Design and Simulation of DC-DC converters using open source tools

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Lecture – 16
Transformer Design

In this video capsule, we shall begin our discussion on the magnetic. We need to design the forward converter transformer and then following that we need to design the magnetics for the inductor. So, these two important topics we will discuss, we will see how we go about choosing the core for transformer and then later on for the inductor, and also to decide on the number of turns the thickness of the copper wire that you would use and all those things for both the forward converter transformer and the inductor.

For this we will use an approach called the area product approach and the follow through in a systematic step by step manner the magnetic is topic which is generally difficult to understand because we are not able to see within the magnetics, but there are few simple rules and if we follow them, we generally will not go wrong and transformers, as you see here this is a low frequency transformer used in 50 hertz applications, but this is not what we would use in switch mode power semi conductor applications where we would use a high frequency core like the ferrite cores and therefore, designing the physical magnetics and trying to relate it to the electrical parameters of the voltages in the current that we have been looking at, will now is the main core issue in the design of this transformer and the inductor and that is what we will be doing in this video capsule.

I have here a transformer with me, this is low frequency transformer and you see here that it is composed of stack laminations these are thin laminations stacked together, and then varnish is applied to keep the air pockets out and these laminations are made of steel. In fact, they are made of silicon steel and they are called cold rolled silicon steel and they have a maximum flux density capability of around one point tesla.

So, these are the common transformers which you would have seen, but these are for low frequency applications or 50 hertz applications and if rotate it over, you would probably see that this is where the winding is housed and this is a parchment paper and underneath is the copper winding both the primary and the secondary are wound here and then they come out of and then terminated here. So, this is the low frequency transformer just to give you an idea, how a normal 50 hertz transformer looks like, but for switched mode power supply applications we will not be using this material, we will be using a high frequency material something like what is called as the ferrite core.

I have here one more example of ferrite cores, you see that this is a ferrite core what you see here is a ferrite core; this is a round topology ferrite core it is called hot core. In fact, this is made by the student in the laboratory and you see here, there is a former and within the former there is the copper coils wound. In fact, you can get a much more clearer picture of a broken ferrite, core here you see that the ferrite core is broken and within that is the former this is the circular bobbin and within the bobbin you have the windings primary and the secondary windings.

So, something like this type of core material will be using and what is very common in the switched mode power converter or DC-DC converter world is the e e type of core. So, this is an e e type of core. So, this e e type of core comes in a sphere, you will see that two e e’s are joined together like that and this forms the e e core and you should understand that the area which is inside the area of this rectangle which I am pointing out is the window area; one rectangle not both is the window area a w which I just mentioned before and all the windings will have to fit in this window area and if I remove this two parts and then if I show to you the facing part this portion what you see is the core cross section area.

When you put the winding here and the flux flows in orthogonally to this core cross section. This is the core cross section area and this then split's into two half core cross sections. So, actually this is a bobbin and on the bobbin the windings are wound. So, then after winding the bobbins are inserted into the core to form a completed transformer. So, you will see that here this portion is the window area which I was saying and the windings will appear.

So, if I make a cut section you will just see circles of the copper here in the window area and apparently the thickness of the wires will be determined by the amount of power and the current that it has to handle. So, understand when I mean window area, it is this area and when I mean core cross section area it is the core cross section area of the core itself what you would be using. So, with this visual background, let us go back to our notepad and start writing the equations for design.

