Electrical Measurement And Electronic Instruments
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Lecture - 43
Review of transformer and magnetic circuit

Hello and welcome.

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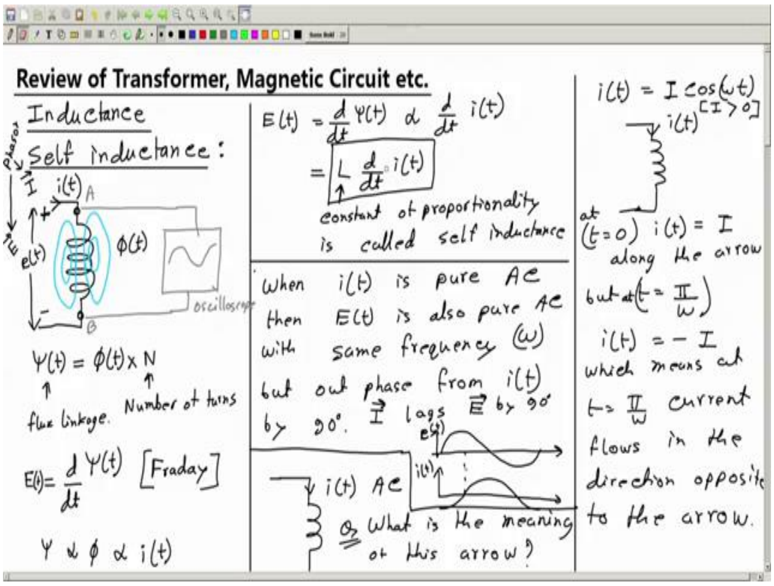

We were starting instrument transformers that is CT and PT, but they are basically transformers and to know them in more detail. It would be better if we just review some concepts some basic concepts of transformer magnetic circuits, which you might have already studied in an electrical machines course or maybe circuit theory course etcetera. So, this is an additional video we will review some concepts we cannot prove everything in one class that is not possible, but we will review some important concepts which will help us in a better understanding ok.

So, let us start with the simplest concept of inductance ok. Now inductance can be either self inductance or mutual inductance ok. So, let us first talk about self inductance, what do we understand by this word self inductance if we have a call which is carrying some current say I let me use lowercase later in this class to denote time varying quantity i (t) is a time varying current. Now, when this current i flows it will create definitely some magnetic flux like this so on and if i (t) is changing then this flux if I call it ∅ this will also be changing with time if current is changing flux $\emptyset$ (t) will also be a function of time. And then we define the quantity called psi which is phi multiplied by the number of turns this is the number of turns of the coil ok. So, phi is time varying therefore, psi will also be time varying and this is called flux linkage.

$$\varphi = \emptyset \; x \; N$$

Now, φ is time varying and therefore,

$$E(t) = \frac{d\varphi(t)}{dt}$$

$$\varphi \; \alpha \; \emptyset \; \alpha \; i \; (t)$$

$$E(t) = \frac{d\varphi(t)}{dt} \;\; \alpha \;\; \frac{d \; i \; (t)}{dt}$$

$$= L \, \frac{d \; i \; (t)}{dt}$$

Now next important concept is the scenario when say i t is pure sinusoidal pure AC ok. So, then we can often express i t as an exponential e to the power j omega t omega being the angular frequency and then we know then if this is sinusoidal of course, this is sinusoidal, then this will also be sinusoidal with a phase lag of 90 degree ok. So, just recall this if this is sinusoidal, this is also sinusoidal with a 90 degree phase lag ok. Then E t is also pure AC with same frequency; same frequency ω, but lagging or leading or that will actually depend ok. So, let me just write, but out of phase from i (t) by 90 degree this much I can write.

Now, this is another important concept which we you know, now let me ask the question that if this is the coil if and it is it has a current i t which is AC ok. Let me ask a basic question, what does this symbol? What does this arrow mean? What is the meaning of this arrow? Because you may say i (t) is AC so, it is changing it is direction every cycle I mean every half cycle. So, why do we put an arrow because we know the current sometimes flowing in this direction and rest of the time in the opposite direction what does it mean when we put this arrow. This arrow is the, it is not the direction of current at all time it is the chosen positive direction or chosen reference direction of this current so, this arrow this is the reference direction.

What do we mean by this, we mean if we write i (t) = I cosωt and if we draw the circuit with this arrow and i (t) here ok. So, then it means that say at t= 0, then from this equation we know i (t) is equal to how much, it is I say this I is a positive number. Then I then at t= 0 the current that flows is I, but in which direction that is in this direction ok, i t is this much or let me write it this way instead of using the mod sign it may be confusing.

So, let me write here that I is positive I is a positive number ok. So, at t = 0 the current that will flow it is magnitude will be I and it is direction will be along the arrow. So, along the arrow ok, but say at t= ω , t=180 degree; 180 degree means pi ready pi then, that means, when t=$\frac{\pi}{\omega}$ ok. So, at this moment i (t) = - I, which means at t=$\frac{\pi}{\omega}$ current flows in the direction opposite to the arrow. So, this is the meaning of this symbol this arrow in case of an AC this is also may be very obvious to you ok.

So, now let us ask the question that ok. So, Michael Faraday said the value of the induced EMF at any moment is given by this or by this ok. So, this is the; this is the expression of the EMF the value of the e m f; now say if I connect a oscilloscope ok, suppose if I connect an oscilloscope then we will see that this voltage is varying sinusoidally when this current is also sinusoidal.

Now, I can ask that at t= 0 which terminal among these two call them A and B, which among A and B will be positive at t = 0 or at any other time which terminal will be positive. We know the magnitude is given by this, but what will be the polarity ok, now the polarity can be found using Lenz's law ok.

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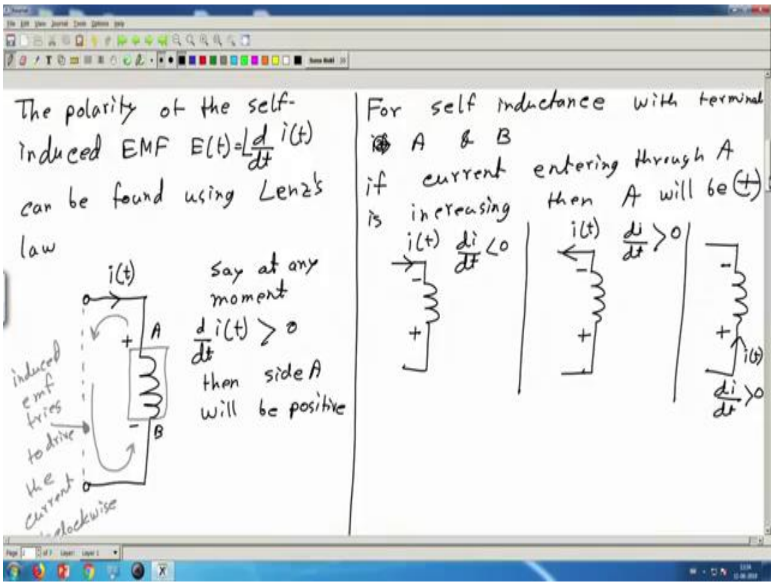

So, next important concept this also you probably know the polarity of the self induced EMF which is E t = L $\frac{d\,i\,(t)}{dt}$ the polarity of this can be found using Lenz's law, how let us see that. So, if this is the coil and these are the two terminals the current i is like this is the chosen direction ok.

