Electrical Machines
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Lecture 13 - Three Phase Transformers-II

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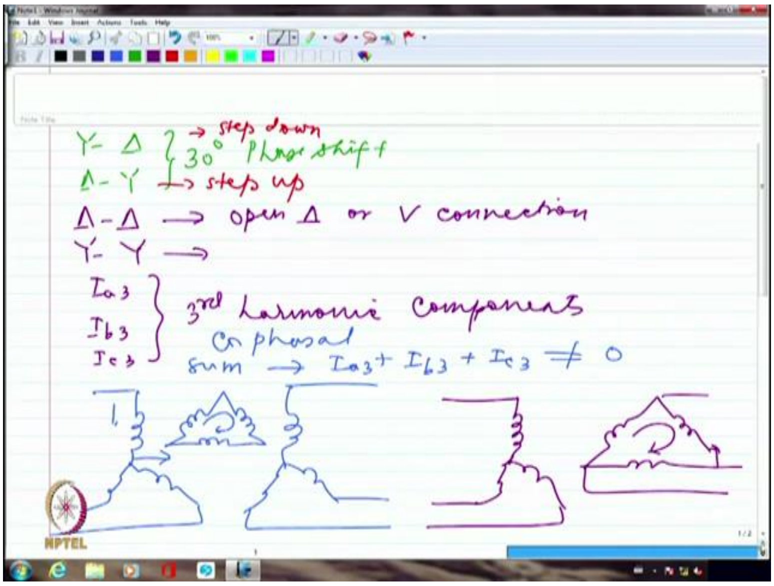

Yesterday, we had a discussion on three-phase transformer, I took up different types of connection and towards the end we actually justified as to why star star connection especially without neutral grounding is not a preferred connection. We basically said that in star delta and delta star both connections we are going to have 30^0 phase shift and inherently we are going to have one of them that is the top one, star delta as a step-down connection whereas the second one is going to be step up.

So we are going to have inherently this as step down and this as step up connection and when we came to delta, delta we said there is no phase shift there is no step up or step down but, the major advantage is you can operate this in open delta configuration if one of them conk out. So open delta or V connection is possible only in delta-delta transformer that is the major advantage of delta-delta transformer. But, when we look at star-star connection we said that one of the major problems in star-star connection is that especially when I am energizing the transformer.

The current that is being drawn is basically the magnetizing current, although there is some core loss component of current primarily if we are looking at magnetizing current the magnetizing current is going to be normally non-sinusoidal if I am looking at the hysteresis property of iron as well as saturation property of the ferromagnetic core. So, this will actually have the current having the fundamental component that is the 50 Hz component, which is sinusoidal in nature. Apart from that it will have third harmonic, fifth harmonic, seventh harmonic and so on and so forth.

So, if there is a third harmonic component which is one of the dominating harmonic components in the magnetizing current that will not find the path to flow out of the transformer winding. Because if I say, A, B and C phases I am going to have I_{a3}, I_{b3}, I_{c3} which are the third harmonic components. They are going to be co-phasal. So, because they are co-phasal we are going to have the sum of these three components that is $I_{a3}+I_{b3}+I_{c3}$ is a non-zero component. It is not equal to 0. Because it is not equal to 0, I have to provide a path for the current.

So, either the neutral should provide the path by grounding it, if not, I have to provide some alternate path for the current. So, the alternate path can come in the form of tertiary winding. If I have a tertiary winding which is connected in delta, so I can have primary in star, secondary also in star whereas my tertiary which is probably not of great rating or larger rating, it doesn’t have to serve any other purpose but, it has to essentially make sure that it circulates the third harmonic current.

If it do not allow a path for the third harmonic current, the current which is drawn as magnetizing current by the primary of the transformer is forced to be a sinusoid, if the current is a sinusoid the flux will be a non-sinusoid and if the flux is a non-sinusoidal quantity then, the voltage induced will be definitely non-sinusoidal. But, what we are applying as voltage is sinusoidal, so because of this there is a discrepancy existing between the injected voltage or applied voltage and the induced EMF which is actually going to make the neutral point itself oscillate or it is going to cause heavy injection of current sometimes into the transformer winding which is not really a good criteria as far as the transformer operation is concerned.

And that is the reason why, if I use the star-star either I have to ground the neutral. If not, use a tertiary which is going to have basically a delta connected tertiary winding.

Student: How will we connect this delta connected tertiary winding?

Professor: We are not connecting it to the secondary at all because they are all mutually coupled, the third harmonic has to circulate somewhere. You better give it the path maybe from the primary, maybe from the secondary, maybe from the tertiary.

So, anywhere if the current is allowed to flow you are not connecting it electrically anywhere, it is all mutually coupled. So, if I have a third harmonic current actually drawn here, if it is not able to find a path through this it will try to just circulate it here, so it is not killed. All we are doing is not to kill the third harmonic, do not kill it. Allow it to survive, that is all we are doing, nothing else. So please understand that any current if it flows either in the secondary or in the primary or in the tertiary it can cause a voltage drop or voltage induction in the other coils as well because they are all mutually coupled.

