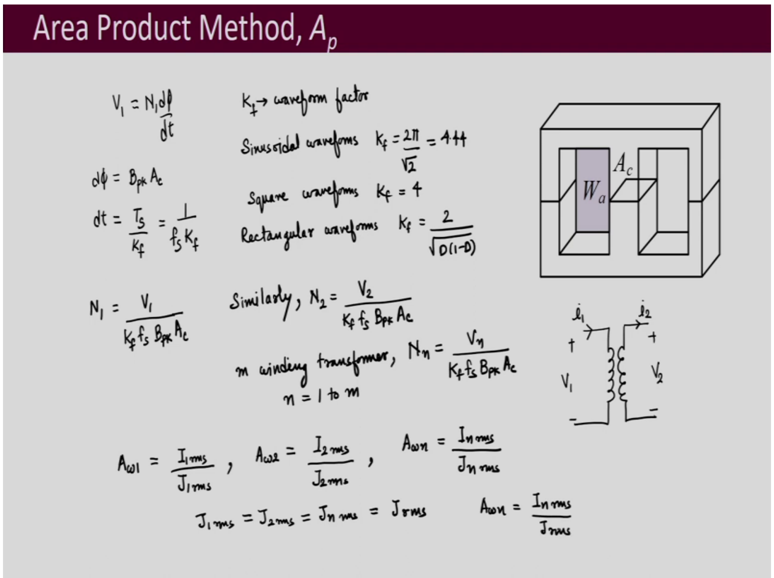
Design of Power Electronic Converters

Professor Doctor Shabari Nath
Department of Electronics and Electrical Engineering
Indian Institute of Technology, Guwahati

Lecture: 51

Transformer Design

Welcome to the course on Design of Power Electronic Converters. We were discussing the module of magnetics design, and we had seen how to do inductor design. Now today, I will give you a brief on transformer design.



To design transformers again, I will show you the area product method. More or less the method is same, but there are some small differences. So, let us look into the equations for area product method. So, if we have a transformer and on the primary side the voltage is V_1 and on the secondary side the voltage is V_2 and the current over here is I_1 and on the secondary side it is I_2.

This transformer is going to be made using a core and winding, the primary and secondary windings on this core and again we have this window area and the cross-sectional area of the core. So, multiplication of both of these two will be the area product. So we have to find out this area product.

Now, for this primary side voltage, we can write as

$$V_1 = N_1 \frac{d\phi}{dt}$$

and $d\phi$ is the change in flux, which can be written as

$$d\phi = B_{pk}\, A_c$$

and dt is the change in time. Now, we will write it as the

$$dt = \frac{T_s}{k_f} = \frac{1}{f_s\, k_f}$$

Now this k_f is called as the waveform factor and it depends on the nature of the waveform. For sinusoidal waveforms,

$$k_f = \frac{2\pi}{\sqrt{2}} = 4.44$$

and for square waveforms,

$$k_f = 4$$

and if we have a rectangular waveform which is the case in power electronics and that has got a duty ratio D. So,

$$k_f = \frac{2}{\sqrt{D(1-D)}}$$

where D is duty ratio.

So, if we substitute for $d\phi/dt$, then we can write

$$N_1 = \frac{V_1}{k_f\ f_s\ B_{pk}\ A_c}$$

Similarly, we can write

$$N_2 = \frac{V_2}{k_f\ f_s\ B_{pk}\ A_c}$$

and if we have m winding transformer, So, in that case N_n could be written as equal to

$$N_n = \frac{V_n}{k_f\ f_s\ B_{pk}\ A_c}$$

where n is equal to 1 to m.

Now, further, we can write the cross-sectional area of the conductor

$$A_{w1} = \frac{I_{1\,rms}}{J_{1\,rms}}$$

Similarly, we can also write the cross-sectional area of conductor 2 or winding 2,

$$A_{w2} = \frac{I_{2\,rms}}{J_{2\,rms}}$$

and if we want to write a general expression for nth winding of m winding transformer, it will be

