Design of Power Electronic Converters

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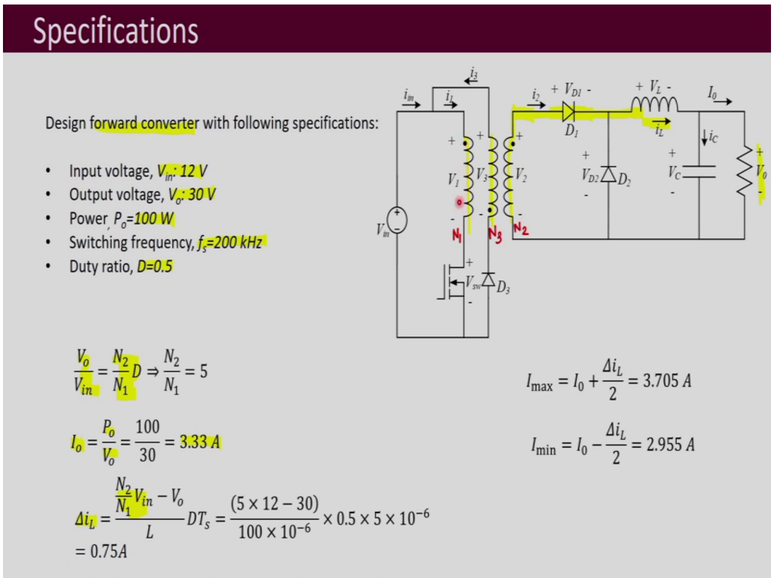
Lecture: 53

Example of Transformer Design

Welcome to the course on Design of Power Electronic Converters. So, we were discussing magnetics design. Now, we looked into the theory of transformer design. We saw the area product method.



Now, let us look into an example of transformer design. So, the example is chosen for forward converter. So, this is an isolated DC to DC converter, where you have this primary and secondary, and then there is another winding also which is the tertiary winding. It is called as the demagnetizing winding. Here, the specification given for input voltage is *12 V*, output voltage is given as *30 V*.

So, this is the output that you will require over here. The power rating is specified as *100 W*. That's the peak power. The switching frequency is chosen as *200 kHz* and we wish to operate with the duty ratio of *0.5*. So,

$$V_{in}: 12\ V,\ V_o: 30\ V,\ P_o=100\ W,\ f_s=200\ kHz,\ D=0.5$$

Now, first of all, you have to do the basic calculation. So, for this converter,

$$\frac{V_o}{V_{in}} = \frac{N_2}{N_1} D$$

So, what are N_2, N_1, N_3? So, N_1 is the turns ratio assumed for the primary, N_2 is the turns ratio over here for the secondary winding, and for the tertiary winding the number of turns are N_3.

$$\frac{V_o}{V_{in}} = \frac{N_2}{N_1} D \Rightarrow \frac{N_2}{N_1} = 5$$

This is just the ratio of N_2 by N_1 and it is not that N_2 is 5 and N_1 is 1. We have not still decided the number of turns that are required in N_2 and N_1. Only the ratio is decided over here.

Then further the output current is

$$I_o = \frac{P_O}{V_O} = \frac{100}{30} = 3.33\ A$$

Then this is the ripple in inductor current given below. For this forward converter it is given by this equation

$$\Delta i_L = \frac{\frac{N_2}{N_1}V_{in} - V_O}{L} DT_s = \frac{(5\times 12-30)}{100\times 10^{-6}} \times 0.5 \times 5 \times 10^{-6} = 0.75A$$

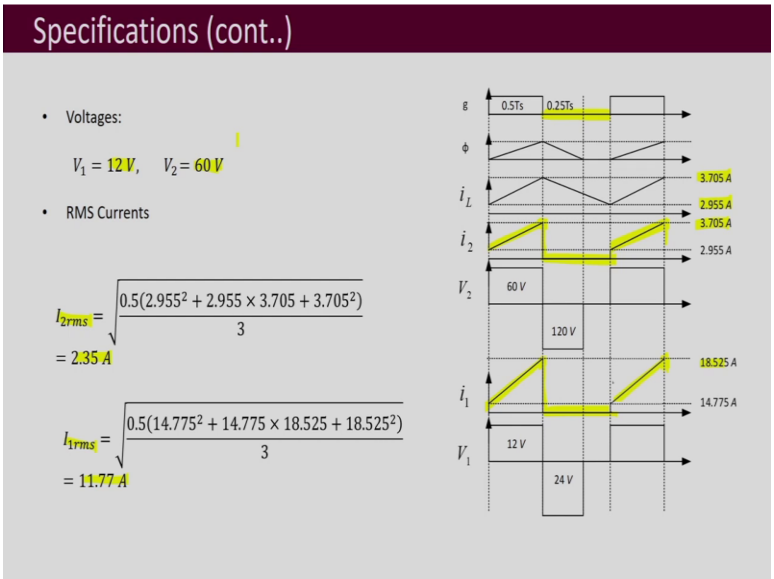
So, what is the maximum current here? That will be

$$I_{\max} = I_0 + \frac{\Delta i_L}{2} = 3.705\ A$$

and the minimum current of this inductor current will be

$$I_{\min} = I_0 - \frac{\Delta i_L}{2} = 2.955\ A$$

Now, we see the nature of the current, i_2 that is going to flow through. So, when this diode conducts at that time, the current is equal to the inductor current. So, the maximum secondary winding will be carrying this and it will be equal to the i_L current, and then the same then gets reflected on this primary site and of course, you have to multiply the turns ratio.