So very clearly if I allow the current to circulate even in the tertiary it is definitely going to have repercussions on the induced EMF on the primary. What I want is the primary induced EMF to be sinusoidal. For that let me allow the third harmonic current somewhere, that is all we are looking at. So, the third harmonic current can definitely flow here. So that is how we actually allow the transformer to went out its third harmonic component somewhere and that is doing through tertiary as simple as that. So much so for the transformers three phase.

Student: Wye-delta…

Professor: Wye-delta will not have the same problem because of the fact that the delta whether I connect the load or not, the delta winding is right here. Let me just show the wye-delta transformer, I am going to have the Y connection like this on the primary, delta is in the secondary, I am going to connect the load here, whether I connect the load in star or delta is a matter of detail, whether I connect the load at all not is a matter of detail, again, but, if there is third harmonic component here, here also it can circulate like this.

Even without load there is a path for the third harmonic current to circulate itself and that is all that matters. Nothing more than that, so as long as you have the third harmonic circulating somehow maybe through the ground, maybe through the secondary or tertiary winding, you are at least allowing it to survive, that is all that matters. Okay, So, far what we had seen was the three-phase transformers that are actually made up of three single-phase transformers but there are cases where we use a three-phase transformer as a single unit.

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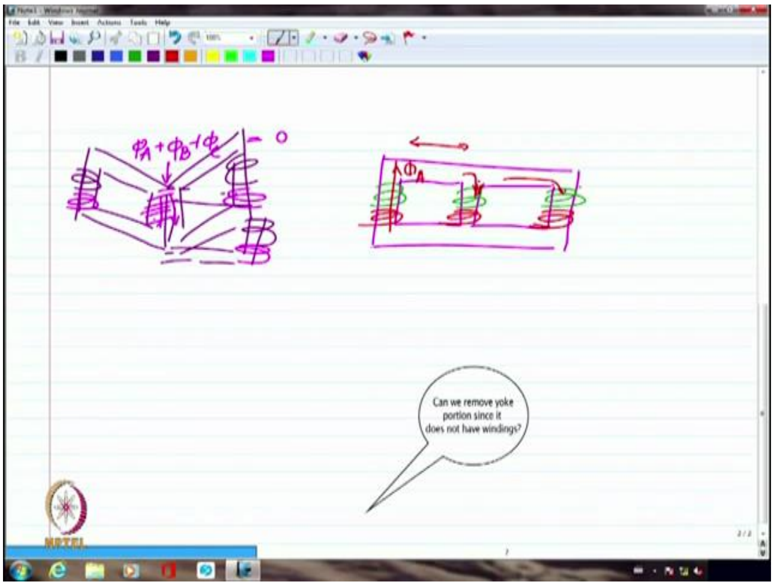

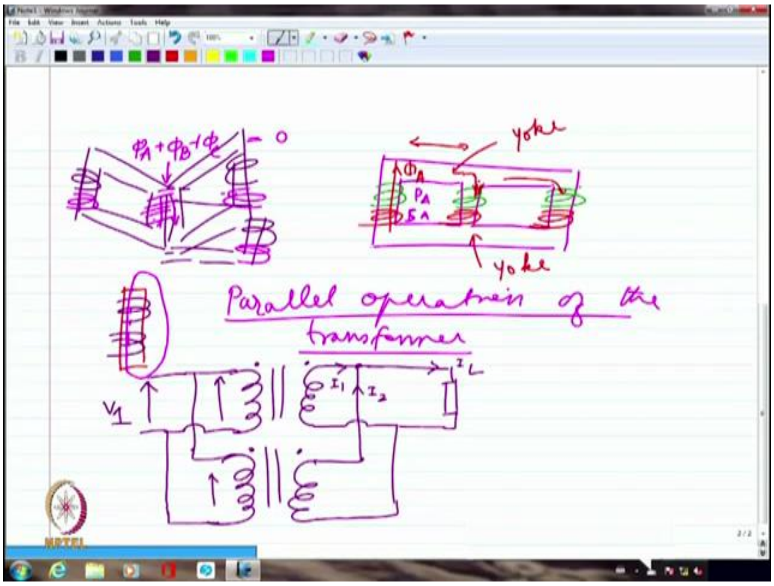

So, when I use it a single unit, I may have actually the three cores somewhat like this, so maybe one of the cores is something like this, I am trying to show how maybe one of the cores will be and the second core can be something like this, and the third core can maybe come out like this, I should have shown it somewhat like this. They may be three such cores which are something in the shape of a Y or something like that, so I have three such cores.

So, I am going to have maybe the windings wound here. This is primary, similarly maybe this is primary, similarly this is primary, whereas secondary maybe wound, I am showing as though it is not even wound in the middle limb at all, I can still have something wound on the middle limb which is actually working as the anchor point for all the three branches but, I might choose to wind the winding only in these branches.

Now, if I look at what is happening in this branch it will be actually the summation of all the three fluxes, $\phi_A + \phi_B + \phi_C$. okay So, if I have in the middle limb $\phi_A + \phi_B + \phi_C$ as the total flux passing through the middle limb because that is probably acting as the returned path for all the fluxes which are coming from A phase B phase and C phase respectively, this has to be 0 if I am looking at this as a balanced three-phase current passing through a three-phase winding.

