Electrical Machines

Professor G. Bhuvaneswari
Department of Electrical Engineering
Indian Institute of Technology Delhi

Lecture: 29

3 Phase Induction Machines: Equivalent Circuit

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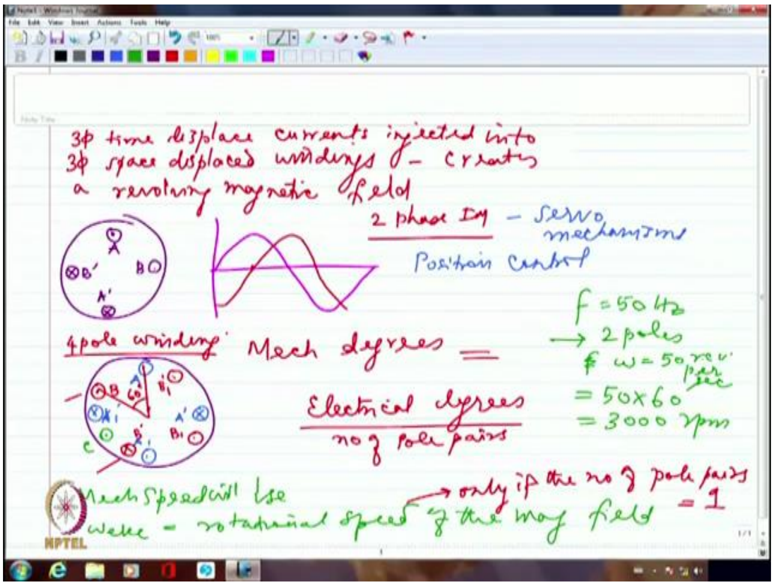

If we inject 3 phase time displace currents into 3 phase space displace windings, it is going to create a revolving magnetic field. So, we said basically 3 phase time displaced current injected into 3 phase space displaced winding. This creates a revolving magnetic field. In fact, although we have looked at the specific case corresponding to 3 phase it is true for any m phase that is, if I am talking about 2 phase or 3 phase or n number of phases, generally it will be true.

So, we are specifically taking a 3 phase case, there are 2 phase induction motors as well where we may have only 2 phase supply but, 2 phase supply is a not displaced from each other by 180 degrees, it is rather by 90 degrees, that all is the difference. They will be displaced from each other by 90 degrees, the windings will be also be displaced from each other by 90 degrees, which means if I have a 2 phase induction motor, I will have maybe A and A ‘ here.

Whereas, I am going to have the next phase somewhat coming like this, so this is dot and let us say this is cross, I will have this as dot and this as cross, this will be A phase whereas this will be B phase. And if I try to look at the 2 currents which are time displaced, this may be 1 phase and the second phase will be 90 degree shifted from this. This is the how it will be.

So, we are going to have basically 2 phase induction motor as well, but 2 phase induction motors are generally meant for a little lower rating, hardly ever we use it for a regular rotational mechanism with high power rating. We generally use it in some mechanisms, which are known as servo mechanism, so 2 phase induction motors are generally used in servo mechanism.

Student: Will the torque and power have a steady value in multi-phase induction motor? (2:57)

Professor: No, this will not have oscillation in the speed because both the powers together ultimately is going to give rise to again a constant value of torque and constant value of power that is one thing, and second thing is also, this will also create a revolving magnetic field which will work at the same speed as that of the frequency of the supply. So, that magnetic field is the one which is the root cause for the induction of the torque ultimately, so it will be a steady value basically because, the flux value is a constant value because of which everything ultimately becomes steady.

So, this is used in something called servo mechanisms, servo mechanism is mainly for position control. What we mean by position control? For example, if for you have a air conditioning unit, there are vents, you may like to keep the vents completely open, you may like to partially close it, depending upon the temperature, or for example, let us say there is a telescope, you want to observe a particular planet or whatever. And then you want to probably change the position of the complete arm by certain angle, so that you observe something which is very close to that.

