

CHARGING INFRASTRUCTURE

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Lecture-46

Lec 46: Transformer Design for Isolated DC-DC Converter - III

Hello everyone, welcome to lecture number 46 of this NPTEL lecture series on charging infrastructure. Today, we will discuss the continuation of our discussions from the last lectures related to transformer design. So, in the last class, we studied the core loss, which is given by

$$P_{core} = K_{core} (\Delta B)^\beta A_c L_c$$

where β is the peak AC flux density. This indicates that $P_{core} \propto (\Delta B)^\beta$ where β is the material property ranging from 2.5 to 2.7 for ferrite material. We then proceeded with our discussion and examined the maximum flux density, which is equal to the flux linkage with winding

$$\lambda_1 = \frac{1}{2N_1 A_c}$$

where N_1 is the number of turns of winding number one and A_c is the cross-sectional area of the core. From this relationship, we can derive

$$N_1 = \frac{\lambda_1}{2A_c \Delta B}$$

We know that core loss depends on ΔB or the peak AC flux density. Similarly, if we examine the total copper loss in the winding, since the copper loss occurs in the winding. The winding losses, if you observe, follow this particular relationship, where $P_{cu,total}$ is

$$P_{cu,total} \propto \left(\frac{1}{\Delta B} \right)^2$$

This indicates that increasing the peak AC flux density, or the flux swing in the core, will increase the core loss while reducing the copper loss in the winding. Now, we need to determine the optimal value of ΔB . From this curve, which plots losses versus ΔB or the peak value of AC flux density, we observe that as ΔB increases, $P_{cu,total}$ decreases while core loss increases.

Therefore, we need to find the optimal value of ΔB where the total transformer losses are minimized. The total losses, P_{total} , are the sum of $P_{cu,total}$ and P_{core} . We observe that P_{total} initially decreases and then starts increasing after a certain point, indicating an optimal value of ΔB where the total losses are minimal. To find this optimal value, we differentiate P_{total} with respect to ΔB and set it equal to zero. This will give us the optimal ΔB for which P_{total} is minimized. For this condition, performing the differentiation yields the expression where the derivative of core loss with respect to ΔB equals the negative derivative of $P_{cu,total}$ with respect to ΔB , giving us the optimal value of ΔB . This optimal value of ΔB ensures that the total transformer losses, comprising core loss and winding loss, are minimized.

Now, this is one way of optimizing or obtaining the optimum value of ΔB . You can perform further advanced optimization to obtain the best possible delta B for which the overall power losses in the transformer are minimal. Now, along with that, we have also seen that in the winding losses, there is a term called γ_j , which is the fraction of the area allotted for that particular winding. Since we have windings going from γ_1 to γ_k , there will be a corresponding fraction of area allotted in the window area of the transformer core for each winding. What we see is that there will be an optimum value of this γ_j for which the total copper loss will be minimal. As we increase γ_1 , the fraction of the area allotted to winding one, we observe that the copper loss reduces. This is primarily because as gamma one increases, the area allotted to winding one increases. For the same number of turns, we can use a thicker conductor, which reduces the copper losses in the winding. Similarly, at the same time, as γ_1 increases toward 1 (which represents the entire window area), the area allotted to windings 2 to k becomes very small. To achieve the required number of turns, the copper conductor must be smaller in size,

increasing the copper losses in the other windings. Thus, when we consider the total copper loss, there is an optimum value of gamma for which the total copper loss is minimal.

The total copper loss is minimal. So, one must perform optimization to obtain the optimum value of gamma such that the total copper losses, or the total winding losses, are minimal. So, this is what we have understood. So, in total, what we understood is that we must obtain the optimum value of gamma such that our total copper loss ($P_{cu,total}$) is minimal. We must also obtain the optimum value of peak AC flux density such that the total losses in the transformer are minimized—meaning the summation of the core loss and the copper loss. At the same time, for that optimum value of ΔB ,

we can then calculate the number of turns in the primary winding (or winding number 1) and, using the turns ratio expressions, obtain the number of turns in the other windings as well. Now, let us try to summarize the different points we have covered up till now. So, when we summarize, there are some quantities which are specified—meaning they can be easily obtained from the specifications. And there are certain quantities we must obtain, such as the core dimensions. Along with that, we must also obtain the peak AC flux density—specifically, the optimum peak AC flux density—such that the overall losses in the transformer are minimal.

