Basic Electrical Technology
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Lecture - 34
3 phase Transformer

Hello everybody, in the last class we concluded our discussion on 3 phase circuits. A natural extension to the 3 phase circuits would be the 3 phase transformers acting as loads on the three on the 3 phase sources. Today's session will focus on discussion on 3 phase transformers.

Recall that we had already studied the single phase transformers. All the principles of the single phase transformers are applicable to the 3 phase transformers also. In fact, we use three single phase transformers and connect it in either star delta fashion to obtain the 3 phase action; the Faraday's laws of electromagnetics that is E is equal to n d phi by dt, the Ampere's law and all the notions of leakage inductance, the mutual inductance, the core loss, the hysteresis loop all those concepts that we studied in the single phase transformers are equally applicable to the 3 phase transformers also. In fact the equivalent circuit will also be similar.

Now, to start the discussion on the 3 phase transformers we shall assume that we are having three single phase transformers and we will connect them in a particular configuration. So let us start with three single phase transformers. So you have the primary and the secondary and you will say there is a 1 is to n, we have another single phase transformer with primary and secondary which is also having 1 is to n and one more single phase transformer with primary and secondary with turns ratio 1 is to n. These are three single phase transformers.

Now it has three primaries we will call that one as a p, b p, c p three three primary windings a p, b p, c p let us say that the dots are shown to indicate the polarities and then there are three secondary windings and we will call that one as a s, b s and c s with dots indicated as shown. So we have three primary windings and three secondary windings.

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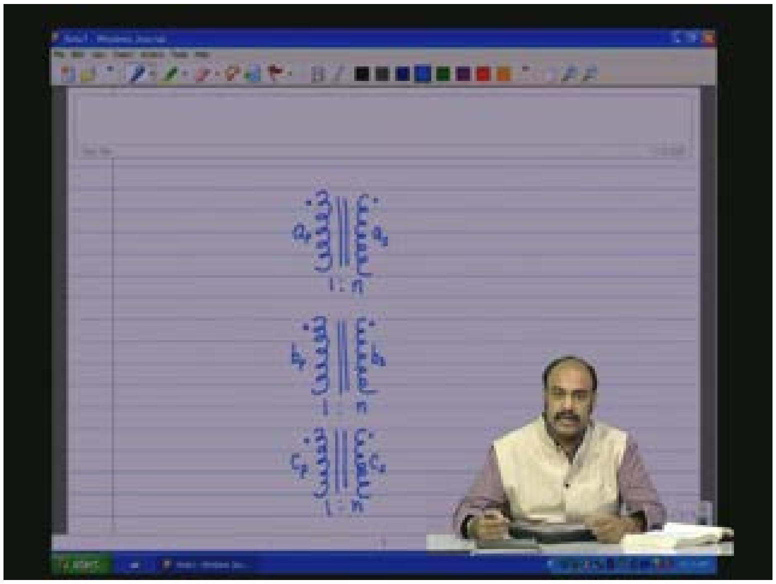

Now the three primary windings can be connected in one of the topology star or delta and the three secondary windings can also be connected in one of the topology that is star and delta which will result in four topologies for the entire transformer.

Now all the non-idealities of the practical single phase transformer are also applicable to each of these three single phase transformers. However, for the purpose of discussion we assume that we know that there are practical non-idealities that will exist. However, for the conceptual understanding of 3 phase transformer we shall not include these non-idealities in our discussion now. but keep in mind keep in the back of the mind that all practical transformers will have the non-idealities like the core loss, will have a finite magnetizing inductance x m, reactance that is the magnetizing reactance x m, it will have a finite leakage reactance on the primary side a finite leakage on the secondary side, a finite winding resistance R primary, a finite winding resistance on the secondary side R secondary all those non-idealities which we had incorporated in the equivalence circuit of the single phase transformer is equally applicable to each of the single phase transformers. However, we are just taking the ideal transformer concept and developing the notion of the 3 phase transformer here. But keep in the back of mind that all these idealities are present.

Now these three single phase transformers can be connected such that on the primary side on the primary side and on the secondary side we can have the following topologies. So first we could have on the primary side delta that is all the three coils a p b p c p are connected in a delta fashion and the secondary a s b s c s are also connected in delta topology and then we can have the primary connected in the delta fashion delta topology and the secondary connected as star and the third we have the primary connected as star the secondary connected as delta and the fourth we can have the primary in star, the secondary also in star topology which means we have a circuit in the delta topology and the delta topology on the secondary side that is called delta delta connection, we have a delta topology on the primary side, a star or a wye topology we can call this also as wye topology on the secondary side. So this is called a star delta star connection and we have a star wye topology possibility on the primary side and a delta connection on the secondary side and that is called a star delta connection. And of course finally we have a star connection on the primary side and also a star connection on the secondary side resulting in a star star connection or a wye wye connection. So these are the possible connections that one could make with the three single phase transformers and based on these types of connections the nomenclature of the 3 phase transformers are made that is delta delta, delta star, star delta, star star type of connections.

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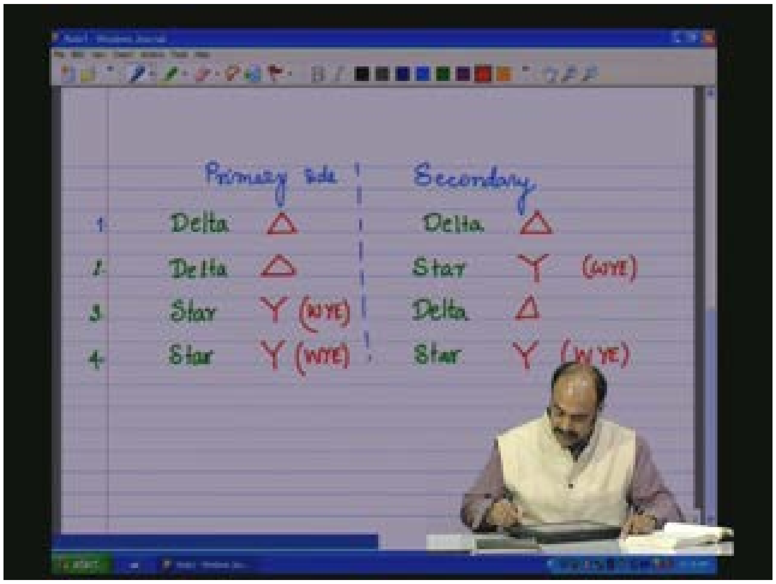

Now let us take each of these types each of these four types, study the way various currents and the voltage relationships across the phase and the line and also the phasor diagram for each of these types of topological connections.

