Basic Electrical Technology
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Lecture - 37
Induction Motor – 2

Hello everybody, in the last class we were discussing at length on the topic of the rotating magnetic field generation in the induction motor, how is the rotating magnetic field generated. So we saw that if we apply 3 phase voltage or 3 phase source to the stator coils then the 3 phase currents in the stator coils which are 120 degrees spaced apart in the time axis or applied to the three coils the poles in the stator which are placed mechanically at 120 degrees apart so this causes the resultant flux or the mmf to rotate in the air gap or rotate in space and this rotation causes a differential relative difference in the speed between this rotating flux and the rotor conductors. This induces a voltage in the rotor conductors.

Of course the rotor conductors in the squirrel cage are shorted which means a huge current flows in the rotor conductors. This current in the rotor conductors interacts with the flux which is produced in the air gap and provides a force which makes the rotor conductors move to try and catch up with the field. So all the accumulated forces of all the rotor conductors on the circumference of the rotor add up and you get a massive torque which makes the rotor to move. So this is the principle of the operation of the induction motor.

But we saw that as the rotor let us say the rotor speed catches up with the speed at which the flux is rotating which means there is no relative difference in speed between the rotor conductor and the flux which means the flux will not cut the rotor conductors and as a result there is no induced voltage in the rotor conductors and thereby no induced current. If there is no induced current then Lorentz force f which is equal to b i l i being 0 there is no force on the rotor conductors and therefore the rotor will tend to lag because of the frictions of the bearings therefore, there will always be a slight difference in the speeds of the rotor shaft and the rotating magnetic field. The speed at which the magnetic field rotates is called the synchronous speed and the speed at which the rotor rotates is called the mechanical speed or the shaft speed and the mechanical speed is always going to be slightly lesser than the synchronous speed by a small amount and that is called the slip. So we saw what the slip is also and how it is defined mathematically.

Then we also saw one interesting phenomena that is if we had more poles per phase if we had just two poles per phase or one pole pair per phase then for every cycle of the currents which are applied in the coil there is one cycle of rotation or one revolution. If we add one more pole pair or two more poles which means four poles four poles or two pole pairs then for every cycle of rotation the magnetic flux or the mmf has rotated 180 degrees which means two cycles are needed for the complete rotation or one revolution. So, if there is two pole pairs you need two cycles, if there is three pole pairs we need three cycles and so on.

So we establish the relationship that is the synchronous frequency is given by 120 f s stator frequency divided that is stator current frequency divided by the number of poles or 60 f s by number of pole pairs or omega in radians per second by number of pole pairs or 2 omega where omega is in radians per second stator frequency divided by number of poles. So these are the various relationships that we try to establish in the last class and we continue from there.

Now, when the rotating magnetic field is moving in the gap and cutting the rotor conductors the initially the rotor is a standstill that is it is not moving so the relative speed between the rotor and the rotating magnetic field will be the frequency of the stator itself. So suppose we have standstill condition so under standstill condition let me put it in both the rpm equation and the radians per second equation n m is the mechanical speed in rpm which is equal to 0, omega m is the mechanical angular speed in radians per second which is equal to 0, n s is equal to 120 f s by P is the number of poles and the omega s is equal to omega s is equal to omega ac omega actual applied to the stator divided by the number of pole pairs or 2 omega actual by number of poles.

So what happens to the slip which is equal to n s minus n m by n s which is equal to 1. Same here: omega s minus omega m by omega s which is equal to 1 because omega m is 0 under standstill condition.

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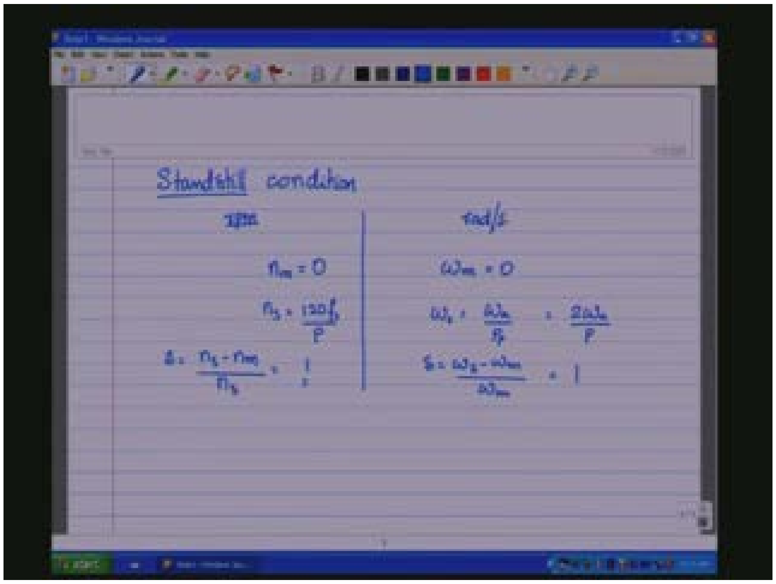

So when the slip s is equal to 1 the relative motion between the rotor conductors and the rotating flux is maximum and that is n s itself and therefore the induced voltage in the rotor conductors is going to be very high but the rotor is short-circuited and therefore instead there is going to be a large current till the motor picks up speed and the relative speed between the mechanical speed and the synchronous speed reduces to a smaller value.

Now if we see that E r is the voltage induced in the rotor; if rotor windings are open-circuited means in the case of squirrel cage motor the end shorted shorting rings you open them then the rotor windings are open-circuited or in the case of wound rotor the slip rings the brushes are removed from the slip rings and the slip ring portions are opened out that is the open-circuited so which means the relative motion between the flux and the rotor conductors is going to induce a voltage, now there is no current flow because it is open-circuited so you have the rotor voltage under open circuit condition and this is at standstill okay and the under any other slip the rotor voltage is equal to s times the rotor voltage when it had been open-circuited at standstill, this is standstill. It is slip times where are the induced voltage is slip times linearly proportional to the slip.

