Design of Power Electronic Converters
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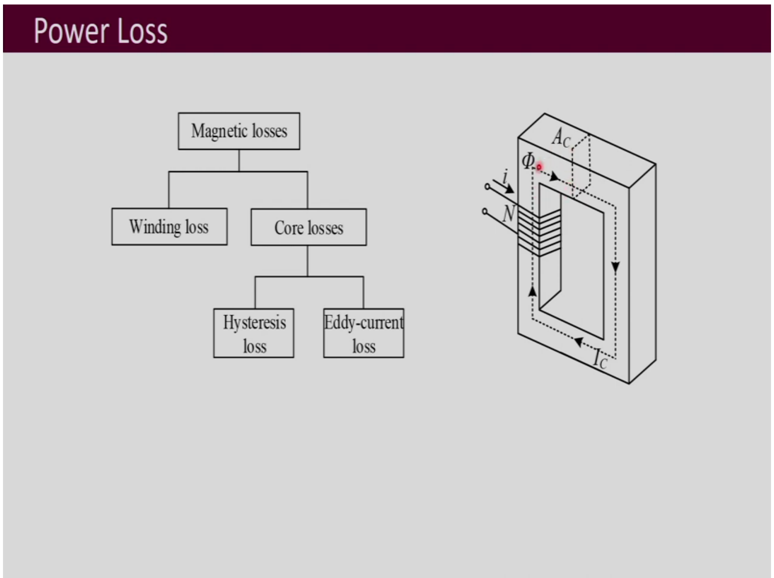
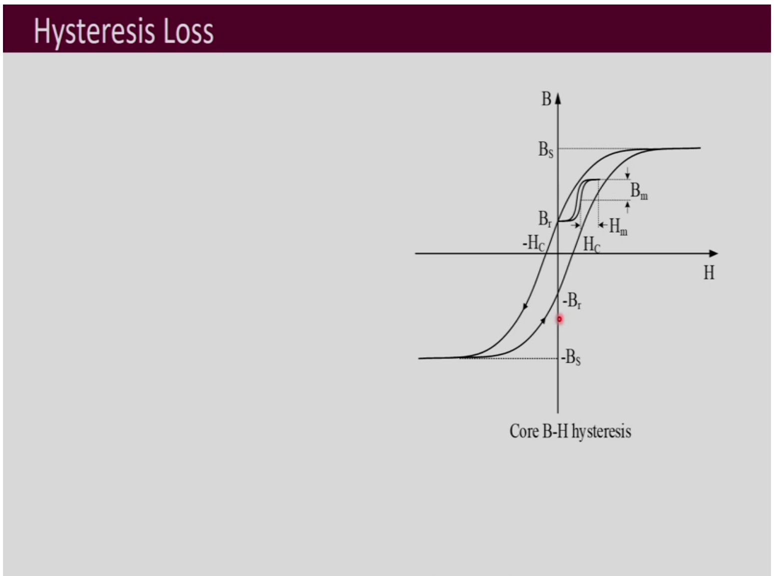
Lecture - 45
Magnetic Losses

Welcome to the course on Design of Power Electronic Converters. We had started with the module of magnetics design. So, let us continue on that module and let us look into the losses which take place in magnetics materials, inductors and transformers.



So, when we use magnetic cores and wind N number of turns on it, we have got windings and the current is flowing through it. So, there are two main types of losses that takes place, one is winding loss and second is core loss. This core loss that consists of two parts, one is hysteresis loss and another is eddy current loss.