So first let us say we meet the connection as delta delta which means that the primary windings a p b p c p are connected in delta and the secondary windings a s b s c s are connected also in delta so which means that we have the primary which is connected like that so these are the three primary coils. Now the secondary coils are also connected in delta as shown here (Refer Slide Time: 10:31). Now there is mutual inductance between the primary and the secondary and that is shown as coupled okay through the by means of core. Now in the primary you have the a, b and the c lines connected to the sources as shown; this is the a b c lines okay so this would be you're a p coil, the b p coil and the c p coil. So the dot polarities are as shown; give some thought to the dot polarities we are keeping the direction of the voltages like this, this is E ab is it not? E ab E bc E bc and then you have E ca. So therefore we are having the following dot polarities and these are the dot polarities as given.

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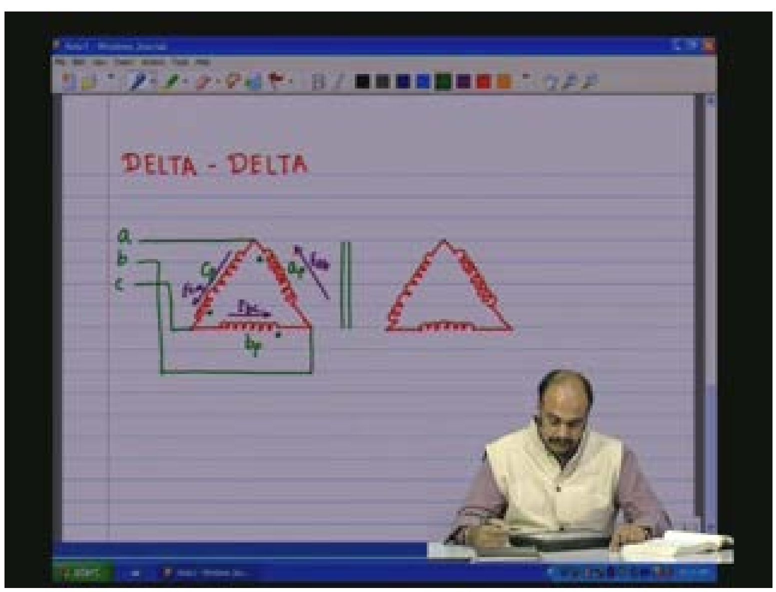

Now, for the secondary for the secondary we have a s coil, the b s coil and the c s coil and let us say the dot polarities are in this fashion as shown so which means the voltage this would be E across coil a s but we will give some point a b a b prime for the secondary or let us say this has a prime attached to that one and this voltage will be E bc prime to indicate it is on the secondary side and we have E ca prime to indicate that it is on the secondary side.

Now we take out these voltages here on the secondary side (Refer Slide Time: 13:47) so you have the a prime, b prime, c prime these are the secondary terminals which will go to further loads. So it should be assumed that on from that on the primary side it is connected to a source 3 phase source and on the secondary side it is connected to a well-balanced 3 phase load.

Now here we have three currents that is I a primary, I b primary, I c primary and the three currents coming out of this line here and we will call that one as I a secondary, I b secondary, I c secondary. Now this is a delta delta connection. If we say that the load is well-balanced then and let us say the effective values here is equal to I, I and I that is the line currents on the primary side are I, I and I, then the phase currents in each of these phases that is each of the primaries of the single phase coils would be I by root 3, I by root 3, I by root 3 is it not? So this would be I by root 3, I by root 3 and also I by root 3 so the phase currents are I by root 3 I by root 3 I by root 3.

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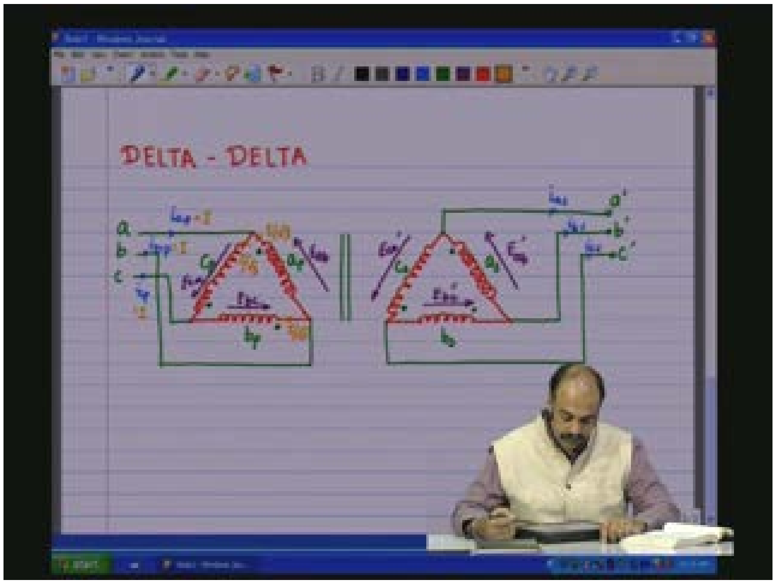

Now this transformer is a 1 is to n transformer ratio. So the voltages get multiplied by n and the currents get divided by n so the phase currents which are flowing here which are flowing on the secondary so if it is entering the dot on the primary it is leaving the dots on the secondary so we will put the direction like that it is leaving the dots on the secondary. Now all have value I by root 3 n, I by root 3 n, I by root 3 n so these are the phase currents in the secondary. And then what comes into the line of the secondary would be I by n into root 3 times; root 3 times phase current will be the line currents I by n and I by n. So this is how the current mapping occurs as it flows through the 3 phase transformer topology.

And the voltages the voltages; let us say all the line voltages are equal in the case of the......... meaning the effective values of all the line voltages in the case of delta and the phase voltages are the same so we have E L as the line voltage effective values and which are also the phase voltage effective values so what happens here is you have n times E L as the phase and the line voltages which are occurring on the other side that is the secondary side. so let us look at the phasor diagram of this.

