CHARGING INFRASTRUCTURE

Prof. Apurv Kumar Yadav

Department of Electrical Engineering

Indian Institute of Technology Roorkee

Week-09

Lecture-44

Lec 44: Transformer Design for Isolated DC-DC Converter-I

Hello everyone, welcome to lecture number 44 of this NPTEL lecture series on charging infrastructure. Today, we will discuss some aspects of transformer design, mostly the transformers used in isolated DC-DC converters. So, if you recall, we have studied in detail about full-bridge converter operation, and then we have seen different PWM methods possible with the full-bridge converter. We have also seen the phase-shift full-bridge converter, its different modes, its conditions for soft switching, and the zero-voltage turn-on of the switches in both the leading and lagging legs, which we discussed in detail. After that, we moved our discussion towards the dual active bridge, where we briefly discussed the different operations of the dual active bridge. In both converters, if you see, we use the high-frequency transformer. Why do we say high-frequency transformer? Because that particular transformer sees high-frequency excitation or high-frequency AC voltage applied across the transformer winding. I mean, if you recall, let's say our simple dual active bridge, very quickly draw the dual active bridge. So, from both sides, we have, let's say, $V_{in}$and V_{out}. On both sides, we are actually applying voltages, and generally, the switching frequencies are kept quite high, ranging from 10 kH to upwards of 100 kH, 200 kH, or 300 kH. Now, people are also talking about frequencies in mH as well. So, if you look very carefully at this, we are actually applying a high-frequency AC onto the terminals of this transformer. So, we can say that this particular transformer is a high-frequency transformer. So, let us try to understand what goes into designing this transformer, what one needs to understand, and what the procedures are to physically realize this particular transformer. Now, if you look very carefully in our courses, in our undergrad courses, we have already studied about transformers. So, a transformer basically consists of a core and a winding. The core is made up of ferromagnetic materials, and the windings are actually wound onto this in this manner. And finally, it comes out like this. Here, mostly in transformers, we have two windings. One, let us say, winding 1 with, let us say, N_1 number of turns. And which is having the current going into the winding. Which actually generates if we take the flux direction. It is somewhere depending on that. And that flux is in the core. So, we have defined that as $\emptyset_c$. Similarly on the other side we have another winding.

Where from the other side we have going like this, going like this, going like this, going like this and then finally coming out from the behind. Here if we see this particular winding will actually be, if we say this is my i_2 going into this one, this is V_2 which we are applying, we are again having flux generated in this direction. and this flux gets linked with this winding and accordingly the voltages are induced if you connect the resistance or the load on this winding then the current direction will be in reverse of that such that whatever flux generated by this winding will actually cancel out by the flux generated by this winding because here because from the lens law we know that the effect will actually oppose the cause If this excitation current has, you know, some AC excitation, so this $\emptyset_c$ will be having the varying flux and that varying flux is actually cutting this winding, which actually induce the voltages at the terminal of the next winding, which has this N_2 number of turns. And this flux is actually cutting down this area of the core and let us define cross section area of the core to be AC.

And if you look very carefully in this if we see this particular this particular flux is actually going into the core and let us say this magnetic length corresponding to this flux line in the core to be my LC. now if you see very carefully in this particular type of setup we are actually applying this excitation current into the into one of the windings now we know that this core material is mostly are made up of ferromagnetic material as a result of which what happens where this ferromagnetic material consists of magnetic domains and whenever there is no external magnetic field is applied those domains are actually arranged in a random manner. So thus, as a result of which the net flux generated by those domains because the domain itself produces the magnetic flux. So, since they are arranged in a random manner the net flux generated by those domains are generally equal to zero and whenever this magnetic material which consists of a magnetic domain are placed in an external magnetic field then this magnetic domain align themselves I mean along the field align with the field you can say. As a result of which they generate a next flux and that flux is actually lead to the magnetization of the core then that particular process called as the magnetization of the core. So that is why it led to a curve called as a BH curve where we have the external magnetic field

