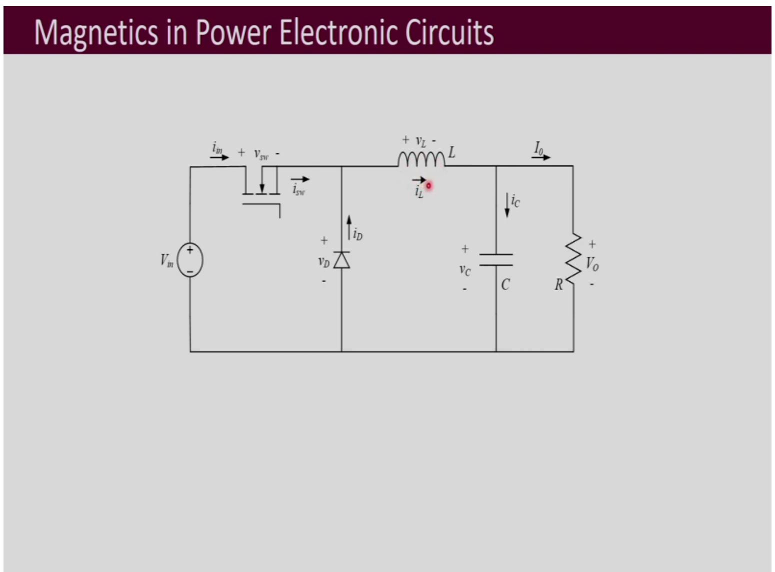
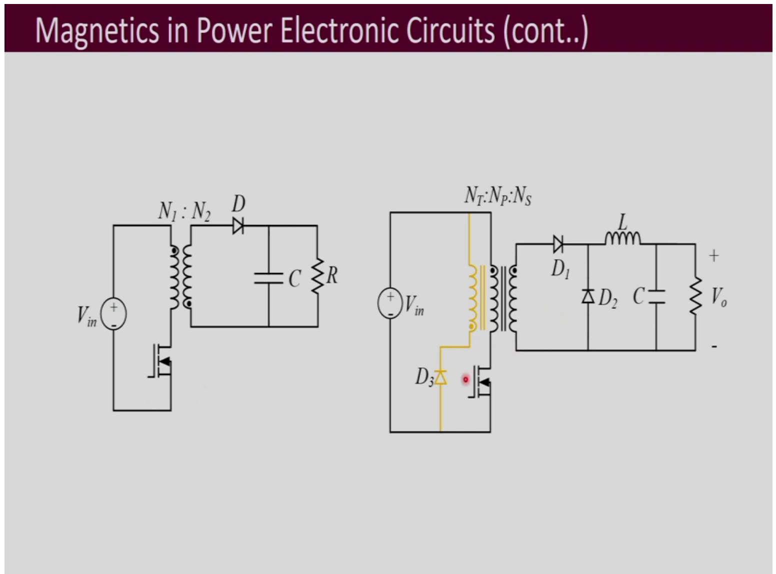
Design of Power Electronic Converters
Professor Doctor Shabari Nath
Department of Electronics and Electronical Engineering
Indian Institute of Technology, Guwahati
Lecture - 44
Fundamentals

Welcome to the course on Design of Power Electronic Converters. Today, we will begin with the next module that is magnetics design. So, to begin with the module, let us first review some of the fundamentals of magnetic circuits, which you have previously studied. First, let us look into the use of magnetics in power electronics.



So, this is the buck converter circuit. You are very much familiar with it, and we have been using it for our discussions. So, this is the inductor which is there in this power electronic circuit. As we have discussed before, this has to operate at high switching frequencies depending on the power rating, and it could be from kHz to even hundreds of kHz and up to MHz also, and for that this inductor might be needed.

So, this is not an inductor which you may be finding out of the shelf. It may be something which has to be designed depending on the specifications of the buck converter. Similarly, there are other non-isolated DC to DC converters which also use inductors and those inductors have to be specially designed based on the specifications of the converter.



