CHARGING INFRASTRUCTURE

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Lecture-47

Lec 47: Filter Inductor Design

Hello everyone, welcome to lecture number 47 of this NPTEL lecture series on charging infrastructure. In today's lecture, we will see the design procedures for the physical realization of the filter inductor. In the last class, we saw the transformer design procedure, where we started off by selecting an appropriate core. After that, we defined our core losses and copper losses. Then, we found out our delta B optimum value, for which our total losses in the transformer are minimal. That will give us the condition which, if not satisfied, will require us to go back and select the next larger core size. Once we obtain the optimum value of delta B, or peak AC flux density, we then calculate the number of turns in the primary winding. After selecting the number of turns in the primary winding, we then calculate the number of turns in other windings. Once we obtain the number of turns in the other windings, we move ahead and evaluate the wire sizes

needed to actually wind the winding. So, before that—I mean, at the start—we have already selected the core. We selected the core which actually satisfies the condition where our P_total is less than or equal to our P_total_allow. That means how much power loss in the transformer we can afford to have. We get this by doing the loss budgeting of the overall system. From there, we can determine the maximum power loss we can afford in the transformer. From there, we then reach a point where we select the core. Once we select the core, we can define the number of turns in the primary winding because, by that time, we would have already arrived at the optimum value of AC flux density. From there, using the turns ratio given in the specifications or obtained from the specifications, we can define the number of turns in other windings. Once we know the number of turns in the other windings, we can then evaluate the wire sizes needed to actually wind the winding. We obtain this from the gamma J optimum value—that is, the optimum value of the fraction of the area allotted to individual windings. We obtain this from optimization such that our total copper losses in the transformer are at their minimum value.

So, that is how we have done the transformer design procedure. Once you obtain the transformer, we will finally do the design check, where we will see whether the losses in the transformer are less than or equal to the allowable losses in the transformer. You know, this is one of the magnetic devices we use in isolated DC-AC converters. There are other magnetic devices as well. If you recall, a simple buck converter comprises a switch, a diode, an inductor, a capacitor, and a resistance (RL, CL, and VE), with an output of V0. So, we have seen that our PSFB is another buck-derived topology. We have seen the full-bridge converter, which is again a buck-derived topology.

We have seen the different kinds of converters which actually have the buck-derived topology, where we have one inductor kept at the output of the half-bridge. This is done to filter out the ripple and to smoothen the current which is coming out of this half-bridge. So, this is another magnetic device very commonly used in our power converters or our isolated DC-DC converters. So, let us try to see how we can physically realize the inductor because the inductance value we can get from our specifications, but how to actually physically realize the inductor—let us see those procedures. So, before starting those procedures, let us discuss some of the things related to the inductor.

So, let us take a core, which again we have taken as a UU kind of core. This first part is U, and the second part is U. So, we have taken a U-core, and let us say the core cross-sectional area is AC. And here, from this point, we are actually supplying a current I, and let's say the number of turns is N. So, as a result of this excitation of the current, there will be a flux generated, which will be in this direction and will go through the core and return back to the coil. Now, in this, we can define one more term, which is called the magnetic path length, which is the length of this red-colored line, and it is given as LC, which is the magnetic path length in the core. And then, let us try to calculate what the inductance of this particular structure is.

So, for finding the inductor, first we will do the simplest thing, which is to apply Ampere's law. By using Ampere's law, we will take the entire loop, which goes from this side and comes back—this is the entire loop we will take. So, in that loop, if we apply—let's take the magnetic field intensity in the core to be HC—we can then write HC LC, which is the magnetic path length—the length of this entire loop—is equal to the amount of current enclosed in the loop. So, the amount of current is I through one winding, and there are N number of turns, so the total current is N times I. In the simplest form, we can write this consideration, assuming there is no fringing effect of the flux and no flux leaking out of this core. I mean, the entire flux generated out of this coil is actually confined within the core itself.

