Basic Electrical Technology
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Lecture - 32
3 phase System – 3

Hello everybody. In the last class we were discussing about the 3 phase system and the 3 phase circuits focusing mainly on the two major categories of the 3 phase circuits that is the star circuit and the delta circuits and we looked at how the voltages and the currents that is the line line side parameters and the phase side parameters are interrelated in the case of both the star and the delta circuits. We also discussed about the power which is observed in 3 phase star connected and delta connected loads.

So in this session today we shall continue our discussion on the 3 phase circuits with few examples to consolidate our ideas. Right in the beginning of the 3 phase circuits we started with the star type of a connection and then eliminate the eliminated the neutral that is we started with the six wire system and then eliminated that is eliminated two wires made three of the return paths common and it became a four wire system and then we eliminated the common neutral wire which is the fourth wire and made in to a three wire system with the assumption that the loads were balanced and because the loads were balanced the instantaneous current flowing through the neutral wire i a plus i b plus i c is always 0. So we saw from the 3 phase sinusoidal diagram that the instantaneous value is always zero. But if the load is not balanced then what happens. So we shall have a look at such a system.

So let me draw the 3 phase load like that. So we have a 3 phase load with the neutral. So let us call this as a b c as usual and we take the b phase and give it here and we take the c phase give it to the three terminals.

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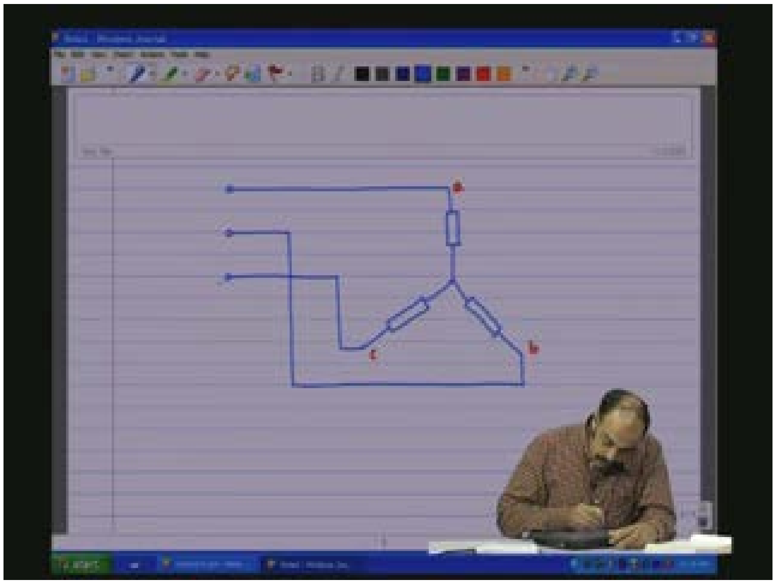

There is also on the source side a neutral terminal something like the center point we will call this one as n. we are not connecting the upper case N and the lower case n assuming that the load is balanced. So in actuality for a four wire system we are connecting the source neutral on the load side neutral such that in the return path here i a plus i b plus i c is going to flow in the return path.

Now what is i a i b i c?
This is i a in the a phase b phase c phase. So you have i b and you have i c.

Now if suppose they were all equal all the 3 phases had equal loads that is the load resistances of every phase is same and value of R then i a i b i c were the instantaneous value I am not talking of the effective values; the instantaneous value is as shown here as given here because here you are giving a voltage which is let us say the reference that is let us say angle 0 there is E line angle 0 E line angle minus 120 degrees E line angle minus 240 degrees. So this is how you are giving.

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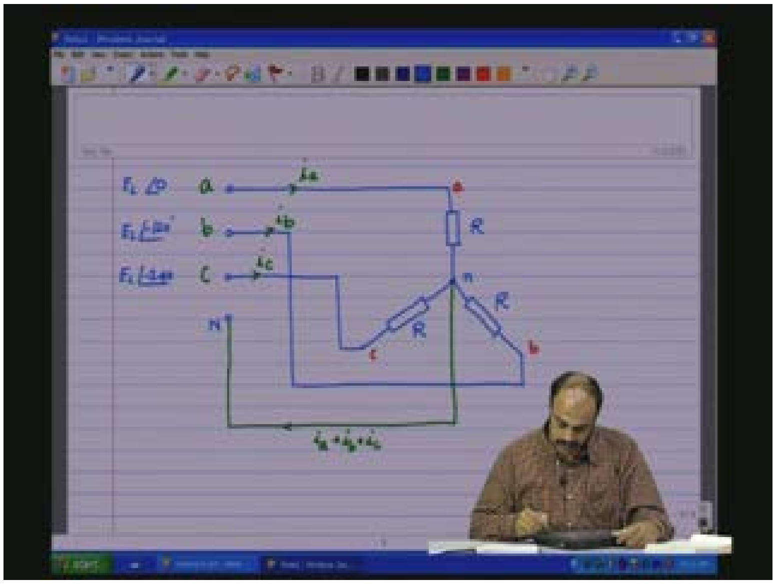

Now the currents if you look at the currents the line currents and the line voltage; if you see this line current and the line voltage there is going to be a phase shift. The voltage we saw that the voltage across the phase E an will be in phase with the line current in the case of the star circuit which is i a or i a into R will be E an E an. However, E ab is going to lead E an by 30 degrees; E ab leads E an by 30 degrees this we saw.

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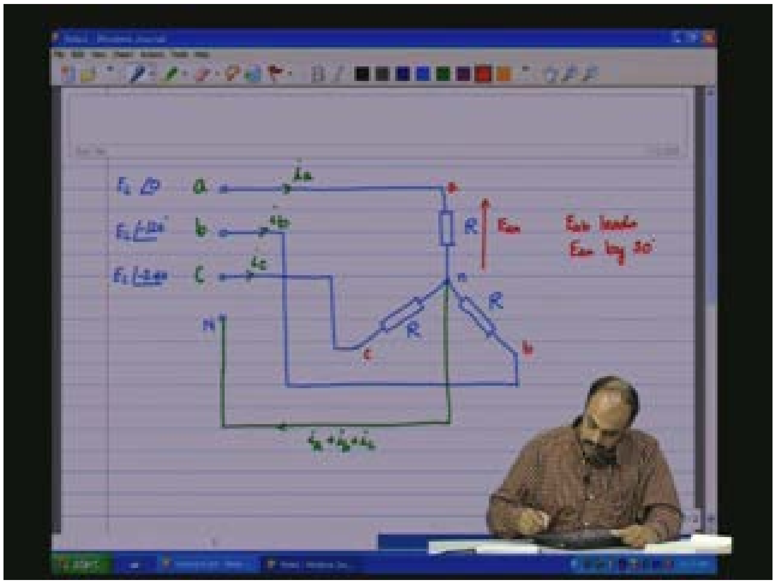

So now let us draw the waveform of i a i b i c. an easy way to draw a 3 phase waveform is as follows. Let us say you just make a set of up and down triangle waveform like this (Refer Slide Time: 8:10) and then you connect the tops by the curves like this and then the bottom portion of the triangles also are connected in this manner neatly and smoothly and that will result in a nice meet.

