Basic Electrical Technology
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Lecture - 40
Synchronous Machine

Hello everybody, in the last class we concluded the discussion of the induction machine and we saw how important the induction machines are the machine was under various applications: the induction machine acting as a motor, acting as a generator and the various other features of an induction motor like almost constant speed, the ability that we can control the speed with added electronics and things like that so it is a very popular motor.

Today we shall try to get a glimpse of another machine called the synchronous machine. So the synchronous machine as the name suggests the rotor shaft will rotate in synchronism with the rotating magnetic field. In the case of the induction machine we had a rotor shaft rotating slightly slower than the rotating magnetic field by an amount called the slip so therefore the shaft speed was always lesser than the synchronous speed.

In the case of the synchronous machine the shaft speed will always be in synchronism with the rotating magnetic field and therefore the shaft rotates have synchronous speed n s which is equal to 120 f by p. Therefore, the synchronous motor is actually a constant speed motor if we keep the stator frequency constant. Synchronous motors the synchronous machine also can act in both the ways that is you can have the power of the energy fed from the electrical domain and take the output energy or the output power from the mechanical domain then it is called the synchronous motor. If we have the energy fed in from the mechanical domain and then take it take the energy out from the electrical domain then it is called as a synchronous generator or an alternator. So the synchronous motor behaves very similar to the way we discussed the concepts that we discussed in the case of the DC motor and DC generator.

So in this class we shall get some insight, we will not go into too much of great details into the synchronous machine but we will try to get a glimpse or insight into the concept of the working of the synchronous machine and try to see its some of its important uses. In fact the synchronous generator that is the alternator is one of the most widely used sources of power sources of 3 phase power that you get that you get at the wall outlet. So almost the almost all the generating sources of the generating stations the shaft is turning an alternator which is going to give you a 3 phase output. So synchronous machines are pretty popular but at a very higher rating compared to the induction machine.

So today's topic is synchronous machine. So let us start with the synchronous motor first. The operation of the synchronous motor and the synchronous generator are exactly similar except for the power flow. Like in the DC generator and DC motor you can use the same machine either way both ways.

See the operation principles of synchronous motor is pretty straightforward and simple. it is more on the principle of attraction magnetic attraction magnetic attraction between poles between unlike poles.

Let us consider a stator and inside the stator let us have a rotor let us draw a salient pole rotor to understand the concept. So let me draw a rotor like that; this is called a salient pole rotor (Refer Slide Time: 6:12) and to the stator we shall connect the 3 phase supply, so to the stator we give the 3 phase supply as shown here. So we have the A B and the C phases which are connected to the a b and c phase of the stator terminals. So this is the stator and the blue inner salient pole is the rotor.

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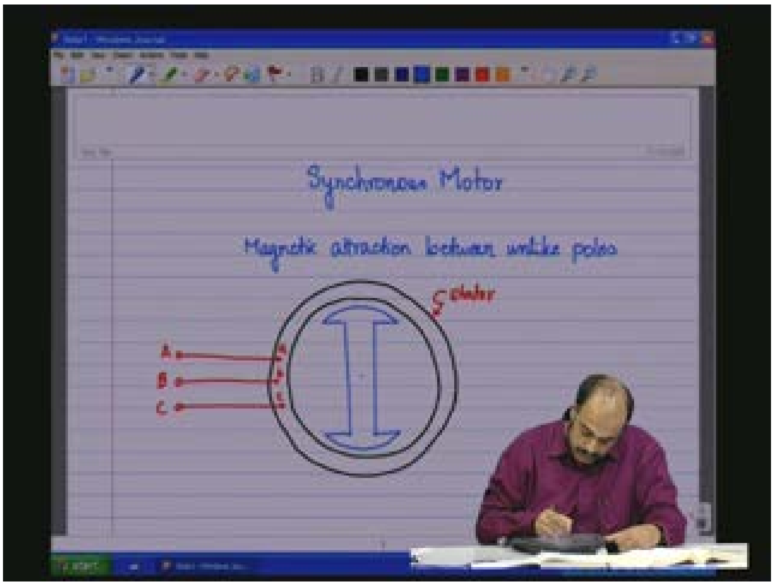

So let us say for the moment that we have some way energized this rotor and this rotor is a magnetic rotor that is it is a magnetic rotor which has a north pole and a south pole. So the rotor is a magnetic rotor, it is a magnet which has two poles north and south.

Now, the moment we give the 3 phase AC supply to the stator and the stator coils are wound 120 degrees mechanically spaced apart in space then what should we get we should get a rotating magnetic field just like in the case of the induction motor. So we are giving 3 phase supply to three coils of the stator which are 120 degrees mechanically spaced with respect to each other. Now this is going to produce this is going to produce a magnetic field and I will put that one as an imaginary magnetic field in the shape of a dumbbell as shown here.

So an imaginary magnetic field is produced. Let us say we have this which is rotating and we have the dumbbell which is the imaginary magnetic field which is rotating at what speed it is rotating at speed n s which is given by 120 f stator by P the number of poles per phase same exactly same as in the case of induction motor. What is different is the rotor the rotor is a magnet which has north and south poles. So therefore at a given instant let us say this portion is south, this portion is north. Let us say the field which is rotating due to the excitation of the stator is having a north and the south pole like that. The rotor is also a magnet it has its north and south poles so the north pole is getting attracted to the south pole of the rotating magnetic field and the south pole is going to get attracted to the north pole of the rotating magnetic field.

Now, as the dumbbell that is the stator generated magnetic field is rotating by magnetic attraction it is also going to pull the rotor poles along with that and as a consequence the rotor is also going to rotate along with the stator magnetic field. So, as the stator magnetic field is rotating at speed n s and as the rotor magnets are also rotating along with it the speed of the rotor is also going to be n s. So therefore the rotor rotates in synchronism with the rotating stator magnetic field. So this is basically the basic concept of the principle by which the synchronous motor operates.

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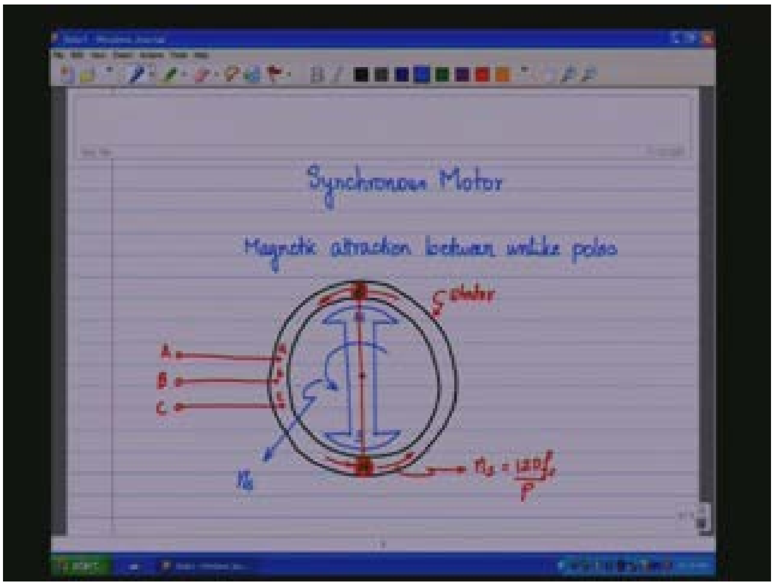

So now the question is we know how to generate the rotating magnetic field. That is in the stator we have the stator like this (Refer Slide Time: 11:38) so let me represent this stator as this ring of two rings of concentric circles hopefully concentric circles and we have the rotor, let us still continue this salient pole type of rotor, it gives the concept very nicely. so this is the rotor rotating about the center.