Now this is the thing we got where hc we can say that the magnetic field intensity inside the core. So, we can then define the second term from here we can just write the flux density in the core due to the domains present in this core. So, let us say the B value is or the magnetic flux density which get produced due to the alignment of the magnetic domains in the core is nothing but will be given by b is equals to mu c h c where mu c is nothing but mu r times mu naught where mu naught is nothing but the permeability of the free air which is nothing but four in four point minus seven and this is relative permeability

Generally, relative permeability is very much greater in thousands or in hundreds. That's when we can say mu C is very, very much greater than mu naught. So, since we have the flux density B is equal to mu C as C, so we can write our flux density to be nothing but phi is equals to b times ac area of cross section of the core which is flux density times area of cross section of the core that implies flux to be ac mu c hc and that implies flux is nothing but Mu C Ac and I by Lc so this is the flux we got from this thing where you know here n is the number of turns I is the current excitation given to the inductor now that particular thing we can then write from here we can then write flux linkage

in the entire loop is nothing but lambda is nothing but equal to n phi and that gives lambda to be equal to mu c ac n square i by lc now this implies my inductance we can write inductance l to be equal to lambda by i and that will be nothing but that gives l equal to mu c ac n square by lc and if we look very carefully this particular structure if we try to define the magnetic circuit model of this structure so we can then write magnetic circuit model from our basic understanding of magnetic circuit we know that it will look like we have one voltage source having the value equal to ni which is mmf and that is actually been connected to a reluctance term called as the rc which is the reluctance offered by the core that means reluctance is nothing but the resistance offered to the flux which is being built in the core so this is the flux which is been flowing through the core so it is nothing but a magnetic circuit model similar to that of the voltage was connected to a resistance and which lead to the current to flow through that particular loop and that we can then define from doing the electrical equivalence we can then say the flux is proportional to current rc is proportional to resistance or the or you can say the reluctance is proportional to the resistance and mmf is proportional to the voltage applied this is the electrical equivalence so then we can then write simply flux phi is nothing but mmf

By reluctance of the core, which we can then write as MMF = NI/RC. Now, if we take—let us define, you know, in the previous slide what we have defined—let us take this as equation number 1, and let us take this as equation number 2. So, from 1 and we can very well say the reluctance offered by the core to that flux is nothing but equal to LC/(μC AC). And this, if you recall, this one—let's say this inductance value, which is justly defined by equation number three—so we can then say, and let's say, defined by four. From three and four, we can then say, inductance is nothing but equal to N^2/RC. So we can then say, if we know the equivalent reluctance offered to the flux path, Using this inductance, we can calculate the inductance of any complex magnetic structure.

So, using this formula—which is N^2 (number of turns) divided by the reluctance offered to the flux path by the complex, you know, magnetic structure—we can easily calculate the inductance corresponding to that complex magnetic structure. So, let us try to insert one air gap and then let us see how the inductance calculation will vary in case we introduce a small air gap Lg, where Lg is the air gap length. which has been introduced in this particular core, and this is nothing but my N number of turns, and I am exciting it with I, and it will generate the flux Φ. And you know, this LC is again—we can define the same LC. This is my LC, the magnetic length LC—this entire thing—and I can also define my area of the core, the cross-sectional area of the core, to be nothing but the area corresponding to this. So, let's take the area offered by this air gap as nothing but AG. We can write the cross-sectional area offered by the air gap.

So, in this case, we can then define the reluctance offered by the core, as well as we have now inserted the air gap. So, there is another reluctance which is introduced because of this insertion of the air gap. So, we can then define this magnetic circuit model to be NI, and then we have one reluctance offered by the core. And then, the other reluctance offered by the air gap, and those two are connected in series because both see the same flux going through them. So, that's why, if you try to draw the magnetic circuit model, it will look something like this, having the same flux which will be seen by the reluctance of the core as well as by the reluctance of the air gap. So, that's when we can then write my flux to be equal to nothing but NI/(reluctance RC + RG), and that I can then define flux to be equal to $NI/(LC/(\mu C\ AC) + LG/(\mu_0\ AG))$.

