Fundamentals of Power Electronics
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Lecture - 62
Magnetics review

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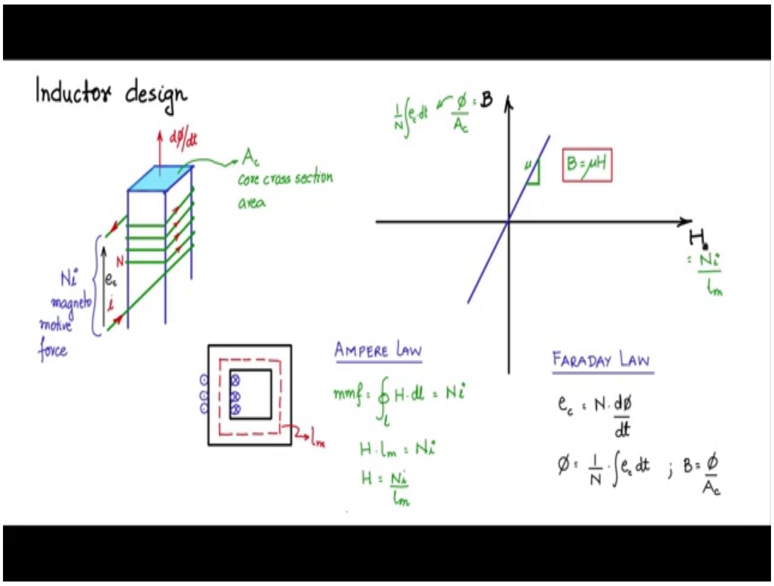

Let us now discuss inductor design and before going into the inductor design let us review some of the magnetic principles. Assume that you have a magnetic core material like this which has a cross section, when I take a cross section it has a rectangular section like this. And over this core material, let us wind some copper conductor turns so, these are copper conductor turns.

So, let a current iv pass through this, it will go and finally, come out through that. So, in the turns copper turn coils you will see the current flowing in this fashion. Now, you will see that all these N coils have the current flowing in the same anti clockwise direction now, this is going to produce a resultant flux rate of change. So, let us say there are N turns and then there will be a resultant rate of change of flux which is perpendicular to the cross section area so, this is the cross section area A c.

Now, all these turns N into i is called the MMF or the Magneto Motive Force. So, this magneto motive force Ni, the current flowing through all the turns included is the forcing function to produce this rate of change of flux or these changing flux lines.

Now, let us now see, what is the fundamental graph between the power variables in the magnetic domain? So, the magnetic domain there are two variables, I will say one is the H or the forcing field and the other is B the flux density yeah. Now, how are these related to the power variables; in the electrical domain the power variables are v voltage and high current. So, let us bring about some kind of a connection between them so, that we are able to visualize and understand them have it better.

So, let us say we have the core so, this thing is a core almost a square core and we have the turns wound here just like here. Now, let us say on the inside on the inside you have the current flowing in and on the outside the current coming out. So, let me just take a section. So, the copper conductors will look like this circular sections and here the current is coming out so I will put a dot here, the current is going in I will put mark like that this coming out going in coming out and going in.

So, if you look at this particular you have three turns here. So, if I take a path any path which encloses these which encloses the current some other current carrying turns here part of them. So, if I take this how along this path l now, I have three such turns; so, three times i will be the mm of magneto motive force. Now, this is encapsulated in a more generic form by the amperes law. So, what does amperes law state? It states that mmf is given by if you take the integral of integral over a path, a closed path or the force field H over the path, now that will be equal to Ni, Ni is the mmf.

Now, in this case if I take for example, the path is the mean magnetic path for this core l m let us say, right through the centre in this fashion. Now, it is enclosing three sections where the current is going in. So, therefore, it will be three i in this case and if there are N turns it will be Ni. So, Hm H into lm lm is the mean path length is N N into i and H is Ni by l m. Now, this is what you have on the x-axis which is Ni by l m you see that, N is N is fixed l m is fixed constant, i is the electrical parameter to which H is linked and you have the current or one part of the power variable coming in picture here.