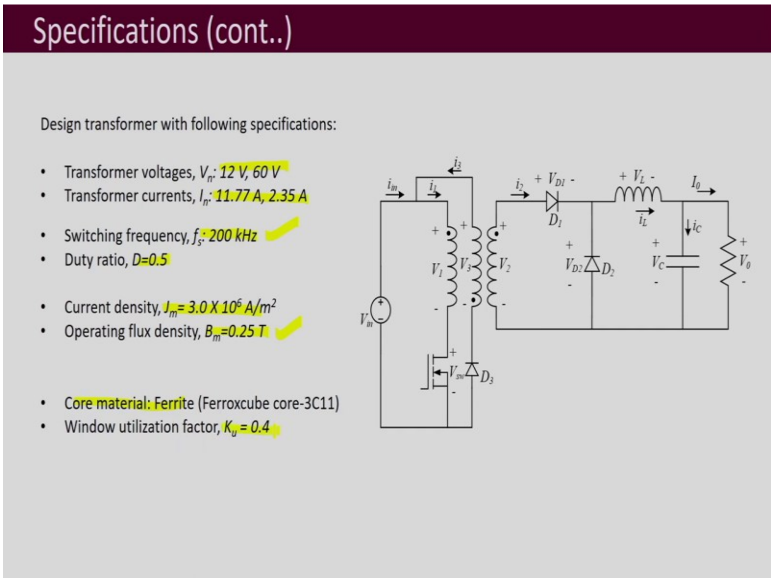
So, accordingly, these waveforms are drawn. So, this is the gate pulse waveform with the duty ratio *0.5*. This is the flux waveform, and this is the inductor current. You can see that here the minimum and the maximum of the inductor current are written and the secondary peak current is same as equal to the inductor current, and for the primary, you multiply the turns ratio, and then that is the peak of the primary current which you obtain, when the primary conducts and that is the time when the secondary also conducts.

When the switch is off in this period, both the primary and the secondary windings are not conducting. So, that's why these currents are *0*. So, we see that this is the nature of the current waveform for the primary winding and the secondary winding. So, we have to calculate the RMS values of these currents. Now, you know how to calculate RMS values. There are standard equations for it.

$$I_{2rms} = \sqrt{\frac{0.5(2.955^2+2.955\times3.705+3.705^2)}{3}} = 2.35\ A$$

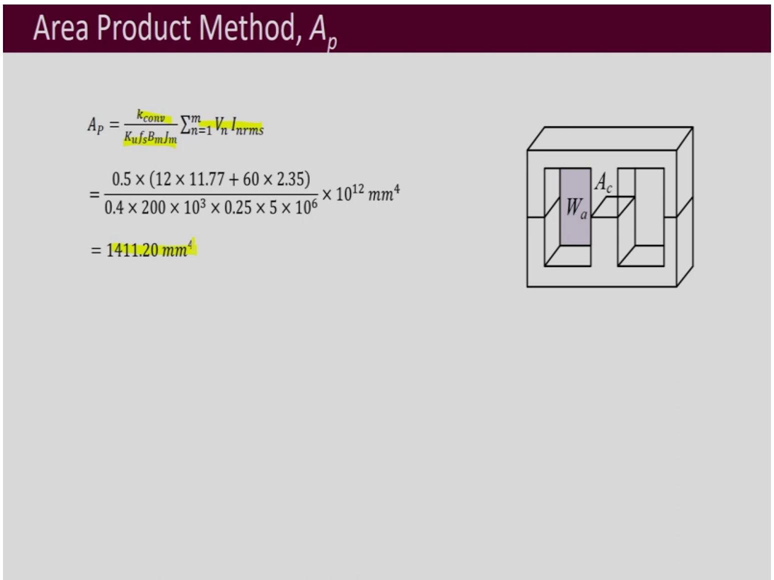
$$I_{1rms} = \sqrt{\frac{0.5(14.775^2+14.775\times18.525+18.525^2)}{3}} = 11.77\ A$$

So, in this way it has been done. For the secondary it turns out to be *2.35 A*, for the primary it turns out to be *11.77 A*, and then further for the primary we see that the voltage is *12 V*, and the secondary voltage turns out to be *60 V*, according to the number of turns ratio that we obtained.



So, then finally, to design the transformer what are the specifications that we get? So, these are the transformer voltages from primary and secondary. Then these are the transformer currents. Switching frequency is already chosen. Duty ratio is also already chosen. Then, we use the current density of this value, $J_m = 3.0 \times 10^6\ A/m^2$ and operating flux density, $B_m = 0.25\ T$.

Further, we choose the core material according to the switching frequency as equal to ferrite. So, depending on this switching frequency and this operating flux density we can choose core material and the ferrite is the material that is chosen here and the window utilization factor is chosen as *0.4*.

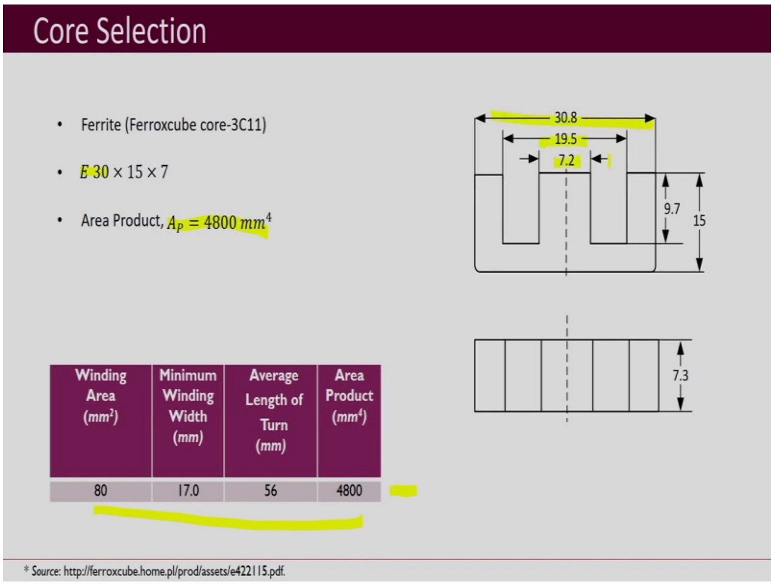


So, then now, we have obtained all the values and we apply those in the area product equation. So, we have everything and so, here we substitute that here for the area product. So, this is the area product that we are going to obtain and here we are doing the area product calculation only for the primary and the secondary winding.