So, how much is the angular movement you want to have, you might have some kind of a close loop control system, you will say whether you have reach this much of displacement or not. So, you might like to move only a little way, it is like a robotic arm movement. So, you might like to have only a very-very short movement, it is not for continuous rotation. It is only for a shorter span of movement, so those mechanisms are generally known as position control mechanism.

We would like to control the position by adjusting the position of a length, position of probably a robotic arm, pick and place kind of robot. In those cases, you might require this kind of a mechanism. So, this may not be of larger rating, but this will be specifically for a smaller rating, but still it might require a rotation for a short while. So, in those cases servo motors are used and 2 phase servo motors, 2 phase induction motor is very commonly used as a servo motor.

One more point I have to mention before we move on further is, we told that the induction motor can be wound for 2 poles, 4 poles, 8 poles, and so on. So, if it is, for example, 4 poles then what I will have is, if this is my stator, I will have basically this is A and this will be A' and this will be A_1 which is also corresponding to A phase and this will be A_1'. So, this please remember, I am going to have everything doubled, A phase winding was only A, and A' earlier. Now, I am going to have 2 positive carrying conductors, 2 negative carrying conductors for A phase.

Similarly, I will have to have for B phase also 2 positive and 2 negative, so which means rather than displacing from A, B was displaced earlier by 120 degrees, instead of that now it will be displaced only by 60 degrees, I will divide everything into by 2 basically. So, this will become B and this will become, again I have to draw here, B' and similarly, I have to have one more here, and one more here. Are you getting my point, so I will have now B_1 and B_1'? Please note the more the number of poles, the more will be the conductors that are carrying positive current, the more will be the conductors that are carrying negative current.

So, so many conductors will be you know making up for one particular phase, so if you actually look at it, although I am having if I look at the displacement between this to this, it is only 90 degrees, but that is going to be equivalent to the electrical displacement of 180 degree because electrically one is positive the other one is negative, so if I look at the electrical displacement it will be 180 degrees whereas if I look at actually the mechanical displacement it is only 90 degree.

So, this leads us to the discussion, on mechanical degrees and electrical degrees or mechanical radiance and electrical radiance. So, if I try to look at the electrical degrees that essentially depend upon how I have wound the windings, for how many poles I have wound the winding and from where to where it is going some positive to negative. So, in this particular case I have wound it for 4 poles. So, if it is a 4 pole winding, I would say 90 degrees of mechanical is equivalent to 180 degrees of electrical. So, I should say electrical degrees divided by the number of pole pairs is equal to the mechanical degrees.

Student: How do we decide that angle? (08:45).

Professor: 60 degrees, instead of 120 this should be 60, I have not shown it probably as 60, but what I am trying to say is this is the center, if I say this is the at 0 degree, this should be at 60 degrees, instead of 120 degrees, now, I will put it at 60 degrees. From here another 60 degrees, I will put C, and so on.

Student: If we have a two-phase induction machine, why isn't the current displaced by 180 degrees? (09:12).

Professor: See, it would have cancelled out each other that is the only reason why in 2 phase it is always 90 degrees, that is the only exception. If I look at 3 phase it is 360 divided by 3, if it is 4 phase it is 360 divided by 4. 2 phase is the only exception. Maybe you can try this exercise, try to give 180 degrees and see whether you will get the revolving magnetic field at all. You can do the same derivation what we did in the last class, and I do not think we will get it; it will cancel out that is what I think.

So, that is the reason why the 2 phase is always having 90 degrees basically. Now, if I am going to have, this angle has to be 60, because previously when I was doing between A and B it was 120 degrees. You remember, now everything is halved, everything is halved previously between A and A' it was 180 degrees now, between A and A' it is 90 degrees. So, what I am trying to do is compress one cycle of the electrical oscillation into half rotation, I am trying to compress one complete cycle of oscillation into half the rotation.

Previously, what happened was, one period of electrical oscillation was also equal to one period of the mechanical rotation. Now, I have just made it half, because I have put 4 poles instead of 2 poles, this is 3 phase. 3 phase I have only shown two, the third one, I have to show very clearly if I have to put the third one, I have to again delay it by 60 degrees from here, I am only worried that I will not be able to draw it very accurately, it will be a problem. That is the only thing.