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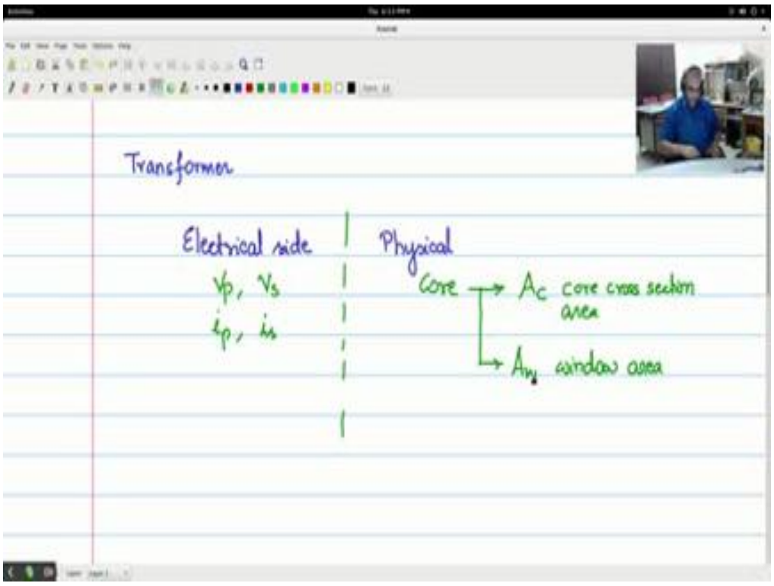

We shall first take up the design of the transformer to start with and then later on take up the inductor design. So, in the transformer design on the electrical side I will say from the electrical perceptive we have the following data with us, we have the voltage of the primary, voltage of the secondary because of the turns ratio current flowing through the primary, current flowing through the secondary and the power and the capability of the transformer. So, on the electrical side these are the aspects that we have with us.

Now, on the physical or the mechanical side we have a core and if you look at the core data sheets, there are two important parameters that would be given; one is called as the core cross section area, let us see what that means, this is the core cross section area and there is another important parameter given in the data sheets called A w also called the window area.

So, on the physical side we have the core cross section area and the window area on the electrical side. We have the voltages from the currents known to us, how do we connect these two and come up with that choice of a selection of a core, now that is the exercise. So, before we go further in the design I would like to show some cores, so that you get an idea of what this core cross section area is one; what is this window area? It will help you in identifying these two areas in any given core and also help you in selection of the cores. So, let us begin by relating voltage and A c the core cross section area.

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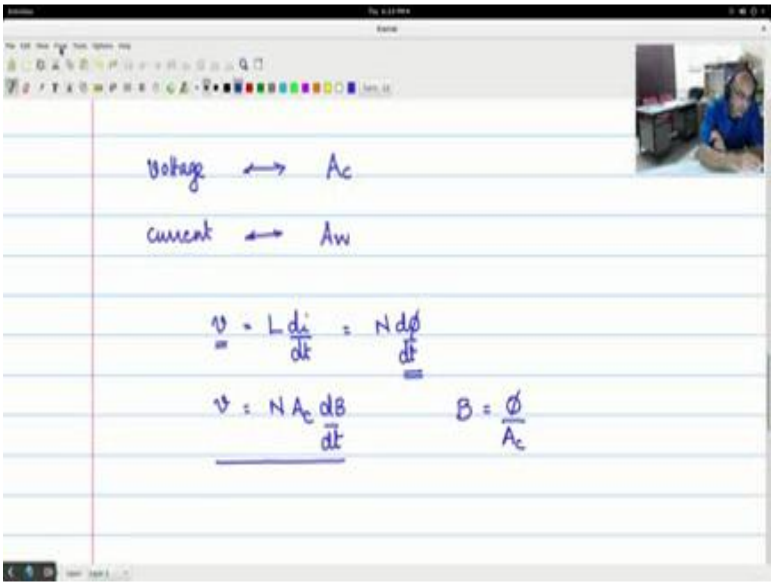

voltage $\longleftrightarrow$ A_c

current $\longleftrightarrow$ A_w

$$v = L\frac{di}{dt} = N\frac{d\phi}{dt}$$

$$v = N A_c \frac{dB}{dt} \qquad B = \frac{\phi}{A_c}$$

The voltage and the A c can be related. So, the core cross section area will give you an idea on the voltage withstanding capability of the windings, and the current carrying capability is determined by the thickness of the gauge of the copper that you use for the winding and they have to be accommodated within the window area. So, the current and the window area will get related. So, these two relations we shall establish and in doing that we will actually be arriving at the design for the transformer and similarly for the inductor.