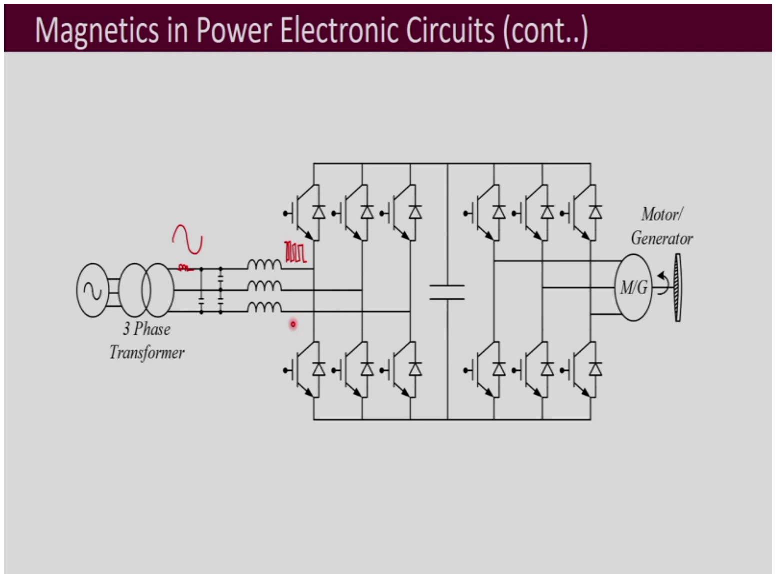
Then these are isolated DC to DC converters. So, this one is a flyback converter and this is a forward converter. So, you can see this flyback converter here. There is a transformer here and this is a high frequency transformer. Again, the switching frequency of this may be in the range of kHz and hundreds of kHz, for which this transformer might have to be designed.

This flyback operation is different. Then the normal transformer step ups, that means just simply step-up, step-down operation is here. It also stores some magnetic energy and then transfers it to the load side when the switch is off. So, that operation takes place. So, sort of energy storage also takes place in this transformer of flyback converter, like the energy storage is there in an inductor. So, these have to be then specially designed. You just cannot buy it from the market, from a shop and then put it in your circuit.

It may happen that you may get some similar specification of a transformer which is of the shelf and you may be able to use it, but not always that is possible. It depends on the specifications of the converter. Then, this is forward converter. Here you can see that there are three windings, this is the primary and this is the secondary. Then there is another demagnetizing winding, which is the tertiary winding and which is denoted here in yellow colour.

So, it is a three-winding transformer. Again the switching frequency of this MOSFET may be in the range of hundreds of kHz and so, this transformer then has to be designed accordingly. Unlike this flyback does not use storage in the primary and secondary windings for its operation. So, this is going to be designed differently than the flyback converter.

Then here you see that there is another inductor, which is similar to the buck converter inductor. So, that also has to be designed for this converter. So, similarly, there are various other isolated power electronic converters, DC to DC converters where we need transformers and inductors to be designed.



Then apart from DC to DC converters, there are other applications of DC to AC and AC to DC. There also we need magnetics, for example here this is shown, and we call it as a back to back converter. So, this is a three-phase inverter. So, it is just an extension of an H bridge. It is also called as H-bridge. So, that has three legs here now. So, this is going to act like an inverter or a rectifier. It depends on this side whether we have a motor or a generator.

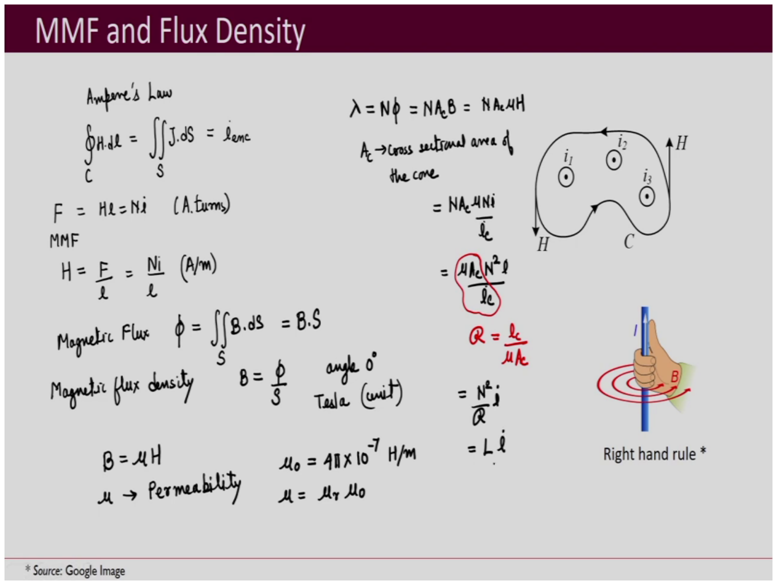
On the other side, you have the three-phase supply. Again, depending on the use, whether you have a generator or a motor over here, it will act as a rectifier or as an inverter. So, then on this point the voltage will be switched voltage waveforms. So, I want to say that the voltage may be coming here and it may be switched voltage.

