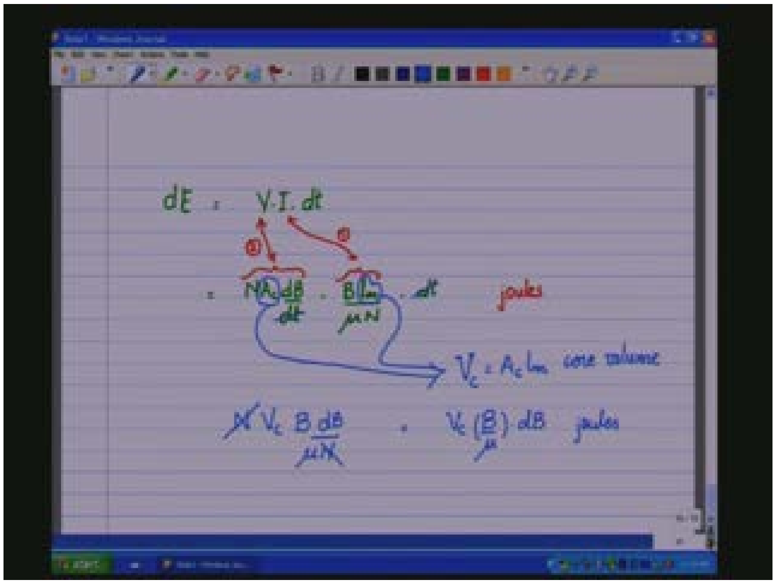

Now energy dE which is equal to B by mu into dB is the energy per unit volume. So in one cycle that is one cycle if we go back and have a look at the hysteresis curve (Refer Slide Time: 50:09), in one cycle as the flux density D is swung from positive to the negative, positive to the negative the hysteresis loop is traversed the hysteresis loop is traversed and we see here that the energy dE is nothing but H dot dB or integral of dE will give you integral of this which is the energy per unit volume which is traversed for one cycle and is traversed for one whole cycle so we integrate it for one period 0 to t.

Now what is this?

From the BH loop B H loop we have………. so H is traversing, the H is traversing positive but as B is traversing from positive and negative H is also traversing along this and an integral of this is going to be basically this area (Refer Slide Time: 52:04) and that area is going to be lost forever; that energy is going to be lost forever and it is not going to be got back that is called the hysteresis loss. So, as B is varied the hysteresis curve is traversed, the integral of H dot dB would yield this area and this energy is lost forever and it does not go to the output and therefore this is called the hysteresis loss. Therefore, integral of dE is equal to integral of B by mu dB which is equal to half B square by mu dB which is equal to half BH dB sorry half integrating half BH half BH.

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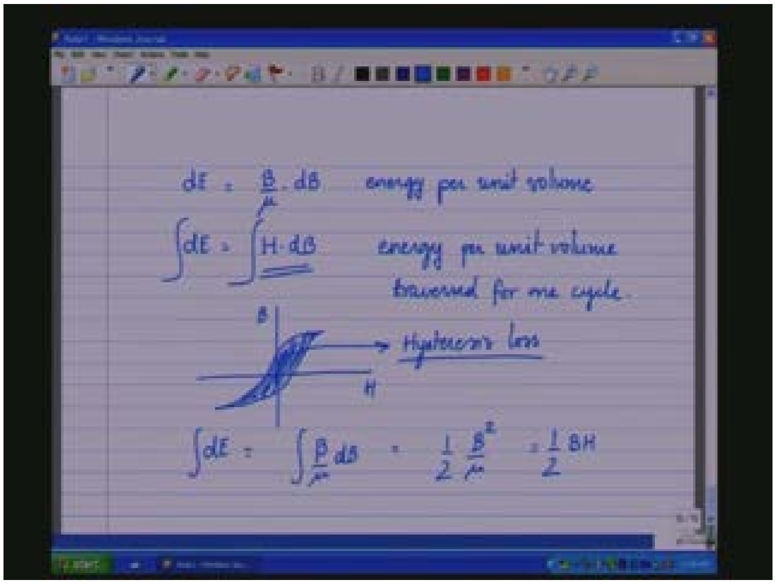

Now the energy including the core volume would be……………… so hysteresis energy including core volume is given by half because that was energy per unit volume; this is half BH into V c the core volume. Now the power hysteresis loss is the rate of energy which is divided by the period, one period, so power is 1 by T E h which is half B H V c into f, this is the hysteresis loss equation.