Now, B let us take another law which is operative with the magnetic domain which is the faraday law. In the faraday law talks about the EMF there is induced across the coil e c, is the induced EMF across the coil and this ec is given by N number of turns, d phi by dt whatever is the rate of change of flux within the coil. So, this is another fundamental relationship that we will be using very much especially during design of this inductor and transformers. So, if you take this flux phi. Flux phi is nothing but 1 by N integral of e c dt. So, this is the flux relationship and the flux density B is flux per unit area, a vapour per unit area flux by A c, A c is the core cross sectional area.

So, you see that flux here is proportional to the integral of the voltage with time there is there is a voltage function voltage function coming into the picture; B is flux phi by A c and flux itself is 1 by N integral of e c dt. So, you see the voltage coming into this into this axis. So, the voltage and the current and this would be the fundamental BH curve or the fundamental BH axis that we that that one will be using in most magnetic design and analysis

So, if you take this BH curve; if take this BH axis and take a typical magnetic material let us say it is ideal then, it will look something like this a straight line and it has a slope and the slope is called mu, mu is the permeability. So, B B is equal to mu times H so, this is one fundamental relationship B is equal to mu H, where mu is the permeability which relates the flux density and the forcing field which is Ni by lm.

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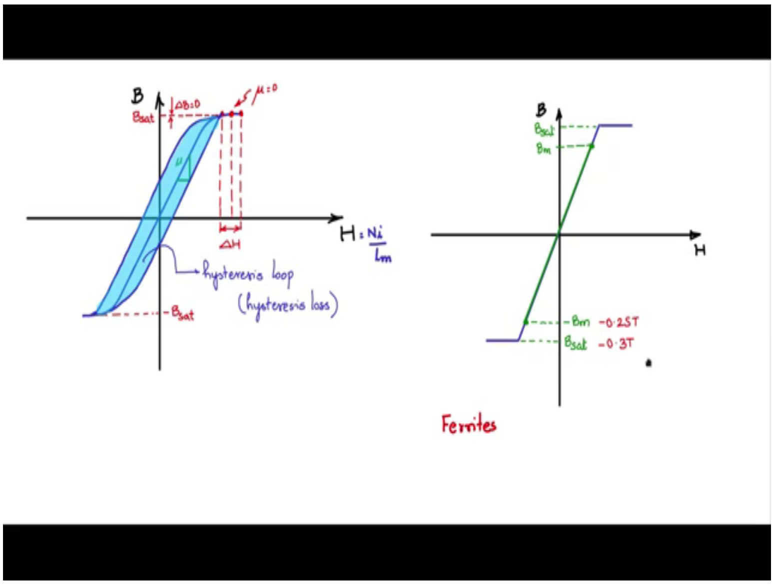

In practice in a real core, the BH curve is not a straight line like this there are non-idealities. So, the first one is that you will see that there is Ni and then it flattens out into a saturation like this, the positive side and also on the negative side there is a Ni and flattens out in this fashion. So, if I take what does it mean, what does this kind of saturation mean. If you take an operating point here and going down there is some value of force field, there is Ni by l that is applied at this point. If you take another neighbourhood point you will have some value of H field here,.

Likewise, another neighbourhood point you will have H field here so, there is a difference of delta H field between this point and this point, but how does it reflect or project onto the B axis. So, on the B axis they all appear to be at the same point; we call that 1. Let us say as the saturation flux density because there is no change in B; the delta B is equal to 0 due I know all these regions in this flattened out region. Therefore, you say delta B is equal to 0 there is no induction, there is no action of d phi by dt the because of that here in this region mu is 0, permeability is 0 is no longer acting as an inductance or as a transformer in this region.

So, we should not operate in the saturation region and most of our discussions in designing l and the transformer is in the linear region, but you should know that there exist the saturation zone and then you should not go near that. Likewise on the negative side also you have a symmetrical value minus B sat. So, not only that you have the saturation non-linearity there is also history or memory in this most of the course they seem to remember. So, you will see that when you magnetize it, when you apply Ni, mmf, it will reach this operating point and then when you remove the current it will go and settle here there is some kind of flux; resident flux density in the core.

So, you have to apply a negative if you take Ni by l, negative mmf so, that it becomes 0 here, then starts going negative. Likewise in the other direction also at this point there is a even though you have removed the mmf, there is some amount of resident flux density at this point which can be removed only by application of a positive mmf and so on. So, this is called the hysteresis loop which is coming because of the memory present in every magnetic core.

