Electrical Machines
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Lecture 11 - Instrument Transformers and All Day Efficiency

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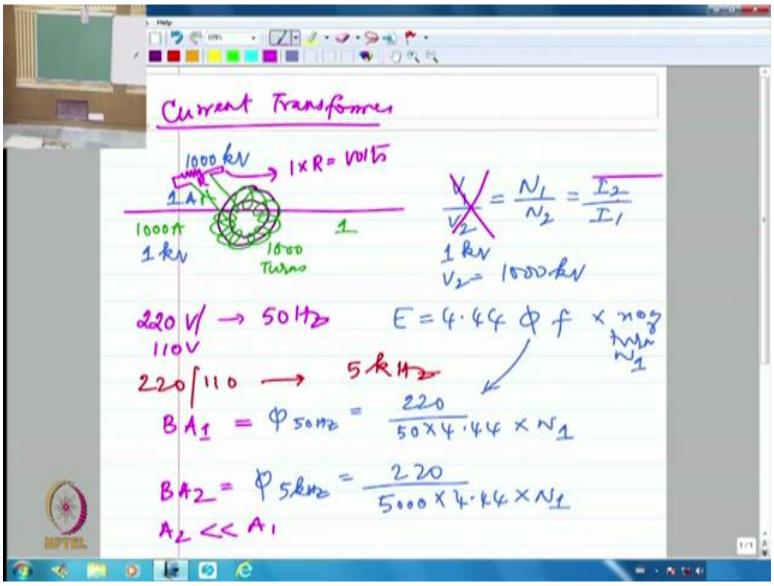

So, we were discussing current transformers in the last class and what we actually said was that if we are having a wire like this through which I want to measure actually what is the value of current and because it is a very large value, I might like to put a transformer around it.

But the transformer has only secondary winding and the wire through which I want to measure the current itself will be taken as the primary winding. So, I am going to have turns around this somewhat like this, so I have huge number of turns wound around this and then if I look at the current that is flowing through this if I say that this is say 1000 A and I am going to have this as 1 turn whereas this is 1000 turns, then I am going to have the current that is coming out here as 1 A, if I assume that the current ratio is maintained properly but at the same time by chance if I had just connected that to a fairly larger resistance, what will happen actually is the voltage ratio will also be maintained.

So, if I say this is 1000 A and 1 kV or something like that, what I get here will be 1000 kV. If I am keeping this on open circuit because I am going to have $\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$, this is the normal relationship in a transformer and if I am keeping this voltage coil the secondary coil as an open circuit then I will have the voltage ratio also being followed or even if I connect the fairly larger resistance I am going to have essentially the voltage ratio being followed.

If the voltage ratio is followed what will happen is from here, V_1 is 1 kV so V_2 will become 1000 kV but what I was meaning to with the current transformer is only to measure the current, I do not want really this large voltage to come up, I am not interested in that large voltage at all and not only that large voltage that is coming up will rupture the insulation, If I have really not designed the secondary corresponding to larger voltage, which I will not, normally I will not design the secondary of a current transformer corresponding to a larger voltage at all, because it is meant only for measuring the currents, stepping down the current and measuring the current.

So, that is essentially going to cause rupturing of the insulation. To avoid that I necessarily need to either short circuit the secondary or connect a very small resistance, the small resistance will work actually as a short circuit, it will make it work like a short circuit that is actually going to make, you know the voltage what appears across this resistance will be whatever is my ‘I’, $1A \times R$. So, what I am getting out of this will be $1 \times R$ volts, so if I measure this voltage, divide that by the nonresistance I will get exactly whatever is the current value.

So, current transformer allows me to measure the current by stepping down the current. In the process voltage will be stepped up if I keep it as an open circuit, so I cannot keep the current transformer in open circuit condition at any stage, never ever keep the current transformer in open circuit condition. Similarly, never ever short circuit a potential transformer, both these are literally rules you guys have to follow whenever you are using CT or PT.

[Professor-student conversation starts]

Professor: Yes.

Student: Ma’am, in the secondary coil the voltage could be 1000 kV, and it might be applied like….