So, I am going to have essentially this flux to be 0. If the flux is 0, I don't have to really worry about any having any solid core material here at all, because I really do not need anything to pass the flux or anything. So, I can very well imagine as though from no limb at all three other limbs are protruding but that is not mechanically going to give me any viable arrangement and it is not going to be strong enough. That is the reason why normally if we are talking about the three-phase transformer the core is somewhat like this, it looks like a shell type construction for a single-phase case. But I am going to have essentially the core somewhat like this.

So, I am going to have in all probability A phase primary wound here, B phase primary wound here and C phase primary wound here and similarly A phase secondary wound here, B phase secondary wound here and C phase secondary wound here. Now that I have all the terminals brought out, I should be able to definitely connect them in star or delta as the requirement may be. I could have removed the center limb completely and then I could have said let me have three limbs protruding from three different 120^0 side.

Mechanically it is not a viable structure because I need some kind of anchor in the middle. So, rather than having an anchor which is a dummy and I am saving on the iron material by simply having three limbs which are not really 120^0 shifted, alright, but I am going to assume that the permeability of the other you know the surrounding air is really so small that if I create probably a ϕ_A which is, this is ϕ_A flux of A phase, this will divide itself hopefully into two halves almost, almost two halves.

Similarly, if I look at ϕ_B it will again divide itself into two halves on the other side and ϕ_C similarly. So I am assuming that although the permeability of this portion is not infinity, so clearly maybe this will occupy more flux ϕ_A, if it is divided into $\frac{\phi_A}{2}$ and $\frac{\phi_A}{2}$, I should assume that the reluctance offered by limb 2 and limb 3 are the same, it may be slightly different because the lengths are a little higher for ϕ_C. I mean for the limb C. But, I am going to assume that it is fairly half, almost half. So, the same thing.

Student: Ma'am, why these lot of (())(13:38) simply three limbs separately which are not connected to (())(13:42) and then auto transformer's individual limbs and then connected them?

Professor: If you don't provide the yoke portion, if I may call that top portion as the yoke, that is what completes the magnetic circuit. This portion is the yoke, similarly this portion is the yoke. Please note that there are no windings there, the yokes are essentially provided to formulate a high permeability path, low reluctance path.

Student: Why do we need that ends of the wires of individual coils at the end of the day? So why do we need this? Why do we need magnetic circuit?

Professor: If you do not have magnetic circuit, where is the question of electromagnetic induction?

Student: Basically, individually A is auto transformer, B is auto transformer, C is auto transformer. And we are taking all of these wires.

Professor: But the magnetic lines that are actually coming up because of the current flowing have to find a closed path. How will they find a closed path? If you do not provide any other path, then what will happen is it will go through the air. See, if I just have one leg like this, I hope you understand his question. What he is asking is if I just have, so if I am going to have one limb like this with A phase primary, A phase secondary, I am going to have essentially the flux going like this, it has to complete itself through Air, there is no other way and I do not want high reluctance of the air path. That is the reason why I am trying to do this.

So, we generally provide the transformer with ferromagnetic core always inclusive of yoke just to make sure that the magnetic circuit offers minimum amount of reluctance. That is the reason. So, this is one of the structures of a three-phase transformer you know which is operating as a single unit and the single unit three-phase transformers are again used probably at distribution level, hardly ever it is used in generation level.

Student: Basically three auto transformers connected to the level.

Professor: Not really, I still have a primary and secondary separately, I am not having primary and secondary together. In an outer transformer I do not have primary and secondary separately, so what I am trying to do is this is the primary of A phase, this is the secondary of A phase. So, I have two distinct windings and I have the opportunity to connect it in either star or delta as per my requirement. Most of the times you might find that flexibility is there in certain specific applications, but that kind of flexibility may not be there when you go to actually, go and see a transformer in a substation.

In a substation like for example what we have here in near the LHC itself on the left side, as you enter you will see it on the right side, that has 11,000/440 V transformer for example. So, what you have on the secondary side will be normally a star connection, secondary will be a star. Primary can be delta or star, invariably it may be delta. Why we have a star on the secondary is I may require, I will require rather a single-phase supply. Unless I have a star, how am I going to derive a single-phase supply? I have to ground the neutral and between the neutral and any of the phases if it a star, I will get single-phase supply.

So invariably you would see that towards the distribution end, fag-end of the distribution, the secondary of the transformer invariably will be star so that we will be able to derive single-phase supply out of the final termination point. Right So much so for three-phase transformer. So, let us try to take a look at now parallel operation of the transformer, so how do we connect two transformers in parallel? Is there any condition for parallel connectivity of transformer? First of all, why do we need parallel operation of transformers at all?

So, any thoughts on why do we need parallel operation? Why should we have parallel operation of transformer, is there any reason why you should have two transformers connected in parallel? You understand first of all what is parallel operation, let me show at least a circuit, then you may be able to understand why we are connecting them in parallel. Let us say these are the primaries of two transformers, I am showing single-phase of course and these are the secondaries of two transformers, and let us see this is dot, this is dot, similarly for this I am showing this is the dot, this is the dot, so I am showing the voltage rise in this direction, here also the voltage rise in this direction.

