Electrical Machines - I
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Lecture - 26
Auto Transformer - Introduction

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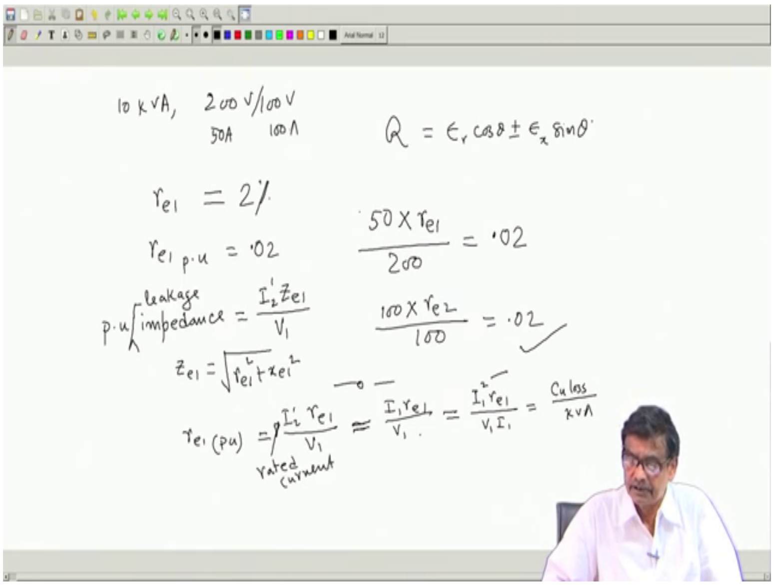

10 kVA, 200 V/100 V

50A 100A

$R = \epsilon_r \cos\theta \pm \epsilon_x \sin\theta$

$r_{e1} = 2\%$

$r_{e1\,p.u} = .02$

$\frac{50 \times r_{e1}}{200} = .02$

p.u leakage impedance $= \frac{I_2' z_{e1}}{V_1}$

$\frac{100 \times r_{e2}}{100} = .02$ ✓

$z_{e1} = \sqrt{r_{e1}^2 + x_{e1}^2}$

$r_{e1\,(pu)} = \frac{I_2' r_{e1}}{V_1} \approx \frac{I_1 r_{e1}}{V_1} = \frac{I_1^2 r_{e1}}{V_1 I_1} = \frac{\text{Cu loss}}{\text{kVA}}$

rated current

Welcome to lecture number 26 on Electrical Machines - I and you recall that we were discussing about regulation of a transformer.

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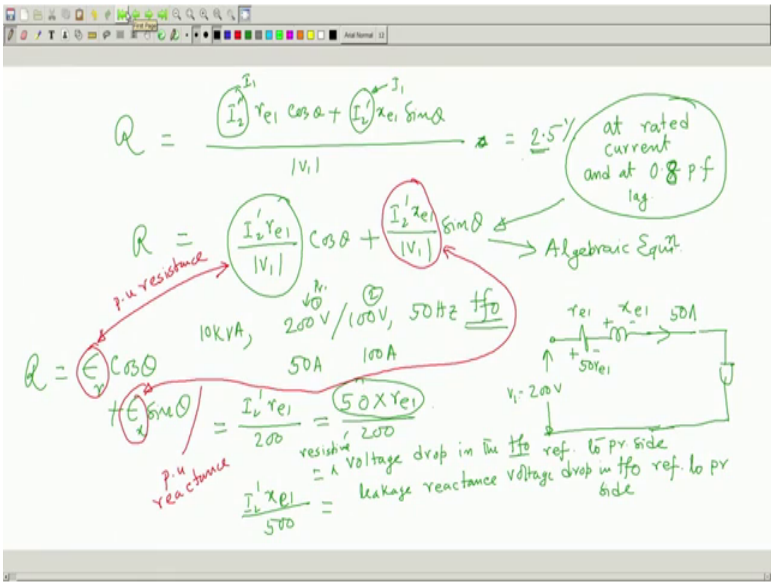