On this side, we have got sinusoidal voltage. So, we can have a filter. A simple LC filter may be there or C might not be put. This may not be present. It may be just connected using inductors or they may be LCL filter. I want to say here that you may have inductors over here as well, LCL filters also might be put. So, irrespective of that I want you to understand here,,that you are going to use inductors here.

These inductors are going to be different than DC to DC converter inductors because on one side it has switched voltage, another side it has a sinusoidal voltage and then the inductor is going to be seeing the difference of the two across it as the voltage. So, the current waveform through it is also going to be different. So, harmonic profile is going to be different and the ratings of these inductors are very different than DC to DC converter inductors.

So, then they also have to be designed accordingly. So, like this, you can explore. You will see that different power electronic circuits have requirements of different types of magnetics. So, they all have to be designed. Now, in this course, we will be discussing the basics of inductors in transformer designs. We will not go into too much of details in the design process, because it is not a dedicated course on magnetics design.

So, it is kind of beyond the scope of this course, to cover all the details and go into design of each and every type of inductor or transformer. So, I will give you the introduction, the fundamentals of those. Then if you need it or if you are interested to learn those things, you should be able to learn on your own.



So, now, let us look into the fundamentals. So, this kind of diagram is familiar with you. So, if you have conductors, which are carrying some current i_1, i_2, i_3 and then if you draw contour around it and if you trace it, then there is a relationship between this magnetic field intensity H and this contour length and also the total current that is inside that contour.

So, you might have already recalled by now, the law what I am talking about? It is the Ampere's law.

$$\oint_C H.dl = \iint_S J.ds = i_{enc}$$

which is the surface vector which is normal to the surface. Here, dS is the incremental surface vector and this is actually equal to i_{enc} and it is enclosed in the contour.

So, if these are all equal, i_1 equal to i_2, equal to i_3 and if you have N number of times, it goes through this path inside it. So, then we can write it

$$F = Hl = Ni$$

This is further written as the (MMF) magnetomotive force. This is magnetomotive force and this unit is given as *Aturns*. Also, we can write from here the magnetic field intensity

$$H = \frac{F}{l} = \frac{Ni}{l} \quad (A/m)$$

Then another important term is magnetic flux. So, this magnetic flux is denoted usually by ϕ,

$$\phi = \iint_S B.ds = B.S$$

What is *B*? *B* is the magnetic flux density. So, if *B* is uniform, then throughout the surface *S* we can also write it as *B.S*. So, in that case

$$B = \frac{\phi}{S}$$

If the angle is 0 between *B* and *S*, then we can write that *B* is equal to ϕ by S and this unit is given by *Tesla*. Now, there is a relationship between magnetic flux density and magnetic field intensity that is given by

$$B = \mu H$$

What is μ? μ is the permeability of the material. So, if you have a magnetic material, then that magnetic material's property is one of the properties is the permeability.

It indicates how easily the material can be magnetized. So, that is permeability and as high as it is, the better as a magnetic material it is going to be. It means that it is more magnetic than something whose μ value is less. μ of free space or you can say that this of air is denoted as μ_o and

$$\mu_0 = 4\pi \times 10^{-7}\, H/m$$

$$\mu = \mu_r \mu_0$$

Where, what is μ_r? μ_r is the relative permeability of that material. So, usually for different types of materials, it is the relative permeability which is normally given for that material instead of the actual value μ. So, relative permeability is the permeability, which is with respect to the air gap. When you multiply it with μ_0 then and μ_r, then you are going to get the actual permeability of that material.

Now, another rule which you should be remembering for this discussion is this right-hand rule. So, when your fingers are pointing in the direction of the magnetic flux density *B*, then your thumb point is in the direction of the current that is the right-hand rule. So, this you will have to apply. Further recall this term λ, which is the flux linkage.

$$\lambda = N\phi = N\,A_c\,B = N\,A_c\,\mu H$$

, where N is the number of turns.

Here what is *B*? It is the cross-sectional area and here I had given this as *S*. *S* could be replaced by A_c. So, *S* was a general notation. When we are specifically talking about magnetics design, there will be a core material and the cross-sectional area of that core is denoted as A_c. So, A_c is the cross-sectional area of the core. So, this can further be written as NA_c, and we substitute for B.

