Basic Electrical Technology
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Lecture - 39
Induction Motor – 4

Hello everybody, in the last class we had discussed the induction motor and quite some detail and did somewhat examples also. We also saw how the equivalent circuit of the induction motor looks like. We saw that it was almost very similar to the equivalent circuit of the transformer that we had discussed much earlier in the course.

Today let us look at few of the applications by induction motor. One is the induction generator that we looked at, the other is the speed control of the induction motors because the induction motor as such if it is applied from the mains the frequency is 50 hertz so which means that the synchronous frequency is fixed if the number of poles are fixed in the case of the induction motor. So, if the synchronous frequency is fixed then the shaft of the induction motor is going to be just only less than the is going to be less from the synchronous frequency only by the amount of slip. So, more or less the induction motor is a reasonably constant speed motor. If you want to have a variable speed what is it that we need to do because many of the applications require variable speed, so how do we control the speed of the induction motor that is the second application that we need to see. And then after that we move into the another topic of machines and that is the synchronous machines. So we look into we just get try to get a glimpse of the synchronous motor and the synchronous generator that is the alternator before we close the topics on the basics of electrical technology.

So now today we shall start our discussion with the induction motor being operated as a generator induction generator. We saw in the previous section that the torque speed characteristic of the induction motor is something like that. We have the speed axis shaft speed, this is the shaft speed given as the x axis, torque as the y axis. So now this torque is the torque that we see from s equals 1 this is stationary standstill to this point s is equal to 0 which means speed-wise you will see that this is n m is equal to 0 n m is equal to n s at this point or the synchronous........ equal to n s this is the synchronous speed. So beyond that is the super synchronous speed and below this one is the negative speed so in the negative speed we also saw one of the examples that there is breaking. So here in this region we are having negative speed or in another words slip is greater than 1 and that is breaking zone. So in the breaking zone we are having slip greater than 1, this is the motoring zone. And then beyond this point that is beyond the synchronous speed point we have the super synchronous speed domain and that gives you the slip that is negative that is slip goes less than 0 that is s is less than 0 it goes negative which means that it is the generator mode. So this curve continues like that and has a mirror image replica of the motoring zone and this is the generate generating zone.

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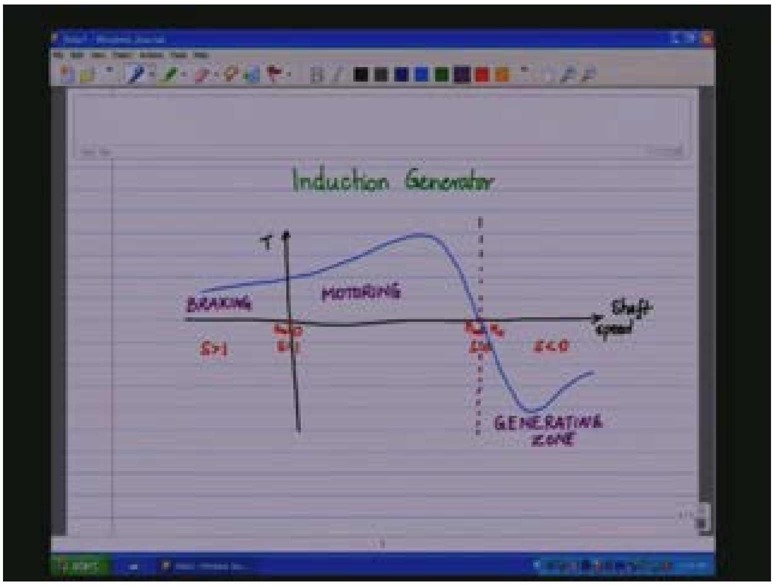

So here up to this operating point so if we take that this is the operating point for the motoring for the motoring let us say these are the operating points that we would like to choose on this portion of the curve and for the generating generator we would like to choose this portion of the operating pointso this is the operating point that we would like to choose for the generator; operating points for generating zone.

So now we will focus our attention on this portion of the torque speed curve because we want to see the application with respect to the way the induction motor can now be used as an alternate that is an alternating current generator that is an AC generator.

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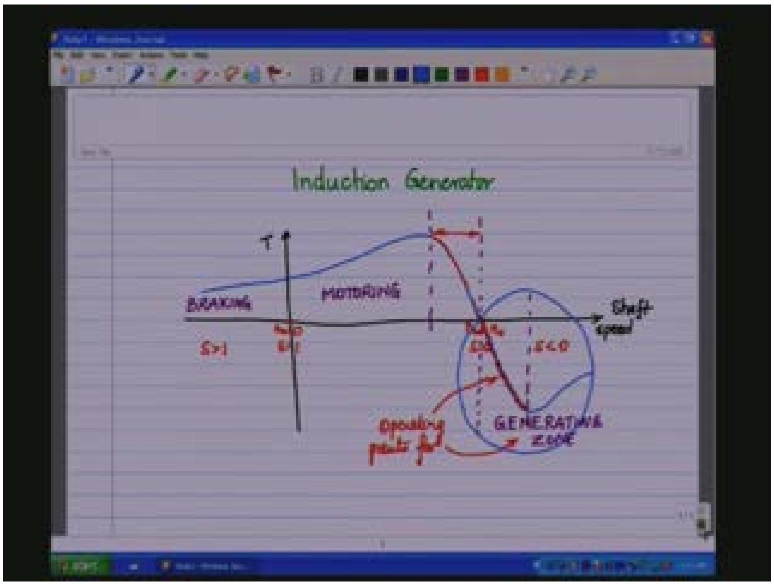

So the moment we say we want to use it as a generator the the power input power should be the mechanical power so the input power is the is a mechanical power which is driving the shaft of the induction motor and the shaft of the induction motor is connected of course to the rotor and the rotor is rotating in the magnetic field and that is going to induce the voltages on the stator side which is connected to the load or to an AC source thereby putting the active power into the source. So the way the energy flows would be in this fashion.

So let us have the shaft, this is the rotor, so let us call this as the rotor and above the rotor we have the stator so let us indicate the stator with green hashes, this is the cross section (Refer Slide Time: 9:09) so this is the stator. Now the rotor is like this with the shaft going in between. So this is the rotor and this is the shaft, it is connected to the rotor. Now this shaft is coupled mechanically to a prime mover and that prime mover can be anything and let us say we have connected it to an ICE engine ICE engine means internal combustion engine which of course takes power input from fuel like petrol let us say.