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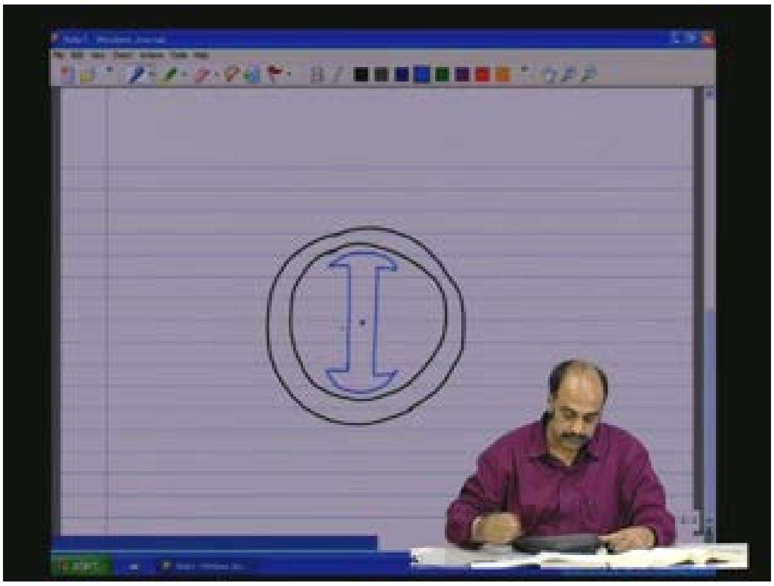

Now as far as the stator is concerned we provide the 3 phase AC source the a b and c from a 3 phase AC source or 3 phase AC mains. So moment you provide such a 3 phase AC source current flows through the stator coils which are spaced 120 degrees mechanically apart with respect to each other and a rotating magnetic field of speed n s is equal to 120 f by P is produced.

Now what remains is that the rotor should be a magnet also. So how do we make it make it a magnet? So, that is by the principle of electromagnetic you wind coils on the rotor let us say. So let us say the rotor is wound with with these coils as shown here and let me bring those coils out. Now here we supply a DC voltage. So if I supply a DC voltage there is going to be a current I that flows and we will call that one as I field; a current I field or I f flows through the coils as shown and this is going to result in a field direction like this which is equivalent to saying that this is north and south pole. So this for this particular rotor this north and south poles are fixed because the voltage here is a DC voltage.

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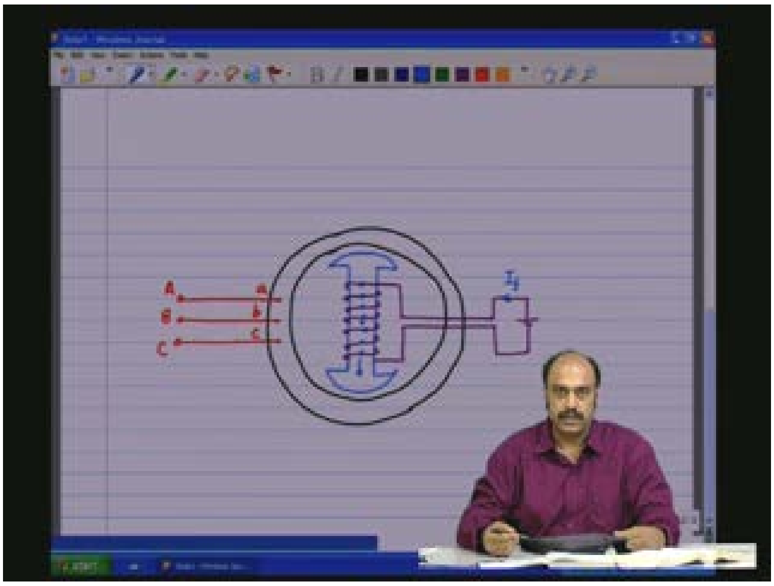

Now the rotor is rotating how do we get this DC voltage to inside the rotor. So what we need to do is generate a DC voltage. So this is normally generated by a very small DC generator which is mounted on to the shaft of the rotor. So let us place a small DC generator. So this is a DC generator (Refer Slide Time: 15:14), it has brushes and then that is connected to the shaft of the rotor mounted on to the shaft of the same rotor. So, as the rotor is rotating the shaft of the the shaft of the DC generator also is rotating; as this rotates this is also going to rotate and this is going to produce a voltage E by the DC generator action: Faraday's laws of electromagnetism electromagnetics and this will take is going to drive a field current through the coils of the rotor which is going to magnetize the rotor the salient pole rotor. This is generally how the magnetization of the rotor is done.

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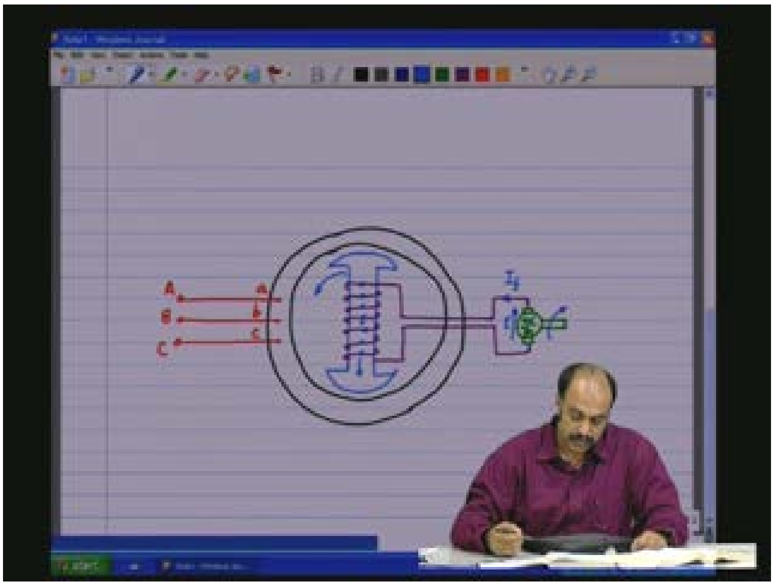

Now there is one question that will arise now. At the time of starting the rotor is not moving and if the rotor is not moving the shaft of the DC generator is not moving, so if the shaft of the DC generator is not moving there is no E and therefore there is no I f which is not going to energize the rotor and produce the rotor fields; how will the synchronous motor start in such a case?

So what is done is to have a squirrel cage on the rotor that is let us have a squirrel cage on the rotor as shown here, let us have the squirrel cage on the rotor as shown here and this squirrel cage rotor can start by itself. The moment we switch on the power this whole machine is going to start as an induction motor and the rotor is going to come as close to the synchronous speed as possible just within the slip distance which means the shaft of the DC generator which is connected to the rotor is now rotating at almost the synchronous speed just by a distance of slip distance that is it is lesser by an amount equivalent to the slip. Now this generates a voltage E.

Now, once the once the induction once the machine has picked up like an induction motor and comes almost close to its full speed the excitation of the DC generator is cut in by a centrifugal switch let us say so that gets cut in and that is going to allow the flow of current into the coils of the rotor and that will magnetize the rotor, once the rotor gets magnetized then the rotor locks on to the rotating magnetic field locks on to the rotating magnetic field which is rotating at synchronous synchronism. So you have the rotating magnetic field with a north and a south and the moment the generator excitation the generated induced voltage has built up the current the excitation current flows through the rotor coils this starts having the magnetic property the rotor starts having the magnetic property, it will have its north and south pole and that will lock on to the rotating magnetic field and then always rotates in synchronism from there onwards. So that is how the synchronous motor is also started.