$R = \frac{I_2' r_{e1} \cos\theta + I_2' x_{e1} \sin\theta}{|V_1|} = 2.5\%$ at rated current and at 0.8 pf lag

$R = \frac{I_2' r_{e1}}{|V_1|} \cos\theta + \frac{I_2' x_{e1}}{|V_1|} \sin\theta \rightarrow$ Algebraic Equn

p.u resistance

10KVA, 200 V/100V, 50Hz tfo

50A 100A

$R = \epsilon_r \cos\theta + \epsilon_x \sin\theta$

$= \frac{I_2' r_{e1}}{200} = \frac{50 \times r_{e1}}{200}$ = resistive voltage drop in the tfo ref. to pr side

p.u reactance

$\frac{I_2' x_{e1}}{500} =$ leakage reactance voltage drop in tfo ref. to pr side

And we found that the regulation is given by this expression ultimately we derived. It could of course, be expressed in terms of either primary and secondary. So, with respect to primary side regulation turns out to be I 2 dashed r e 1 by rated voltage cosine theta plus I 2 dashed x e 1 by V 1 these are magnitudes this is an algebraic equation and cos theta is the power factor of the load, then I told that this quantity I 2 dashed by r e 1 by V 1 is called the per unit resistance.

In fact, it means that how much of the rated voltage is dropped across the equivalent resistance of the transformer at rated current. Similarly, I 2 dashed x e 1 v by V 1 is the how much of the rated voltage is dropped in the leakage reactance of the transformer and so, we start from here and then I told the meaning of this, suppose I say that this is the rating of a transformer r e 1 is 2 percent, what does it mean? r e 1 per unit is then 0.02, it simply means that 200 into 0.02 will be dropped in the resistance when rated current will be flowing that is 50 to r e 1 will be equal to 200 into 0.02, that way you interpret.

Extending these you can also say per unit impedance; per unit leakage impedance of the transformer can be written as I 2 dashed or I 1 because no load current is neglected into Z e 1 is the magnitude of this one by V 1. All are numbers only where Z e 1 is per unit impedance where Z e 1 is the actual impedance in ohm and this is equal to r e 1 square plus x e 1 square.

And per unit values per unit resistance and impedance or reactance, they are same no matter whether you are calculating the per unit values from the high voltage side or from the low voltage side, this will come out to be same ok. Another interpretation of per unit for example, r e 1 per unit I will just point out, it is I told you it is I 2 dashed r e 1 by rated voltage V1. Now, as you can see if you multiply and these I 2 dashed is nothing but approximately I 1.

So, I 1 r e 1 by V 1 I 1, you multiply this is sorry this is this then what you do is you multiply the numerator and denominator by I 1 to get I 1 square r e 1 by V 1 I 1. So, per unit resistance can be told in language that amount of voltage drop in the equivalent resistance expressed as a per unit value of the rated voltage or it is the and this current is rated current rated current at rated current.

And this is equal to therefore, copper loss as a percentage of kVA rating of the transformer ok. So, there are various ways of telling so anyway. So, if you know the per unit values regulation expression then comes out to be epsilon r cosine theta plus minus epsilon x sin theta, minus sign to be used for leading power factor of the load. So, this is the thing.

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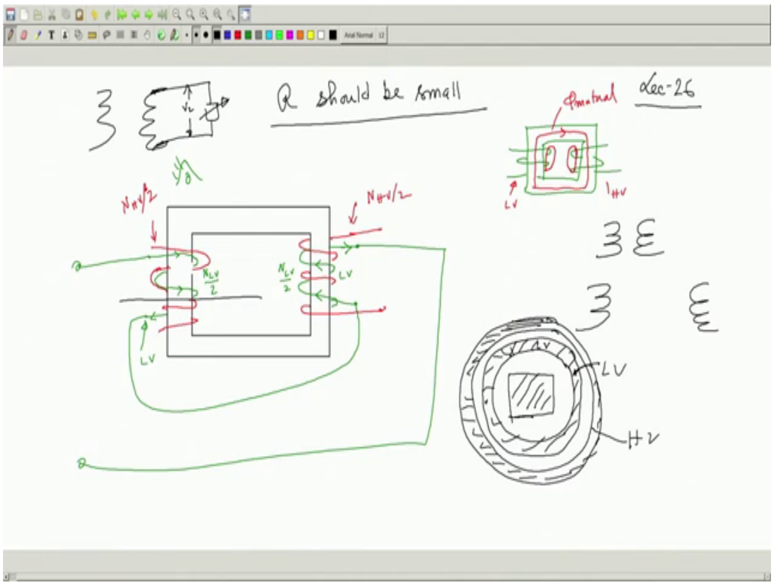