We know from parleys law V is equal to L d i by d t and which is equal to N d phi by d t. So, you see that the electrical parameter gets related to the parameter within the magnetic material which is the flux. So, taking those two we see that voltage is related by N A c d B by d t, where B is the flux density; flux density B is actually the flux by the core cross section area. So, these are fundamental relationship I will be reviewing them as we go along this in case you are forgotten you can probably start recalling them.

Now, this is an important relationship we will use now consider the forward transformer. So, in the case of the forward transformer as I have said this is the primary, which is connected to V in and then you have the secondary and you also have the third winding, when the demarcate is winding, we will come to that later because that contains almost negligible power.

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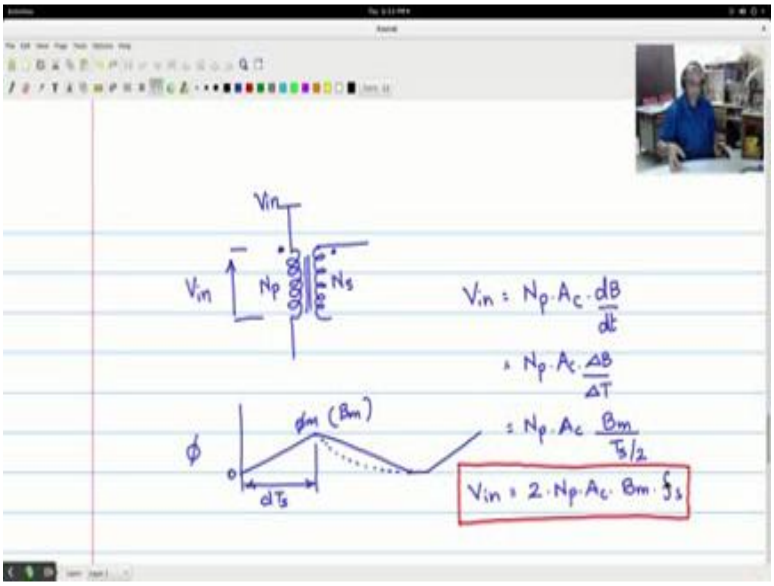

$$V_{in} = N_p \cdot A_c \cdot \frac{dB}{dt}$$
$$= N_p \cdot A_c \cdot \frac{\Delta B}{\Delta T}$$
$$= N_p \cdot A_c \, \frac{B_m}{T_s/2}$$
$$\boxed{V_{in} = 2 \cdot N_p \cdot A_c \cdot B_m \cdot f_s}$$

So, let us say this winding is having N p number of turns and this is having N s number of turns and across this winding when the transistor is formed, you will see a voltage of V in. Now, we will apply that V in is equal to N p into A c core cross section area d B by d t and which is equal to N p into A c and because the flux transitions are linear in nature I will without loss of generality I could say it is delta B by delta t. Now, if you look at the forward converter we saw the flux file wave form take similar wave shape like the current. So, we saw that flux went from 0 to phi m and flux either went in a linear way or in an exponential decay way depending upon whether it was a loss flux again to 0 and then after some time it again next cycle started going this fashion.

So, there is a swing of 0 to phi m and if you take in terms of B there is a swing of 0 to B m B is nothing, but phi m by A c and we have already put A c there this is N p into A c it can swing a maximum of B m and in what time the time period is this this is d t s and in the case of the forward converter, we know that the on time cannot go beyond 50 percent of the duty cycle, 50 percent of the total period. So, d is 0.5 max therefore, let us say worst case this can be t s by 2. So, V in is equal to 2 times N p A c B m f s. So, I will correct this to A c now this is a very important relationship this is one relationship which relates the voltage to many other physical parameters. So, in a voltage is related to number of turn core cross section area the magnetic materials B m.

