Electrical Machines - I
Prof. Tapas Kumar Bhattacharya
Department of Electrical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 51
Specific Magnetic and electric Loudings

Welcome to 51st lecture on Electrical Machines – I and so far we have analysed the transformers that is we found out the equivalent circuit of the transformer, how to analyse ideal transformers, then auto transformers, then you know three-phase transformers, core type primarily and how to represent it in per phase equivalent circuit and various tests like open circuit, short circuit and Sumpner's test and then finally, we in our last lectures we told you about the parallel operation of the transformer.

See, so far, I have not really told you about the construction of the transformer in details and what are how it will look like externally if you look at a transformer big transformer for example, 100 MVA transformers which are used in power stations and so on.

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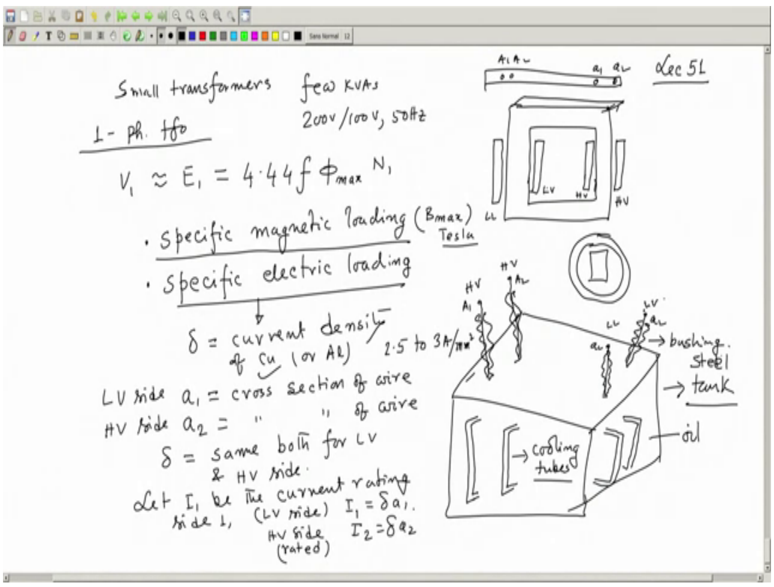

Perhaps we are used to see transformers in the laboratory which are very small ratings for example, 5 KVA small transformers we are used to see small transformers which are power transformers can be termed as few KVAs few KVAs and voltage rating may be 200 volt, 100 volt, 50 hertz and so on. If you see a big transformer you will find and this transformers if you look at in the laboratory you have seen, you will be able to see the coils and windings just like as it is ok.

There will be LV windings here I will just show it like this, this is suppose LV windings sectional view LV and this may be your HV side HV core type and this is the sectional view windings are if you see from the top, this HV windings are like this around the core, similarly for the LV side. And, also I told you to reduce the reactance of the transformer leakage reactance, LV windings may be divided in this two limbs. So, also HV windings and they may be connected in series respectively so that leakage flux is reduced and leakage reactance is reduced.

So, here I have drawn that LV on this limb and on the other limb and terminals will come out from the transformer on a terminal box in the laboratory you know LV terminals, all terminals will be brought in here, HV terminals are brought in. So, A 1, A 2 and small a 1, a 2 will be appropriately brought in for your external use. Although you will not be able to make out the sense of the coils otherwise it is exposed and it is everything is exposed. This is the core, you can easily identify here is core, here is LV windings, the windings you can see and this terminals are brought out.

But, if you see a big transformer you will always see nothing is visible except that a big tank, steel tank will be there steel tank; tank and on the top of the tanks there will be bushings through which terminals will come out. This is may be HV terminals, single phase I am drawing and another pair of bushings will be there whose insulation level will be less just to give you the idea another bushings two terminals will come out these are LV terminals.