Professor: 1000 kV, yeah.

Student: And the current is (())(04:49) but could we have the low resistance?

Professor: Low resistance is as good as short circuit, I am going to have literally 1 Ω or 0.1 or whatever. Low resistance again is compared to the base impedance, you will compare it with the base impedance and compared to base impedance it should be 1,000 or 10,000 or something like that, so it is as good as a short circuit.

Student: Could we follow the Ohm's Law like could we use volts, in place of volts kind of (())(05:17)?

Professor: See, the thing is that you are really not allowing the transformer to follow the voltage ratio at all just like how I told you that in potential transformer this is invalid, in current transformer this is invalid. Because I am going to short circuit it $V_2=0$. Because V_2 become 0 it doesn't make any sense further, so you are going to have basically $\frac{V_1}{V_2}$ absolutely not valid in the case of a current transformer.

[Professor-student conversation ends]

So, I would say just to reiterate, we have talked about open circuit test and short circuit test of a transformer and the open circuit test condition of a transformer only $\frac{V_1}{V_2} = \frac{N_1}{N_2}$ is valid, no question of $\frac{I_1}{I_2}$ because I2 = 0.

Same way short circuit test condition of a transformer V2 = 0 because of which $\frac{N_1}{N_2} = \frac{I_2}{I_1}$ is only valid, that cannot be equated to $\frac{V_1}{V_2}$, that is not valid because $V_2=0$. Only thing normally we say as a problem in current transformer and potential transformers are the linearity may not be maintained especially when you come to very low values of current and low values of voltages in current transformer and potential transformer respectively, because of hysteresis, because of saturation phenomena.

Very high values you may encounter saturation, very low values you may encounter hysteresis phenomena. So, there will be some amount of retention of the magnetic field because of which even when you are applying very very minimal current, you may get the you know much smaller current or much larger current depending upon you are going in the same direction or coming back in the opposite direction.

So, you may not get exact linearity in current transformer and potential transformer when you talk about extremely larger values or extremely smaller values. Extremely larger values you may encounter saturation, extremely smaller values you may see hysteresis.

So, in both the cases you may find that the transformer is not working in the linear region, But in general these CTs and PTs are very commonly used in power system measurement and instrumentation where thousands of amperes of current are normally you know passed and thousands of kV of voltage are encountered. Especially, when you are transmitting a very large capacity of power, we may go as high as 765 KV, 400 KV and so on. So, in those cases measurements really become difficult unless you have potential transformer and current transformer.

So, I am not even mentioning into three-phase now, two topics are mainly pending in transformers now, one is three-phase transformer. One more finally I would like to do if time permits is parallel operation of transformer, that is if I have some capacity increased suddenly let us say we are talking about LHC itself, so two topics are pending, one is parallel operation of transformer, the other one is three-phase transformer.

[Professor-student conversation starts]

Student: When frequency increases, why would the transformer size decrease?

Professor: When the frequency increases why would the size of the transformer decrease? that is the question. So, if I say I am comparing 220 V, 50 Hz transformer, of course 220/ 110 V. Another one is 220/110 say 5 kHz, I am going to compare the sizes of these two transformers. In both the cases I am going to have $E = 4.44\phi f \times \text{number of turns}$.

[Professor-student conversation ends]

Now, if I look at the flux in the first case, ϕ corresponding to 50 Hz will be $\phi = \frac{220}{50 \times 4.44 \times \text{number of turns}}$, let me call this as N_1, Whereas ϕ corresponding to 5 kilohertz will be $\phi = \frac{220}{5000 \times 4.44 \times N_1}$.

So, clearly when I increase the frequency flux required decreases because $\frac{d\phi}{dt}$ is the one which decides how much is the voltage induced, so dt will shrink when I look at higher frequency. So, I can go for less and less amount of flux as I increase the frequency further and further.