So, I am going to get C here, right? and so on and so forth. So, we are actually looking at multiple poles coming into picture, in which case I am going to have the mechanical speed decreasing. So, the mechanical speed will decrease because it is actually divided by the number of pole pairs. I said originally that ω electrical will be equal to the rotational speed of the magnetic field. This we could say only because it was having only 2 poles or 1 pole pair.

So, this is true, only if P, the number of pole pairs, is equal to 1, if the number of pole pairs is increasing more than 1, then I have to divide whatever I am getting as the mechanical velocity that will be electrical velocity divided by the number of pole pairs. So, if I say that it is actually 50 hertz, if I say it is a 50 hertz supply, which is the normal supply what we use. So, if say that f=50 hertz, then I am going to get for 2 poles, I am going to get the rotational speed also as 50 revolutions per second, right? Because, both of them are exactly the same, 50 times oscillations correspond to 50 revolutions, so this is 50 revolutions per second or I can say 50 multiplied by 60 which is 3000 rpm, revolution per minute. So, if I have 2 poles in an induction motor you should be able to tell that the synchronous speed is 3000 rpm.

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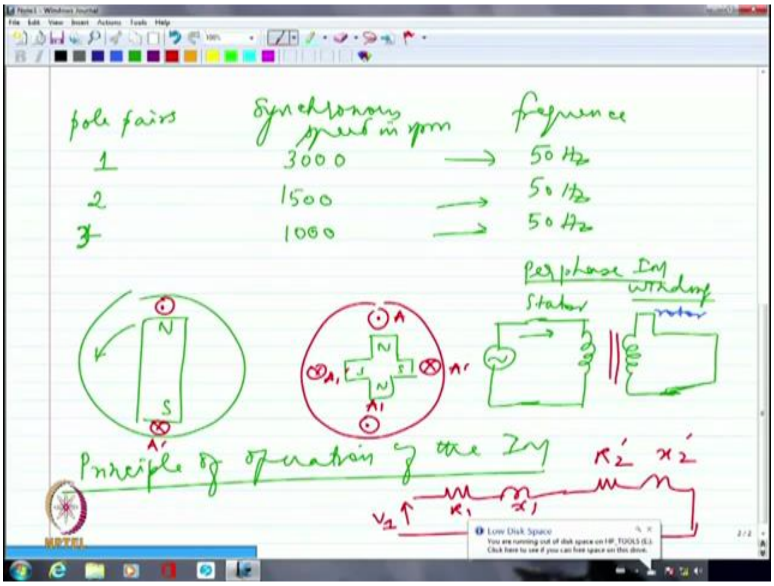

So, if I have instead, so let me write, pole pair and synchronous speed for the frequency, so if I say frequency remains constant at 50 hertz, if I have 1 pole pair, I am going to get 3000 rpm, if I have 2 pole pairs it will be 1500 rpm for 50 hertz itself. Please understand it has to be in pairs. I cannot have odd number. So, if there are 3 pole pairs I am going to have how much, 1000 and so on, and so forth. All the frequencies correspond to 50 hertz.

Student: What is a pole pair? (14:29).

Professor: Pole pair is, if I am going to have, let us say, a north pole and south pole, which is an imaginary pole, it is not really an actual pole, so it as though I am rotating this, so this is 1 pole pair, if rather than that, so previously I had A here, and A' here. So, I was creating only one north and one south, rather than that if I am going to have one A here, one A' here, one more A_1 here, and one more A_1' here.

Then I am going to have actually the poles as though, this is the North Pole, this is the South Pole, this is the North Pole, and this is the South Pole. So, that is equivalent to 4 poles being rotated. That is what it is. So, between this North Pole and South Pole although it is 90 degree displacement, I am actually having 180 degree traversal as far as the electrical current is concerned. So, essentially the traversal of the electrical degrees is being divided by 2 when actually I come to the mechanical degree. This is what I am trying to emphasize.

So, depending upon how many poles, for how many poles you have wound the induction motor stator, correspondingly our synchronous speed is going to change and according to the frequency as well but, the frequency invariably happens to be 50 hertz. So, you are going to have basically the number of pole pairs, which is going decide the synchronous speed. If you have understood this, now, we will go ahead and look at the principle of operation of the induction motor.