applied onto the core material and as a result of which there is a magnetization in the core which actually lead to the generation of the some net amount of flux and which is actually defined by this flux density term which is called as a B. So this particular thing will have these shapes something like this where where what happens the moment you are increasing the external magnetic field the more and more magnetic domain align themselves that's when net flux produced in the core gets increased and there is a point when almost all the magnetic domains align themselves and that's when the core gets saturated or you can say that the flux in the core these two is maximum value and that's when you can say it the core gets saturated. So that's why we see that after certain point we see that there is no increase in the net magnetic flux density even though my external magnetic field is increasing and this because of this thing you know this BH curve is one of the curve which actually which actually determines how well the material core material get magnetized and how much amount of energy is needed to magnetize the core itself however if you see while going in one direction it follows in one path however while going from another direction going downwards it actually follow the other path that means this particular curve has some hysteresis it is nonlinear as its saturates beyond the certain value of H. So, this is the BH curve which is one of the critical core material properties. So whenever if we try to if you try to see this particular transformer if we try to see this particular transformer magnetic circuit model from the magnetic circuit model we can then write actually, we can then draw the model and we can then say our transformer will be something like will look something like this where we have N_1 and N_2 number of turns we have you know we are actually applying V_1 voltage in the transformer and we have $i_1$current going into the transformer and let's say taking the generality if the current from the other side also is going into the So, we will get the core to be something like this where the magnetic flux generates inside the core can be represented by the amount of current which is going into the magnetizing branch of this transformer and this magnetizing branch of this transformer has the magnetizing inductance. Here we have not considered any winding resistances or the resistances corresponding to the core losses. Here we have assumed the transformer to be a lossless transformer.

So we can then write the transformer model using the magnetic circuit model. This is the transformer model what we have. And in this transformer model, we have assumed that we have the magnetizing branch where the amount of flux which gets generated inside the transformer is obtained by the current which is going through the magnetizing inductor. Let us define this as to be i_{m1} where $i_{m1}$is the magnetizing current referred to the primary side, winding 1 you can say and I_{m1} is the magnetizing inductance referred to the So, then what we can do is from this particular circuit model we can then define our the magnetic field which you get generate inside the core to be nothing but we can say this is N_1 number of turns and the current which is going through the magnetizing inductance then divided by L_c which is the magnetic length in the core.

So this we can say that it is nothing but the magnetic field which you get generate in the in the core and which because of this magnetic field there will be the magnetization of the core or you can say the alignment of the magnetic domain which actually led to the net flux generated in the core. Now this particular thing comes from the amperes law you know us from mps circuit law we can just we can obtain this particular thing. From this magnetic circuit model, we can derive the current going through this magnetizing branch. Now, in this particular thing, if you see because of this thing, there is a magnetic flux and that we can just say over here, the amount of SC in the core will be lead to the magnetizing. From there, we can easily draw the, you know, the marking in the BH curve.

Now, in this, if you assume that there is some voltage which has been applied, so from the Faraday's law of electromagnetic induction, we can just write voltage applied $V_1$to be

$$V_1 =- \frac{N_1 d\emptyset_c}{dt}$$

which is let's see here $V_1 =- \frac{N d\emptyset_c}{dt}$

again, if we take only the magnitude terms we can just write this

$$\int V_1(t) = N_1 \phi_c = \lambda_1$$

λ_1 =flux linkage

dt integration to be equal to n1 phi c and that we can just write this particular term to be lambda 1 and this particular term lambda 1 is nothing but the flux linkage And that is happening only when we are giving excitation only from one of the winding that is N1 winding. Now, because of that, let us see what particular things we get. Now, if you look very carefully, this is the integration of excitation voltage V_1, which has been applied in the one of the winding in the transformer.

Since we got this particular thing, we can also write one thing that since the current which is going into the magnetizing inductance is the one which is actually lead to the magnetization in the core. So, we can then write us

$$i_{m1} = \frac{1}{L_{m1}} \int \frac{V_1(t)}{L_c L_{m1}} dt$$

which is the current which is going into the winding and let us say V_1 is the excitation voltage. This is V_1 let us say it is some periodic voltage which has been applied, arbitrary periodic voltage.