Now, continuing our discussion on regulation what do you like to have as a good source of power from the secondary side? Secondary side will be supplying load it is load I will connect on the secondary side. Therefore, I would like to see that as the value of load impedance changes from no load to full load condition, the voltage applied across the load that should remain constant, but unfortunately that is not going to be with a practical transformer because r e is present x e present.

Therefore, there will be some change in magnitude of the voltage and all, frequency of course, remain same. So, so regulation should be small maybe 2 to 5 percent of the rated voltage that is one thing. Now, therefore regulation should be small should be small no doubt.

So, that constancy of voltage across the load is not disturbed that much. Now, how this should be made small? Recall that a transformer for example, you see. Suppose, you have a transformer like this and as I told you the windings are wound on the limbs this horizontal portion is yoke. So, suppose because the leakage reactance is to be reduced, to reduce the regulation of a transformer r e 1 and x e 1 you cannot play much with them because number of turns is fixed based on the voltage ratings and you will be using copper.

So, resistivity is there r e will be there, but x e is the you know is because of the fact that as I told you this I will draw roughly, this is suppose the one winding primary I drew while we started discussing then I told there will be flux mutual flux which links both the primary and secondary, this is the mutual flux phi mutual and there will be leakage flux which will be linking only primary or only secondary.

So, this leakage fluxes will not contribute to the energy transfer from primary to secondary except, that they will cause some extra voltage drop as voltage drop takes place in the resistance. So, it was represented by leakage reactance. Now, therefore, to reduce the value of regulation, it depends on R 1 x 1. So, R 1 copper you use that is ok, but can I reduce the value of x 1; leakage flux.

So, this winding is the say LV these winding is HV whatever it is. You know the two coils, we will just discuss in terms of, suppose there are two coils if you take the coils far away leakage flux will increase mutual flux will decrease from common sense we can say that.

Therefore, if LV side coil is wound on limb1 and HV side is totally wound on limb2, there is separation and leakage flux is there, but this can be reduced to a great extent if this windings are distributed both the windings are distributed in both the limbs, what do I mean by this is whatever is the total number of turns of the LV winding you arrive at, you take half of the turns here only LV I am drawing this is suppose LV winding LV.

And this also I called LV; this is also LV, half of LV turns on this limb and half of LV turns on this. So, when you pass current through this and these two coils you connect them in series, got the point? So, LV number of turns, you divide like this N LV by 2 N LV by 2 and distribute them on both the limbs instead of trying to put all the turns N LV on the single limbs.

Then I told you also that HV winding are wound over the first LV winding then HV winding, then what you do; I am using different color to indicate the HV winding then you also wound the HV winding like this the separate coil, are you getting? So, you make the LV winding half of LV winding here, then half of LV winding there over the HV winding.

So, this red one is N HV by 2, this red one is N HV by 2 and these two halves, you connect them in series properly. So, that fluxes are produced in the same direction when they carry current ok, then you say ultimately after connecting series for example, LV winding you will get two turns here, these are the two turns two terminals of the LV winding. Similarly, HV winding also can be connected in series ultimately two terminals that is, you distribute the low voltage winding on both the limbs.

Similarly, HV winding on both the limbs and these two halves of each of LV and HV windings will be connected appropriately in proper way in series to give you LV terminals and HV terminals. By doing so, what you will be reducing; that is these two coils will be now brought in close proximity. So, leakage flux will be reduced because they are close by.