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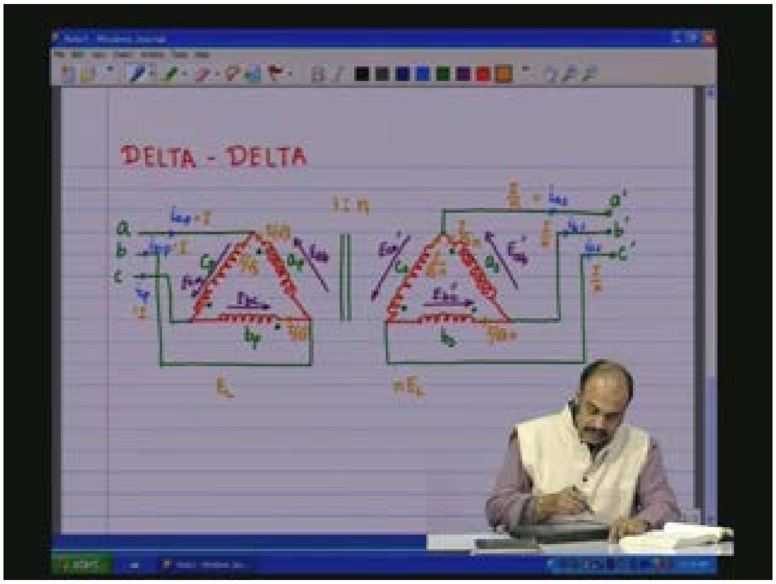

let me push this up a bit, we shall push this up okay?

Now starting on the primary side we have E ab this is the E ab axis so also there is the ab axis this is the ca axis and this is the bc axis all are 120 degrees out of phase with each other. Now if we take the case of the delta the line currents will be lagging the line voltages by 30 degrees if it had been resistive loads but as they are not resistive loads they will lag by a further so the I ap would be along b c, I bc would be the along c a and I ca will be along I ab the phase currents.

Now let us take the voltages so this would be E ab, E ca and E bc on the primary side. Now if you take the dot polarity the secondary also will be along the same directions but only by a factor of n it is going to change so let us say that we have E ab prime which is nE L this is E L if n is less than 1 let us say and then you have E ca dash which is again nE L and you have E bc prime which is also equal to nE L effective value. So this would be the relationship that you would have in the case of the delta delta connection.

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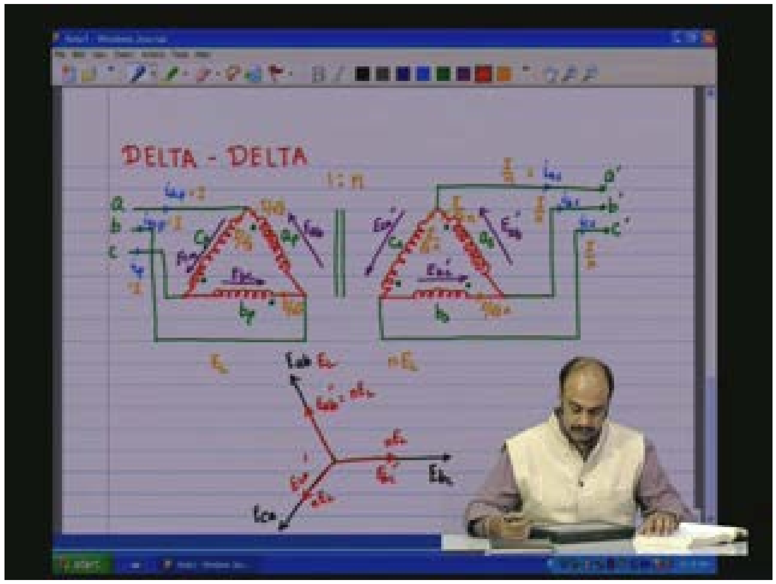

Now let us look at the delta star connection. So let us say we have the delta star connection. So, in the delta star connection the primary is connected in the fashion of the delta and the secondary is connected in the star or wye topology and as usual we have the three primary phases which are now connected in the delta like before. We have the primary so we have a, we have the b phase of the line and then you have the c c so these are the three points in delta. Let us have our polarities in sequence like that, this would be the a p phase, the b p coil and the c p coil.

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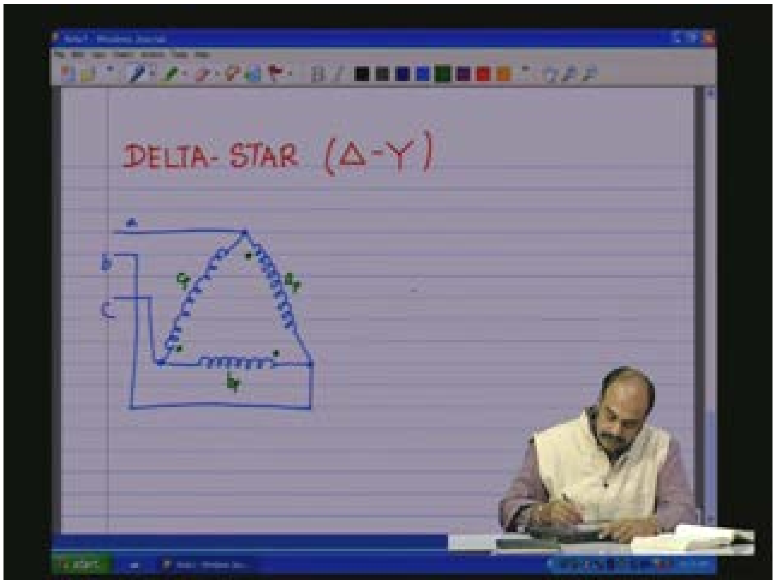

Now the secondary is connected in star fashion. So let us........ (Refer Slide Time: 23:30) like this, this is the secondary connection and let us also put the dot polarities all away from the neutral; one end of the secondary windings are connected at the neutral, these are a s winding, the b s winding, the c s winding. Now this is the neutral point.

The voltage across the a p winding is E ab which is equal to E L. Now this and a s the voltage across the coil of the a s has a ratio 1 is to n. So the coils have the ratio 1 is to n. So when in the star in the delta star connection when there is when there is indication of turns ratio the 3 phase transformer we say that the phase the primary side phase coil to the secondary side phase coil or the secondary side phase coil to the primary side phase coil whichever is applicable that would be the scaling factor that you have to use for the voltages. So, if it is E L here then the voltage across just only the a s coil which is the phase circuit coil would be n times E L. Likewise, we have the E L across b p coil and E L across the c p coil and therefore you will have voltages in this fashion here n times E L n times E L.