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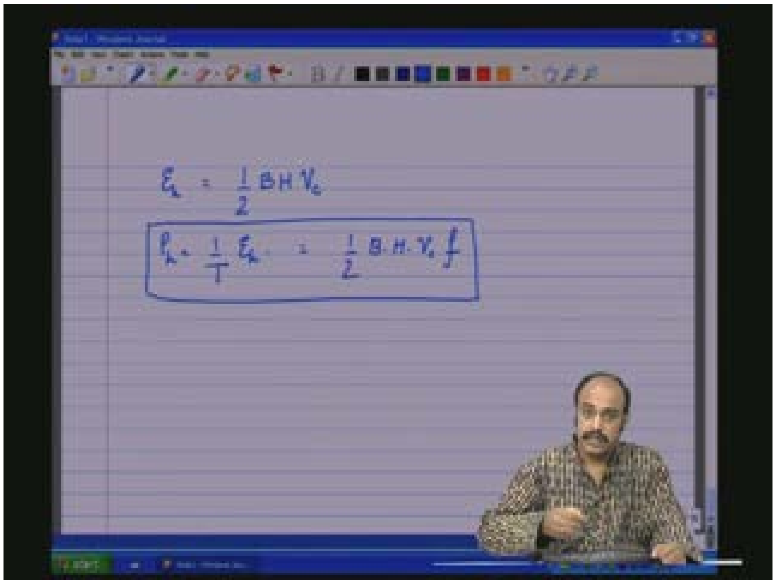

See that the hysteresis law is directly dependent on the flux density, magnetic field intensity; on the core volume larger the core more the hysteresis loss and another important thing is the frequency of operation. As the frequency of operation increases the hysteresis loss is going to increase, this is also this is also in keeping with what we understand because we are talking of the hysteresis loop.

Now the one traversal of the hysteresis loop means this area is covered and that amount goes into what is called the hysteresis loss which is unrecoverable. More number of times if this is traversed in a second you are going to have more loss which is basically the frequency issue which is coming up here. Higher the frequency more number of times this hysteresis loop is going to be traversed in a second therefore higher is going to be the loss. Therefore hysteresis loss is also proportional to the frequency of operation.

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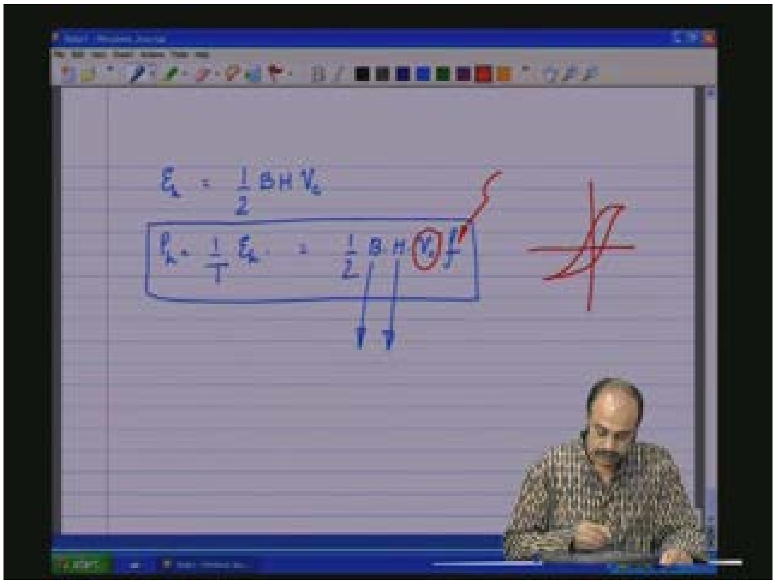

And then we have the Eddy current loss the Eddy current loss. The Eddy current loss can be explained easily from our Ampere's law. We have a core, let me draw a three dimensional view of this core which is like that, this is the three dimensional view of this core. Now this this core let me take a cross section, the flux is going through the core in this fashion. So, as the flux is going through this core of course that is due to a magnetic field intensity there is going to be a current loop like that. Well, we saw that the (c………57:32) of the Ampere's law is also true; if there is a current in the conductor there is a flux around the conductor, if there is a flux around the conductor there has to be a current through the conductor. Now these currents I is going to produce I square loss in the core material, this causes a loss which is unrecoverable and that is called the Eddy current loss. We will discuss about the Eddy current losses and the other aspects of the transformer in the next session.

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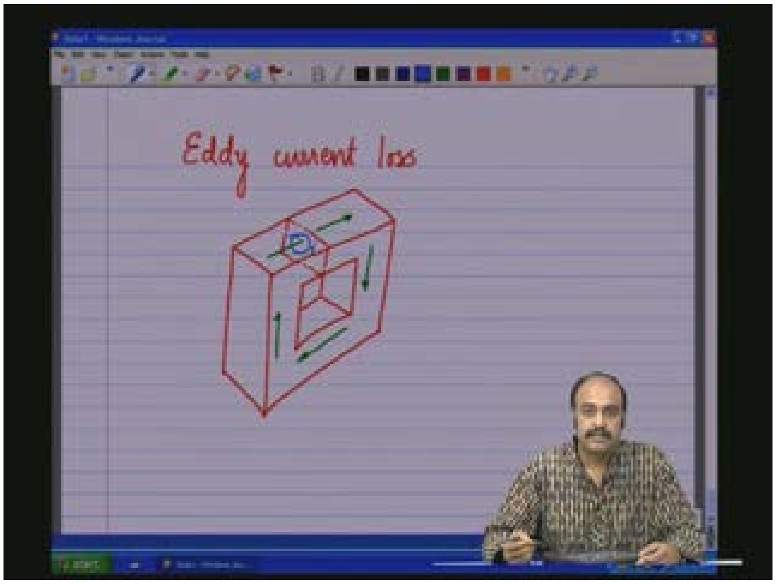

Thank you.