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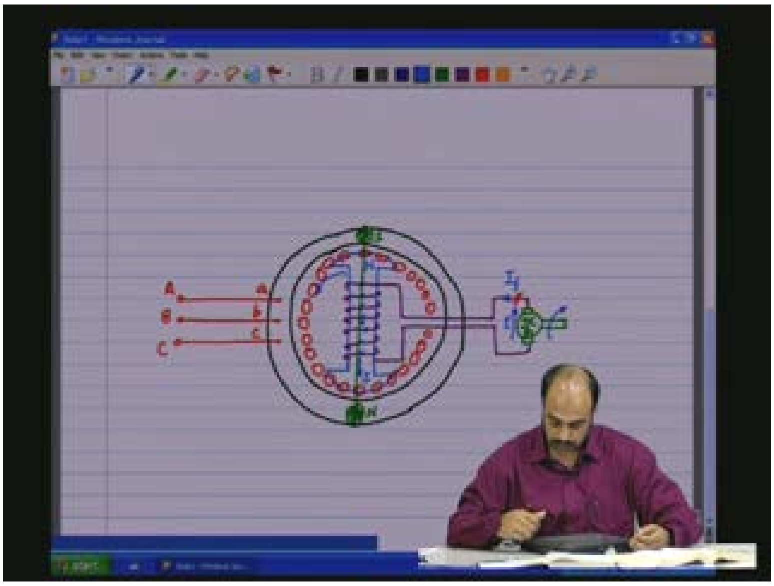

So if you look at the entire synchronous machine it has a shaft. So let us show show the rotor shaft like that. So this is the rotor shaft (Refer Slide Time: 20:12). So, on the rotor shaft on the shaft let us have the rotor, let us have the rotor like that and we have the stator which is shown in green with the cross section and on the shaft we have a small DC generator DC generator. The electrical output of this is given to the windings of the rotor; as both are rotating in the same shaft there is no relative movement between the two and the stator is provided with a 3 phase AC source a b c. So this is a synchronous machine is the synchronous machine. So the rotor also has squirrel cage bar and they are used for starting of the synchronous motor, bring it close to synchronism, and then the DC generator provides the excitation which magnetizes the rotor and makes the rotor to lock on to the rotating magnetic field, from there on the rotor rotates in synchronism with the rotating magnetic field.

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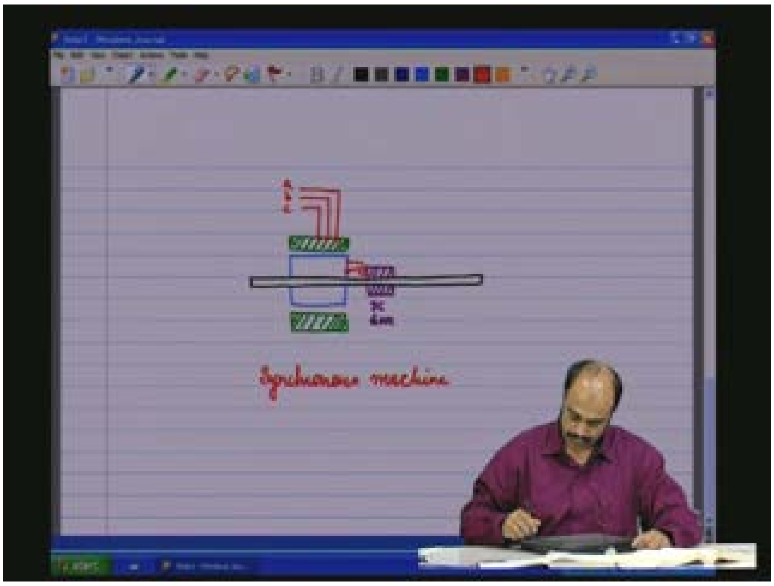

So now the rotation of the rotor is in synchronism in rotating magnetic field and the rotating magnetic field is given by, as we saw in the case of induction motor, 120 f s by p the number of poles per phase. Or you could say 60 f s by P p the number of pole pairs. Or you could say it is omega s by P p the number of pole pairs or which is equal to 2 omega s by P where P is the number of poles okay. So this is number of poles per phase. P p is number of pole pairs north and south together per phase. So this is this value will always be number of poles divided by 2; P p is always number of poles divided by 2 okay. So this is the speed equation for the synchronous machine the synchronous motor.

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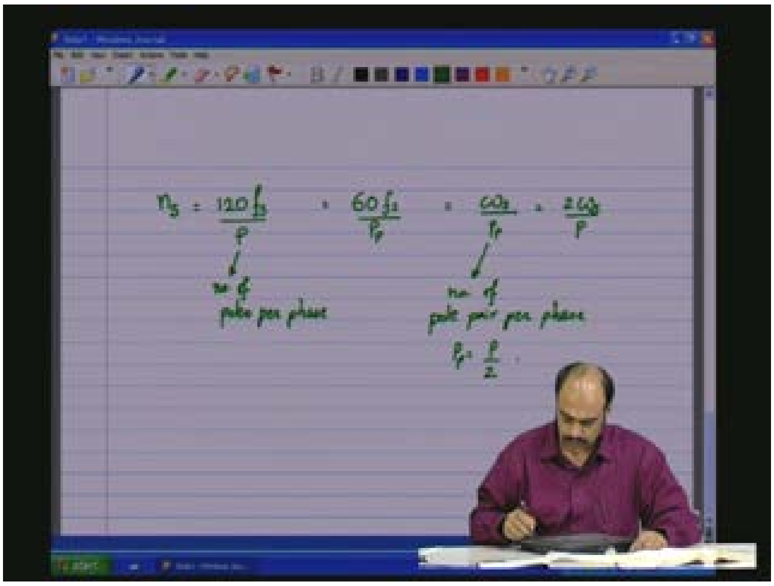

So now let us come to another important point which is which the back emf. So let us say we have the AC source represented as a square block and then we have the synchronous motor with the shaft rotating at synchronous speed. Now this synchronous motor for the rotor is getting an excitation from an excitation coil which is provided by the output of a DC generator like this. So this DC generator is going to provide an output which is E. Now this E is going to allow E g we will say is going to is going to provide the field excitation E f. This is the DC engine.

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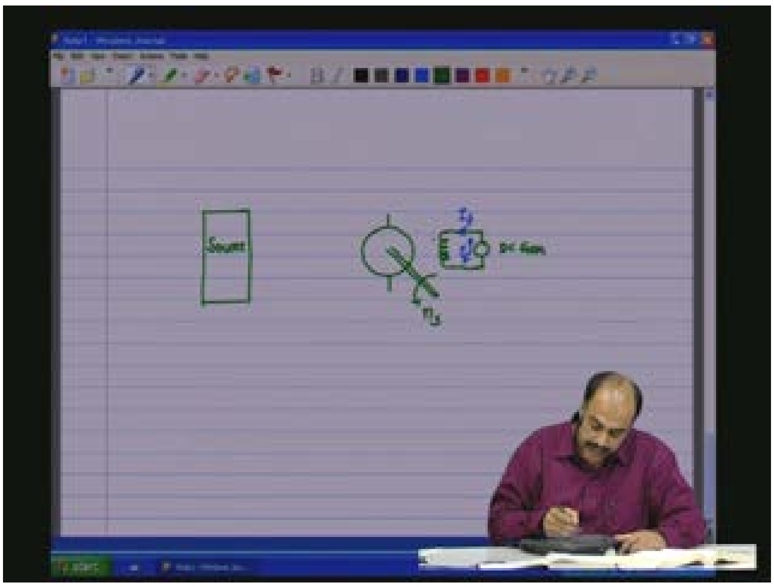

Now the I f is going to magnetize the rotor which is going to cause this to rotate and there will be a back emf like any generator action and that is E b. And between the source we are representing like a single phase equivalent; between the source and the motor there will be an equivalent reactance. Of course there will also be the resistance which is the winding resistance of the stator coils. However, the reactance X is so large compared to the winding resistance, in this case we can neglect the winding resistance for the purpose of the discussion because we want to get the concepts right. So we will call these reactants as X s and that is called the synchronous reactance the synchronous reactance.

