Power Electronics and Distributed Generation
Prof. Vinod John
Department of Electrical Engineering
Indian Institute of Science, Bangalore

Module - 03
Lecture - 35
AC Inductor Design and Need for LCL filter

Welcome to class 35 in topics in power electronics and distributed generation. We have been discussing the need for inductive filter in a power converter.

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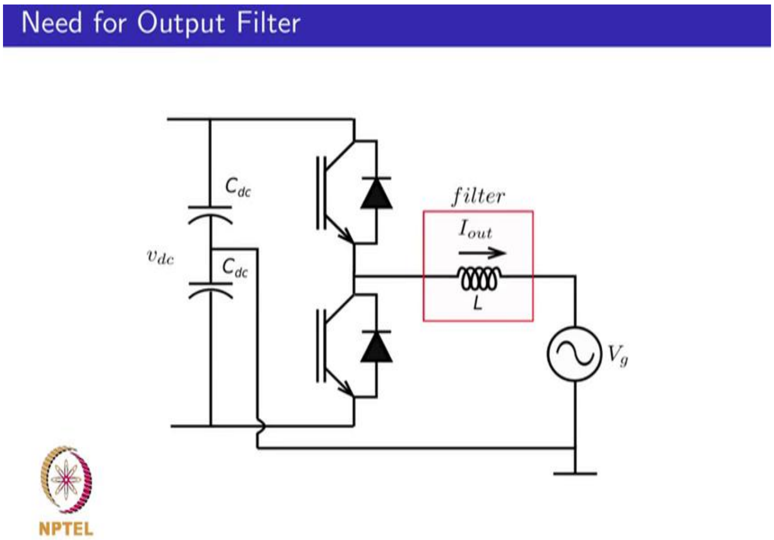

There is a primary requirement of minimizing the amount of ripple that can be sent out into the grid and there are standards such as I E E E 5 1992 and I E E E 1547 which provide recommendations on the level of harmonics that can be injected into the grid. We can also then last time we saw how we can derive an expression for the peak to peak ripple current.

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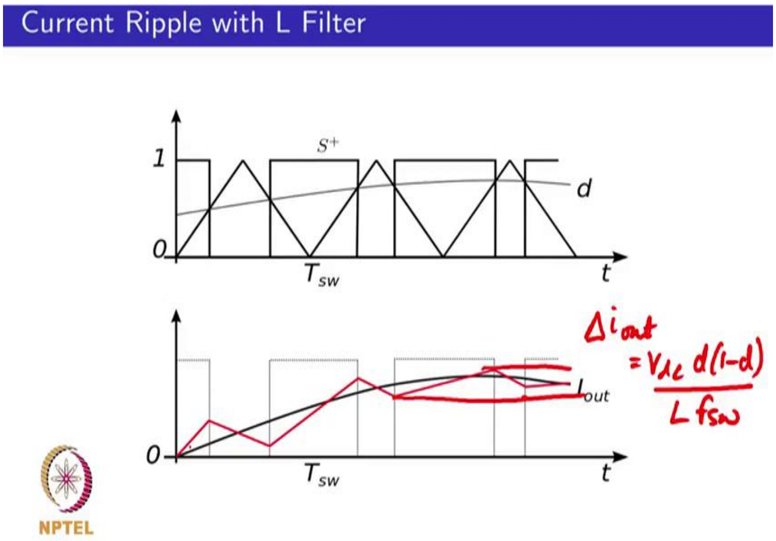

So, you are talking about the ripple current, so to calculate a ripple current we assume that things are in a cautious steady states so the valley returns back to the same point at the from one cycle to the next cycle. So, with such an assumption what one could then write an expression for delta I out as V d c into d into 1 minus d divided by L f s w. And, we saw how one could then derive relationship between the d c bus voltage, the filter inductor switching frequency and the level of ripple in the output.

The actual decide output is this black line over here which correspond to the fundamental frequency which might be 50 Hertz when you are trying to inject real power into the grid. So, say at unity power factor it would be in phase with the voltage ideally you would not like to have any ripple at all.

But, in a practical power converter you will always end up having some amount of ripple also we saw that there are a number of constraints in the selection of the filter. You have constraints related to ripple attenuation you have constraints on how much surge current can actually go into the flow into the power converter.

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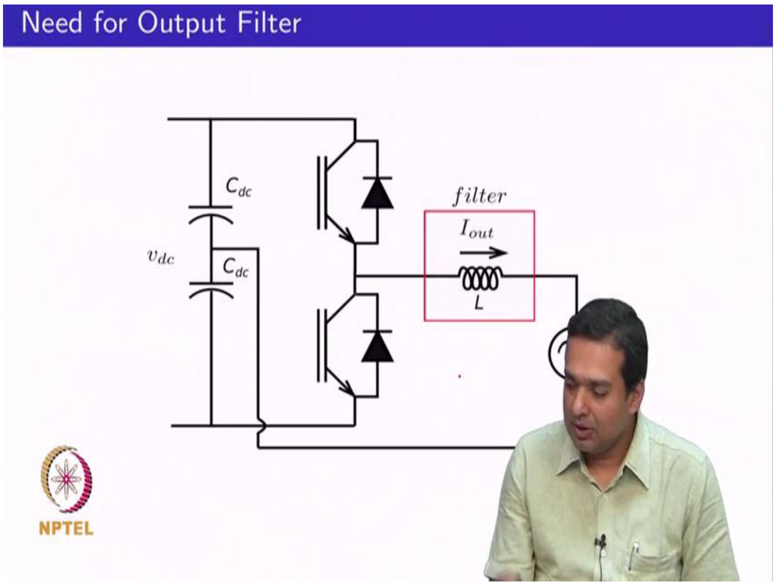

So, if you have say transients in the grid you have also constraints on how much fundamental voltage drop would occur across a filter inductor and which can then influence the amount of d c bus voltage that is required you also have. So, if you have a large value of L the dynamic response to the system would be relatively sluggish, so we know that if the inductor is too large.