Then this can be then further written as

$$= N\,A_C\,\frac{\mu \mathrm{Ni}}{l_C}$$

which further could be written as

$$= \frac{\mu\,A_C\,N^2\mathrm{i}}{l_C}$$

So, here this term is called as the reluctance, R. So, then

$$\mathcal{R} = \frac{l_c}{\mu A_c}$$

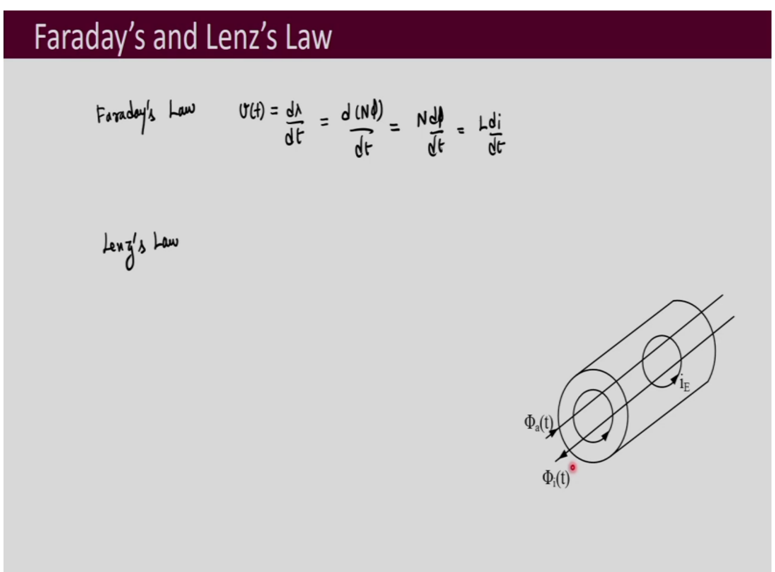
.So, flux linkage (λ) will be

$$= \frac{N^2\mathrm{i}}{\mathcal{R}}$$

You know that this is

$$= L\,i$$

. So, L is equal to N^2 by reluctance.



Now, another important law is Faraday's law. So, in Faraday's law you know that

$$v(t) = \frac{d\lambda}{dt} = \frac{d(N\phi)}{dt} = N\frac{d\phi}{dt}$$

So, if there is a time varying magnetic field flux $\phi(t)$ passing through closed stationary loop then it induces a voltage and that voltage is given in the equation.

Then we can then also write it as

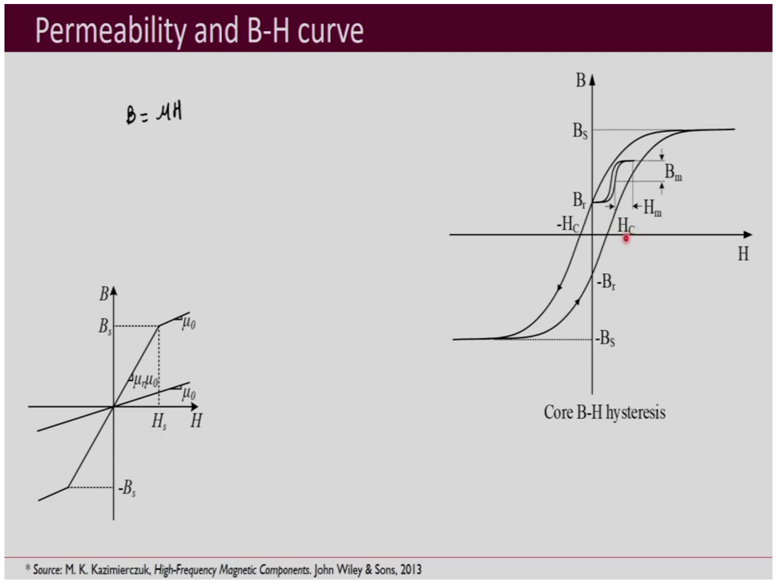
$$v(t) = \frac{d\lambda}{dt} = \frac{d(N\phi)}{dt} = N\frac{d\phi}{dt} = L\frac{di}{dt}$$

So, that is the Faraday's law. Then there is another important law which is Lenz's law and what does the Lenz's law say? Lenz's law say that if you have applied flux and that is going to induce voltage and correspondingly there will be a current because of it.

The direction of the current will be such that it produces a flux which opposes the change in the applied flux. So, if you have an applied flux like this ϕ in this direction, then a voltage will be induced in this conductor or in this surface. Then that will be induced such that, and the current direction will be like that it opposes this flux $\phi(t)$. So, the flux opposite to it will be in this direction.

You should remember that it opposes the change in flux. So, if the applied flux is going to increase then it would be such that it will be opposing the increase in the flux that means the flux obtained because of the induced current will be in opposite direction as that of the main flux. Whereas, if the main flux is decreasing, then it would try to oppose the decrease in flux that means, it will produce a flux, which is going to be in the same direction as the main flux.