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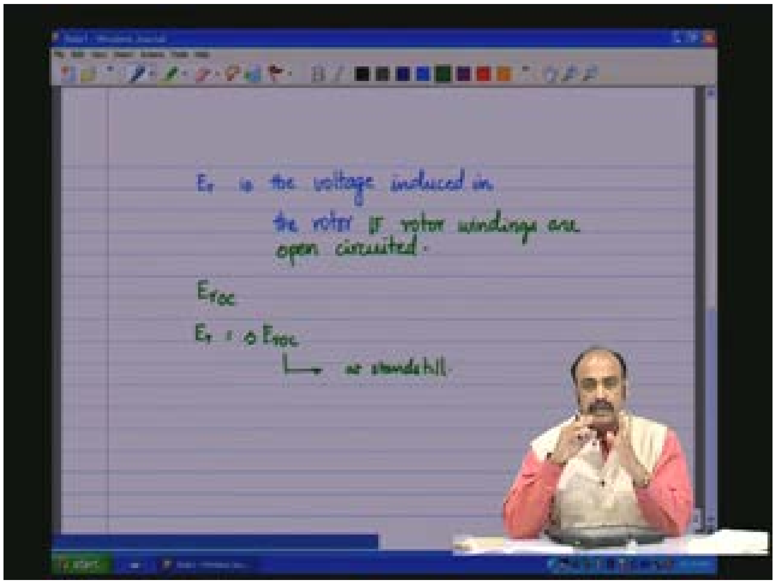

And what about the frequency?

When the rotor is standstill the rotating magnetic field has a frequency of let us say omega s then the relative speed is also omega s and then the induced currents in the rotor has a frequency of omega s. Now as the motor as the rotor is catching up with the rotating field let us say it is rotating at omega m but the relative difference in speed is only omega s minus omega m and therefore the currents in the rotor will have that frequency which is omega s minus omega m that is the slip frequency. So therefore, if f r is the rotor frequency then it is s times the stator frequency. So these two relations relationships are important to remember; the rotor voltage and frequency relationship with respect to the slip.

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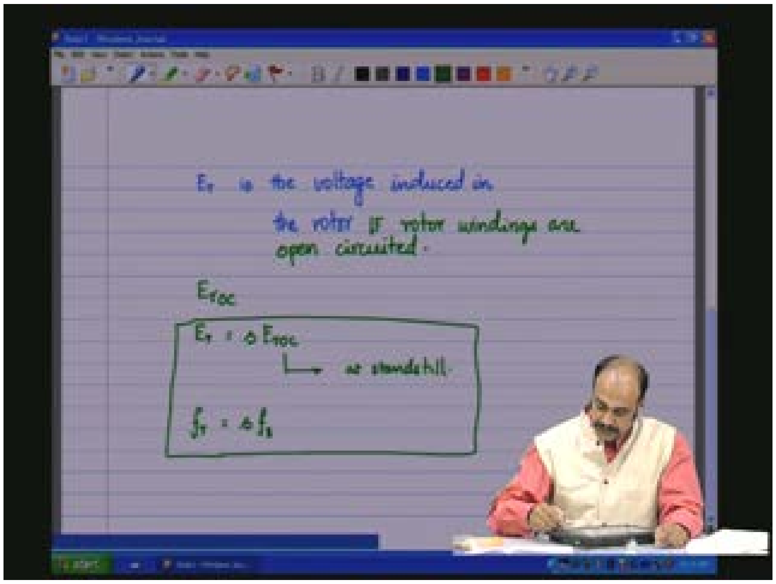

Now let us clarify the speed slip and the rotor frequency with a small example that I have worked out. Let us take a let us take a four pole 3 phase 50 hertz induction motor induction motor. Now for this induction motor calculate calculate the frequency of the rotor currents meaning calculate f r for the following conditions: 1) at standstill meaning the rotor shaft is not moving; 2) motor is running at 500 rpm in the same direction as the field; 3) motor is running at 500 rpm however in opposite direction as the field rotates and fourthly what is the condition when the motor is running at two thousand rpm in same direction as field same direction as the field. Let us understand the operation of the motor under these four running conditions four conditions.

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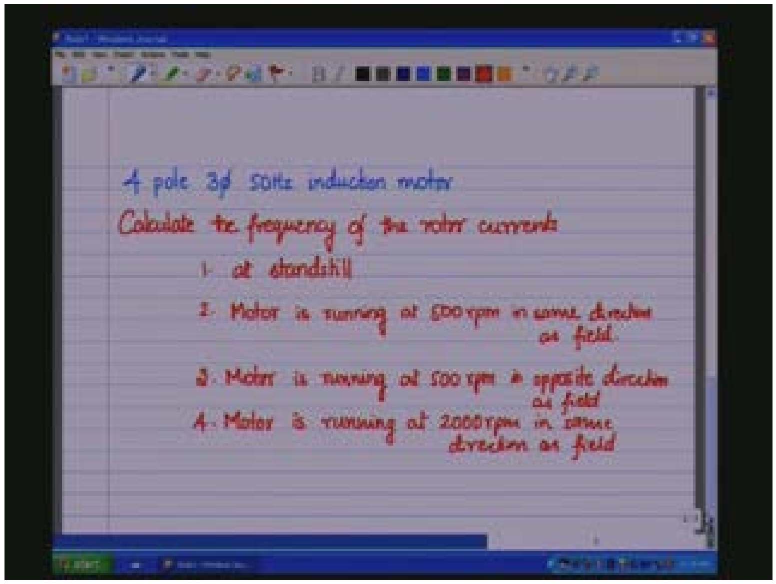

So we say it is a 4 pole 3 phase 50 hertz induction motor, so first let us find out the synchronous frequency let us find out the synchronous frequency n o u s. Now we know that the synchronous speed n s is equal to 120 f stator by number of poles P which is 120 into 50 hertz in the stator frequency by 4 poles that we have said and this is 1500 rpm, this is synchronous frequency. So now, if we take case 1 this is at standstill at standstill. Now under standstill condition what is n m? n m is 0 rpm; what is slip? slip s is equal to n s minus n m by n s and that is equal to 1500 minus 0 by 1500 and that is equal to 1 slip is equal to 1.

So what is the rotor frequency f r which is equal to s times slip times the stator frequency which is 1 into 50 hertz which is equal to 50 hertz. So the rotor currents are having a frequency of 50 hertz at standstill.