This is suppose capital A 1, A 2 this is small a 1, a 2 just I am giving you the ideas. Where from this has come out? The transformer essentially has a core and coils this whole thing is within the tank and the tank is filled with oil ok. Sometimes you will find if you look at distribution transformer in your city, there will be some tubes around the walls of the coil. This is visually what you will see several these are called cooling tubes, that is in other words this whole thing is inside the tank and tank is filled with oil something like that.

Now, the question is for low KVA transformer I do not require any oil to cool the transformer, but for high rating I need a transformer which should be immersed in oil.

Oil will serve two purpose insulation from the tank which is steel tank the essential thing is this thing is there inside for big transformers that is what I am telling may be 100s of KVAs transformers.

So, and these are cooling tubes. I will give you a better picture later, but a just roughly you know that these are the things you see in real life. Now, the question is what for this oil is there and so on. For example, these voltage may be why I mean ceramic insulators will be there, these are called bushings things like that. [FL] To understand that cooling is a must in big transformers will be can be understood provided we go slightly deeper into the KVA equation of transformer and we will start with that then we will end up with this thing.

I will be trying to be very lucid to explain that, so that you can appreciate this is what it should be otherwise how. For example, I have told you that the voltage equation forget about that leakage impedance this that V 1 is approximately equal to E 1 for a single phase transformers say a single phase transformer. And, this was equal to some 4.44 f phi max into N 1 is not? That is the thing.

And, also I will tell you from this equation how can you relate it to the size of the transformer and two other things – one is called specific magnetic loading and specific electric loading. We will try to understand these two first, then I will show that the KVA which essentially tells you about the size of the transformer, can be shown to be proportional to specific magnetic loading, specific electric loading and the physical dimension of the transformer that is the first thing. You know when a transformer will be operating and hopefully it is operating at full load condition.

Both copper loss and core loss will take place and it will raise the temperature of the whole thing. And, suppose a transformer is now at room temperature, you have switched on and the transformer is operating at full load then you will see temperature will grow and after certain time the temperature will attain a constant value. What is the constant value at to which the transformer will attain to? Anything, if you go on pumping heat into a system temperature will rise and it will attain a constant temperature; that means, at whatever rate you are generating heat in the system at the same rate it is also dissipating heat to the outside world.

When such a thing will happen, then only that fellow will attain a constant temperature because after all copper loss and iron loss will be constantly taking place, always you are pumping energy into the system heat energy and your from the surfaces of the transformers heat is being dissipated out. The rate at which heat is generated inside the transformer, when it is saying as the rate at which that energy is given out by this surfaces of this so called transformer if it is a transformer, then only it will attain constant temperature. It is not only true for transformer, but for rotating machine also. There will be losses switch on the machine from cold condition that is at ambient temperature and operate it at full load after switching on, then temperature will exponentially grow and finally, attain a steady value.

It is this temperature rise that limits that puts the condition that is this is the current rating because if the temperature is allowed to rise more for example, if you overload the transformer then your windings may be spoiled, your insulations may be spoiled and things like that will happen. Anyway, so, we will try to see all these things. These are the interesting topics. So, first thing is first. So, this is let me try to relate the output of a transformer KVA rating of a transformer in terms of physical dimensions and specific magnetic and specific electric loading.

First of all specific magnetic loading is very simple; it is B max that is all in Tesla ok. Now, specific electric loading is the current density this one, this is denoted by delta is the current density. If you are using copper of copper or aluminium whatever you are using. Copper is the better because aluminium is brittle large transformers are build with copper nothing like aluminium. So, current density and its value is if I remember correctly about 2.5 to maybe 3 ampere per millimetre square where copper is used to make the coils, is not?

And, I told you LV side the section of the coil is a 1. So, LV side a 1 equal to cross section of the wire which makes the coils. Similarly, a 2 suppose is the cross section of wire on the HV side whatever it is this could be also LV HV reversed, but a 1 this one then obviously, the delta if you are using copper why they should be different? No matter whether that where is used for LV side or HV side delta will be same. So, delta is equal to same, both for LV and the HV side is not? Copper is used.