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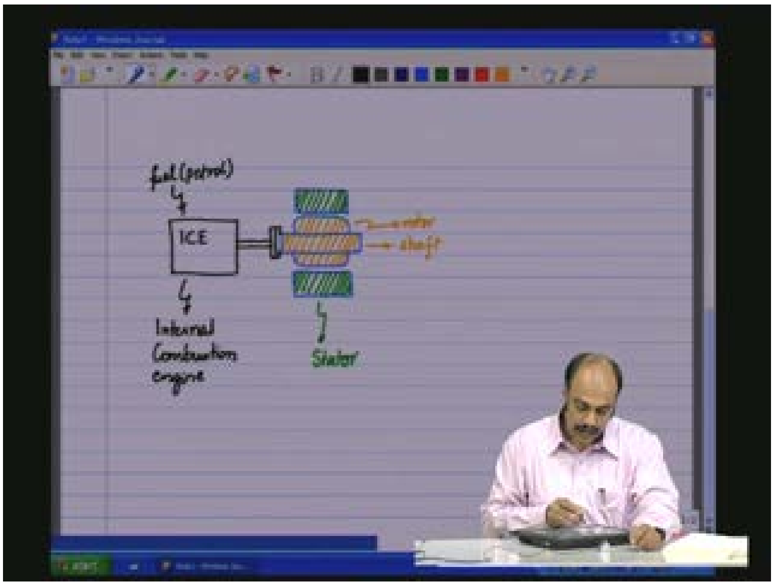

So now this is rotating, the engine is something similar to the ones that are used in automobiles and this is providing the mechanical input power which rotates the rotor and you have the 3 phase electrical outputs being taken out of the stator 3 phase electrical outputs being taken out of the stator. Now this stator can either be connected to the mains or the load whatever so this will get connected to the load. So this mechanical energy will flow into the rotor mechanical to magnetic and then magnetic again back to electrical so this is in the electrical domain. This is in the electrical domain the actual output, the input is the mechanical domain and the transformation is taking place from mechanical to electrical in the magnetic domain. So mechanical to magnetic, magnetic to electrical so that is how the power flows in the case of an induction generator.

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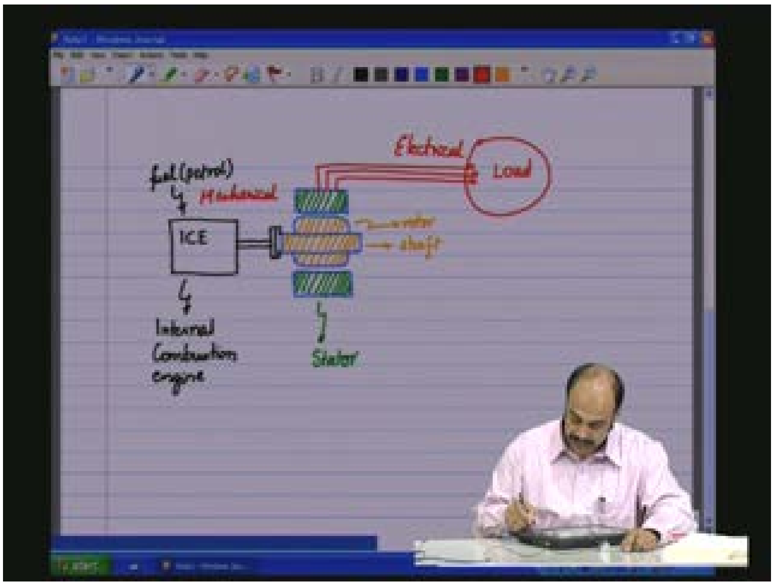

Now let us represent it schematically. We have the stator and the stator is connected to 3 phase sources and let us say that is the a b c phases okay so this is the stator. Now, inside we have the rotor and the rotor is connected to an external mechanical prime mover prime mover which is providing the torque and the speed for making the shaft rotate above synchronous speed and that the rotor the rotor is in the magnetic field and therefore that energy goes in the magnetic field comes from the magnetic to the stator and in the electrical field.

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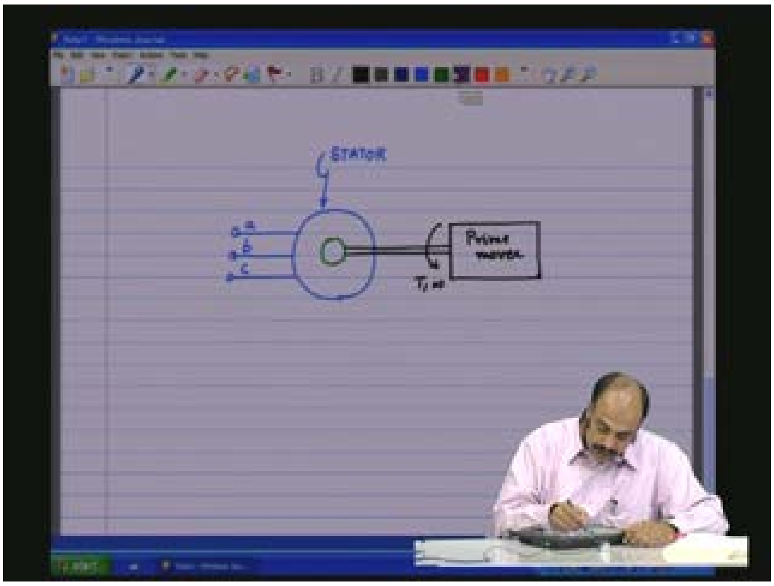

Now let us say the sources are connected to the 3 phase mains. So let us say you have 3 phase mains, this is the 3 phase source. So these are the feeder lines of the 3 phase source and we make the connection. So this is the a, b and c phases so let us say under the condition when this is omega m note that let us focus on omega m; let us say omega m is less than omega s, n m is less than n s. What is omega m? Omega m is the mechanical shaft speed, omega s is the synchronous speed of the rotating magnetic field within the induction machine and n m is in rpm, n m and n s are in rpm and omega m omega s is in radians per second.

So if the mechanical shaft speed is less than the synchronous speed it is in the motoring mode so the induction machine here is acting like a motor so it is drawing the active and the reactive power so we will call this one as this source which is giving both let us say P is the active power which is supplying the losses in the stator, is going to the rotor, the losses in the rotor going to the shaft and then to the load whatever it is.

There is also a reactive component and that reactive component is used for supplying the magnetizing energy to build up the flux in the induction machine to build up the rotating flux in the induction machine so you have the reactive power also coming in from the mains in this direction so it is going into the induction machine and the active part let us say the efficiency is one the active part goes here the active power.

