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Design of Power Electronics Converters
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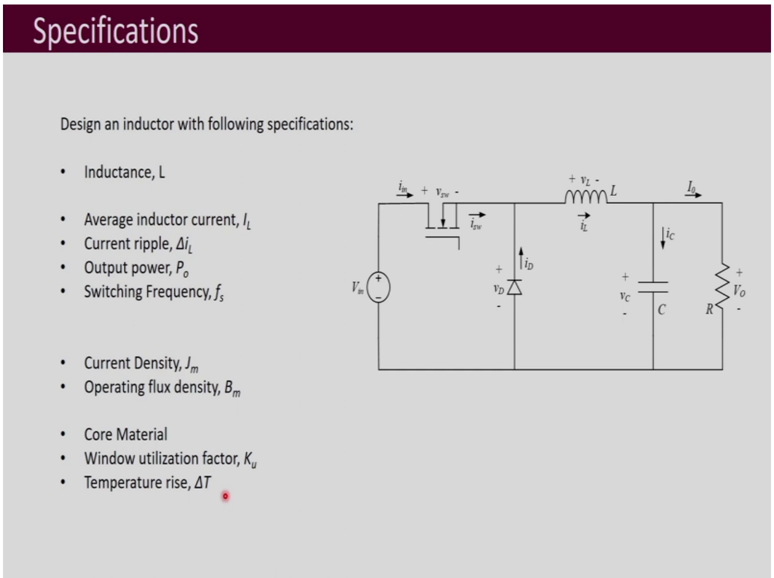
Module: Magnetics Design
Lecture 50
Inductor Design - II

Welcome to the course on Design of Power Electronic Converters. We had started discussing inductor design. So, let us continue on that and let us look into the different steps in designing inductors using area product method. So, before designing an inductor, you have to know for the application, and the power electronic circuit, where the inductor is going to be used.



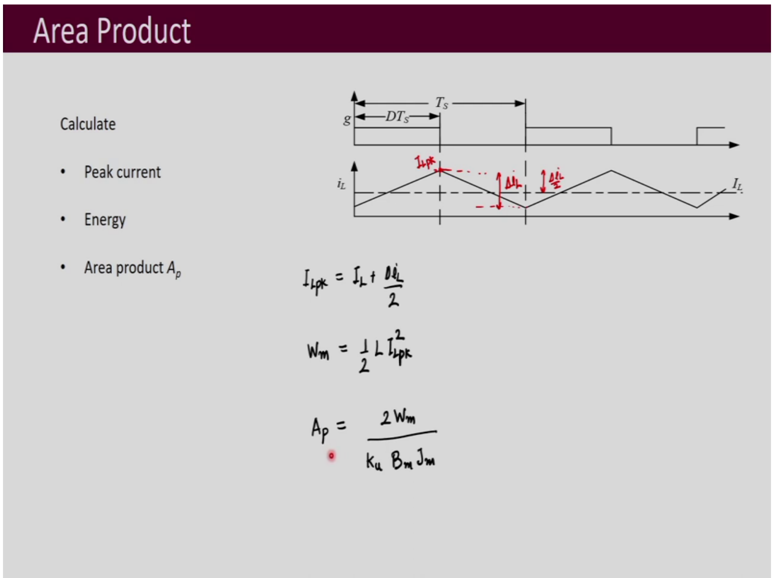
For example, if you have to design a buck converter, then you should be knowing the switching frequency of the buck converter, the output power (Po) for which the inductor is going to be used, and the average inductor current (I_L) that will be passing through the inductor and also the current ripple, Δi_L that has to pass through that inductor. Of course, you have to know the inductance value, L that has to be designed for. So, this may change depending on different applications.

Now, I am covering here for this example of buck converter. Then further you should choose some reasonable values of current density, J_m and the operating flux density, B_m. Now, we have an idea of the peak flux density for that particular inductor and the current density of the conductors that we will be using. Now, you will be knowing these by practice. Looking at previous designs you may be able to get these values, but most of these designs are standard design.

So, for many of them at various places in textbooks and in different places or in different application notes and design sheets you will be able to get these values. So, you have an assumption of the current density and the flux density for which you will be doing the design. Then further you should choose the core material. Now, we have discussed this again before.