Here, assume that the flux which is coming through this will actually cross this air gap and get into the core. However, there are some fluxes which actually get fringed out, you know, in this manner. And that's why we can say that AC is nearly equal to AG, but AC is not equal to AG. So, these two terms are nearly equal, but not exactly equal to each other. Now, using this one, the overall equivalent reluctance, if we put it, is nothing but RC plus RG. And that's when we can then write the inductance of this complex structure as nothing but N squared divided by R equivalent, which is nothing but equal to N squared by LC by mu CAC plus LG by mu naught AG.

Now, we can then take another approximation because we know that our Mu C is very, very much greater than Mu 0. That's when we can say that in this term, we can say that RC is very, very much smaller than RG because RC, the reluctance offered by the core, is nothing but LC by Mu C AC, and the reluctance offered by the air gap is nothing but LG by Mu 0 AC. So, because of that, my RC value is very, very much smaller than RG, and that's when I can, in this particular denominator term, this is very small, going towards 0, and that's when we can say that my L is nothing but N squared by LG by mu naught AG, and that's when we can say L is nothing but mu naught AG times RG. mu 0 AG times N squared by LG. So, the entire inductance is only due to the air gap length, the area of this air gap, the number of turns of this winding, and the mu 0, which is, you know, mu of the air gap. If you look very carefully in the previous part, whenever there was no air gap, it was mu C AC N squared by LC. Here, it is

mu naught AG N squared by LG. So, we can see that because of the insertion of this air gap, the entire inductance is only dependent upon this air gap's dimensions. The core has no role to play the moment we put the air gap. But because of this thing, we also see that this inductance, which we get by this value, is very, very much less than the inductance we got without putting this air gap because our mu C is very, very much greater than mu naught, and that's when we can say that The inductance which we got when there was no air gap is pretty much larger as compared to the inductance we got with the insertion of the air gap.

Now, let us see how the BH curve will change. So, if we draw the BH curve, we know that the BH curve, where we can also define the 5H curve—you know, the 5H curve if we define it—which is nothing but a flux versus magnetic field curve if we see, which is nothing but B times AC, which looks like, you know, a straight line going from 0 to some point and then it becomes saturated. And this is, we can say, the phi saturation. So, this we have assumed; this curve is drawn with the assumption that the nonlinearities are absent. So, if we take this one, this is the Ni, or you can say this is the Ni max, after which my core will get saturated, or you can say after which the relationship between B and H is no longer a straight line and all the magnetic domains get fully aligned.

Now, if we see, the slope of this curve is nothing but equal to—if we see this is the phi versus H curve— or 5 versus Ni curve, so if we take from equation number 1, the 5 versus Ni curve, if we say it is nothing but the slope is nothing but 1 by lc by mu c ac. Since my mu c is very much bigger, this value is smaller, that's why the slope is larger, and that's why you will see that this curve will reach saturation faster. Now, when we introduce the air gap, what happens is that it will take a good amount of time to reach saturation, and this value is nothing but Ni set with air gap, and this one we can replace and define that thing to be Ni set. So, what we see is that since we have the air gap, which has been introduced in this. So, because of that, the slope of this curve, if you draw it, is nothing but 1 by LC by mu C AC plus LG by mu naught AG.

This you can see from this particular equation number 5. From equation number 5, this will be the slope between phi versus H, which is nothing but equal to Ni. Now, if you look very carefully, we know that my mu c is greater than mu naught. And that's why we can say that our lc by mu c is very, very much lesser than lg by mu g. And that's why this particular slope will, we can say, is nothing but the slope with air gap. is nothing but mu naught

ag by lg and that's when the slope is proportional to mu naught and that's when the slope value is very small that's when you see the curve will reach to hit the saturation value only after reaching to new value of iset g and there we can say that iset g is greater than iset value is very very much greater than iset value but it indicates that when the air gap is introduced there are things which happens first the inductance value goes down second if we see very carefully one important thing which will happen is that say the current at which the second thing what happens is the current at which the co-saturate saturates increases that means you can now allow more current to flow through the inductor without going into the saturation and fourth thing is the inductance with air gap is nothing but we can say mu naught a g n square by lg and inductance without air gap if we recall from previous slide is mu c ac n square by lc if we introduce the air gap the inductance value of that particular magnetic structure is actually independent of the core dimension so we can say that inductance is independent on the core dimensions.