So, you might need lot of turns and you have lot of winding resistance, so there is power loss factors also that one need to consider. But, often in many designs a starting point might be to consider a inductor which is having a value of point 1 per unit or 10 percent.

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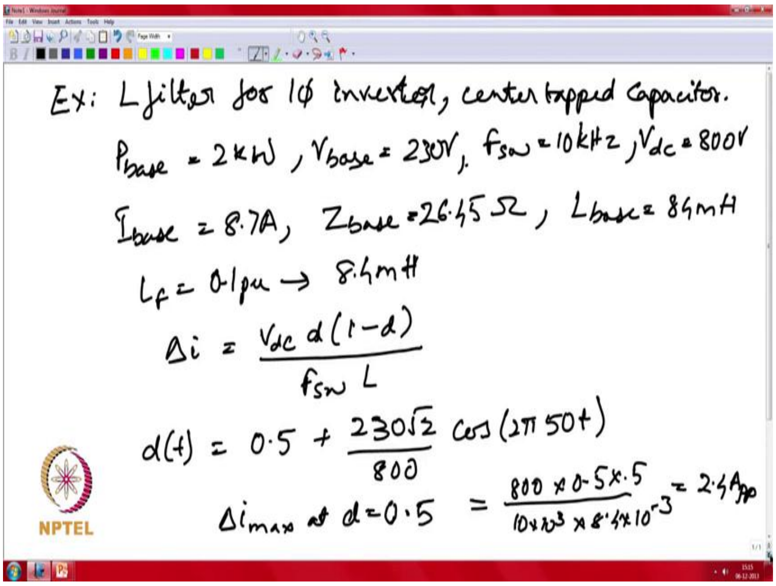

So, we will look at an example where one is looking at say filter inductor design, so we are looking at a single phase inverter the same center tapped capacitor topology and we have let us say consider a 2 Kilo Watt single phase inverter. So, P base is 2 Kilo Watts, V base is 230 volts 10 Kilo Hertz switching frequency d c bus voltage is say 800 volts and you could then derive expression. So, your expression for I base is 8.7 Amps, Z base is V base by I base, so this is 26.45 ohms and L base is Z base divided by 2 pi, 2 pi omega.

So, that would be 84 milli Henry, so when one talks about a 10 percent inductance you are talking about L f to be 0.1 per unit. So, this would correspond to 8.4 milli Henry, so one could then look at what is the peak to peak ripple we have delta I is given by V d c into d into 1 minus d divided by f s w times L.

We know our duty cycle the d is a function of time because you are trying to synthesis a sine wave is 0.5 plus 230 root 2 divided by 800 cos 2 pi 50 t. So, we saw that the maximum ripple occurs when d has a value of point five so and that is has a value of 800, so this is 2.4 amps peak to peak.

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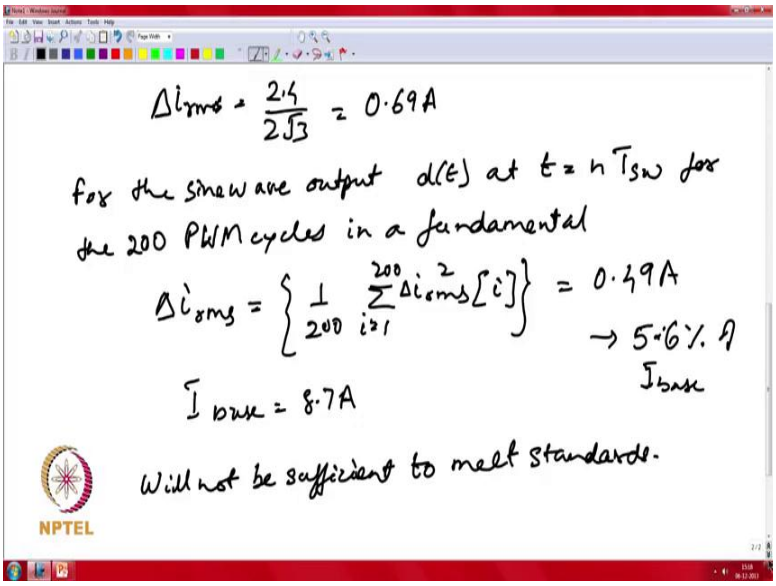

So, if you are assuming the ripple to be a triangular in shape than your r m s your ripple r m s current is 2.4 divided by 2 divided by root 3. So, this is about 0.69 amps we know that as the inverter is going to be operating all along the duty cycle you may not have the worst case ripple at all the points along the sine wave. So, you could actually look at each point of time each switching often each switching frequency cycle and look at then the overall r m s currents.

So, for the sine wave at t is equal to n times T s w for the 200 points P W M cycle that excess in a fundamental because your switching frequency is 10 Kilo Hertz. Again, assuming static ripple at each of those duty cycles you can then evaluate delta I r m s over the fundamental to be 1 by 200. So, you evaluate the values at each ripple each duty cycle level on the P W M cycle and you can calculate the r m s value this turns out to be about 0.49 amps. If you look at a 0.49 amps are I base was 8.7 amps, so we are talking about the ripple which is about 5.6 percent, so this might be a reasonable filter for some applications.

But, in many situations that especially for the standards you are talking about not 5.6 percent, but 0.3 percent, so you need much stiffer much tighter filtering. So, to meet the standard requirements you need lot tighter filtering, so the options that one could consider are one could think about say increasing the value of inductance.