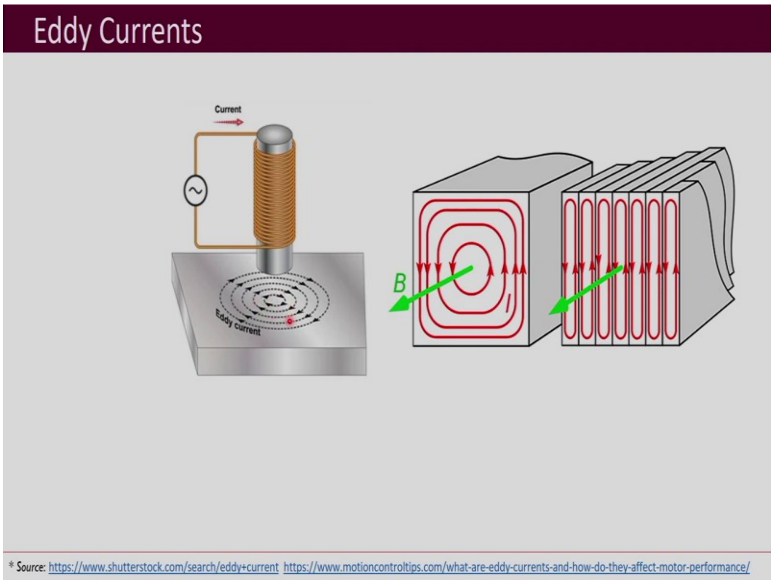


So, hysteresis loss is associated with this *BH* curve. Now, I have explained this *BH* curve before. So, as we pass AC through the core, and when magnetic field intensity increases in one direction then it decreases in that direction and then it goes in the opposite direction, builds up in the opposite direction. This again decreases in the opposite direction and this keeps on going, when we have an AC application.

Now, that AC need not be always sinusoidal, it may be switched voltage waveform when we have a PWM. So, depending on that, the loss may get affected. So, each time it traces this full path. Then the loss occurs during this tracing of this complete path that is the hysteresis loss. Now, for this hysteresis loss people have done analysis and they have come up with the equations to obtain this hysteresis loss.

So, in this course, we will not be going into it. But note that this hysteresis loss is something dependent on the material properties. It is less dependent on the geometry of the material. It is dependent on the material properties that means permeability, *BH* curve, and it also depends on the frequency of operation.

If you are operating at higher frequency, then the hysteresis losses are going to be higher. Because more number of times you trace this complete circle of a BH curve, every time corresponding to that there will be loss, which will be taking place. Then other type of important loss is eddy current loss.



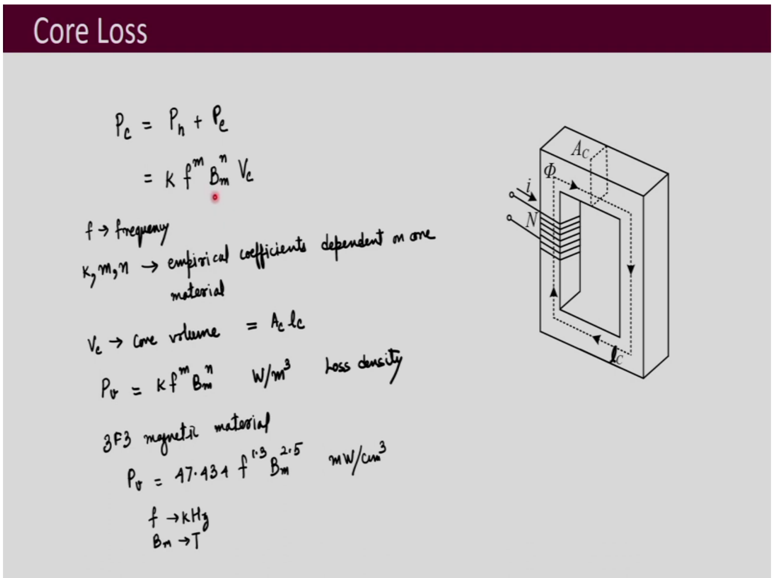
Now, what are eddy currents? You might have studied eddy currents before. So, when you have this kind of a coil which is producing a flux, and then if you have another surface or another conductor which is also seeing that flux then a current will be established in it. It is basically a voltage, which will be induced because this is a closed circuit and this is a conducting material. So, current can flow through it.

So, there will be currents induced which are called as the eddy currents and the flux produced by those eddy currents will be such that they oppose the change in the main flux. So, that is shown here. You can see that it is eddy current, and this will be shown here like circles. So, when we have a magnetic core, that has the main flux and this core material have certain levels of conductivities, that means it can conduct a current to some extent. So, that's why resistivity of the material of the magnetic material is very important. If it is very high then very small currents can flow through the material and it will have lesser eddy currents and so lesser eddy current losses will be there. But sometimes it may be having higher conductivities that means, more current can flow through that material.