Student: In an induction machine how many pole pairs are there if there are 2 coil groups? (16:35).

Professor: If I have A and A', A_1, A_1', it is for 4 poles, if I rather say A, A', A_1, A_1' A_2, A_2', then there will be 6 poles. In which case, I have to rather look at 60 degrees equivalent to 180 degrees, you got my point, 60 degrees will be in mechanical, 180 degrees will be corresponding to electrical, that is all.

Student: Pole pair or poles? (17:19)

Professor: 4 poles or 2 pole pairs either way is fine. Many books write it in terms of pole pairs.

Student: In the servo motor example can we use stepper motor? (17:36)

Professor: Yes, very much, servo motor is one of the mechanisms which are used in position control; stepper motor can also be very well used. Only thing is servo motor can give better torque than stepper motor. Stepper motor is you just give a pulse, it creates a movement. So, the torque capability of the stepper motor is generally limited, whereas in the case of servo motor it can give continuous torque also, if it is needed to be given that way. That is not a problem.

Student: How the pitch of a stepper motor is fixed?

Professor: Pitch of the stepper motor is fixed depending upon how you have designed it.

Student: Why mechanical speed is reduced? (18:31)

Professor: See, if I am saying that from here to here, to come from here to here, actually one complete oscillation takes place in the electrical cycle, from this point to this point to come it is actually taking place in one complete electrical oscillation, one complete electrical rather half the electrical oscillation, because this is A and this is A', half the electrical oscillation, half the electrical oscillation corresponds to let us say 10 millisecond in a 50 hertz cycle. So, in 10 milliseconds my revolving magnetic field would have moved only from here to here, nothing more than that.

But, if it had been a 2 pole configuration only, then it would have moved from all the way from here to here. So, the way it is moving is from the north to south or from the positive to negative. So, when it is moving from the positive to negative that corresponds to half the cycle time, so that is the reason the more the number of poles, that angle traverse keeps on decreasing mechanically, that is the reason.

So, in general if I wind it for a larger number of poles, I am going to see that, generally, the speed is going decrease further and further. As a converse you may understand it better, when we talk about synchronous machines later. I am very sure, maybe I can just make a passing mention, if I have the North Pole, South Pole like this, may be in a synchronous machine imagine, this A is going to face first North Pole, this is going face North Pole.

Then within 90 degrees it is going to face South Pole, again it is going face North Pole and after another 90 degrees it is going face South Pole, now what happens as per as the induced EMF is concerned. The induced EMF will become, double the original frequency if it had been only one North Pole and one South Pole, A would have gotten induced EMF corresponding to North Pole after 180 degrees only it will get an induced EMF corresponding to south pole, so it is exactly matching with whatever was the mechanical rotation.

But, if I have 4 poles, it will face North Pole at 0 degrees, it will face South Pole at 90 degrees itself, but by then electrically it has completely reversed. So, electrical rotation in this electrical reversion has taken place even before it has traversed the complete 180 degrees as per as mechanical is concerned. So, that is the way it works, the number of poles increase then correspondingly the mechanical rotational speed is going to decrease.

Now, let us try to take a look at the principle of operation of induction motor. I am going to assume that the rotor is short circuited, if it is the cage rotor it is already short circuited, if it is not a cage rotor, if it is slip ring rotor, externally I have brought out 3 terminals, those 3 terminals have to be short circuited, if it is not short circuited the induction motor will not start rotation. I need to short circuit it, if I need to short circuit it, why bring it out, that is the question mark you may have, I might like to modify the characteristics at a later point.

So, I will have, I reserve the rights to modify the characteristics that all it means. So, unless I short circuit the induction motors rotor terminals, the induction motor will not start rotating. Let us see why. I have the stator, let me show stator per phase one winding as a simple transformer winding. There is nothing much other than that, and let us say the rotor winding again I am showing it as the simple transformer winding secondary, and not even worried about the turns ratio right now, so this is per phase induction motor winding.