third thing which will happen so when we have any inductor which carries both dc and ac we generally use the core with the air gap interviews in them as a result of which what happens is that it can able to carry larger value of current before going into a saturation and as well as what happens is that the inductance becomes independent of the core dimensions So in case when we have the buck converter, which is like this, if we take this one and if we assume to be having a CCM operation, so continuous conduction mode operation, that's when we can say that my inductor current, when my switch S is on, that means let's say if I draw DTS period for DTS period, this is up to TS period, that means up to DTS period, when my switch S is on, S is on, At that point my voltage across inductor is Vin minus V0 and that's when the inductor current will rise because we know that our Vin is greater than V0 as it is a buck converter. So what we see that the inductor current will rise linearly with the slope V0. Nothing but equal to V minus V0 by L. And in this point S is off and that's when my D is on.

S is off. That's when D is on in order to ensure the inductor current gets a freewheeling path. And that's when we see that inductor current falls down with the slope equal to minus V0 by L. And this will continue like this. Now, if we take very carefully, you know, the ripple content which is there, which is there in inductor. Now, this ripple content is, you know, is delta I. Generally, delta I is less than 10% of I. So, we can say that delta I is very, very much smaller than I0.

Before that, let us also draw one simple thing for this one. Our magnetic circuit model will be looking like we have ni and we have rc we have rg you know reluctance due to the air gap so this is our magnetic circuit model we got which is nothing but the mmf ni is imposing on this series connection of reluctance offered by the core and the reluctance offered by the air gap and we can then write the mmf drop happens across the rc to be equal to Ni across C is nothing but from the ampere circuit law HClC and this is nothing but my overall flux which is going which is Ni by Rc I mean reluctance of core plus reluctance of air gap multiplied by the reluctance of the core and that's when we can say my hc ni by r you know the reluctance offered by core plus electron offered by air gap multiplied by reluctance offered by core divided by lc if you take the average value of this current

is nothing but I0 and thus we can obtain the H0 value corresponds to the average inductor current which is nothing but I0 is nothing but Ni0 by RC plus RG times RC by LC so now we can then plot our BH curve which is like this and let us take at this point my HC or H naught which is coming which is nothing but N I naught RC by LC reluctance of the core plus reluctance of air gap and then over that we have our nothing but the ripple I naught ripple which goes like this to this here like this so if we try to draw ripple in this manner and on this side ripple to be drawn on this way then we can then see our curve will look like going in the top and you're going at the bottom so it will look like something like going here comes like this and then goes here so this is you know This is something like curvy shape it will look like. So, only this much is the area which is been enclosed in the BH loop and that will actually be corresponding to the very small area.

Area enclosed in BH loop is this. very small and since this area enclosed in the bs loop is very small we can then say because of that the core loss the core loss associated with the core material is very small since my area enclosed in the curve is very small the core loss associated with that is very small and it is primary because the ripple in the inductor current is very small as compared to the average value of inductor current so now let us try to see whatever the understanding we got related to filter inductor what we have seen is that since the area enclosed area enclosed in the bs loop is small, what we can say that the core loss in the inductor is negligible as the area enclosed in the BS loop is very small. Second thing what we can say is that since the ripple in the inductor current is very small, we can also say that the AC winding resistance is also negligible.

So, we can also say that since the ripple component in inductor current is small, we can say that the winding AC resistances that means the resistances corresponds to the skin effect of resistances or the increased resistances due to the skin effect and proximity effect is negligible. this resistance is due to this. So, then we can say that the flux density will now need to be chosen based upon the saturation value of the magnetic flux density which the core material can have. So, it is chosen based on saturation value that means for the selected core material that will have a corresponding b set value so we must ensure that the flux density whatever we are getting in our inductor has to be less than this b set value or you can say the maximum flux density what we can have in in the inductor during the operation of the inductor must be less than the saturation value of the magnetic flux density Similarly, we can say one more thing we can say as we have understood that air gap is employed to avoid saturation. So, now these are the things which we have understood while doing the discussion related to filter inductance and since we are introducing the air gap, we need to know the air gap length. Since we are obtaining the flux density based upon the saturation value of the flux density value, so we have to know what could be the maximum value of flux density we should keep in. and then we should also know what will be the core sizes we have to select and at the same time we should also know what will be the number of turns we needed to obtain the required value of inductance value.