So, if you see the section of this limb for example, what I mean this is the cross sectional area this is cross sectional area. First, you see the LV winding; it will be wound like this. What is this diagram I am drawing? Your sectional diagram looking from the top, this is LV and then over which. So, this is LV winding the turns which I am showing by shaded line and this is HV winding like that.

So, this is HV and this is LV this inner one is LV, outer one is HV. Therefore, the leakage flux will be reduced to a great extent. So, this is how at the design level people try to adjust the leakage reactance. Anyway, this is just now mathematical derivation just from common sense we are trying to tell how leakage reactance can be reduced.

Now, the next question is, is it that I should go for trying to have leakage impedance, 0; that is use better and better material, make r e close to zero. Similarly, x e tight coupling between the two coils, leakage flux is also reduced; so that the leakage impedance is brought to very low value, is it like that? No, if you bring it down to low value as I told you that is our goal then the constancy of voltage across the load will be maintained, it is picked if of degree of loading of the transformer.

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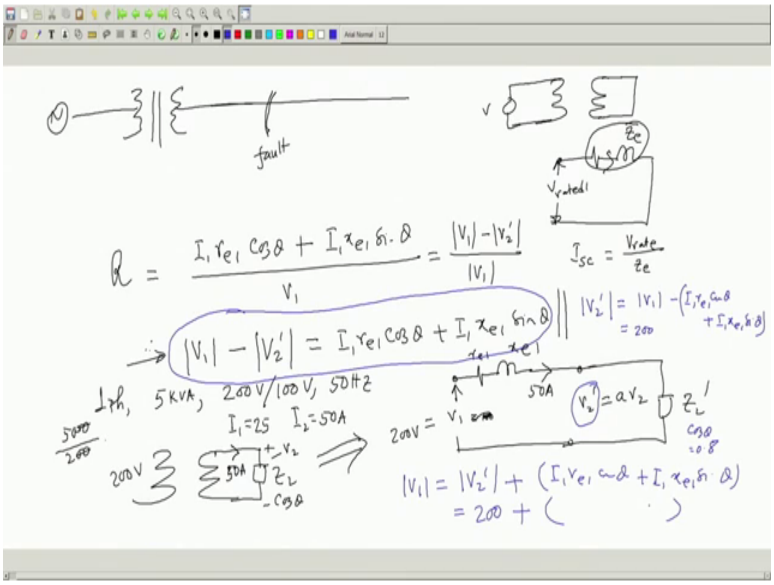

But there is one problem, the problem is from this fact because after all these power transformers are integral part of a power system you know, I drew it there is generator, there is transformer here, then transmission line and high voltages and so on.

So, for example, look at this transformer there are three lines three phase lines RYB, if a direct short circuit occurs if a fault occurs in the form of direct short circuit across the secondary of a transformer, what will be the order of the current? Now, mind you the primary is excited with full voltage ok. If primary of a transformer is excited with full voltage and secondary shorted, how much will be the current? Current will be very large. In the short circuit test of course, this voltage we apply is very little that is why we apply little voltage so that rated current flows.

But you think a situation, a transformer is ready to supply load rated voltage frequency we have applied secondary voltage is also rated secondary certainly short circuited, then what happens is there will be large short circuiting current, who will limit that short circuiting current? That is in terms of equivalent circuit r e 1 x e 1 this is shorted and here it is now rated voltage of that particular side1.

So, current will be limited by the equivalent leakage impedance of the transformer and if you make it very low, this current will be very high of course, protections are taken in the circuit, but suppose somehow the that fails for some reason or other then both the transformer and the your source maybe at danger because it will supply almost infinitely large current and if that current sustains for long time, you relay circuit breaker does not operate there will be problem.