Similarly, we have to also obtain the wire sizes or you can say the area of cross section of the wires. That also we have to find out. And then the number of turns, some things we have to find out. So, those were the design outcomes. So let us try to see what are the specified quantities we have.

So if we talk about the specified quantities, what we have is we have wire resistivity. Again, it is dependent on the material of the wire if it is a copper then that has a specified value and this you know it is defined by rho and we can define using ohm centimeter so if it is a copper wire Then, rho value could be 1.724×10^{-6} ohm centimeter at 25 degrees Celsius. Again, it depends upon the temperature and the material which is being used to actually realize that particular wire.

Similarly, the other specified quantity is depending upon the operation of the circuit in which this transformer is being kept. One can estimate the total RMS value winding current that means

current in the winding and that they can refer it to the primary sign or you can say the winding one which we can define the term called as the

$$I_{total} = \frac{N_j}{N_1} \times i_1 = \left(\frac{N_j}{N_1^2} \times i_1^2 \right)$$

Now, using that you know this we can use this particular expression in this particular you know in this for this particular expression that means n_j by n_1 square into i_1 square.

$$I_{total} = \left(\frac{N_j}{N_1^2} \times i_1^2 \right)$$

to represent it to be I_{total} terminology

so that's what is the another one which is the total rms current referred to the winding number was sorry this is the i_j so it depends upon the what is the rms current in different windings we have. Now this particular i_j you can for every winding you can calculate and then you can refer it to the primary side to obtain the total rms winding current what we have now after that you can define the desired turns ratio Now, this desired turns ratio you can obtain it depending upon the circuit operation and depending upon the nominal input and output voltages and you can define it to be N_2 by N_1 , N_3 by N_1 and so on $\frac{N_k}{N_1}$ by. So, this particular value is obtained using the operation of the circuit and knowing the sum of the specification input and output voltages. Now, after knowing these things, so this is the turns ratio which we will be using it to put it in this term and then obtain the total copper losses. Then, another quantity which you can define is nothing but the applied volt second of winding one and depending upon the operation of that particular circuit in which the transformer is being kept.

So, we can then write applied volt second of winding. winding one and that we have already defined it to be a flux linkage which is nothing but $\int V_1(t)dt$ where V_1 is nothing but a arbitrary periodic signal and this is for the positive portion of cycle because if we consider for negative portion then overall it may lead to zero so we can just do it for the positive portion of the cycle and this is nothing but defined in terms of volt second now after this there is another specified quantity which you can define which is nothing but allowed total power loss which is you can

say p total allowed and now this you can obtain by doing the loss budgeting of your entire power converter which you are using and then you can define what could be the maximum power loss in transformer you can afford and that is one of the specification you can define depending upon the overall converter specification generally power converter specification the efficiency term has been defined so from there you can do different loss weighting like semiconductor losses and passive losses and then you can define the maximum power loss which you can allow in the transformer then there is another term which you can define the specified value winding fill factor that is again

you know K_u value it is the constant K_u value and this is again you know depending upon what kind of winding you are doing depending upon the specification you can find out and then core loss exponent It is again β , again 2.5 to 2.7 for high frequency ferrite materials, for different high frequency ferrite material, it is in this range. However, most precise information you can get it from core manufacturer data sheet. Then you can also define core loss coefficient. this you can get it from core loss curve by doing the curve fitting in the core loss versus ΔB curve which is provided by the core loss manufacturer that is nothing but k core and again this is a constant terminology now these are some of the specified quantities we have you know which will be given from the different specification values you can easily predict these are the specified quantities

Now, these are some of the quantities which you can obtain from the specification, depending upon the kind of material you are selecting, the kind of circuit you have, and the operation of the circuit. You can define this quantity. Now, there are certain outcomes which you have to obtain. You need to find out certain quantities, particularly the core dimensions, peak AC flux density, wire sizes, and the specific number of turns. We have defined the turns ratio, but we have not defined the specific number of turns in individual windings. So, the design outcomes, if you see them, are nothing but your core. Cross-sectional area, defined as A_c , the term we have defined, then we have core window area, which is W_a , which we have defined. Then we have also seen mean length per turn. Which is nothing but MLT. Then we have defined the magnetic path length, which is L_c .