So we can then obtain the filter inductor design. Now we see the filter inductor design which has the fixed DC and a very small ripple current over it. Here the design outcomes are same. The core size defines the core cross sectional area AC. The window area which is WA same as what we have seen the window area in the case of transformer.

If you see the U core then the window area will be this area. only this part of the area that means what you can say that if this is looking from this thing if this is the core this is the core then this is the window area we are talking about and then again the mean length per turn because the first turn will be on one side wall of the core and the other winding will be on the next wall of the code so the mean length per turn will be somewhere in between that and that way we can calculate the mean length per turn and we have seen in detail how we can calculate the mean length per turn in the last lecture as well and then we have to also find out the magnetic path length which is nothing but defined by lc and our this mean length per turn is defined by mlt Then after finding out the core size or core dimensions, one need to also find out the number of turns. Let's say if we are introducing an air gap, then we also need to know what will be the air gap length.

And once we know the air gap length to realize the required value of inductance, we must have the required number of turns. So, in that way both are interlinked to each other and then finally we must know how much will be the size of the wire such that that many required number of turns will get accumulated within the window area. So, these are some of the design outcome which we need to find out you know to physically realize the inductor because inductor just like a transformer also has the winding and the core which will be sitting on the bobbin as we have seen in the last lecture. Now, some of the specification we will be provided for example we will be knowing what will be the required inductance we wanted to actually physically realize because that will actually determine the number of turns some of the core dimensions wire sizes air gap length

and then we will also define what will be the allowable power loss we can actually accumulated in our loss budgeting of the entire converter so what we do is we generally do the loss budgeting of the entire converter and then we say that this much is the amount of power loss i can allow from the inductor so the allowed power loss is nothing but p is equals to i square r because here the core loss Core loss is very negligible since the area enclosed in the BH loop is very small as our ripple current is very small. So we can say that the loss in the in the inductor is only due to the copper loss and that we can say it is nothing but I square RMS times. resistance and this resistance is again since the magnitude of the ac excitation is very small so we can say that the resistance is nearly similar to that of rdc or the resistance due to the dc excitation that means which is nothing but we can say rho l by a where l is the length of the turn and a is the area of cross section of the wire we will see that as we go along And then finally we must also know what will be the maximum current because that will actually determine what will be the size of the wire I can select.

So these are, you know, the design outcomes we must get, and these are the specifications which we have in our hand. Now, considering this particular structure, let us try to define the magnetic circuit model, which will look something like this. Now, this will imply I can write this down to be my NI to be nothing but flux multiplied by Rc plus Rg, and as we know that our Rc value is less than Rg, we have already discussed this in the previous slide. We can then write our NI is nothing but Φ times Rg. That's when we can say that the NI for the maximum value of the inductor current is nothing but my Φmax times Rg because Rg will not change, as the Rg value is nothing but your Lg divided by μ0Ag. Once you select the core and define the air gap length, your Rg value will not change, as the Rg value depends upon the dimension value. So we can then write this to be nothing but

NImax equals Bmax Ac Rg, and this particular thing we can then write from this expression. We can then put the Rg value to be nothing but Ac Lg divided by μ0 Ag. And if we assume that my Ac is very close to the Ag value, or you can say the area of the cross-section of the core is very near to the Ag value, that means we have assumed that the fringing of flux through the air gap is very small. So we can then say that our Ac is nearly equal to Ag, and that's when we can write NImax is nothing but your Bmax Lg divided by μ0. So what we have understood is that, depending upon this Imax value, the Bmax value will vary, and we have to ensure that whatever Bmax value we are getting, or the maximum flux density obtained in the core during the operation of the inductor, has to be less than the Bsat value. That means we can say that the maximum flux density must be less than the Bsat value.