So, in the case of ferrites B m will be around 0.2 tesla, you see the saturating flux density for these ferrites is point three tesla. So, allow one point two tesla and the frequency the switching frequency it would be ten kilohertz twenty kilohertz depending upon what you are setting as the switching frequency. So, this is one part of our work done, we now have to relate the current to the window area which we will do now.

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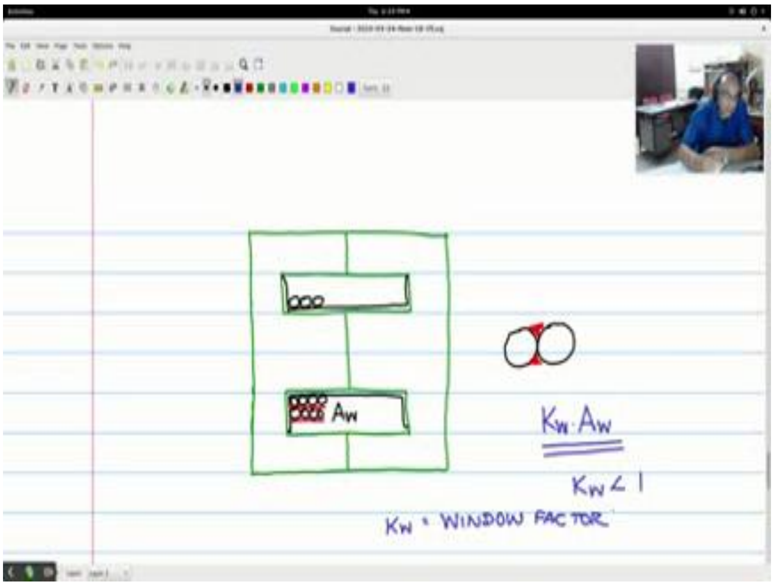

Now, the windings will have to fit within the window area. So, I will give the example of the e e core can be drawn the cross section of the e e core I am going to draw that and this is in this fashion I think we saw this just now physically, but I am going to draw this.

So, that it becomes easier to explain external you have the two e e parts here, now it is complete you see that two e sections joining together to form the core and these two rectangles that you are seeing or the window area rectangles this area here is called the window area.

However, you should know you saw that there was a bobbin; there is a part of the window area which goes off for bobbin. So, let us say there is a part of wave which goes off for bobbin and then the windings are placed in this fashion. When you are winding that comes on both sides and both sides you see the bobbin coming into the picture, the windings I will circle the bobbin in this fashion, you will notice that when you are placing to conductors there will be gaps here this are not filled.

So, this is also loss of some of the area, and if you are having multiple windings primary secondary one secondary two, on every layer is separated by insulation layer then you will have another secondary and if you are having multiple secondary's you will have one more layer of insulation and this also will eat up into the available window area. So, what you should understand is the whole window area is not available to you, there is a factor K w.

Now, K w is less than 1 and K w A w is the available window area. So, it is lesser than much lesser than K w. So, K w is called the window factor and this window factor can vary from transformer application to application, but it general it goes most on the experience.

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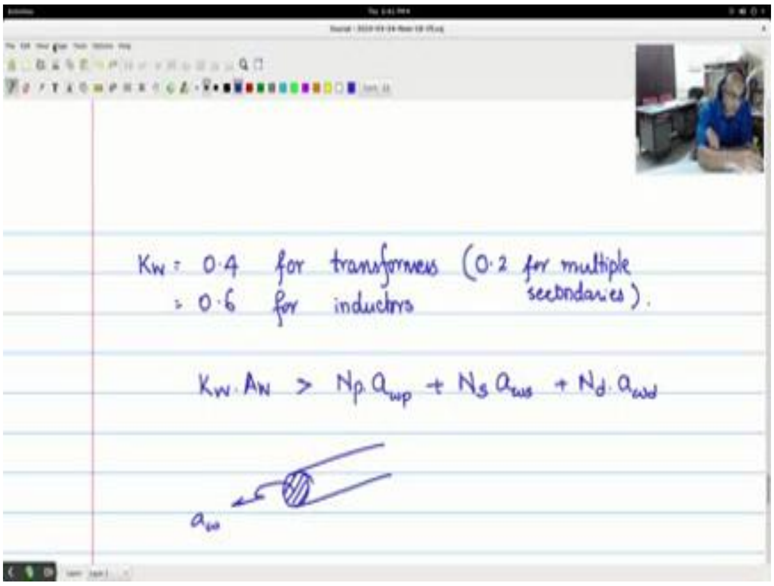