Now, if you see take the area an area within this; the shaded area within this, every cycle the amount of energy that is enclose in this shaded area because if I take 1 axis as the potential variable, other axis as the kinetic variable. The product of them will be the power variable and integral of that over a period will give you the power. So, within a cycle the area under this is a power variable and that is amount of loss that goes within the core and that is called the hysteresis loss. So, this loop the hysteresis loop significance is that the amount the number of times this hysteresis loop is travelled will results in covering that much amount of area which will result in that much amount of energy being lost and that is called the hysteresis loss.

But for the purposes of design, let us not complicate with this complex non-linear curve; BH curve we will reduce the complication in this fashion. Let us take a simple, linear BH curve and flatten it out at the ends to account for saturation. So, we will call the top flattening as plus B sat, the bottom negative side has minus B sat. The operating point well below the saturation will be the maximum operating point and an operating point below on the negative side just above the negative B sat will be the negative max operating point. So, ensure that the system or the core is of having an operating point well within the saturation in this green portion of the curve.

So, there are many core materials available the most popular is the ferrites for the high frequency switched mode converter applications. So, the ferrites have a B sat of points 3 tesla and we normally operate at a maximum flux of 0.25 tesla for inductors and 0.2 tesla for transformers. Likewise on the negative side, you do not go below minus 0.25 tesla and these are negative sat is minus 0.3 tesla.

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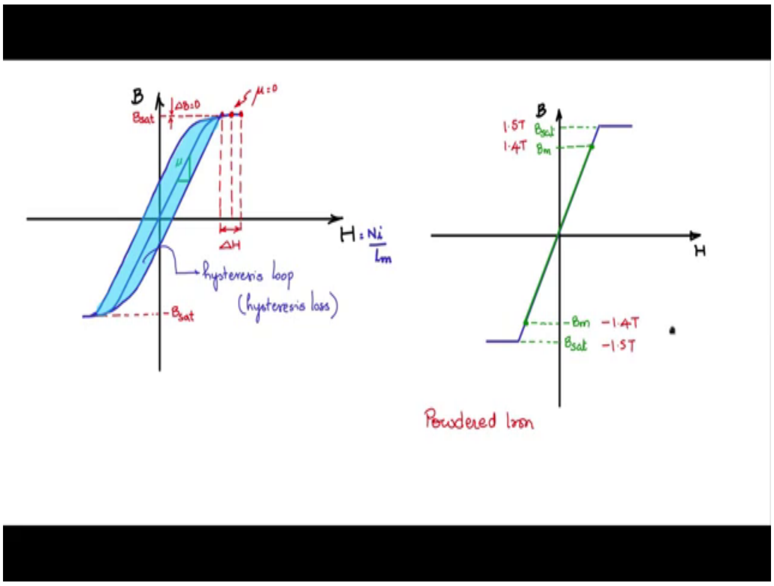

So, there is another core material called powdered iron. Powdered iron is also used for high frequency applications, it has 1.5 tesla as B sat and we normally do not go beyond 1.4 tesla; likewise on the negative side minus 1.4 tesla and minus 1.5 tesla or the limits.

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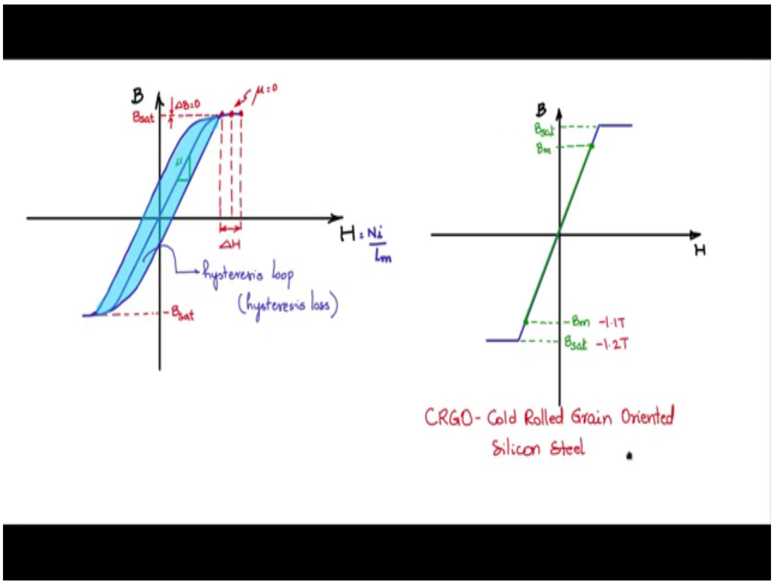

We have another common material called the CRGO. CRGO is Cold Rolled Grain Oriented; cold rolled grain oriented silicon steel. This is one of the most common material used in all low frequency transformers where you see the laminated transformers, that is the laminations it is generally CRGO cold rolled grain oriented silicon steel and it has 1.2 tesla as B sat and we normally limited to 1.1 tesla plus or minus 1.1 tesla, saturation is plus or minus 1.2 tesla.