$$A_P = \frac{k_{conv}}{K_u f_s B_m J_m} \sum_{n=1}^{m} V_n I_{nrms}$$

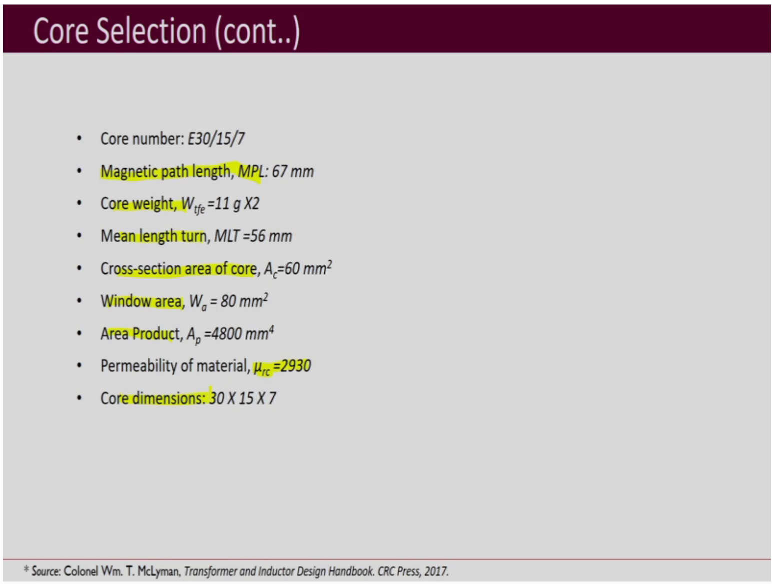
$$= \frac{0.5 \times (12 \times 11.77 + 60 \times 2.35)}{0.4 \times 200 \times 10^3 \times 0.25 \times 5 \times 10^6} \times 10^{12}\ mm^4$$

$$= 1411.20\ mm^4$$

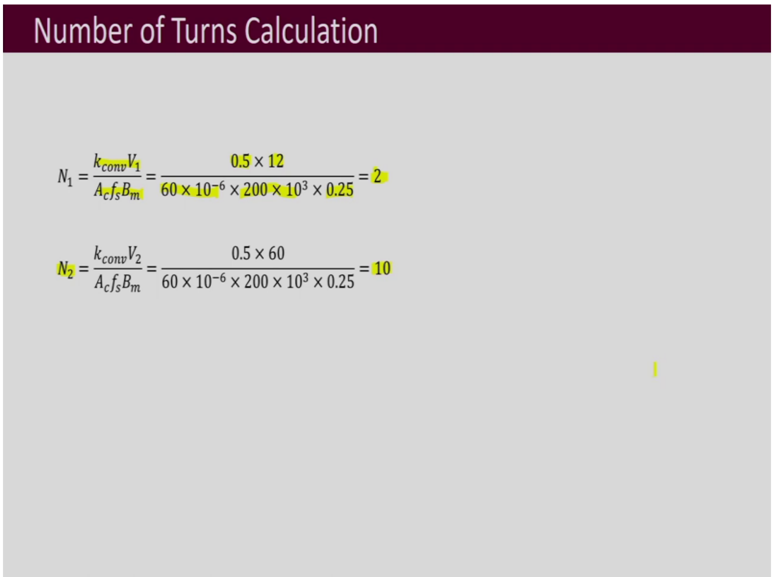


Then based on the area product you look for datasheets of different cores that are available and then finally, we chose this core, whose area product, *A_P=4800 mm^4*, and it is *E 30*. These are the various other specifications of the core that are written over here. Those are the winding area, minimum winding width etc. So, these are the dimensions of the core that are shown here.

$$E\ 30 \times 15 \times 7$$



Then, you further note down various other parameters related to the core. So, those are magnetic path length (*MPL*), the core weight, and the mean length turn, the cross-sectional area of the core, the window area, the area product, and the permeability of the relative permeability of the material and the core dimensions.

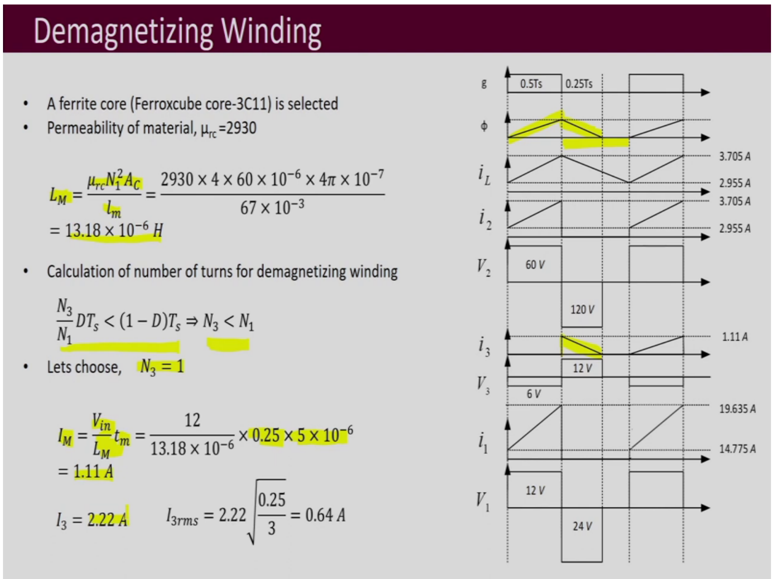


Then further we have obtained the cross-sectional area of the core. So, now we can substitute those values in the equation to obtain the number of turns, N_1.

$$N_1 = \frac{k_{conv}V_1}{A_c f_s B_m} = \frac{0.5 \times 12}{60 \times 10^{-6} \times 200 \times 10^3 \times 0.25} = 2$$

Similarly, we obtain the number of turns of the secondary winding which is obtained as *10*.

$$N_2 = \frac{k_{conv}V_2}{A_c f_s B_m} = \frac{0.5 \times 60}{60 \times 10^{-6} \times 200 \times 10^3 \times 0.25} = 10$$



Now, we have to find out the number of turns for the tertiary winding and the current which it carries. Then the tertiary winding will be carrying much lesser current because it is a demagnetizing winding. So, the rule of this demagnetizing winding is that once this flux is reached to that point while the switch is on, the magnetizing current which was flowing in the primary winding that all of a sudden cannot become *0*. Because it is a practical transformer and not an ideal transformer. Then somebody has to carry that current and that is carried by the tertiary winding.