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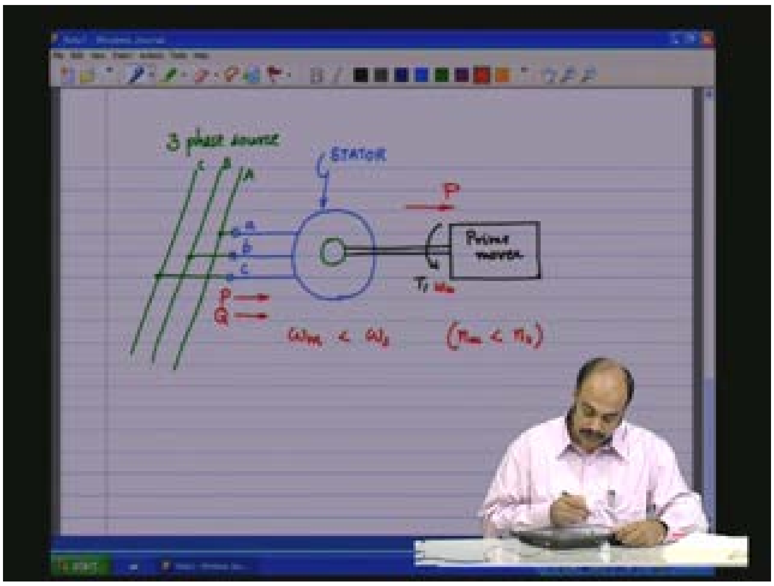

Now if we have omega m greater than omega s or n m is greater than n s then this is in generating more generate there is a generator whereas what was in red was a motor. So in this mode the power is the prime mover whatever or the load side the mechanical side is now actually giving the power the active power. So during this time we have a reversal of flow of the power and that is in this direction. so the power is flowing in this direction and that is the power which goes through the rotor the rotor losses, there will be some of the power which will be lost, there will be the stator losses where some power will get lost and ultimately there will be some the remaining power will get put into the source so here also you will see a reversal at this point (Refer Slide Time: 17:30) so we reverse this.

So we see that the active power is going from the mechanical side through the induction motor into the source. However, to generate the rotating flux we need the reactive power and the reactive power has to still come from the AC mains. So the reactive power Q still comes from the AC mains. So this is how it would look like in an induction generator, we still have the reactive power in the same direction.

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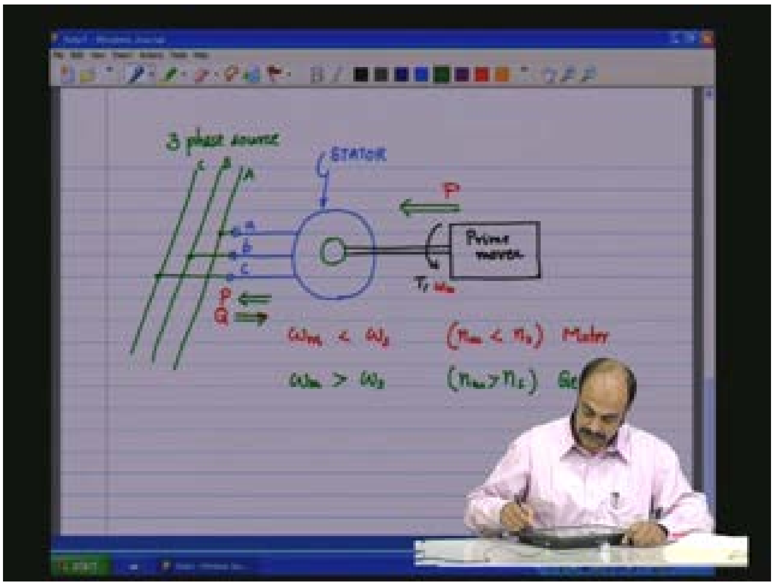

Now, instead of connecting it to a 3 phase source what happens if we connect this to a 3 phase load meaning let us.............. so we have and now we have the a, b and c we erase these things okay (Refer Slide Time: 19:05) so now we have a prime mover and this is now connected to let us say a star load. So, instead of a 3 phase source we are connecting the stator side to 3 phase resistive load as shown here which is going to take the active power. So the mechanical side when it starts rotating beyond the synchronous speed that is when it makes omega m greater than omega s then the mechanical power is flowing to the left, the input to the system the input power is flowing to the left and that is P, the active power which goes through the machine and then let us for the moment assume 100 percent efficiency the active power is coming to the 3 phase load.

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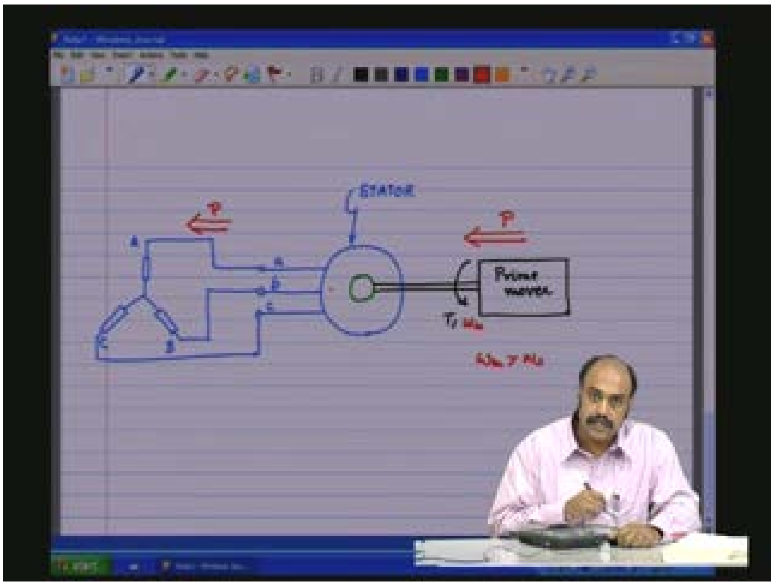

Now how is the reactive energy generated to maintain the field in the machine? So we cannot have an induction motor just like this in this manner because there is no component here which is which is supplying the reactive energy so therefore we put a component which supplies a reactive energy to the machine to maintain the rotating magnetic field within the induction machine or the induction motor. So, for that if it is supplying only standalone loads like this we connect we connect three capacitors and the job of the capacitor is to supply the reactive energy and reactive energy to to the induction motor to maintain the rotating magnetic flux so the reactive energy will be supplied by stored and supplied by the capacitance, so the Q. So, if an induction motor is to supply a standalone load in such conditions you have to put capacitors bank capacitors like this to supply the reactive energy.