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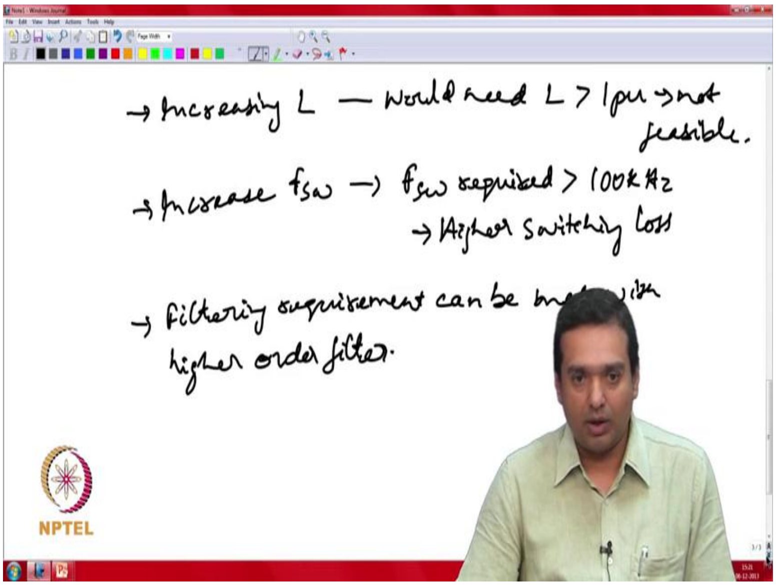

But, we saw that our inductance is already at 10 percent and the reduction in ripple requirement is going from 5.6 percent to 0.3 percent more than a factor of 10. So, your inductance required will be more than 1 per unit, so which will not be a feasible design, not feasible with a realistic value of d c bus voltage.

So, the other thing that one could do is we could say for example we are switching at a 10 Kilo Hertz you could increase your switching frequency to reduce the ripple, so the required f s w would be greater than 100 Kilo Hertz. Again, in especially at a high power application where you talking about Kilo watts of power this may not be a feasible as your switching losses would go up quite drastically. So, the third option is instead of considering just a inductive filter we can consider using a higher order filter and this is something that will discuss later.

So, before we consider a higher order filter we will take a brief look at, what it takes to actually build a inductive filter itself. So, the things that you need to start considering a filter design is to know what is the value of L that is required in this place.

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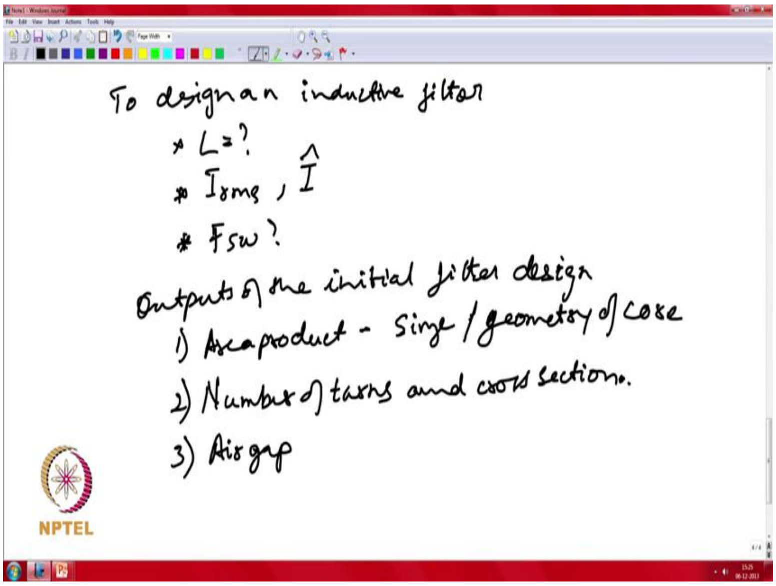

So, one is what is the value of L the second requirement is what is your r m s current flowing through the filter and what is your peak current flowing through the filter. So, another important consideration is what your switching frequency is because the switching frequency has implications on the type of core material that you would select for the inductor. So, the outputs of the, of the initial design of the filter would be one is the area product and this is something that you may be familiar from basic power electronic course.

This gives a feeling of the core size the geometry if given the geometry of the core, so it gives a feel for, so then it is essentially the product of the core area and the wind over area. The second item that one could be interested in is the number of turns and essentially its cross section, so this is important for deciding on the type of winding. Now, that you would be using a third important factor is the air gap how much air gap one would select there are other important considerations which one would, one would be able to finalize at a later stage of a design.

So, for example one would need to know of what is the winding insulation and how the bobbins are done. But, how the, how the inductor is actually assembled together and how it is mounted how it is cooled etcetera, but these three would be initial starting points in your design.

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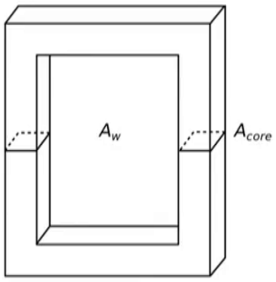
Area Product Sizing

$$L\hat{i} = N\hat{\phi}$$

$$A_w A_{core} = \frac{V_{rms}\hat{i}}{k_w k_f \hat{B} J_{rms}\omega_o}$$



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So, when you are considering the area product of the filter you are essentially looking in this particular case you have to looking at double c course. So, there is a upper c and a lower c structure and essentially you are looking at the product of A, the window area and the core area cross sectional area of the core. So, to derive the expression for the area product you start off with the definition of inductance which is the flux linkage is proportional is given by L i in the inductor.

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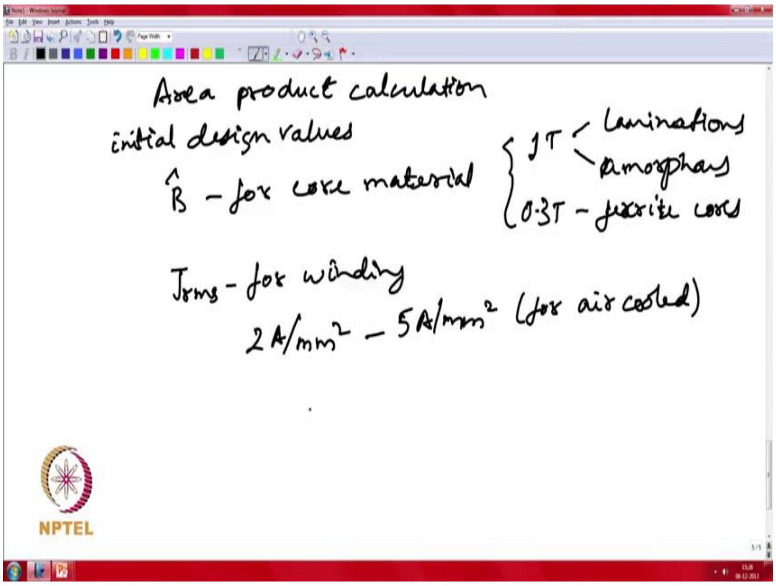

So, if you start off with that you also need to know some initial design values one is what is the maximum flux density for your core material one might have start off with reference designs is of the order of say 1 Tesla. So, for say steel laminations or for amorphous course or even powdered course or you might have the 0.3 or lower than that, for ferrite course another quantity which would be a initial assumption is your current density.