That is what I am drawing. This is equivalent to primary which is the stator, and this is equivalent to secondary which is the rotor. Now, I told you that it has to be short circuited so I am short circuiting it. I have applied 3 phase currents to all the 3 phases of this induction motor stator windings. So, I have just connected a voltage source and I have applied the current. So, the current drawn should be actually enormously high, we talked about this, in the transformer if I short circuit it, I will have huge current being drawn if I am going to actually you know not include any load. Simply, short circuit it that is it.

So, in that case I am going to have a huge current drawn no wonder induction motor normally draws a very large current during starting, whether I like it or not, I would see that induction motors draw a very-very large current during starting because it is as good as the short circuited transformer. Only saving grace is, in the transformer I do not have any air gap between the primary and secondary, I try to minimize the air gap, I put also or sorts of things sandwiched coil or concentric coils, I try to do whatever I can to reduce the air gap, so that the magnetizing current drawn is minimal.

Here, I cannot do that because the rotor has to rotate, so I need to provide the air gap, so that air gap serves as a blessing in this case. That air gap actually will increase the reluctance because the increase of reluctance, it will draw definitely some current, agreed, but the leakage is also more. You remember, the equivalent circuit of the transformer, where actually we drew that this is R_1, this is X_1; X_1 was leakage and I had R_2, and X_2 was leakage clearly, and I had the entire thing connected; I am not even worried about the parallel parameter, if I have short circuited, so I am not really unduly worried about it, so I am going to apply V_1 here.

This is what we wrote as the transformer equivalent circuit, of course, R_2', X_2' fine. Now, X_1 and X_2' are quite large as compared to what I would have in a transformer because the leakage is definitely more, in the case of an induction motor because of the path that I have an air gap, so this is going to serve as the limiting factor of the starting current. If I had done the same short circuiting in a transformer, it will be 20 to 25 times the full load current where as in an induction motor it is about 6 to 8 times, which still is tolerable.

It is not as high as 20 to 25 times the full load current like what you see in a transformer, in the case of induction motor it may be 6 to 8 times, which is still okay, not too bad, fine. So now, what is going to happen is, this is going to definitely induce an EMF, the moment I initially apply a voltage that is going to create a revolving flux, the revolving flux is created in the air gap and the rotor is right now stationary. The rotor coil act like the secondary of a transformer, they get induced EMF, it is already short circuited, so it will also carry a current.

So, unless rotor current flows, I am not going to have any further action. Now rotor current is flowing because I have short circuited, this is the motor, no generator, electrical load you are talking about.

Student: Is the starting load zero? (27.17)

Professor: I did not say starting load is zero, I said that I will short circuit the secondary. Induction motor is short circuited if you look at the squirrel cage, you cannot remove the short circuit. Even in the case of a slip ring induction motor, unless you close the rotor circuit the induction motor action itself will not take place as we would see just now.

You will have secondary induced EMF in a transformer, the same way in the rotor there is an induced EMF. The moment there is an induced EMF because the rotor is short circuited, there will be a rotor current, the moment there is a rotor current, the rotor currents are not going to keep quiet, they are also 3 phase current after all. And it is a space distributed winding, if I am talking about the slip ring rotor. Even if it is the cage rotor the currents will distribute crisscross, but ultimately it is the 3 phase current in a distributed winding, so it is going to create another revolving magnetic field. So, there is a revolving magnetic field created by the stator winding current.

There is a revolving magnetic field created by the rotor current which is an induced current, I did not apply that current, it was because of induction. Now, these two currents are going to interact, these two fluxes are going to interact, when they interact, they will try to align themselves with each other. If the North Pole and South Pole of the stator flux is in particular direction, the South Pole and North Pole of the rotor will try to align itself with those North Pole and South Pole.

So, in the process the rotor is going to develop a torque, the motor is going to develop a torque, for the alignment purposes it will develop a torque. The torque will be in which direction, that is the next question we have to ask as well. Lenz's law comes in handy. So, Lenz's law will say that the torque generated would oppose its own root cause. What is the root cause, rotor current? And why was the rotor current actually flowing because there was a rotor induced EMF. Why was there a rotor induced EMF? Because there was a revolving magnetic field it is a flux which is changing.