So, more eddy currents can get induced and there will be corresponding i^2R losses through that magnetic core. So, if this is the block of the magnetic material and if it has this magnetic flux density B which is in this direction, accordingly there will be currents which will be established which are eddy currents.

These eddy currents will have corresponding i^2R losses depending on the resistivity of that material. So, to reduce it you might have already studied before that we use laminations. Because resistance depends on the cross-sectional area. If you have a higher bigger cross-sectional area of conducting material, then it will have a less resistance. But if you have lesser cross-sectional area of the conducting material, then the resistance will increase.

Hence the eddy currents should decrease and this is shown here. You can cut this into different sections or small layers. So, that is called the lamination. So, then also it will have any current, but the resistance will be higher and the currents should be lesser. So, eddy currents loss is basically i^2R loss.



So, together these are called as the core loss. So, this core loss P_c is the sum of hysteresis loss and the eddy current loss.

$$P_c = P_h + P_e$$
$$= k\, f^m\, B_m^n\, V_c$$

Here, B_m is the flux density through the material and f is the frequency. This is the frequency of operation and k, m and n, these are empirical coefficients. They are dependent on core material and V_c is the core volume. This core volume is given as

$$= A_c l_c$$

So,

$$P_v = k\, f^m\, B_m^n \qquad W/m^3$$

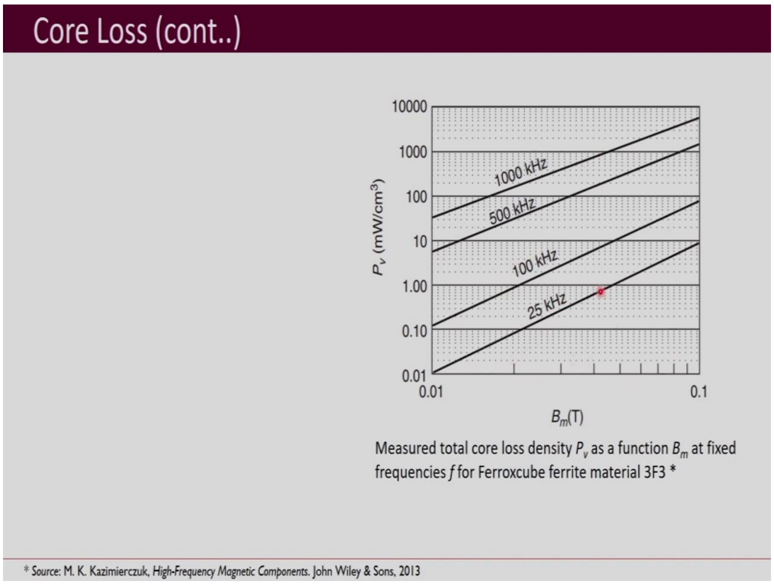
This is the loss density. The manufacturers of the cores usually give you the core density instead of the actual loss. When you have a particular material, then we test for the material and then from that we get to know the values of k, m and n. So, depending on the frequency and the flux density, we can obtain the core loss density.

Then depending on the core size we can obtain the total core loss that may be happening in that particular core. So, for example, there is a material which is known as the 3F3 magnetic material. It is the name of that material. So, for that

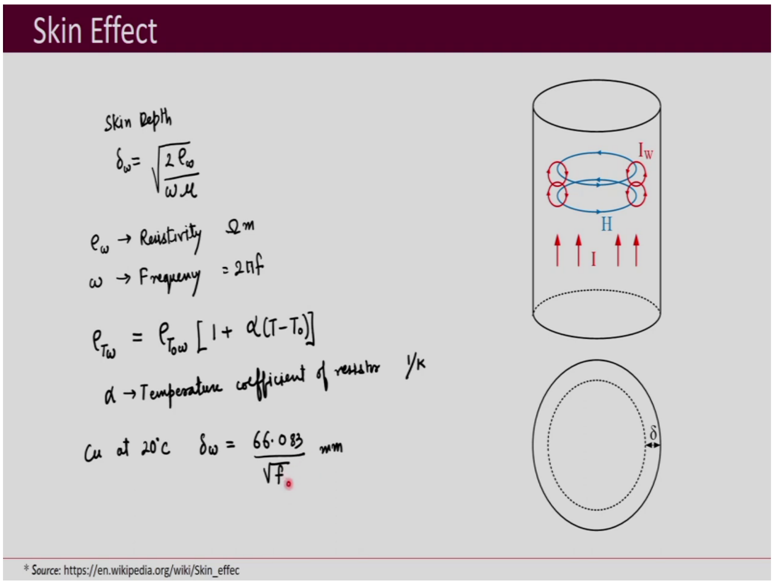
$$P_v = 47.434\, f^{1.3}\, B_m^{2.5} \qquad mW/cm^3$$

This f is in kHz here and this B_m is in T.