So, this is very important, because usually people just remember that it opposes the main flux. It is not that it just opposes the main flux, it opposes the change in the main flux. If it is increasing, it will oppose the increase and so, it will be in the opposite direction. If the main flux is decreasing, it will oppose the decrease and then it will produce the flux which is in the same direction as the main flux.



Then further for the permeability this is relationship between *B* and *H* and it is a property of the material. So, do not think that this is a constant. This is not a constant. It varies depending on the values of *H*. So, to understand it better, let us look into this diagram. So, for free space, it is more like a constant, this μ_0 value.

Irrespective of *H*, the flux density in the free space will hold the linear relationship with *H*. Whereas for any other material and especially for magnetic materials, you can approximate it like this to a certain extent. To a certain value of *H*, it has a permeability which is higher than μ_0 and we are denoting as μ_r into μ_0.

So, this is the relationship that you are going to obtain. After that it tends to saturate and then it's almost like that or you can approximate it like that of the free space. So, that is also called as the saturation flux density, it sort of saturates. So, even if you increase the *H*, that means if you increase the magnetic field intensity, still magnetic flux density will not increase in that material.

So, an asymptotic line is shown here. So, then it leads to this, when you actually do it. We get the hysteresis curve, what is called as the *BH* curve. So there, you see that it is not only that *B* and *H* does not have a linear relationship, the relationship is nonlinear. How much *B* you get from *H*, you cannot always get it just by multiplying with the permeability.

It also depends on *H* which you are applying and depending on the *H*, the value of μ also changes. So, this is shown by this diagram. Further when you are applying AC that means you first applied magnetic field intensity in one direction, and then you kept on increasing it and then it reached to the close to the value of saturation, then you try to decrease the magnetic field intensity and then you apply in the opposite direction.

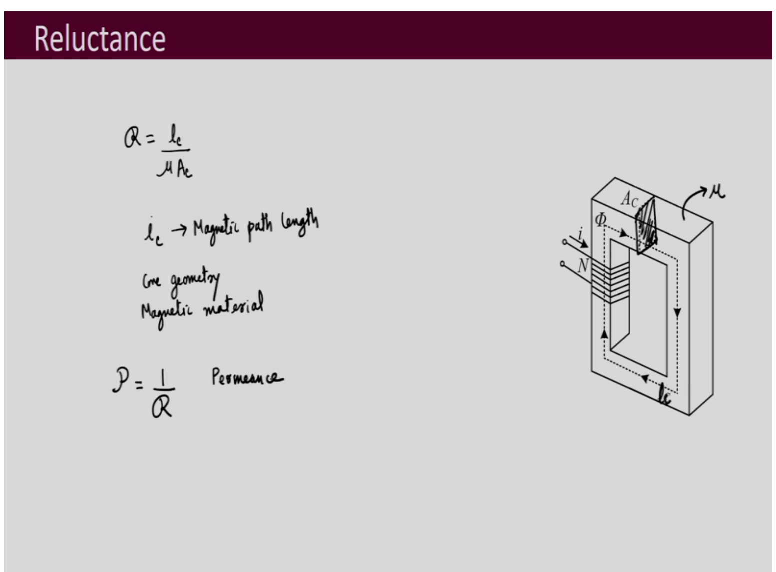
There also in the opposite direction you went down to the saturation levels and then you tried to reduce and then come back to 0. If this is in that process, or if we plot the values of *B* and *H* you will be getting this kind of a *BH* curve, and this happens because mostly our use of magnetics is in AC applications. So, here you observe that that when *H* is 0, at that time, there is a non-zero residual magnetic flux density which is present, and it is denoted here as minus B_r.

Then to make it 0 you need some magnetic field intensity, that is H_c, what is called as the coercive force. Then as we keep on increasing magnetic field intensity, *B* increases and finally it reaches to the saturation value. After that if we start decreasing the value of *H* then what will happen? It does not follow the same path, but it follows a different path, a slightly different path.

It comes back in this path and here you can see again that there is a residual flux. *H* is 0, but flux density is not 0. Then further to make it 0, you have to apply *H* in the opposite direction which is equal to $-H_c$. Then further if we increase the magnetic field intensity in the opposite direction, *B* increases in the opposite direction and it reaches to the saturation flux density in the opposite direction.

Then again if we increase *H* that means, we reduce it first in the opposite direction and then we increase it in the positive direction, then this is the path that it is going to trace. So, we observe that that while increasing of *H* and decreasing of *H*, it exactly does not follow the same path. It follows a slightly different path and there is a residual flux which is present when magnetic field intensity is 0.