Which means flux density, B multiplied by cross-sectional area, A that is what gives me the flux. So, cross-sectional area can be decreased if I assume that I am using the same material whose flux density is fixed. B_{max} is fixed for any material. So, if I am using a particular material then I can say for 5 kHz I can definitely choose smaller cross-sectional area, so I should be able to say in this case if I say BxA_1 this will be BxA_2. So, A_2 is going to be much smaller as compared to A_1. So, if the cross-sectional area decreases, automatically the core size will decrease.

I can assume that the core size will also decrease, that is one reason why if you look at the electronic systems, generators, all those things in aircrafts, they will all be operating at 400 Hz generally, they will not be operating at 50 Hz. We are not transmitting it anywhere, it is within the aircraft itself. So, we may have generator, we may have electronic system. All of them are going to work normally at much higher frequency so that they are miniaturized, and space is at a premium in aircraft and all, so you want to reduce the size as much as possible when you are going to aerospace electronics systems. So, all of them are going to work at higher frequencies not at 50 Hz.

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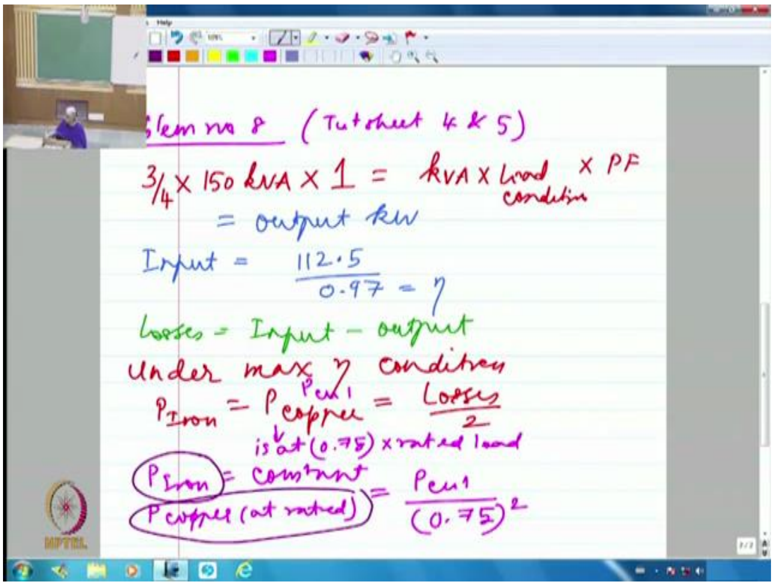

So, this particular problem statement goes as follows: the maximum efficiency of a 150 kVA 3300/500 V, 50 Hz single-phase transformer is 97% and occurs at three-fourth of full-load at UPF.

So, three-fourth of load first of all I can say $\frac{3}{4}\times 150\text{kVA}$, this is three-fourth of load and unity power factor means 1 is the power factor. So, this is going to be kVA multiplied by whatever load condition multiplied by power factor, this is what we have got. And this is the output, this is the output because we have been talked about three-fourth of load condition that is what we are talking about, so that is going to be the output. So, this is my output kW, so input will be so 150×0.75 is how much? Can any one of you tell me? I remember that is some 112.5 or something, that is what I remember from what I calculated.

So, it is $\frac{112.5}{0.97}$ this is the efficiency, so this will be the input power. Whatever is the output divided by efficiency will give me the input power, now once I get the input power and output power I can say losses will be equal to input minus output. so I should be able to calculate what are the loses. Now, under maximum efficiency condition right, under maximum efficiency condition $P_{Iron}=P_{copper}$, so this will be actually $\frac{\text{Losses}}{2}$ because total losses are only considered to be iron loses and copper loses. If they are equal, I should have the total loses whatever occurs at maximum efficiency condition divided by 2 will give me the actual losses of iron and copper.

But, please note this copper loss is at $.75\times \text{ratedload}$, because we already said the maximum efficiency occurs at 75 percent of rated load. So, what I have got here I should say P_{iron} is a constant not a problem but P_{copper} at rated load will be whatever I am getting here, let me call this is P_{cu1} or something like that, so $\frac{P_{cu1}}{(0.75)^2}$. Because, copper losses at any load condition x if x square multiplied by copper losses at rated condition, so I am just using the same expression. So now I have got what is rated copper loss, I have got what is rated iron loss, what is being asked next? If the impedance is 10 percent calculate the regulation at full load for power factor 0.8 lagging.