At this point you should note that as the shaft is rotating at n s n s is constant once f s is fixed because P is fixed for the machine so n s the synchronous machine is constant which means the generator shaft is rotating at constant speed which means the induced emf E f the field emf is constant therefore I f can be a constant value there.

Now the source voltage we shall call it as E, the voltage which is generated as back emf is E b and there is a current and we will call that one as I x. This is the current I x which is flowing through the synchronous machine, that we will just call it as a current I, it does not make much difference there because that is the only current which is flowing to the stator, so E into I will be the apparent power of course. Now for this let us draw the phasor relationship or the phasor diagram.

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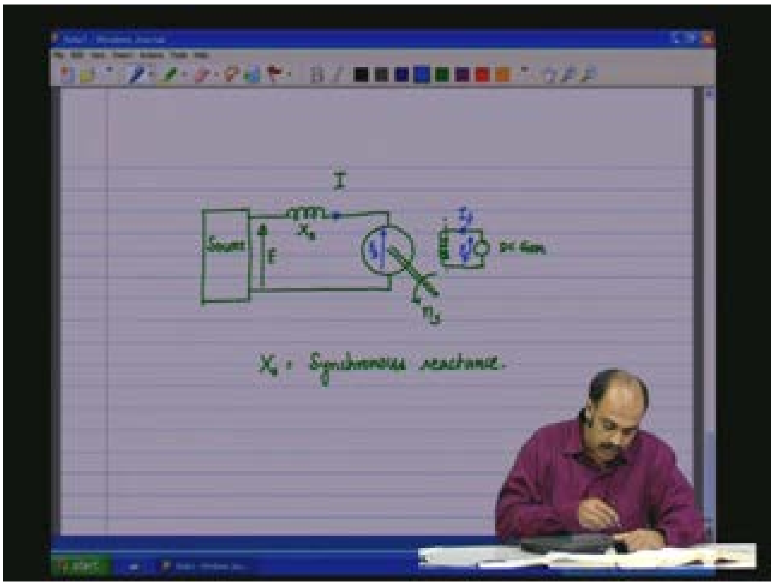

So let me first copy this to the next page. So we have a copy of that. Let us make some more space here and let us now take E as the reference, E is the E is the supply voltage which is applied. Now the back emf there is a reactance coming into the picture so the back emf will also have the same amplitude of E same effective value of E because there is not going to be any power dissipated in X s but E b will be delayed, it will lag the supply voltage E.

Now of course E b E b is going to be proportional to the speed n s of the shaft and the flux phi inside. Now the speed n s is actually the rotor speed and if I if I represent the red arrow as the stator and the blue dumbbell as the rotor, so if the stator field is rotating the rotor also rotates and both are rotating in synchronism therefore E b will be along E because E b is going to rotate as E is our source and E b will also be along the same value as E. So we will put value E across this under the condition when when there is no current.

So if I is equal to 0 if I is equal to 0 then there is no drop across this therefore E and E b will be along the same line will be along the same line and exactly the same point which I am going to show as this. So this would be E comma E b when I is equal to 0 that is no load.

Now let us make E b small, let us make E b small smaller than E. how do we make E b smaller than E? We have it as proportional to n s, n s cannot be touched because n s is fixed, the only thing that we can do is decrease phi. So, E b can be decreased by decreasing the flux phi which means by decreasing the current. This is obtained by decreasing I f. So what will happen? Under such condition we have E and E b is going to be lesser than E.

And now what is the drop across the X s synchronous reactance?
It is E minus E b. So E minus E b E minus E b is going to be E minus E b this is across the synchronous reactance. Now as it is reactance inductive the current has to lag the voltage across the reactance by 90 degrees and therefore I has to be like that, this is I by 90 degrees. And now let us say if E b is increased beyond E by increasing phi which is obtained by increasing I f what do we obtain? We now obtain a situation...............

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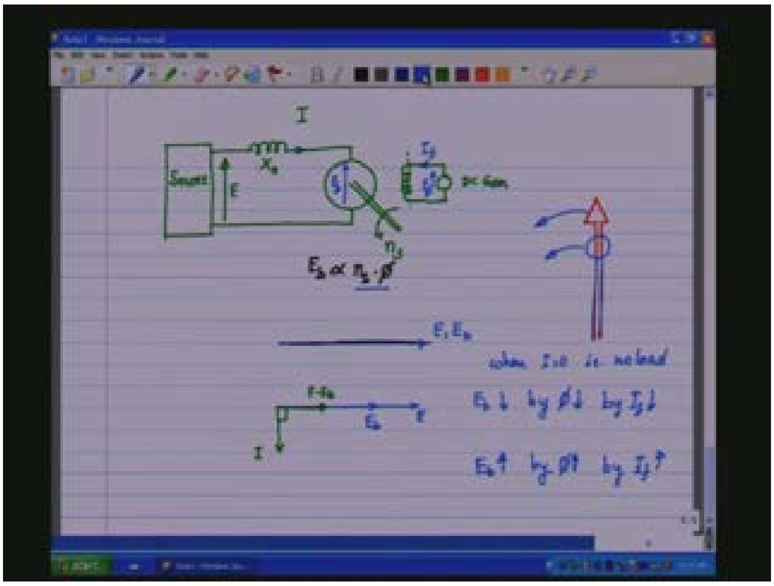

We will go to the next page. We have E, E b is now higher than E and what is the voltage across the synchronous reactance E minus E b? E minus E b is going to be in the other direction like that this is going to be E minus E b.

Now the voltage across the synchronous reactance is going to lead the current by 90 degrees or current has to lag this voltage by 90 degrees and that will be the direction of I, this is 90 degrees.

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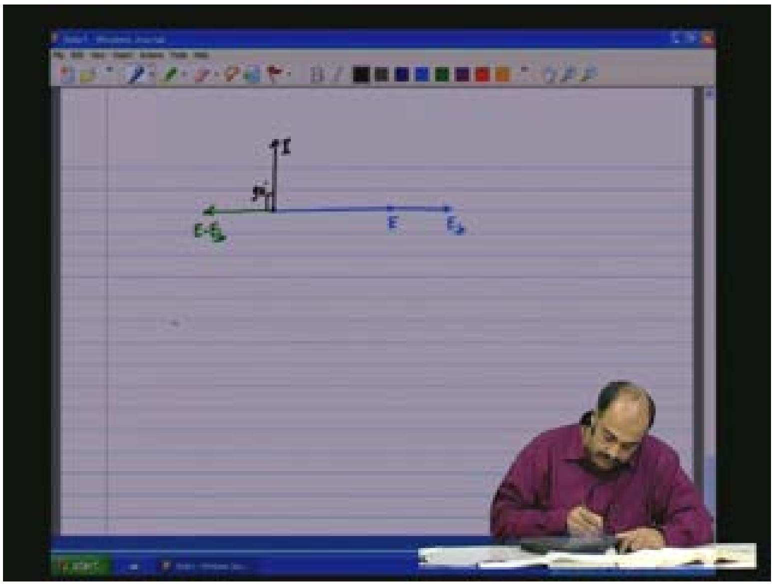

So we have now three nice situations. First situation is we have E and E b, current is 0 I this is no load. Second situation we have E and E b is lesser and what is happening to the current, current is lagging by 90 degrees and we have the third situation where we have E and E b is more than E and as a result E minus E b is negative and the current is given like this. So, with respect to E that is the input voltage.......... so if you compare the input voltage and the input currents input voltage and input current you see that here the input current is lagging the input voltage.