So, then the magnetizing current that is associated with the primary winding then gets reflected in the tertiary winding. So, that is this nature of the current of the tertiary winding, and that current is associated with this flux. So, first of all, we find out the magnetizing inductance L_m value, and we can find out that by referring it to the primary windings. So, magnetizing inductance L_M of the primary winding will be given by

$$L_M = \frac{\mu_{rc} N_1^2 A_C}{l_m} = \frac{2930 \times 4 \times 60 \times 10^{-6} \times 4\pi \times 10^{-7}}{67 \times 10^{-3}} = 13.18 \times 10^{-6}\ H$$

Now, we want to demagnetize such that, that the core gets demagnetized before this interval that is $(1-D)T_s$ interval. So, accordingly, this relationship has to hold true, that is

$$\frac{N_3}{N_1} DT_s < (1-D)T_s \Rightarrow N_3 < N_1$$

So, N_1 is equal to *2*. So, obviously, you have to choose

$$N_3 = 1$$

So, for the magnetizing current we can find out that.

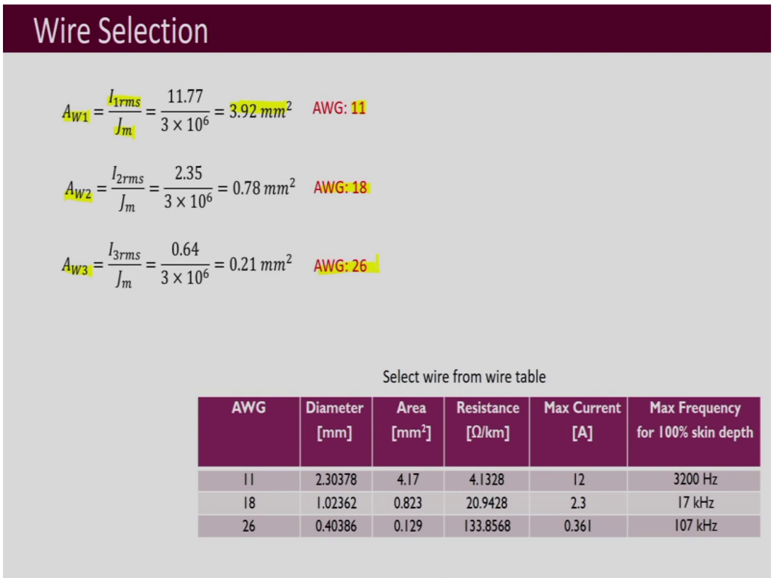
$$I_M = \frac{V_{in}}{L_M} t_m = \frac{12}{13.18 \times 10^{-6}} \times 0.25 \times 5 \times 10^{-6} = 1.11\ A$$

We have to refer it to the tertiary winding. So, that turns out to be as equal to

$$I_3 = 2.22\ A$$

$$I_{3rms} = 2.22\sqrt{\frac{0.25}{3}} = 0.64\,A$$

As N_1 is equal to *2*, N_3 is equal to *1*.



So, now, we have got N_1, N_2, N_3. For all the three number of turns we need to select the wire. So, this is the gauge calculation, cross-sectional area calculation for the primary windings. So,

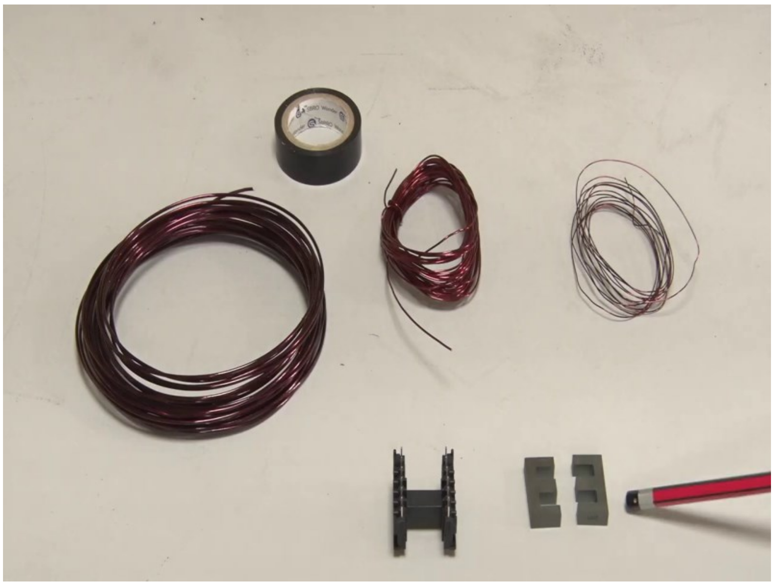
$$A_{W1} = \frac{I_{1rms}}{J_m} = \frac{11.77}{3\times10^6} = 3.92\,mm^2$$

So, we can select a wire whose gauge is greater than what we have obtained. So, accordingly, *AWG 11* is chosen and similarly, the calculation is done for the other two windings also.

$$A_{W2} = \frac{I_{2rms}}{J_m} = \frac{2.35}{3\times10^6} = 0.78\,mm^2$$

$$A_{W3} = \frac{I_{3rms}}{J_m} = \frac{0.64}{3\times10^6} = 0.21\,mm^2$$

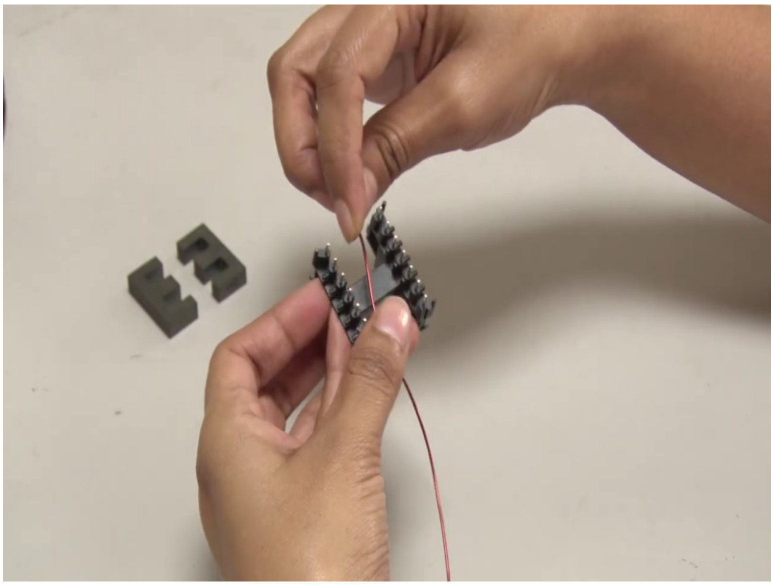
Accordingly *18* and *26 AWG* wires are chosen for secondary and the tertiary windings.