Further if you want the magnetic flux density to be 0 in the material, then there will be H_c, a coercive force which is required. So, that is the *BH* curve. This is very important, because the shape of it is important in choosing the material that will be suitable for the particular application. Different types of materials have different types of *BH* curves. Permanent magnet materials have *BH* curves which are much wider. Whereas, which are ferromagnetic that means, which are used as electromagnet then they get demagnetized when you remove the electric current. Then those have got different types of *BH* curve as compared to permanent magnet materials.



Then let us come to reluctance. I already defined the reluctance,

$$\mathcal{R} = \frac{l_c}{\mu A_c}$$

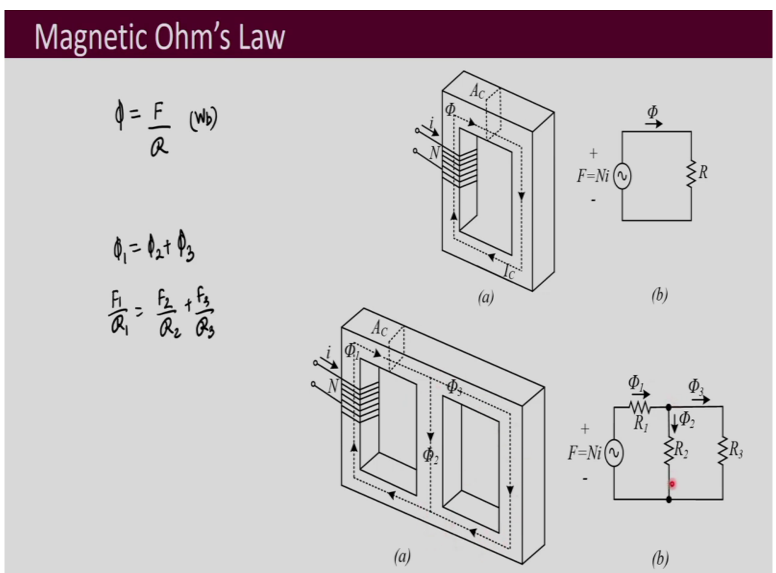
Now, let us understand in terms of this magnetic core. So, here we have got a magnetic core. A simple magnetic core diagram is shown. This is N number of turns which are wound on this limb of the core. Let us say a current *i* is passed through it, then it will establish flux ϕ.

It has to trace this entire path and that length is l_c. So, l_c is the magnetic path length. I have told A_c before also to make it clear with the use of diagram. So, this is cross-sectional area, A_c. So, you can see cross sectional area here, this is A_c. This whole length is l_c and μ is the permeability of the material which is used for making the magnetic core.

Now, what is the meaning of reluctance? Reluctance is the resistance, which the magnetic flux sees when it flows through a particular magnetic core. So, it is something, which depends on the geometry as well as on the magnetic material. So, in reluctance you should note about two things that it depends on core geometry and it also depends on the magnetic material. Now, there is another term which is associated with reluctance which is actually

$$P = \frac{1}{\mathcal{R}}$$

That is called as the permeance. Sometimes the manufacturers of these magnetic materials give you the permeance instead of the reluctance.



Now, this flux that is established in the magnetic core and this is given

$$\phi = \frac{F}{\mathcal{R}} \quad \text{(Wb)}$$

Its unit is in *Wb*. It can be drawn like this electrical equivalent circuit. So, this is called MMF, denoted by *F* which is equal to *Ni*. It is like a voltage source and flux is like the current and reluctance is like the resistance. So, you can draw an electrical equivalent circuit in this manner, for this core.

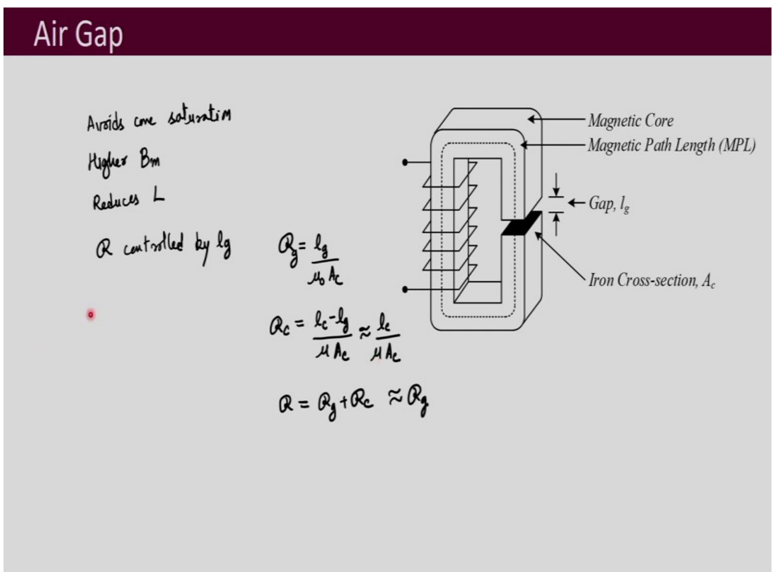
Then further if you have a core of this shape of this geometry and a flux of ϕ_1 is established here, then this will get divided into two parts which is ϕ_2 and ϕ_3. Then it can be written as that