$K_w = 0.4$ for transformers (0.2 for multiple secondaries).

$= 0.6$ for inductors

$$K_w \cdot A_w > N_p \cdot a_{wp} + N_s\, a_{ws} + N_d \cdot a_{wd}$$

So, K w you can take it as point four for transformers two winding or three winding transformers and is equal to 0.6 for inductors; inductors have this normally single winding and there are no insulation between windings and things like that and therefore, you can utilize the window area much better. Also, remember that if there are multiple windings the K w window factor can go as low as 0.2 for multiple secondary’s multiple. So, these are some things that you need to take into account.

So, K w a w should fit one should be greater than it should fit N p number of turns with wire cross section area of the primary wire plus N s number of turns with wire cross section of the secondary wire plus N d number of turns of the demagnetizing winding the wire cross section of demagnetizing wire. So, when I say wire cross section area when I am having a copper conductor. So, this is the wire cross section area A w. So, it could be A w p for primary wire cross section area A s w for the secondary wire cross section area A w p or the way the wires come also we can enamel around that. So, that it insulates when you are winding the touching windings should not become short circuit. So, it is enameled and insulated that way the above also is another possible or. So, window area, this relationship is important now let us say.

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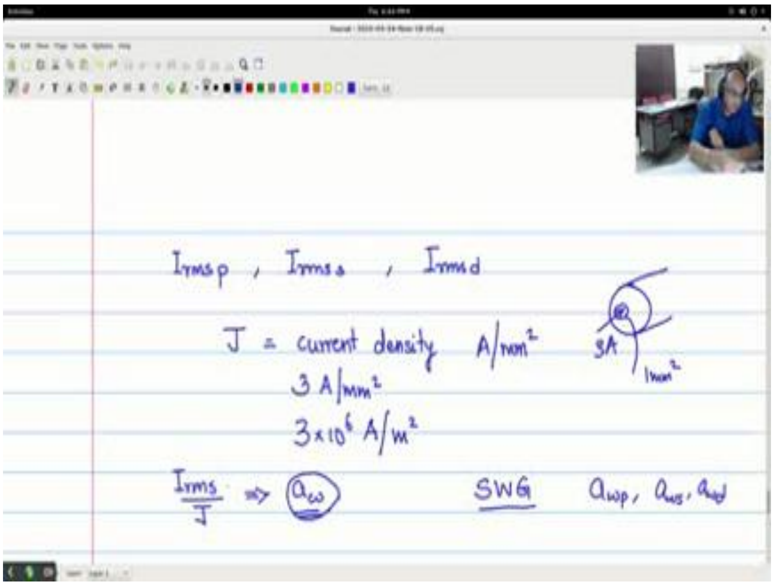

I_{rmsp} , I_{rmss} , I_{rmsd}

J = current density A/mm^2

$3\ A/mm^2$

$3 \times 10^6\ A/m^2$

$\frac{I_{rms}}{J} \Rightarrow \boxed{a_w}$

SWG a_{wp}, a_{ws}, a_{wd}

For example, we know that r m s value of current that should flow through each of the windings. So, r m s value of current flowing through the primary, we know that from the electrical perceptive r m s value of the current flowing the secondary is known r m s value of the current flowing through the demagnetizing winding. So, if you know that there is another new term that I am going to introduce called J, you may or may not have used it. J is called the current density for different materials like copper aluminum there is a particular current density that is allowed as a standard some international standard. So, this is generally in terms of amps per mm square.