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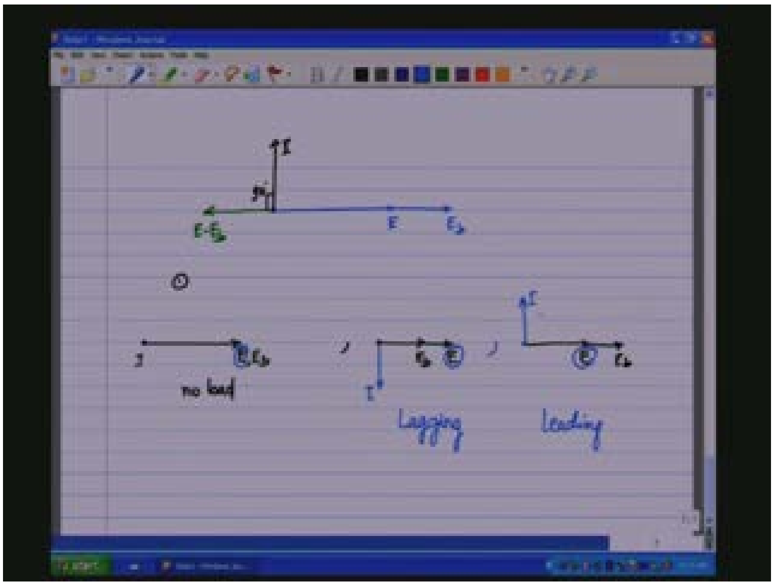

The input current is leading the input voltage. By adjusting the value of E b anywhere in between these two points we can get different lead and lag angles of the input current. This means that we can adjust the power factor of the machine by adjusting E b or by adjusting the field excitation I f, so this is a very powerful feature which makes the synchronous motor to compensate for the power factor lagging power factors of other loads and that is why the synchronous motor is also called a synchronous capacitor where in industrial loads where in large industrial loads with lagging power factor as synchronous motor is put with just no load and it is connected to the mains and the excitation of the synchronous motor is so controlled such that the E b is at such a position that it compensates for the lagging power factor of the load and the overall the AC supply can be made to see just unity power factor by means of this synchronous motor. So the synchronous motor can act like a capacitor which provides the reactive energy to the load that is the downstream load which is lagging in nature.

Therefore, the mains is presented with as though a unity power factor. Therefore, the synchronous motor is also called a synchronous capacitor if it is used in such applications.

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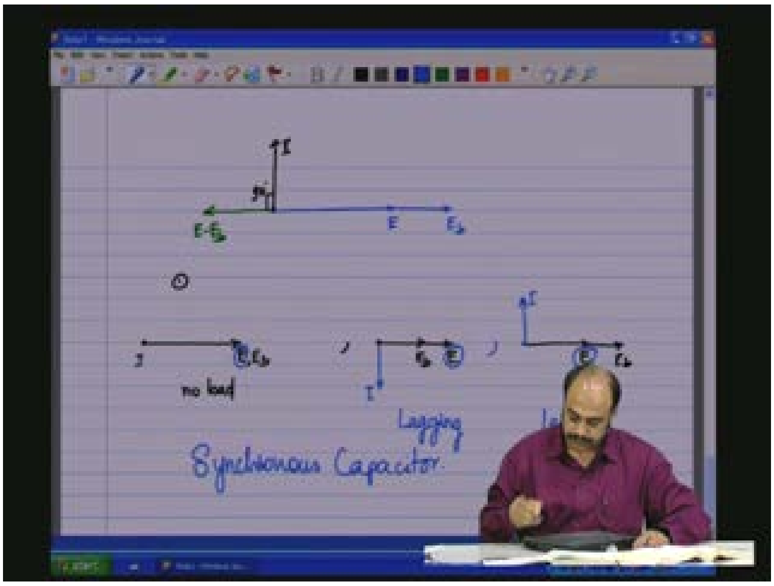

When you load the synchronous machine and if I take this to be the stator rotating magnetic field of the stator and if we take this as the rotor (Refer Slide Time: 37:22) this is the rotor, under no load conditions both are together and then they are going to rotate in synchronism. But when you load the rotor will lag the stator field by some amount by an angle called delta called the load angle, this is called the load angle or torque angle. However, both are still going to rotating at synchronism so this is under load, this is under no load; this is the rotor blue is the rotor with the stator magnetic field stator rotating magnetic field.

So, under this condition as the let us say the stator conductor has a reference; this is the stator conductor stator conductor. the stator rotating magnetic field comes and cuts first and then after sometime the rotor the rotor field that is it also has its north and south pole is going and coming and cutting the stator conductor after a lag and therefore the back emf will peak after the source voltage E has peak and therefore there will be a lag electrical lag between the source voltage E and the back emf E b induced and therefore under such condition under load if E were the source voltage the same amplitude the back emf will also be of the same amplitude but it will lag by some angle which is proportional to delta or the load angle equivalent electrical angle of the load.

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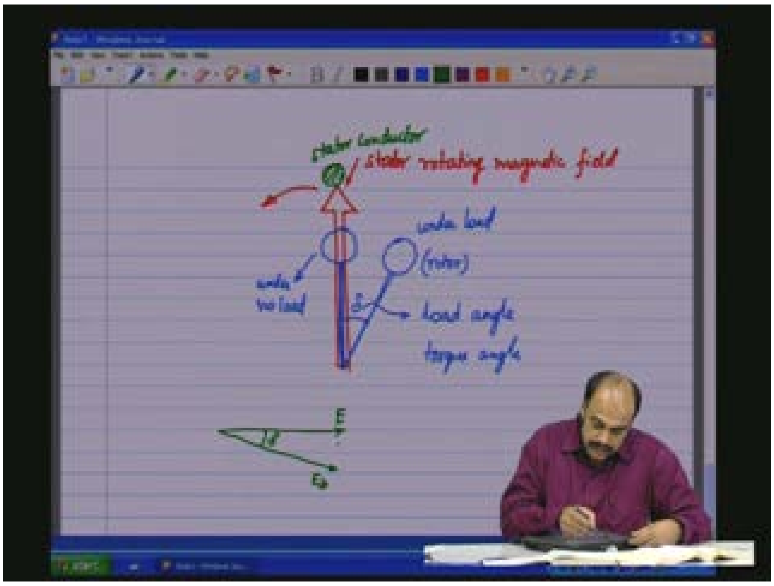

Now what is this?

This is E minus E b, this is the voltage across the synchronous reactance and that I am writing it parallel here this is E minus E b and the current is going to be just directly orthogonal with respect to.......... so this is I which is 90 degrees lagging E minus E b and this is going to be theta is going to be the power factor angle P f or the power factor angle theta. So we see that major portion of the active power goes on to the shaft and the power factor angle can be controlled by controlling the amplitude of E b here.

So, by controlling the amplitude of E b so let us say if we make E b more that is if this is made like that (Refer Slide Time: 40:53) so you will have E minus E b like that which means E minus E b is like that and you will you can have a current just 90 degrees so the current can either lead or lag depending upon the field excitation, this is proportional to I f. So as you may as you control I f you can make the input current lead or lag, so that is one of the major advantages of the synchronous motor. So the synchronous generator acts exactly like the synchronous motor, only the power is taken from mechanical side and then the output is taken from the electrical side.