Let I 1 be the current rating of side 1 current rating rated current of side 1 that is in this case LV side, then I 1 rated current must be equal to delta into a 1 similarly rated current of the secondary coil HV side rated current will be delta into a 2, what else? Current rating. So, this is a rated current, this will be the thing [FL].

Then we come to this interesting thing.

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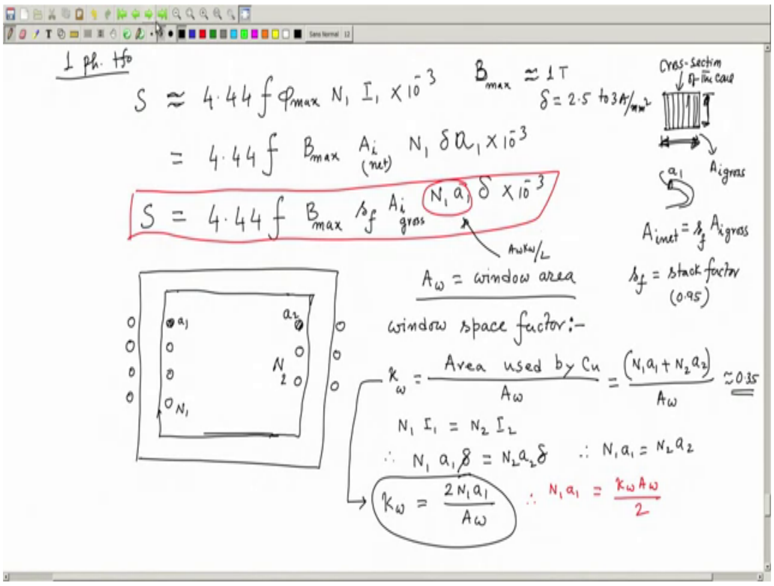

Now, KVA rating of a single phase transformer suppose single phase transformer, I will say it is equal to 4.44 f phi max N 1 into I 1; I 1 is the rated current forget about that leakage impedance drop etcetera. So, this is the approximately this is the KVA very close to. Now, what my plan is, to express this KVA rating of this transformer in terms of specific magnetic loading, specific current loading and the physical dimension of the transformer that is my goal.

So, this I can write it as 4.44 f; for phi max I will write B max and iron cross sectional area, but net iron cross sectional area. We have seen that irons area cross sectional area to realize this iron we use stampings. So, phi max is B max into the net area. Overall area will be slightly higher, is not? If you because of the plates are kept side by side there may be little bit of air in between. So, this is A i net B max into A i net gives you phi max then N 1 is there and I 1 is delta into N 1 delta into a 1.

What is a 1? a 1 is the LV side copper wire you are using side one, the cross sectional area of the wire which makes your turn are you getting this area a 1. I could write it in terms of secondary also 4.44 f phi max N 2 I 2, but one side we will do because I know N 1 I 1 is equal to N 2 I 2. So, this is the thing. So, let us understand each term. B max that happens to be the specific magnetic loading in Weber per meter square in typical transformer the values of B max where will be very close to 1 Tesla, may be 0.9 Tesla, 1.01 Tesla etcetera and delta if you are using copper I wrote it may be 2.5 to 3 ampere per millimetre square ok, CRGO material – 1 Tesla, copper this one and you get this.

Therefore, at least one physical dimension I have been able to brought in here that is the with this cross sectional area has something to do with physical area. Now, this length into this breadth this is the cross section of the core. So, this length into this breadth if you do what you get is A i gross and through which flux is passing not through air. So, it is slightly more. So, A i net will be slightly less than this.

A i gross means you take a scale measure this outside dimension of the core get the area. So, it must be multiplied by a factor s f. This factor s f is called stack factor. The value of which will be 0.95 very close to 100 percent, but may be 0.9 like that, got the idea? So, I will because overall dimension I want to know. So, this can be written as 4.4 f B max this is already specific magnetic loading, then this I will write s f stack factor into A i gross then N 1 a 1 delta into 10 to power 3. If these are in volts etcetera I hope you are getting this, this will be the KVA rating [FL].