Now, say at any instant say at any moment $\frac{d\,i\,(t)}{dt} > 0$ which means what, this current which is entering the coil through terminal A this current is increasing. So, this means the current that is entering the coil is increasing, it may also mean actually that the current that is living through A is decreasing it is same equivalent ok, but we say this current which is entering is increasing.

Now, so, it will generate an EMF whose polarity I am telling you the answer whose polarity will be such that this side is positive and this side is negative at this moment when the current is increasing the entering current is increasing ok. Then so, say at any moment this is greater than 0, then side A or terminal A will be positive, let me quickly justify this very quickly. So, when I am saying this is positive, this is negative you think of this inductor this coil as a battery as a source of EMF. So, this source of EMF; this source of EMF which has or the battery which has plus side here and minus side here, can try to drive a current if we provide a closed circuit here.

So, if we close this circuit then this battery you know a battery any battery will try to drive a current from plus to minus outside the battery, but inside the battery of course, minus to plus this is how a battery behaves ok. So, this battery the source of EMF will try to drive a current in this direction ok. So, induced EMF tries to drive the current in this direction in this anticlockwise direction current anticlockwise in this diagram ok.

Now, so what happens, now you see that this is this current this induced current is actually opposing the cause of the induced EMF, what was the cause of the induced e m f? It is this i t which was increasing i t is flowing clockwise and that was increasing and this induced current is therefore flowing in the opposite direction, it is opposing it is cause it is opposing it is own very cause ok. So, i t was increasing which was clockwise therefore, induced current or the current driven by the induced EMF is in the opposite direction. So, that is inconsistency with Lenz's law it can never be in other way, this side positive, this side negative is not possible this is not possible, this is plus, this is minus ok. So, this is how we can find the polarity of the self induced EMF use using Lenz's law.

Just to remember it quickly, I use a thumb rule which I can share with you for our self inductor self inductance if the current self inductance with 2 terminals with terminals A and B, if current entering A current entering through A is increasing then A will be positive. So, now you can extend this idea that if current entering through B is increasing then B will be positive, similarly if current entering through A is decreasing then A will be negative like this.

If this is the situation this is I say this is i t in this direction, but say $\frac{d\,i\,(t)}{dt}$ is negative then this side will be minus, this side will be plus. Similarly, if we have say this is the reference direction of i t and $\frac{d\,i\,(t)}{dt} > 0$ so; that means, current leaving through this terminal is increasing. So, therefore, this will be minus, because this is leaving current this is not entering current ok.

Similarly, if we have current say entering through this if this is the direction of i t and again say di dt is positive then this side will be positive this will be negative so on. So, you can extend this rule so, this is the rule, if current is increasing and entered I mean if entering current is increasing through a terminal then that terminal will be positive that is the rule for self inductance.

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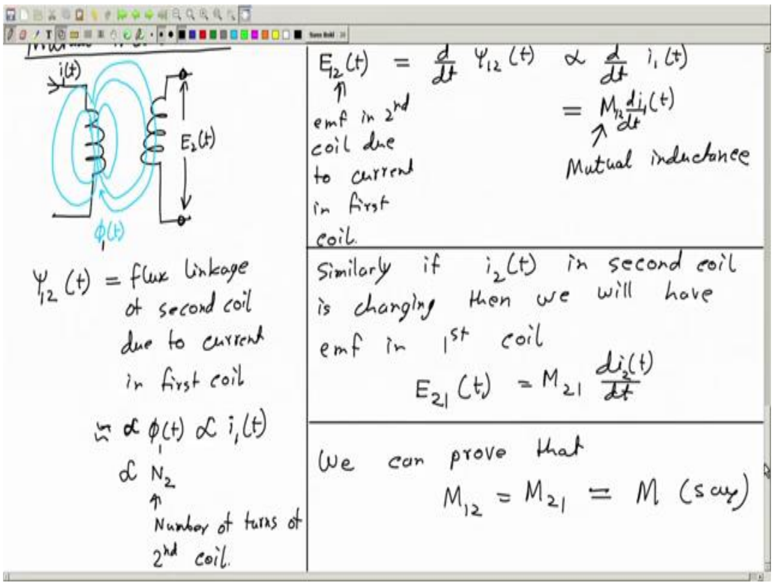

Now, let us talk about another concept which is mutual inductance, what is mutual inductance? If we have 2 coils place side by side close to each other in close proximity and then if we pass some current i t which is varying with time then of course, the flux created in this coil which will be like this that call it $\emptyset$. So, phi will also be time varying so, $\emptyset(t)$ is a function of time and this $\emptyset$ also goes through this second coil not all the flux, but part of it ok. So, the part of the flux goes through part of the second coil maybe not through the entire coil, but part of the second coil.

$\varphi 12$ (t) α i_1 (t) α $\emptyset$(t) α $N2$

Now, let us apply Faraday's law, Michael Faraday says any coil if it experiences a change in flux linkage will generate an EMF. So, therefore, if this current is changing this flux is changing therefore, the flux linkage in the second coil is changing so, an EMF will be created between the 2 terminals of the 2nd coil, call it E 2. This can be also a function of time E 2 t and Faraday's law says E 2 t so, this is the EMF in second coil due to current in first coil ok.

$$E_{12}(t) = \frac{d\varphi_{12}(t)}{dt} \ \alpha \ \frac{d\, i1\,(t)}{dt}$$

$$= M_{12} \frac{d\, i\,(t)}{dt}$$

let us call it M 12 this is called the mutual inductance due to the current in first coil and due to the EMF induced in the 2nd coil call it M_{12}.

$$E_{21}(t) = M_{21} \frac{d\, i2\,(t)}{dt}$$

$$M_{12} = M_{21} = M$$

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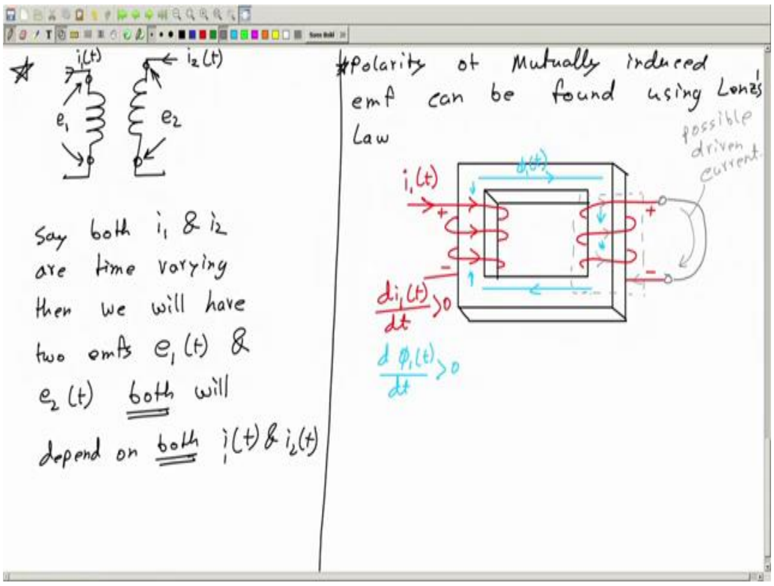

So, that is another important fact now the very important question is about the polarity of the mutually induced e m f ok. So, let us go back a step, let us come here ok. So, here we know that this current i 1 is changing therefore, we have this e m f e 2 induced across the second coil whose value magnitude is given by this term, but what will be the polarity at any instant say at t = 0 which side will be positive this side or this side. So, that is the question so, the polarity of mutually induced. So, this is another point e m f can be found using again Lenz's law how, let us take an example.