So let us say i a this is 0 of the i a and this is 180 degrees of i a, this is the 120 degrees point, this is the 60 degree point and somewhere here is the 30 degree point and this would be also 30. So let us say i a lags the line voltage by 30 degrees. This is time, these are the 3 phase currents i's these are the currents.

Now let me keep i a in blue this is i a and we can take the green colour for i b which is lagging i a by 120 degrees, see that i b is lagging i a by 120 degrees, this is 120 degrees, now this would be 30 degrees, you see that i a is lagging the reference and in this case the reference would be the line voltage, let us say it is lagging by 30 degrees with respect to the line and let us take the red waveform to 40 degrees. This would be i c. It is a very easy way of constructing the 3 phase waveforms and now you can complete the this portion of the curves and likewise for i b.

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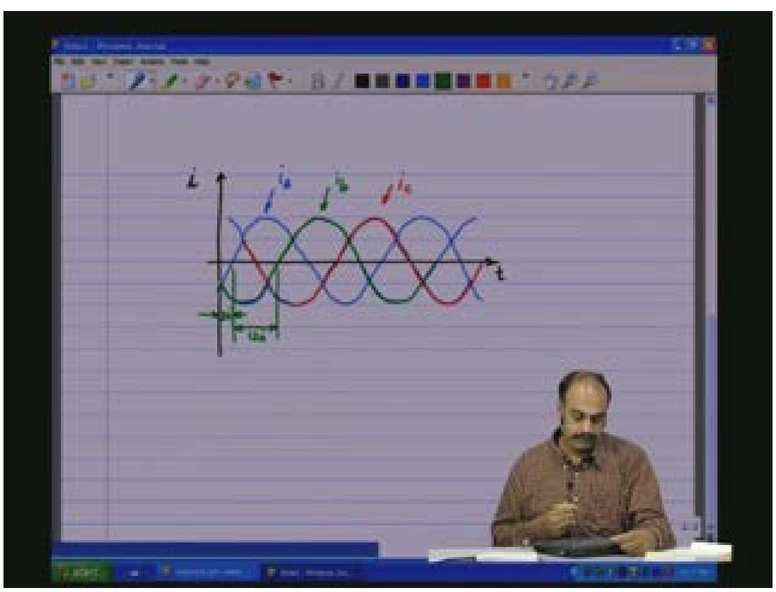

So, if at any section if we take any section if the load is balanced, by balanced we mean that all the loads are of equal magnitudes then at any section at any given instant i a plus i b plus i c is equal to 0. So i c is positive max, i a is negative half, i b is also negative half at this point and therefore you have 1 minus 0.5 minus 0.5 which is equal to 0 and so on throughout the range. So now what happens when the loads are not balanced which means some value of the load or the resistance is of a different value.

So let us say that the i a value that is the R connected to the a phase is instead of R it is R 1 and R 1 is not equal to R so what happens is that let us say R 1 is lesser than R which means more current or more i a flows through flows through the R 1 resistance. So this would mean that we have an i a which is having a different magnitude compared to the other two. So now the i a is not the blue i a is now the violet or the purple colored waveform, this is our new i a. Now this i a is having a different amplitude compared with i b and i c. So this makes this relationship invalid meaning i a plus i b plus i c has a finite value which is not equal to 0.

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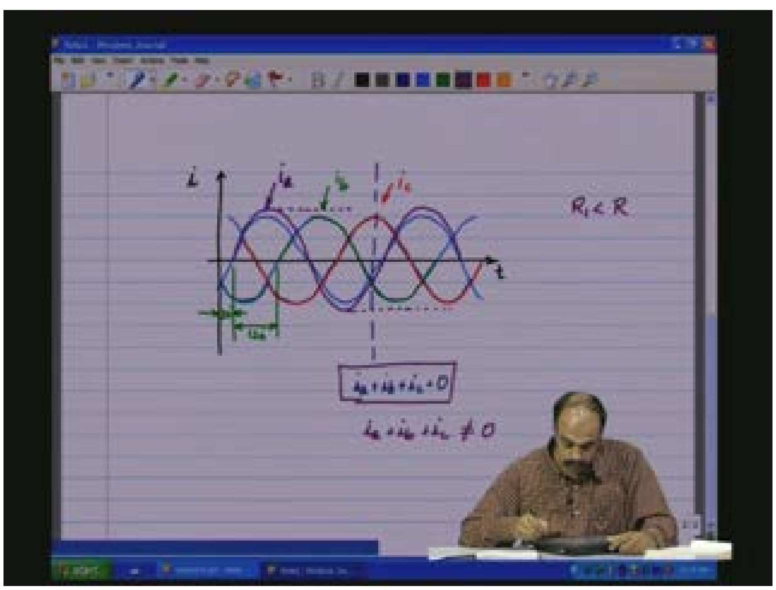

Now suppose in the circuit (Refer Slide Time: 14:27) we are not connecting this we are not connecting the neutrals of the source and the load then there is no path for i a plus i b plus i c to flow in this return path that is the neutral line so therefore what happens at this point the summing point junction; Kirchhoff's law current law states that the sigma i a plus i b plus i c should be equal to 0 which means the excess current should get divided into other two phases so it is not purely i c which which was in the case of the balanced load that would be flowing here and i b so it will be there will be a path of i a which will get mixed into i c and there will be a part of i a which gets mixed into i b and that changed magnitudes of i b and i c is going to get multiply by R get reflected as the voltage drops. So the voltage drops in this phase will now change.