Now, the moment you select a particular core, all these quantities will be defined in the core datasheet. So, these are the core dimensions. Then, finally, we also have to evaluate peak AC

flux density. Which is, you know, ΔB , and which is in terms of Tesla. So, that is the unit of ΔB we are talking about, and this ΔB is the one for which we have the minimum total loss in the transformer.

So, we have to then calculate the optimum value of ΔB , and from there, we can define the core geometrical constant. From there, we can then start our transformer design. So, after this, we can then define our wire size. Obviously, here we are talking about the cross-sectional area of the wire, which also has to be defined because we will calculate the number of turns and know the mean length per turn, but still, we don't know the actual size of the wire. That we will define as aw_1 , Aw_2 , up to aw_k for k winding, and along with that, you also need to know what is the Number of turns in each winding you need to have such that you can obtain the required operation or the required transformer. So, these are some of the outcomes which we have to define.

We have to define core dimensions that means particularly we have to define which core size we have to select. We have to define the optimum value of A_c flux generally such that the total loss is minimal. We have to define what will be the size of the wire which will be using it to bound in the winding and then we have to define the exact number of turns which will be nearly in the different windings. And now once we know all those things we can then physically realize our transformer which we can use it in isolated DC-DC converter. Now let us define our transformer design procedure.

Let us define our first step of transformer design procedure to physically obtain the transformer. Now in that the first and foremost thing is we need to select the appropriate core. Select the core. That means let's say we select the E base core. e-waste core then we have several types of ee core that means we have ee5 we have ee25 we have ee30 and so on now ee core means what I'm talking about is this one

Something like this. Two EE cores you can take and put them like this. And you can place them on a bobbin. And over that bobbin, you can do the winding such that you will get the required transformer. So, the first and foremost thing is to select the required core.

What will be the size of the core? Whether it is an EE5 core, EE25, EE30. So, the first, let's say, you know, it starts with, we have to select the core. For example, let's say you have

selected an EE25 core. your starting point is e25 core again the transformer design procedure is not the single step procedure it is a multi-step procedure so we have to do several iteration to reach to a best possible transformer design so the first and foremost thing is you select the required dimension of the core let's say you selected the e25 core

The moment you selected the E25 core from the core data sheet, what you can obtain is, you can obtain the area of cross section of the core. You can get the Lc value, magnetic path length. You will get the mean length per ton value. You can get the window area. Now, you have also selected the material of the core.

So, the moment you select the material of the core, you know your beta value, you know your Kcore value. so this is from the core material from the core material data sheet you can select the beta value and k core value that so this is the first iteration you have done you have selected one core i mean depending upon design procedure you can able to decide that whether that particular core is the smallest core or not or whether we can further go below see the our idea is what our idea is to obtain the best possible transformer design that means we can able to obtain the smallest transformer design because for that purpose only we are going for high frequency isolation in the isolated dc-dc converter and at the same time we wanted it to ensure that the losses in the transformer will be as minimal as possible so both the things has to be obtained so that's why we our aim is to obtain the smallest of the smallest code which need to be used to obtain the required transformer design we satisfy the required condition at the same time able to ensure that specifications are been met so this is our step number one so with this our first iteration the values of ac lc mlt wa and d10 k code is been obtained So now comes the step number two.