So, this time I will draw a transformer so, this is the core of a transformer you can think this in 3 D and it has 2 coils. So, let me draw it like this instead of drawing like this because then the direction of the winding will be more clear ok. So, this is one coil and we have another coil now, say this is my chosen direction of i 1 t, say at any instant at any instant I have this current increasing ok. Then according to the rule or self inductance which we have seen just few minutes back we can say that this side will be positive this side will be negative the self induced e m f will have positive here because this current is entering and increasing, but what will be the polarity here, this side positive or this side positive ok.

So, to find that, let us first find the direction of the flux ok. So, let us switch back to the overhead camera let us find the direction of the flux. So, let us apply right hand rule so this will so, this is the directs this is the direction of the current here, you can see this is the direction of the current and therefore, this is the direction of the flux and this flux is increasing call it phi.

$$\frac{d\,\emptyset_1(t)}{dt} > 0 \quad , \quad \frac{d\,i\,(t)}{dt} > 0$$

Now, I am telling you that at this instant I am telling you directly the answer I am telling you the answer fast that, this side will be positive and this side will be negative, why or how to verify this. So, to verify this let us assume if we had a closed path if we had a closed path then this e m f or this coil will act like a battery. So, this will think now like a battery so, this is the battery with plus here, minus here and this will try to deliver a current in this direction.

So, this is the driven current possible, if driven current possible because if there is a closed path I mean let us think the e m f is trying to drive a current I do not know what is the good English possible driven current ok. And so, now in which direction the current flows, the current here will flow like this so, like this, this and this plus to minus sides outside minus to plus inside the battery inside this source. Now what will be the direction of this e m f ok, let us look at once again from the top. So, this is the direction of the current so, this is the direction of flux.

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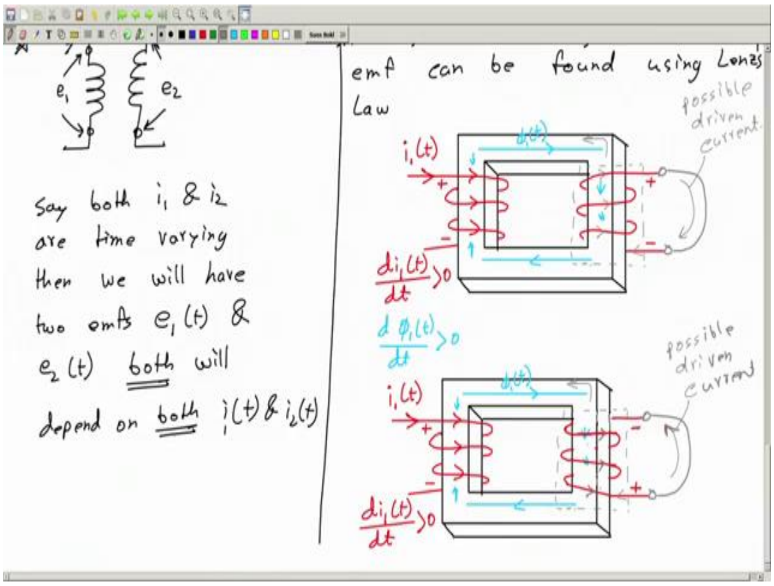

So, flux is now in the opposite direction so, this flux is in opposition to the original flux which was the cause of the induced e m f. So, this is in accordance to Lenz's law, it is not violating Lenz's law ok. So, this side will be positive, this side will be negative, you can verify that the other possibility that this is plus this is minus will violate Lenz's law ok.

So, this is how you can do it, now let me show you another example quickly. I will copy this diagram I will copy and paste it ok. So, now, what I will do? I will change the direction of the winding here ok. So, this time I will take the winding in the opposite direction, it will go from the back and then like this ok. So, you say the this winding is now in the direction opposite to this ok.

Now, if you do the same analysis assuming that this current i 1 is like these and this is increasing. So, this flux is also increasing, phi 1 is also increasing, then you can so that this side will be positive and this side will be negative, this is according to Lenz's law once again and here also I have to change the this direction ok. So, the current here now they will be in the direction like this. So, it goes like this and then this so, the current now flows like this ok. Plus to minus outside and minus to plus inside once again you can see that, the direction of this flux is in the opposition of the main flux. So, this is in the direction opposite to the main flux so, this side will be plus.

So, in general I can now write that it is important that which side will be plus or minus that depends on the sense of the winding that will also depend on the sense of this winding. If

I change the direction of this winding then also the plus minus sign will be affected ok. So, now, the which side will be positive in this second coil that depends on the sense of the winding now ok.

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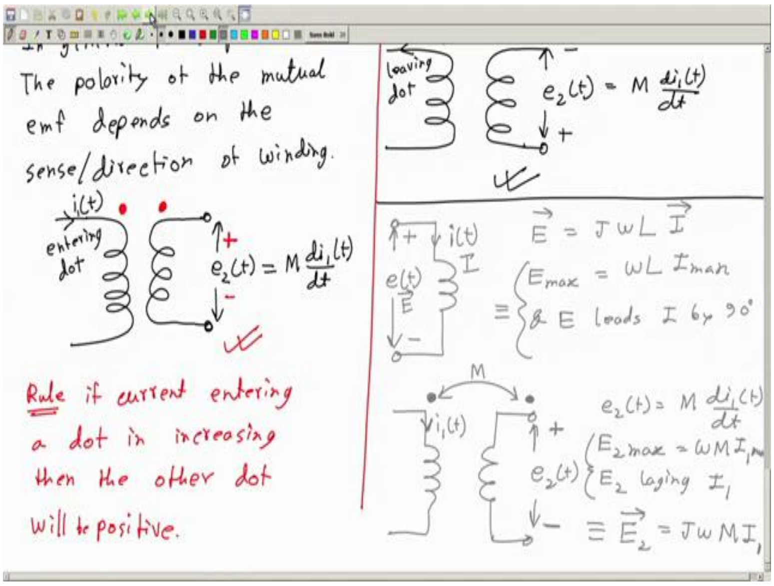

So, now in general for a pair of coil which the polarity the polarity of the mutual e m f depends on the sense or direction of winding how the coils are made in which direction the coils are owned ok. So, what we do we generally ok, often sometimes I mean we draw the coils like this they have seen it. So, this is a pair of coils and if we denote this current as i t, then we know that this e m f call it i 1 and say this is a there is no current in second coil. So, we have only the e m f induced due to the first current when only call it

e 2 = M$\frac{d\,i1\,(t)}{dt}$

So, often we denote this hidden sense hidden sense of winding with a symbol like this. So, like this so, we put a dot here and here, indicating that this means this dot means if the current entering the dot is increasing, then the other dot will be positive. So, what is the rule, once again I repeat the rule if the current entering a dot entering a dot is increasing then the other dot will be positive ok.

Similarly, if this current is entering this dot and this is increasing. So, the other dot this dot I will put a dot here. So, I have to put a dot here to indicate that this side will be positive. So, now, I can hide all these internal things I can just put these dots. So, I just put say dot here and maybe here now this means, the rule let me write the rule. If current entering a dot is increasing then the other dot will be positive. This is called dot convention this drawing is called dot convention will be positive ok.