North Pole and South Pole are continuously rotating, if the rotor had not been stationary if that had also rotated in the same direction as that of the revolving magnetic field, in the same speed it would have seen in a constant magnetic field. So, the torque would have a tendency to rotate the rotor in the same direction as that of the revolving magnetic field and try to push it towards the synchronous speed, go and lock up at the synchronous speed that is what it will try to push it.

Let say it really succeeds and it reaches a synchronous speed, the moment it reaches a synchronous speed, the rotor reach a synchronous speed, the rotor conductors would see a stationary magnetic field, there is no rate of change of flux, there is no rotor current, there is no rotor flux, there is no interaction, there is no torque, then the speed will fall. So, this will take place until a beautiful balance happens in such a way that the frictional torque or whatever is overcome.

If I do not have any load on the rotor shaft the frictional torque will be overcome with the small torque developed by a small current flowing by a small induced EMF, which will come in handy if there is a small relative velocity. So, what happens it starts basically from standstill condition, please, again I am repeating, I am trying to repeat the whole thing. The rotor was at standstill condition, it was as good as a transformer nothing better than that. And there is a revolving magnetic field already set up, because there is a revolving magnetic field I am going to see that continuously the North Pole and South Pole are rotating at a very-very fast rate that is how it is, I am talking about 2 pole machine, I do not want to go into multiple poles, fine.

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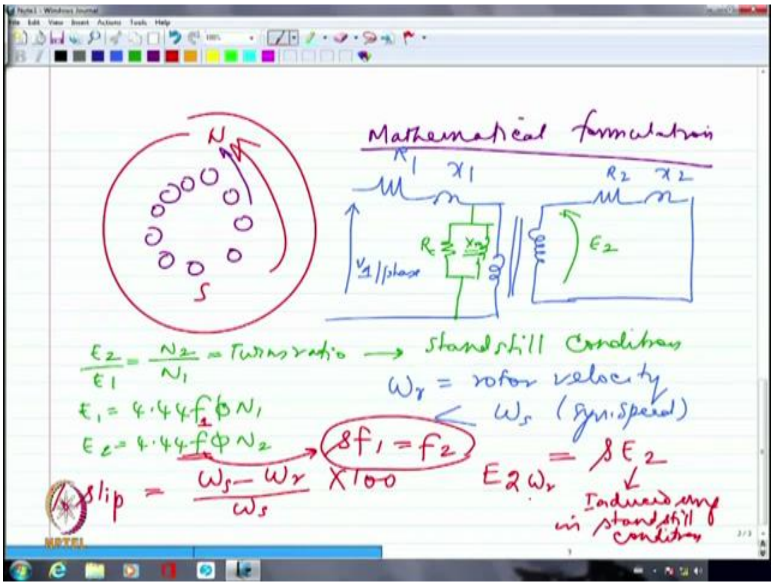

So, in a 2 pole machine, it is going to continuously rotate, and I have the rotor conductors sitting here, these are the rotor conductors, the rotor conductors are looking at this particular revolving magnetic field, it is definitely seeing a rate of change. So, there will be an induced EMF.

$\frac{d\phi}{dt}$ is there, there will be an induced EMF in the rotor. That induced EMF causes a rotor current, because I have short circuited the rotor, if I do not short circuit the rotor there will not be any current in the rotor, there will not be any flux in the rotor, there will not be any interaction, there will not be any torque production, the motor will not rotate. You cannot call it a motor anymore; it is like a transformer, open circuited transformer, nothing more than that.

So, I have to short circuit the rotor otherwise it will not work. So, I am going to have a rotor current, because of the induction, that rotor current is going to cause again a 3 phase currents flowing through the conductors, in space distributed winding of the rotor will cause another revolving field to be set up. That revolving field will try to interact with the stator created magnetic field, and that is going to produce the torque in the process of aligning with each other. That torque essentially will oppose whatever is the root cause for the torque production.