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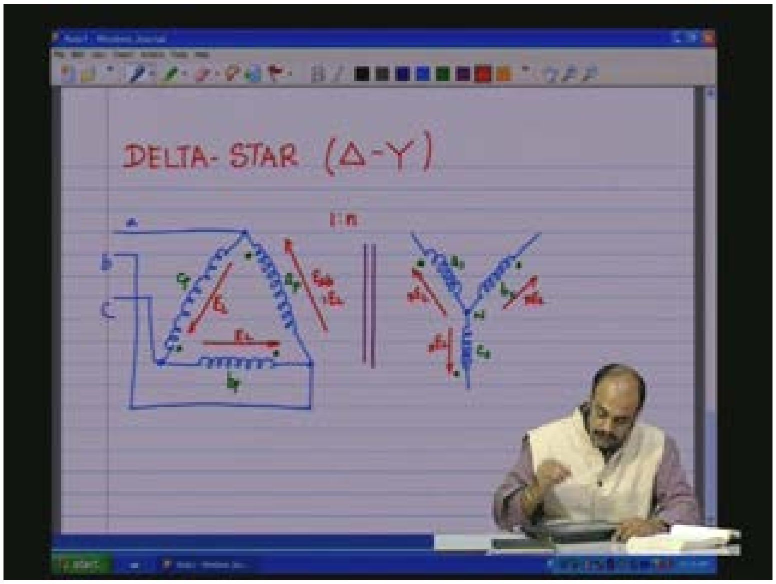

Therefore, if you look at the phasor diagram for this....... let us take this selection tool, let us copy and paste. Let us consider the phasor diagram of this. This is the secondary side this is the secondary side and this is the primary side. Of course this would be connected to the 3 phase load a prime, b prime, c prime. Now if we take let us say the load side E a s the b s and c s they are all the phase voltages of the star circuit. So let us draw the phase voltages of the secondary side which is E let us say a dash N that is the reference, this is E a s that is this voltage what I am showing across the a s coil and E b dash N this is across the b s coil and we have E c dash N which is the voltage across the c s coil taking E a dash N as the reference line the horizontal line they are all 120 degrees phase shifted with respect to each other.

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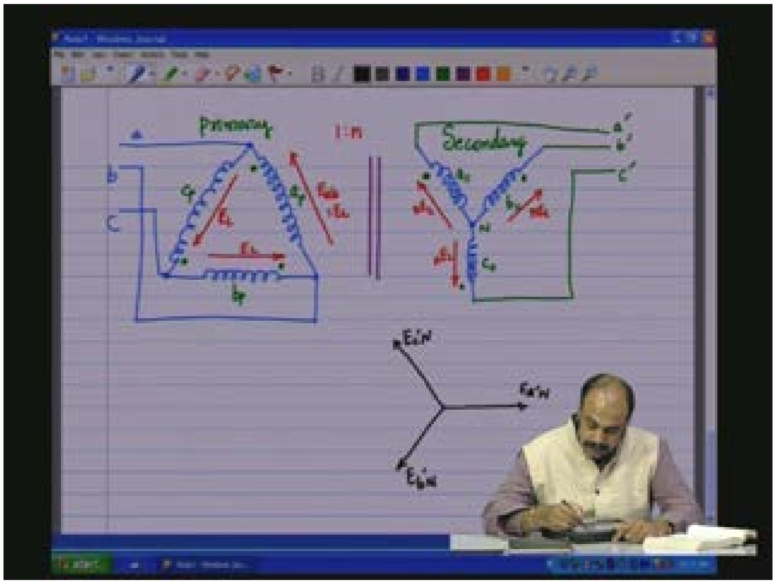

Now the line voltages that is a dash E a dash b dash is 30 degrees leading and I will show that as a different....... this is 30 degrees leading like that the E a dash b dash which is nothing but E a dash N plus minus E b dash N which is what I have shown here and likewise it is 30 degrees leading for oh so E c dash a dash and so on E b dash c dash okay so that is 30 degrees leading.

Now if we look at the primary side there is exact one to one phase relationship the in phase relationship between the voltage across a p and the voltage across a s because of the dot polarity okay. So therefore on the primary side if you see a p which is the phase voltage along this is along a dash N dash a b so that depends of course on the ratio so E E a dash N dash is nE L is it not? This is nE L, nE L, nE L. So, along this line itself we will have E ab on the primary side.
So let us say N is less than 1 and therefore we have E ab, E bc, E ca of the primary circuit.

So if we look at the terminal voltages of this transformer that is E ab, E bc, E ca and the terminal voltages of the secondary E a dash b dash, E b dash c dash and E c dash a dash there is a 30 degrees phase shape between those two and of course there is also a matter of amplitude which comes in to the picture this is so the values are E L, E L and E L amplitude. That is if we are applying E L as the line voltage on the primary side if we apply E L as the line voltage on the primary side this is the E L that becomes converted n times E L on the secondary phase coils which becomes root 3 into n times E L on the terminals of the secondary of the transformer so what you get here would be root 3 into nE L. So this is root 3 into nE L, root 3 into nE L, root 3 into nE L. So that would be the amplitudes of the voltages there now with a phase shift.

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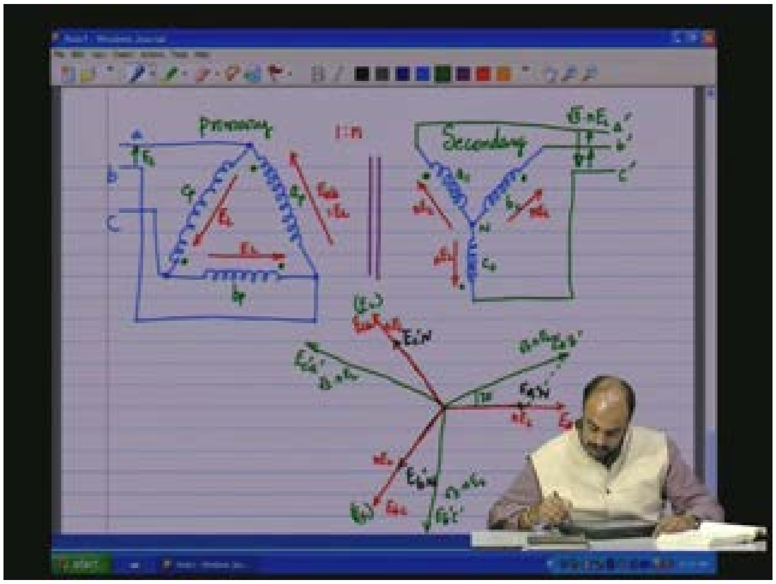

Now you see that the primary three terminals and the secondary three terminals are phase shifted with respect to each other by 30 degrees on top of it the amplitude is root 3 n times if E L is applied what you get at the terminals would be root 3 into n, remember that.