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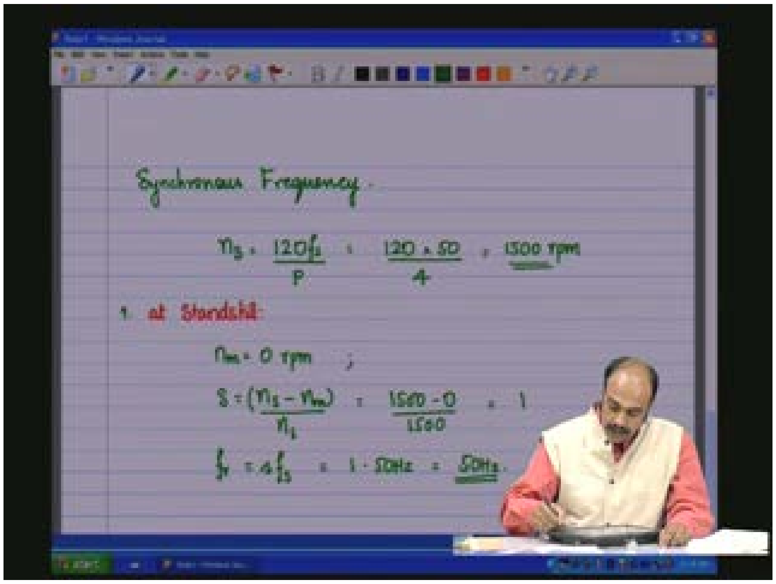

Now let us take case 2. Now here we said that motor turns at 500 rpm in the same direction as the field. So this is the second condition. Now here what is the slip? Now slip is 1500 rpm minus 500 rpm divided by 1500 rpm so this is 1000 by 1500 this gives you a value of 2 by 3. So the slip is having a value of 2 by 3 or which is equal to 0.66.

Now what is the rotor frequency?

f r which is equal to slip times the stator frequency f s which is 2 by 3 into 50 and that is 33.33 hertz. This is at an rpm 500 rpm the same direction as the field; this means that the motor is motoring in its regular manner, the speed is lesser than the synchronous speed.

Now the third condition is slightly different. Now the motor turns at 500 rpm but in opposite direction, in opposite direction as the field with respect to the field. So this means the speed is negative so we take let us say counter clockwise as positive, clockwise as negative, so if it is rotating if the rotating the magnetic field is rotating in a counter clockwise or anticlockwise direction which is considered as positive by convention, then let us say that the motor is rotating shaft is rotating in clockwise direction and it is minus and therefore we have the slip now which is 1500 rpm minus of minus 500 rpm see the negative sign here (Refer Slide Time: 20:52) it is because of the reverse of the direction 1500 rpm. So this gives you 2000 by 1500 which is 4 by 5 sorry 4 by 3 this is 4 by 3 which is equal to 1.33. So you see the slip is greater than 1. So if the slip is greater than 1 if the slip is equal to 1 is there is less there is no speed, if the motor motor is at standstill condition and the slip is less than 1 it is motoring, when the slip is greater than 1 it is breaking. So this whenever you have a slip is greater than 1 it is breaking operation and whenever the slip is between 0 and 1 this is normal motoring operation.

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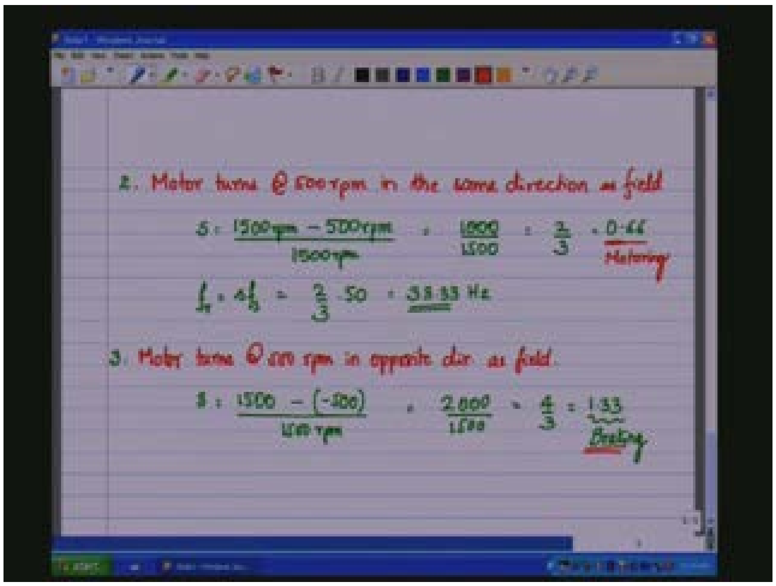

So let us look at the fourth condition. So the fourth condition motor is rotating in the anticlockwise direction itself along the field motor rotates along field direction at 2000 rpm. So we see here n s is 1500 rpm, n m the speed of the shaft is 2000 rpm. This means that the mechanical shaft speed is greater than the synchronous speed so what happens to the slip the slip goes negative; n s minus n m by n s is now 1500 minus 2000 by 1500 which is minus 500 by 1500 which is minus 1 by 3 which is equal to minus 0.33.

Now the rotor frequency f r is s times f f s which is 1 by 3 minus 1 by 3 into 50 hertz which is minus 16.66 hertz. So what does the negative frequency negative slip mean? Take a situation that you have vehicle to which the induction motor is connected like in the locomotives you have the train and the train is moving uphill. So as the train is moving uphill the rotating the mmf is moving at synchronous speed and the shaft is trying to catch up with it and it is motoring and it is pulling the train. And once the train has gone uphill and then it starts going downhill the motor is also going to be aided by the gravity, so the motor is also going to rotate not only by the electrical energy that is being supplied but also is going to get aided by the gravity and if the gravitational acceleration is high that is gravitational at the force due to the gravitational acceleration is high then the shaft speed can go beyond the synchronous speed in which case the mechanical energy inertial energy which is there in the mass of the train is getting put back into the supply that is the power is energy is being is flowing from back into the mains from the mechanical side to the electrical side and in such a case the motor is acting like a generator, and then it is called an induction generator. So when the slip is negative it means that it is acting like a generator and that is the significant negative sign and it still means that when you see a waveform on the scope it will be just 16.66 hertz and the negative side only indicates that the energy is put back from the mechanical side to the electrical side. So this means that this is acting like a generator because of the negative side.