So, we can then write it is nothing but integration $V_1(t)dt$. So, this is the i_{m1}which has been going into the winding. And here if you look very carefully, this flux linkage is the one which will be defining amount of flux which will be generated in the core. So let's say if we have our excitation to be you know let's say if we assume our excitation to be sinusoidal assume having some positive sinusoidal here and then some negative sinusoidal excitation which we are giving from let's say $V_1(t)$ we are giving If we take this $V_1(t)$to be a sinusoidal excitation so we will actually obtain this corresponds to the you know maximum V_1 which will be applied so that's when this is i_{m1} will be going through this one according to this integration of $V_1(t)$that's when my H_c will be there which is coming over here and that's why we have this point my H_c point is there which is we can say nothing but corresponds to

$$H_c = N_1 \int \frac{V_1(t)}{L_c L_{m1}} dt$$

So at that point at that point actually I am we are giving the we are giving the excitation because of that what happens is that the flux in the core will go up from this to this point there was some residual flux which was there which goes from this to this point and then it forms actually you know at this point it forms. Let's say here it is ΔB which is there which is coming over here and then finally once it reaches in the negative direction this negative direction will come over here and that's when my BH curve comes over here and then finally it goes it forms ΔB , $-\ \Delta B$, $-\ \Delta B$ we have and then finally this is my entire BH curve which gets you know enclosed while this particular kind of excitation is given to this particular core. So, if you look very carefully we have you know the A_C component of this magnetic flux goes from ΔB to $-\ \Delta B$, this is V_2.

So, if we take arbitrary excitation to be a sine wave 't' and let us take the area under this curve in this particular part let to be a $\frac{\lambda_1}{2}$.

we can then write

$$V_1(t) = \frac{N_1 d\emptyset_c}{dt}$$

$$V_1(t) = \frac{N_1 A_c d\emptyset_c}{dt}$$

$B_c =$ magnetic flux density.

$$B_c = \emptyset_c A_c$$

So that from here we can then put so this one if we take this one we are having this

$$\int V_1(t) dt = N_1 A_c \Delta B$$

this integration will if you take only in half the cycle integration Flux density goes from 0 to ΔB. So, we can then write

$$\lambda_1 = 2N_1 A_c \Delta B$$

and that integration we can get λ_1 and divided by 2 so that we can get AC delta V into delta. These two terms we get because we have only considered the half cycle that means positive cycle. In other words, we can also say that the ΔB goes from $+\ \Delta B$ to $-\ \Delta B$. So, we can write $2\Delta B$. Then with this phenomenon we will get ΔB value to be, and that we can then write here to be

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

So what we see in this particular thing in the core the whenever the excitation voltage is applied in this particular winding there is a magnetic field which gets generated in the core and that magnetic field is due to the current which is flowing through the magnetizing branch the transformer and because of this magnetic field will get magnetic domains in the core will get aligned and as a result of which you will get you know some net magnetic flux density and that we have understood how we can get for the simplest excitation which is a sinusoidal excitation now this particular delta with the magnetization which is happening in the core is actually responsible for the core loss and because of the current which is flowing into the transformer we have the winding loss as well so these two are very significant and both these losses are dependent on flux density which we will discuss as we go along and then our aim is to find out we have to optimize this flux density such that we can able to reduce both this core loss and winding loss because see in the transformer when we are giving excitation we only have this winding which has you know resistance in the winding so there will be copper loss in the in the winding and then because of this you know magnetization of the core that means the alignment of this magnetic domains there will be some energy which is required to do the alignment and that energy goes into the core which gets converted into the heat and gets dissipated from the core so that's why this core loss and the winding loss are very significant and we need to optimize this flux density which is you know delta b to be such that we can able to reduce both these losses in the transformer and along with that we should be in a position to actually obtain different parameters of the transformer which includes you know several things which are which we need to calculate like number of turns the magnetic length of the core the area of the core different design outcomes has to be obtained so in the transformer design if you talk about the design outcome it means nothing but we have be required to define the core size different dimensions of the core like core cross sectional layer which is this Ac which we are talking about then window area this is the area window area you can say in the transformer which actually accommodate the winding and this window area has to be sufficiently large enough where we can actually accommodate the windings for example if you look from this side if you look from this side then our window area will be our window area will be this area over which the winding sits over the bobbin Then we have the mean length per ton which is nothing but you know in the transformer if we look in the transformer we have several windings which is been done and this winding goes from this particular surface to this particular surface facing that side.