Now, you look at this sectional view of the transformer core and this one. I am sorry these two are same width make it corrected ok. Now, how these windings are there? LV windings or side one wind coils. How many sections you will see here? N 1. What is the sectional area of each conductor? a 1. Similarly, on the other side the coils are wound like this sectional view will appear like that. How many things you will see here? N 2 and what is the cross sectional area? a 2 [FL].

This area is called the window area in which copper will be receding. So this area internal rectangular area is the window area; A w is the window area, this length into this height [FL]. There is a factor like stack factor we called it window space factor window space factor. It is usually denoted by K w. This tells you how much of this window area is utilized by copper. So, area used by copper divided by the total window area that is all.

So, obviously, you can see that this will be equal to N 1 a 1 plus N 2 a 2, is not? Divided by A w. Generally, the window factor is about 35 percent or so I mean some may be 0.35 not 100 percent is utilized to fill it with copper. We will see because there will be some oil will be filled up circulation of heat is necessary and so on. So, practical value of this is only 35 percent of this window area will be utilized for that. So, this is called window space factor. But, A w will certainly going to decide A w along with a i, physical dimension of this core is going to decide the physical dimension of the transformer.

Now, you see when the rated current will be flowing we know N 1 I 1 is equal to N 2 I 2, but current density of copper remain same in the primary and secondary. Therefore, I will write N 1 a 1 delta must be equal to N 2 I 2 delta N 2 a 2 sorry, N 2 a 2 delta this delta goes. Therefore, N 1 a 1 is equal to N 2 a 2. So, come back here windows space factor then will look like. It will look like 2 N 1 a 1 divided by A w, is not? So, this is the thing.

Now, we will come back to this equation and we note that from this N 1 a 1 is equal to K w A w divided by 2. So, for this N 1 a 1 I will put this there. So, I do that in the next page.

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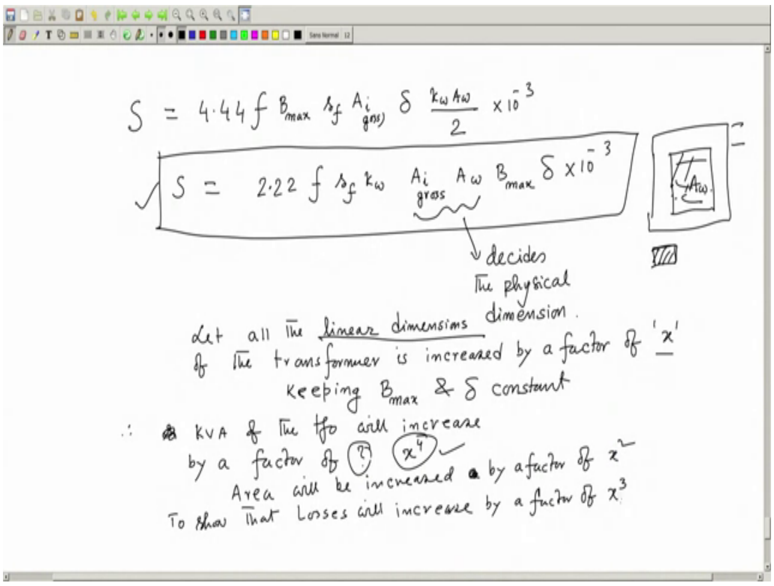

So, it will be equal to we have seen that output equation is what 4.44 f phi max, phi max is B max into stack factor into A i gross that this together will give me A i net then what we had? A i gross then N 1 a 1 delta then oh my god then delta and N 1 a 1 I have got to be K w A w by 2. So, I will put this there K w A w by 2 into N 1 is there or it is over? N

1 N 2 I have taken into account. So, N 1 a 1 is at K w A w. So, in this case that is this part only you write A w K w by 2, that is what I am doing. I think I have written everything there into 10 to the power minus 3.