$$\phi_1 = \phi_2 + \phi_3$$

Which is similar to KCL equation. Further you can write it as

$$\frac{F_1}{\mathcal{R}_1} = \frac{F_2}{\mathcal{R}_2} + \frac{F_3}{\mathcal{R}_3}$$

So, that is shown here, and this kind of equivalent electrical circuit can be drawn here. So, this is main MMF which is being applied. Then this is the reluctance R_1 over here of this path and you have reluctance R_2 of this path and then you have reluctance R_3 of this path and the corresponding fluxes are ϕ_2 and ϕ_3.



Further, let us talk about the importance of air gap. Now, air gap is something very much used for magnetic design in inductors and transformers in power electronics. Now, why air gap is introduced? In air gap it tends to increase the flux which can be passed through that particular core. So, what are the benefits and limitations of using air gap? It avoids core saturation.

So, it provides higher levels of flux density. So, higher flux density B_m will be denoted for the magnetic material M. B_m can be passed through this core, if you are using air gap. But it reduces the value of *l* to certain extent, and you can obtain the inductance from it. Also, one more thing is that that this reluctance of a core which has got an air gap is controlled by l_g. l_g is air gap length. So, this is the air gap length l_g. So, reluctance can be controlled by l_g.

That is another feature of it. Now, why it is important? Now, reluctance of the air gap

$$\mathcal{R}_g = \frac{l_g}{\mu_0 A_c}$$

That is the reluctance of air gap and reluctance of the rest of the magnetic material will be

$$\mathcal{R}_c = \frac{l_c - l_g}{\mu A_c}$$

So, l_c is the total length of this core. Now, this l_g is usually very small. So, this could be approximated as

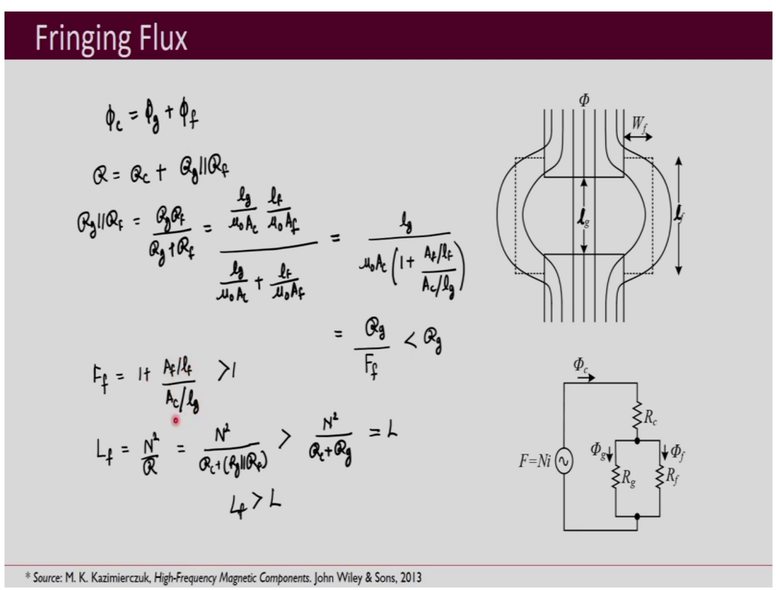
$$\mathcal{R}_c = \frac{l_c - l_g}{\mu A_c} \approx \frac{l_c}{\mu A_c}$$

You can see that that this reluctance of this is going to be much higher than that of the core.

So, reluctance will be given as

$$\mathcal{R} = \mathcal{R}_g + \mathcal{R}_c \approx \mathcal{R}_g$$

This can be directly then controlled by l_g because μ_0 does not vary, whereas μ does vary with the applied H. Another important feature is that you have better thermal stability. If you use air gap, the permeability is more stable because it is more driven by the air gaps permeability. So, reluctance is also stable and it is less affected by other variations that may be taking place in the circuit.