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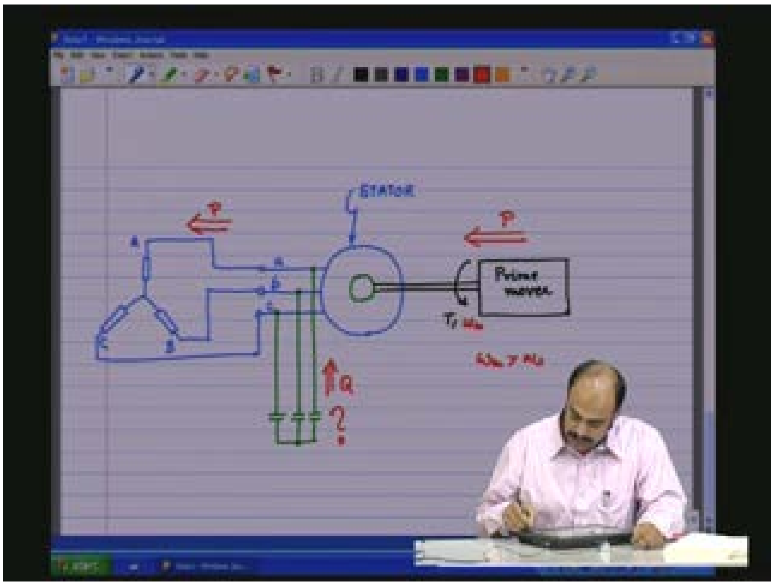

How much is the amount of capacitors that we need to put that would depend upon the amount of flux we need to build up or that is the reactive energy that is needed to build up the flux; probably an example will clarify that particular issue.

So let us now work out an example from the textbook and let us start with the following specs. So we have a 40 Hp 1760 rpm 440 volts 3 phase squirrel cage induction motor squirrel cage induction motor. The rated current of the motor rated current of the motor is 41 Amps. The full load power factor is given by 0.84 given as 0.84. So now let us calculate the capacitance required required per phase per phase if the capacitors are connected in delta configuration are connected in delta configuration.

So we have the scheme which is something like this (Refer Slide Time: 24:54), only this portion is now connected in delta which means we have a capacitance connected like that; instead of star the delta so we have this so it is in the delta. So these are the c's that we need to calculate and evaluate how much of these are going to flow. So, for that we need to evaluate what is the reactive energy that the capacitor needs to supply.

So first let us calculate the apparent power. the apparent power VA under full load condition is given by VA equals............ now this is root 3 line voltage into line current so that is going to be root 3, the line voltage is 440 volts this is the value, the line current is 41 amps the value is given here, so four 440 volts into 41 amps and that is 31.2 kVA.

And now the active power the active power is given by the active power P. We have information here in the specification which says the full load power factor is 0.84 so that is equal to VA into cos of theta which is equal to 31.2 into 0.84 and that amounts to 26.2 kilowatts. Therefore, now we have the reactive power Q which is root of P sorry root of VA square minus P square VA square minus P square and that is equal to 17 kVAR.

So, when the machine operates as a generator it has to supply 17 the capacitance has to the capacitance components should have should supply 17 kVAR or each phase should supply 17 by 3 which is 5.7 KVAR per phase.

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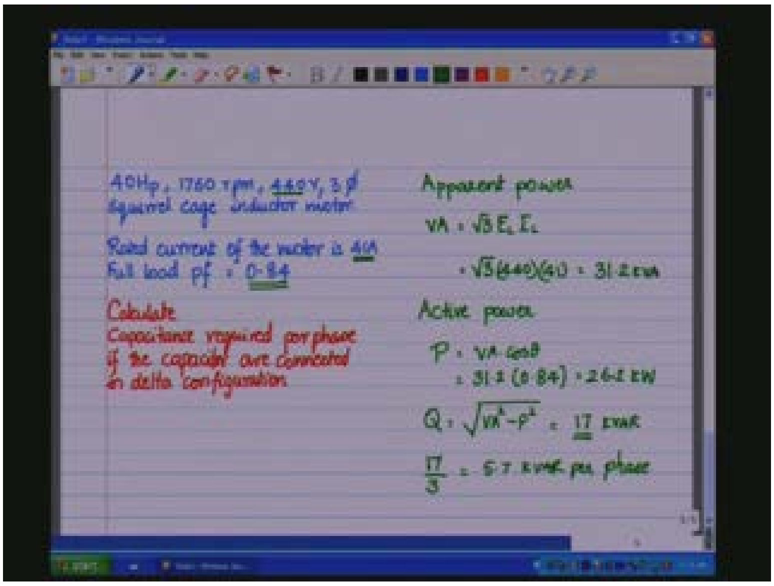

The capacitances are connected in delta therefore the voltage across the capacitors is 440 volts that is the line voltage themselves and therefore the capacitance current effective value I cap will be Q by E and that is equal to 5770 or divided by 440 volts and that is 13 amps. So the capacitive reactance X c is given by 1 by 2pi f into C 2pi f into C and that is equal to E by I cap so which is equal to 440 by 13 and that is equal to 34 ohms. So therefore C is equal to 1 divided by 2pi f into 34 ohms. So if f were 50 hertz then C is equal to 1 by 2pi into 50 into 34 Farads. So this is the way one goes about calculating the capacitance that needs to be connected to the 3 phases of the stator of the induction motor if the induction motor has to be used as an induction generator and supplying a standalone load not connected to another source so that the reactive energy can be drawn from the capacitance which can be used for maintaining the rotating flux.

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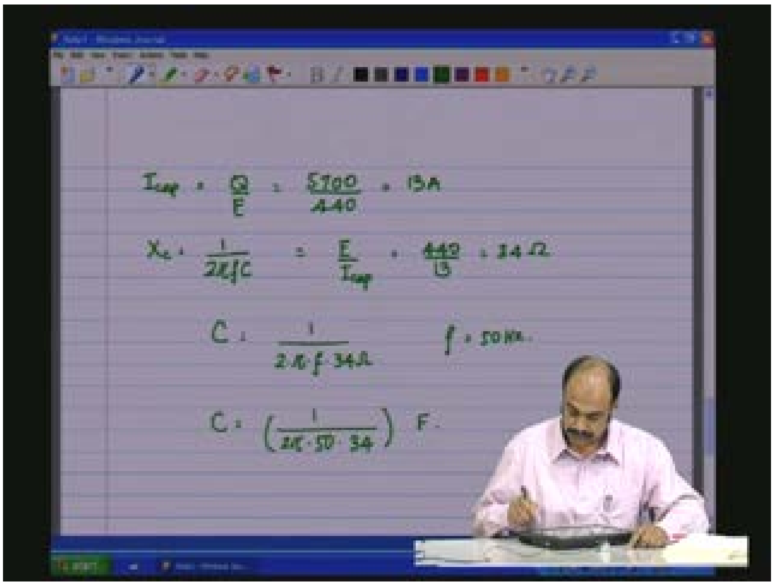

Now let us do one more example which will give a good idea of the various power flow issues when the motor is acting as a generator based on the equivalent circuits. Now let us draw the equivalent circuit of the induction motor. The equivalent circuit of the induction motor is given like this; the per phase equivalent circuit, the approximate circuit, the one which is valid for higher powers and we have that.