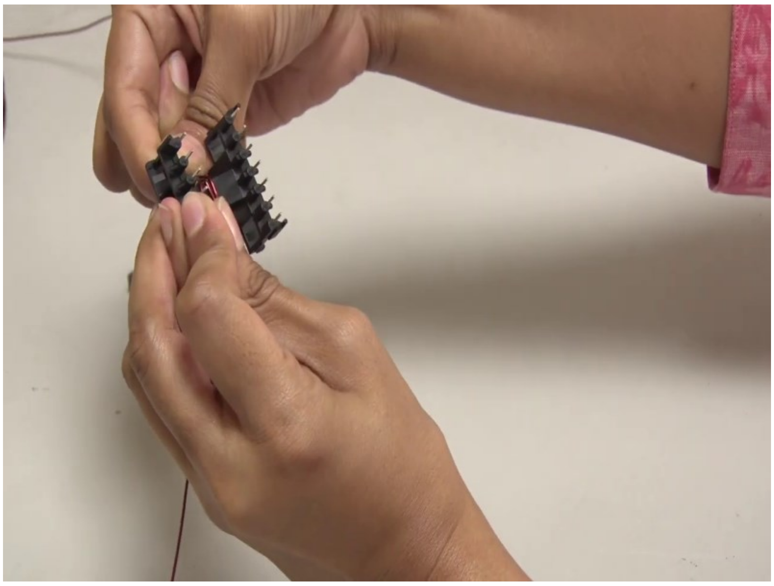


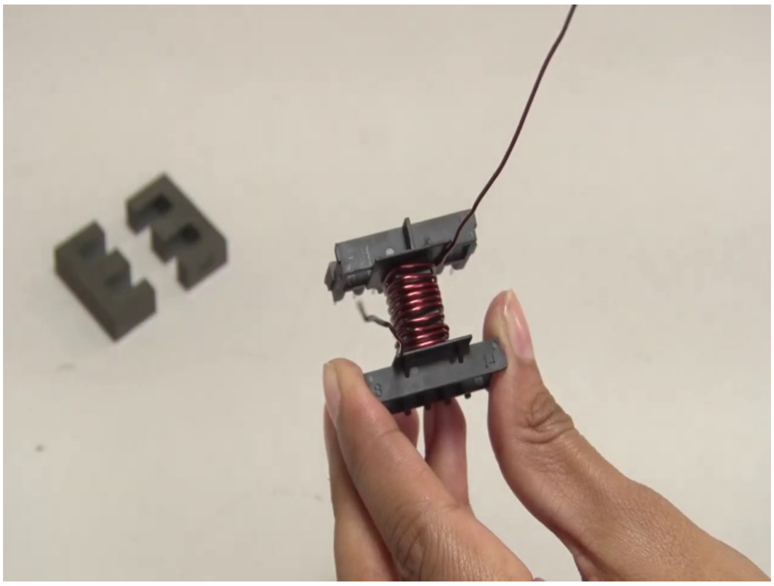
Now, let us look into a demo of practically designing this transformer.

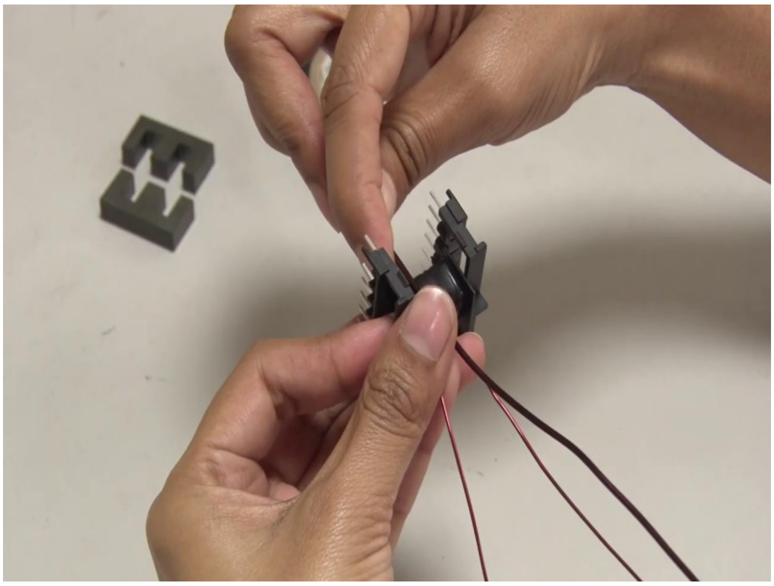
Student: Now, I will show the design procedure for transformer design. The transformer is designed for a forward converter with input voltage of *12 V*, output voltage of *30 V* and the duty ratio of *0.5* and the switching frequency is *200 kHz*. Based on area product the selected core is E shaped ferrite core made by ferrox cube. It’s dimension is *30 mm X 15 mm X 7 mm*.
This is bobbin where windings will be done.