In step number two, what we will do is evaluate the core loss term, which is k core. Now, here we will do it in terms of ΔB . Still, we do not know what delta B is. We will just define this particular term with respect to ΔB because we have not yet done optimization to obtain the optimal value of ΔB , So, we will just write—or rather, define—our expression in terms of ΔB , and then we will evaluate it. Our total copper loss in the winding, or you can say total winding losses, is defined again. We will define this particular

$$P_{cu,total} = \frac{\rho(MLT)}{w_a k_u N_1}$$

$$P_{cu,total} \propto \left(\frac{1}{\Delta B}\right)^2$$

Now, here when we are defining the PCU total, we will ensure that this gamma j value is the optimum value of gamma j. That means gamma j optimal, such that the pcu total is the minimum value that we have to define. And again, this particular thing is in terms of ΔB .

Still, we don't know what our ΔB term will be. Now, here when we are obtaining this optimum value of γ_j , we can apply certain optimization principles. One such optimization principle is defined in the references, like recurrence multiplier. Optimization method or someone can use the advanced optimization method to obtain the best possible gamma j or to obtain the best possible fraction of area routed to that particular winding, which will lead to the minimal overall total copper losses. That's what we will get, and that's when p core and p2 total are defined. Now, after that, what we will do is go to step number three, where we will do the optimization for ΔB . We will obtain the optimum value of ΔB . Again, one simplistic method is you can do it by setting p total divided by $\Delta B = 0$, where our p total is nothing but our p core plus total copper loss. This will imply that what we will get is our ΔB . Now, when we solve this, what we will get is the ΔB optimal. Once we obtain our ΔB optimal, let me write down what we are getting: we will get the ΔB optimum value here. From here, we will get the γ_j , optimum value.

And here, we will get the ΔB optimum value. After this, we will go ahead and do step number four, where we will then evaluate once we know our delta v optimum. We can then obtain our Ptotal value, which is the total loss in the transformer, which is nothing but pcu total. We will obtain it at the delta b optimum point, which we have obtained in step number three. So, we can put this from step number three, and this we can put from step number two. We will get this value at the same time we get the p core value, which is obviously at the optimum value of delta b. The p total value we are obtaining here must be less than or equal to Ptotal allow, which is the allowed total loss in the transformer, which we obtain from the loss budgeting. That means it is one of the specified quantities. So now, what we have to do is we have obtained the delta v optimum value and from there calculated the p total. This Ptotal we obtain should be such that it is less than the allowable total loss in the transformer—that means it should be less than the specified value, which we obtain from the specification. If this particular condition is not met, then what you can do is go ahead and select the next bigger core, which is nothing but, let's say,

if we are selecting an e25, then the next bigger core is e30. Then again, follow steps two, three, and four, and see at last whether your p total is less than p total allow or not. If it is not, then again you go back and select the next bigger core. This procedure keeps on going until you reach a point where you obtain the minimal total loss in the transformer, less than the allowable loss in the transformer.

and that is when it's a iterative process it is a multi-step process now the optimization need to be done such that to obtain the optimum value of ΔB and the optimum value of gamma j which is the fraction of the area allotted to the windings and so on now once we know this thing what we have is we have obtained our delta b optimum value now this condition is actually defines this condition defines whether the next iteration is to be done or not. Now, if this condition is satisfied, then we can go ahead and then define the step number 5. We can define the number of turns in the winding now how we can obtain the number of turns so for that for the first winding we know that from our discussions in the previous classes n_1 is nothing but $\lambda \frac{1}{2} \Delta B_{ac}$ and here our this value is the specified quantity that means depending upon the operation of the circuit in which this transformer is being used

This is the value from the selected core, from selected core size. This is the delta B optimum value which we obtained from the optimization in step number 3 and using that one we can calculate our N_1 and from there we can calculate the N_2 by doing the nothing but turns ratio as our turns ratio of the specified quantity multiplied by N_1 . So, this is the specified quantity. again depends upon the operation of the circuit and the nominal winding voltages which are being given. Now, after that you can again calculate N_3 which is N_3 by N_1 again turns ratio between the winding 3 and 1 and then similarly you can do it for N_k which is N_k by N_1 into N_1 .