Now, I am going to connect this dot with this dot and similarly, I am going to connect this non-dot terminal with that of the non-dot terminal. right Now, what I am doing is, going to apply V_1 here, okay so the primaries are connected in parallel, this is what we mean by connecting them in parallel. I have connected the primaries in parallel. Now as far as secondaries are concerned, again I have to connect this dot and this dot together. I have to connect this and this together.

Now if I want to connect the load, if it is an open circuit, that is it, I am not doing anything further. If I have to connect the load I have to connect the load here. Right The load is common to both of them. So, if I say that the load current totally is I_L and what is the current flowing from here is I_1, the current that is flowing from here is I_2, so I_1+ I_2 will be I_L. This is what we mean by parallel operation of two transformers, right so together the load is being supplied with the help of two transformers, not a single transformer.

For example, I may have 1 kVA and 1 kVA two transformers, I might like to actually supply 1.5 kVA to a load, so maybe I would like 0.75 to be supplied by one of the transformers, another 0.75 to be supplied by another transformer. So, I have the leverage to go until 2 kVA, maybe I will have load variation right from 1 kVA to 2 kVA. That is the reason why 1 kVA transformer was not sufficient. So, I had to necessarily put one more transformer, so that gives the answer indirectly.

Let say when we started probably with the IIT building there was only textile technology department and the couple of administrative blocks. The total load would have been of the order of maybe 20, 30 kVA nothing more than that. So maybe we had a transformer which is amounting to even thinking about expansion, maybe 100 kVA transformer was installed.

And now, everything has proliferated in exponential fashion. So, we are really not having sufficient capacity for the transformer. One way of doing it is to remove that 100 kVA transformer completely and put 1 MVA transformer, that is one way of doing it. Even if I put one 1 MVA transformer there is no guaranty that, that 1 MVA is going to be sufficient enough tomorrow. So, rather than that along with this particular 100 kVA transformer maybe another 200 kVA transformer was added, one more 200 kVA. So, step by step, more and more transformers were added so that as it expands you are going to have more and more capacity being added to the substation.

So, in all probability what would have been done in a distribution system which is expanding slowly is to have more and more transformers added so that all of them operate in parallel, so what we mean by parallel operation is they all work together to supply a collective load.

So, whenever there is an expansion taking place in a distribution system, you are going to add more and more capacity transformers to operate in parallel so that we are able to get the complete load being met by the summation of all the power levels of this transformer, ratings of these transformers. There are couple of advantages to this parallel operation of transformer, one is let us say I have 20 kVA, 20 kVA and 10 kVA transformer taking care of a 50-kVA load, total 50 kVA load.

In case a 10 kVA transformer conks out, I would still be able to supply that 40 kVA without much difficulty, so reliability improves quite a bit because I am doing it in partial ratings. So, I would be able supply at least part of the load. There are some emergency power supplies that are needed. For example, for hospital, for some other you know important data center so, in those places if I have to give power at least I can give power using part of the transformer capacity.

This is one major important thing which actually contributes to reliability improvement. The second one is when I store backups for my transformer rather than storing for you know complete 50 kVA as a backup transformer in case the 50 kVA fails then I have to immediately replace it by the 50 kVA transformer. Rather than storing it as a 50 kVA transformer I can store it in the form of maybe 10 kVA or 20 kVA, that is more than sufficient. So, backup cost is going to be brought down. Definitely, no doubt that if I install 150 kVA transformer, just one single unit of 50 kVA transformer, that will be less costly at the time of installation as compared to 20+20+10.

Very clearly because everything has individual core, everything has individual, whatever so, you are going definitely increase the overall cost during the installation but looking at the reliability feature and also looking at the storage of inventory item or backup item this generally is recommended and especially in a system where it is developing like our nation where it is developing still and power system still expanding in a big way. So, it will be much better to have parallel operation of transformer, so that is the reason why parallel operation is again considered as one of the important topics when we study about transformer because it is very much prevalent in India. Right

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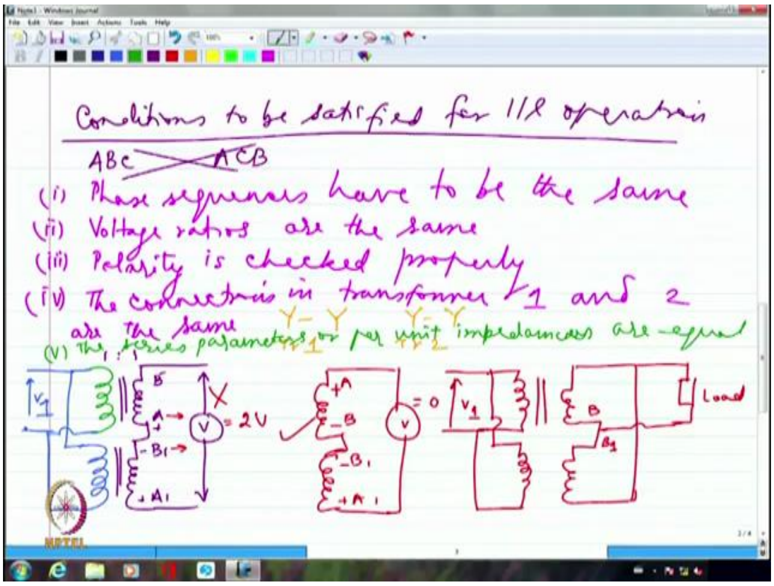

So, let us try to look at first of all what are all the conditions to be satisfied for parallel operation and please note that what I am showing is a single-phase case here, just for simplicity otherwise what we use normally is in three-phase. All the distribution system, transmission system everything is in three-phase. So, that is why whatever we actually do it in practice, that is all three-phase, it is not single phase.