So, now you see this is increasing sorry this is from left to right and say this is increasing so; that means, this value is positive, then the e m f will be such that this side is plus this side is minus. So, in general I can write that the magnitude of the e m f $= M\frac{d\ i1\ (t)}{dt}$

and it is polarity is such that the plus side is towards the dot if the current is entering the dot ok. So, this is a correct diagram.

Similarly, if I have a situation just for explanation if I have 2 coils with dots like this ok. So, whenever I do not draw the internal diagram clearly some information is hidden that is and that information is conveyed to you through the use of this dot. And now these dots are like this which means if say I choose i 1 t in this direction if this is the reference direction of i 1 t. Then the e m f induced here e 2 (t) will be of course, $M\frac{d\ i\ (t)}{dt}$

and the direction of this emf will be this side positive this side minus, why because this is leaving the dot, leaving dot entering through dot.

So, that is the convention that is the dot convention if current. So, for self-inductance if current entering is increasing for self-inductance then that terminal through which current is increasing is positive and for a pair of coils if current is entering through this dot this terminal the other dot is equivalent to this. So, this side will be positive that is the rule ok. Then and of course, one obvious thing in this diagram if I say $\frac{d\ i1\ (t)}{dt}<0$

is negative if this is negative; that means, this current is negative.

So, then of course, that means, this side will be plus, this side will be minus this if. So, let me write it and then I will erase if $\frac{d\ i1\ (t)}{dt}<0$ then of course, this side will be plus, this side will be minus, but I do not have to put sorry. This side plus, this side minus, if this is negative, but I do not have to write it this way, I can still write it this way plus and minus, because now this is negative anyway this is negative. So, the magnitude will automatically be negative ok. So, I do not have to do it explicitly.

So, in general I will always write the $e2 = \frac{d\,i1\,(t)}{dt}$<0 and put the plus sign towards the dot if the other current i 1 is towards the dot, if i 1 is towards the dot then plus should be towards the dot. If i 1 is away from dot plus should be away from dot that is the rule. And M general is a positive number for particularly for when we are considering only 2 coils there are exceptions, forget that.

So, now last not last next thing next important thing is this ok. So, let us go back also let me just mention a point here which I forgot ok. So, we know that E t will be 90 degree out of phase and we also know that the current. So, we say sometimes that ok. So, switch the context now so, now, we are we have gone back to self inductance where we have a voltage sorry current through this coil. And so, therefore, some e m f will be induced small e t is the time varying quantity ok. So, this is the time varying quantity and you know that we also have a concept of phasor say the corresponding phasor value is I let me put a bar. So, this is the phasor and similarly here the phasor is this, these are the symbol for the phasors you know what they mean ok.

Then and then we also know that I lags E by 90 degree, but this is not complete if I just say this is not complete, because I have not shown the reference direction of E ok. So, I have to show plus and minus then only I can say that this current lags this voltage by 90 degree. If I put the reference direction like this plus here and minus here in the opposite direction then I have to say I leads E leads E by 90 degree. So, these are some crucial small sensitive concepts you should be very clear about. You know all this, but maybe you have not thought in this way before so, I am reviewing this ok. So, therefore, this symbol is important, if I put the plus and minus and this way then only I lags E by 90 degree which means. So, let me draw here and then I will erase ok. So, or.

Now, I can draw the timing diagram like this. So, if this is E then I. So, this is e t not capital e small e t this is i t i t will be 90 degree lagging ok, e provided the ease chosen to have the reference plus here and minus here. If I had chosen plus and minus here then that e would have when actually this, this is nothing, but minus of this e and then you see that this current is actually leading this one not lagging that one. So, this one you also think a bit it is better if you think yourselves then it will be more clear instead of listening to me I believe. So, one more point which I wanted to mention.

So, now this fact that I lags E by 90 degree and the magnitude of I is such that I mean this relationship holds ok. So, now you know that this e m f the maximum value of this e m f can be written as

E= J ωLI

Emax = $\omega LImax$

When we write phasor to denote both the magnitude relationship and this phase relationship we write it this way, let me do it once again no problem in doing it many a times it will be our practice. So, this is equivalent to and E leads I by 90 degree. So, that is the phasor information.

So, therefore, for mutual inductance also when if we have 2 coils call this current i 1 t and if we have the e m f induced call it e 2 t, if the corresponding phasor I have made a mistake what is that in the previous diagram, what is that mistake? I have forgotten the plus minus sign without the sign this is meaningless ok, that is important. So, here also I have put this symbol for the current, similarly I put this symbol here and then I put some dots, I should actually put the dot first and then the symbol ok.

So, I put the dots and then this current is entering through the dot. So, I choose the reference direction in this way ok. So, this is the e m f and then the fact that $e2 = \frac{d\, i1\,(t)}{dt}$, this is the mutual inductance we can denote it like this. So, which means E 2 max ok, call it E 2 max the peak value of the induced e m f this is a sinusoidal e m f. So, the peak value will be J not it will be omega M omega M I 1 max and E 2 lagging I 1. So, these two facts are equivalent to writing the phasor relationship that E 2 = J ω M I_1 that is it I mean.

Now, we will go to transformers. So, we have reviewed self are mutual inductance, now let us go back not go back or let us start the discussion on transformer and it is equivalent circuit an equivalent circuit ok.

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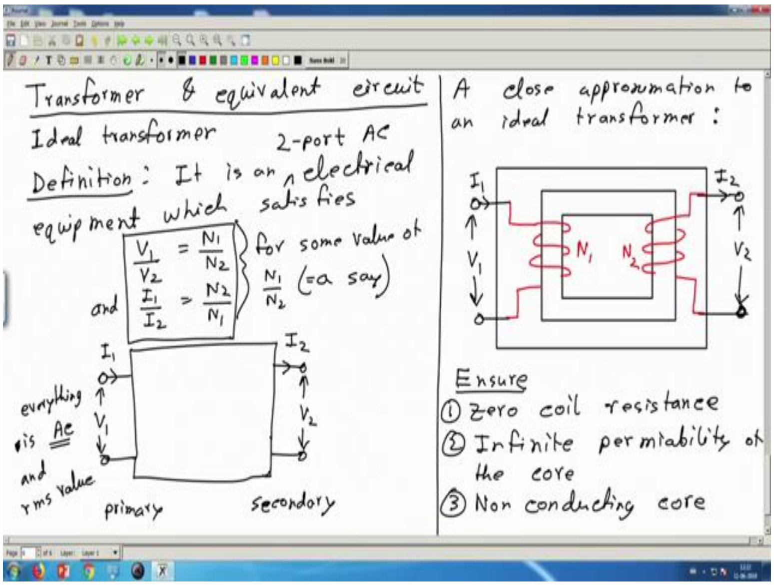

We will start this talk with ideal transformer ok, what is an ideal transformer? Let me give a definition. So, it is an I can define it this way; it is an electrical equipment electrical equipment with 2 ports. So, it is an 2 port electrical equipment like this.

So, we draw an equipment like a black box, which has 2 ports 1 and 2 ok. It is a 2 port electrical equipment; that means, it has 2 sets of terminals, you can call them as primary and secondary side. So, we can apply some voltage across these or these we can pass some current through this. So, call this current I 1 and say this voltage, let me draw it this way I 1 this V 1 here. We will we can apply some volt I mean we will get some voltage if we apply some voltage here and if I have a closed path then I can also have some current I 2 all these are AC everything is AC ok. So, this voltage current everything time varying assume them to be pure now pure sinusoidal everything is AC ok.