If it had been as in the case of the balanced condition let us say i c let us say i c balanced so during the i c during the balanced condition i c balance plus sorry i a balanced plus i b balanced plus i c balanced is always equal to 0 and therefore you have E cn would be equal to i c balanced that is effective values so it would be i c balanced effective value into R and E bn is equal to i b balanced into R and now when this is removed i c current is not the same as what was under balanced condition so there would be a part of i a which is also going to flow into i b and i c and they get modified and it is no longer balanced it is just an i c which is now containing within it even a portion of i a. Now this means that i c into R is different from what was the voltage across it under balanced condition and so also i b into R. This means that the voltage across the c phase and the b phase will get modified. So if you have harmonics in a due to some loading impedance change there then that harmonics will also get reflected on the other two phases so there will be distortion (Refer Slide Time: 17:39) in the other two phases so which means under unbalanced load condition condition the phase voltages will get distorted. So the distortion may be in magnitude or frequency or both to have harmony to have a harmonic distortion also in it is possible depending upon the type of the mismatching the load. So this is a condition which can occur if the neutrals are not connected.

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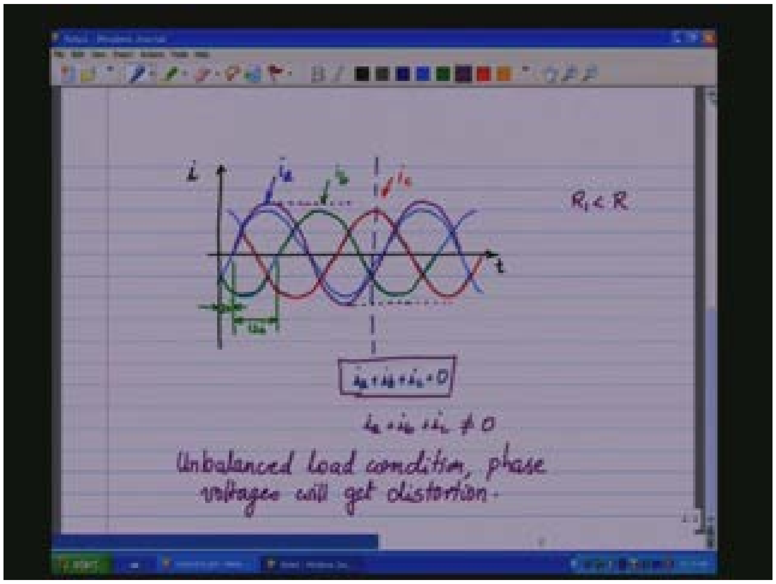

So therefore when you have a situation therefore when we have a situation that the load may be unbalanced then one has to connect this; one has to connect the neutral of the star connected load to the neutral of the source so that there is a path for N balanced currents to flow through the neutral wire so then each phase becomes independent, you have the i a currents then you have the i b currents and the i c currents and the currents through the other two phases will not get unbalanced as in the as in the case of a three wire system.

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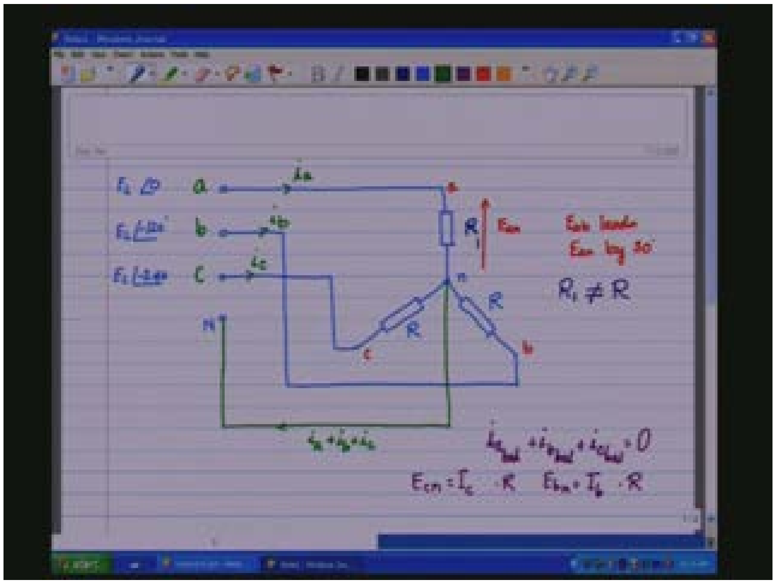

In the case of a delta connected load such a situation does not arise because in the case of the delta connected load the phase circuits are directly across the line and there is a source and therefore there will not be any distortions in the there will not be any distortions in the line voltage even if the loads are unbalanced and there is no concept of the neutral point in the case of a delta connected load.

Now let us see if we have multiple what happens if we have multiple loads; a common situation would be that we have a 3 phase we have a 3 phase source a b c. Now these 3 phase source will supply power to a 3 phase load and let us say it supplies power to an inductive load like in the case of a motor. In general the 3 phase load is in an industry it is going to supply to let us say a motor type of a load which is inductive in nature meaning lagging cofactor. So let us have the load which is like this equivalent load which is like that let us say. So this is our load.

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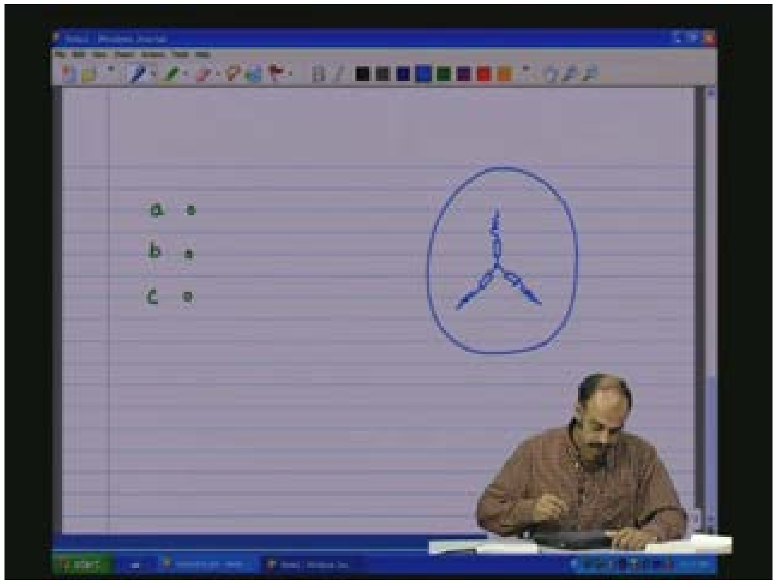