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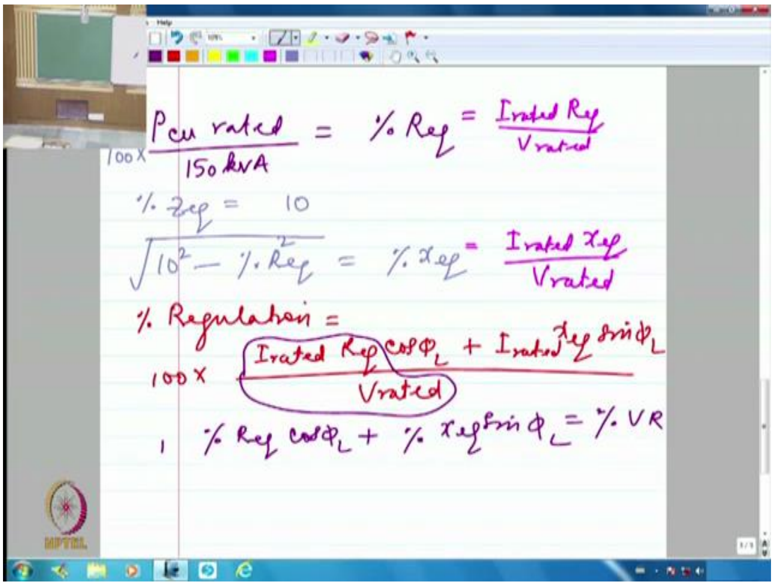

What I have got is rated copper loss. If I have got rated copper loss, what we wrote just some time ago for per unit measurement, I should say $\frac{P_{cu\ rated}}{150kVA}$ will actually give me $\%R_{eq}$.

Because, this is essentially $\frac{I_{rated}\ R_{eq}}{V_{rated}}$ that is what is $\%R_{eq}$, I am multiplying the numerator by 'I' and denominator also by I_{rated}. Then I should be able to get at the denominator whatever is the rated kVA of the system which is 150 kVA and at the top what I would get is $I_{rated}{}^{2}R_{eq}$, which is rated copper loss itself.

So, this is going to be actually $\%R_{eq}$ and what is given is $\%Z_{eq} = 10$, so once I get this, I should say $\sqrt{10^2 - \%R_{eq}{}^{2}}$. Of course, I have to multiply this by 100, if I want everything in percentage I have to multiply by 100.

So, this will give me what is $\%X_{eq}$, please note that this is $\frac{I_{rated}\ R_{eq}}{V_{rated}}$, maybe I have taken everything from the primary side. This will be similarly $\frac{I_{rated} X_{eq}}{V_{rated}}$. So, now if I want regulation, I can write the expression as $100 \times \left\{ \frac{I_{rated} R_{eq} \cos\phi_L + I_{rated} X_{eq} \sin\phi_L}{V_{rated}} \right\}$.

Now I can say that this $\frac{I_{rated} R_{eq}}{V_{rated}} \times 100 = \% R_{eq}$, I got that directly, so I can write directly $\left\{ \frac{I_{rated} R_{eq} \cos\phi_L + I_{rated} X_{eq} \sin\phi_L}{V_{rated}} \right\} \times 100 = \% \text{Voltage Regulation}$, that is it. So, this is based on per unit or percentage expression of the impedances, resistances, reactance's and so on and so forth.

[Professor-student conversation starts]

Student: (())(20:37)

Professor: See, if I am taking I_{rated} from the primary side I better take V_{rated} also from the primary side, if I take I_{rated} from the secondary side I better take V_{rated} also from the secondary side. But when we express it as a percentage it does not matter because if I am taking I_{rated} and V_{rated} from the secondary side either taken R_{eq} also from the secondary side, so it will essentially $\frac{I_{rated} R_{eq}}{V_{rated}}$ on the secondary side will be very much equal to $I_{rated} R_{eq}^{1}$ if you may call it as what is calculated from the primary side divided by V_{rated} on the primary side itself.