So we have the windings which goes from here till here till here. Then the winding which goes like this, the winding goes like this, winding goes like this. So, in the entire area, this entire area windings are wounded. So, the mean length will be, you know, the mean of this winding and this winding, the mean length of the wire which is required to do the one turn. We will see what is the meaning of mean length per turn as we go along.

And then finally, the magnetic path length, which is this particular length we are talking about. So, if we can identify these four or five terms—core cross-section area, window area, mean length per turn, magnetic path length—we will be in a position to select our core accordingly, or rather, to select the appropriate core size where we can ensure that the magnetic flux density is below the saturation magnetic flux density. As well as it being the optimum value where our losses—I mean the core loss and the winding loss—will be minimal. Then, we also have to know the number of turns in different windings because, in a transformer, we have multiple windings. So, what are the number of turns we have? Then, what is the size of the wire used to wind the transformer? That is also needed because, you know, wire size generally refers to the wire being— The copper wire, which looks something like this, and this copper wire will have—if you look very carefully—a size that depends upon the diameter of this wire. So, that is the wire size we are talking about. Then, we have another important thing: what is the peak flux density? Because this peak flux density is essential to understand whether the core hits saturation.

Saturation means it's the value where, at this point, we have the saturation point—that means the point where all my— Magnetic domains get fully aligned, and there is no further magnetization that takes place, even if you increase the external magnetic field. So, that's the saturation value. So, we need to know the peak flux density present in the core. It has to be obviously less than the B_sat value.

At the same time, it should be such that the losses in the transformer—which we will discuss—should be at their minimum value. This will be the design outcome we obtain when we design the transformer. Now, these design outcomes can be obtained using quantities that are either specified—meaning given in the specification—or need to be obtained using first principles. So, for that, let us first understand the core loss in the transformer and, using— That understanding, we can estimate some of the design outcomes or some of the dimensional quantities. Now, as we know, the core—meaning the core material, the ferromagnetic material—is used to generate the flux. Now, in the core, we have losses associated with it, and those losses are the hysteresis loss and the eddy current loss. There are two kinds of losses associated with that.

The hysteresis loss is due to the energy required to change the magnetization of the core. What I mean by that is, let's say if you have a magnetic core and you apply a magnetic field in one direction, the magnetic domains will align themselves with the field. Now, when you change the field direction or the external field direction, the magnetic domains rotate, and because of that rotation, it requires some amount of energy to rotate those magnetic domains. That energy will actually go into the core from the external sources and then get dissipated in the form of heat. So, we can say that this particular phenomenon occurs due to the rotation of the magnetic domains.

Because magnetic domains resist that rotation, it takes some amount of energy to rotate those magnetic domains. Because of that, we have losses corresponding to that energy, and that particular loss is called the hysteresis loss. Now, another kind of loss in the core is due to the current that gets induced in the core material. Generally, core materials are conductive in nature. So, the core material is conductive in nature.

So, because of that, whenever the core experiences varying magnetic flux, there will be voltage induced in the core material, and because of the induced voltage, there will be currents in the core material. These currents lead to losses, heating the core, and that is called the eddy current loss. So, let us try to see how the hysteresis loss and eddy current loss occur. First, we will discuss the hysteresis loss. As we mentioned, the hysteresis loss occurs whenever there is a change in the magnetization of the core. That means whenever the magnetic domains have to rotate, some amount of energy goes into the core to support that rotation of the magnetic domains.

And that's when it leads to some losses associated with that. So let us try to define or let us try to derive quickly what the hysteresis loss will be, how the hysteresis loss will look like. So we can say that the energy which is going into the core, and this energy is going into the core whenever there is a periodic excitation of the voltages which are happening from one of the windings, because we are actually exciting from one of the windings. So the energy going into the core obviously via winding, and in one cycle, obviously, we have to write in one cycle. We can say, let us say, we define this to be W, which is, let us say, we have applied the voltage V_1. There will be current going through the winding corresponding to that, and that will be integrating over the time in one cycle. That could be one periodic cycle we can take, and this V_1 excitation voltage could be any, you know, arbitrary voltage.

$$W = \int V_1(t).\, i_1(t)dt \quad (1)$$

Now, this from Faraday's law, we can write. We can write

$$V_1(t) = \frac{d\lambda_1}{dt} = N_1 A_c \frac{dB}{dt}$$

and that we can then write to be N area of cross-section of the core N1. Let's say there is winding 1, it has been applied $N_1 A_c \frac{dB}{dt}$, obviously this dB is in the core, so we can write that. Similarly, from Ampere's law, we can write. We can write from Ampere's law,

$$H_{Lc} = N_1 i_1(t)$$

$$i_1(t) = \frac{H_{L_c}}{N_1}$$

$H_{Lc} = N_1 i_1(t)$, which is going into the first winding. And that I will not do to be HL_c by N1. Now this I can put it in equation number 1.