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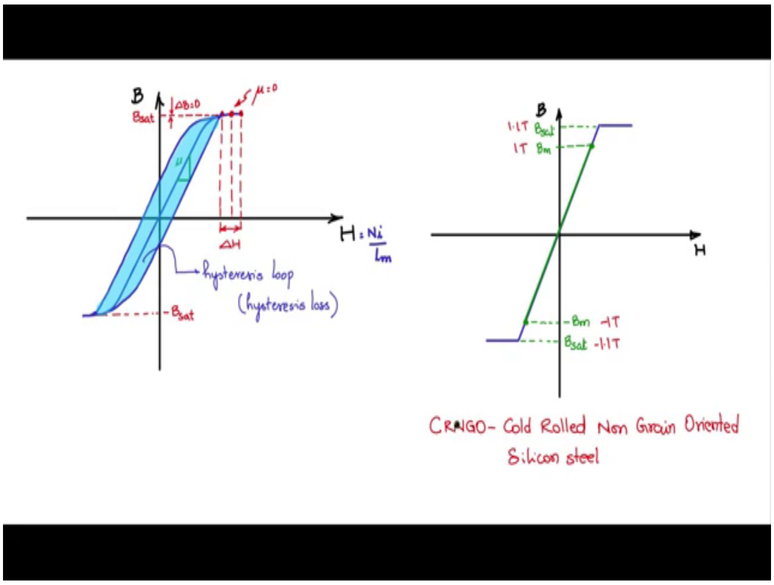

Another cousin of the cold rolled grain oriented silicon steel is the CRNGO which is Cold Rolled Non Grain Oriented silicon steel. It is also used for transformer; low quality transformers, but mostly CRNGO is used for making machines; induction machines. It has 1.1 tesla saturation and we limit the operation of the maximum flux density to 1 tesla plus or minus 1 tesla. But generally, for good quality low frequency transformer cores, it is CRGO that is used and not CRNGO.

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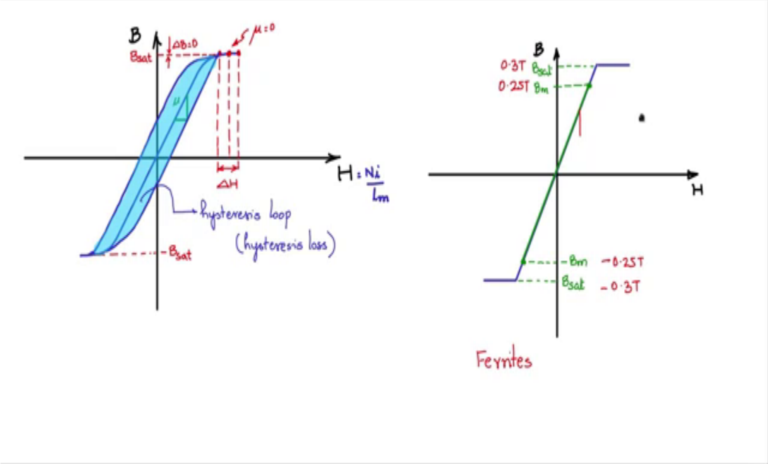

But for our discussion and of the switch mode converters we will mostly use ferrites which has 0.3 tesla plus or minus 0.3 tesla as the saturation flux density and we limit for the inductors between 0.25 and minus 0.25 tesla for the inductors and for the transformers 0.2 to minus point minus 0.2 tesla for the transformers.