[Professor-student conversation ends]

So, percentage calculation if you do. From either side it will essentially cancel out with each other because the moment you write $\frac{V_{rated}}{I_{rated}}$ it gives you Z_{base} either from the primary side or from the secondary side and when you calculate the $\% R_{eq}$ you will always calculate it with reference to the Z_{base}.

So, if you are talking about high voltage side you are going to have the Z_{base} itself to be larger and if you are talking about the low voltage side the Z_{base} itself will be smaller, so ultimately when you calculate the percentage everything will come out to be the same.

Student: But if we take that, the answer will be very different.

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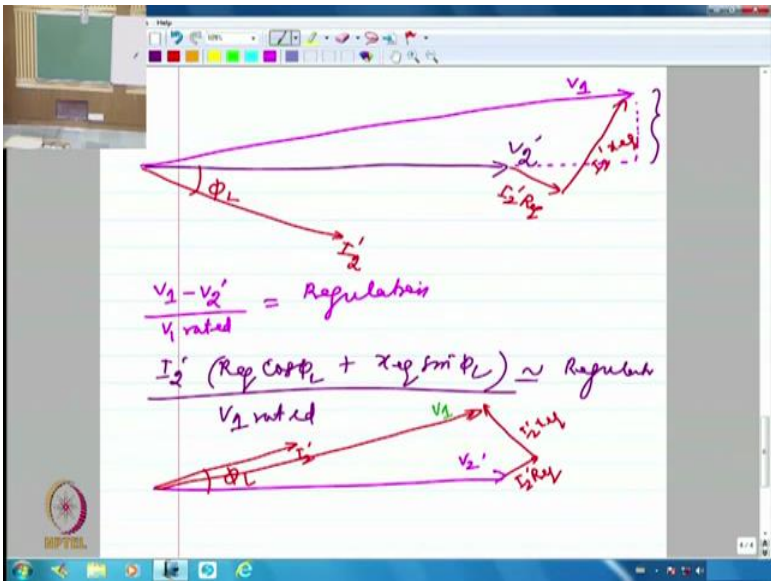

His questions is about 6th problem in the tutorial sheet, he says when we actually drew the phase diagram if you may recall for the transformer, we wrote let say this is V_2 or $V_2^{'}$ if I am talking about it from the primary side and let say this is my current, this is the power factor angle.

So, let me write this as $I_2^{'}$ and this is the load power factor angle and if we are saying this is going to be $I_2^{'} R_{eq}$ and I am going to have this as $I_2^{'} X_{eq}$ now the total what we are getting is something like this, this is what is V_1, so $\frac{V_1 - V_2^{'}}{V_{1rated}}$ or $\frac{V_1 - V_2^{'}}{V_{2\ rated}^{'}}$, either way is fine, is the regulation. And when we actually calculated we said we can neglect this vertical portion, that is how we got the expression as $\frac{I_2^1 (R_{eq} \cos\phi_L + X_{eq} \sin\phi_L)}{V_{1rated}}$, this is approximately the regulation.

So, what he is trying to say is if we neglect that vertical component whatever I have shown, this particular vertical component if we neglect then we are getting the regulation value to be different. Definitely, if you do not neglect that vertical component it will be more accurate but most of the times it happens to be you know negligible, maybe in this case it so happens that it is not negligible.

So, either way if you calculate it, you should be given due weightage, that is all I am trying to say. So, don't bother too much about the answer as long as you know that the methodology is right. And when we neglect something or when we approximate something, we look at the practical conditions but most of the time the values given in the problems may not be all that practical, that is also there.

So, sometimes that can actually give rise to some difficulty. I hope so that you guys are understanding why leading power factor actually gives you increase in the voltage rather than reduction in the voltage. Please try to draw the phasor diagram corresponding to leading power factor condition or if we quickly draw the phasor diagram for leading power factor condition maybe this is my $V_2^{'}$. If it is leading power factor, I am probably going to have a current like this, this is the load power factor angle.