So we have the magnetizing reactance, core loss component R c, this is the magnetizing reactance, this is R 1 plus R 2 and this is R 1 and this is J x sigma 1 plus j x sigma 2 and this is R 2 by S okay and we are applying normally the source here.

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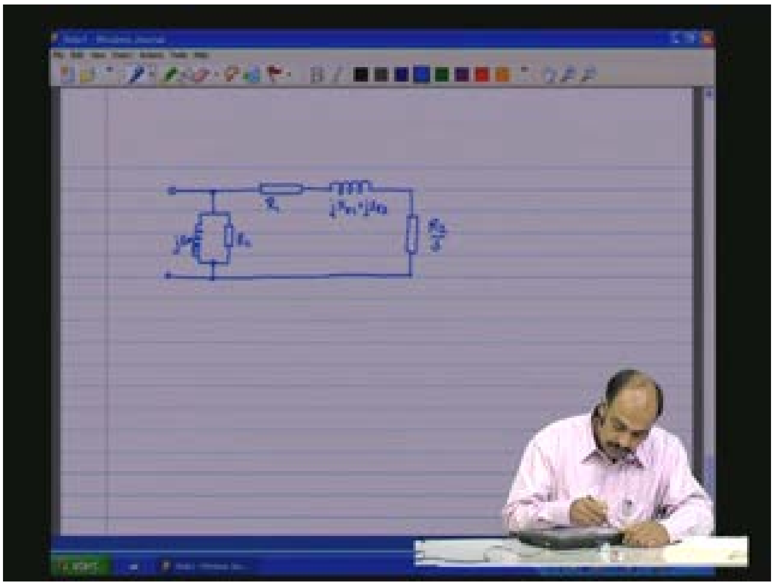

Now what we shall do is that we will give some values typical values of the motor to these. So we shall give the inductance the inductive reactants a value which is j 110, the value for the core loss component 900 ohms, the value for R 1 the winding resistance theta side is 1.5 ohms, then the value for the combined leakage reactance j 6, then R 2 by S minus 48 ohms.

So here the source, so we have 254 volts obtained here across the terminals. Now let us say this is the I P and this is the I 1. Now having this one let us analyze the situation. So this is R 1 this is basically R 1 and we will call this as just j x this is equal to j x okay.

Now from this let us have the synchronous yeah now let us say this is a 440 volts 3 phase motor and it is having an n m of 1845 rpm driven at that speed and we have the synchronous speed given as 1800 rpm so which means we are having the shaft speed rotated at super synchronous speed that is with the speed 45 rpm above synchronous speed and therefore s which is equal to 1800 is the n s minus 1845 by 1800 which is minus 0.025 and R 2 by S is equal to minus 48 and therefore R 2 is equal to 1.2 ohms.

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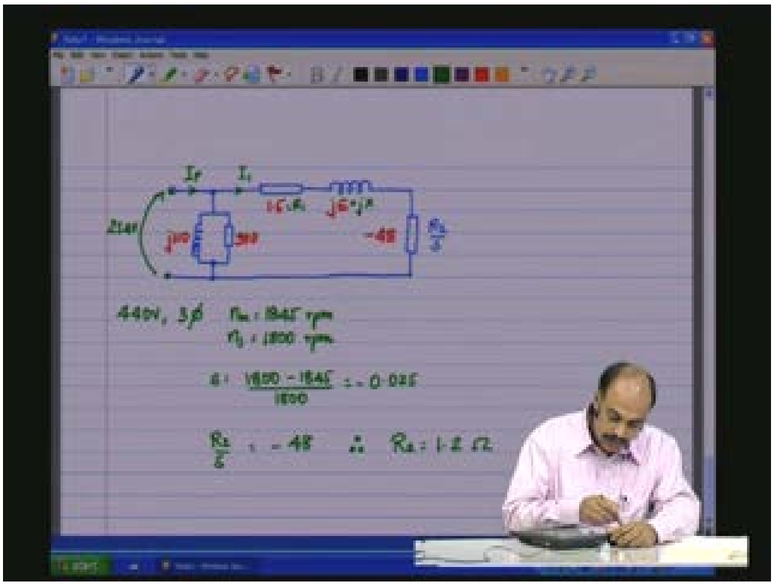

Let us have this picture. We will copy it and go to the next page and then paste it so that we have this in the background when we are working out the solution.

So we have first the net resistance of the branch and that is let us say R n is given by minus 48 plus R 1 which is equal to minus 46.5 ohms okay that is this and this added. the impedance of the branch impedance of the branch that is we are talking of this portion (Refer Slide Time: 38:02) and that is given by Z which is equal to square root of R n square plus X square and that is equal to square root of minus 46.5 square plus 6 square and that will be equal to 46.88 ohms, impedance of the branch.

I 1, the current in the branch I 1 which will be equal to E by Z where E is that and that will be equal to 254 divided by 46.88 and that is equal to 5.42 amps that is 5.42 amps.

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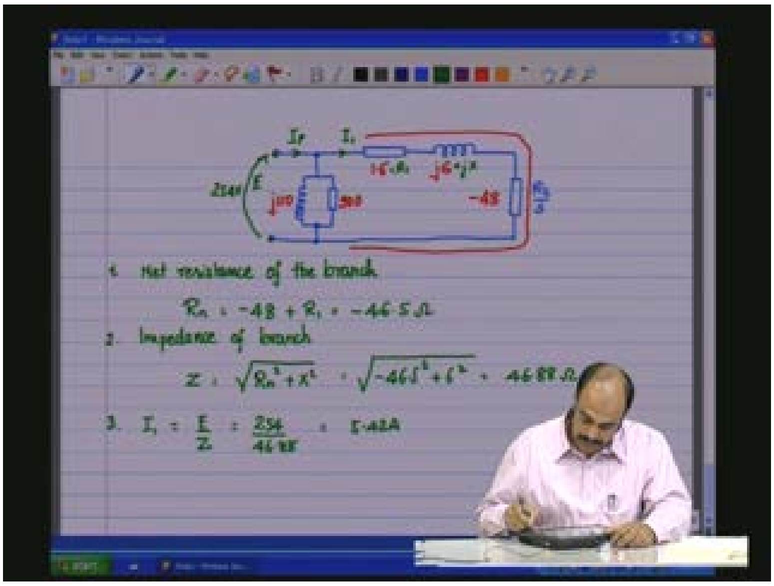

Then we have the current there. Now, the active power the active power...... because in the negative slip the power is going from the mechanical side and it is coming to the rotor, the active power delivered to the rotor from the mechanical side delivered to the rotor from the mechanical side that is from this side is P r and that is equal to I 1 square into the resistance R 2 by S R 2 by S and that will be equal to 5.42 square into minus 48 and that is minus 1410 watts; minus sign indicating the power is flowing in the reverse direction.