But, that you assume for your winding and commonly values of 2 amperes per milli meter square to 5 amperes per milli meter square is used for air cooled inductors. These are essentially initial values this can be altered later on based on a thermal evaluation of the inductor, for example if the power dissipation in the core is excessive one can actually reduce your peak flux density. Similarly, if your temperature of the winding is excessive found to be excessive the end of your design then you could actually reduce your current density.

In the other side, if you find that your temperature of your winding is too cool this means that you are not fully utilizing the winding. Then you could increase the current density and get a cheaper inductor design which reduces the amount of winding copper that would be used.

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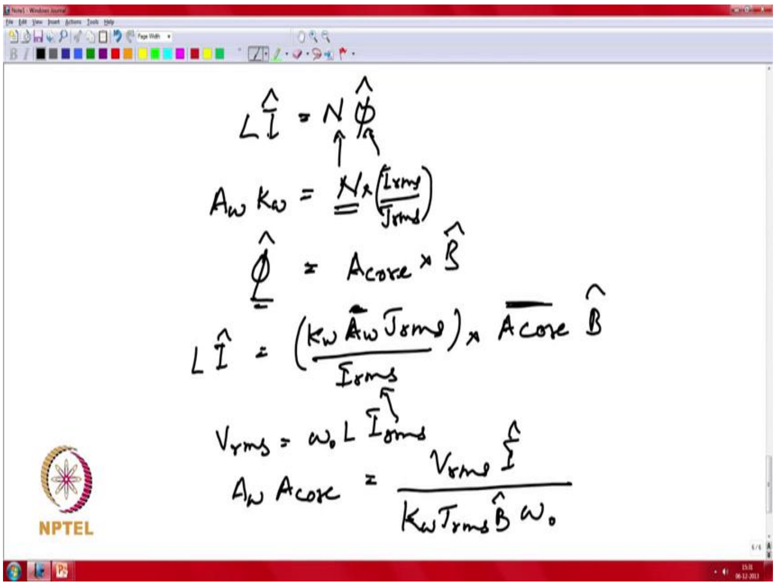

So, we know that the starting point for the design is essentially your L I hat is n times your peak flux flowing through the core. So, you could also then make use of these two expressions, one is about the winding window area. So, the winding window area A w times your utilization of your window the K w is a window utilization factor is essentially the number of terms times the cross sectional area of each turn. So, the cross sectional area of each turn is essentially I r m s divided by J r m s, so with this you can actually get n which you can plug in to this particular equation.

Similarly, you know that your peak flux is given by the area of the core times your peak flux density, so with this you can calculate your peak flux and plug it into that expression. So, you get L times I hat is you also make use of the fact that your r m s voltage across the inductor V r m s is omega naught L times I r m s at the fundamental frequency.

So, you can then make use of this particular relationship to plug in for your I r m s in this particular expression, so one would get then collecting your A w and area of the core together. So, c collecting these two terms together you get, so you can see that the product of the geometric dimensions of the core is related to V r m s times I peak gives an indication of the V a rating of the inductor.

So, the parameters at the bottom are things like K w which is the field factor, how good you are at winding the preparing the winding G r m s is indicative of how much current.

So, you can actually inject into the winding and the b the peak flux density is indicative of the material property of the core and the frequency fundamental frequency at which you are using the filter. So, the next step in the design is to actually look at what the number of turns and the air gap is and to do that one would find it useful to actually look at the concept of magnetic equivalent circuit.

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Magnetic Equivalent Circuit

Magnetic circuit	Electrical model	Units
Magneto-motive force (Ni)	voltage source	Ampere Turns
Flux (ϕ)	current	Weber
Reluctance ($\Re$)	resistance	H^{-1}

$$\Re = \frac{l}{\mu A}$$

$$MMF = \Re\phi$$

$$V = RI$$

So, in a in a magnetic structure one looks at the what is driving the flux which is essentially your M M F the magneto motive force that can be modeled as a voltage source in a equivalent electrical circuit. Now, this could be in ampere turns what flows as a result of applying a M M F is flux and that can be considered as a current in your electrical model of the circuit and the units would be Weber.

So, what prevents, what links the proportionality between the M M F and the flux is essentially the reluctance and the reluctance would correspond to resistance in a electrical circuit model has a unit of Henry inverse 1 by the inductive term. Also, the reluctance of the magnetic path has a formula which has a similar nature to linking resistive resistance of a, of a conductor to the length area and conductivity.

In this particular case, you are relating reluctance to length area and the permeability of the material of that is present. So, the mu might correspond to the iron or it might correspond to air in case you are having an air gap in the inductor, so you could actually derive reluctances for different parts of your magnetic circuit. So, what then corresponds to ohms law for a magnetic equivalent circuit is similar to V is equal to R I, so you have M M F is equal to reluctance times your flux which is flowing through the magnetic circuit.