Now we have the a phase terminal, the b phase terminal and the c phase terminal. So let us bring this out like that. So we have the b phase terminal, we have the a phase terminal and then we have the c phase terminal is it not? So this is a load, this is R L load, let us say they are all balanced, you have R X L X L R R X L. So we make a connection the source between the source and the load. Now if this is having a large reactive component then the power factor is going to be very bad very poor is it not? The power factor angle is given by tan verse of X L by R for every phase and therefore you could if the L value that is the inductive reactance is going to be very large then the angle can be large and therefore the reactive power that is being drawn from the source can be quite high.

So in order to reduce the reactive currents that are being drawn from the source side so that the ratings of the source of the generator can be more more optimally used; normally in the industry they try to improve the power factor from the line side by connecting a capacitive kind of a buffer in between the load here to act as a reactive generator. So let us have the capacitors connected in a fashion as shown here. So let us connect three capacitors in the delta as shown here. So let us call this one as a b c of the capacitors and let us link it up a connected to the a phase, b is connected to the b phase, c is connected to the c phase these are c c or X c X c X c capacitive loads.

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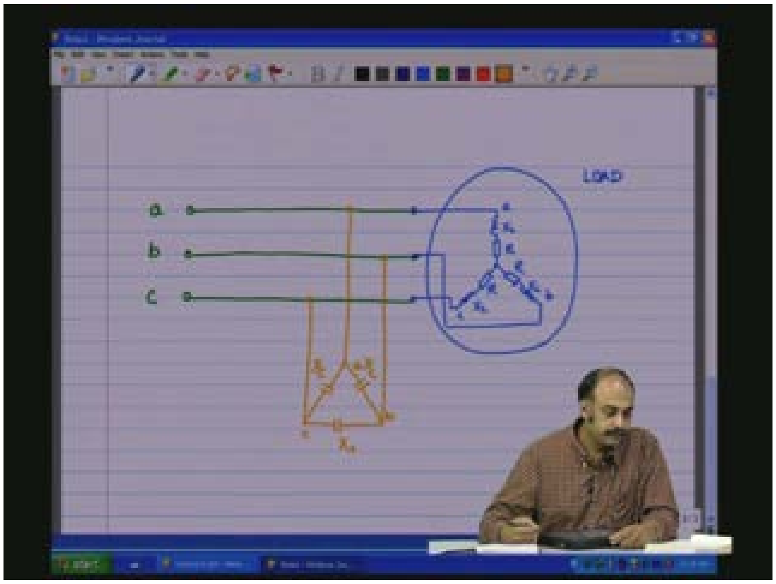

So now let us analyse this particular configuration a pretty common and configuration that you will come across and study the vector diagram how it looks like. For us let us now have the reference. The reference is, this is E ab this is E bc and we have E ca so these are the line voltages line voltages. Now let me also have the line currents i a i b i c. Now at this point the current gets split between the reactive capacitive reactive load and the R L load. So let us distinguish them by the following symbols. so we have let us say i aL i bL i cL the L subscript has been used to indicate that it is going to an inductive reactance type of a load and here you have i ac i bc and i cc the c subscript has been included there to indicate that it is the currents that are going into the capacitive reactive load just for distinguishing.

Now the capacitive delta circuit here as you see the capacitive delta circuit here is seeing the same line voltages E ab E bc and E ca same line voltages. The star circuit is also seeing the same line voltages E ab E bc E ca they both are seeing the same line voltages. So let us have the line voltages as our reference and then from there let us try to build up our phasor diagram.

Now here at this point let us also include in the star circuit a point called the neutral point so that we can say that this is E an and we have here E bn E cn. So this is the schematic of a very general 3 phase circuit system where the actual load that we are seeing here is inductive in nature which is what is generally in industrial loads; as they are generally inductive in nature because most of them are going to drive the motors which are basically lagging power factor loads. And then as the powers if the powers that are to be delivered to the load are very high than the reactive component that can be that can be taken from the generator can be really very high prohibitively high and therefore to compensate for the reactive components so that the reactive component can be delivered to this buffer capacitance and then can be again taken in as and when required. The capacitance reactive network as shown here is generally used so that the power factor as seen from the line side or as seen from source side is improved that is that will become evident once you look at the phasor diagram.

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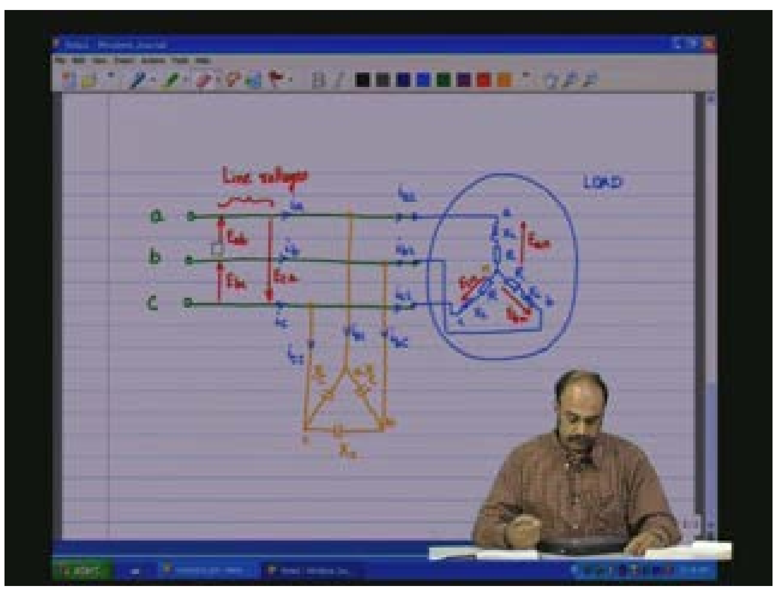

So this let us copy using the......... so we make a copy of that and keep it for future reference and let me paste it here and bring it as close so that we make some space here to write the phasor diagram. Now the line voltages: So let me draw the line voltages with black color. So E a E b E c can be shown in this fashion so E ab let me put E ab like that because there is a delta circuit I am trying to follow that triangle E ab. Now the capacitance current i ac i bc i cc they are the line currents for the delta network and E ab E bc E ca are the line voltages.