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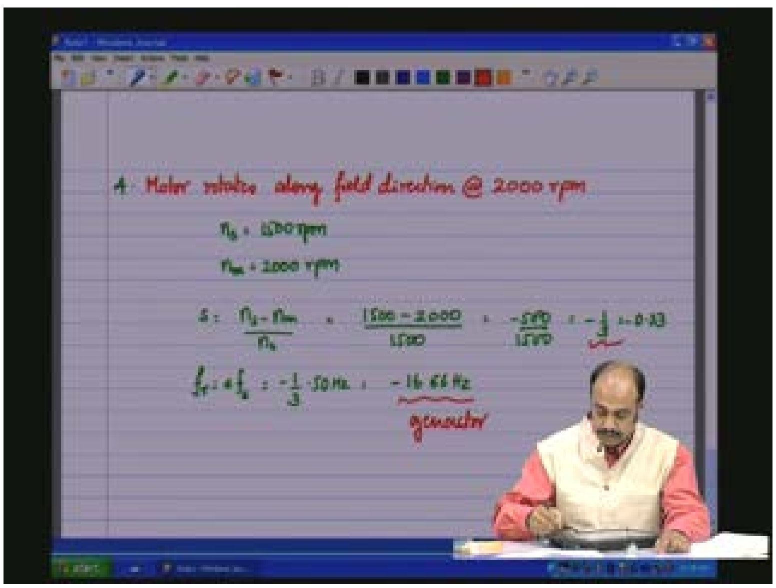

So if we look at the axis that is the speed axis and let me have the let me tell you what that vertical axis is later. But for now that is the x axis is the speed axis that we have identified and this is zero speed and somewhere here let us say is the synchronous speed. Now at standstill when it is zero speed s is equal to 1 and at synchronous speed.......... what is slip is equal to? n s minus n s by n s and that is s is equal to 0. So here s is between 0 and 1 0 and 1 so s is having a value 0 here, gradually goes on to 1 and then it becomes greater than 1; s greater than 1 and then on this side from 1 it has reduced to 0 and then starts becoming less than 1 less than 0; s less than 0 so this is where the negative slip comes into the picture and this is slip greater than 1.

So, when slip is greater than 1 we said that it is in the breaking mode; so in breaking operation the speed is negative in the other direction compared to the rotating magnetic field and in the region which is beyond the synchronous speed it is in the generating mode; acts as a generator and in the region between zero and synchronous speed the motor behaves like a motor or in the motoring mode. These are the three modes in the case of the induction motor.

And if we look at the points on the x axis at standstill case 1 this was case 1 of the problem (Refer Slide Time: 29:18) s is equal to 1 then somewhere at around this point you have 500 rpm and this point is case 2 and at 500 rpm we had the slip of 0. s is equal to 0.66 and then we had the point which was breaking which is greater than 1, a slip of greater than 1 let us say somewhere here where you had rotating with minus 500 rpm means counter this is counter if this is if positive is counter clockwise then the negative is in clockwise direction rotation and here this slip S was equal was equal to 1.33 breaking and the fourth operating condition was that the slip was negative, somewhere here we had 2000 rpm and we had the synchronous speed of 1500 rpm and this was case 3 and this is case 4 and the slip here was negative minus 0.3. So these are the various operating points on the x axis. The y axis we would like to see what are the torques at the various points as the speed evolves. Today we will look at that also. Got this concept clear; the various operating points the various zones operating zones of the induction motor.

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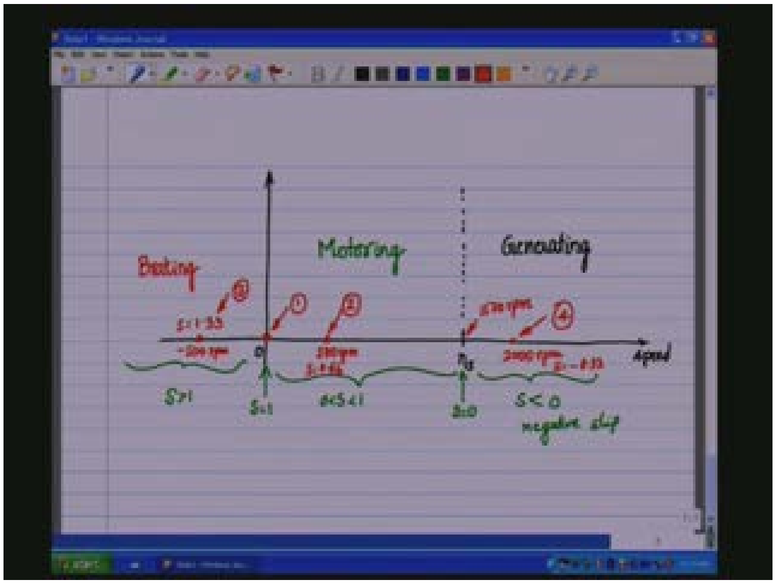

So now let us look at the same diagram, we have the speed and we have let us say the torque so the motor torque generated standstill and somewhere here let us have the let us have n s synchronous speed.

Now at standstill there is there is the rotating magnetic field which is rotating at synchronous speed and there is l large difference that is slip of one, there is a large difference in the relative space between the rotor conductors and the rotating magnetic field, the currents induced in the rotor are also of 50 hertz.

Now at this point there is some starting torque that is generated to pull the to pull the motor out of standstill condition and make it to move. So actually the torque characteristic starts going like that and reaches some kind of a peak and then starts to fall like that. So the the torque characteristics as it sees here if you look at this point you see that torque is zero when the motor speed or the shaft speed is at synchronism with the rotating magnetic field because there is no relative difference or the relative speed between the rotor conductors and the rotating magnetic field, there is no induction of the current in the rotor and as a result there is no torque that is what is shown here at this point, this is one crucial point.