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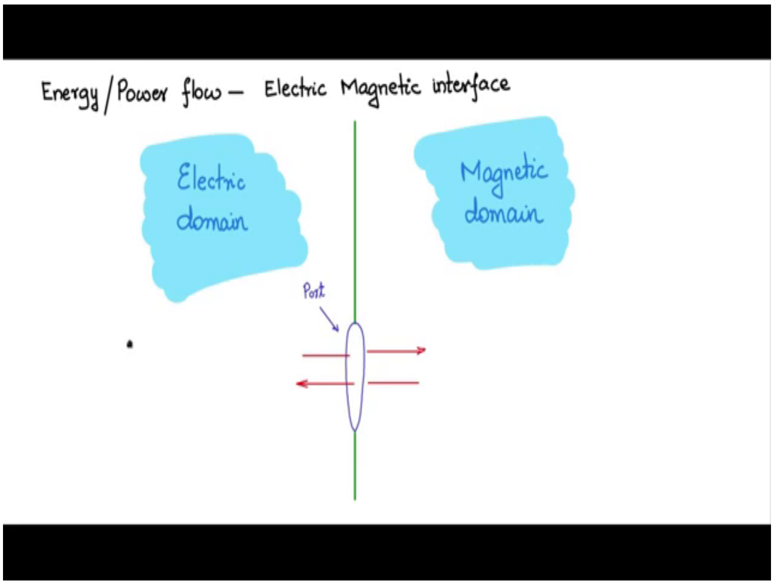

Now, this has in order to understand the operation of the inductor and the transformers, we should understand the energy or the power flow from the electric to magnetic domain and from magnetic domain to electric domain how it reflects back. So, this understanding of power or energy flow across these domains electric magnetic; across an electric magnetic interface is very very important.

So, let us consider that. So, let us say on the one side you have an electric domain and on the other side you have a magnetic domain within the core. So, electric domain is measurable with oscilloscopes the parameters like voltages and currents are measurable whereas, in the case of the magnetic domain it is within the core and the parameters d phi by dt and the mmf or invisible.

So, let us say you have a interface boundary between the electric and magnetic domain and we would like to see how the energy exchanges across these domains. So, let us create a port. So, this is a port and it is through this port there is an exchange of energy between these two domains. So, the energy can flow from the electric to magnetic and it can flow from magnetic to electric both ways.

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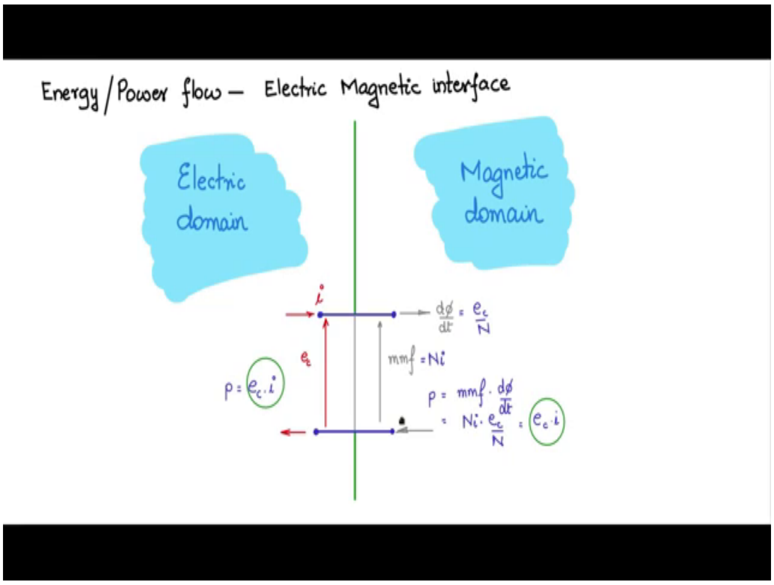

Energy / Power flow – Electric Magnetic interface

So, let me create an invisible membrane across this electric magnetic interface and let me mark two terminals here on the electric side, you have an inflow of current and current that comes out from the other terminal, there are two terminals here. So, we say there is a current input, a current part of the power variable. Power has two variables, one is the current and the voltage in electric domain, current is the kinetic variable and the potential variable is the voltage. And across the terminals there is a potential and we will say it is the potential of across the coil e c voltage across the coil.

Now, likewise on the magnetic domain let us say there are invisible terminals and there is potential across invisible terminals and that is the mmf magneto motive force, very similar to the electro motive force on the electrical side. Now, from the invisible terminal, there is some flow kinetic part of the power which goes out and comes back in and that is d phi by dt and completes the circuit in this fashion. So, d phi by dt is equivalent to the current i mmf is equivalent to the electromotive force.