Now if you look at the currents in the phase the currents in the phase are going to are going to lead the voltages across the phase because it is a capacitive unit. If it had been resistive with respect to the line or with respect to the phase voltages the currents which are there within the phases would be lagging the line voltage by 30 degrees as we saw in the last session. If you want to recall (Refer Slide Time: 32:00) if I put back the delta network circuit which we discussed in the last session we have i a i b i c and then the currents within inside in the phase circuit.

You see that the phase currents make up the phase current is in phase with the line voltage and the line current is now lagging by 30 degrees E ab if it had been resistive. Now it had been capacitance capacitive pure capacitive then the line current here will now lead corresponding to this point by 90 degrees. Or we will say i ab is going to be 90 degrees with respect to this here and i ca also capacitive is again 90 degrees with respect to here and therefore the whole thing is the whole triangle here is going to shift by 90 degrees with respect to the current position which means i a will lead E ab by 60 degrees.

So, coming back here for the capacitive network you will see that i a is going to lead i ac is going to lead E ab. Now if you look back to this particular diagram here i aL is the line currents of the load side of the machine side and i aL is passing through an inductive network and it is the star network and that is going to lag the phase it is going to lag the phase voltages of this phase network.

Now how is E an E bn E cn related to E ab E bc and E ca?

Now E an is going to lag E ab by 30 degrees. Again we saw this in the last class E c n and E b n. So we have E an E bn E cn. Now with respect to.............. if everything had been resistive loads i aL would have been along E a n but now i aL is passing through a reactive network so i aL is going to lag E an by some angle theta and this would be i aL and you could probably have I will put that in a different color you have i aL i cL and you have i bL as shown. So this is lagging by an angle theta which is given by tan inverse of X L by R. So, depending upon the load the theta angle here is going to be different.

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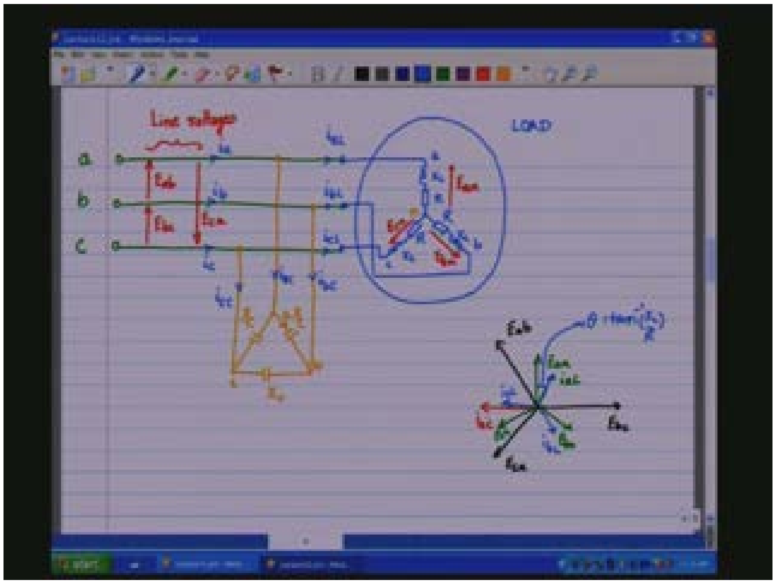

Now if we look at the current i a; now i a is the vector sum of i ac and i aL i ac and i aL and therefore if we superpose i aL on i ac we get i a we get i a. Now i a is the........... By applying K cL we get i a as the vector sum of i aL and i ac and you see that i a is now almost in phase with the E ab because we have put a capacitive network. If the capacitive network had not being there i a would have been i a L itself which means lagging E a b i a would have been i a L itself which is lagging E a b by a significant angle. But because you have put i we have put a capacitive network which is resulting in an i ac a leading current which combines with i aL the load current to provide a line current which is almost in phase with E ab. So this improves the power factor as far as your line side portion or the generator side or the source side is concerned. So this is an important industrial application which is normally practiced.

So let us take a textbook example where there is a capacitance buffer, there is also a motor load. Now here you are having 4000 volts 3 phase system, power is getting generated from here, We are trying to put the power to the load here. now this is only capacitive and therefore it is going to give a reactive power we will say Q c. now this power is having two components because it is inductive there is one part which is active which flows into the motor we will call that one as P 1, there is another part which is reactive inductive which is again fed back to the mains and that we will call it as Q m of the motor. So therefore the line side we will have two components of power flow again a reactive and an active. The active portion is only to supply the active part in the motor which goes to the mechanical load so the source is going to supply of course P 1 and it is also going to take in some reactive component of power we will call that one as Q line. so you have a reactive component of power Q line the line side, Q c in the capacitive side, Q m on the motor side; there is only one active component which is taken from the motor to the mechanical domain that is P 1 and it gets supplied from the mains which is similar to the diagram that we have been seeing here (Refer Slide Time: 39:34), we have the 3 phase delta connected capacitance network which is the reactive component which can which will supply the reactive power which is stored in it and we have also the active power which is getting into the load here which is represented by the Rs and we also have the reactive component in terms of X L.

Now if you look at his diagram here of course we have taken the direction of currents in this way. But if let us say we put the direction of currents in this direction to indicate the power is reactive power is being put back to the mains there or to the point of oaring here you will see that this load current goes negative that it goes in it is assumed to be in exactly 180 degrees phase position let us say so this is minus i ac. So then what happens to the what happens to i aL and i ac which gets odd at that point by Kirchhoff's current law is interesting to see that is we add a line parallel to i aL here, line parallel to i aL and then we would have i a that would be i a. So this would be i a under the condition that we are using this capacitance the reactants to pump back the reactive power so we invert the direction of the currents there and the resultant i a here is now leading the voltages rather than lagging the voltages which would have been the case if it had been just only the R L load.

Now if we adjust the values of the capacitive reactances here such that we i ac currents are adjusted then one can adjust it to the extent that i a just about manages to be in line with E ab then you have unity power factor from as far as the lines are concerned from the line side so that would be the function of the capacitance c.