So very clearly, I can't have one of the transformer in ABC phase sequence, the other one in ACB phase sequence, this cannot be done. Both have to have ABC and ABC power supply, only then I can connect them in parallel. What I mean is I have three windings; A, B, C, I have three more windings in the primary of other transformer A_1 B_1 C_1. I have to connect A to A, B to B, C to C. So, the phase sequences have to be the same when I connect them in parallel, so phase sequences cannot be different, have to be the same.

Second thing that I had to take care of is voltage ratios. If I am looking at $\frac{V_1}{V_2}$, right they have to be the same because I simply cannot connect, let us say how one transformer which is 240/440, the other one is 240/480, I can't connect 480 to 440, immediately there will be a huge circulating current, you are short circuiting almost 40 V, that is what it is. Right So, we have to make sure that voltage ratios are the same.

The third condition that needs to be checked before connecting is the polarity, that is dot we talked about. So, the dots have to be connected together and the non-dot terminals have to be connected together. So, we have to make sure that the polarity is checked properly before connecting. And the fourth one of course if it is a three-phase transformer if I have a star-star, I better have a star-star for the second transformer also, I can't have simply star-star connected to a star delta transformer, it will not work because of the phase shift.

So, I have to make sure that basically you know the connections in transformer 1 and 2 are the same. What I mean is that is I am talking about a star-star connection for the transformer 1, transformer 2 also should have star-star connection, or star delta I should have star delta, otherwise they will not work properly unless I have the connections to be the same. So, whenever we operate two transformers in parallel, last time this experiment was removed from ELL203 I am trying to see whether it can be included again so that you understand the parallel operation of transformer.

The first and foremost thing that we do is to check the polarity, so for that what we do is if I am having the two primaries like this, I am going to connect them in parallel first of all, simply I am going to connect them in parallel, it does not matter whether where the dot is, I may not even know. It does not matter, so I will simply connect two terminals together and the other two terminals together and then I am going to apply let us say a voltage V_1 here.

And this is my secondary here. Right Now, what I am going to do is let me probably name this, this is A, B, this is A_1 and B_1. So, I am going to connect these two together and connect the voltmeter across this. And if I assume that it is a one is to one transformer if I am connecting V_1 here, voltage applied is V_1 and what is coming out on the voltmeter is $2V_1$. That means they are in series addition, if they are in series addition I am going to have plus here, minus here, maybe plus here, minus here.

Then they are in series addition so, definitely I can say with conviction that these two are of different polarity. That is whatever I have connected together they are of different polarity. So, if they are of different polarity, obviously I can't connect them together for parallel operation. So, the first thing we do for parallel operation is to do polarity test. But in the laboratory what happens invariably is the previous batch which has performed will tell you this is how the terminals are and then you would be able go ahead with it even without polarity testing.

And generally, many times the kids do it like in the exam they do not want to do the polarity test because they are falling short of time, that is what they claim and then go ahead and connect it generally. okay So, sometimes they can make a mistake and do, we are going to see the fuse blowing that is what happens. Okay So, generally polarity testing has to be done, so the polarity testing essentially tells you by looking at the voltmeter reading whether the polarity is of opposite nature what you have tied together or if you are going to get the voltmeter reading to be 0, if I had connected it the other way around, let us say this is one of my winding, this is the other winding.

Let us say this is A, this is B and this is B, this is A and I had connected these two together, so I would have had is this is plus, this is minus but, I am going to have this is plus and this is minus. So, they will definitely cancel out each other and if I put the voltmeter here, it is going to read 0, the RMS value will be 0. Right So, if I get the voltmeter reading to be 0, then I know for sure that I have tied up the correct terminals together for parallel operation, so, what I will do now is primary side again it doesn't matter how, I connect them. So, I am going to connect actually these two together and these two together and apply the voltage between these two which is V_1.

Whereas on the secondary I am going to make sure that my connection is like this, this is the correct connection if voltmeter reading is 0, here it is 2V, so this is not correct for parallel operation. So, I am going to connect basically V and V_1 together, right similarly, these two together. Please note already it is a closed circuit, so the voltages are somewhat different let us say I may have 220/110 V transformer in both the cases but instead of getting 110 I get 109.8 that 0.2 volts is going to circulate the current because please remember the resistance and leakage reactance's of the transformer are really really small.