The fifth point the I square R losses in the rotor I square R losses in the rotor are slip times basically so P loss R is equal to the amount we have calculated R 2 as 1.2 ohms and that is I 1 square into R 2 which is 5.42 square into 1.2 and that is equal to 35.2 watts. Then sixth point the mechanical power input to the shaft P m which is equal to P r plus P losses so therefore you have minus which is 1410 plus 35.2 which is equal to 1445 watts.

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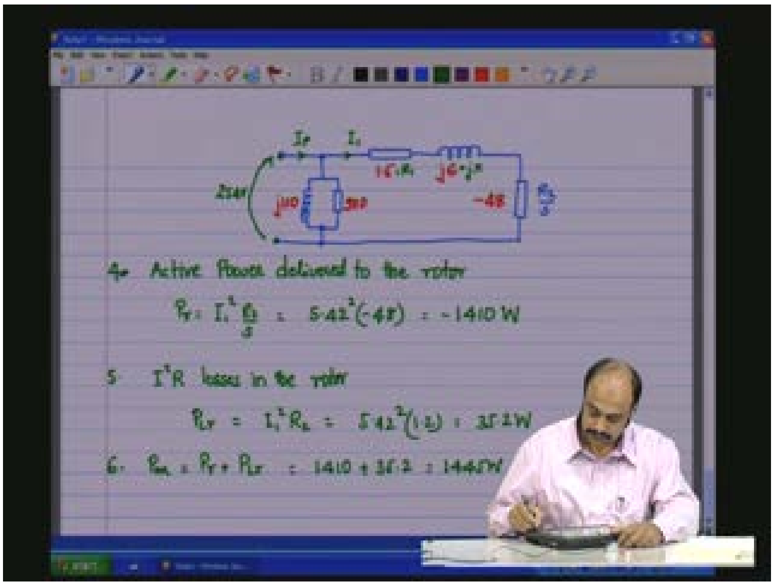

next So the losses in the stator: the I square R losses in the stator is equal to......... P loss stator is equal to I 1 square R 1 which is 5.42 square into 1.5 that is equal to 44.1 watts. The the stator core losses, core losses in stator is given by E square by R m R c which is 900 so 254 square by 900 ohms and that is equal to 71.7 watts.

The active power delivered to the line feeding the motor is 1410 minus 44.1 minus 71.7 this is the this is the stator I square loss and this is the core loss or the iron loss in the stator and this this is the power available at the rotor from the mechanical side which is equal to 1294 watts. So this is the active power fed into the 3 phase lines. Okay

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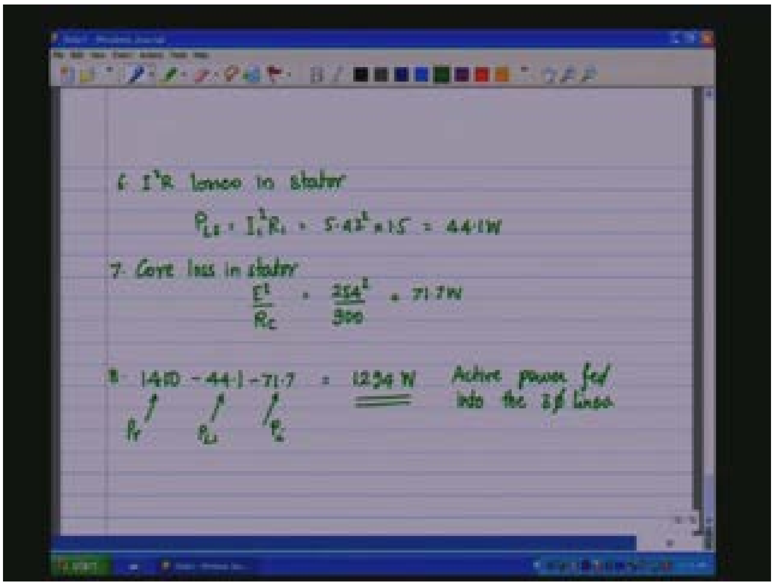

Now let us talk of the other application and that is the speed control speed control of induction motor. The induction motor as I as I stated earlier in the beginning of this class that it is more or less a constant speed motor because if the synchronous speed is kept fixed then the mechanical speed is going to vary only by an amount of slip. But if we want to have a much greater range of the speed more than what is supposed to be the operating range....... so this is called the synchronous speed (Refer Slide Time: 45:06) and n m verses the torque and this would be the operating speed range operating speed range.

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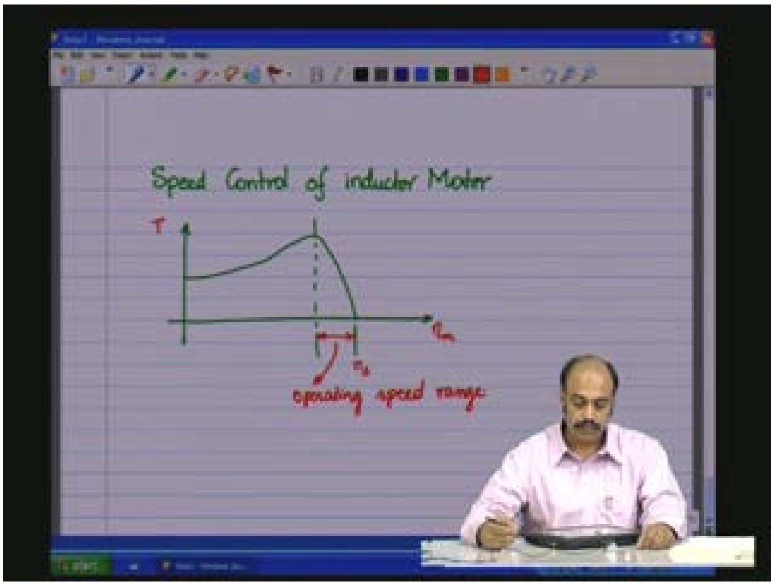

What happens if we change the stator voltage?