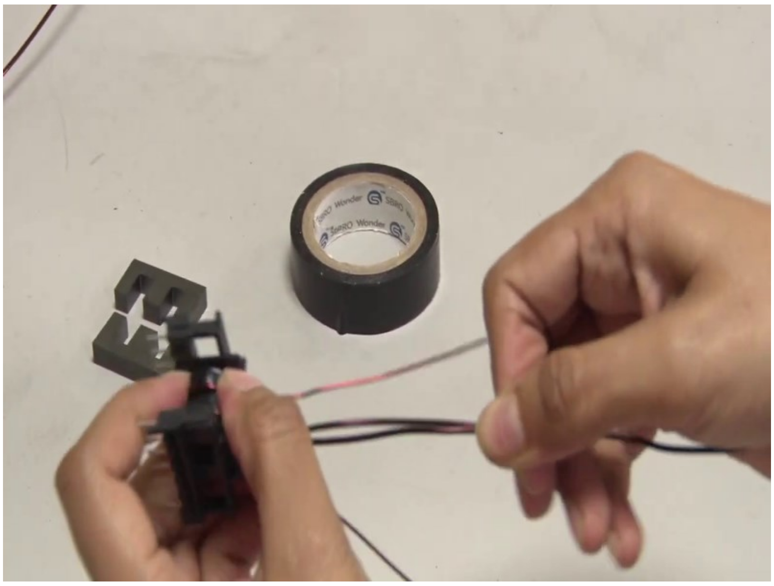
For three windings of the transformer, three copper wires are selected. This is enameled copper wire of *11 AWG*, this is used for first winding of transformer. This is enameled copper wire of *18 AWG*, this is used for second winding of transformer. This is enameled copper wire of *26 AWG* which is used for third winding of transformer. This is the tape which will be used for securing these two cores.







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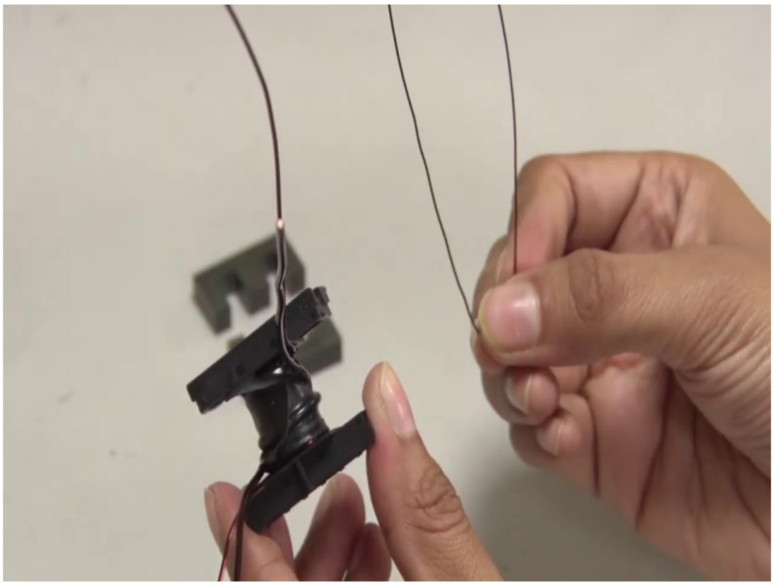