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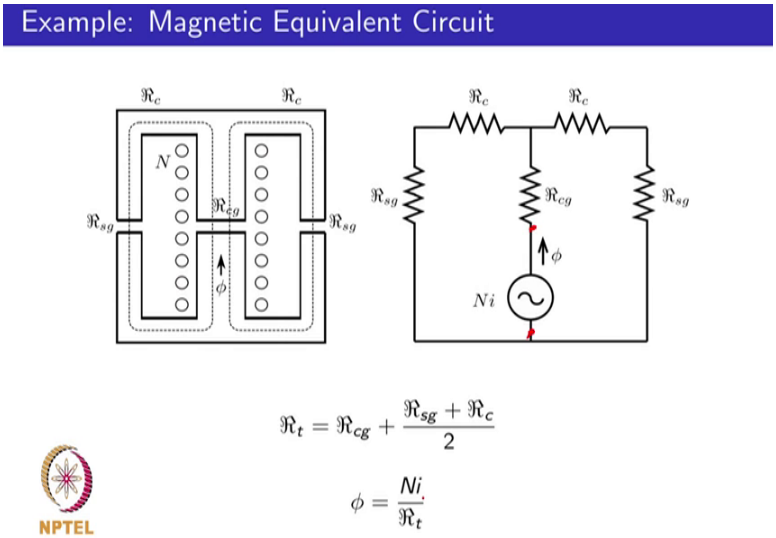

So, we will look at an example of a magnetic equivalent circuit for say doubly core, so here you have 2 e shaped cores and separated by an air gap. So, there is the wider air gap at the center and narrower air gap on the sides and you have n turns which correspond to the coil which would be injecting the coil, across which would be measuring your inductance. And the flux flowing through this particular circuit would then be what you are trying to relate through the reluctance terms to your M M F which is N i. So, an equivalent circuit for this particular structure could be you would have a reluctance of the air gap the side air gap would have a different reluctance than the center air gap will take the two side air gaps to be similar.

The center air gap to be R c g and the balance of path through the core we can take it as R c, in fact in the, in a circuit such as this the air gap reluctance might dominate. So, because your relative permeability of the core might be many or orders of magnitude rather than that of air in which case it would be dominated by R of the side gap and R of the center gap.

So, in this simple electrical circuit one can then get the effective resistance seen between these two terminals. It is essentially R of the center gap plus R of the side gap plus R of the core divided by 2 and then you can actually re relate your flux with the M M F, so flux is equal to N i by R t.

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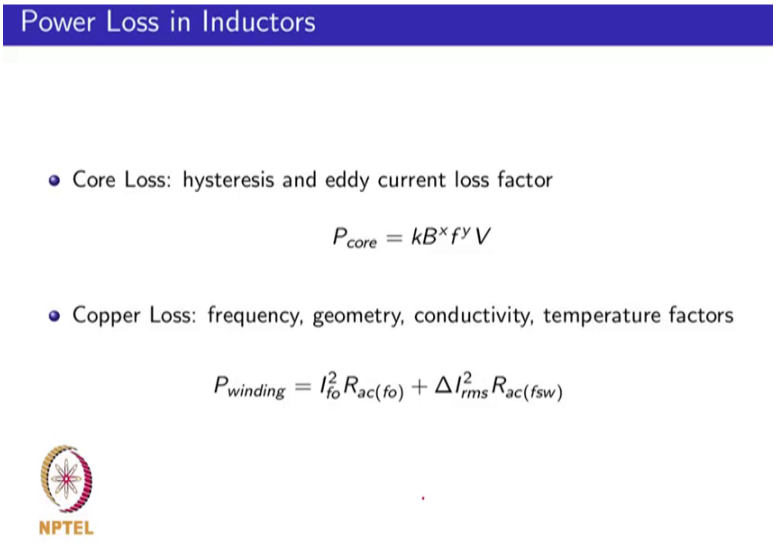

So, the next step in the design of the inductor is actually to figure out what is the number of turns and the air gap and this can be obtained from the following expressions.

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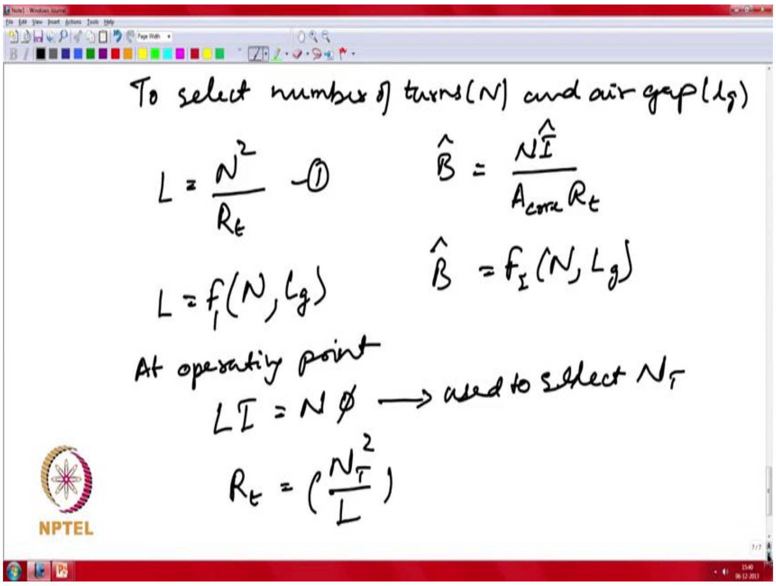

So, L g we have L is N square divided by your total reluctance, so this could be structure 1 equation 1. So, you have another equation which is essentially your flux is equal to N I p B B peak is N times I peak divided by area of the core times divided by reluctance total. So, we can see that essentially in this particular expression you can think of it as L being a function of the number of turns. Now, we saw in the previous slide the total reluctance is actually a function of the reluctance of the air gaps, so it is actually function of the air gap.

Similarly, you have your B max to be another function of your number of turns and your air gap, so essentially what one would like in your design is that you meet the constraints on what is your designed value of L. So, that is to be met and what is the peak value of a flux that is to be T hat the inductor is to operate at you have two equations and two unknowns. So, it can be solved and you can actually find what the value of N is and what the air gap is you also have at the particular operating point at the selected value of L N L G your L and your B B peak you have you have L I is N times flux.

So, we know that the flux is essentially B B hat times the area of the core and L is the designed L that we want to use and we know what the peak flux is that correspond to this peak value of current corresponding to the operation at the peak flux. So, that can be used to select your number of turns, so your number of turns and then you could actually make you once you know the number of turns then you can go back to expression 1.