If we change the stator voltage, let us say if we make the stator voltage lesser than what it is you will see that the curve starts going in this fashion (Refer Slide Time: 45:42) so we get a much better range; let us say this is V 1 V 2 V 3 V 4 with V increasing V as increasing. So V 1 is greater than V 2 is greater than V 3 is greater than V 4 which means as you decrease the stator voltage the torque speed curve becomes like this and the operating point is extended so you have a much larger range at a lower voltage larger speed range. However, as the voltage keeps reducing the current drawn from the motor will be higher because it has to support the same flux in the it has support the same flux rotating flux within the machine and for the same load the current increases for the given lower voltage and therefore the I square R losses increases and as a result the efficiency will come down by just reducing the stator voltage.

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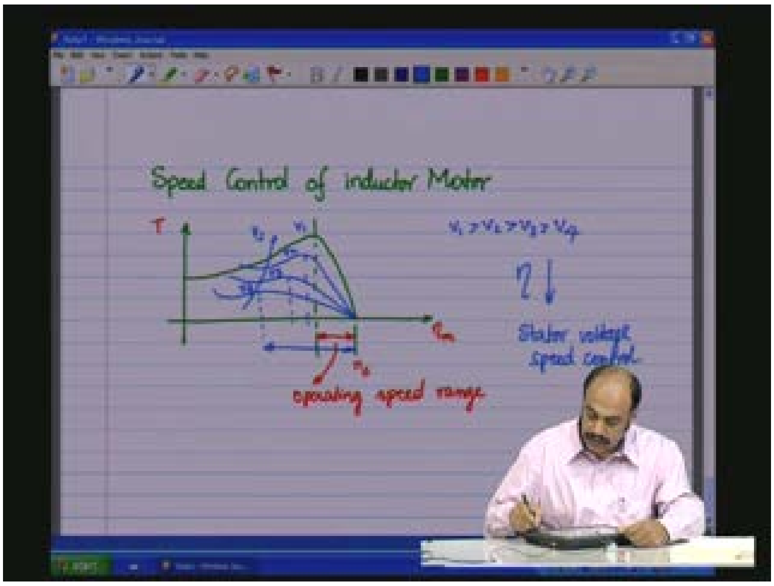

Of course this method of speed control is called the stator voltage control stator voltage speed control. One could also have a two-step speed control by having the source. We have the 3 phase source coming in the picture here and let us say the motor is connected initially in star form in the star form. The windings........... So initially when the motor is getting started up let us say we apply the motor windings in a star type of a volt in a star type of fashion which means the phase voltages are reduced by root 3 times and then we have some kind of a switch mechanism here such that the motor has picked up speed we put this in at delta fashion such that the phase voltages winding voltages see the line to line voltages which is a higher voltage. So you have two possible voltages that you can apply in star delta fashion: one is in the star fashion you have e line by root 3 which is applying across the phases and the delta fashion you have e line applying across the motor coils the stator coils.

So you could have two possible voltage values that are applied to the the stator coils and therefore the range of the motor can be slightly extended which is basically the same as the stator voltage control.

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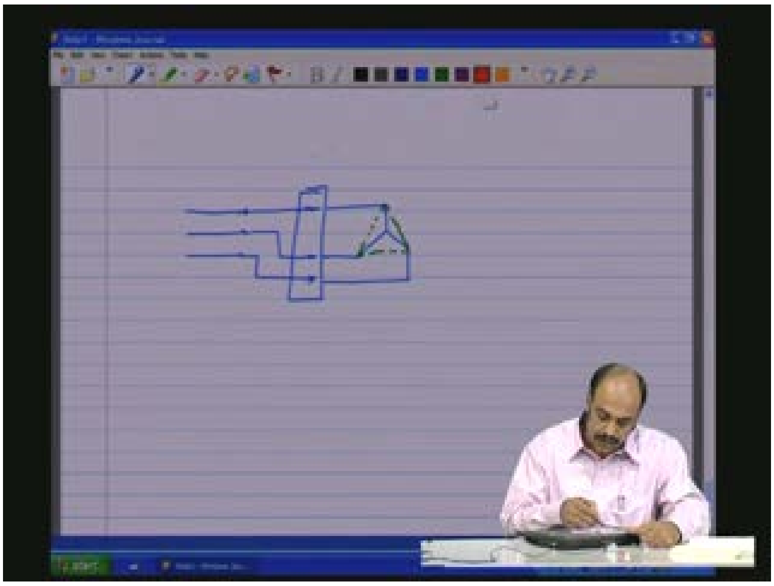

However, if we keep the flux constant with respect to this, now this is the speed and the torque. In the case of in the case of the stator voltage control as the voltage is reducing and if we neglect the leakage reactants drop and the winding resistance drop, essentially the voltage E stator is applying across the magnetizing reactance and therefore E by X m is the magnetizing current I m. So, as the stator voltage reduces what happens to the magnetizing current; the magnetizing current also reduces because the X m is the same. As a consequence, as the magnetizing current has reduced the torque generated is not sufficient for the load and the load requirement should also be lesser and the motor is underutilized.

But if let us say the applied voltage is stator is such that let us say the voltage across the magnetizing reactance is now E s which is j X m into I m the magnetizing current. Let us say we want to keep the magnetizing current constant which means we need to keep E s by X m constant. This implies E s by j that is E s by X m is nothing but 2pi f into L m this is the magnetizing inductance. Now this is anyway constant, pi is a constant factor, 2 is a constant factor, the only variable is f. so, if we keep E stator by f constant then the flux I m is a constant so which means if the stator voltage is reduced will reduce the frequency also proportionally such that it is constant and I m is a constant then you can utilize the whole range of the torque. So we saw that the torque is like this for let us say some n s 1, this is at f s 1 and then as f s changes we have a family of curve with the operating points getting shifted in this manner, this is n s 2 synchronous frequency 2 at f s 2, n s 3 at f s 3 with the frequency reducing to 0.

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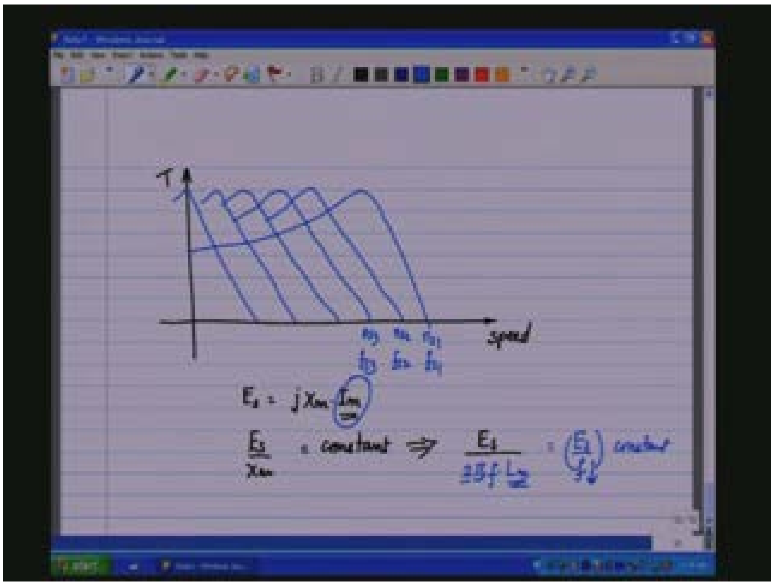