And then if there is a current I which flows through the line of the primary side delta on the phase it becomes I by root 3 and this I by root 3 becomes I by n root 3 and on the line it is same as the phase in the case of the star circuit and therefore the currents here are I by n root 3, that is the relationship.

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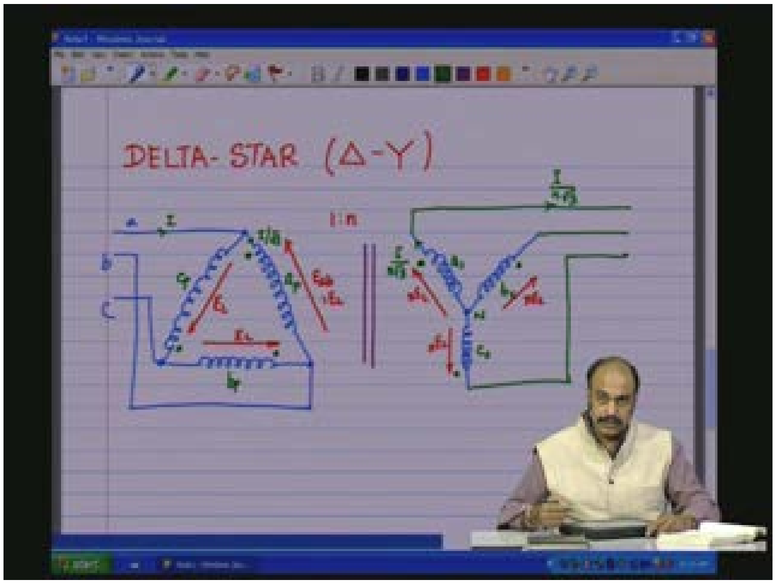

So remember, in case of the delta delta two things that you need to remember always; if you apply a voltage of E L the voltage on the secondary side that is secondary side is at the terminals would be n times E L and with a primary line current is I then the line current on the secondary terminals is I by n, this is for the delta delta. In the case of star delta on the primary side if you are applying a voltage of E L then on the secondary side what do you get E L becomes nE L phase voltage into root 3 so root 3 nE L on the secondary side. Then this is primary, secondary.

Then if you have a line current of I on the primary side this results in I by root 3 in the phase current phase the phase coils, I by n root 3 in the secondary phase coils which becomes the line currents and therefore you have I by n root 3 in the case of............ so we have to summarize this later.

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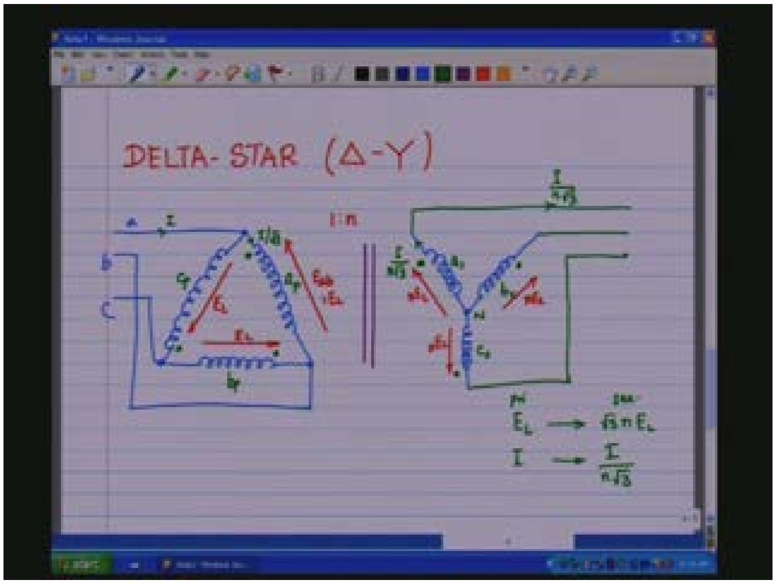

Then we have the third connection which is the star delta. The star delta connection is exactly similar to this topology exact except that the power instead of the flowing from the delta side to the star side it is flowing from star side to the delta side like the primary and the secondary are reversed. So we have the primary connected as as star as shown here, the secondary is connected in delta as shown here (Refer Slide Time: 36:45) let us indicate the polarities, never forget to indicate the dot polarities in the 3 phase transformers in sequence.

So let us say this is the a p coil, the b p coil and the c p coil and this is the a s coil, the b s secondary side coil and the c s coil. The coil on the primary are connected as shown. We have the connections in this manner. So you have the a phase, b phase, c phase sources connected to the primary.

Now there is an induction, turns ratio 1 is to n between the phase coils of the primary and the secondary and the secondary is connected to 3 phase balanced load in this fashion and we will call that one as a prime, b prime, c prime. So if we apply a voltage if we apply a voltage E L on the primary line to line the phase voltage across the a phase coil is E L by root 3. Now there is a turns ratio which comes in to the picture between the phase voltage of the a phase coil and of the primary and the secondary and that is n times E L by root 3. Now that is also the voltage that comes across the line voltage that comes across the terminals which is nE L by root 3. So, between primary and the secondary if you apply E L what you get here is n by root 3 E L.