Now, the definition of an ideal transformer is that it is such a 2 port equipment 2 port AC electrical equipment, which satisfies the relationship between V 1 and V 2 like this V1/ V2 = N1/N2. And the relationship for between I 1 and I 2 like this I1/I2= N2/ N1 for some value of N 1/ N 2 or N 1 and N 2 for some value of N 1 and N 2 you can call it a equal to a say ok. So, you can call this issue as one number a; a for anything a.

So, if we have a equipment like this and where these are AC quantities. So, this means these are r m s quantities. So, everything is AC and so, I 1 is the r m s value and r m s value this is also true in terms of peak value because yes, but in general I can think this is the r m s value. So, if you have such a equipment we call this an ideal transformer. If any equipment what is so ever has 2 ports where we have 2 voltages V 1 and V 2, 2 currents I 1 and I 2 and if this relationship is true then we call this as an ideal transformer. Is there an ideal transformer in nature or in real life? No not at all, but what we can get is, something very close to an ideal transformer so, a close so a close approximation to an ideal transformer is just this.

So, this is the black box which has 2 ports current here is I 1 current here is I 2 voltage across this is V 1 and voltage across this is V 2, you may ask why I am not putting the plus minus sign, I say that is important I will put that soon. Right now it is not required because we are not considering the polarity we are only considering the r m s value. So, this relationship is for the r m s value ok. So, this is not in terms of phasor yet I will put the plus minus sign soon ok.

So, now what you can do to get a close approximation of an idea transformer, you take a core magnetic core and wind 2 coils on top of it this which turns N 1 and here with number of turns N 2 and you connect this ok. So, now, you have to also ensure a few facts like ensure facts like 0 coil resistance 0 not possible; that means, very small coil resistance use very teak conductor may be made of gold 0 is not possible so, as well as possible.

Secondly, very high infinite theoretically infinite, infinite not possible, so that means, very high infinite permeability of the core ok, infinite permeability of the core. So, that means, the flux will be very high and also ensured it is possible non conducting core ok. I mean 2 and 3 it is not possible to achieve together if we want high permeability material; that means, we have to use iron or some alloy of iron and iron is conductor and if we want say non conducting core we can use air core transformer, but then the permeability is not infinite not very high. 2 and 3 is not of course so, therefore, not possible together yes what one can do in practice take a laminated core you may know that and thereby reduce the conducting effect of the core.

So, if you make such an arrangement then it becomes if you make this arrangement exactly 0 resistance exactly infinite permeability and exact 0 conductivity of the core then this will be a perfect ideal transformer. So, that is not possible. So, take low resistance high permeability that will be a close approximation to a ideal transformer. Now for a practical transformer of course, we will have this non zero this non infinite and if it is iron core of course, some hot conducting core. So, that is what we call a practical transformer. Now in a practical transformer so, in a practical transformer ok.

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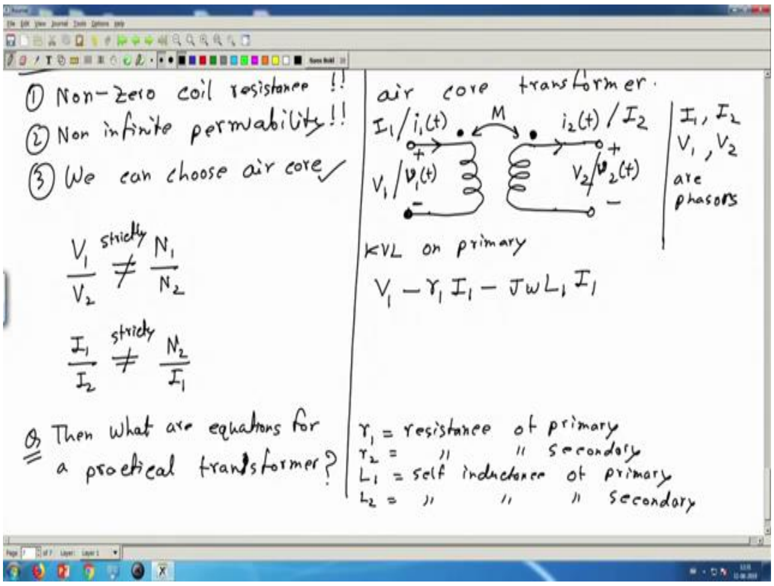

So, the previous thing was so this is for ideal transformer and for practical transformer of course, we will have you know all the other conditions opposite conditions non zero coil resistance and then non in finite permeability of the core permeability of the core and the core can be conductive. So, for simplicity we can choose; we can choose air core. So, the conductivity will be that problem is gone.

So, we can choose air core this is fine, this is sad this is sad so, non zero resistance is sad, non infinite permeability sad. So, therefore, the relationship between $\frac{V1}{V2} \neq \frac{N1}{N2}$. So, strictly not equal, it can be approximately equal to this, but strictly speaking it is not going to be equal. Similarly I 1/I 2 is not going to be strictly not strictly equal N 2/N 1. So, this is so, this so, V 1/V 2= N 1/N 2 is not the rule for a practical transformer.

So, therefore, you can ask the question then what is the or what are the equations for a practical transformer? Because the ideal equations are not true so, transformer. So, what are the equations for a practical transformer? So, this is what we will see next ok. And for simplicity; for simplicity we will stick to air core transformer; that means, no core loss, no eddy current possible, no hysteresis loss ok. So, for simplicity we will stick to a air core transformer.

Now, so we have 2 coils air core. So, I do not I cannot draw this means iron core. So, I cannot draw that. So, they have these 2 coils will of course, have some mutual inductance call it M and whenever there is a mutual inductance I must put some dots to indicate the polarity relationship between the 2 coils, otherwise the diagram is incomplete.

So I am not putting these arrows because I have to then put arrows many at times I am just bit lazy ok. So, these are the phasor quantities V 1 V 2 ok, without and these are small letters instantaneous quantity these are capital letters phasor values, now I choose the reference direction for v like this. So, I will always measure V 1 as the voltage of this terminal with respect to this terminal this voltage minus this voltage. Similarly I will always talk about v 2 like this voltage with respect to this voltage or this voltage minus this voltage ok, that is my chosen indifference that is what I choose ok. Now what will be the equations? So, let us apply KVL on the primary side this side so, in this loop on primary. So, what can we write? So, from let us start.

So, we start from this point and we will go around like this, we will add all the voltage drops and voltage rises ok. So, say we start from here, we now we go from here to here there is a voltage rise I consider is as positive. So, V 1 this is the rise and then from here to here through the coil I will have a lot of voltage drops. What are those drops? Drops I will consider as minus. Firstly, there will be a drop due to resistance of the coil has some resistance call it r1 I1, r 1 is the resistance of the first coil ok.