So, you have your reluctance total is your selected number of turns square divided by land you can then figure out what is the air gap that would correspond to this particular decide reluctance. So, when you consider the air gap you should also in include factor such as fringing that would occur in the air gap to come up with a number that meets these particular constraints.

So, once you have the air gap and the L you can go back and verify these air gaps and the number of turns meets both these equations and verifies that both these constraints are being satisfied. Also, one can actually see if you at a particular number of turns that you have selected may be if you are you have some tolerance around your actual operating flux. So, you can see whether you could adjust the amount of air gap that you have to actually see whether you could reduce the number of turns with the point of you reducing cost or reducing the power loss in the inductor.

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Power Loss in Inductors

- Core Loss: hysteresis and eddy current loss factor

$$P_{core} = kB^x f^y V$$

- Copper Loss: frequency, geometry, conductivity, temperature factors

$$P_{winding} = I_{fo}^2 R_{ac(fo)} + \Delta I_{rms}^2 R_{ac(fsw)}$$

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So, the power loss in the inductor is actually a important factor the power loss in the inductor correspond to two factors, one is the core loss that is happening in the magnetic material and the copper loss that is happening in the windings. So, and one looks at the core loss the dominant terms are the hysteresis and eddy current loss factors and when you look at the core loss in a material it depends also on the type of material that one would select for the core.

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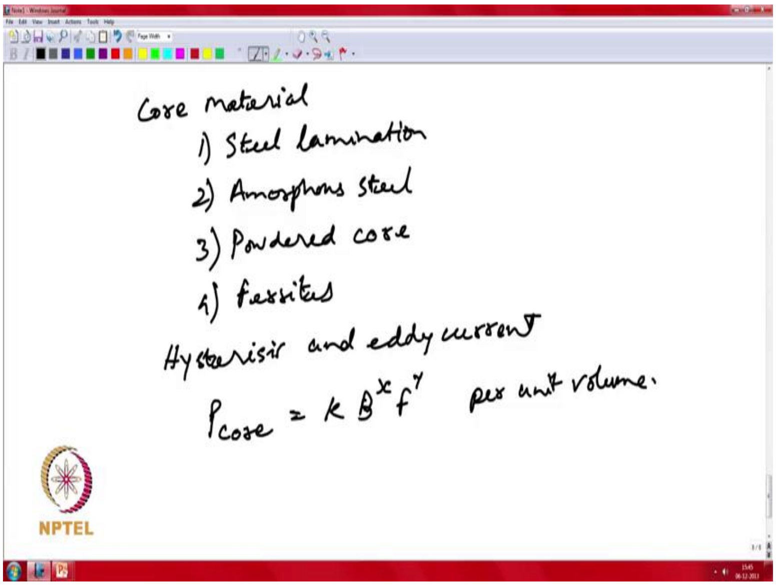

So, one could use steel laminations, so for transformer or inductor one would be using grain oriented steel or one could use amorphous material one could use powdered course. So, when one is talking out powdered course it is essentially powdered magnetic material in is sine, so the air gap is actually embedded along with the magnetic material.

So, you do not have discrete air gap you have a distributed air gap you could also have ferrites often the choice of what type of material you would use is related to the switching frequency of operation. So, when one is considering frequencies of the order of 1 Kilo Hertz, but not too much further away steel laminations might be a good solution whereas 1 when one considers frequencies of the order of few Kilo Hertz 10 Kilo Hertz etcetera.

So, one would have too much loss in the steel laminations even the final laminations and one could then consider amorphous steel. But, one could also considered a powdered core which would have similar range of frequency similar to that of amorphous scores may be it is a little bit higher for the powdered material. Now, one would consider ferrites for much higher frequencies, one can use ferrite core inductors in A at frequencies of the order of even tens of tens hundreds or even mega hertz range.

So, a wide frequency range one can use ferrites, but we saw just a few slides back that the peak flux density of ferrites tend to be much lower than that of the other material. So, the size of the, of your magnetic component would tend to be larger, so when one considers the core laws you have the hysteresis and eddy current. But, it depends on the material that are used in the laminations the resistivity of the material the whether you are using powdered course the geometry. So, the finer the thinner laminations would have lesser losses the stone med sequence is used to model the core loss as a function of flux level and frequency.

So, you have p core is equal to some constant B to the power of x f to the power of y and often this is expressed as power loss per unit volume and one can see that when you have an applications such as a inverter. So, you might have multiple frequencies you have the fundamental frequency of operation you also have the frequency corresponding to the switching of the power converter and the core loss expression is not linear.

So, your expression x and y often in the range of 1.4 to 1.6, so you cannot just directly add the individual losses together, but one can actually make use of expressions such as this. So, to look at what is the dominant loss component and see what would be the main driving force behind the losses in the particular core.

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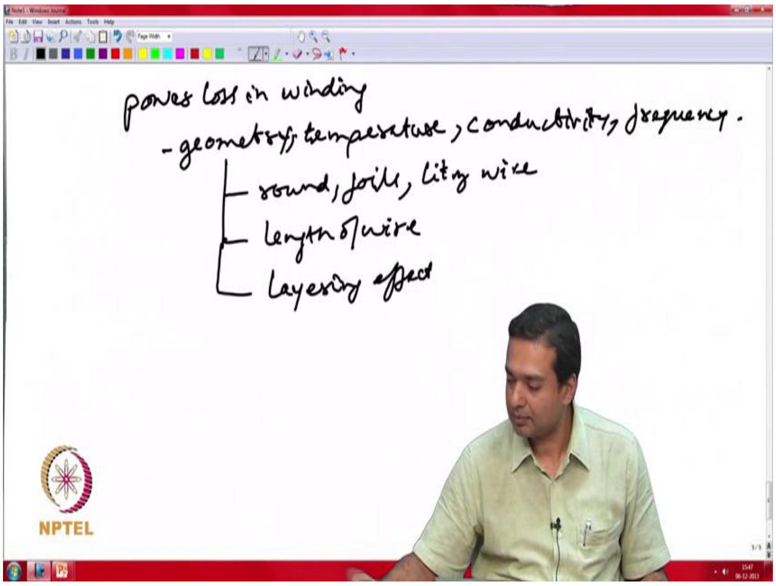

If you look at the power loss in the winding again it depends on factors such as the wire geometry whether on temperature conductivity of the material the frequency at which it is operating. So, whether the conductivity whether you are using say a exotic materials like gold silver or copper or aluminum many of these winding metals have a positive temperature coefficient of resistance.