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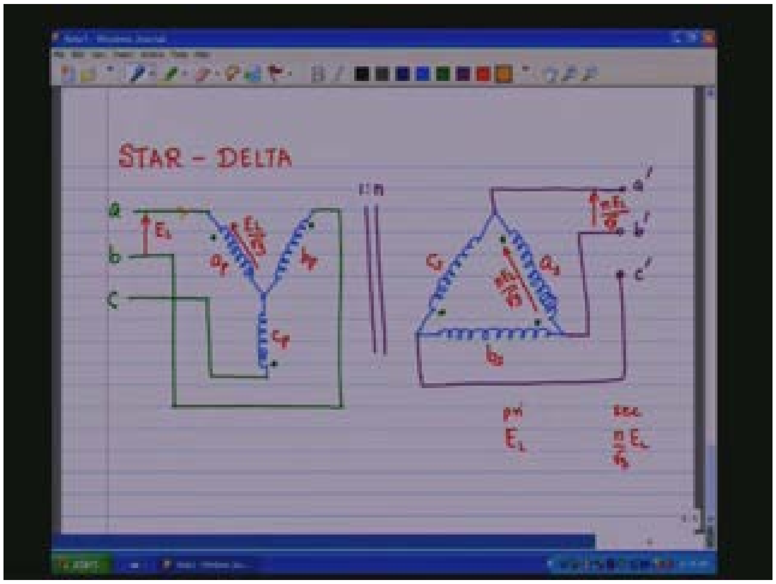

What happens to the current?

So, if there is a current flowing through the line and let us say that is I, so we have I. Now that I is flowing through the phase which is the same in the star connection, the line current and the phase current are the same and this phase current I which flows through the primary is entering the dot, E is the dot with a value I by n because of the turns ratio. Now this I by n when it comes on to the line gets multiplied by root 3 because the relationship between the line and the phase in the delta is root 3 I by n. So the current that you will get here is root 3 by n into I. Simple, is it not?

So this is the relationship between the primary and the secondary side currents the star delta. Basically it is the reverse of the delta star what you saw here (Refer Slide Time: 41:19). The delta star E L is root 3 nE L and when you apply I what you get at the output is 1 by n root 3 the flow of power is just reversed and the phasor diagram is likewise similar in the case of star delta.

Then you have the fourth one which is the star star connection the star star, the primary is connected in star or wye pattern and the secondary is also connected in star or wye pattern and that is called a star star connection or a wye wye connection. We will see both these names in the literature.

In the case of the star star connection as the name indicates the primary is connected in star all the primary coils that is the a p a p b p c p are all connected in star fashion and it is connected to N p the neutral point on the primary side. And on the secondary side also you have the star format as shown here and one end of all the secondary coils are connected to the point N as the secondary side neutral point.

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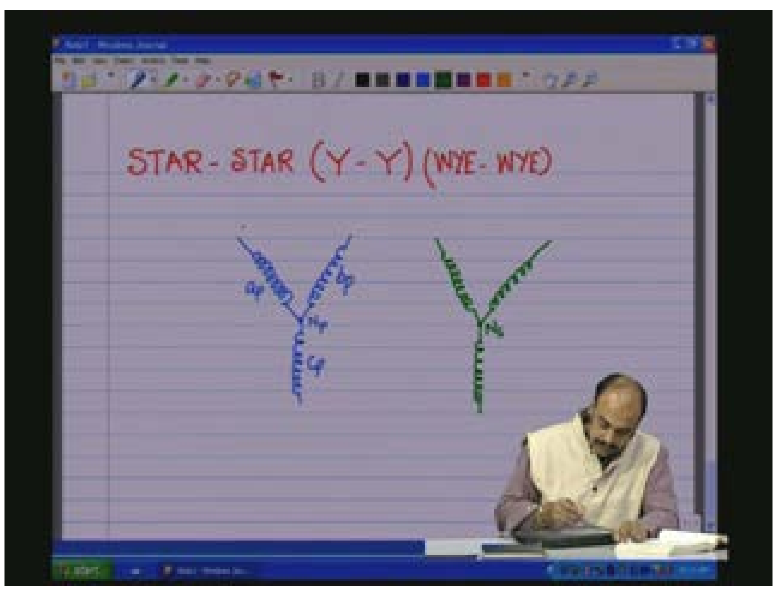

Now, the a phase is connected to the a line, the b phase point is connected to the b line and the c phase is connected to the c line on the primary on the primary. Likewise, on the secondary side you have the a, you have the b and you have the c as shown here. So you have the a prime, b prime, the c prime. So this is the a s coil, the b s coil, the c s coil that is important we have to show the dot polarities. So we have the dots away from the neutral, dots away from the neutral here also the dots indicate that those points of............... if the measure if the measurement is made with respect to that those points then the phases on the primary and the secondary will be exactly in phase that is what it means like as we studied in the contexts of the single phase transformers. We have cos induction between the primary and the secondary side and with 1 is to n, this is the primary and this is the secondary set.

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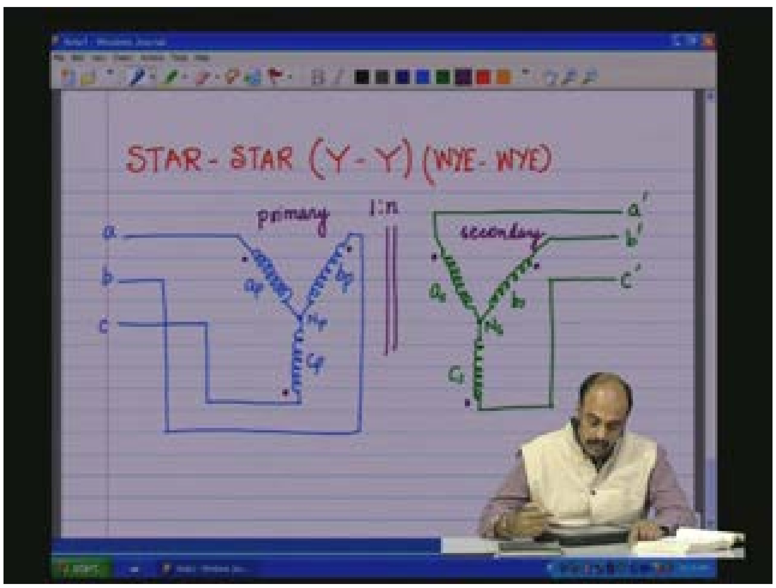

Now if we apply a voltage E L what voltage a voltage E L effective value to all the phases the phase all the 3 phases on the line and E L will get reflected as a phase voltage of E L by 3 let me take that one phase voltage at the a phase voltage and that would be E L by root 3 because the phase voltage and the line voltages are related as phase voltage is equal to line voltage by root 3 and this gets inducted or induced in to the secondary a phase coil and that is by turns ratio value nE L by root 3 and that is the phase voltage with respect to the neutral nE L by root 3.