So, generally for a default by stocking value you can take 3 amps per mm square, you can allow three amps per mm square for m every mm square a cross section area you can allow three amps for every one mm square of cross section area of the conductor. So, this will work to be 3 into 10 to the power of 6 amps per meter square in s i unit's. So, this is the current density. So, current density is something once copper you have decided you are going to use copper conductor to start with the amp per mm square people in the industry depending upon the quality of the manufacture therefore, you have to 6 amp per mm square

So, the current density I r m s value divide by J will give you the area of cross section of the wire. So, you will go and look into the data sheet and check for the wire gauge size. It is called standard wire gauge size in the wire data sheet or wire table or you can also go on into the internet and use the standard wire gauge table, you know the value of the r m s, you know what should be the current density which is in ampere mm square or ampere meter square. You will calculate some wire cross section area requirement, you go into the wire table standard wire gauge table and pick that wire gauge which has a cross section area greater than this calculated and set that one as A w p or A w s or A w d depending upon the depending upon the which winding you are going to use for.

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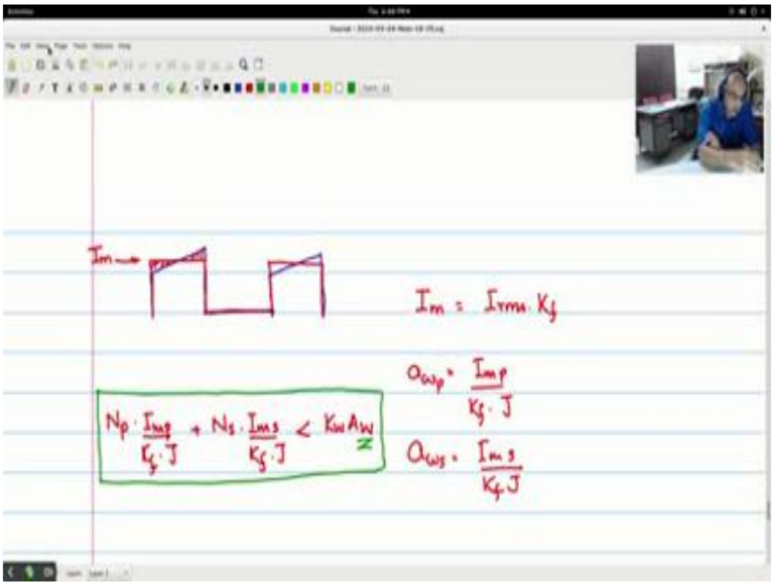

$$I_m = I_{rms} \cdot K_f$$

$$a_{wp} = \frac{I_{mp}}{K_f \cdot J}$$

$$a_{ws} = \frac{I_{ms}}{K_f J}$$

$$\boxed{N_p \cdot \frac{I_{mp}}{K_f \cdot J} + N_s \cdot \frac{I_{ms}}{K_f \cdot J} < \underset{=}{K_w A_w}}$$

So, now what we shall do is I will put it as in this forms, I will take the peak value in the case of the forward converter. We have the currents flowing in this fashion we have the currents flowing in this fashion. So, I am going to equate it the more you take the equivalent current as square current within this on time, there is this area is same as this area and this can be taken as let us say I m.

So, I r m s value will I will can be taken as the peak value into root of root of the duty cycle or you can you could say I r m s into I r m s is equal to I m into form factor and form factor in the case of square wave form is one. So, as per cross section are will be I m sorry K m sorry I should have done it in the other way I m equals I r m s into K f in the form factor. So, I m by K f J will be the wire cross section. So, if it is for primary this will be I'm for the primary if it is for secondary it be I m for secondary by K f J and so on and all this N p number of turns into I m p by K f J plus N s number of turns I m s by K f J should all be less than K w A w, now that is another relationship which relates A w with the current parameter K f J is the current density and the number of turns. Now, these two relationships one with A w and the other with A c core cross section area are the core relationship that we will use.