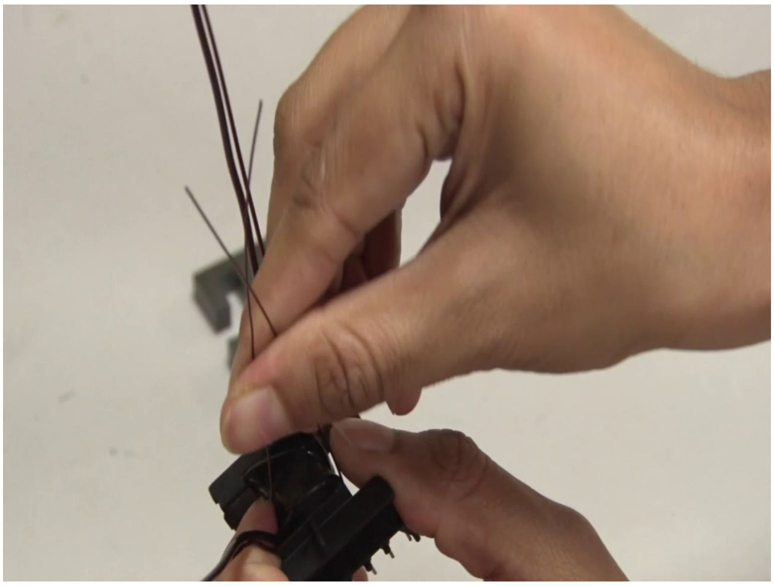

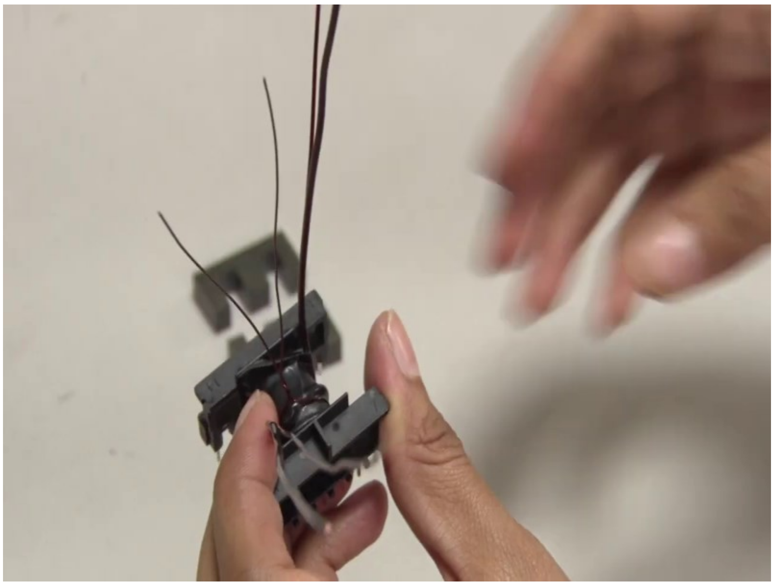

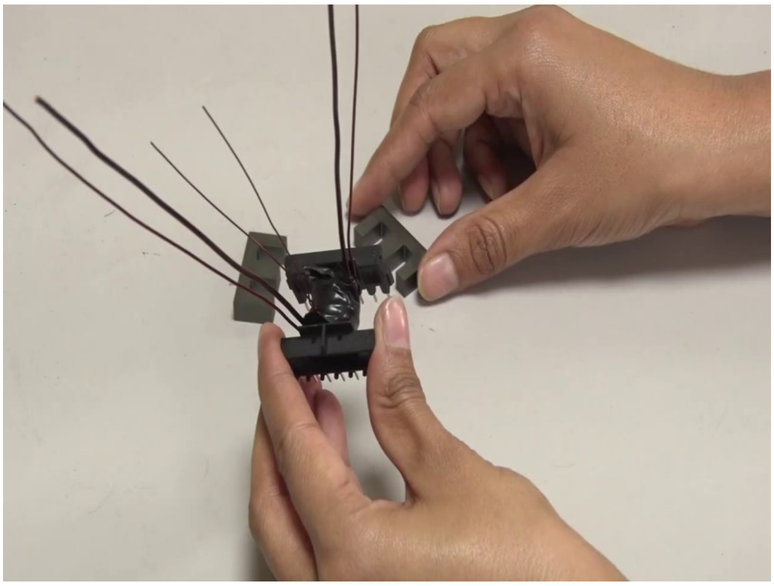

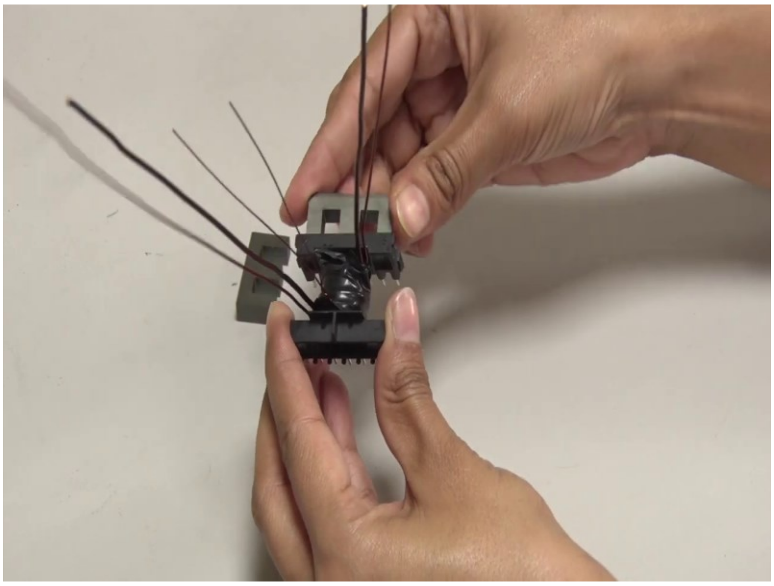

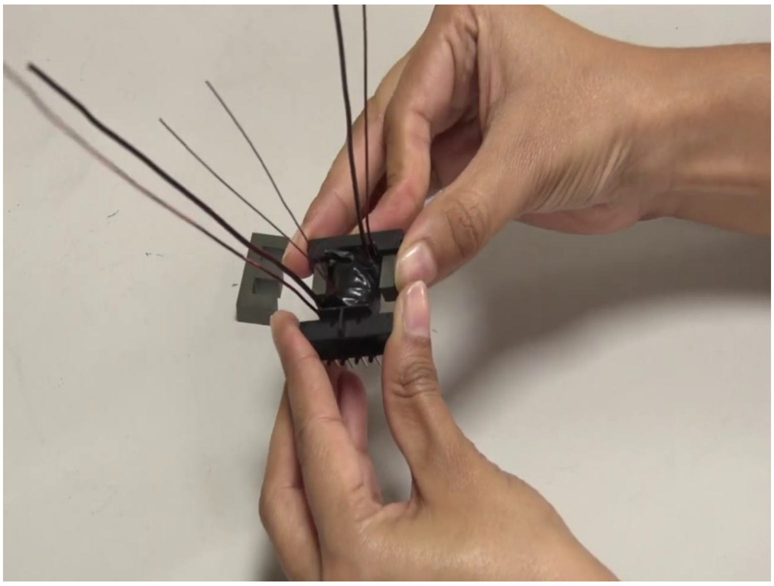

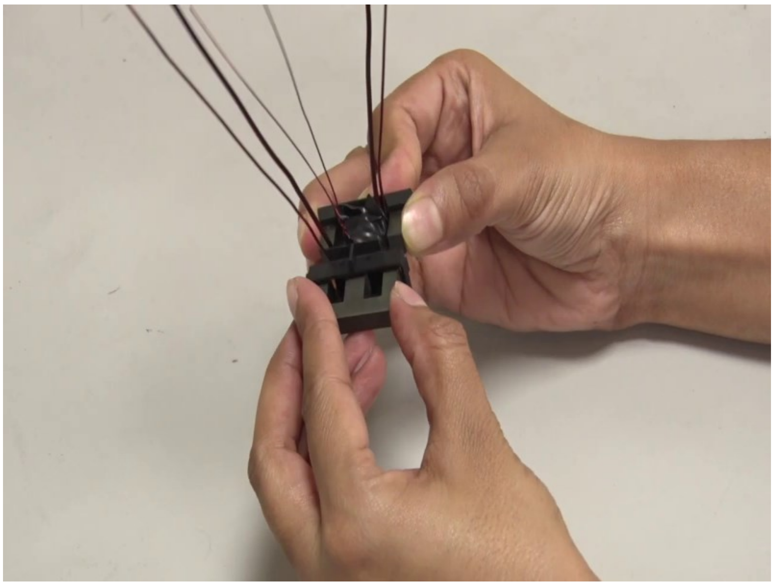

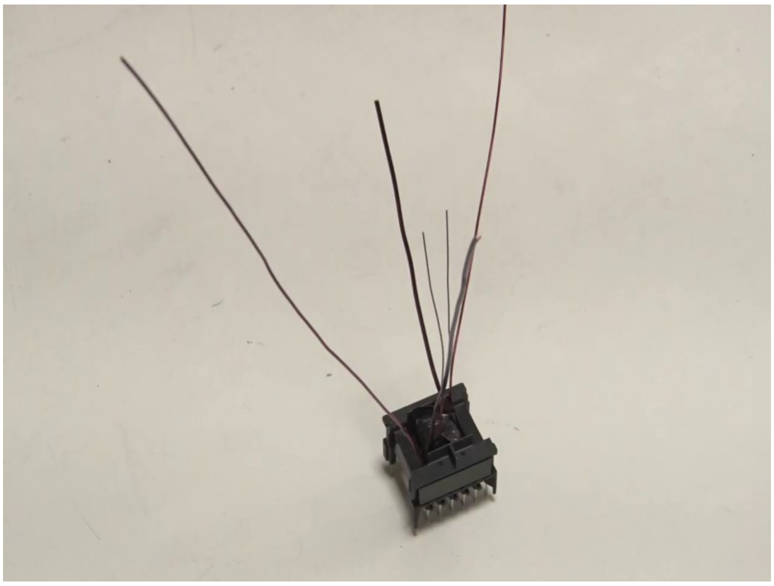

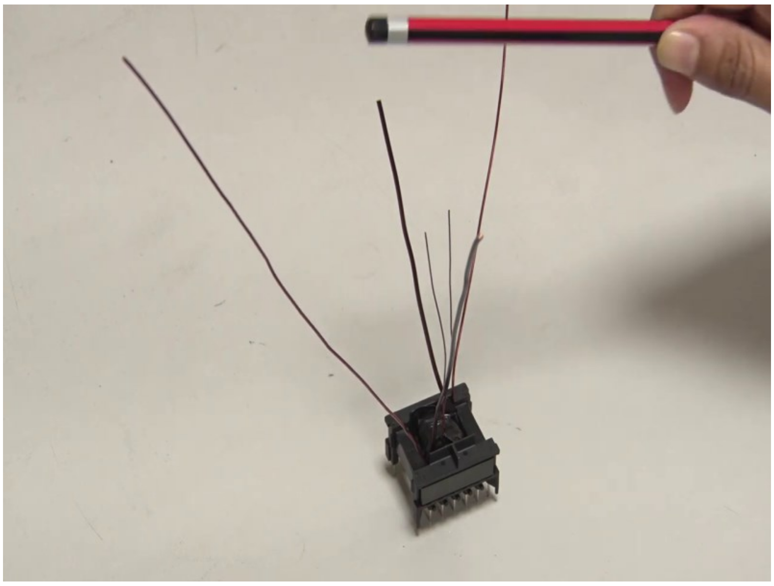

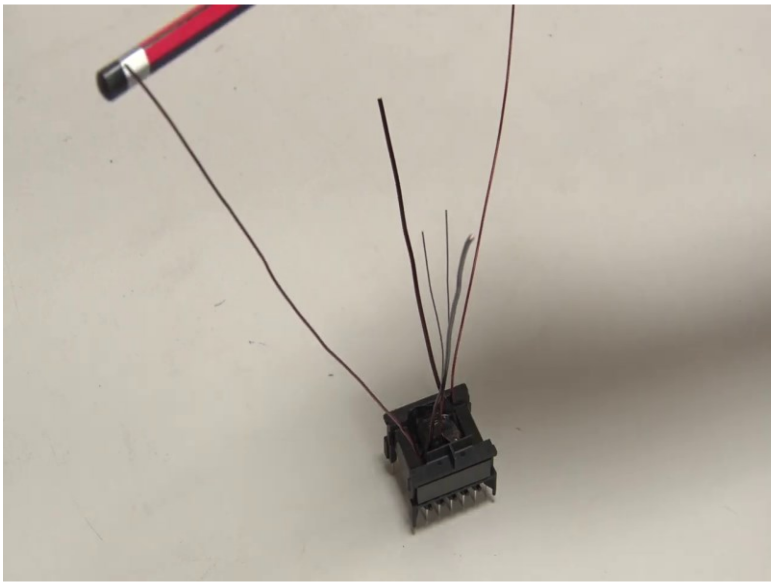

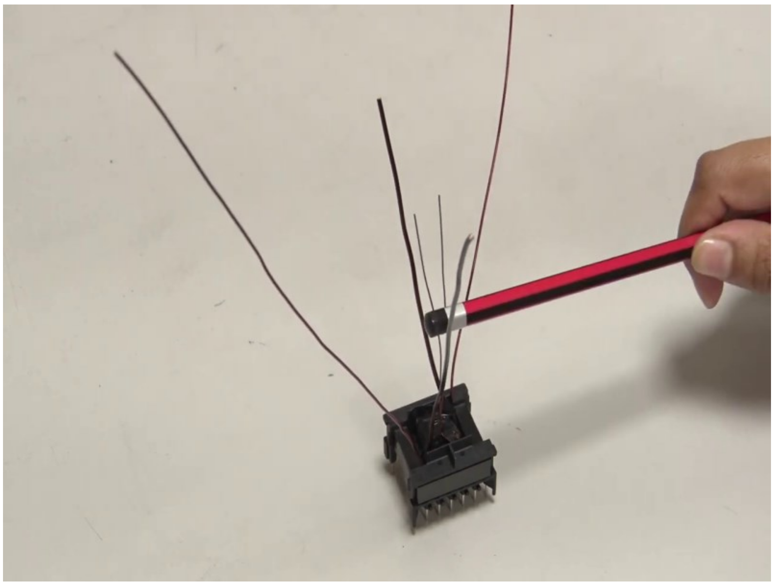

Now, I will start winding this *18 AWG* wire for second winding or transformer. The number of turns calculated for second winding is *10*. So, this is the first turn this is the second turn and similarly, I will go up to *10* turns. Now, as you can see, this *18 AWG* wires has been wound, the number of turn is *10*. This is the second winging of the transformer. Now, I will secure the second winding using the tape.

Now I will start winding this *11 AWG* wire for the first winding of transformer. So, number of turn is *2*. So, this is the first turn and this is the second turn and now I will secure this using the tape. Now, I will use this *26 AWG* wire for the third turn of transformer. Here the number of turn is only *1*. Now, I will secure this using tape, now I will assemble the transformer. One core is placed here, now I will place the second core here. I will use the tape to hold them together. This is the final look of the transformer. So, this is the first winding This is the second winding and this is the third winding.