Now the line voltage is root 3 times the phase voltage and that is equal to n E L. Clear? So you have E L being applied on the primary side and on the secondary side you get nE L at the terminals of a star star connected circuit. Likewise, if I pass a current of I in the primary line, I is the same current which flows through the primary phase into the dot and therefore the current that comes out of the dot on the secondary is just only I by E N scaled by n turns ratio and that is the line current also for the secondary side. And therefore if you give I on the primary line you land up of with I by n on the secondary side. So that would be the relationship between the primary and the secondary.

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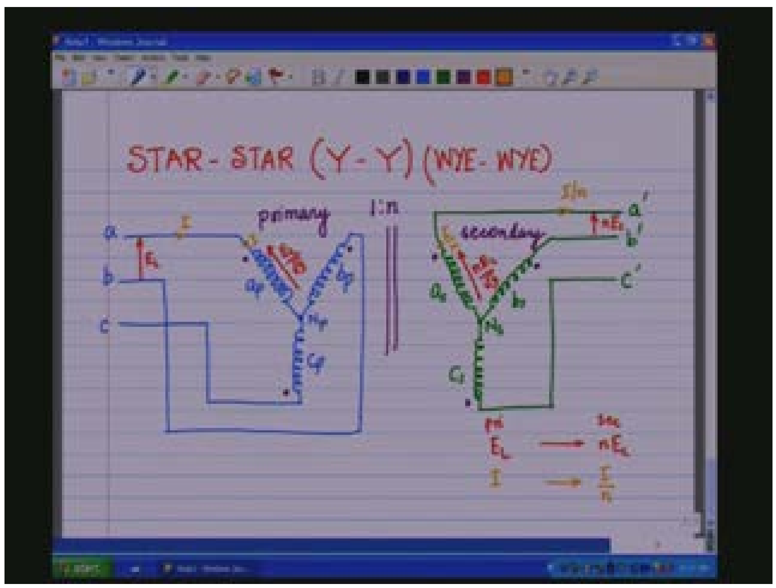

Now what about the phasor relationship?

So the phasor diagram for the star star is like this. Let us first copy, go to the next page, let me paste that. So let us take this up like this and let me start, let us stay with the secondary side. Now we know that this is the phase E as, E cs, E bs this is the phase voltages the coil voltages and that is nE L by root 3 with respect to the neutral. Then the terminal line voltages are going to lead by thirty degrees and this is nE L this is also going to be nE L and this nE L leading by 30 degrees the star.

Now the phase voltages of this side of the star that is the primary side of the star will be in phase with these and that will be let us say n times that is E L by root 3 this is the primary primary phase voltages for one phase likewise for the other two phases also. And the and the line voltage is going to lead the phase voltage by 30 degrees so therefore you will have the line voltage E L applied here; this is E ab, this is E a dash, b dash okay. This is E ap for the finite for the primary phase voltage, this is E as. So this is how the phasor diagram is going to be related with respect to the primary.

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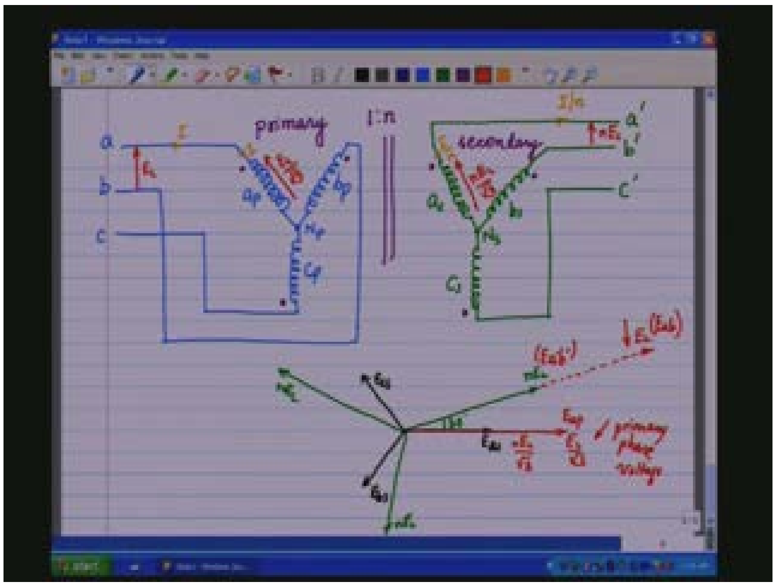

So we see that the line voltage here will be in phase with the line voltage phase voltage here will be in line in phase with the phase voltage.

So let us summarize the four main topologies. So let us say we have the four main topologies and that is delta delta, you have the delta star and third the star delta, fourth star star so these are the four main topologies. So let me let us give the relation, summarize the relationship for the currents and the voltages on the primary and the secondary side. So let us draw these columns in this fashion to indicate that we are going to write down the relationship. One is the voltage relationship voltage or shall we say line voltage line currents, the loads are well balanced. The 3 phase sources are the same amplitude and equally displaced 120 degrees apart and under these conditions and the at least here we have not considered the practical non-idealities but as far as the concept is concerned it is valid still, these following relationship.

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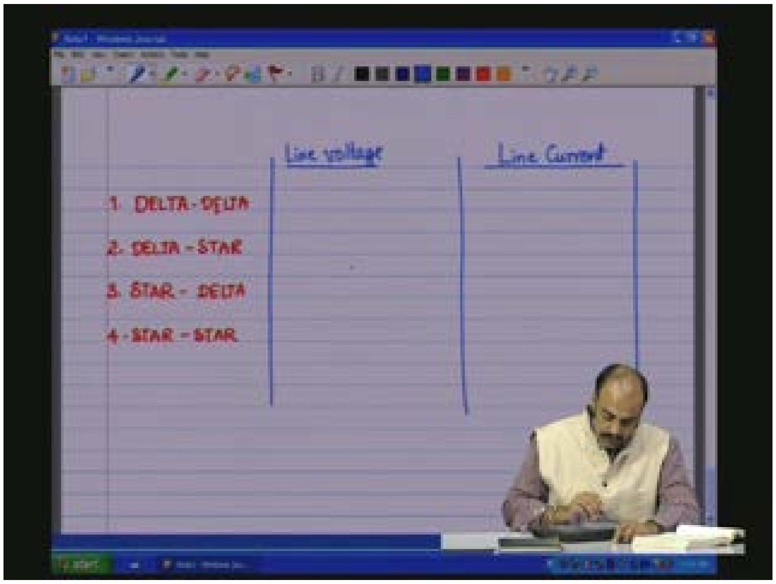

Now in the case of the delta delta if we apply a line voltage E L on the primary side it gets reflected as nE L on the secondary side. And if there is a current line current I on the primary side that becomes I by root 3 on the phase coils, of each of the primary phase coils, becomes I by root 3 by n in each of the phase phase coils of the secondary and it becomes I by n that is the secondary side line current where you have a ratio of 1 is to n as the turns ratio; n is the turns ratio; we will write on n is equal to turns ratio; secondary voltage by primary voltage or the secondary number of turns by the primary number of turns which is secondary number of turns by primary number of turns of each coil for each coil.