Core material again is something which basically you decide mainly on the switching frequency and the saturation flux density and the power rating for which you are going to be designing.

Further the window utilization factor is again another important term which has to be assumed its value. Now, usually this K_u is between *0.4-0.5*. Sometimes you can take *0.4*. Sometimes we also take *0.5*, but these are the usual values which are chosen for the design of inductors. Temperature rise ΔT, now is depending on again the application where you are going to use the inductor, the ambient temperature, the maximum temperature rise that is allowed. You have a specification for the temperature rise ΔT. How much ΔT is allowed for that particular design?



So, to begin the design, the first step is that you will be calculating the peak current. Now, this is for you to recall. We have discussed this before, when we analyze this buck converter. So, if this is the gate pulse, then in this way in continuous conduction mode the inductor current rises and then it falls and the average of this current is this I_L. Further this part is ΔI_L and half of it is ΔI_L by 2. This part is the peak value which we will call it as I_{Lpk}. So, first you need to calculate the peak current.

So, peak current will be given by

$$I_{Lpk} = I_L + \frac{\Delta i_L}{2}$$

Then we calculate the energy, which is

$$W_m = \frac{1}{2} L\, I_{Lmax}^2$$

So, this is the maximum energy that is going to be stored in that inductor. Further we calculate the area product A_p. So,

$$A_p = \frac{2\, W_m}{K_u\, B_m\, J_m}$$

Now, if you wish then you can call it as B_{pk} also. Earlier I had written this B_{pk}, the peak flux density or the operating flux density. Whatever is the flux density that you have assumed initially for the design, you will be substituting this here. J_m is again the current density which you have assumed or the specification is given for the design. What will be substituting here?

K_u again is assumed as 0.4 or 0.5. You will be substituting that and so, in this way you will be getting the area product A_p for the design.

Core Selection

Part No.	W_{tcu} gm	W_{tfe}	MLT cm	MPL cm	W_a/A_c	A_c cm^2	W_a cm^2	A_p cm^4	K_g cm^5	A_t cm^2	*AL mH/IK
EE-187	6.8	4.4	3.8	4.01	2.239	0.226	0.506	0.114	0.0027	14.4	501
EE-2425	13.9	9.5	4.9	4.85	2.010	0.395	0.794	0.314	0.0101	23.5	768
EE-375	36.4	33.0	6.6	6.94	1.769	0.870	1.539	1.339	0.0706	45.3	1160
EE- 21	47.3	57.0	8.1	7.7.5	1.103	1.490	1.643	2.448	0.1801	60.9	1696
EE-625	64.4	103.0	9.4	8.90	0.825	2.340	1.930	4.516	0.4497	81.8	2330
EE-75	111.1	179.0	11.2	10.70	0.831	3.370	2.799	9.433	1.1353	118.0	3519

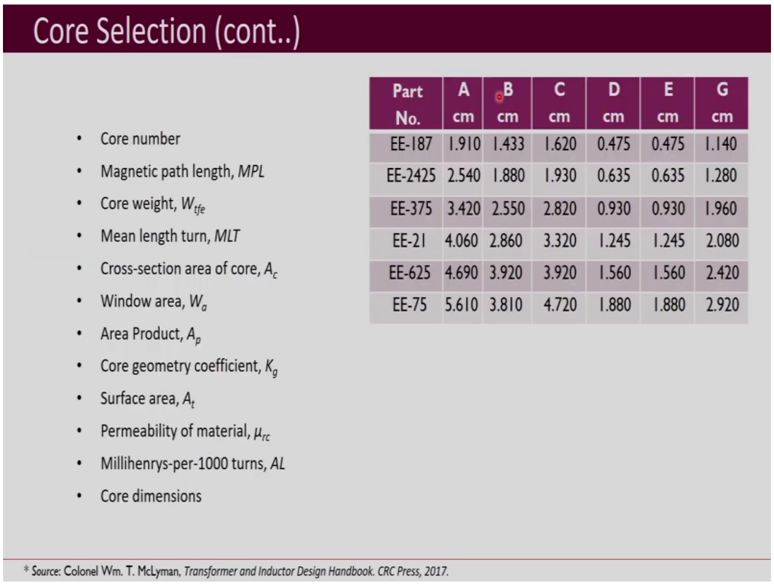
* This AL value has been normalized for a permeability of IK. For a close approximation of AL for other values of permeability, multiply this AL value by the new permeability in kilo-perm. If the new permeability is 2500, then use 2.5.