So, S, the KVA rating of the transformer is 4.44 root 2 pi this 4.44 is f these two factors you write stack factor and the windows space factor K w ok. Then you write A i gross into A w then you write B max into delta into 10 to the power of minus 3. In fact, these two cancels this so, it will become 2.22. So, these are the two factors stack factor about 0.95, windows space factor is about 0.35, 0.33 like that. A i gross area is window area is this area and A i is this area and this is the window area, are you getting? A w.

So, this will determine the physical dimension of the transformer. Height of the transformer into this because the moment you know A i you know these things. So, it is related, but what I am telling. So, these are the you a decides the decides the physical dimension of the transformer. It is going to decide that is all ok. So, this is the output equation of the transformer. Similarly, for the three-phase transformer it can be also derived, that we will do later, but for the time being look at the single phase equation and listen carefully what I am telling.

A transformer when it will be operating at full load condition your B max will be at rated value I told you rated voltage, similarly your current density also will be highest than corresponding to rated current. At that time the full load losses will take place and finally, that is going to decide what will be the temperature rise.

Now, I am telling you that suppose I increase let all the linear dimensions of the transformer is increased by a factor of x; all the linear dimensions are increased, keeping specific magnetic loading B max and delta constant, got the point? All the linear dimensions are increased and B max and delta I will not touch because that is the capacity of that iron CRGO material, 1 Tesla per meter square delta copper say 3 ampere per millimetre square and so on.

So, if you increase all the linear dimensions by a factor of x, what do you think the size of the transformer will be? So, size KVA of the transformer will increase by a factor of what? Look at this equation linear dimensions have been increased by factor of x, so, areas will be increased by a factor of x square. So, there are two areas, this area will increase by a factor of x square, this also will increase by factor of x square. So, your initial KVA was S. So, it will become x to the power 4 into S, is it not? So, will be increased by a factor of x to the power 4.

At least from this I can say that your lab transformer same CRGO you are using B max same copper you are using B max delta is same. So, you imagine a large transformer is nothing, but you have increased the physical dimensions by several factors because no more copper can be accommodated now, keeping of course, stack factor same, windows space factor same more copper you are using definitely and your size of the transformer will increase by a factor of x is 4.

As I told you earlier, that when heat will be generated, that heat will be also dissipated through its exposed areas and when the rate at which it is generated within the transformer matches with the rate at which it is dissipated out to the outside world, then constant temperature will be attained.

Now, the question is I have increased all the I am imagining all the dimensions are increased by factor of x, B max delta constant, stack factor, windows space factor remaining same, then I conclude oh transformer rating will be increased by factor of x to the power 4 [FL]. Now, what will be the areas increased by what factor? Areas which ever dissipating energy area will be because linear dimensions I have increased by a factor of x.

Areas will be increased by a factor of by a factor of x square that is area through the areas only exposed areas only it was dissipating therefore, that area increases by a factor of x square. Now, we have to examine by what factor losses will increase you know and I think I will continue next time, but please go through this one. This topic is very interesting.

It will give you now an fair idea how a practical power transformers is going to look like and what are the implication of B max delta and why elaborate cooling arrangements are a must for a large sized transformer. Otherwise what happens I may feel a small transformer without any extra cooling arrangement, air natural cooling is sufficient and it is working then what happens if the size of the transformer is very large that is what we are examining. Ok you increase the physical dimensions of the transformer then you see size KVA ratings will increase by a factor of x to the power 4, giving you same large KVA rating. Then at least I know this much area will be increased by a factor of x square.

In our next class, I will show you that the losses in the transformer that is copper loss and iron loss, losses will increase by factor of x cube that will show to show and you can also think yourself to show that losses will increase by a factor of x cube. So, these informations are essential to draw conclusions about whether extra cooling arrangement is to be done or not. So, we will continue next class.

Thank you.