So, you need to know at what temperature is going to operate and we will see that frequency has an effect on the resistance in terms of geometry. So, you are talking about whether you are talking about round conductors or foils or litz type of wire also it depends on the length of the wire and also layering effects especially when one considers things like proximity effect.

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Power Loss in Inductors

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- Copper Loss: frequency, geometry, conductivity, temperature factors

$$P_{winding} = I_{fo}^2 R_{ac(fo)} + \Delta I_{rms}^2 R_{ac(fsw)}$$

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So, when you are operating at higher frequencies things like the proximity effect will result in the resistance of the winding been different for different frequencies. So, you might have a lower resistance that your fundamental and a higher resistance at your switching frequency.

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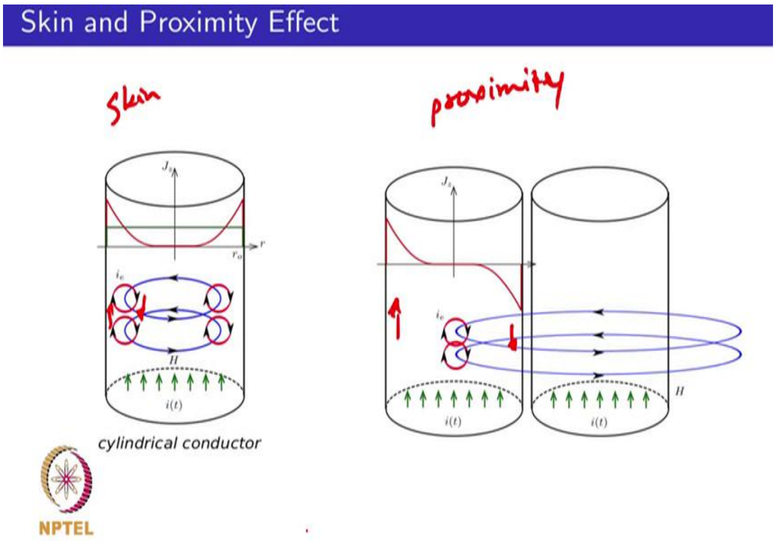

So, if you look at the high frequency losses in the winding you have two factors to consider one is the skin effect. So, if you are having a eddy c current which is flowing through say round conductors such as this you will end up with uniform current density all along the, all along the winding cross section. But, once you start varying the current as a function of time, so instead of d c current you are start applying a c current, you can actually then calculate what would be the H field being cause by this particular current.

Now, that is flowing within the conductor and essentially you will have then induced currents these are small eddy loops which would try to counter the flux cause by this H field. So, the nature of this particular minor eddy loops would be to increase the current on the edges and reduce the current towards the center. So, the overall structure of the shape of current density instead of being uniform will tend to the current would tend to crowd towards adjust of the conductor.

So, this is called skin effect, similarly if you have multiple layers of windings you can think about what the high frequency flux could do for cause by the current flowing in conductor and causing induced currents in a neighboring conductor. So, again you would have induced minor loops of currents and the induced current would be in such a fashion, such as, so increase the current at one edge and reduce the current at the other edge.

So, if you now have third layer the summation of these two currents would cause the eddy current in the next layer, so the proximity effect can actually increase with a number of layers. So, both these factors cause the current the density to actually been an extremely non uniform causing greater power dissipation at the edges of the conductors. So, you need to ensure that your skin depth is actually comparable to the diameter of your wire or you might end up under utilize under utilizing the wire where large portions of the wire is not carrying any current.

Now, all the current is being just carried by the outer skin a small layer on the outer edge of the conductor, so as with any component you that we have been looking at so far to evaluate, to look at the component. So, in terms of what is its reliability one needs to evaluate its operating temperature, so to find what the operating temperature of this inductor is one need to actually have a good understanding of a three factors.

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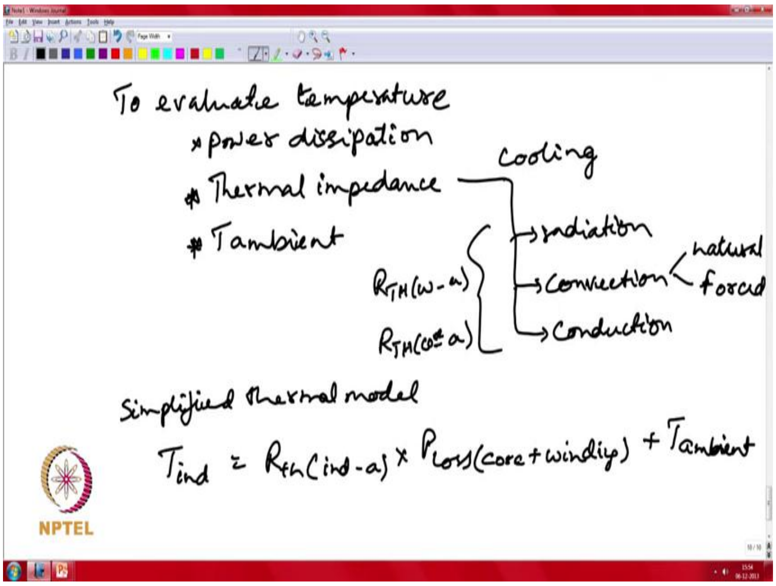

So, one is what is the power dissipation the second aspect is the thermal impedance and the third factor is what is your ambient temperature. So, your actual operating temperature of the your inductor would depend on all these factors and we are just discussing about the power dissipation.

If you look at the thermal impedance essentially you are looking at what is your thermal resistance of your inductor between the inductive material. So, it surrounding and the cooling that is being that is being provided can be because of radiation convection or conduction. So, you have and again convection you can have natural convection or force convection forced air cooling. The outcome of both of this could be you could have factors like the thermal resistance R T H from say your winding to ambient or your thermal resistance from your core to ambient simply.