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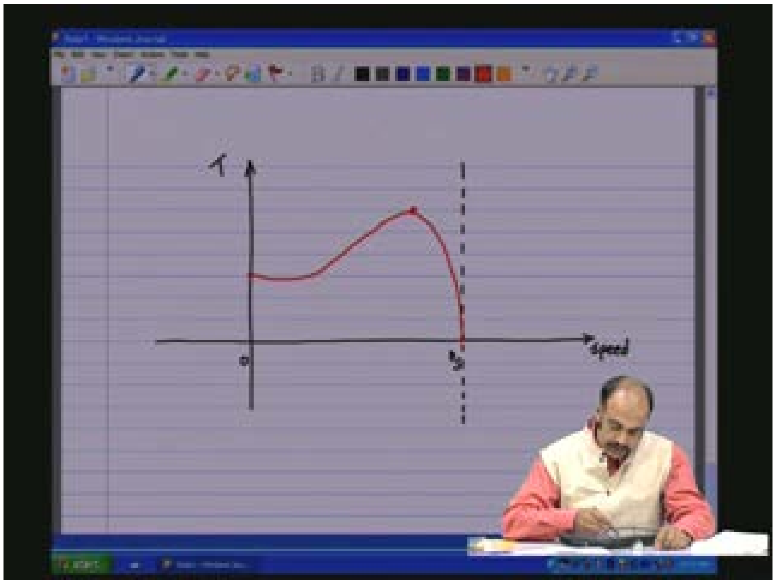

Now there is another crucial point here this is called the maximum torque T max or the breakdown torque breakdown torque; torque is in newton meters Nm. Now there is this torque and this is called the starting torque or also called the locked rotor torque or also called the blocked rotor torque and this point of course has a very small difference there it is called the pull down torque, slightly down, slightly lower than this starting torque and that is called the pull down torque.

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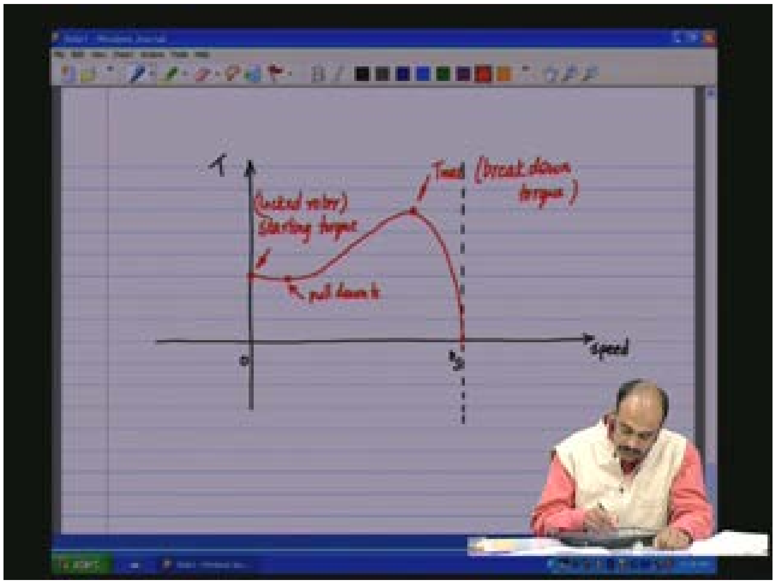

So now if we extrapolate this into the breaking zone you will see that the torque continues in this direction and in the generate it is a mirror image, it starts coming like that and goes like that so it will be mirror image of what you see there, so this is in the generating zone, this is the breaking zone, that is the breaking zone, this is the generating zone which is a mirror image of what is there in the motoring zone.

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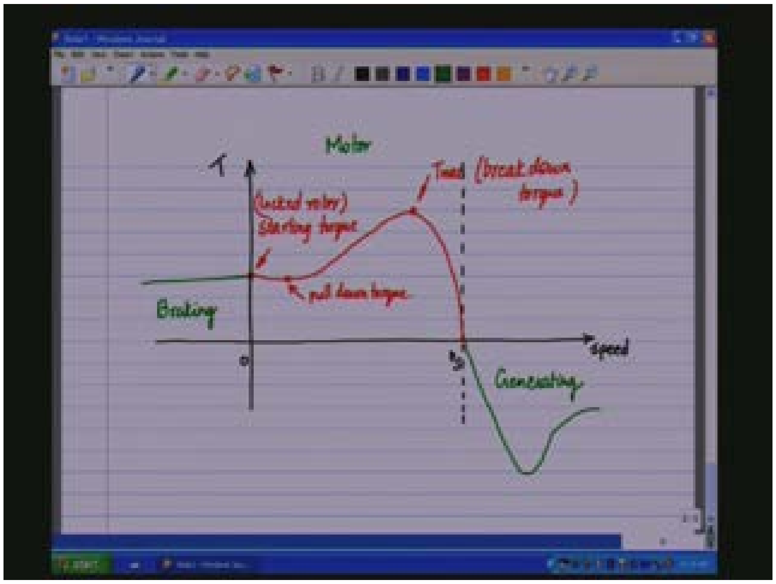

So let us have a look at the torque characteristic a bit more in the motoring zone, let us discuss it a bit more. So we have the motor torque, shaft torque and we have the speed of the shaft we have the speed of the shaft and somewhere here we have n s and at n s it has to become zero.

So let us have the torque of the motor which goes like that (Refer Slide Time: 37:52) and then let us have it like that, it goes up there and then comes down, let me make it a bit smoother here okay so this is the torque characteristic of the motor.