now again these are all now again these are all the specified quantity now using this we what we can get is we can now obtain our n_1 n_2 n_3 and so on and k and this will lead to the next step which is to obtain the area of cross section of the wire or what will be the wire sizes we have to select so we can now after this we can then obtain obtain the area of cross section of wires by the formula which is AW_1 should be less than equal to gamma 1 optimum value into $K_u W_A$ by N_1 . There if you see you know generally this is obtained from the core dimension. on the selected core because once we select one core we know our w_a this is from step number four we obtain this value we can obtain it from step number two by doing the optimization such that

the total copper loss in the winding is at its minimum value and this is nothing but the winding fill factor which is you know to accommodate the area which got lost while doing the winding for example if you take the circular conductor and if we place them nearby each other then still we will not be able to use the entire space which has been allotted to that particular winding because you know this area is still vacant and we cannot use that so obviously we have to define a term called as the

winding field factor which actually accommodates this area which will not be used and obviously K_u is always less than 1. Depends upon what kind of windings these are with there. Also in the windings we have the enamel coating like this. We have enamel coating such that nearby conductors are not short circuited or does not come in contact with each other. Now if we place the windings like this with enamel coating in them then there are some areas obviously there are areas which is not been used.

This is your enamel coating. So, it is just a bare copper wire with the enamel coating which is an insulation coating and you know this is the area which is not been used because you know they are circular conductor they cannot occupy the entire square area. So, there are some spaces which are actually lost from the area which is been allotted to that particular winding. So, that is why fill factor has to be considered that portion of area has to be considered which got lost while doing the winding or by placing the windings in the area which is been allotted. So, that is why if you see this γ_1 optimum K_u and W_a is the area which is been taken up by the winding number 1 and this has to be greater than equal to the number of turns multiplied by the area which is been taken up by the individual wire.

Then only we can able to accumulate that many number of turns in the allotted area in that particular window of that particular transformer using this particular relationship we can get aw_1 and similarly we will get the aw_2 also by doing the optimal $k_u w_a$ by n_2 and so on you can define for k th winding γ_k optimum $k_u w_a$ by n_k now using this formula what you will get is you will get aw_1 aw_2 you will get aw_3 and then using this value you can then select the appropriate wire gauges you know generally wire gauges are defined in awg or in swg depending upon it is which part of the world it is american wire gauge or it is standard wire gauge and using that thing you can select the appropriate appropriate wire gauge can be selected it could be you know awg 8 10 and so on you know it keeps on going awg 40 44 also

you have so all those wire gauges there are there from that list which is a very standard you know list you form there the you can select those wire gauges which satisfy this particular criteria and then select the maximum area of cross section of the wire which satisfy this criteria so using this one you can then select the wire sizes and then using that you can actually able to then purchase the required wire size and then you can use that to wind your transformer because you already do number of turns you already know what is a core size

And just you have to bought the required wire sizes and then bond it. Now in the entire thing what we have assumed is that we have assumed that the wire geometry and the skin and proximity effect are are not there that means we have already considered winding losses what we have defined is just $i^2 \rho l$ by a which is just the losses corresponds to the dc excitation but generally these transformers are applied with a high frequency ac so accordingly that approximations can be taken and then required thing can be obtained similarly we have not considered any wired geometry What I mean by that is we don't consider how the wires are laid down particularly in case of Litz wire we don't know that so that part also is not being considered or we have assumed that they are not there and so that has simplified our transformer design procedure. now one can also use other transformer design procedure one simplistic way is to obtain the transformer design using the area product method however in area product method we assume that the flux swing is between the maximum positive b_{max} value to the negative b_{max} value there we have not done any optimization where our overall losses is reduced so this is the next kind of transformer design where we can reduce the overall losses as well

Now, there are also another kind of transformer design procedures which have been there where one can also accommodate the AC effects, the skin effect and the proximity effect and then design the transformer according to that. Further, here we have assumed that the excitations are nearly sinusoidal excitation. One can also consider the excitation could be the square wave excitation and then can generalize that particular process. the value of core loss using the improved descendants equations and can obtain the more real transformer design so there are several design transformer design procedures are there where the simplest thing one is the helioproject method where the maximum flux swing we have considered however in this case we have assumed that the flux swing is such that we will get the minimal total losses that

transform that means we have the optimum value of maximum flux swing and that is when we will get the minimum total losses in a transformer similarly one can also consider the skin effect the proximity effects or you can say the ac loss effects and then can able to design the transformer design procedure so what we got following our design procedure we have got the core dimensions

which is nothing but our AC, LC, WA, MLT value. Then we have got the peak AC flux density which is nothing but delta V optimum value. We have also got gamma J optimum value for which our PCU total is minimal or is minimum and this is done for which the P total is minimal. Then after that we have got our AW1, our AW2 that means area of cross section of wires.