So we will see that you could operate it as almost a constant torque mode up to the synchronous or the base frequency. And if we have to increase the speed beyond the base frequency then the voltage cannot increase any further, the voltage has reached its rated. But I can increase the frequency to go beyond this. But if you go increase the frequency the flux decreases. So therefore, beyond a particular point you will have only field weakening. So I could have constant flux constant torque at this point, beyond a particular point the field weakens and the torque also reduces. So this is the field weakening zone. This is the constant torque zone; this is also called the constant power zone. So this will give you a very wide range of speed control right from 0 to very large value of speed and beyond the 50 hertz component.

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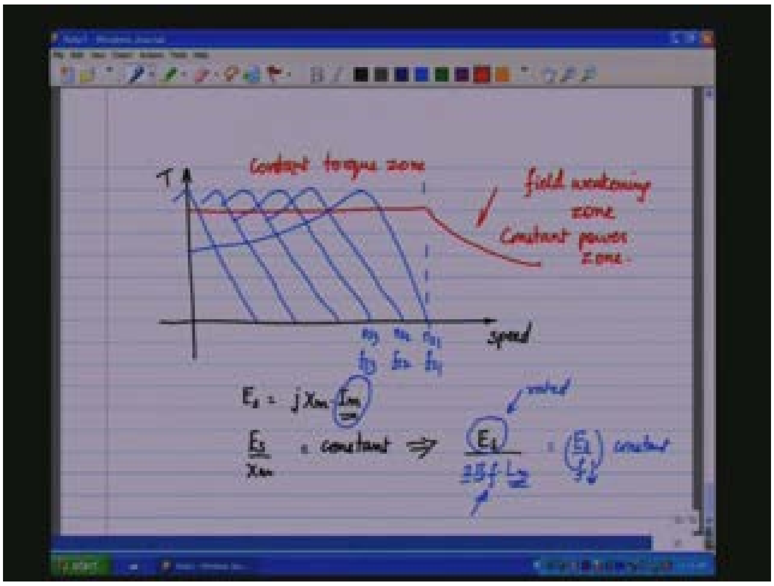

But if you how do you change the frequency if you want to use a V by f?

This is called V by f is equal to constant type of control type of speed control. How do you make this constant? Meaning if you change this, this should also be proportionally changed to keep this constant. how is frequency changed so which means we cannot directly feed the 3 phase mains to the induction motor it should now pass through a rectifier filter and this is now made into a DC a DC bus.

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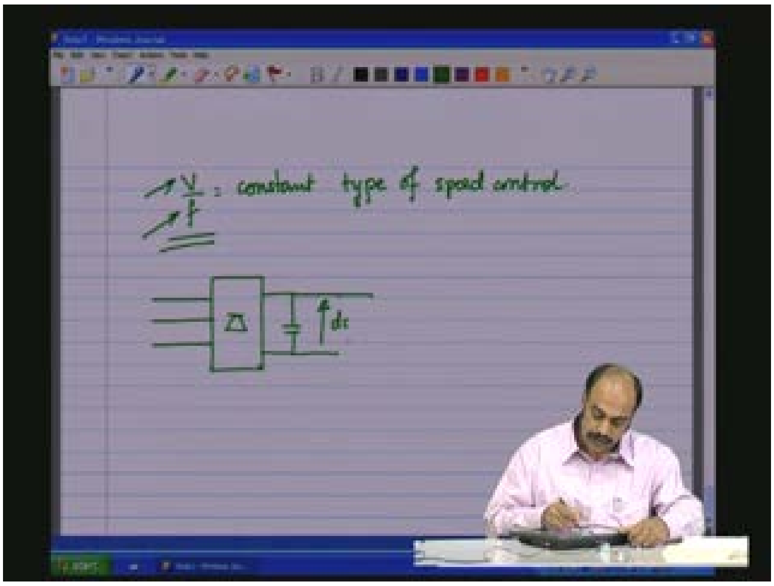

Now this DC bus should now pass through an inverter 3 phase inverter which now gives 3 phase AC. But the 3 phase AC here the frequency can be controlled by giving PWM or pulse width modulation. So, by pulse width modulation the frequency of the inverter here can be controlled from 0 to 50 hertz or even greater, the modulating signal. So this will be applied to the induction motor which can get variable voltage variable frequency 3 phase supply by means of this inverter and therefore the frequency can be controlled and you can have V by f type of a speed control and you can have a whole speed range right from close to 0 up to even over base speed or over 120 f by P.

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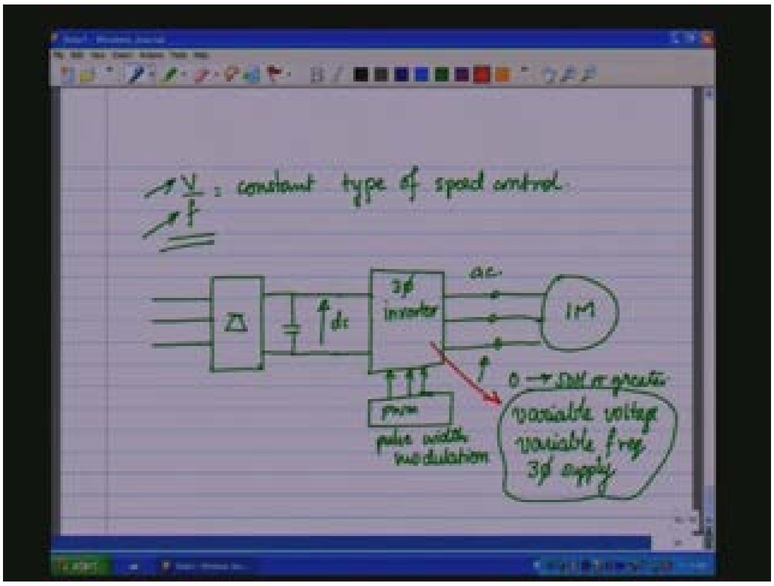

There are also different other methods of speed control which gives much better improved dynamic performances like the field oriented control or the vector control of the induction machine. Of course that is beyond the scope of this particular basic course but it can be considered and discussed in an advanced topic.

So today we conclude the induction motor topic and stop here and in the next class we take the discussion on synchronous machines. Thank you.