So, I am going to have I_2R_{eq} somewhere here and maybe $I_2^1X_{eq}$ somewhere here, so what I am going to get is something like this, this is what is going to be my final value of V_1. And you can see that V_1 and $V_2^{'}$ are almost of comparable length, infact if you had x to be more inwards then actually your V_1 would have been smaller in all probability than even $V_2^{'}$ which means the applied voltage happens to be smaller or slightly less as compared to what you get on the secondary side. If it is 1 is to 1 transformer, I am talking about 1 is to 1 transformer.

So, you can say that capacitive voltage, capacitive loads normally increase the voltage that comes out on the secondary side. This happens because inherently what is there within the transformer is inductive in nature, so the capacitance kind of nullifies it, what is inherently the impedance of transformer happens to be inductive in nature.

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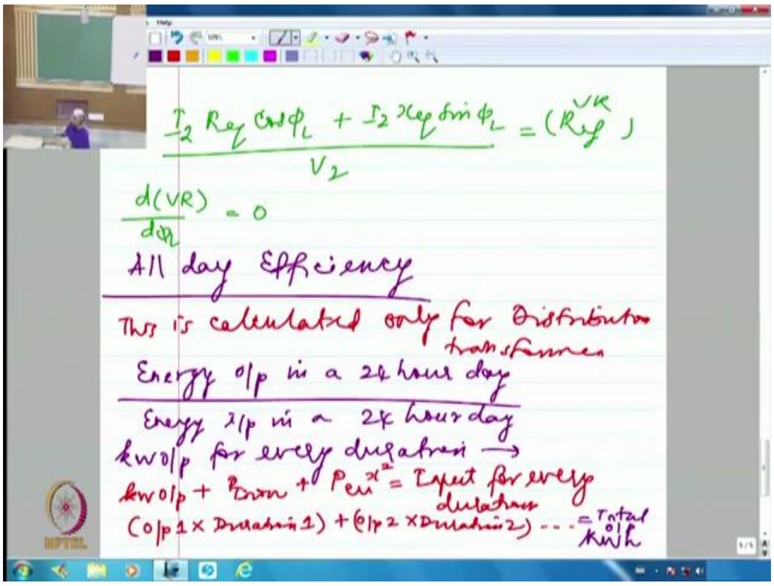

And there are conditions for voltage regulations where maximum regulation occurs and where minimum regulation occurs, you can try to derive those as well, that is when you write $\frac{I_2 R_{eq}\cos\phi_L + I_2 X_{eq}\sin\phi_L}{V_2}$ is regulation.

So, you can say at what point $\frac{d(VR)}{d(\phi_L)} = 0$, you can try deriving this and this will be able to give you clearly at what point voltage regulation is minimum and at what point voltage regulation is maximum. All day efficiency is done only for, so this is calculated only for distribution transformer. See, if it is a power transformer I told you that power transformer normally is loaded to 100% all the time because the generator will generate full power or it will not be commissioned at all, that is how it will be.

So, if it is generating full power then the transformer will also be handling full power, so the generator transformer or power transformer will be designed in such a way that it will always have maximum efficiency at 100 % load. Whereas, distribution transformer will always have variable load because it has a variable load it is very difficult to say you know like at what point you have to design it for maximum efficiency.

So, that is the reason why you generally when you want to install a distribution transformer you tend to look at the load profile in that area in the distribution area and if the load profile says out of 24 hours in a day for 12 hours it is going to work at 65% load, then you would try to get a transformer which will have maximum efficiency at 65% load. That is how you generally you know ask for a transformer, when you go and purchase a transformer for being installed in a distribution system.

So, this all day efficiency for a distribution transformer is calculated at energy efficiency, so it is essentially $\frac{\text{energy output in a 24 hour day}}{\text{energy input in a 24 hour day}}$, this is the all-day efficiency normally. So, if we say that a transformer is going to be on a 100 % load for 4 hours which unity power factor, maybe it is going to be on 80 percent load for you know 10 hours at 0.8 power factor lag, and for the rest of the times it is going to be on no load. For example, so we have got only 8+4=12 hours and then another 12 hours it is on no load which is actually a criminal ways, but it is happens that way you are going to essentially calculate what is the kilowatt output for every duration or every time interval given, you have to calculate.