So, a very simplified model of the inductor could be to take the entire dissipation within the inductor as a inductor the entire inductor both the winding and the core as a symbol single component. So, is T temperature of the inductor would be R T H of your inductor to ambient times power loss of core plus your ambient.

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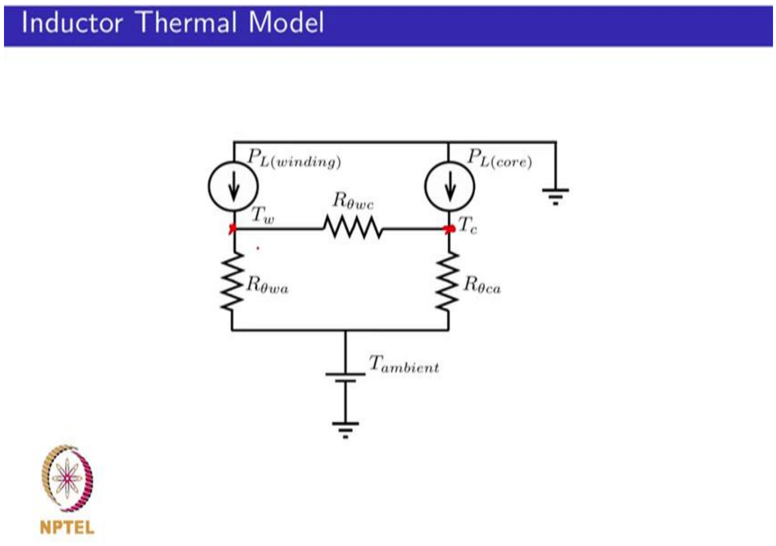

So, one could then also look at a slightly more sophisticated model of the of you of your thermal model of the inductor one can consider thermal resistance between your winding to ambient. So, you could consider thermal resistance from your core to ambient, you could also consider because the winding and core is mounted close by. But, you could have conduction paths or small air gaps through which you might have heat transfer between a winding to your core.

So, you could then consider your temperature of you winding and temperature of your core, one could also then look at a dynamic thermal models. If you know the thermal capacity of your core material and the thermal capacity of your windings one could also consider the dynamic thermal models. So, the question is what would be the implications of these temperatures on the life of the inductor and essentially, if you look at the inductor.

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Insulation Class

Insulation Class	Operating temperature (T_o)
A	$105^o C$
B	$130^o C$
F	$155^o C$
H	$180^o C$

The insulation class of given inductor is specified in terms of the temperature at which it can operate, so class a insulation would operate at 1 naught 5 degrees you centigrade or below class be would correspond to 130 class F 155, class H 180. So, you have actually many newer classes of insulation for which you could actually conduct test to actually evaluate what would be the temperature level at which you could operate. So, if you look at the relationship between what these temperature specifications mean and the life of the given insulation material simplified model for the inductor is essentially.

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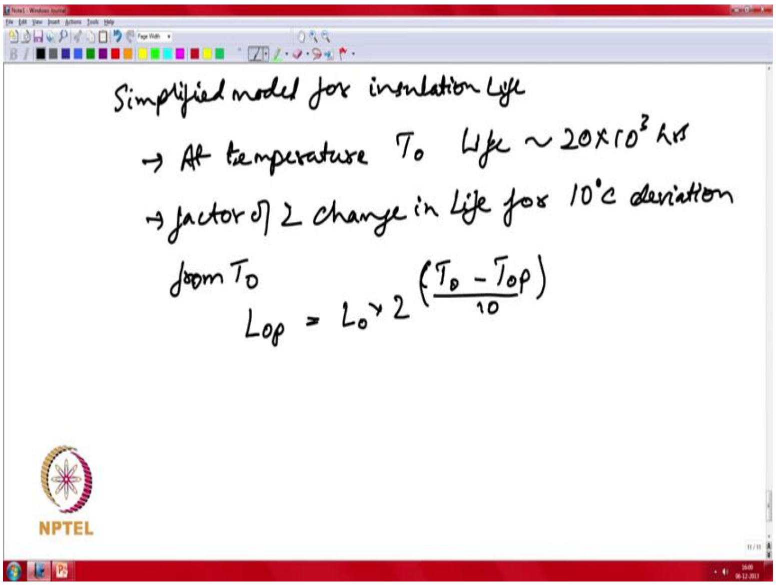

So, you are essentially looking at the insulation life you have at temperature T naught you are talking of a life of the order of 20,000 hours and similar to what we did for our capacitor life analysis. So, we could, we could consider a factor of 2 changes in life for a 10 degree deviation from the temperature specified as T naught. So, your L operational would be L naught into 2 times T o minus T operational by 10, so you could actually relate the expected life of using particular type of insulation.

So, one thing to keep in mind is that class of insulation A B H N etcetera has been round for long time there are newer classes of insulation that would not belong to any of these particular class. So, you would have to actually do accelerated life time testing to actually see what type of life models could actually be fitted for the type of insulation material that you are using.

There are many hybrid materials which consist of layers of multiple in S types of material which can have a more complex the life time characteristics. So, once you have the your operational life for a given temperature one could also, then consider the concept of accumulation of damage to see what is the operational life under practical power converter condition running conditions.

So, with this we can see that we can, now take the major components of the of the power converter and in the, what we have just discussed is for the filter with a simple inductive. So, for the power converter with a simple inductive filter one can look at the power loss the cost of the inductor would essentially be the cost of the core plus the winding plus the assembly cost. So, you have implications on of power loss which would affect efficiency and also you have implications of power loss in terms of temperature you have also magnetic properties which can degrade with temperature.

So, you need to ensure that the operational temperature of your core does not damage exceed the values which would alter the properties of the core material by a large external. So, it is important to ensure that you do not exceed your temperature, so that your insulation life is getting affected. So, will also then next look at how one could consider higher order filters, but this would be for a simple inductive filter that is used with a power converter.

Thank you.