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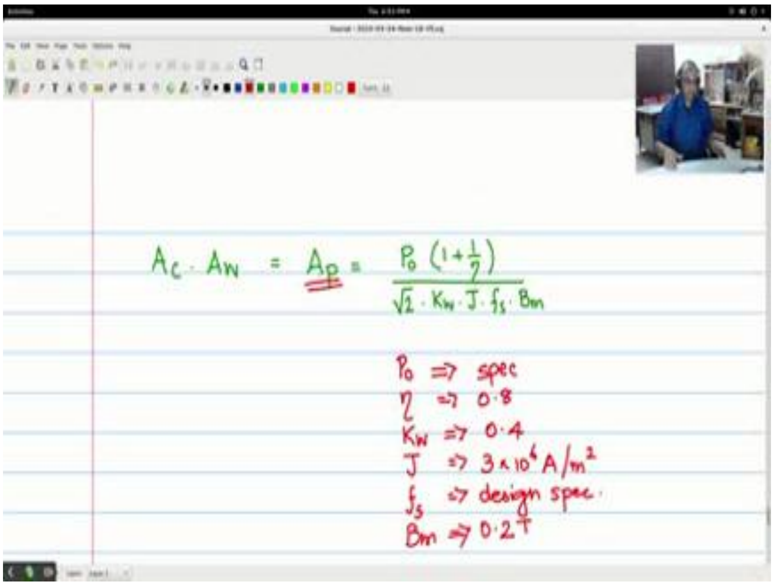

$$A_c \cdot A_w = \underline{\underline{A_p}} = \frac{P_o\left(1+\frac{1}{\eta}\right)}{\sqrt{2}\cdot K_w \cdot J \cdot f_s \cdot B_m}$$

$P_o \Rightarrow$ spec

$\eta \Rightarrow 0.8$

$K_w \Rightarrow 0.4$

$J \Rightarrow 3\times10^6\ A/m^2$

$f_s \Rightarrow$ design spec.

$B_m \Rightarrow 0.2\ T$

So, if I take the product one is A c into A w, now A c into A w will give you a product called area product A p this is the meter to the power of four. This product is this area product is a parameter that you can use for choosing the core. So, if you look at the core data sheet there is a parameter for area product sometime it is given or A c and A w will be given you will multiply and find out the area product. So, you can list out the area product and you can choose that area product which is higher than next higher than the calculated area product.

So, you can use you can derive with those two equations for each of the transformer topologies and for the forward converter, it is given in this form p naught is the output power 1 plus 1 by efficiency; efficiency is assumed at around eighty percent divided by root two into K w into J into f s into B m. So, this is the area product for the forward converter and you see that p naught is available from spec. This is a spec input to the design efficiency you can assume it to be around 0.8; 80 percent K w.

You have a stocking figure which I told to start it around 0.4 J you start with 3 amp per mm square or 3 into 10 to the power of 6 amp per meter square, f s is the switching frequency and this is the design spec again and B m for ferrite you can design your transformer core at point two tesla remember that for most of the ferrites the saturation flux density is point three tesla and you can safely design at 0.2 tesla, but there are cores high frequency cores like powder Diane, amorphous, cores with brand name Metlas they have pretty high saturation flux density around 1.6.

So, you can safely design it around 1.5 tesla which will give you much smaller size core, in this way you can find out the area product once you plug in this value for a particular application. Find out the area product go into the data sheet take up that core which has an area product greater than what is calculated that will give you the size of the core.