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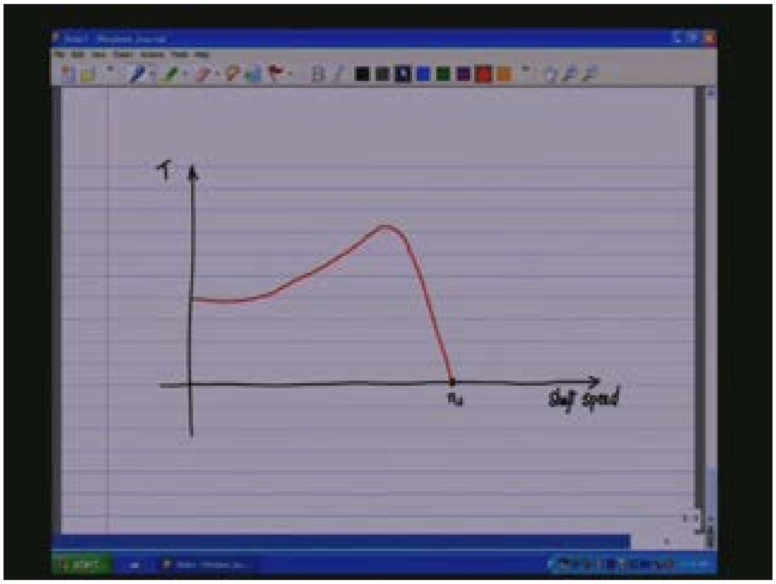

Now let me divide the torque characteristic into two portions that is this is the operating zone. So it is in this zone that the whole motor should operate and the motor should very quickly go from starting into this zone of operation because this is the stable zone and this is the transient zone and it is unstable.

What does it mean by saying stable and unstable?

Now let us say this is the torque that is generated by the motor, we we call this as the torque the red one let me let me say that it is the red curve that is the torque that is generated by the motor generated by induction motor IM. Now let us see the load requirement. Let us say the load torque requirement let me give that in green let us say so let us say that the load torque requirement is something like that. This is T L load torque requirement or that is required to the motor so which means that there are two possible operating points, there is one operating point which is here, there is also another operating point which is here. So let us take this operating point here. So let me call this as point 1 and let me call this is point 2.

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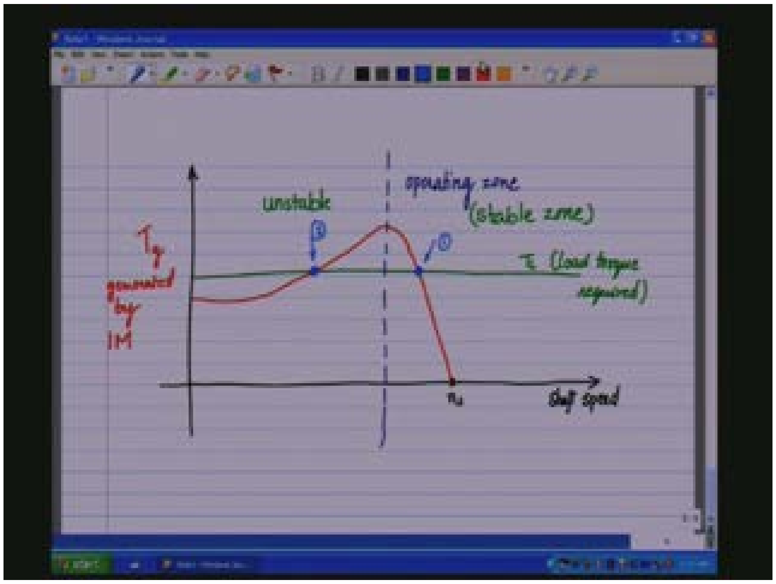

Now due to some disturbance let us say the operating point has shifted. So let us say the operating point has shifted operating point has shifted slightly here due to some disturbance external disturbances or change in parameters so whatever so which means that here the speed what was rotating at n m is now going to be rotating at a speed that is much higher than n m but the torque that is generated by the motor is lower than T L so the motor is not able to supply the load torque here because of because of so much discrepancy in torque. So therefore the motor will try to stall and the speed will start coming down. As the speed starts coming down the operating point shifts from here to this point again which brings back to the (( )) (42:16).

Likewise, if the operating point had shifted here the speed here is lower the speed here is lower compared to the normal operating point n m and the torque is higher so because of the higher torque it tries to make the motor shaft move faster and the speed increases torque decreases till it comes back again to the operating point. So therefore even if there is a slight deviation in the operating point the characteristic is such that it pulls it back to the operating point to supply the load.

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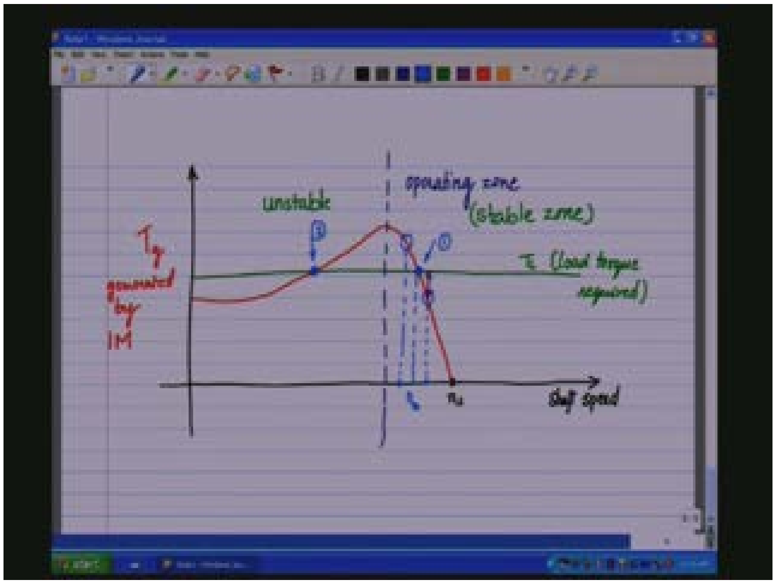

Therefore, anywhere along this line here (Refer Slide Time: 43:07) what I am showing that is in the operating zone portion of the line they are all stable, any deviations can be pulled back into the normal operating point of the for a given load torque.

Now, in the case of this zone if there is any deviation let us say here. From the operating point the torque is higher, speed is higher, so therefore, it will go still higher in speed and it will try to move away like this away from the operating point so it is not being brought back to the operating point. Likewise, if the operating point shifts here, the speed is lower, torque is lower, it is not sufficient to meet the load requirement therefore it will try to stall and starts the operating point still starts moving further away from the nominal operating point. So any disturbance will cause the system's operating point to shift away from the nominal operating point where it is supposed to have been positioned therefore anywhere in this region we should not position the operating point because that is the unstable zone. So it is important to note that we position our operating points only in this zone called the operating point zone so that is very important.