* Source: Colonel Wm. T. McLyman, *Transformer and Inductor Design Handbook. CRC Press, 2017.*

Further based on the area product A_p you go to the datasheet of different manufacturers of cores and you just check these area product values, and you just find out a core which is having an area product close to that value of A_p that you have calculated and slightly higher than that. Mostly the A_p core is chosen higher than your calculation.

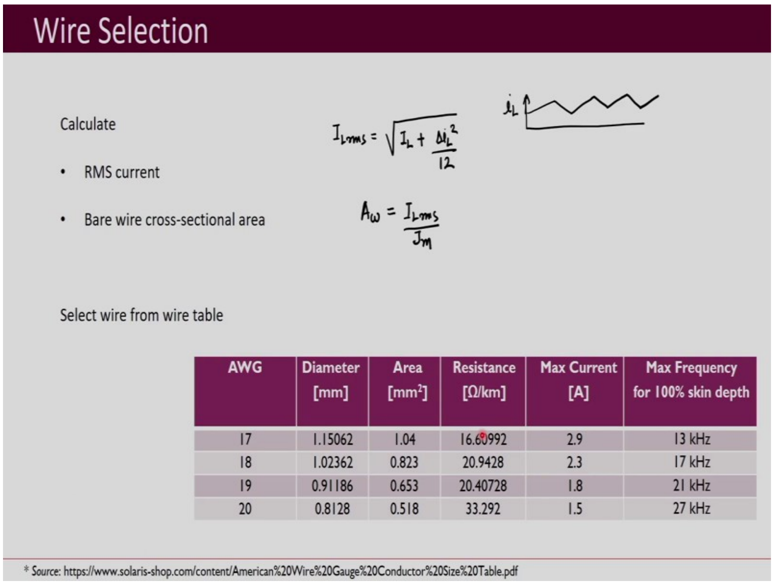
So, next step that is the core selection. So, once you select the core based on this A_p, area product, you will be obtaining different values. That means you will be obtaining the mean length turn for that core, the magnetic path length and the window area (W_a), the cross sectional area of the core (A_c) and then the surface area (A_t) and several other values will be provided by the datasheet.

So, you should also note down this part number of the core that you have selected, and you can say that it is usually a core number. So, we have discussed this before. I had shown you this. So, based on area product A_p you choose the core and based on it you will be getting different values associated with core selection.



Further, you will be also noting down the core dimension. I had shown this before. This is just for you to recall. We have discussed this in previous lecture. So, different core dimensions also will be obtained by you. So, that means once you have selected the core, a particular core number or the part number then you can note down values of various terms, like that magnetic path length, core weight, mean length turn, cross sectional area of the core, window area, area product, core geometric co-efficient.

Now, this is another term which is actually another method of inductor design. But, we are not discussing here right now. So, these are surface area (A_t), permeability of that material and then *mH/IK* and of course the core dimensions. So, based on the core selection, you get a lot of values which you can further use for the design purpose.



Then next step is the wire selection. Once you have selected the core, next thing is that you select the wire and you have to wind it. Basically that magnetic design is actually just like that. So, for that you should be calculating the RMS current. Now, RMS current I_{Lrms}, which is for here in this buck converter, that is written as