Now, because of this air gap another thing that happens is fringing effect. So, the flux flows through this magnetic core. But when you have an air gap, it is always not going to flow straight. But, there will be a fringing effect that is going to take place. That means, this air gap will not be straight, but will be fringing out from this area. So, this can then be represented by this equivalent circuit, where you have this reluctance of the core.

Then you have two parallel paths, one is of the air gap which is just concentrated on the core area, core's cross-sectional area and the other part which is bulging out which is reluctance of the fringing part, R_f and the flux will be

$$\phi_c = \phi_g + \phi_f$$

and the total reluctance will be

$$\mathcal{R} = \mathcal{R}_c + \mathcal{R}_g \parallel \mathcal{R}_f$$

So, now if we do R_g parallel to R_f, and if we try to find out so, that will be given as

$$\mathcal{R}_g \parallel \mathcal{R}_f = \frac{\mathcal{R}_g \mathcal{R}_f}{\mathcal{R}_g + \mathcal{R}_f} = \frac{\frac{l_g}{\mu_0 A_C}\frac{l_f}{\mu_0 A_f}}{\frac{l_g}{\mu_0 A_C} + \frac{l_f}{\mu_0 A_f}}$$

Now, what is this l_f? So, this is l_g and this is l_f. So, the cross-sectional area corresponding to this fringing is A_f and A_C is the cross sectional area of core. It will be

$$= \frac{l_g}{\mu_0 A_C \left(1 + \frac{A_f / l_f}{A_C / l_g}\right)}$$

If you solve it what you can write it as

$$= \frac{\mathcal{R}_g}{F_f} < \mathcal{R}_g$$

What is this factor F_f? It is the fringing factor,

$$F_f = 1 + \frac{A_f / l_f}{A_c / l_g} > 1$$

So, from there the inductance with fringing if we denote it as L_f that will be

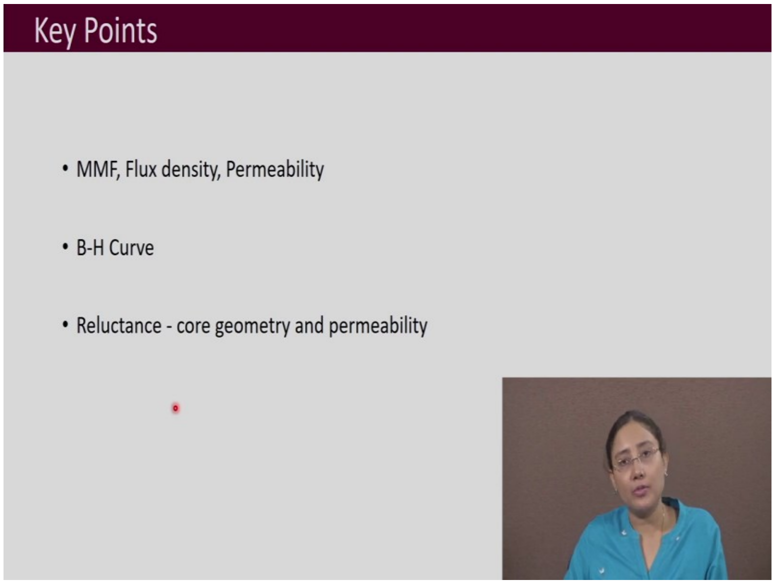
$$L_f = \frac{N^2}{\mathcal{R}} = \frac{N^2}{\mathcal{R}_c + (\mathcal{R}_g \| \mathcal{R}_f)} > \frac{N^2}{\mathcal{R}_c + \mathcal{R}_g} = L$$

This should be very clear from here that this is greater than 1. So, this is going to be less than R_g. So, since this is less than R_g, therefore this L_f is going to be greater when if we would not have taken account of the fringing effect, and this is equal to L. So,

$$L_f > L$$

that means L is that where no fringing effect has been considered.

So, if you want for more accurate design, you can take into account this fringing effect. Now, one more thing is that this is not something dependent on the material properties, but this fringing factor F_f is dependent on the core geometry. So, it is completely dependent on the core geometry. So, based on different core geometries, you can find out the fringing factor and you can use that in your design process for better designs.



So, the key points of this lecture are that we discussed magnetomotive force, flux density, field intensity, magnetic field intensity and then other important term is permeability. This is very important term, which denotes that how easily the material can be magnetized and to what extent the material can be magnetized. Then other important thing is *BH* curve, which you should note down that for different materials the *BH* curve appears to be very different. Then it is another important term, which is called reluctance and it is dependent on the core geometry and the magnetic material property. Thank you.