Then in the case of the delta star we apply a voltage E L it gets it is the same as the phase voltage in the case the primary side coil, in the secondary side coil it becomes n times E L and this n times E L is the phase phase voltage of the secondary side star connected circuit and therefore the line voltage at the terminals of the secondary side transformer is root 3 n E L so root 3 into n into E L. And if we apply a line current I it becomes I by root 3 as the phase current in the primary side and becomes I by root 3 by n the current that is induced on the secondary side and that itself is the line current on the star side which is I by root 3 into n.

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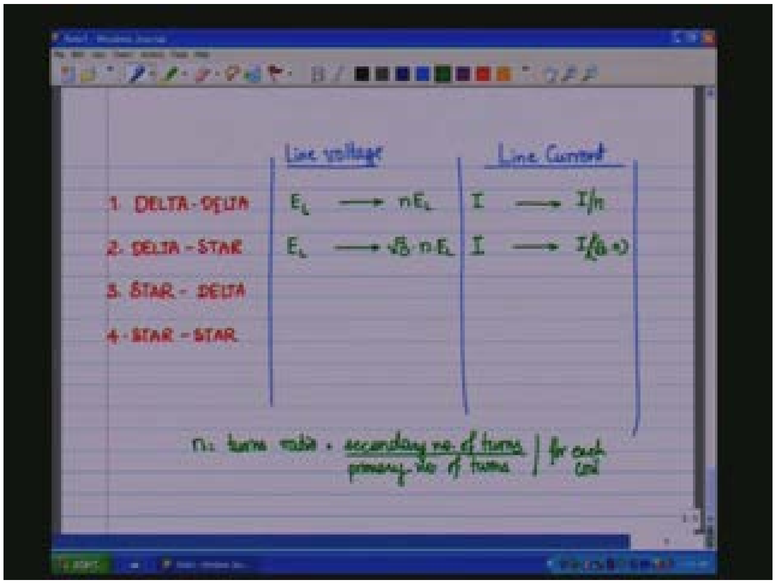

Then the star delta; if you apply E L as the line voltage on the primary side the phase circuits get a voltage of E L by root 3 which becomes n times E L by root 3 on the secondary phase coils and that itself is the line voltage nE L by root 3 and a current I remains as I in the primary phase coils, becomes I by n in the secondary delta phase coils and I by n into root 3 I by n into root 3 will be the secondary side line current. And in the star star if you are applying E L on the primary side it gets converted to E L by root 3 on the phase coils, becomes E L by root 3 into n on the secondary side phase coils and at the line it becomes n times E L. And if you have a current I through the primary the current I remains as I in the primary phase coils, becomes I by n in the secondary phase coils and remains as I by n in the line because the phase current and the line current are the same in this star connected topology. So these are the various relationships between the different types of voltages.

So if n is a step-up that is if the secondary number of turns is more than the primary number of turns then it is a step-up transformer. In the case of a step-up transformer, you see that in the case of delta star connection the line voltage is much higher than what would be the phase voltage by a factor root 3. So the root 3 is act as a the line voltage is actually root 3 times the phase voltage and therefore the coil differential coil voltages is going to be a factor less by root 3 because the line voltage on the star secondary star connected is going to be root 3 higher. So therefore the in the case of the delta star the insulation breakdown specification is 1 by root 3 lesser than in the case of delta delta for the same primary secondary voltages because here the secondary phase coil and the primary phase coil are seeing a difference of n times E L. Whereas here (Refer Slide Time: 59:26) for the same secondary voltage the primary and the secondary phase coils are seeing n by root 3 as the voltage difference between the phase coils and therefore the insulation requirement is less stringent in the case of delta star. For a very high voltage transformer delta star could be as an alternative.

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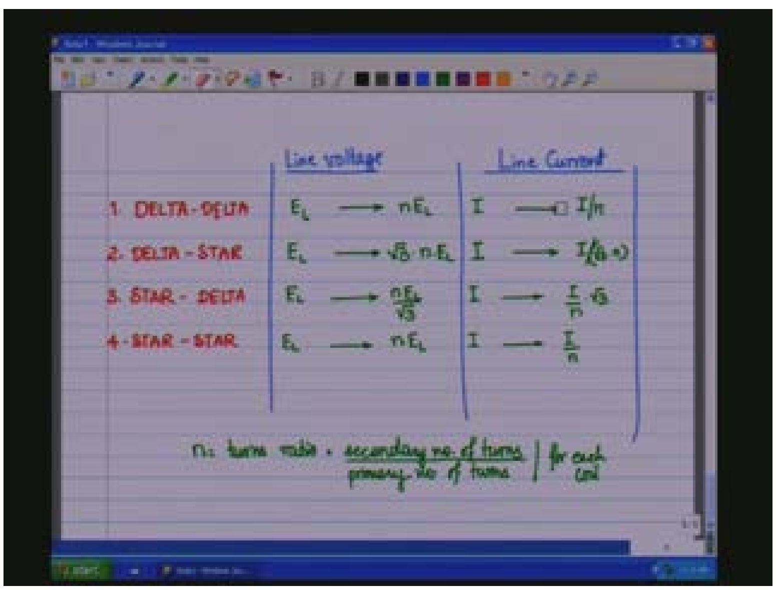

Likewise, you could study that you could see that if it is n is greater than 1 the line currents in the case of the delta delta is going to be less on the secondary side. The phase current in the case of the delta star is going to be is going to be I by root 3 n but on the primary side the phase coils will be rated at I by root 3 rather than I and therefore the primary side phase coils can have lesser smaller gauge. So one could specifically argue along these lines and suitably rate and pick the proper topology of the transformer for a particular application.

We stop here and continue in the next class.