$$I_{Lrms} = \sqrt{I_L + \frac{\Delta i_L^2}{12}}$$

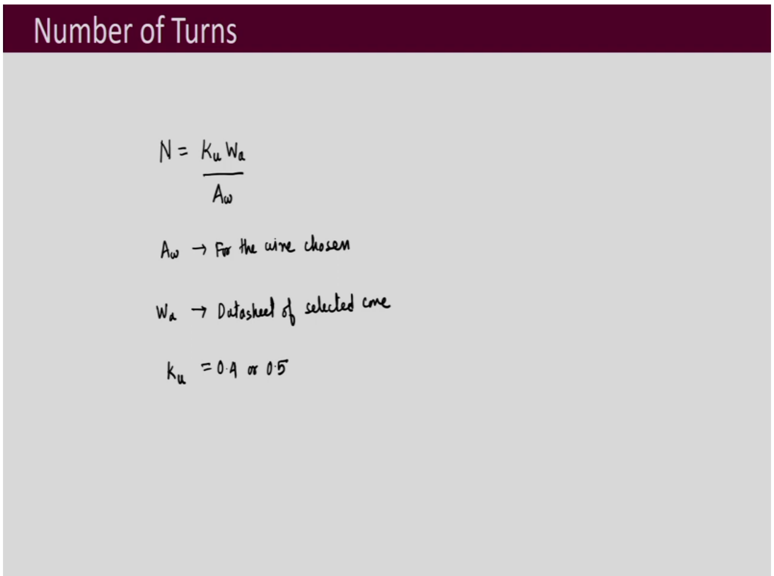
For the nature of the current we have chosen I_{Lrms} here or we are discussing this nature of the current I_L, for that I_{Lrms} is given by this. Now, you must be knowing how to calculate RMS current.

So, based on shape of the waveform of inductor current, you can use the proper method of calculating RMS current. But, here I have just written expression for this type of current. So, do not use it for everywhere blindly. Note that this is for this nature of the current. If it is not so, nature of the kind is different. You have to calculate or you have to find out RMS value of inductor current. Further you can calculate the cross sectional area (A_w), this will be given by

$$A_w = \frac{I_{Lrms}}{J_m}$$

So, J_m is the current density and I_{Lrms} is RMS value of current. So, divided by J_m gives you the cross sectional area of the wire. So, once you have calculated the cross sectional area of the conductor that you need, again you go to the wire tables and then you compare different cross sectional areas of conductors like this kind of tables which I had shown you before. So, we can see here this cross sectional area are given.

So, then you find out the gauge of the wire which is going to be suitable based on A_w calculation. So, this is different gauge wires of AWG number which you can find out from there. So, once you chose this you will be also be knowing the resistance per *km* per unit distance. So, you will be obtaining resistance per unit distance. So, that is another value that you will be knowing once you choose the wire.

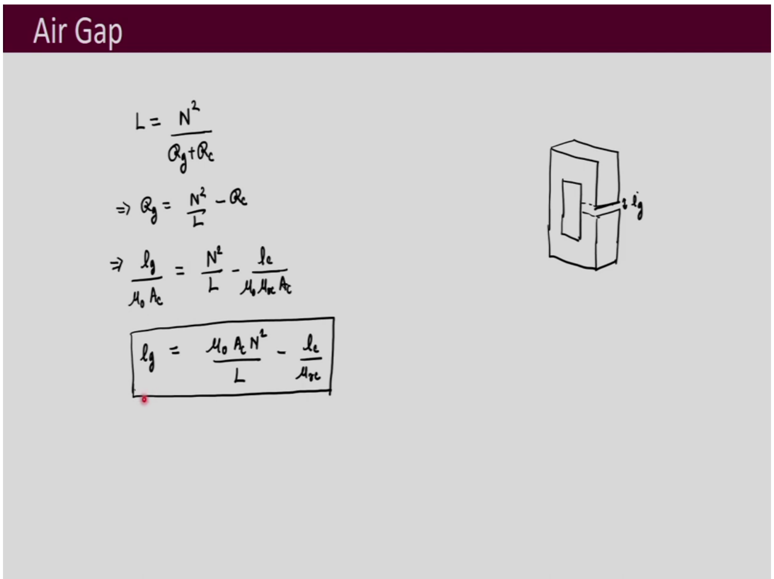


So, using that then you can calculate the number of turns, that will be

$$N = \frac{K_u W_a}{A_w}$$

Now, this A_w is going to be for the wire that you have chosen. Do not substitute A_w for the one that you have calculated because once you have chosen a particular wire, then that cross sectional area may be a little higher than your calculated A_w.

So, you should be careful for this and you will be obtaining W_a from the datasheet of the core that you have selected and K_u is a value which you have chosen. So, you can take it like *0.4* or *0.5*. So, this will be giving you the number of turns N that are possible to fit in that window of the core which you have selected.