During that time itself you have to calculate kilowatt output+iron losses which will be a constant plus whatever is the copper loss corresponding to that load, that also you have to calculate for every duration.

So, this will give you the input, so this will be the input for every duration, very clearly it has to be multiplied by x square if x is the fraction of the load. Similarly, the output has to be always multiplied with the power factor, if it is anything other than unity power factor. So, if I am given for 5 hours it is working in 0.8 power factor lag with 100% load then I have to multiply whatever is the capacity of the transformer, that is 100 % multiplied by 0.8, so this will actually give me what are all the total inputs and here it will give me total output.

But, for everything I should say $\text{output1} \times \text{duration 1 in hours}$, so I will get kilowatt hour. Then similarly $\text{output2} \times \text{duration2 in hours}$ and so on, this will be the total output kilowatt hour, that will be the total output kWh.

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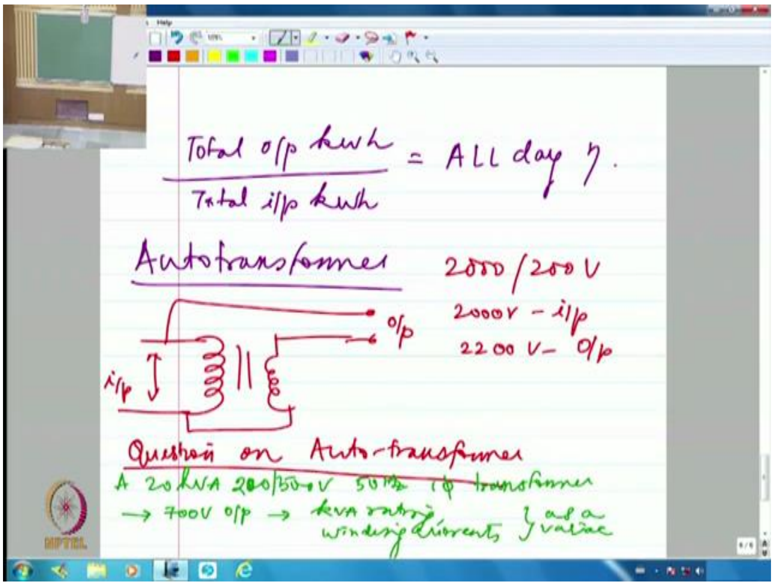

So, I will have to have $\dfrac{\text{total output kWh}}{\text{total input kWh}}$, this is what is all day efficiency.

[Professor-student conversation starts]

Student: Ma’am, in the auto transformer we can have two types of (())(34:03) like if we have input on one coil and if we have input on second coil, then the power input will be different in the two cases.

Professor: Come on, again, if...

Student: Output will be different in the two cases like if we have two coils in an auto transformer.

Professor: Yes, Auto transformer that is made from two winding transformers, right that is what you are talking about. But both windings are rated for the same kVA clearly, now you going to connect them in say series addition. So, if I am connecting them in series addition like this and then I am going to get the output maybe from only both of them or whatever…

Student: Both of them.

Professor: Both of them together, so you want to apply the voltage only here but you want to take the output from here and here, this is the output whereas this is the input. This is what you are talking about, right, so come on again.

Student: There could be two cases like if I apply into (())(35:11), there could be two cases and there could be two possible output somewhere.

Professor: Yeah, but you are given a situation clearly. When you are trying to calculate you are calculating for a given situation, so if I try so say that it is a 2000/200 V transformer and I am applying 2000 volts in the input and I am trying to derive 2200 volts at the output, at this condition what I calculate as kVA would be different from, if am applying 2200 volts as input and I am trying to derive 2000 volts as output, it will not be the same. It will be different, so you should be given a situation to derive the kVA rating, under that given situation you have to derive. So it will not be a unique answer arbitrarily. For a given situation you will get one particular answer.