So, for that material I am showing you this example. So, this is the kind of relationship that you will be obtaining for P_v. Then depending on frequency and B_m you can obtain P_v and further you can also obtain the core volume and multiply with it and you will be obtaining the core loss. The core loss is preferably a loss thing. So, it should be as small as possible. So, you can clearly see that it depends on the volume of the material and also on the material that you choose.



So, this is a graph between B_m and P_v. So, we see here that as B_m increases for any particular frequency, then core loss is going to increase. If we go for higher frequencies, then also core loss is going to increase. It is kind of a linear rise that we can see here in this graph. This is over here is logarithmic. So, it is a linear in terms of logarithmic representation.



So, we saw what are the core losses? Core losses consist of the eddy current loss and hysteresis loss. Then with magnetics the other loss part is there, that is associated with the windings. So, let us look into some of the important terms in the windings. So, one effect is very important and it is called as the skin effect. Now, when we are passing DC through a conductor, then there is the flux, which is not changing. The established flux is not changing.

So, then there are no eddy currents because of it. So, there is no problem. But, if we have AC current flowing through the conductor, then because of it there will be this varying magnetic field which will be established. Since this is varying, that magnetic field will induce a certain currents on the conductor.

So, here it is shown that this is *I*, which is flowing in this and this is magnetic field intensity *H,* which is established and because of it there will be currents that are established in it. So, it is like small loops. So, these are eddy currents. So, this is the conductor. It is a solid conductor what is being shown here. Now, if you observe here these currents, then here this direction is opposite to the direction of the main current.

Whereas outside it is the same as the direction of the main current. So, these eddy currents are established such that inside the conductor the eddy currents direction is opposite to that of the main current. So, they kind of cancel each other. Whereas the current outside on this towards the surface are in the same direction as the main current and they aid to the main current.

So, the entire current then remains on the surface of the conductor, instead of passing through the entire cross-sectional area of the conductor. So, this is the cross-sectional area of the conductor, or circular cross-sectional area which is shown here. So, this current may just get limited to only certain depth of the conductors. That means it is limited to this cross sectional area instead of the entire area. So, this is the skin depth.

That is giving as this skin depth delta this is given by

$$\delta_\omega = \sqrt{\frac{2\rho_\omega}{\omega\mu}}$$

Where, ρ_w is the resistivity of the conductor. It's unit is in Ωm. ω is the frequency and this is equal to

$$= 2\pi f$$

μ is the permeability of the conductor. Now, this ρ_w is a function of the temperature. So, for a particular temperature T this will be given as

$$\rho_{T\omega} = \rho_{T_0\omega}[1 + \alpha(T - T_0)]$$

Where α is the temperature coefficient of resistance. It is given as *1/K*. So, if we know the resistivity at a particular temperature T_0, then we have to know this temperature coefficient α. We can find out the resistivity at a different temperature T. So, I want to say that this skin depth is also then dependent on temperature because this ρ_w is a function of temperature.

So, usually we use copper conductor. I mean many times we use copper conductors of course. There are other conductors also which are used. So, for copper at *20°C* this skin depth,