So, even for 0.2 volts I may get a current of the order of a few 10s of ampere, it is very much possible if the transformer is of large capacity. If it is a large capacity transformer, because the resistances are going to be really small, I am essentially going to have a huge circulating current. So, as much as possible the open circuit voltages should be close enough, as much as possible the open circuit voltages should be close enough. Even if the open circuit voltages are slightly different, I will have a circulating current simply going through this transformer. right

Now, I will connect the load between these two terminals, so here is my load, this is how parallel operation of the transformer connection is made. right Now, let us see whether we are able to get the expressions actually for how the load is being shared when two transformers are operated in parallel. Right

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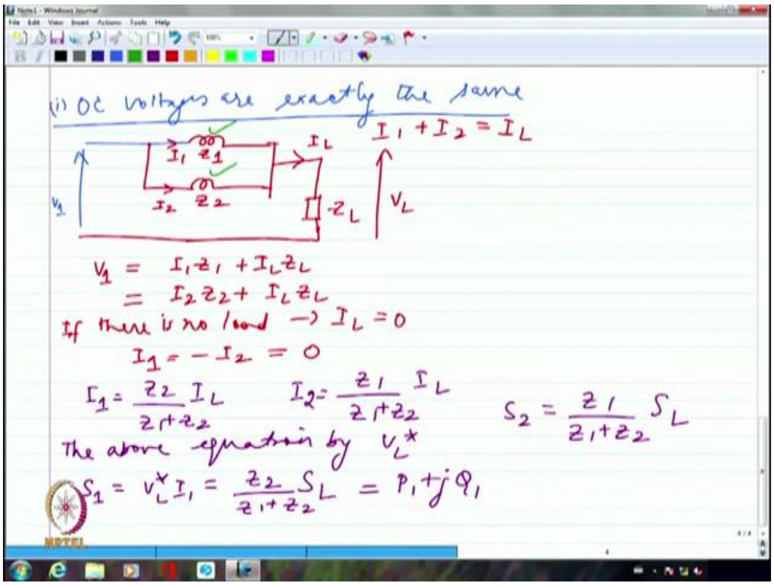

So, let me show that I am applying the voltage V_1, and I am assuming that first case there are two cases I am going to discuss. The first case I am going to assume that the open circuit voltages are exactly the same, exactly, which is very unrealistic but nevertheless that is one of the simpler cases. So, we are starting off with simpler case, so OC voltages are exactly the same, this is case 1. Right so I am having V1 here, I am showing one transformer's equivalent impedance as Z_1, this is actually Z equivalent one, I am just abbreviating that to Z_1.

I have one more transformer which has been connected in parallel which is actually having an impedance of Z_2. Okay So, if I have these two as the impedances and finally, I am going to connect it to the load and the load is connected between the common point of the secondary, please understand that if I kind of hide Z_2, this shows the equivalent circuit of a transformer 1. If I hide Z_1, just Z_2 alone gives me the equivalent circuit of the second transformer, I am neglecting the parallel branches because we are not unduly worried about exactly what are all the iron losses, I am not worried about that.

I mainly worried about the terminal condition because the terminals are tied up together and what is the voltage regulation, that heavily depends upon R_{eq} and X_{eq}. So that is why I am worried about only Z. So, this is what is my load here, so I may call this as I_L, I may call this voltage as V_L which should have been $V_2^{'}$ basically and I am applying V_1.

So, I would be able to say $V_1 = I_1\ Z_1$ if I may call this as I_1 and I may call this as I_2, $I_1Z_1 + I_LZ_L$, right similarly I should also be able to write this as $I_2Z_2 + I_LZ_L$, because the input voltage is the same and I am assuming open circuit voltage is the same, I am able to write it like this. Induced EMFs are essentially the same, that is what I am assuming. So, this going to be valid if there is no load, then I am going to have I_L=0. And I can write definitely in this case $I_1 + I_2 = I_L$ Kirchhoff's law. Right So if I_L=0, I_1 is going to be -I_2 and vice versa.

I_1 will be equal to -I_2 and I am definitely going to have right in this case if I am really not having any difference in the voltages once I open this out, no current will flow anywhere, it is a dead circuit basically, there is no question of any current flowing anywhere as soon as I open the load. So, under no load condition I_1=-I_2 which is also equal to 0, because I have opened up the complete circuit.

Now, if I look at how the current division takes place, I should say I_1 is equal to parallel current division law, so I am going to have $\frac{Z_2}{Z_1 + Z_2} I_L$. Similarly, I_2 is going to be $\frac{Z_1}{Z_1 + Z_2} I_L$.

Please remember all of these things are complex numbers, I can simply multiply the above equation by V_L or V_L^* if I am talking about a complex multiplication, $V_L^* I_L$ or $I_L^* V_L$ will give me apparent power. We talked about this when we were talking about complex representation.

So, I will get basically S_1 which is actually $V_L^* I_1$ will be equal to $\frac{Z_2}{Z_1 + Z_2} S_L$ where S_L is the total load apparent power. So, I am getting this in P+jQ format I am not getting it as just a volt ampere value without any phase angle, I am getting a phase angle. That phase angle I am calling this as $P_1 + jQ_1$. Similarly, if I am looking at S_2, I should write that is $\frac{Z_1}{Z_1 + Z_2} S_L$, so I should be able to get how exactly the apparent powers are divided between the two transformers provided I know the impedance.