So, it is better this leakage impedance try to see it is small, but at this same time not too small ideally 0, you should never attempt to do like that. Although from regulation point of view this is fine, but you should be prepared you do not know there may be a direct short circuit at the secondary of the transformer and then huge current will flow and that is if some leakage impedance is there the short circuit current will be at least limited by V rated by this Z e is not; by this, instead of 0; have some finite small values small it is, but anyway it will try to limit the current.

So, these are some of the points I wanted to tell you about the regulation of a transformer. Now they so solve lot of problems as I told you from open circuit short circuit test then efficiency of a transformer and how to calculate regulation, but last word about regulation I must tell you that, if you look at the regulation formula it was nothing but I 1 r e 1 cos theta. In terms of primary side I 1 x e 1 sin theta divided by V 1 rated voltage, is not? That is the thing and if you remember the numerator was like this V 1 minus V 2 dashed this was the thing change in magnitude this was the thing. Therefore, you see that this V 1 magnitude minus V 2 dashed the numerator only is this one I 1 r e 1 cos theta plus I 1 x e 1 sin theta.

What this thing means? This expression is often used to calculate one important thing apart from regulation. For example, what I am trying to tell what is this thing equivalent circuit r e 1 x e 1 this is V 1 and this is V 2 dashed. V 2 dashed is nothing, but a into V 2 is not actual voltage across the load this side load is connected some Z 2 dashed.

Therefore, from this formula suppose they I pose the problem in this way. Suppose, you have a transformer say 5 kVA, 200 volt stroke 100 volt, 50 Hertz transformer single phase, this transformer and if it is 5 kVA, its rated current of this side I 1 will be how much?;It will be 5000 kVA divided by 200, is not?

So, 25 ampere this rated current is and LV side current, rated current will be I 2 is equal to 50 ampere. Now, suppose I say that I have applied a voltage rated voltage I have applied 100 volt on the a 2000 volt on the primary side, please be with me what I am telling listen carefully. Suppose, I have applied rated voltage 200 volt then I ask myself, if you deliver rated current and what is the actual scenario?

Actual scenario is this these the equivalent circuit, here 200 volt you have applied, here you have connected the load Z 2, is not? And then this is equivalent to this, from this I have got that. Now, what I am telling; suppose the transformer is delivering here 50 ampere current rated current at some known power factor angle cosine theta you are delivering.

If I simply ask you, what will be this terminal voltage V 2 with load connected? With load connected, what will be V 2? Without load this voltage would have been equal to 100 volt with this (Refer Time: 24:18) open 200 hundred volt you have applied. Voltage across the terminals of the secondary of the transformer would have been 100 volt, but you have now connected load, how much do you expect? I will expect this voltage will drop it will be less than 100 volt because of these drop here; it is 100 volt 200 volt. So, there will be drop here.

Now, if rated current is flowing 25 ampere there, 50 ampere is flowing there. So, I will use this formula and tell that V 2 dashed magnitude of V 2 dashed is equal to magnitude of V 1 minus I 1 r e 1 cos theta plus I 1 x e 1 sin theta, bring it to this side you will get V 2 dashed.

So, you will put all the values, that is V 1 is 200 volt blah blah blah. I mean I 1 is 25 ampere cos theta if it is known say 0.8. I will put that and get by what amount this difference is how much? I will be able to calculate maybe it will come out to be 5 volt, then you will be able to calculate V 2 dashed and then I want to know what is V 2. So, I can easily calculate V 2 how much it will be? From a V 2, I will divide and get it. Therefore, this formula is very useful in getting the secondary voltage of the transformer rather quickly, if you know the degree of loading on the secondary by how much the voltage will fall. So, try to use it efficiently.

On the other hand, I can also say suppose I would like to get 100 volt across the load of the transformer secondary of the transformer then how much voltage is to be applied, it must be greater than slightly more than 200 volt. That also can be estimated if I insist, no across the load when the load is there at rated current I must get 100 volt here, then certainly this should not be 200 volt.

If you give 200 volt you know the fact, it will be less than 100 volt maybe 95 volts, but if I insist that no, I will when the load is connected I want to get 100 volt then how much should be applied voltage? Then once again I will use the same formula which is algebraic in nature, no phasor equation.