Next, you will have to decide the air gap length which you may be requiring for the inductor. I had shown also this you before. Like this you may be having some air gap in the inductor design. So, this is that air gap (l_g) length which you have to find out for inductor design. So, for that recall the inductance L this is written as

$$L = \frac{N^2}{\mathcal{R}_g + \mathcal{R}_c}$$

So, from there we can write that reluctance of air gap is equal

$$\Rightarrow \mathcal{R}_g = \frac{N^2}{L} - \mathcal{R}_c$$

Further you know that this can be written as the reluctance is given as

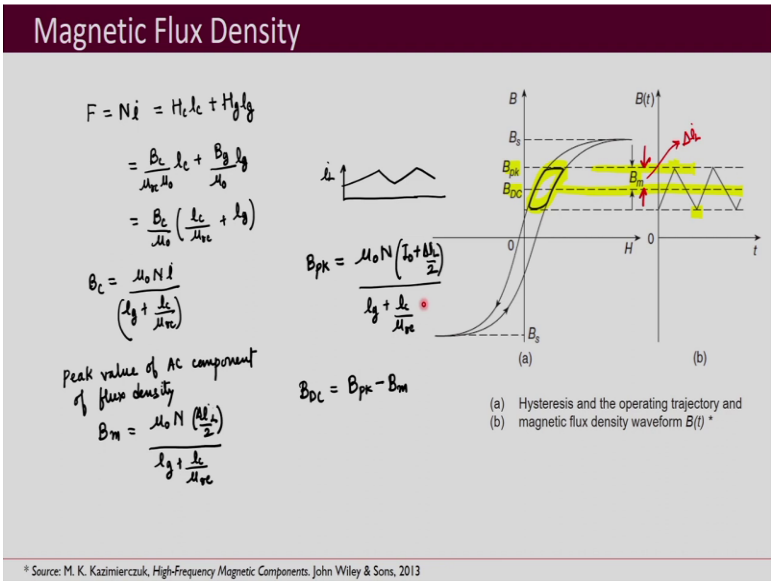
$$\Rightarrow \frac{l_g}{\mu_0 A_c} = \frac{N^2}{L} - \frac{l_c}{\mu_0 \mu_{rc} A_c}$$

Here, we are ignoring the fringing effect. From here, you obtain this air gap length.

$$l_g = \frac{\mu_0 A_c N^2}{L} - \frac{l_c}{\mu_{rc}}$$

This is the equation that you can use for calculation of air gap. Now, here μ_o is the permeability of a free space. That value is known. The cross sectional area of the core, which is A_c that you have chosen.

So, you will be getting it from the datasheet of the manufacturer. We have already calculated N value number of turns, and you are designing L. So, you know the value of L. l_c is the magnetic path length. So, once you have chosen the core, you know the magnetic path length and μ_{rc} is the permeability of the core that you have selected and that also is a value which you will be obtaining in the datasheet of the core. So, using all these values, then you can find out the air gap length that is required for the inductor.



Now, up till here the design of the inductor is completed. You have chosen the wire, you have chosen the core where you have also found out the air gap length that is required. So, the number of turns are also calculated. So, this is the inductor design. Whatever you need is basically completed.

Now, the next part is just that you may do some calculations and you may verify that the temperature rise and the core losses, all those are within limits using those specifications, what you initially had started with. So, for that first let us find out magnetic flux density and that is going to be there for particular values of inductor currents that will be flowing.

Now, this is the BH curve or hysteresis curve. Now, we are discussing here for buck converter. So, for buck converter, you know the nature of the current. So, nature of the current is like this. So, it is a DC current which has got a ripple in it. So, then in that case, for this BH curve, this part will be traced only. It is not going to be tracing the negative part and it will have some average value. So, that average value is going to be B_{DC}. So, this is BH curve. We can also draw a flux density versus time curve and that will be something similar to the inductor current waveform.

So, here first it increases and it reaches to the peak value that is B_{pk} and then it comes down and it reduces to the lower value and the average of this is B_{DC} and in between these, this part is B_m, the AC part of it or the part which is associated with Δi_L. So, you know that MMF is equal to

$$F = Ni = H_c l_c + H_g l_g$$

where H_c is the magnetic field intensity in the core and l_c is the magnetic path length, H_g is the magnetic field intensity in the air gap and l_g is the air gap length.