So from this particular expression, if you know your Lg value, if you know your number of turns, and if you know the Imax value, you can understand what your Bmax value will be. And this Bmax value, you have to ensure that it is less than the saturation value of magnetic flux density. So this is how, you know, one can decide what the value of Bmax could be. One can keep it. For example, the Bsat value for ferrite cores is generally

are generally kept somewhere around 0.25 tesla so you can then take your beam x value somewhere between 0.2 to 0.22 and that's when you can then understand depending upon what will be your imax value in the inductor depending upon the circuit operation in which inductor is being kept you can obtain the imax value and from the imax value you need to ensure that this lg and number of turns is kept such a manner that the beam x value is less than the b set value so that is one of the check one has to ensure so that's why this is one of the condition one has to see whenever they are actually selecting the core size for the filter inductor design then the constraint number two which is associated with the inductance we know that the moment we insert the air gap in the inductor and we are inserting the air gap because we wanted to avoid saturation so the moment we insert the air gap we know that the inductance is only due to the air gap and since we know that the fringing effect is effect is neglected so we can say that our area of core area of cross section of the core is nothing but equal to ag and that's when my inductance is nothing but equal to mu naught ac n square by lg where lg is the length of the air gap and mu naught is the 4 pi into 10 h to power minus 7 which is the permeability of the free space. Now, this is my constraint number 2 which is related to the inductance value and this inductance value because we have inserted the air gap to avoid the saturation, this inductance value is actually only dependent upon the air gap.

Now, we can then define the flux density in the core, which is

$$B = \mu_C H_C,$$

where $\mu_C = \mu_0 \mu_\tau$. Generally, μ_τ is very large. So, we can write flux as $\phi = BA_C$, which implies

$$\phi = \mu_C A_C NI/L_C.$$

From here, we can then write flux linkage as $\lambda = N\phi$, which gives $\lambda = \mu_C A_C N^2 I/L_C$. This implies inductance

$$L = \lambda/I = \mu_C A_C N^2/L_C.$$

Now we know that this is our core and here we are putting the winding and so our you know if we see our winding area or window area if we take our window area our window area will be nothing but equal to this part. Only in this area I can accommodate the turns and since if we have n number of turns which is one of the unknowns we have to calculate If we have N number of turns, then the total area taken by copper conductor will be N times AW where AW is area of cross section of the wire used for winding. and since this winding is accommodated or housed in this window area it is like this it will be it will be drawn like this one after the other like this it will be arranged it will be arranged like this in the core like this maybe take this this to be straight line then our things will be much better this is our core and in this entire area we are actually putting all our windings so this is housed in that one and since we know that in the window area because since we are we are using circular conductors this conductor are placed even if they are placed nearby each other it is this area which is not been consumed.

So, that is when there are only portion of area which we can use out of this window area and that is when we got this term which is called as the winding fill factor. And which is nothing but greater than equal to NAW. Similarly, we can also define the winding resistances because winding resistances are the one which will actually determine the required area of cross section of the wire which has to be used. so we can write resistance of the winding to be Rho L by AW where AW is the cross section of the wire area of cross section of the wire this is what I am talking about AW L is the length of the wire and we know that since we have the winding going from this side to this side So this is mean length per turn.

We can then write this particular thing R to be N times R to be rho times N N MLT divided by AW. Now this is the number of turns we are using N where here N is number of turns. So we can then calculate the mean length per turn and then multiply that mean length per turn by n number of turns and that's when we can get the overall resistance of the winding and this is we can say that AC effects are neglected. AC effects are neglected like skin effect or proximity effects are neglected. because we have a very small percentage of ripple in the this current which is used for exciting this particular winding so we have very small ac component so in summary what we can do is we can write down the four things what we have obtained the first thing what we have obtained is nothing but you know the relationship between the imax and bmax

$$\phi = \frac{NI}{\frac{L_c}{\mu_c A_c} + \frac{L_a}{\mu_0 A_a}}$$

$$L = \frac{\mu_0 A_g N^2}{L_g}$$

Which is given by this. Let's say define this as equation number 1. And here we are ensured that the Bmax value should be less than Bset value. Now the second thing what we have obtained is the inductance due to the air gap. And that inductance value what we get is nothing but mu naught AC n square by LG.