And that my energy lost in one cycle or energy going into the winding in one cycle. Because that energy is actually going into the core and it gets lost. So we can then write down in this one. So, we have

$$W = \int N_1 A_c \frac{dB}{dt} . \frac{H_{L_c}}{N_1} dt = A_c L_c \int H dB$$

Now this is the energy lost in one cycle. So we can get the hysteresis power loss by multiplying the energy which is going into the core multiplied by number of times this cycle occurs and this is nothing but given by let's say P_{hys} is the you know our hysteresis power loss. Is nothing but whatever the energy which is going into the core. We will multiply it with the number of times this cycle occurs. And that you know that number of times will just multiply it with the frequency.

And then this is the energy. You know this is $H\Delta B$. This is for one cycle. This particular part. now this is nothing but the you know if you see this one this is nothing but the volume of the core this is the excitation frequency if we see this integration HDB you know it is for one cycle is nothing but the area of B=H loop enclosed during one cycle of operation.

So, when the magnetic field is going in one direction, so our flux density is going in this direction and it reaches to the point where it is given as ΔB, where ΔB is nothing but peak value of AC component of magnetic flux density on one direction and then while going in a opposite direction we will get the ΔB going in the negative direction which is given as minus ΔB. So this particular area is nothing but is the area which is enclosed in the BH curve during the one cycle of operation and this particular thing we can say that this particular thing is nothing but is given in this particular part. So from this curve we can say that this is the area enclosed within the BH curve.

So what we can say is that the hysteresis loss is directly proportional to the area which is enclosed in the BH curve. Whenever this core in the transformer is used in the circuit operation, What happens is that it is very difficult to evaluate this particular integration. So we can write our P hysteresis or you can say the hysteresis power loss is nothing but we can say that it is proportional to fΔB raised to the power alpha $A_c L_c$ where our ∝ is the constant term. Term and it is nothing but it is dependent on the material property and also this f is the frequency of excitation of winding and our A_c and L_c are nothing but the volume of the core and we can say that this ΔB is nothing but the peak value of AC flux density.

And that is actually from the average value so if we see So, if we see in this curve, the average value is nothing but 0.0 and when we say that delta B, it is nothing but the peak value of AC flux density going in one direction. So, from the average value, this is our delta B on one side and on the other side, it is the minus delta B. Now, this particular stasis was we have written down for the case when our BH curve is not changing. For the particular excitation frequency, so that means we assume that whenever we have given excitation of certain frequency, Then the BH curve will still be the same, that means there is no change in the mu value due to the other operating conditions. So this is what we get for the hysteresis law. Now if you see, the hysteresis law is proportional to delta B raised to the power α , where alpha is nothing but the constant term which is dependent on the core material.

Similarly, let us see our eddy current losses how it looks like. Now in the eddy current losses, if we look very carefully in this particular thing, whenever we are applying current in this particular winding, let's say N_1, this one, there is flux which got generated in this one as a result of this if we see in this cross-sectional area. In this cross-sectional area, the flux lines are coming and it is going into this cross-sectional area. So, we can just take this particular cross-sectional area like this.

If you look very carefully, the flux is going into this particular area like this; we can then draw it that way. Now, if you look very carefully, because of this flux which is going into this particular cross-sectional area, there will be a voltage induced. Because of that induced voltage, there will be a current that flows through this particular area, and that current will oppose the cause due to which it gets induced—the cause being the varying flux going into the area. So that will have the

We will have the eddy currents that get induced. This is nothing but the eddy currents that get induced due to this in this direction.