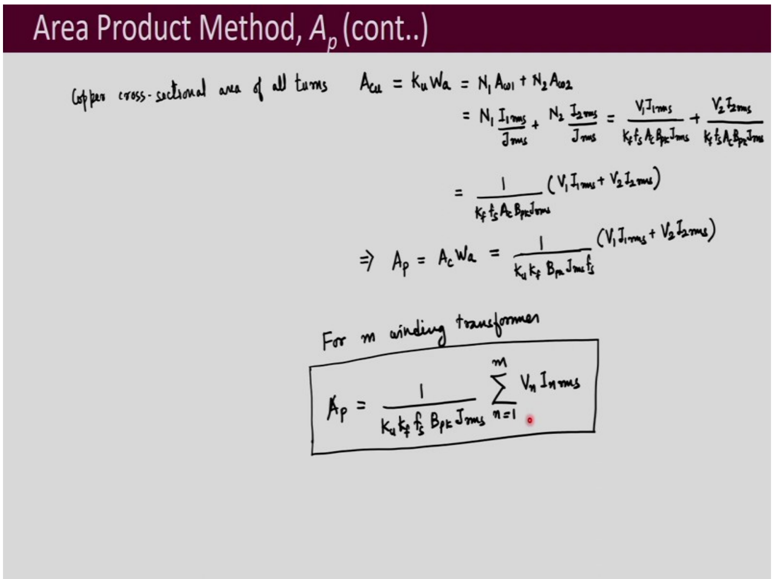
$$A_{wn} = \frac{I_{n\,rms}}{J_{n\,rms}}$$

Now, usually, we will take the current density to be same for all of them. So,

$$J_{1\,rms} = J_{2\,rms} = J_{n\,rms} = J_{rms}$$

So, in general then this expression will become

$$A_{wn} = \frac{I_{n\,rms}}{J_{rms}}$$



So, the total cross-sectional area or we can say that the total copper cross-sectional area of all turns will be given as

$$A_{cu} = k_u W_a$$

So, W_a is the winding area and K_u is the window utilization factor which we have seen before. So, this will be equal to

$$A_{cu} = k_u W_a = N_1 A_{w1} + N_2 A_{w2}$$

This then can be further written as if you substitute for A_{w1} and A_{w2},

$$= N_1 \frac{I_{1\,rms}}{J_{rms}} + N_2 \frac{I_{2\,rms}}{J_{rms}}$$

Further, we can substitute for N_1 and N_2. So, this will become

$$= \frac{V_1 I_{1\,rms}}{k_f\, f_s\, A_c\, B_{pk}\, J_{rms}} + \frac{V_2 I_{2\,rms}}{k_f\, f_s\, A_c\, B_{pk}\, J_{rms}}$$

So, then this can be then written as equal to

$$= \frac{1}{k_f\, f_s\, A_c\, B_{pk}\, J_{rms}} \left(V_1 I_{1\,rms} + V_2 I_{2\,rms} \right)$$

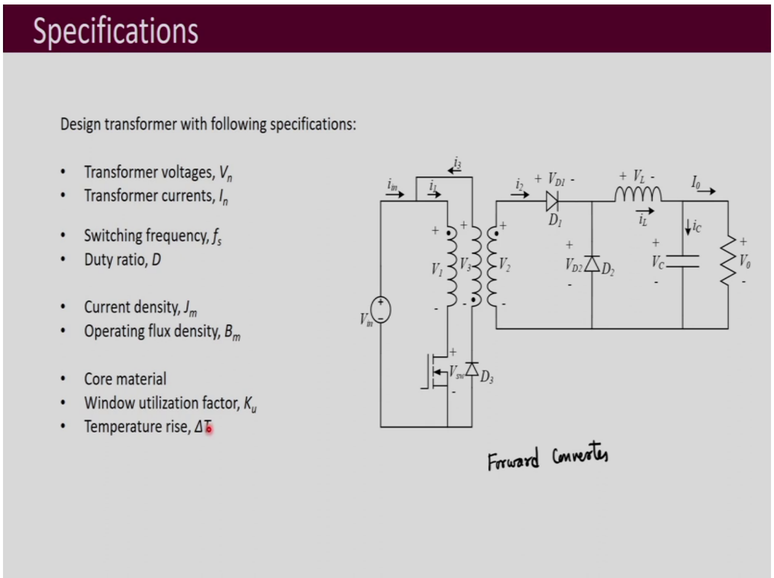
So, from here it implies that if we take this A_c on the left hand side, area product

$$\Rightarrow A_p = A_c W_a = \frac{1}{k_f\, f_s\, k_u B_{pk}\, J_{rms}} (V_1 I_{1\,rms} + V_2 I_{2\,rms})$$

So, for m winding transformer, we can write

$$A_p = \frac{1}{k_u\, k_f\, f_s\, B_{pk}\, J_{rms}} \sum_{n=1}^{m} V_n I_{n\,rms}$$

Where n goes from 1 to m. So, this is the equation for area product and you can use this equation to calculate the area product for the core, that you need. Once you have calculated the area product, then the procedure becomes the same. As we have seen for the inductor design, you go to manufacturers datasheet, you choose a core which has got similar area product, and then you get all the core dimensions and other terms related to the core. For the properties of core you obtain those values and then further using that you can do the design of the magnetics.