So, I will then calculate V 1 is equal to, V 1 is equal to V 2 dashed plus this thing I 1 r e 1 cos theta plus I 1 x e 1 sin theta. So, currents r e 1 power factor is known V 2 dashed if it is 100 volt I want to get there; that means; here it is 200 volt so 200 plus this thing. So, you have to apply to the primary then a voltage higher than 200 volts slightly higher I mean, one should not think oh, higher voltage but its rated voltage is 200 volt, but as I told you r e 1 x e 1 are in general small.

So, regulation maybe of the order of 5 percent. So, its slightly more voltage applied you will be able to maintain 100 volt across the secondary of the transformer, you can have several nice problems on it. So, regulation formula is useful.

So, also useful is this formula that is the V 1 minus V 2 dashed, the magnitude of V 1 and magnitude of V 2 dashed can be easily computed for a given load and power factor of the transformer. Now, I will just mention because as a continuation of this that; this I will leave for later discussion, but our next topic will be what I have thought is Auto transformer.

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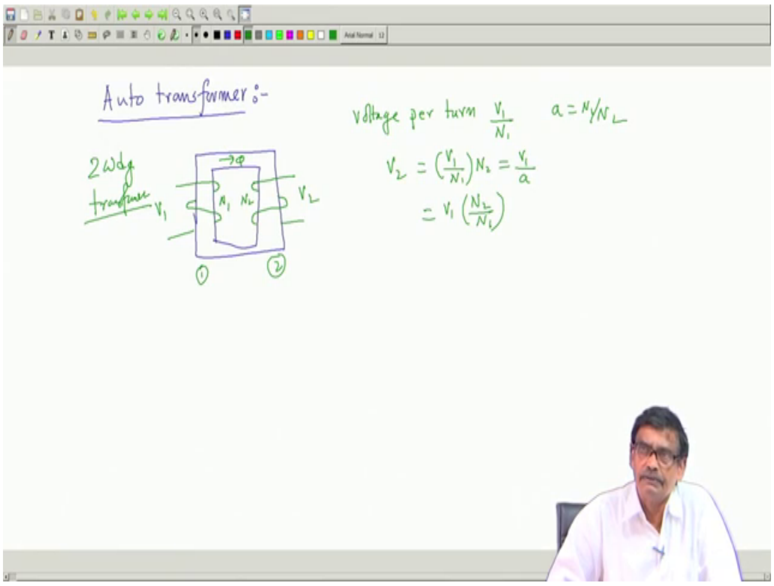
Auto transformer :-

voltage per turn $\frac{V_1}{N_1}$ $a = N_1/N_2$

$$V_2 = \left(\frac{V_1}{N_1}\right)N_2 = \frac{V_1}{a}$$
$$= V_1\left(\frac{N_2}{N_1}\right)$$

Our next topics will be auto transformer. Only the idea I will tell, we have so far seen that a two winding transformer essentially means that you have a core and there are two separate coils at least two separate coils and these coils will be distributed, but that is not generally shown here to reduce the leakage flux, but the this is understood, but this is the side1 and side2; two coils are there and you can then change the level of voltage from V 1 to V 2, N 1 turns N 2 turns. Mutual flux is common to both of them.

Then we know that if you have applied the rated voltage, it is better you use voltage per turn concept, voltage per turn. This is equal to V 1 by N 1 and that remains same for both primary and secondary. Therefore, V 2 will be voltage per turn that is V 1 by N 1 into N 2 and we know this; this is equal to V 1 by a, a is N 1 by N 2 whatever it is.

So, you can then either step up or step down a voltage depending upon this ratio V 1 may be stepped up or stepped down. So, this is one way of doing. Now, this is two winding transformer this one is two winding transformer, two separate coil. We will see that the same transformation of voltage AC voltage from V 1 to V 2 level can also be done by another kind of transformer, work on same principle d phi d t that is all and that transformer is called auto transformer and we will continue with this in the next lecture.