KVL on primary

$V1 - r1\ I1 - J\ \omega L1\ I1 + J\omega\ M\ I2 = 0$

KVL on secondry

$-I2\ r2 - J\ \omega L2\ I2 + J\omega\ M\ I1 = 0$

$V2 + r2\ I2 + J\ \omega L2\ I2 - J\omega\ M\ I1 = 0$

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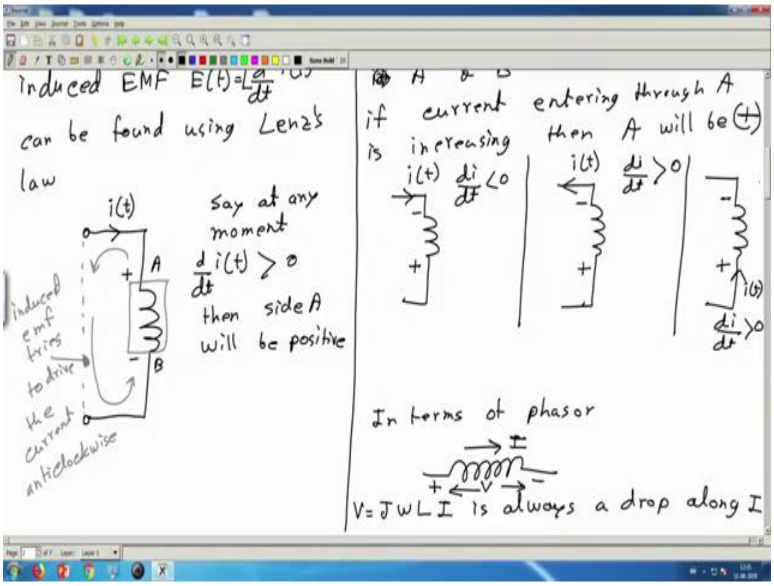

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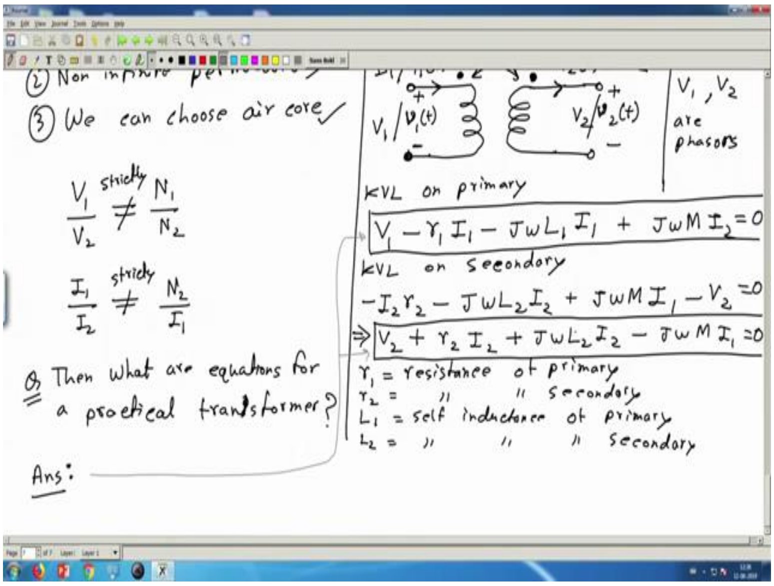

Now, so, the question was, what are the rules for a practical transformer? These are the 2 rules for a practical transformer, rule number 1 and rule number 2. So, these are the equations that a practical transformer obeys, a practical transformer does not obey this rule, this is the rule which a practical transformer obeys ok. So, the answer is this ok.

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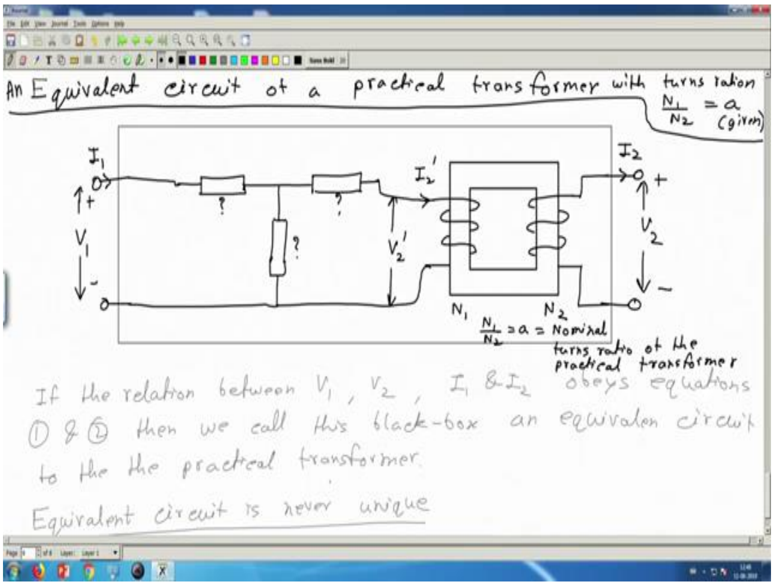

Now, next question of this is the final topic in this video is to find the equivalent circuit of a practical transformer. What do you mean by an equivalent circuit? An equivalent circuit is a circuit or is a circuit which will again have 2 ports like a transformer primary and secondary ok.

So, an equivalent circuit will be a will be some circuit whatever it is, it will have 2 ports of course and there will be something inside this circuit I mean whatever it is. It can be a very complicated circuit, it can be a very easy circuit, it can be a transformer itself, it can be something else, it can be even an electronic circuit anything ok. Equivalent means if I if the voltage here I denote as V_1 ok, plus minus chosen reference, current chosen I_1 in this direction, current I_2 chosen in this direction, voltage V_2 with this reference the reference polarity, see everything is similar to this practical transformer.

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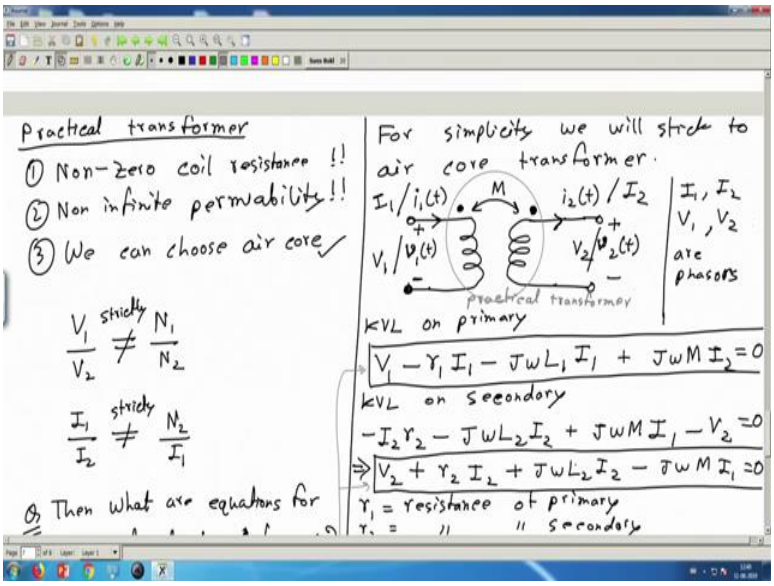

So, this is the; this is the practical transformer, this is the practical transformer it does not matter ok. So, this is the practical transformer and see you see that the current I 1 I 2, V 1 V 2 ok, note their directions I have chosen same direction similar directions for all of them ok.

Now, if the relationship between V 1 V 2 I 1 and I 2 in this circuit in this black box is same as this relationships then we will call this black box to be equivalent or a equivalent circuit of the practical transformer ok. So, if the relationship relation between V 1 and V 2 similarly I 1 and I 2 or V 1 V 2 I 1 and I 2 everything together V 1 V 2 I 1 and I 2 obeys equation call this equation 1, call this equation 2, obeys equations 1 and 2 then we call this black box and equivalent circuit to the practical transformer to the practical transformer.