and awk we have got number of turns n1 n2 n3 goes up to nk and that is when using this particular things we will be in a position to now physically realize our transformer so using all these particular quantities we have all the things with us we can select the required wires we can select the required core purchase the required corresponding bobbin and then actually physically realize our transformer and then put it in the converter in which it has to go and then do the required operation and finally after doing that one can then do let's say if the transformer let's say if you have the transformer if you draw the model of the transformer so it is lm1 refer to primary side im1 let's say it is N1 N2 I1 current is going and let's see you know resistance of the winding is 1 on the secondary side it is R2 and it is the output is going similarly you have other windings as well let us draw the kth winding Rk which has number of turns Nk So, then we can then do a simple design check and see whether our values are within our required specification or not. So, for that what you can do is you can also calculate you know magnetizing inductance refer to primary

Here we are assuming the winding one to be primary. Let us say here we are applying V1 of T voltage. So, refer to primary and refer to primary of winding one. We can write LM1 to be mu, you know mu C which is mu naught mu R times N1 square AC by LC. Similarly, you can then find out peak AC magnetizing current.

$$L_m = \mu_c \mu_r \frac{N_1^2 A_c}{l_c}$$

which you can get it IM peak to be lambda 1 by 2 lm you can easily lm1 refer to primary side this is obviously refer to primary side

$$I_{m,peak} = \frac{\lambda}{2L_m}$$

and then finally you can calculate the winding resistances obviously these are DC resistance corresponds to the DC excitation which is R1 which is nothing

$$R_1 = \rho \frac{N_1 MLT}{A_{w1}}$$

$$R_k = \rho \frac{N_k MLT}{A_{wk}}$$

Now using this thing once you know the R_1 to R_k you can then evaluate you know losses which is you know both core as well as copper because all the dimensions and everything from the core manufacturer data sheet you can calculate the core loss per unit volume and you since you have already selected these dimensions of the core you know what will be the volume and from there you can easily calculate the core loss because you also know what will be your delta b and obviously you know what will be the frequency of excitation of this v1 voltage so from there you can easily calculate the core loss and for the copper loss already in using the specification what will be the rms current in different windings and then we know the resistance we can calculate the resistances for the different winding and then we can do i square r loss again here we have not considered the ac effect we have not considered the ac losses are here you can consider and that will be another kind of design procedures you can look for so you can evaluate the losses and then check and then check if it is within the allowed limit of

Power loss or Ptotal allowed, which we have already considered, is one of the specified values that you know. You can get it by doing the loss budgeting of your converter. You can define how much loss you can afford. To have it in the transformer, you can define the core dimensions, number of turns, and the cross-sectional area of the wires used for winding. From there, you can calculate the copper loss, sum both losses, and check whether it is within the specified limit or not. If it is within the limit, it is good. If not, you go back and select the next bigger core. For

now, we have selected a Ke25 core. You can then select an E30 core and repeat those steps to calculate the number of turns, the wire cross-sectional area (A_w), and ΔB . Finally, check if it is okay. If so, you can use that core and winding to physically realize your transformer. The transformer design process is a multi-step approach. Here, we have not considered the AC effects or the losses corresponding to high frequencies. You can also consider those and understand the winding pattern, how far the windings should be placed, and the number of turns in different winding layers. Accordingly, you can decide and design your transformer physically.

This is all about transformer design. In the next lecture, we will cover inductor design. These designs are important because, in our actual DC-DC converter, we extensively use transformers and DC inductors to perform the required operation. Thank you very much for patiently listening to this lecture. We will meet you in the next lecture.