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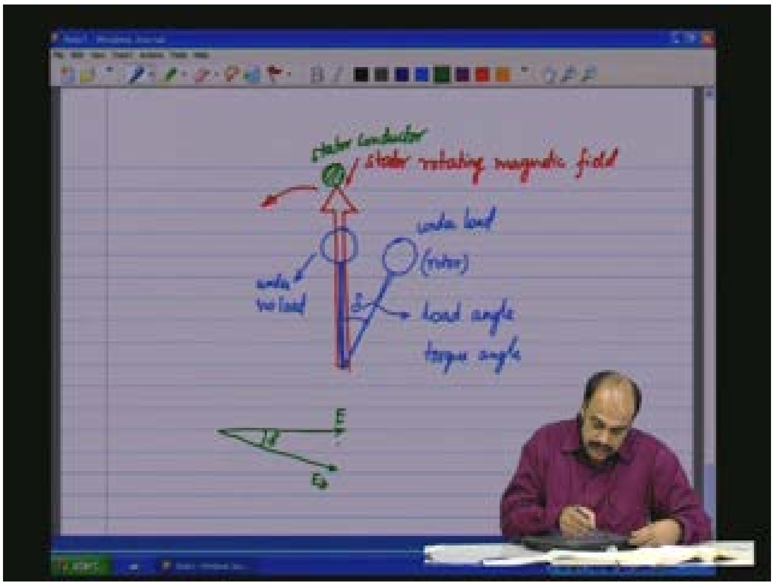

So a prime mover will be moving the motor on the mechanical side in the case of the synchronous generator. In the case of the synchronous generator we have we have the synchronous motor and let us say we have the shaft and that is connected to a prime mover. So, when the prime mover moves there is a of course on the DC gen so DC gen is going to give the excitation for the rotor coils, so this is I f, let me make some space here, so the DC generator is going to produce I f which is going to energize the rotor inside within and that is the rotor so the rotor becomes permanent magnets and that is rotating and because it is rotating it is inducing the voltage on the stator on the stator coils by the Faraday’s principle with nd phi by dt and that is being used to supply the electrical loads on the stator side the 3 phase electrical loads, under such conditions this is called the alternator and the frequency of the wave shape here is always n s is always n s is equal to 120 f s by P and therefore f s is equal to P into n s by 120. So the frequency of the supply here is always equal to f s which is P n by 120. Otherwise all other concepts of the generator synchronous generator is similar to the synchronous motor and here also by excitation control you can control the amount of active power that is being put on to the load.

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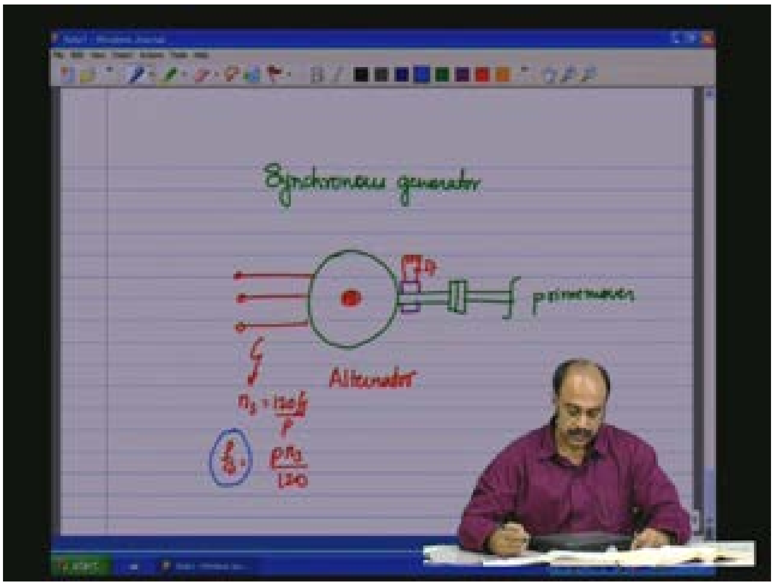

So with this we shall conclude the synchronous machine. We just had very brief insight into the synchronous machine. But along the lines of the induction motor or the induction machine one could also develop the equivalent circuit and try to modulate in greater detail. However, for the syllabus of the Basic Electrical Technology the scope for the synchronous generator is just enough if you get the basic concepts right.

We shall now focus our attention on some of the projects that we can do with what we have learnt till now. What have we learnt till now is the basics of electrical technology and various equipments which are based on the basics. So if you recall right from the beginning we started the discussion on the sources, the various components and then followed it up by modeling issues and then the power factor issue, the phasor diagrams and then finally we started discussing on the equipments and the machines.

So we started with the a discussion on equipments with a DC machine, the DC generator and the DC motor and followed it up with the transformer discussion on the transformer, and then 3 phase transformers following it up with the most popular rotating machine which is the induction machine and it being acting as a generator and then the synchronous machine where today we got a brief glimpse of it.

So let us see or let us list down and discuss what we can do as projects in the under area in the under graduate class with this particular background. So if I recall and list down some of the projects that we could think of we could think of related to these major categories: one is the DC machines and second is the transformers and third is the induction machine. So, when we can think of lot of these projects on these directions and of course the fourth one is a simple project on a synchronous synchronous machine.

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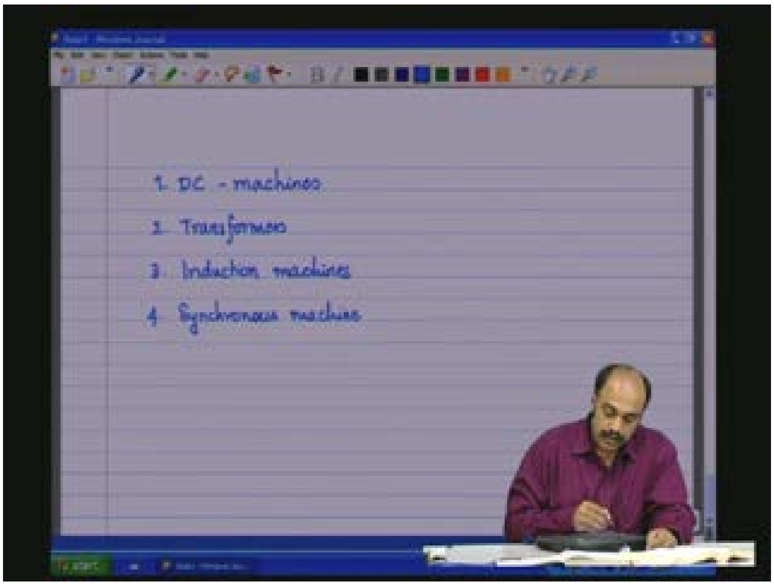

Now if we take the DC machine itself one of the important interesting projects would be speed control of DC motor. Now the speed control of the DC motor can have various applications like it can also be fitted on to a small two wheeler and used as torque control used with torque control for let us say driving a two wheeler two wheeler vehicle.

Then in the case of the transformer we can have a nice interesting application that is we take single phase transformers, generate two phase sources from 3 phase input source and drive a single phase motor single phase induction motor or an AC motor that would be an interesting application.

Now in the case of an induction machine one of the most popular applications would of course be a simple stator voltage speed control. You can have a v by f speed control and also more advanced control techniques like the vector control and things like that one which we need not cover at this point of time because it would be on the scope. And as far as the synchronous machine is concerned a very nice and simple experiment that one could do is a power factor improvement by excitation control of the synchronous motor such that it acts like a synchronous capacitor okay. So these are some of the very interesting examples example projects that one could do as part of their undergraduate study or undergraduate curriculum.

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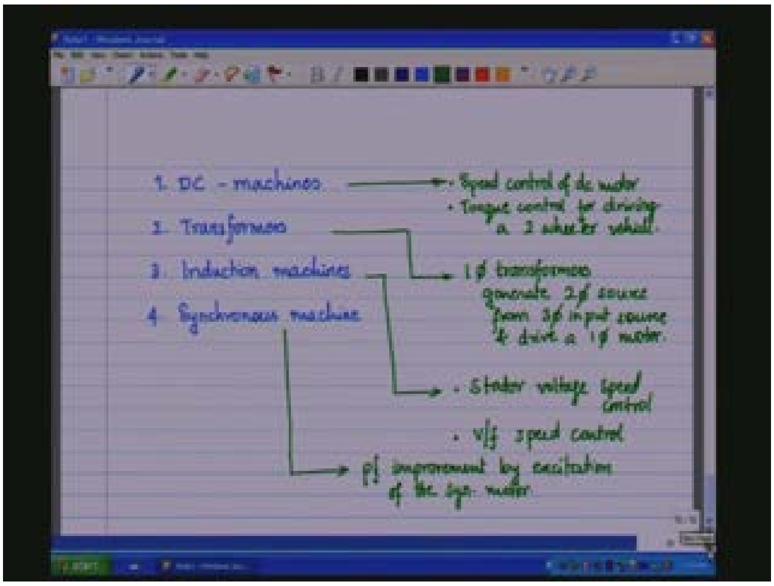

So let us see what is speed control of the DC motor. So when we take up the speed control of DC motor speed control of DC motor I will also include speed and torque control of the DC motor here. We have the DC machine, it has the shaft connected to the load so we have the brushes here and the brushes brought out as electrical terminals available here.