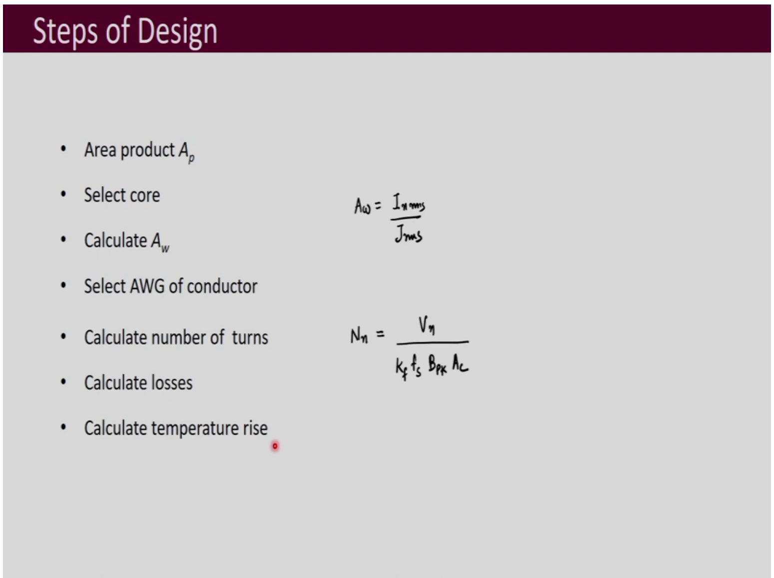
So, let me brief you on the transformer design steps. Now, here I am showing you by giving this example of this converter, which requires this transformer and this is a three winding transformer and this is a forward converter. Now, we have not discussed this converter in this course. You might have studied it before. But, this is just being used to help you understand the transformer design procedure. Now, in this converter, even you turn on this switch, then this gets shorted and the voltage is applied across V_1. So, V_1 equals to V_{in}, when the switch is on and then at that time this diode also conduct.

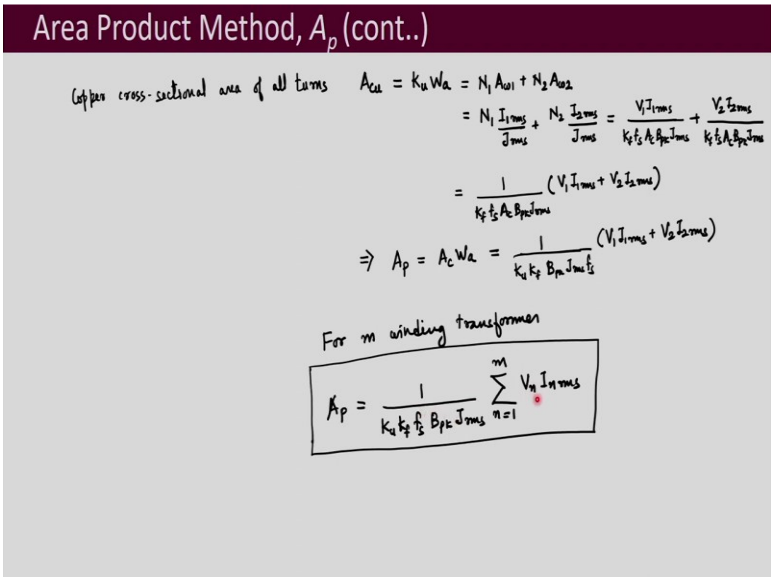
So, when this switch is on, the voltage here is equal to N_2 by N_1 into V_{in}, and further this side operation is similar to a buck converter. So, if you replace this part with the switch over here then you can see that this becomes the familiar buck converter. So, forward converter is actually an isolated buck converter. So, since it is isolated, it has got the transformer inside it. Not necessarily the ratios are limited in the buck converter, it depends on the transformer ratio, also the input to output voltage transfer ratio or that means V_o by V_{in} depends not only on the duty ratio of the switch, it also depends on these turns ratio of the transformer.

So, here when the switch is off, this also turns off at that time. Because of the leakage inductance flux developed in it needs a path and so, this diode gets forward biased at that time and through this tertiary winding there was the flow of the flux because of the leakage inductance that is maintained. Now, so, to design this transformer you will be needing that you have to know all the transformer voltages, V_1, V_2, V_3 and then the transformer currents and by analyzing this you will be able to know that.

Further, you need the switching frequency (f_s) of the MOSFET and the duty ratio D. Then further you need that you have to assume the values of current density and the operating flux density B_m. Now, these two actually remain the same. I mean you have to assume it here as well as in inductor design.