And if I am having let us say two 1 kVA transformers 1 kVA plus 1 kVA and let say I have a 1.5 kVA load coming up, I would like both of them to share that load equally, I want them to take 0.75 each rather than taking one of them taking 1, the other one taking 0.5. Because if I increase it further, if I say that I have put 2 kVA transformers together, two 1 kVA transformers together because I wanted to supply a 2 kVA load, at 1.5 itself maybe one of the transformers has reached its brim. You can't load it further. So, if I try to increase the load further than 1.5 kVA one of the transformers which has already taken this 1 kVA will be overloaded in all probability.

So, how exactly a particular kVA is divided between two transformers depend heavily upon what is the impedance of each of these transformers. If the impedances are equal then I am going to have equal current division, if the impedances are not equal I will have definitely different values of currents being taken by different transformers because of which I am going to have discrepancy in terms of load sharing. If the load is shared not equally, then I will not be able to load them to the fullest capacity of the total transformers put together.

Because one of them shares the load much more it will break down faster. Right So, it is essential that the impedances are almost comparable if not exactly equal. Exactly equal is very difficult to get but as much as possible they should be close enough, so that is one more condition which I didn’t mention earlier.

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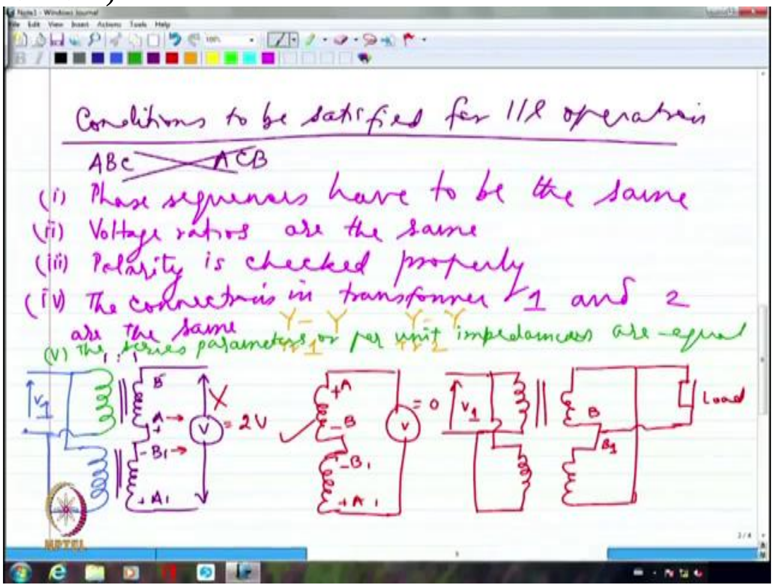

In the conditions to be satisfied for parallel operation that is the fifth condition, I didn’t want to mention this before showing the load sharing. So, please include that as well that the series parameters or I would say per unit impedances are equal, their per unit impedances should be equal.

Let us probably try to look at this more closely when we are doing the tutorial, okay I am going rather give you a few problems on parallel operation with you know different impedances. Let us try to check how exactly they are sharing the load and then go from there. The second case now let us try to take a look.

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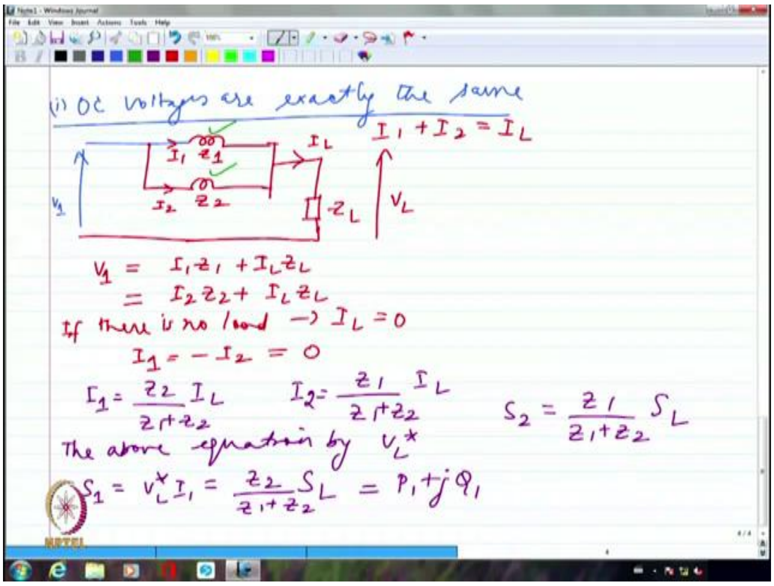

This is the first case where open circuit voltages are the same.