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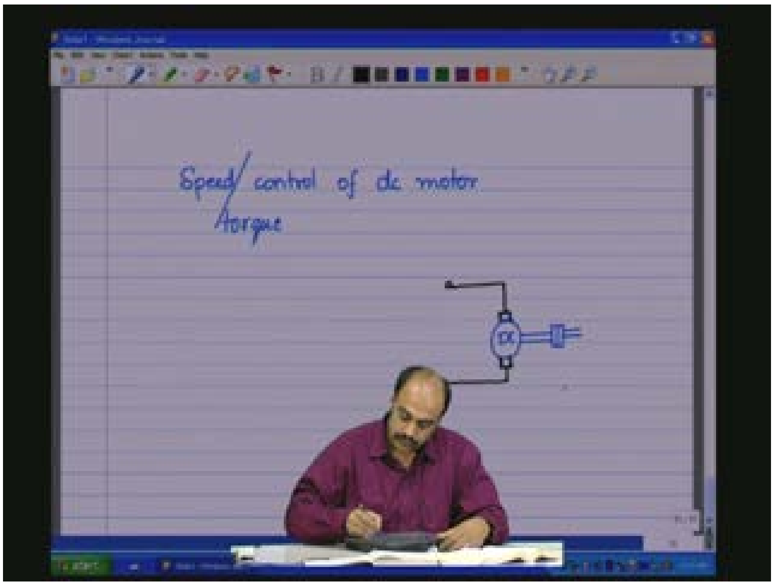

So we know that the speed here can be controlled by adjusting the torque of course. Now the torque here on the mechanical side is proportional to i a that is on the electrical side; the torque therefore is proportional to the flow on the electrical side and we have the back emf here E b which is of course proportional to the speed omega on the mechanical side. So, if we control i a we can control the torque and for a given load the speed is going to change depending upon the amount of torque that you are going to produce and this means that we need to have a variable DC source at the input.

So if you vary this source here i a is going to vary which is going to vary the torque which is going to vary the speed therefore E b is going to....... now how do we produce a variable source? So that is produced by having a DC to DC converter which is having pulse width modulation pulse width modulation and that is going to produce a variable DC source which can be connected across the motor terminals.

The voltage here can be adjusted depending upon the torque that you will need. So if we have let us say a reference torque reference torque let us say plus and minus compare it with the feedback torque compare it with with torque fed back and that is obtained as a function of i a is it not? A torque feedback is proportional to i a. So, if you sense i a process it electronically and bring it back and that would be when you compare a plus and minus you get an error E and that error is passed through a controller let us say a PI controller and that would be used for producing a pulse width modulation.

So, as the as the current here increases beyond the reference torque you have the torque applied more than the reference torque then the error is negative the pulse width modulation reduces, reduces the voltage, reduces the current so that would be the torque control. Over and above that we can also have a speed control by measuring the speed of the DC machine by a (ta.......54:35) or the voltage across the brushes which gives you the back emf and if you have a speed reference let us say n ref and the speed feedback which is proportional to actually E b which is measured which can be measured again you compare and the error is passed through another PI control and that output of the PI control becomes the torque reference and now that becomes a speed control of the induction motor.

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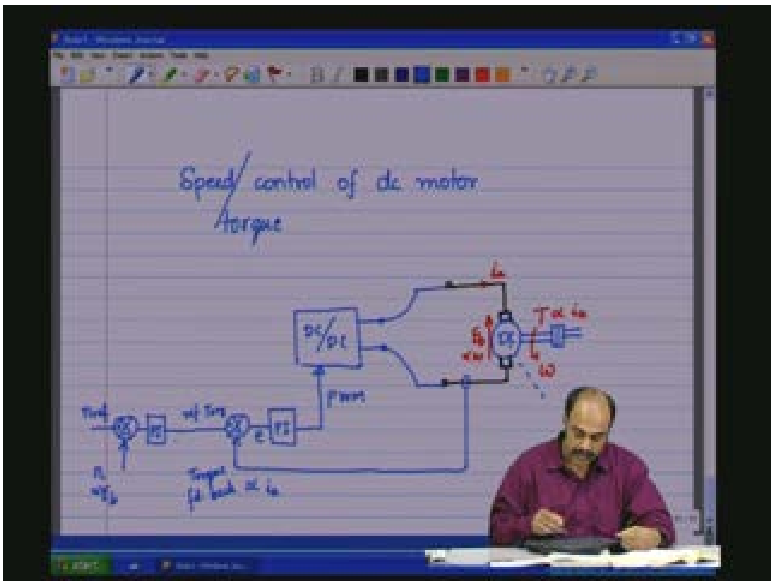

So you have the inner torque control loop which is faster and the outer speed control loop which is slightly lower, this would be an interesting be your undergraduate project.

The next one as i was saying you could place the transformers a single phase transformer that is 3 phase to 2 phase conversion. So we have a b c, we have the a phase connected to a single phase transformer, we have the b phase connected to another transformer, the c phase is brought out, let us say we have the center tab then we take the center tab, this is one output and then across here we take another output with proper turns ratio 0.86 times as we discussed in the class.

Now these two let us say E alpha and E beta are orthogonal that is you will have E alpha and E beta like that, E alpha and E beta and this can be applied to a single phase motor single phase induction motor with the windings the orthogonal windings brought out and it can be made to run a single phase induction motor like that; that would be another interesting application.

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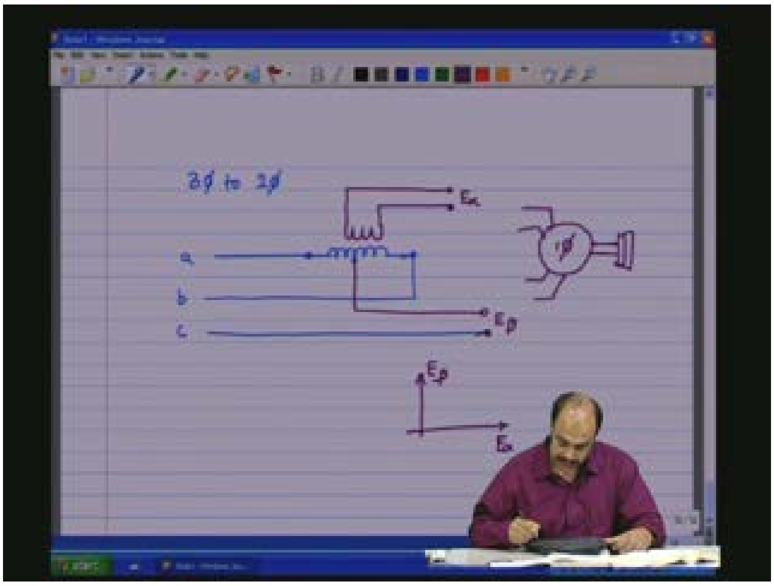

A third application would be an induction motor an induction motor is operated as a generator sorry the induction motor is operated as a generator so let us have the prime mover on this side coupled to the prime mover okay so you have the flow of energy on this side and then we have the 3 phase output power, let us have the delta connected capacitance bank as shown here which will supply the reactive energy to maintain the field and let this go to a 3 phase load as shown.