$$\delta_\omega = \frac{66.083}{\sqrt{f}} mm$$

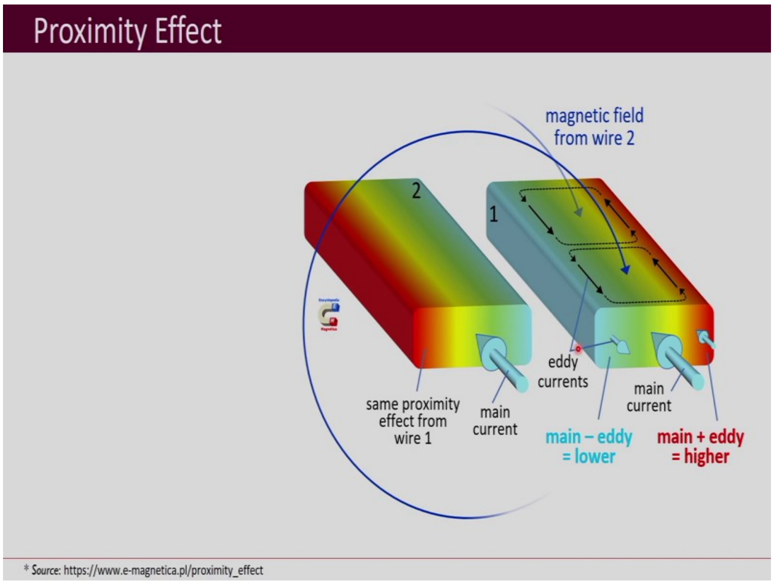
where f is the frequency and skin depth is in *mm*. So, if you substitute the values for copper in this equation, you will be getting at *20°C*. So, this much is the skin depth that you will be getting.

Skin depth for copper at T = 20 °C

Frequency f	Skin depth δ_{Cu}
60 Hz	8.53 mm
400 Hz	3.3 mm
1 kHz	2.53 mm
10 kHz	0.66 mm
20 kHz	0.467 mm
100 kHz	0.209 mm
1 MHz	0.066 mm
10 MHz	20.9 μm
100 MHz	66 μm
1 GHz	2.09 μm
2 GHz	1.478 μm
10 GHz	0.66 μm

* Source: M. K. Kazimierczuk, *High-Frequency Magnetic Components*. John Wiley & Sons, 2013

So, this is a table which shows how does it vary with the frequency at *20°C*. So, you can see here as the frequency increases, skin depth reduces. That means, the current is confined more to the surface as frequencies are going to increase. So, that obviously means that resistance of the conductor will increase as frequencies are going to increase. There is another effect which is called as the proximity effect.

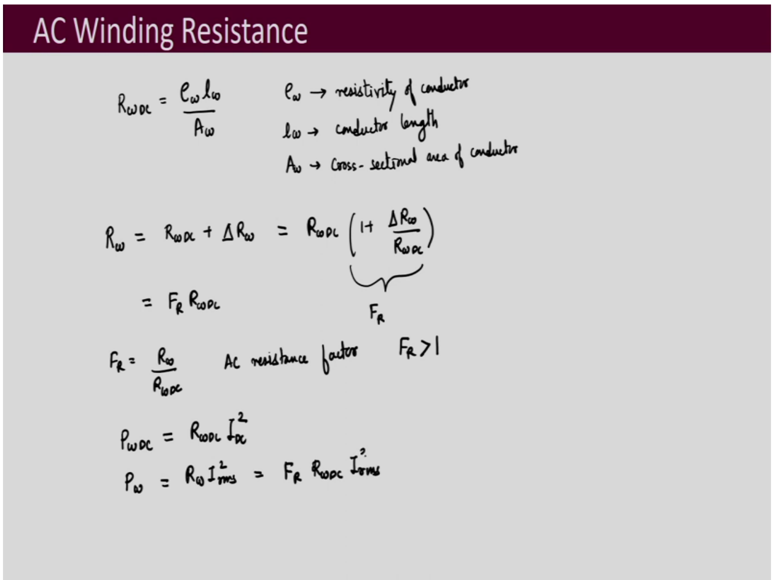


Now, we may be having situations where we may have conductors close to each other in proximity of each other, because you have several conductors in any converter. They may be obviously in close to each other. They are in proximity to each other. So, in that case, the effect that takes place is called as the proximity effect. So, this is shown here like this. So, this is wire 1 or the conductor 1 and this is the conductor 2.

So, there will be a magnetic field from wire 2. So, this is the current that is flowing in wire 2 and this is magnetic field which is established because of it. Then that magnetic field will also induce an eddy current in the conductor or in wire 1. So, this is the direction of that eddy current. This is the main current, that is flowing in wire 1. So, you see here that in this part the direction of the eddy current is such that it is opposite to the main current.