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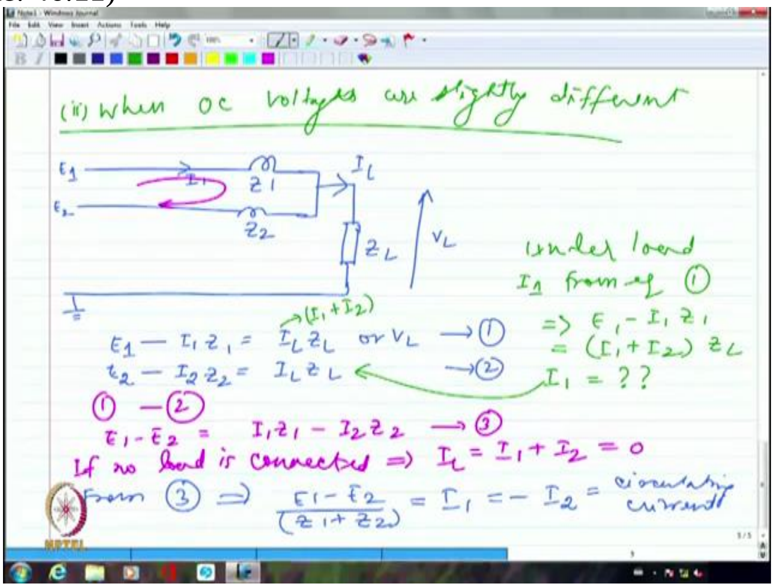

The second case is when OC voltages are slightly different, so when I say that open circuit voltages are slightly different, I am looking at now the secondary side completely. Okay So, I am assuming that one of the transformers has the voltage as E_1, the other transformer has the open circuit voltage as E_2, both these things are $V_2^{'}$ what we are looking at or V_2 what we are looking at. V_2, for one of the transformers, the secondary side open circuit voltage for one of the transformers is E_1. The secondary side open circuit voltage for the second transformer is E_2.

They are slightly different, maybe like what I told you instead of having 110 each maybe one is having 109, the other one is having 110, right again I am going to show the impedances here, this is Z_1 and this is Z_2, and both of them are connected together. And I am going to have a load coming up here, and this is what is the return path. So, this is Z_L, right so this is going to be V_L, so maybe there are unequal voltage drops also through Z_1 and Z_2. That is why, I am getting the same voltage V_L across the terminal. right So I can write in this case so this is the ground if I am talking about a reference point.

So I can say $E_1 - I_1 Z_1 = I_L Z_L$ or V_L I can say either way. Similarly, $E_2 - I_2 Z_2 = I_L Z_L$ so, let me call this as maybe equation 1, this as equation 2. So, let me get what is (1)-(2), I should be able to write $E_1 - E_2 = I_1 Z_1 - I_2 Z_2$, let me again examine this for no load condition. If no load is connected then I am going to have I_L which is actually equal to $I_1 + I_2 = 0$, so $I_1 = -I_2$ right but I cannot say in this case the circuit will be dead, it cannot be because I am going to have essentially a circulating current going like this whether I like it or not, right and that circulating current clearly is going to be from this expression. I can say from three, I can write $\frac{E_1 - E_2}{Z_1 + Z_2} = I_1 \text{or} = -I_2$, this is the circulating current.

So, the circulating current through the transformer when I am having the open circuit voltages even slightly different that is going to be quite a bit if the impedances of the transformer are very very low inherently, which happens in a very high capacity transformer. Whenever I have a very high capacity transformer I am going to have basically the circulating current to be extremely large because inherent impedances will be low.

I hope you understand if it is a large capacity transformer it is going to carry a lot of current also, if it is a lot of current that means the thickness of the windings will be very very high, the thickness of the windings is high, obviously I am going to have the resistance to be smaller. So, if you look at the 1 kVA transformer in the lab, vis-à-vis the 100 kVA transformer in a substation, you would see invariably that 100 kVA transformer in the substation will have much smaller actual ohmic impedance.

When I calculate it in per unit, all of them may be comparable because percentage impedances are calculated in terms of their rated current carrying capacity and their rated voltage capacity. That is how it is generally calculated, so, I will have basically you know the circulating current to be large in large capacity transformers even if the voltage discrepancy is very small.

Now, under load condition, I should be able to write what is actually I_1 from equation (1), right because I_L I can substitute as $I_1 + I_2$. So, I_1 will be written as $E_1 - I_1Z_1$ is equal to $(I_1 + I_2)Z_L$, so I should be able to write the expression for I_1. Not a big deal. You can write it in terms of Z_1, Z_2, Z_L and I_2 all of them. Right So you will eliminate I_1 from this expression by substituting this I_1 into equation 2, some arithmetic you know jugglery, that is all.

So, you are essentially going to do some algebraic jugglery and then get an expression for I_1 separately and I_2 separately, that will give you directly how the loads are shared, that is about it. Whenever you have unequal voltage ratios still you will be able to get how the loads can be shared by using the expressions that you guys will complete the derivation. So, parallel operation of transformers is possible whenever the voltage ratios are equal but even if they are of different capacity, I can definitely operate 100 kVA transformer in parallel with 50 kVA transformer, no problem, only thing is if I am sharing a load of 120 kVA. I would like 100 kVA to take 80 and I would like the other transformer 50 kVA to take 40.

Whether I am actually looking at the load division in proportion to their rating that is what is very important. 100 kVA should take lions share, 50 kVA should take lesser amount and that is what should happen ideally if the impedances are comparable.