The direction is such that the flux created by this eddy current opposes the particular cause. I mean, the flux that is actually causing the eddy current to be induced in the material. Now, if you look very carefully, this particular eddy current is, you can say, a resistive loss. Why can we say it is a resistive loss? Because if the core material, let us say, has a resistive impedance—let us take that as R_{core}—

that resistive impedance term. So, we can then write our

$$P_{eddy} \propto i^2_{eddy} . R_{core}$$

Now, this eddy current, if you see, the amount of eddy current that gets induced is directly proportional to the amount of voltage that gets induced. This voltage, whatever gets induced, depends on the change in the amount of flux crossing this cross-sectional area, which is delta phi. We can also say that

$$i_{eddy} = V_{induced}$$

$$V_{induced} \propto \Delta \emptyset_c$$

$$V_{induced} \propto f$$

$$i_{induced} \propto \Delta \emptyset_c$$

$$i_{induced} \propto f$$

our V_induced is again proportional to the frequency with which that particular flux— So, we can then define it as also proportional to the frequency of excitation because, depending on the frequency of excitation—that is, the frequency of the current $\dot{i}_1$—there will be a varying $\dot{\emptyset}_c$, which has the same frequency as that of the excitation frequency given by this current $\dot{i}_1$.

So now we can say that from these two things we can say that our eddy currents which get induced is directly proportional to the change in the flux delta phi and it is also proportional to the frequency of excitation. So, from here we can write our eddy current loss is nothing but

$$P_{eddy} \propto f^2(\Delta B)^2 R_{core}$$

$$P_{eddy} \propto f^2(\Delta B)^2 A_c R_{core}$$

proportional to $f^2(\Delta B)^2 R_{core}$ excitation. resistive impedance of the core and it is considering our core is having the resistive impedance because if we have the capacitive impedance then this relationship may vary it may also have some other frequency term coming into picture. So, then we can write down that this P_{eddy}, you know, if we put it this value in terms of A_c flux density value, so it is nothing but delta V square, you know, A_c

square comes out and this is R_{core}. Now, this R core, we know that is actually, you know proportional to the length of the core or you can say the magnetic length in the core and also it is inversely proportional to the area of cross section of the core.

$$R_{core} \propto L_c$$

$$R_{core} \propto \frac{1}{A_c}$$

Now that implies my eddy current loss is actually

$$P_{eddy} \propto f^2(\Delta B)^2 R_{core} A_c L_c$$

Now this A_c times L_c is nothing but we can say it is the volume of the core So what we see is that in case of hysteresis power loss, our hysteresis power loss is proportional to ΔB raised to the power alpha while our eddy current power loss is directly proportional to F square times delta V square. And there if you see the hysteresis power loss is proportional to the frequency and delta V raised to the power alpha. Here our eddy current power loss is proportional to the f^2 and $(\Delta B)^2$.

$$P_{eddy} = f^2.(\Delta B)^2.$$

Now if you look very carefully this eddy current power loss and hysteresis power loss are the losses which is happening in the core and because of that losses the core gets heated up.

Now if you see it is very difficult to separately measure the eddy current power loss and the hysteresis power loss because we only have the winding terminals. So we can only measure the amount of power which is going from the winding into the core. That means the amount of power loss which is happening in the core. So we can then from that we can only predict the overall core loss by measuring amount of power corresponding to the power loss which is going into the winding. And we know that our core loss is actually a combination of eddy current power loss and the hysteresis power loss.

So that is the reason why the core losses are generally defined using the empirical Steinmetz formula, which is given as Pcore (the overall core loss) is nothing but equal to

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

this is for a given excitation frequency. Purposefully, this particular excitation is nothing but the sinusoidal excitation, and this particular formula is the empirical formula, which is also called the empirical Steinmetz formula. Here, if you see, our K_{core} is the constant of proportionality, and it depends on the excitation frequency. That means for different excitation frequencies, this K_{core} value will be different. It also has this β term, which is the exponent term, and which is obtained from the manufacturer's datasheet. So, this is actually determined by the material property. For different materials, this β value will be different, which you can obtain from the manufacturer's datasheet. Generally, the β for ferrite material is nothing but between$\beta = 2.5\ TO\ 2.7$ for ferrite material. For different materials, it will be different. So, if the ferrite is made up of different alloys of different materials, then depending upon the concentration of alloys, this

$\beta = 2.5\ TO\ 2.7$ The manufacturer generally provides this P_{core} value, and this P_{core} we can write

We can write this P_{core} as, if you see this one, this is nothing but our volume of the core. So, we can then write P_{core} versus volume, or you can say core loss per unit volume, is nothing but equal to Kcore × ΔB raised to the power β. Again, this is for a particular excitation frequency, and that excitation is nothing but the sinusoidal excitation. So, generally, the manufacturer provides this core loss per unit volume curve with respect to the various values of ΔB, where ΔB is nothing but the peak value of AC flux density.