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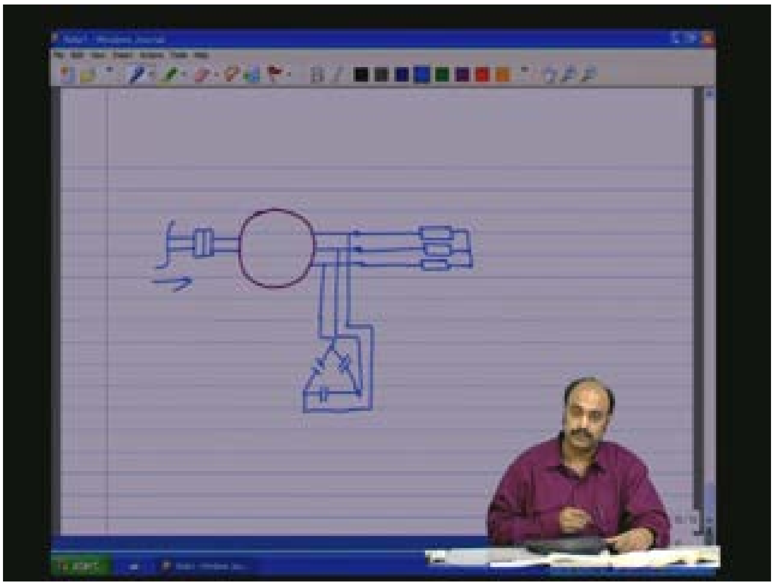

So, driving the induction motor with respect to a prime mover you can make you can supply a 3 phase load like a simple in the case of a simple house hold community lighting system where the loads are properly distributed to get a balanced load system. this is an induction motor.

And then we have discussed the the speed control of the induction motor control of induction motor. So one can use auto transformers and auto transformers is nothing like the transformer, you had just the transformer primary and then you tap at various points with a tap which is connected to a rotary arm so that you can tap along the various points of the windings with the primary and get any voltage which is which can be taken out of that one. And using the auto transformer the stator of the induction motor....... using the 3 phase auto transformer let us say you have something like that, you have something like that and you have something like this all these are connected like that and this is........ because of these are the windings (Refer Slide Time: 59:08) and you can tap equidistance from all the things and give it to the induction motor and you can do stator voltage current.

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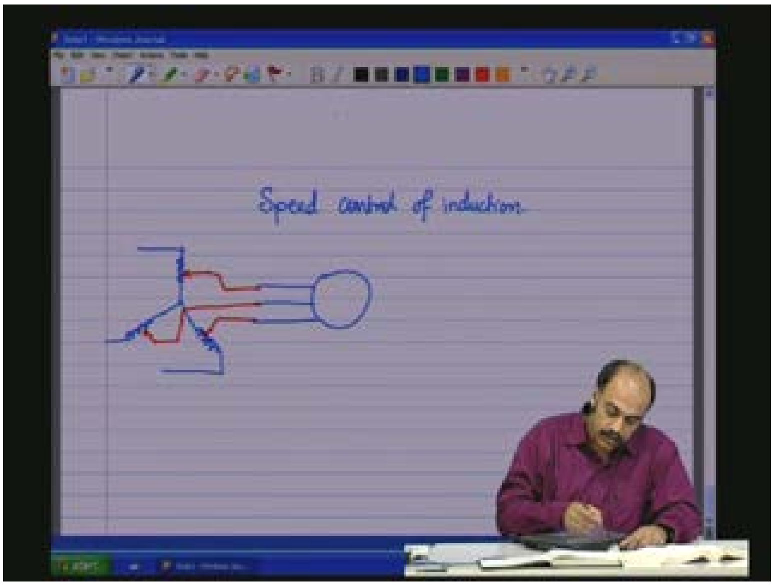

One could also do a (........59:28) control by introducing some electronics. That is you have an induction motor, a 3 phase induction motor is driven not directly from the source but a 3 phase inverter, this is an inverter which is getting DC........ from the capacitance bus you have a rectifier 3 phase rectifier and a 3 phase source. So, a 3 phase AC source gets rectifed at DC, passes through an inverter and then you have an induction motor and to this you have a pulse width modulator where you can modulate both the amplitude and the frequency that is applied to motor. This will this will see that you have variable E and variable f.

So, if we are able to vary E and f in proportion such that we keep E by f constant equal to a constant then the induction motor will be running in V by f mode whereby you can utilize the whole range speed range right from close to zero to up to base speed and beyond base speed with field weakening. So that would be the speed control of the induction motor.

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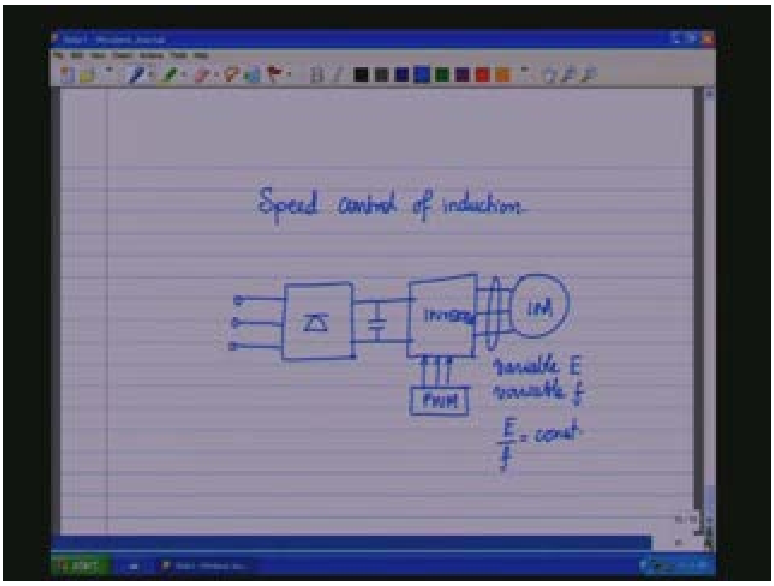

And finally the interesting project is with the synchronous motor where you have the where you have let us say variable resistance here and this is a synchronous motor synchronous motor and you have the field excitation for the motor with stator supplied here. So this would be E and what you have the back emf would be E b.

Now E b E b is proportional to I f. So, by controlling I f by controlling this resistance you can adjust the power factor between power factor sorry you can adjust the power factor angle between E and the input current I and keep adjusting I f such that E and I are in phase so that the main C is a unity power factor whatever may be the load across it. So this would another interesting application of the synchronous motor.

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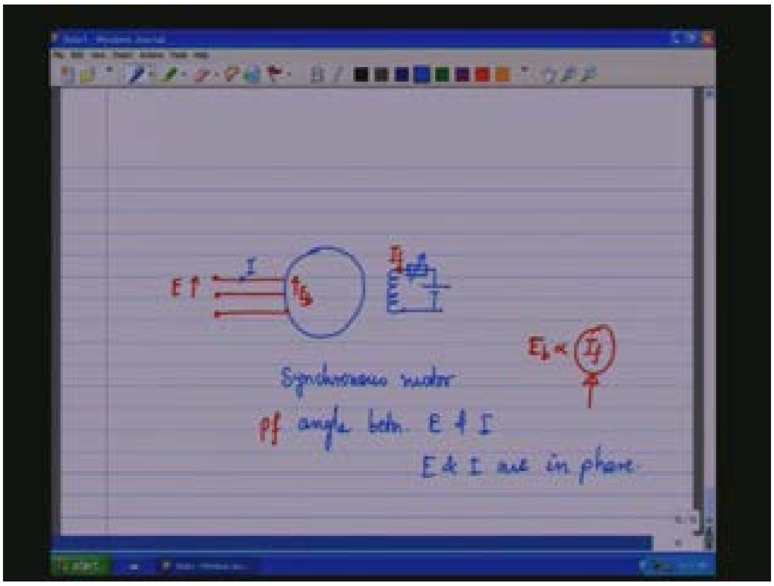

So with this let us conclude this session, thank you very much.