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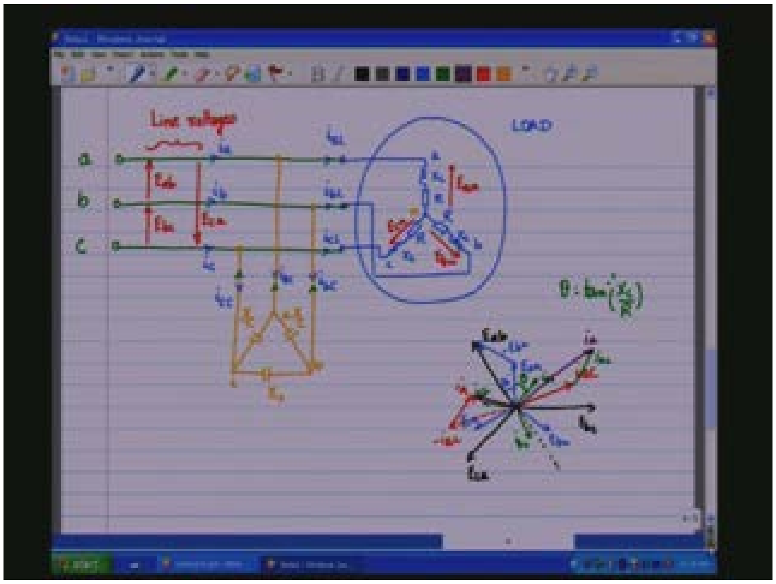

Of course with the numerical example it will become clear.

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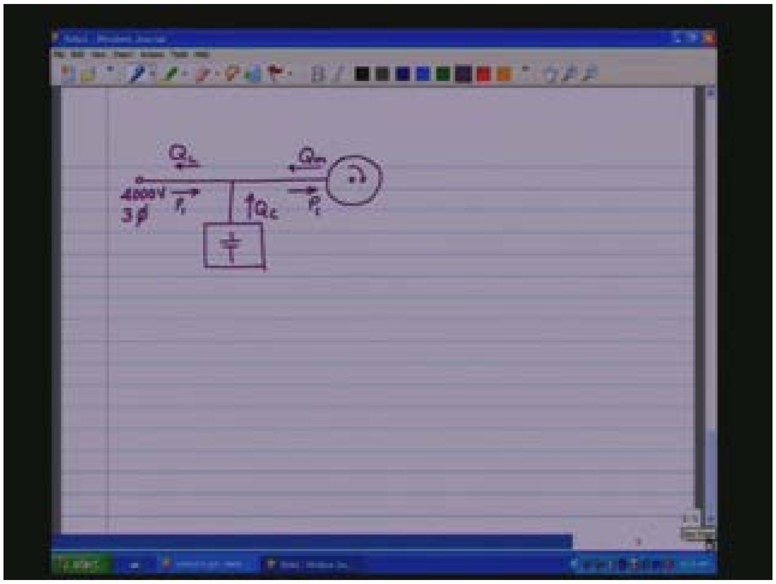

Now let us say that this capacitance network is rated for 1800 KVAR that is the reactive power and let us say that the motor is rated for 3594 HP I am taking it from this book, I will refer it much later. Let us say the motion the motor is having an efficiency of 93 percent and the power factor of 0.9. So let us say these are the things that are given about this motor.

Now let us try to analyze this system. Let us first select this, copy it I may push it a bit up, we have more space. So first of all we have an output here we have an output here which says it is 3594 HP or 3594 into 0.746 conversion factor and which will give you 2681 kilowatts 2681 kilowatts; this is the amount of power that is going to be put put to the mechanical load the active power. So we call this one let us say as the active power.

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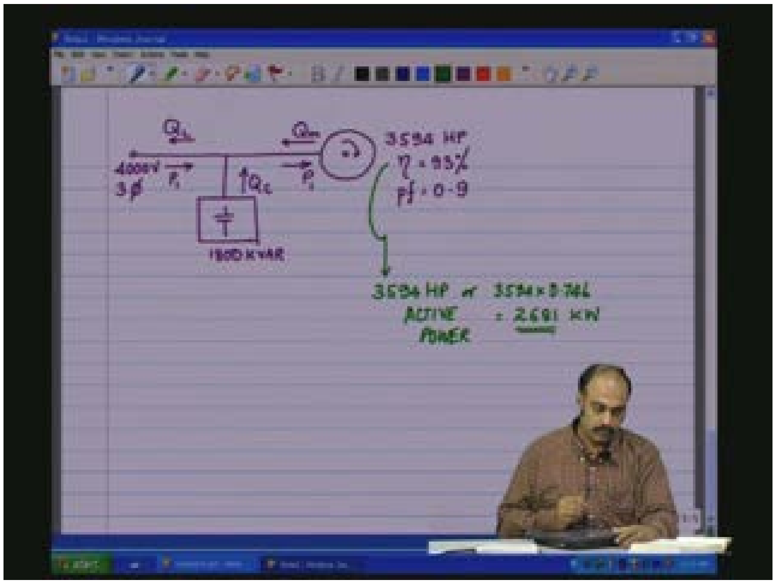

Now this is at the active power at mechanical shaft let us say. Now the active power observed by the router by the motor would be by the efficiency so P 1 will be equal to 2681 by efficiency which is 2681 by 0.93 which comes out to be 2883 kilowatts so this is the active power that we are putting to the load of the motor.

Now what is the apparent power; the VA. So the KVA is the active power by the power factor; active power divided by cos of theta and cos theta is given as 0.9 and that is 2983 by 0.9 which is 3203 KVA as far as the power is concerned. This is how it...................... so which means you have 2883 kilowatts active power, there is some reactive power component and then because we have known the angle theta theta is cos inverse of 0.9 so cos inverse of 0.9 is 25.8 degrees so we will say this is 25.8 degrees and the KVA is 3203 KVA.