Why, because from outside we cannot tell what is there inside is it the actual transformer or is it something else, because from outside the behavior of V 1 V 2 I 1 and I 2 will be same similar as this thing. So, we therefore, call this thing as an equivalent circuit no matter whatever is there inside, it can be a simple circuit, it can be a complicated circuit.

Now, an important fact is that equivalent circuit is never unique, what is an equivalent circuit? It is something which behaves in a way similar to the original one from outside, but inside can be a lot of different things. So, inside I can have lot of different circuits which will behave in the same way from outside ok. So, what is there inside, we cannot say.

So, therefore, equivalent circuit is never unique equivalent circuit is never unique. So, I can design many different circuits which will obey this equations 1 and 2 from outside. So, this is not unique, but we will design or show you one circuit which is most commonly used in electrical engineering. So, this so, we will show you the most practice, most standard, most common equivalent circuit that people use, but this is not unique. Now, the way I will design this equivalent circuit, once again I am repeating this is not unique. So, I can design it in many different ways, but I will do it in a way that is common to people. So, what I will do, I will take inside I will take a ideal transformer. So, I will take an ideal transformer with turns ratio ok.

So, the turns ratio will be same as the given turns ratio of the practical transformer. So, equivalent circuit of a practical transformer with turns ratio N 1/ N 2 is equal to say a given I will write an equivalent circuit because this is not unique. So, this turns ratio is given. So, what I will do, I will take an ideal transformer N 1 N 2 and N 1/N 2 is equal to a is equal to nominal turns ratio or given turns ratio of the practical transformer. I will choose it this way, I can choose it in other ways as well that is also possible, but this is my choice I can make this choice, because I know the answer is not unique.

So, I can make any choice as long as the relation between V 1 V 2 I 1 and I 2 is same as this and I will so the choice that I am making will obey this relationship also that. Then I will connect this here and I will connect this here and here I will take 3 impedances connected in the form of T ok. So, this is a T network, 3 impedances, I will connect this side, here, here and I will connect this to the transformer I. So, questions.

So firstly, you may ask I said idea ideal transformers do not exist. So, how can I take an ideal transformer? This is only; this is only a theoretical circuit ok. So, I am not going to make or manufacture this circuit and install it this is only a theoretical circuit. This theoretical equivalent circuit is useful for doing calculations and for doing simulations in computer then I am not going to manufacture it, this is only a theoretical circuit.

Next question, what should be the values of these 3 impedances? That, I will calculate and find out so, that the relationship between V 1 and V 2, I 1 and I 2 is as desired ok. So, these are the things I have to find out so, but before that I mean. So, this is what I will found out, but before that I can write this voltage that because this voltage as V 2 prime and this current as I 2 prime, now this is an ideal transformer. So, therefore, I can write so, for an ideal transformer we know that V 2 prime by V 2, let me do it here.

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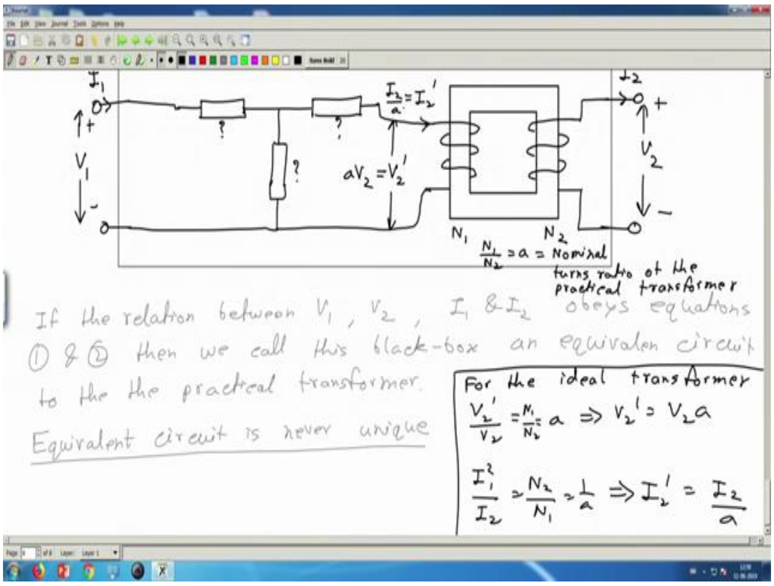

$$\frac{V2'}{V2} = \frac{N1}{N2} = \mathrm{a}$$

V2’ = V2 a

$$\frac{I2'}{I2} = \frac{N2}{N1} = \frac{1}{a}$$

I2’ = I2 a

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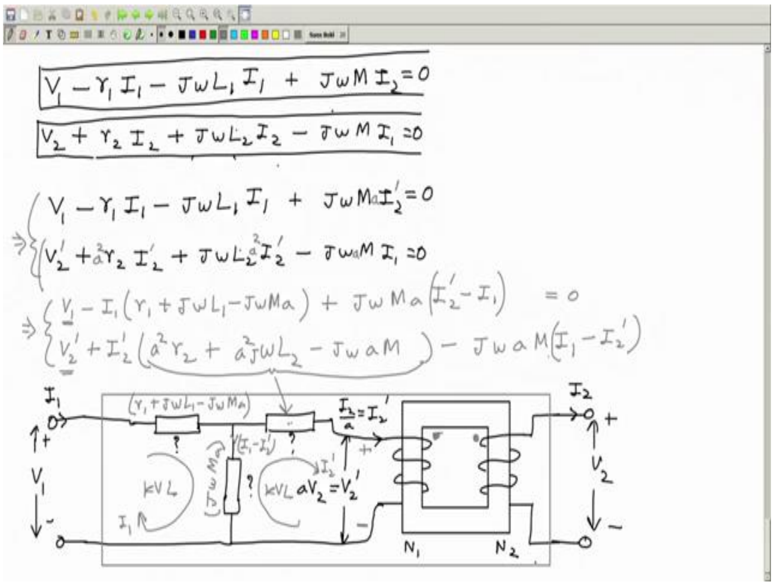

Now, I will need these 2 equations I have to satisfy these 2 equations, somehow by choosing these impedances these 3 impedances I have to satisfy these equations. So, when this equations will be satisfied we have to we have to satisfy these 2 equations and this is the equivalent circuit I have copied yup ok, we have to find these 3 values such that these 2 are satisfied.

V1- r1 I1 -J $\omega L1\ I1 + J\omega\ M\ a\ I2' = 0$

V2' + a r2 I2 + a^2 J $\omega L2\ I2$ - $a\ J\omega\ M\ I1$ =0

V1- I1(r1 + J$\omega L1 - J\omega Ma$) $+ J\omega\ M\ a\ (I2' - I1) = 0$

V2' + I2' (a^2 r_2 + a^2 J$\omega L2 -$ JωaM) - J$\omega aM\ (I1 - I2')$

So, what I have done you just verify it yourself once that the KVL equation for this these 2 KVL equations with the value of this impedance equal to this, the value of this impedance equal to this and value of this, impedance equal to this it is same as these 2 questions. So, these 2 KVL equations are same as these 2 equations, which mean if I choose this impedance if I choose this impedance to be this equal to this and this equal to this, then the overall equation between V 1 I 1 and V 2 prime I 2 prime will be like this and; that means, the overall equation between V 1 I 1 V 2 I 2 will be like this.