Now there is one more thing that happens to the torque characteristic with the change of some particular parameter and this is where the wound rotor induction motor comes into picture and gives some useful insights. So let us say we have the torque and we have a shaft speed and this is the torque in newton meter, and we have somewhere here the synchronous speed; let me first draw the characteristic curve. So we have one thing: this is the torque speed curve where this point is n s.

Now, in the wound rotor induction motor there is a possibility of introducing external because the brush because the windings can the currents can flow through the external brushes and in the external circuit after the brush we can introduce some impedance or resistance to create some additional features in the motor. Or, if the motor is designed with a given............ even in the squirrel cage induction motor the resistance of the rotor conductors play a role on the torque speed characteristic. So let us see what happens if the resistance is increased; meaning, if the resistance of the rotor conductors.

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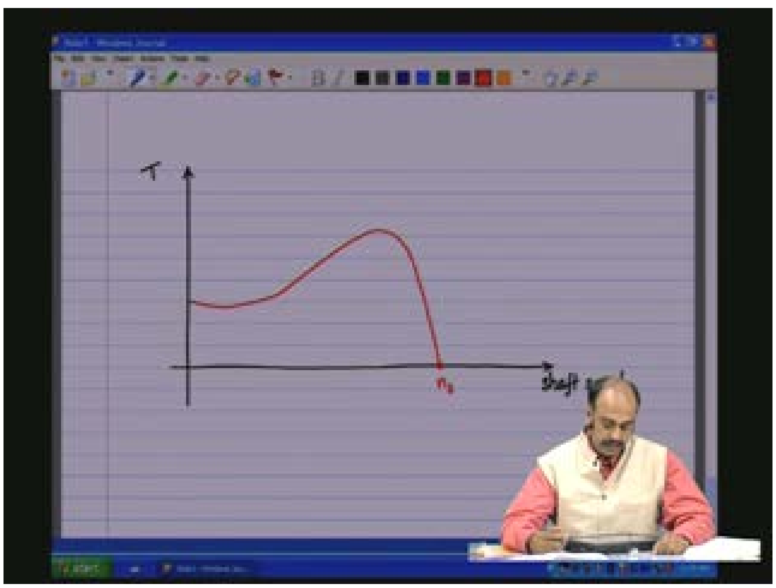

So let us say this is at the nominal value. Now let us say on increasing the rotor conductor resistance of the rotor conductor the curve changes shape and starts going in this fashion. So you see that the T torque of course is the same, this is T max so this is let us say rotor resistance R r 1 now here R r 2 which is greater than R r 1. So what has happened here, two things: we have a higher starting torque and the maximum torque is the same and third, the range, operating range is much higher meaning the operating speed range if you look at the x axis is larger when compared to the operating speed range of the lower resistance motor. If I further increase keep increasing it one could probably have a curve which is like that.

So you see that the starting torque is still further brought up brought up to the maximum so this would be R r 3 greater than R r 2. On further increasing you will see that this starting torque still goes lower now from there it starts going lower. So the torque characteristic can be modified and the starting torque characteristic can also be modified so we have: starting torque increases as R r increases; operating speed range operating speed range increases as R r increases. Power dissipation power dissipation in the rotor in rotor increases as R r increases because now the R r the rotor resistance is higher, the I square R r loss is going to be that much more higher and as a consequence efficiency decreases. So therefore, it is not advisable to permanently increase the rotor conductor resistance because the efficiency will come down drastically. Therefore, in the case of the wound rotor induction motor as the windings are brought out through the slip rings to the external circuit we connect resistance. So during starting the torque is pretty high so you have a very high starting torque very high starting pull.

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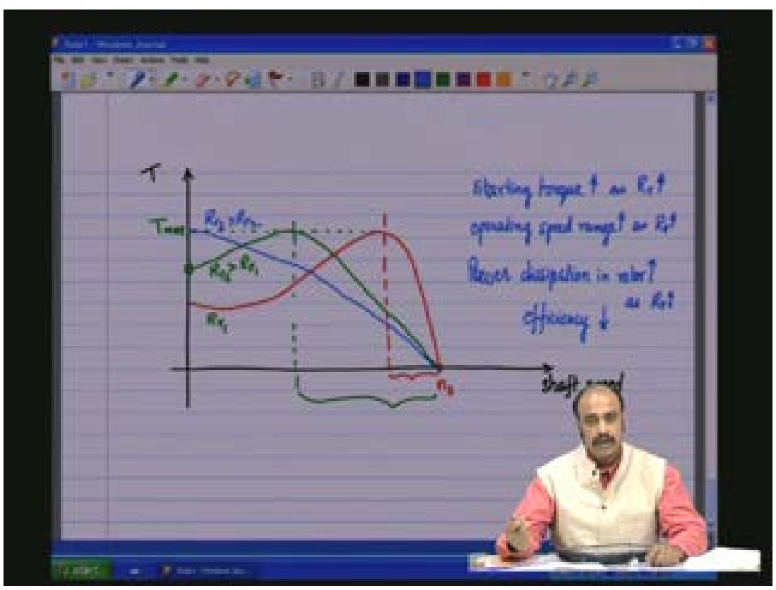

Now as the speed increases you cut off the resistance, modify this torque characteristic such that it takes the form of that of the red line and in the operating zone is narrowed and the efficiency becomes higher okay. So the operation characteristic can be modified that is the torque speed characteristic can be suitably modified by including external resistance which is possible only in the case of the slip ring or the wound rotor induction motor. So that is where the torque speed characteristic looks like.

There is just one more point that you need to know about the torque speed characteristic. What happens to the torque speed characteristic as the speed synchronous speed is changed? This is the shaft speed; it is a torque speed characteristic. So let us say so we have a torque speed characteristic which is like that okay, this is at n s. Now let us say the new n s, this is N s 1, this is N s 2 new n s the torque speed characteristic is actually parallel and starts and at N s 3 the torque speed characteristic goes in a parallel manner and goes like this and so on.