So, for inductor design also you have to know some values before. I mean some specifications are given and based on it, then you design it and here also in transformer design it remains the same. There are some specifications and these are the specifications which you have to note down first before designing the transformer. Then you select the core material and I have told you before how you select the core material. Then you have to know the window utilization factor K_u. Now *0.4* is a good value to begin with as the window utilization factor, and the temperature rise (Δt), what is the allowed rise in temperature.





Then further for the steps of design first you calculate the area product and we have seen the equation of the area product equation. So, let us go back and look into it. So, in area product equation K_u is something that you have assumed, and K_f is a waveform factor. Depending on the power electronic circuit, you will be knowing the nature of the waveform and then for that you can find out the waveform factor. Then switching frequency (f_s) will be specified and B_{pk} and J_{rms} are also something that you will be knowing before you begin the design.

Of course, also you have to find out all the voltages of the transformer and the rms values of the currents of the transformer based on your power electronic circuit. So, once you know all these things, you can substitute here and you can find out the area product. So, once you know the area product, A_p value then you go to the datasheets of different manufacturers and there you find out the core which is having a similar area product.

Further, you do the calculation of the cross-sectional area of the conductors. We have seen the equation

$$A_w = \frac{I_{n\,rms}}{J_{rms}}$$

Now, only thing is that in inductor design, you had to do this calculation only once because there is to be only one conductor.

But now in transformer you may have multiple windings and so, you will have to do it several times depending on the number of windings. That means, you have to find out those many cross-sectional areas as many windings of transformer and they will be different for different windings. Then further you go to the wire table and find out the gauge of the wires that you need for each of the windings.

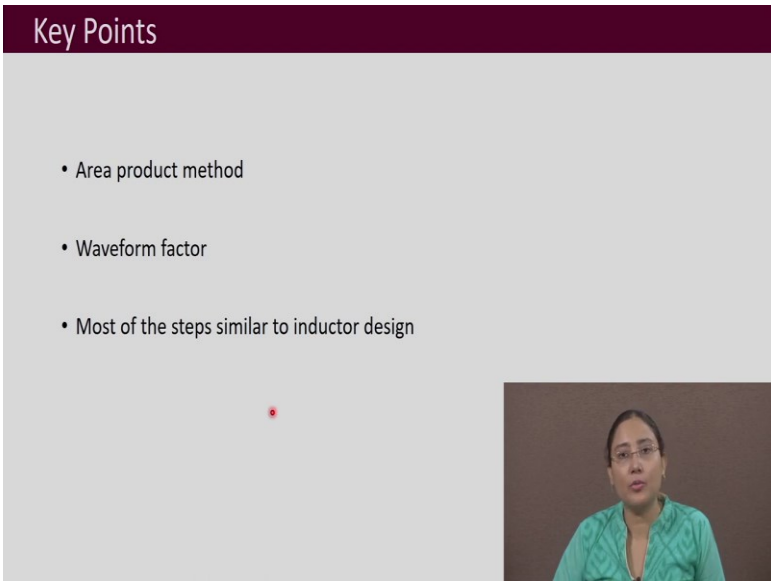
So, you select the gauge of the conductors for different windings. Then further you calculate the number of turns. Now, also we just saw this equation to calculate the number of turns. So,

$$N_n = \frac{V_n}{k_f\ f_s\ B_{pk}\ A_c}$$

So, now once you have chosen the core, you know the cross-sectional area of the core. So, A_c value will be known to you and other things will be already known to you from before.

So, you can calculate the number of turns and you have to do it multiple times depending on the number of windings of the transformer, Then I had shown you before the procedure to calculate losses. So, you can do the loss calculation also. First you can calculate the core loss and then you can calculate the copper loss. Again this copper loss calculation has to be done several times because you may be having multiple windings.

For inductor design I had shown you copper loss only for one winding. Since now you have more windings, you will be doing it different times and you have to be careful about using the value of resistance per unit distance because that may be different for different gauge of wires. Further you can use the equations that were shown to you before to calculate the temperature rise. So, these steps are more or less similar to the inductor design steps for area product method.



So, the key points of this lecture are that we have discussed area product method and this is a very well-known method and widely used method for magnetics design. Further for transformer design, you have to know the waveform factor. Now we have not really discussed in great detail how do you find out the waveform factor.

But in textbooks and in different application notes you should be able to find out waveform factor for particular converter. For that you will be using the nature of the waveforms. As we saw most of the steps for transformer design and inductor design are similar with the very small differences, you have to be noting down and be careful about those differences while you do the transformer design. Thank you.