Whereas here, it is same direction as the main current. So, here on this side it is aiding the main current. Here you will have main plus eddy currents, which is higher than the main current and on this side you will have main current minus eddy current. So, it is lower than the main current. So, that is like an uneven distribution of current.

On one side you have higher current density, on the other side you have lesser current density and this is called as the proximity effect. An uneven densities of current in the conductor, that means one side you have higher current density, other side you have less current density. This also leads to increase of resistance of the conductor.



So, then we have DC resistors and let us denote it by

$$R_{\omega DC} = \frac{\rho_\omega l_\omega}{A_\omega}$$

where ρ_w is the conductor's resistivity, l_w is the conductors length and A_w is the cross sectional area of conductor. So, when we have AC winding resistance, it is denoted by R_w that will be equal to R_{wDC} plus additional resistance because of the skin effect and proximity effect. It is denoted as ΔR_w.

So, we can write it as

$$R_\omega = R_{\omega DC} + \Delta R_\omega = R_{\omega DC}\left(1 + \frac{\Delta R_\omega}{R_{\omega DC}}\right)$$

This is called as the AC resistance factor or DC to AC resistance ratio. We can denote it by F_R. So, then this will become

$$= F_R R_{\omega DC}$$

So, F_R is the ratio of AC resistance by DC resistance.

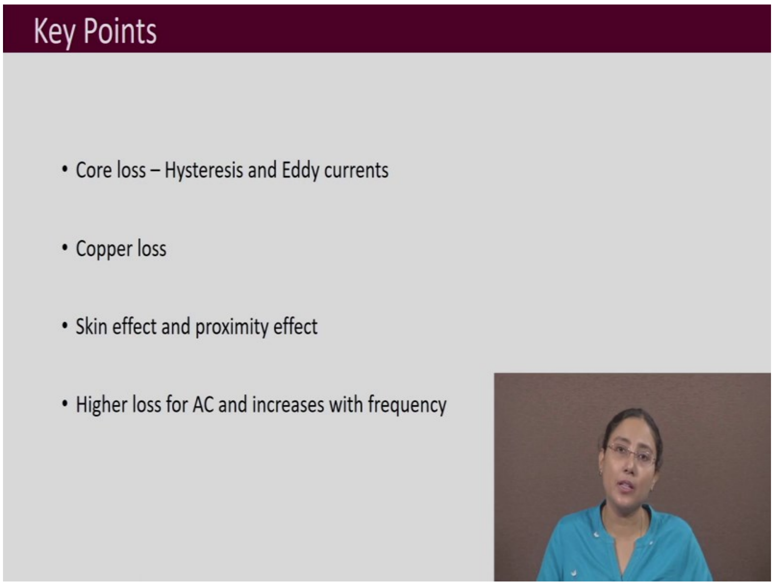
$$F_R = \frac{R_\omega}{R_{\omega DC}}$$

This is known as the AC resistance factor. This FR is going to be greater than 1 because AC resistance is higher than the DC resistance.

So, when we calculate copper loss-

$$P_{\omega DC} = R_{\omega DC}\, I_{DC}^2$$
$$P_\omega = R_\omega\, I_{rms}^2 = F_R\, R_{\omega DC}\, I_{rms}^2$$

So, when you obtain the copper loss of the inductor or transformer design, note that depending on frequency of the operation, resistance is going to be increased by that much factor and that you have to incorporate while calculating copper loss.



So, the key points of this lecture are that there are the inductors and transformers, there are two types of losses. One is copper loss or the winding loss and second is core loss. Core loss is in two parts, those are hysteresis loss and eddy current loss. Hysteresis loss depends on the magnetic materials and eddy current loss. This is similar to copper loss. Because of the induced eddy currents this loss takes place.

I told you the equation of core loss, which is an empirical equation. You can obtain the values of k, m and n from the manufacturers datasheet. Further for winding loss you should keep in mind, there is skin effect and proximity effect that takes place, because of AC operation and as the frequency increases those effects increases and AC resistance is higher than that of DC and it increases with increase in frequency. So, accordingly when you calculate the copper loss, which is the i^2R loss, you should use corresponding AC resistance for the particular frequency of operation. Thank you.