So, if you want to express it in terms of B, so we can write it as

$$= \frac{B_c}{\mu_{rc}\,\mu_0} l_c + \frac{B_g}{\mu_0} l_g$$

Now, if we neglect the fringing effect, these B_c and B_g are same. So,

$$= \frac{B_c}{\mu_0}\left(\frac{l_c}{\mu_{rc}} + l_g\right)$$

This is going to be equal to MMF. So, from here we can write

$$B_c = \frac{\mu_0 N i}{\left(l_g + \frac{l_c}{\mu_{rc}}\right)}$$

So, this is a general expression for magnetic flux density. So, then the peak value of AC component of flux density that will be the written as

$$B_m = \frac{\mu_0 N\left(\frac{\Delta i_L}{2}\right)}{l_g + \frac{l_c}{\mu_{rc}}}$$

This is the AC component and the peak value of the flux density

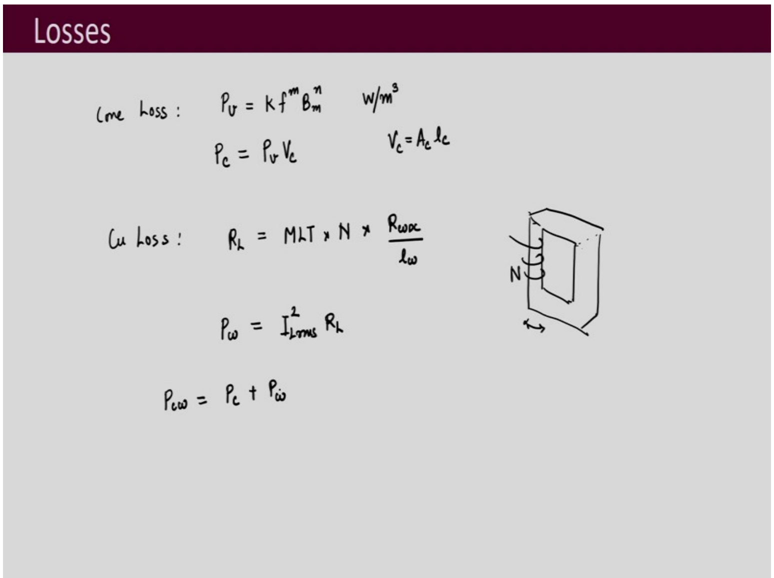
$$B_{pk} = \frac{\mu_0 N\left(I_0 + \frac{\Delta i_L}{2}\right)}{l_g + \frac{l_c}{\mu_{rc}}}$$

and this flux has a DC component B_{DC},

$$B_{DC} = B_{pk} - B_m$$

So, then you can use these expressions to calculate peak value of flux density and peak value of the AC component.

Now, this peak value of AC component is responsible for core loss because this is the part which is going to be traced again and again as a loop and this tracing of this loop is going to lead to the core losses. So, this will be using for computation of the core loss and this B_{pk} is also important because whether it is going towards saturation or not it should be less than B_s, the chosen saturation flux density of the core material.



So, next you need to calculate the losses. So, first you can calculate the core loss. So, for core loss first you can compute the core loss density. So, the core loss density

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

Where B_m is the AC part of the flux density. So, you will be substituting here the AC power of the flux density. So, then you have to multiply it with the volume to get the total core loss which will be

$$P_c = P_v V_c$$

What is V_c? Vc is equal to be

$$V_c = A_c l_c$$

Next you can calculate the copper loss. So, to calculate the copper loss first you have to calculate the resistance of the conductor. So, that will be

$$R_L = MLT \times N \times \frac{R_{WDC}}{l_w}$$

Now if it is given as per *km* in the datasheet of the conductor, then l_w will be *1000 m* and you may be using this R_{WDC} value as the DC resistance. We have discussed before that AC resistance is higher than the DC resistance.