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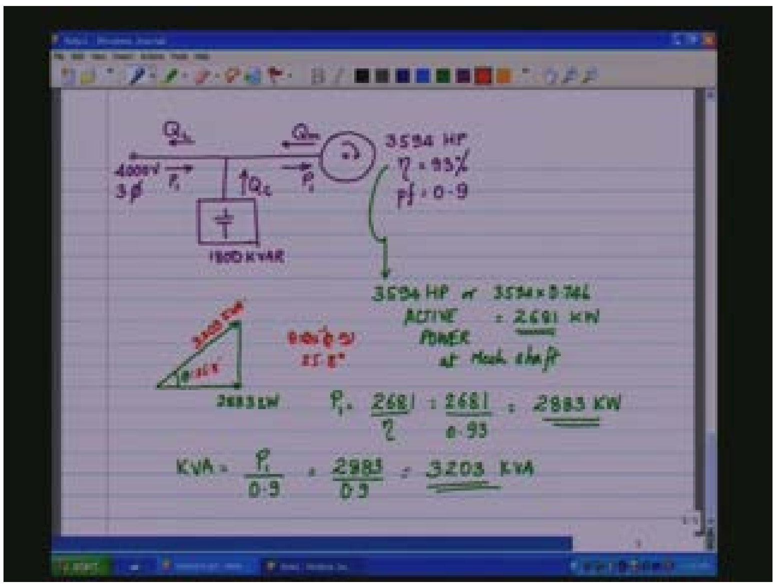

So what is the reactive component?
So the reactive component is given by root of 3203 square minus 2883 square and that is equal to 1395 KVAR. So this is 1395 KVAR so this would be our power triangle as far as this portion that is the load portion is concerned without now having considered the capacitance reactive circuit that we have put in there.

Now if the capacitance circuit is put which is 1800 KVAR rated now that capacitance is going to generate Q c. So you see that Q c we are showing in this direction but actually this is a passive circuit so if this is 1800 K V A R reactive circuit passive this is not a generator; the Q c now we are pointing it in the other direction is minus.

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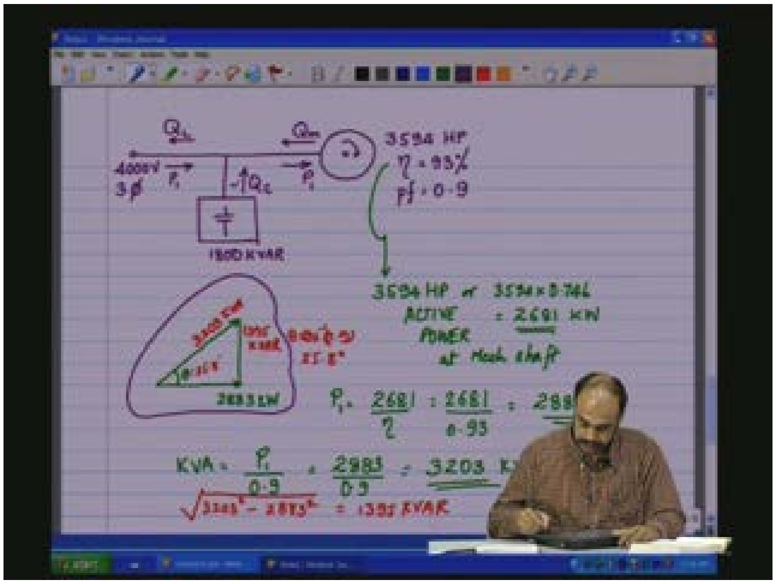

So therefore Q c is......... but still I am going to put it back again to minus 1800 KVAR. So, on the line side what you actually see is Q c plus Q m of the motor which is minus 1800 plus because this is capacitive whereas Q m is positive which is inductive so inductive is having a polarity 1395. So, in the power diagram we have this as inductive and therefore the positive and this is capacitive and therefore the negative sign. So therefore Q L in total will be minus 405 KVAR.

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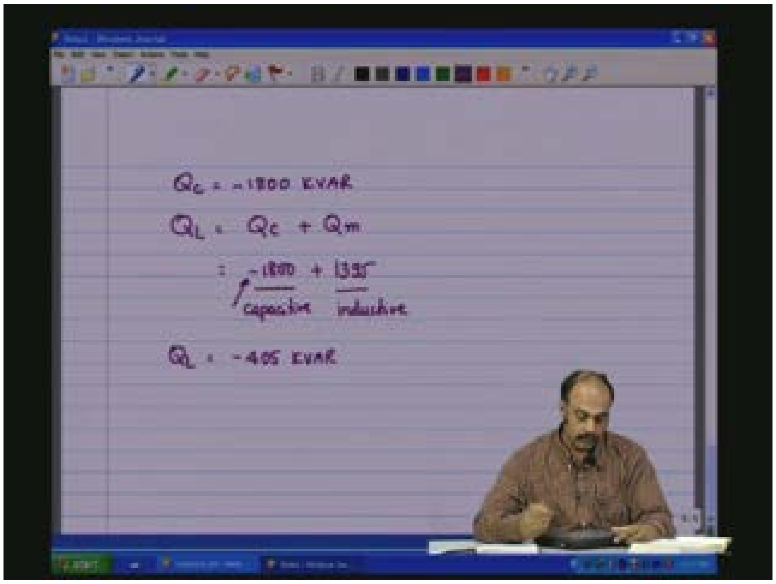

So you see here that interestingly in this whole scheme of things this is 2883 kilowatts and this is having a minus 1800 KVAR this is minus because capacitive, now this is having a reactive component which is 1395 KVAR and Q L is this minus this and therefore this is 405 which is capacitive and therefore minus KVAR. So the reactive component of the load alone would have been 1395 but because we have put this capacitance compensating network the line side KVAR as now grossly reduced and in fact it has gone leading it has gone in to the capacitive side as minus 405 KVAR.

If we have put only 1395 KVAR rating capacitance here then that would perfectly cancel and then the reactive component in the line side would be zero and the line would be just giving you active power. Anyway for this circuit now we we now check the apparent power on this side. What is the apparent power? So the KVA rating line side is root of 2883 square plus 405 square which is 2911 KVA and what is the line current I L which is equal to I L is equal to KVAL divided by KVAL is nothing but root 3 E L I L we saw the power equation in the last class root 3 into EL which is 2911 KVA which means VA divided by root 3 and we have a 4000 volts machine so therefore this comes to 420 amps. So the current through the mains would be 420 amps. So what would be flowing here would be 420 amps.