This we can define equation number 2. This is inductance due to air gap. Because in the structure what we have assumed where we have introduced the air gap. So what we get is the inductance is primarily dominated by the air gap. And after that, we have then also obtained the things related to winding area where we obtained that KUWA must be greater than equal to an AW.

That condition we have obtained, and this we can define to be equation number 3. That means the window area which has been there has to be greater than the amount of area taken by the wires used here. While making that particular winding or while realizing that particular winding. And finally, we have also obtained the things related to the winding resistance. The value we have obtained is that rho times n times MLT, which is mean length per turn, divided by AW.

Now, in this, if you see, what we have is some of the quantities which we can obtain from the specification and the material of the core which has been selected. For example, we know our Imax value; this we can obtain by understanding the circuit operation in which this filter inductor is being used. Then we know our Bmax value from the core material. We know what can be the Bmax value; it should be less than the saturation value of magnetic flux density. So generally, if you select the core material, you have already defined what could be the maximum value of B which you can go. Then after that, you can define. We also know our mu naught value, which is nothing but 4 pi into 10 to the power minus 7. Similarly, from the specification and from the circuit operation, we know what will be the inductance value which we have to obtain. Similarly, we also know what is our winding fill factor; again, this is a constant which is defined for a required kind of winding which we are doing. And then we also know our maximum resistance which we can allow in our winding from the specification. That means the amount of loss which has been allotted to the transformer, so from there we can know what is our winding resistance value we can afford to have. And we also know our rho value because, depending upon the material of the wire which we have selected, which we have already defined in the last class.

So, these are the quantities which are obtained from specifications, core material, and circuit operations. However, whatever things which we do not know is nothing but the number of turns which we have to do in the core to obtain the required value of inductance. Similarly, what is the magnetic path length which we need? The MLT, the mean length per turn for the core which has been selected, the window area which is required in the core, then what are our area of cross-section of the core and the area of cross-section of the wire which is to be used to wind the turns such that to obtain the required value of inductor. So these are the things which need to be known; these are unknowns, and we have to somehow know them. So what we can do is we can rearrange. Let us define this as equation number four. We can rearrange equation number one, two, three, four, and we will get a relationship which is nothing but Ac square Wa divided by MLT has to be greater than rho L square I square Imax divided by B square max times R Ku. Now if you look very carefully

In this particular relationship what we get is these are the specified values that means which we can obtain either from the specification or from the circuit operation in which this particular filter inductor has been kept and this left side quantity is nothing but the core dimensions. And let us define you know this particular equation to be nothing but equation number 5. Now this is one of the important condition which will help us in actually determining what will be the core size which we can select. Now let us try to understand the inductor design procedure. So in the inductor design procedure the step 1 will be select the core.

Now, by selecting the core, we have to select the core in such a manner that such that the core is large enough to ensure that our condition which is mentioned in equation number 5 which is AC square WA divided by MLT has to be greater than rho L square I square divided by B max square RKU. So we need to select the core in such a manner that this particular expression must be greater than equal to the expression in the right hand side. Now this expression is from the specified values that means from the circuit operation and from the specification we know all these values and then after knowing all these values we have to select the core in such a manner that the core will give you the value like LC AC WA MLT value after selecting the core and once you evaluate this term and this term has to be such that this is greater than this particular thing. So, this condition has to be met and we need to select

the smallest core whose dimensions satisfies whose dimension means whose core dimension that means your LC, AC, WA, MLT value satisfies the condition in equation one so once we select a core for example if let's say we decided that we will use the ferrite material any ferrite material let's say we choose a particular e type of course so we will start with e5 e10 e 25 and so on because you know you have a different this thing let's say e 45 so you will select the core and for individual core we can calculate this expression and we must ensure that the expression in the left hand side must be greater than equal to the expression on the right hand side which is been actually defined by the specification or the circuit operating condition and the smallest core we satisfy this particular condition we will select that core for example let's say we have select the E5 and we saw that this condition is not met then we go ahead and select the E10 and then we will see if this condition is met or not let's say this condition does not met then we will go and see the E25 core and if this E25 core condition is met so we will select that E25 core and that will actually will give us the things like our LC AC window area and mean length pattern and once we know this particular things we will then move ahead