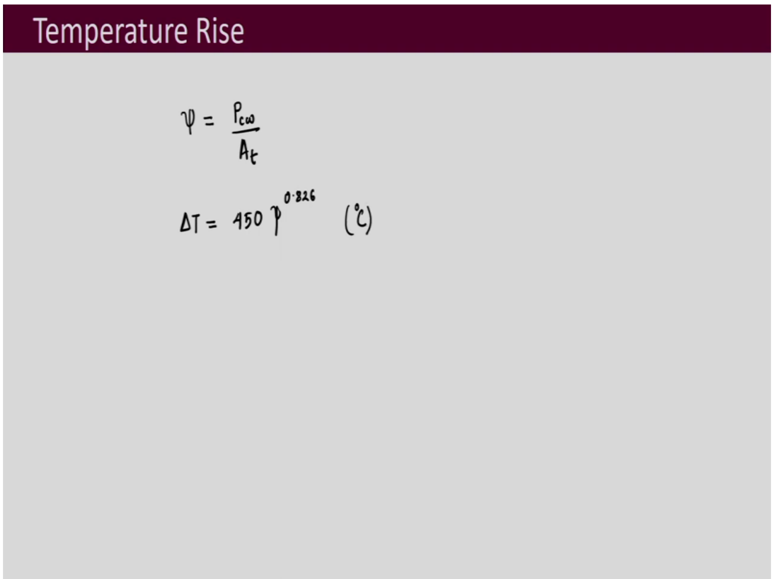
For simplicity we are not calculating here the AC resistance. But, if you want a more accurate calculation, you can look for the AC resistance for the switching frequency, what you will be using. So, why are we talking about this mean length turn? So, if this is the core and you are going to wind it, this mean length turn multiplied by the number of turns N will be providing the total length of the winding or total length of the conductor.

So, that total length multiplied by the resistance per unit distance will be giving you the total resistance of the conductor. So, once you have obtained that, you just calculate the copper loss

$$P_w = I_{Lrms}^2\, R_L$$

and finally, the total power loss

$$P_{cw} = P_c + P_w$$



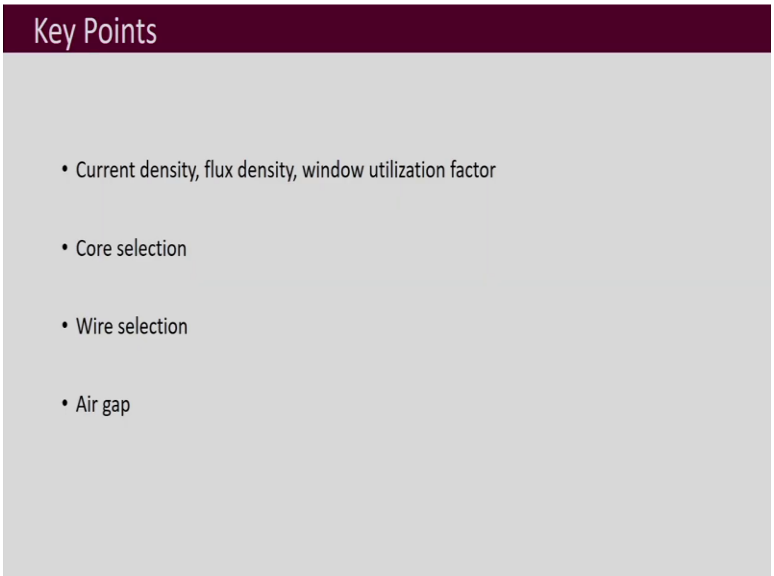
Next you calculate the temperature rise. For that you first calculate the surface power loss density which is given by

$$\psi = \frac{P_{cw}}{A_t}$$

A_t is the total surface area and we have seen that you will be obtaining this from the datasheet of the core. You can compute P_{cw} and so, the temperature rise

$$\Delta T = 450\ \psi^{0.362} \quad °C$$

So, from there once you compute the temperature rise, you will know whether the temperature rises are within limits or not.



So, to summarize the steps of the inductor design, you have initially some specifications and you have to assume the current density and also the flux density for the design and you will be also assuming the window utilization factor. You will be obtaining other specification for the power electronic circuit, for which you will be designed. Then further the first step will be that area product method. Then, you will be calculating area product (A_p) and you will be selecting the core based on it.

Once you have selected the core, then you will be selecting the wire, and its gauge. Further you will be also designing the number of turns N and then you can compute the air gap length if anything is required for the inductor. Apart from that, you can do some verification, calculations, also like computing the flux densities and then the core losses and the temperature rise. The temperature rise has to verify, because whatever you have designed whether it is going to meet the specifications or not. Thank you.