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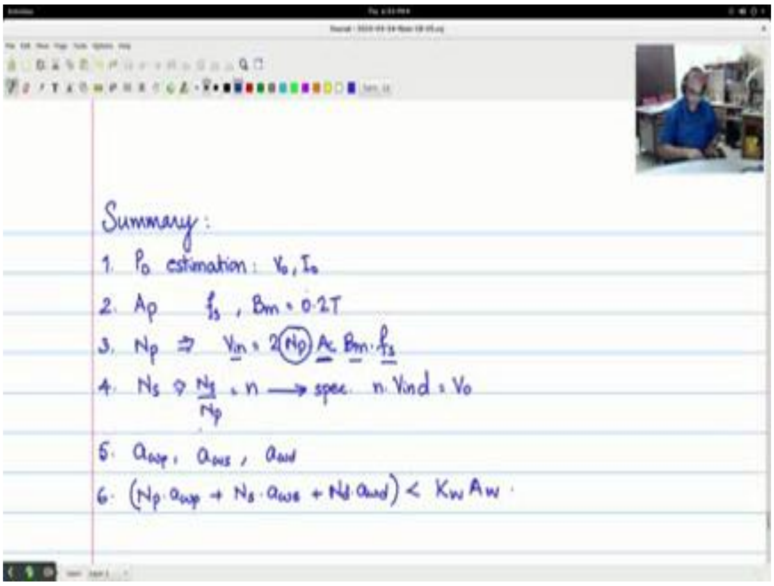

Summary:

1. P_0 estimation : V_0, I_0
2. A_p f_s , $B_m = 0.2T$
3. $N_p \Rightarrow \underline{V_{in}} = 2\boxed{N_p}\underline{A_c}\,\underline{B_m}\cdot\underline{f_s}$
4. $N_s \Rightarrow \frac{N_s}{N_p} = n \longrightarrow$ spec. $n \cdot V_{ind} = V_0$
5. a_{wp}, a_{ws}, a_{wd}
6. $(N_p \cdot a_{wp} + N_s \cdot a_{ws} + N_d \cdot a_{wd}) < K_w A_w$.

So, let us now list down step by step the design process for the transformer. Let us summarize and list the design steps for the transformer. So, first we start with p naught calculation p naught estimation, we know V naught, we know I naught these are coming from spec and you can evaluate the p naught value next, once you know p naught value you can evaluate the area product A p, and for this you need to assume a switching frequency and switching frequency is a designer choice depending upon what devices that you are going to use how fast the mass specs are going to be you may want to switch at 20 kilohertz, 50 kilohertz or 1000 kilohertz and then you use B m and if it is ferrite you can start with a value of 0.2 tesla.

Then afterwards you choose the turns for N p. Now, this is coming from that V in is equal to two N p A c B m f s this is known because you have already calculated, you have chosen the core the moment you choose the core A c is known and B m is known f s is known V in is known only N p is not known. Calculate this then afterwards, calculate N s using N s by N p is equal to N and N is spec again design spec because we would like to use it in N V in into d which is equal to V naught. So, V naught is a spec V in is a spec B and m will come into the picture then. So, N can be a design spec designer spec then after they choose the wire gauges sizes of the copper.

So, knowing the r m s value evaluate, what should be the wire cross section for the primary wire cross section, for the secondary wire cross section, for the demagnetizing windings knowing the currents that are flowing through the windings and choose the wire gauge from the standard wire gauge cable and for the wire that you have chosen. Note down the cross section area and then use that to do a cross check N p into wire cross section area of the primary plus N s into wire cross section area of the secondary plus N d into wire cross section area of the demagnetizing winding all this put together should be accommodated within the window area not only the window area within the available window area all this should be less than K w A w.

So, make this cross check A w value is known the moment you choose the core from the area product moment. You do all these things the design of the transformer is complete, you just have to buy the various materials, the core or the pore, the number of turns of the gauge with that particular gauge bobbin wind them together and then stack them and put them together. This way you can physically design the transformer from the electrical spec starting from the electrical spec.