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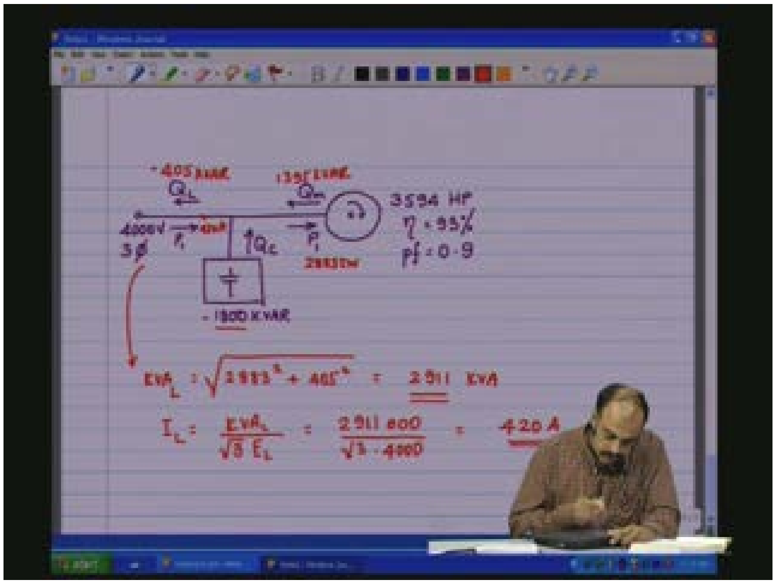

Let us........... Now what is the motor line current? That is what would be the current here motor motor current or the motor line current. Let me let me say it is motor line current. What is that? So we know that the motor has a........ at this point we saw that the KVA on the motor side was 3203 KVA. This we saw from the power triangle here (Refer Slide Time: 54:41) so that is what we will be using and the motor current here I m will be 3203 KVA divided by root 3 the same line line current into 4000 volts and that would be 462 amps 462 amps. So you will see that here the effective value is 462 amps and what is here is 420 amps reduced because of putting this kind of a reactive............

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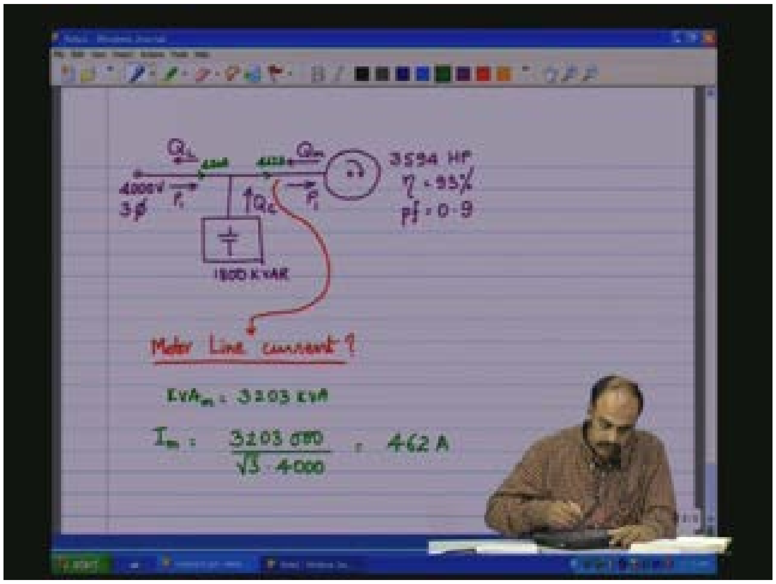

Now what is the current that is flowing through here let us call this as i c. So i c is Q c which is 1800 KVAR divided by root 3 in to E L which is 4000 which is 260 amps and this is 260 amps and that is actually minus because of the reactive nature.

Now if we look at the vector diagram let me have this in picture (Refer Slide Time: 56:51) the motor is generally star connected and therefore the phase voltage is given by line voltage by root 3 which is 2312 volts. So you have the phase voltage of one of the phases let us say which is 2312 volts so with respect to that phase we are having an I L which is 420 amps this is the I L in the line.

Now, with respect to this the motor current is going to be lagging and that is 462 amps this is I m and that is lagging by what amount; by the power factor amount as given which is 25.8 degrees and then we have the i c which leads that is 260 amps. So you will see that you will see that here let me draw this properly 462 amps this is I m so I m plus i c will give you I L and because of the reactive nature of i c we see the improvement in the power factor as we discussed earlier and that makes it in phase.

Come the that would be

So if we adjust the value of i c by adjusting the values of the capacitive reactance one could make it in phase. Now I L had leading reactive common has a leading current because the reactive component of the line side has minus 405 KVAR which is due to excessive capacitive or the capacitive reactance on the compensating network. So this had more capacitive reactive power being fed into the mains and therefore this leading path. So if this is adjusted that could be made in phase. So this is one such interesting example, a bit complex but still it gives you the whole picture of the 3 phase circuit.

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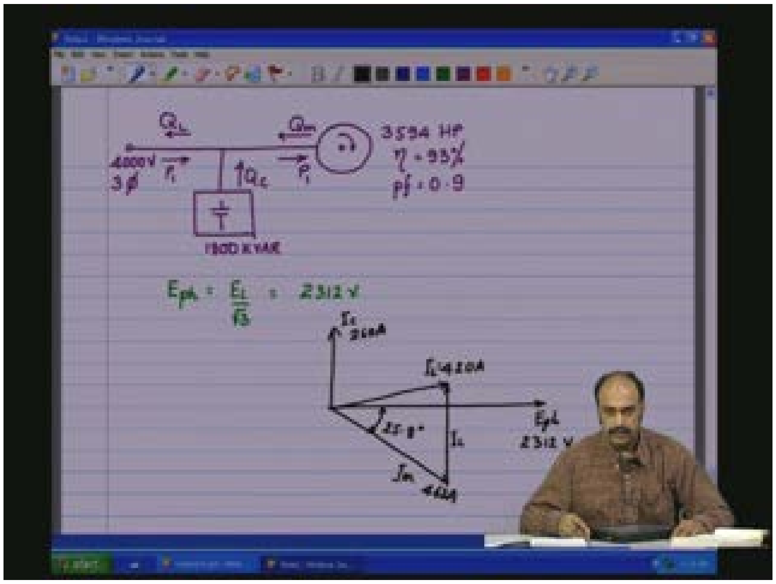

We stop here and continue in the next class. Thank you.