Generally, the manufacturer provides core loss per unit volume versus ΔB curve, and if you see those curves, it looks like, for different frequencies, they will provide the curve, and this is nothing but f1, f2, f3, and so on. Assume this is f6 or f6. So here, f1 is greater than f2, which is greater than f3, and so on, greater than f6. That means for the same ΔB, the core loss per unit volume will be more for higher values of frequency of excitation. So, that is what we will get for the core loss per unit volume. Now, this is nothing but the logarithmic curve. The logarithmic curve it is.

Generally, it is the logarithmic curve which is been given in the video. given in the core data sheet that is core material data sheet they will generally provide the this core loss per unit volume versus delta v curve now depending upon the chosen core the volume can be obtained and from there we can roughly predict the core loss which is happening in the required core material So, in this thing what we have understood is that my P core is directly proportional to delta B raised to power beta where beta is nothing but somewhere value between 2.5 to 2.7.

Now, we know that our core loss is a combination of eddy current power loss and the hysteresis power loss. The eddy currents

$$P_{eddy} \propto \Delta B^2$$

power loss is proportional to delta B square.

The hysteresis power loss is proportional to delta B raised to power alpha and so that is what it becomes very difficult to for one to actually predict what is the core loss because we cannot directly measure the eddy current power loss and the hysteresis power loss so that's why generally they provide this core loss using the empirical standman's formula which is shown over here and this is especially for one particular excitation frequency and that excitation is nothing but the sinusoidal excitation For excitation other than sinusoidal you may have to use the modified statement formula and then able to predict what is the core loss which is happening in the core of the transformer. now if you look here you know generally this k core which is the proportionality value which depends upon the excitation frequency this k core one can obtain you know by taking the curve for core loss per unit volume versus delta b for one particular frequency we can take two points two different points and then from two different points we can put it in this formula and from there we can predict what is my k core value because for two different delta b's you can from there you we have two variables k core and and beta beta sometimes you can also know so from there we can calculate the k core for different excitation frequency if we have this particular curve. Now we have already known that from faraday's law of electromagnetic induction from faraday's law of electromagnetism we know that our flux linkage is nothing but equal to integration

$$\lambda_1 = \int V_1(t)dt$$

where $V_1(t)$ is nothing but the arbitrary we can say arbitrary periodic input given to the given to the primary winding. and we have calculated this thing and we got that the in our previous discussion if you see we got that the peak value of AC flux density is nothing but what we get is

$$\Delta B = \frac{\lambda_1}{2nA_C}$$

$$\Delta B \propto B_{SAT}$$

So in this particular lecture we have understood two important thing which is the core loss and we know that our core loss is proportional to the ΔB raised to power β and along with that we have understood that the peak value of AC flux density or you can say the maximum flux density which is there is nothing but can be calculated by doing the $\lambda_2/2$ and $1/A_C$. Now this lambda 1 can be obtained by integrating

the $V_1(dt)$ that means the arbitrary periodic input which is given to the primary winding because depending upon the operation of the circuit you can get the different kinds of periodic excitation or input which is being given to the primary winding. So, from these two things, we have understood how we can obtain the ΔB. And obviously, we always wanted that this maximum value of Ac flux density should be less than the B set.

$$\Delta B \propto B_{SAT}$$

It should not go beyond the saturation value of the magnetic flux density. So, here if you see, you know this particular point. this particular point is nothing but Bmax.

So, we must ensure that the ΔB must be less than the saturation value of magnetic flux density and at the same time it should be such that we can get the required flux linkages such that we will get our proper magnetization of the core. Thank you very much for patience listening to this lecture. Thank you.