You will see a family of a torque speed characteristic which goes like that (Refer Slide Time: 52:54) so the torque speed characteristic are at different synchronous frequencies because if the stator frequency is just 50 hertz then yes, this is only torque speed characteristic. But if the stator frequency changes then we can have a series of torque speed characteristic, it is a family of curves as the frequency decreases. So here you see the frequency decreasing sorry the frequency is increasing like that; from zero the frequency is increasing. This is very useful in the sense that when we want to do speed control of the induction motor this kind of an approach is used, we will discuss about that later.

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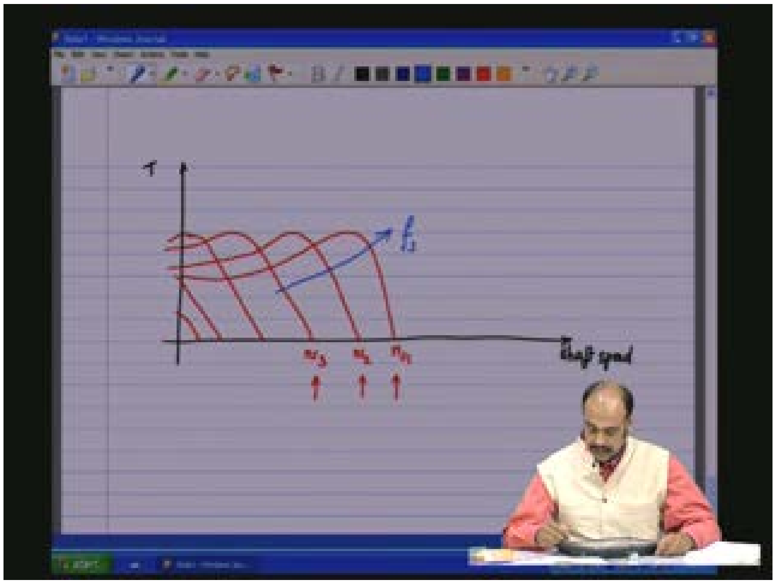

Now let us have a look at how the active power active power flows through the machine through the machine. So the machine, let us say through the machine we have the energy being input the electrical domain and will call it as P s as the power stator power which is put to the induction motor. So this is the power input to the stator and the stator we will represent it as a circle this is the stator. And in the stator whatever power comes into the stator there are some losses in the stator, what are these losses? So we could have some loss in the stator loss in the stator P loss in the stator which is due to i square R that is there is a stator coil and the stator coil is made up of copper and that is having a finite resistance so current is flowing through the resistance of the stator coil therefore there has to be i square R loss.

And the other thing like in a transformer we have the iron loss; the energy is transferred from the electrical domain to the magnetic domain through the core, the core is made of silicon steel, non-rain oriented silicon steel and that is called the iron loss or the core loss, this is basically the core loss and core loss can occur due to hysteresis or eddy currents like we discussed in the transformer. And then the remaining power after all these gets subtracted, goes into the magnetic domain and core loss component is removed and then it goes into the rotor. So the rotor the rotor input power we will call that one as P r so the power input to the stator P s some amount from P s is removed and goes off as i square loss this stator resistance and core loss and the rotor and the remaining power goes as P r into the rotor and in the rotor also we have these two losses: P loss in the rotor, this is also i square r loss that is the rotors have conductors and the conductors are having finite resistance and there is i square loss in the rotor. The rotor is also having a core material and therefore it also has its iron loss and we will call that one as we shall we shall call it as core loss. But what we could do is we can club the iron losses in the rotor and the stator because it is the same magnetic domain and put it as a single core loss component.

So what we will do we will say that the loss after the power input to the rotor a portion of it is lost in i square r, the iron loss comprises the total magnetic core loss including the rotor and the stator and then further this goes as mechanical power P m (Refer Slide Time: 58:48). Now this mechanical power P m could get some portion lost here as I put the loss here as friction losses because there could be friction in the bearings and b square omega sorry omega square b..... so what would be this: omega square into b would be the friction loss which we will see and that finally the remaining power is actually the shaft or the shaft power. So this is how the power flow diagram is in the case of the induction motor.

So you have the stator power which is P s which is the input to the motor that is the stator and out of that a portion P ℓ s goes off as a stator loss i square r loss and an amount of P i goes as the core losses in the magnetic domain of the stator rotor then the remaining portion P r enters the rotor and there is some amount which goes off as the copper loss P loss or P ℓ r as i square loss due to the rotor resistance conductor resistance, remaining power goes as P m and out of the P m an amount of power omega square b goes off as friction loss in the bearings and the remaining power is the shafts power which is available to the load, this goes to load.

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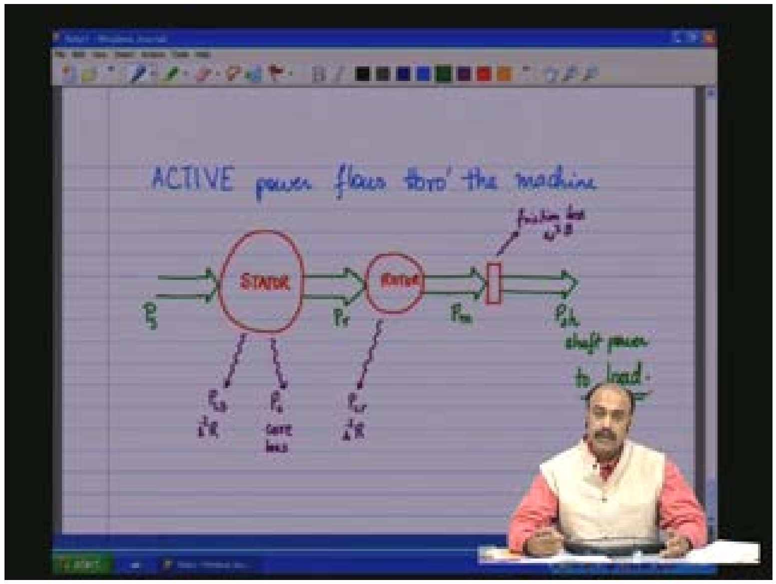

So this is the active power flow diagram. We stop here at this point and continue in the next class. Thank you.