Student: Winding time, it will be (())(36:14)

Professor: See, we are essentially trying to make sure that the winding current should not exceed the rated value, that is all. The care has to be taken to make sure that you do not exceed rated current value, that is it, nothing more than that.

Student: A 20 kVA…

Professor: A 20 kVA.

Student: 200 upon 500 volt, 50 hertz.

Professor: 200 by 500 volts 50 hertz.

Student: Single phase transformer is connected as an auto transformer supplied load requiring 700 volts, that when the kVA rating holds for….

Student: And winding current also.

Professor: kVA rating and winding current as a variac, okay. So, this question apparently has been given as one of the exercise questions for you guys, so this is on auto transformer, it says a 20 kVA, 200/500 V, 50 Hz single phase transformer requires a 700 V output from a 500 volts input, it may be or 200 volts input, this has to be given. If it is not given then you are going to have difficulty. It should be given clearly whether you are deriving it out of 500 volts input or 200 volts input, one of them has to be given for sure.

[Professor-student conversation ends]

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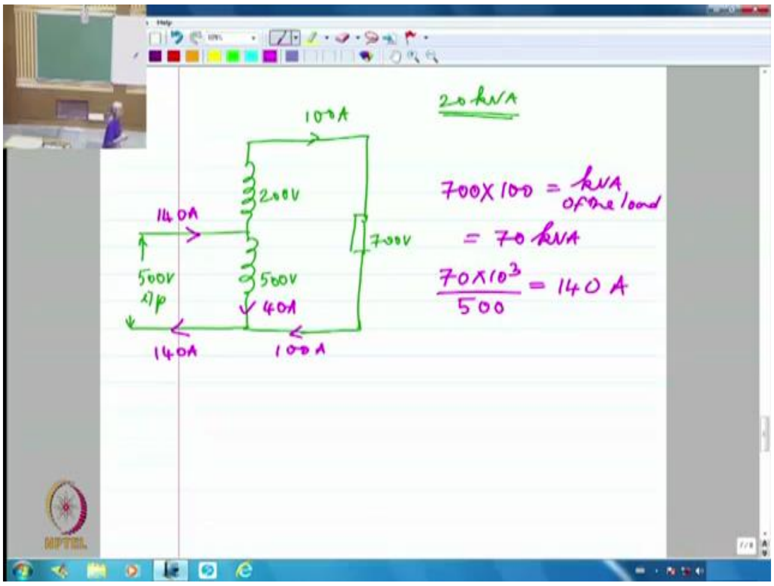

So let us probably go ahead and assume that it is 500 volts input, so I have 200 volts, then this is 500 volts and what we are giving is a 500 volts input right, and what we are having as a secondary side is this is 200 volts this is 500 volts, so what we have got is 700 volts, fine.

Now, 20 kVA is given as 20 kVA is given as the rating of the transformer, how much is the current on this side? It will be 100 A, so this has to be 100 A. Without overloading the transformer you would be able to get 100 A, right. And now the total thing what I am getting is $700 \times 100 = \text{total kVA of the load}$. So how much is it? 70,000, 70 kVA so from which we should be able to calculate what is the current here, so this is $\frac{70\times10^3}{500}$, right 14 how much? 14 into 5 is 70, 140. 1400 or 140?

Student: 140.

Professor: 140, so this is going to be 140 A. So, if this is 140 that means this also has to be 140, this is 100 A, so this has to be 140 A. So, hopefully it is matching with whatever is the kVA rating even in the primary side. So, you should be given clearly what is the kind of source that you are you know adhering to, that has to be given. If that is not given then it cannot be worked out.

I had taken this from one of the books and then I had, there are some problems that are there in NPTEL, I had seen there are very good problems on auto transformer in NPTEL, NPTEL course has one section completely on auto transformer. There is one from IIT Madras, there is one from IIT Kharagpur also, and it’s pretty good, the problems are pretty good, so you might like to take a look at those also.

Because auto transformers there not too many problems available in many books, so in that sense it may be of you know some value if you try to take a look.