and then calculate our number of turns for that what we can do we will just use a simple relationship which is li is nothing but n times phi and that implies my li max is nothing but number of turns times b max times ac and that implies my number of turns is nothing but equal to li max by b max So, using this expression we can say that the number of turns to be used is nothing but n equal to li max by b max ac. Also, we need to ensure the units of these particular quantities if they are in SI units then all the things should be in SI units. Now after defining the number of turns we can then select the next important thing which is the air gap because we are considering that we are using a core with air gap so we have to now use the air gap because you know why we use air gap because we can then avoid saturation of the core material so that's why air gap is introduced so this air gap value can be not given directly as mu naught ac n square by l

$$B_{max} < B_{at} \quad L = \mu_0 A_C N^2 / L_g \quad K_v W_A \geq N A_w \quad R = \rho N MLT / A_w$$

Now, here we know our N value, we know our AC value from the selected core and we know our inductance value from there we can calculate our the length of the air gap. Again depending upon the units of this quantity one must have to ensure that the LG value is defined either in meter or in centimeter that one has to ensure that. So, this is way by which we can calculate the air gap. So, the first step is selecting the required core. The second step is defining the number of turns.

Now, the third step is defining the air gap and then after that comes the step number four which is evaluating the wire cross sectional area. which is nothing but aw less than equal to ku wa divided by n. Now, here again we have to ensure that whatever the unit of this wa the same will be the unit of aw and then using this aw value we can select appropriate We can select wire having required AWG or SWG values or you can say the required wire gauges. Again here we have not considered the AC effects like skin and proximity effect because we have assumed that the ripple in the inductor is very minimal and that's when the effect of the AC resistance in the losses is minimal. So here we have not considered any AC effects.

Here, assuming no AC effects. So, this is how one can design the inductor, where using this, we have obtained the core size, and after obtaining the core size, we have defined the number of turns required to obtain the required value of the inductance. After that, we have defined the air gap length which has to be introduced. After that, we have defined the AWG or wire sizes which are needed to actually wind the inductor and which can handle the required value of the current going through the inductor, such that the resistance offered by this wire is below the allowable losses in the inductor.

So, using this, we can define how we can physically realize our inductor, where we have selected the appropriate core size and the required number of turns. We have also calculated how much air gap length to introduce and then what the size of the wire should be to wind this particular inductor. And that is how one can obtain the inductor. Finally, once we get everything, we know our number of turns. Since we have already selected the core, we know our mean length per turn, and since we have already selected the wire size, we know the cross-sectional area of the wire. From there, we can calculate the resistance and then check if this resistance will correspond to a loss which is less than the defined copper loss or not, which is nothing but the copper loss or the overall inductor loss, as the core loss is very minimal. So, this V is nothing but we can find out by I squared times R.

$$\frac{A_C^2 W_A}{MLT} \geq \frac{\rho L^2 I_{max}^2}{B_{max}^2 R K_u}$$

So, whether this value of R is less than this particular defined copper loss or not—if it is not, then we will go back and start our design from step 1 by precisely selecting a slightly bigger core, which will give us different values of AC, LC, and WA. Then, we can use those AC, MLT, and WA terms to calculate the number of turns, the air gap length, and finally select the cross-sectional area of the wire. This is the iterative process one needs to go through to finally obtain the physical parameters related to the filter inductance and then physically realize that filter inductance. With this, we will finish our discussions related to the design steps for the filter inductance. We will see you in the next class with the next module, where we will discuss the different charging sequences when the charger gets plugged in, from the communication perspective and the connection perspective. We will discuss this from the next class onwards. Thank you for patiently listening to this lecture.