Now to just verify that energy or power is same across the domains so, basically their units should be same and power should be conserved. So, let us say the power on the electric side what is it and what is it on the magnetic side let us try to find out. Now, how is mm of related to the electrical parameters it is Ni that we saw, ampere turns and how is d phi by dt related to the electrical from the Faraday's law we know, e is equal to Nd phi by dt. So, d phi by dt is equal to e c by; electrical side potential by N.

So, if you take power on the electrical side which is nothing but e c into I we know is vats, on the imaginary invisible magnetic domain side power is equal to its potential variable mmf into its flow variable which is kinetic variable which is d phi by dt and if we substitute back you see that Ni into e c by N which is e c into ic. So, power is conserved it is one on the same and has the same units flowing across the electrical to the magnetic domain. And therefore, mmf has to represent the potential variable and d phi by dt has to represent the kinetic variable. So having made this equivalence, let us symbolically represent the interface between the electric and the magnetic domain.

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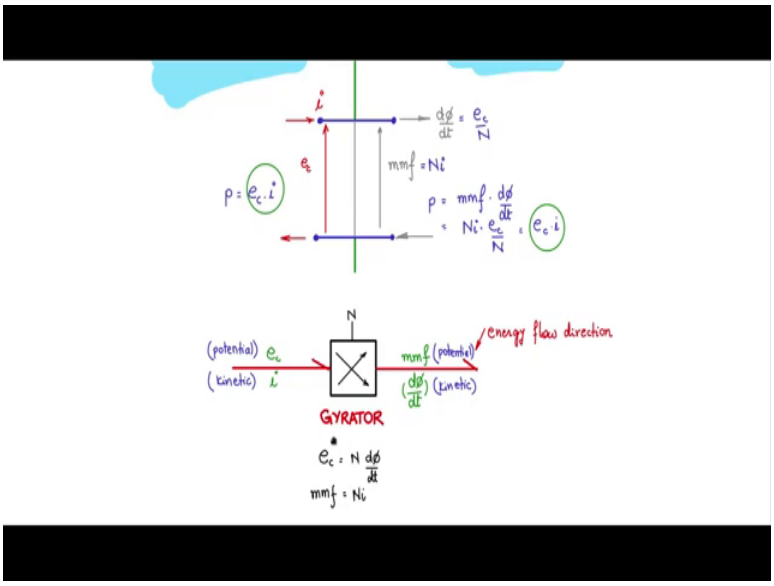

So, let us draw a block like this, now let us say this is the interface between the electric and the magnetic domain we will give it a name later. And on the primary side I am I am putting indicating a bond and I am indicating a half arrow to indicate energy flow direction. Energy is flowing from the side into the magnetic domain in this fashion. So, this is the energy flow direction this is just to indicate the energy flow direction.

And on this electrical side there are two variables energy variables or power variables one is the potential variable called e c the other is the kinetic variable called the current. On the magnetic side also we have a potential variable called mmf and the kinetic variable d phi by dt always the product of potential and kinetic variable in any domain has to be power, that we have verified e c into i is the power in the electrical domain, potential into kinetic mmf into d phi by dt is power even in the magnetic domain.

So, we will say that these two domains are related by one parameter called, that is the turns or the number of turns which relates these two the variables on both the sides. So, e c is the potential variable current is the kinetic variable likewise, d phi by dt is the kinetic variable mmf is the potential variable.

Now, the relationship between these variables a very unique in the sense that, the potential variable of the electric side voltage is related to the kinetic variable of the magnetic side which is d phi by dt by the Faraday's law which is e c is equal to N by this parameter N d phi by dt. And the other variable, kinetic variable electric side is related to the potential variable of the electric side the cross linkage and there mmf is equal to Ni; again, with the parameter N, N coming in both the cases therefore, N is the parameter.

Such a device, where you have a port, a power port separating two different energy domains, one is electric and one is magnetic in this case and the relationship between the power variables on both sides of the domains. Potential variable linked to the kinetic and kinetic variable linked to the potential cross linkage is called a gyrator. So, the gyrator is the port element that links the two domains magnetic and the electric by this cross linking mechanism. So, keep this in mind that this will help in doing the derivations later.