Let me state this once again summarize this once again, verify yourself if I choose this impedance to be this, this impedance to be this, this impedance to be this and if I have this transformer an ideal 1 with N 1 N 2 equal to a given value of a then the relationship between V 1 I 1, V 2 I 2 will be same as this one same as the practical transformer. So, this is therefore, is going to be a equivalent circuit of the practical transformer equivalent circuit of the given practical transformer ok.

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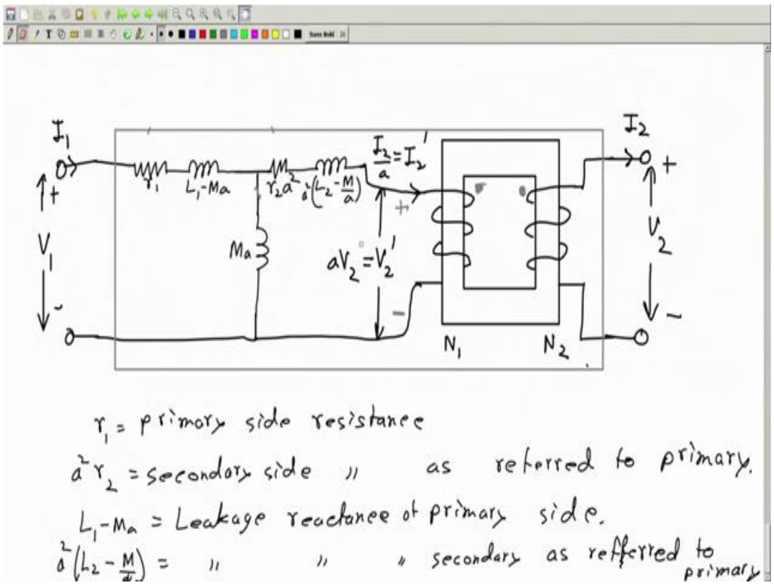

r1 = primary side resistance

a^2r_2 = secondary side resistance

L1-Ma =leakage reactance at primary side

$a^2(L2-\frac{M}{a})$ = leakage reactance at secondary side

So, this will be leakage reactance of secondary as referred to primary ok. So, this is called the equivalent circuit and so that is what we need it I mean before we can proceed. So, basically in this class this is an additional video it is not part of the main course measurement, this is an added. This was an additional video it was a complete innocence I do not know whether how complete. It is review a recap of all the background knowledge one needs about magnetic circuit, transformer equivalent circuit, which will be helpful and understanding ct pt instrument transformer in more detail ok. So, let us take few more minutes to just show you an import a nice interesting fact ok.

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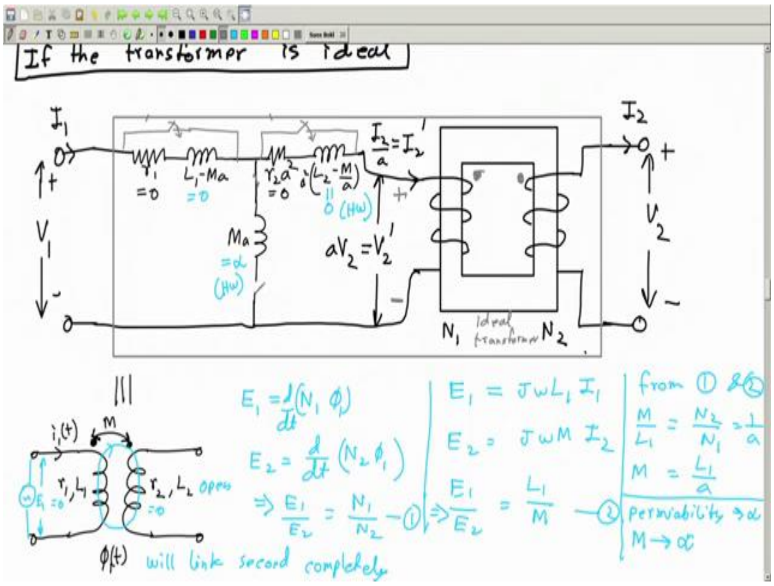

So, if you like so, you can it simply erase it, this will also become 0 because that is the condition for an ideal transformer we have written see here going back. So, for an ideal transformer the coil resistance would be 0. So, r 1 r 2 will be 0 and then I will show you that this will also be 0 this will also be equal to 0, why. So, the practical trans so, the this is equivalent to this practical transformer right dot M. So, this is the mutual inductance this side I have r 1 L 1 self inductance, r 2 resistance l 2 self inductance. So, this is actually the equivalent circuit of this.

Now, if I have say very high permeability they a core material then all the flux that is created will link through the secondary coil. If current I 1 is flowing it will create a flux phi t it will go completely through the other coil ok, phi 1 t will link second coil completely.

So, then we can write that so, if so how much is then L 1; L 1 is nothing, but this is the emf. So, we can write e m f induced or across the first one we can write E 1. So, assume this is open so, this side is open and this side is excited ok. So, E 1 self induced e m f not the resistive drop ignore the drop and r 1 is 0 actual r 1 is equal to 0 so, r 2 is a or the 0 ok.

$$E1 = \frac{d\, N1\, \emptyset 1}{dt}$$

E2 = $\frac{d\, N2\, \emptyset 1}{dt}$

E1= Jω L1 I1

E2= J ω $MI2$

$\frac{E1}{E2} = \frac{L1}{M}$

$$\frac{E1}{E2} = \frac{N1}{N2}$$

$\frac{N2}{N1} = \frac{M}{L1} = \frac{1}{a}$

M = $\frac{L1}{a}$

so, now, if you put the value L 1 by a you will see this is becoming 0. Similarly a homework you can show that this is also equal to 0, homework with the similar analysis you can. So, this is equal to 0 ok.

So, that is ok. So, that is what happens for an ideal transformer all these things become 0 ok. So, that is it so, we had a long class, but this is actually a recapitulation review of all the elementary concepts required to understand transformers better and also this M will be very high. So, this will be infinite for an ideal transformer why, because we have said that permeability of an ideal transformer should be very high.

Permeability is tending to in finite so, this will imply M tending to infinite why, because more permeability means more flux more flux with less current. Now more flux means there will be more e m f with so; that means, with less current, we will have more e m f so of course, the impedance will be high, impedance is proportional to M so, M will be high. So, if permeability tending to in finite you can so, M is equal to infinite tending to infinite ok.

So, this also let this be also a homework you think; you think that if permeability is high then this is infinite and if so, then you see this is 0; this is 0. So, you can virtually short circuit this so, you can do it like this. So, you can short circuit this, this is not there you can also short circuit this, this is not there because these are 0 and similarly this is in finite means you can keep it open right. So, if we assume that the resistance is 0 the permeability is infinite, then it boils down that this is 0, this is 0, this is 0, this is 0, this is infinite. So, this branch you can forget this branch you can forget. So, this point is directly connected to this, this point is directly connected to this and none of this is present.

So, inside this box inside this box we have only this ideal transformer. So, this was the ideal 1. So, what we have shown is that with the assumption of very high permeability and low coil resistance this equivalent circuit of a practical transformer boils down becomes same as same as an ideal transformer only that is interesting.

Thank you.