What was the root cause? The root cause was the induced EMF and induced current in the rotor. The induced EMF would not have taken place, or it would have been 0, if the rotor also had rotated at the same speed, then it would be seeing a stationary magnetic field. If both of them are running at the same speed, there is no way it would see any change in the magnetic field. So, in that case there will be induced EMF which will be 0, there will be no current, there will be no flux, there will be no torque.

So, the root cause has to be opposed, for opposing the root cause, it starts rotating in the same direction as that of the revolving magnetic field. Now, once the rotor picks up speed, it will go further and further until it reaches almost synchronous speed. When it reaches synchronous speed, the entire operation will seize to exist, it will stop because you are not going to have any more induced EMF, you are not going to have any more induced current, and you are not going to have any more rotor flux all that completely disappears.

If it disappears there is no torque, if there is no torque the rotation will automatically try to come down, the velocity will come down. The moment the speed comes down from the synchronous speed, again you have induced EMF current and torque and everything. So, induction motor can run only at the speed which is slightly less than synchronous speed, it can never ever run at the speed of synchronous velocity or it cannot run above synchronous speed.

Student: What happens if the rotor achieves synchronous speed? (35:21)

Professor: The rotor current will seize to exist, the rotor flux will seize to exist at that moment because of which the torque will also seizes to exist, because the torque seizes to exist it will have to fall down. There is no the way. And the moment it falls down even slightly, you will see that again the rotor current reappears, rotor flux reappears, torque is produced and where this delicate balance exists between the torque produced and the frictional torque requirement. That is where the motor will settle down. That is the reason why, when the motor is running on no load and I suddenly put the load on the motor.

Let's say, I hold probably my shaft of the induction motor, then what will happen immediately you would see that it will require more torque, if there is a requirement of more torque it will need more rotor current. If it needs more rotor current, the speed will decrease because of which the relative velocity will increase, that relative velocity will induce a larger EMF because of larger EMF there will be a larger current, and there will be a balance. That is what happens every time you load an induction motor.

We will talk about loading mechanism and so on and so forth further. So, I hope qualitatively you have understood how the induction motor runs, how it picks up speed. So, if you have understood this, now we will go to the mathematical formulation. So, if I look at the mathematical formulation, we are going to look at the 3 phase induction motor on a per phase basis. We are not going to look at it for all the 3 phases, so whatever we calculate we calculate for 1 phase multiplied by 3. That is what we are going to do.

So, let me first of all draw the equivalent circuit of an induction motor under standstill condition when it is not moving at all. So that is as good as a transformer, so all of us know exactly how the transformer equivalent circuit is drawn, so I can simply say this is R_1, this is X_1, and here is my magnetizing reactance or the actual coil and I am going to have this as the secondary and I am going to have R_2, and X_2. That is it. And what I am applying here is V_1 per phase.

I have to short circuit it definitely. I am first starting off with open circuited and I know for sure that it would have been V_2 at the terminal because hardly any current flows, in the primary also very limited current hopefully, so I am going to have V_2 as the induced EMF. I am not unduly bothered about that because I am going to anyway as he correctly pointed out, I have to short circuit it, so I have short circuited.

Student: Why you have drawn these two parallel lines between the windings? (38:43).

Professor: It is iron core. Core is still iron, there is an air gap, agreed, but there is a huge amount of ion involved in induction motor. The rotor core as well as stator core are made up of iron, there is the small air gap and you will make the air gap as thin as possible in an induction motor, as thin as it could be, mechanically whatever is permissible. So, it will be only a few mm, even in a very big induction motor, we will try to minimize the air gap as much as possible why, we will look at it again.

So, we are going to generally have very thin air gap, this clearly indicates the iron core corresponding to stator as well as rotor. There is iron core, of course no machine will work without ferromagnetic material, that is the reason we started off with magnetic circuits. And that is why we went into transformer because transformer and induction motor, resemble each other quite well, that is the reason.

Now, what is going to happen, if, of course, I have to include the iron loss component and the magnetizing reactance as well. That also I have shown now. So, this is going to be X_m and this is going to be R_c. Both will be there. I cannot help it; these will be there, definitely, so this is the equivalent circuit of the induction motor, when I was having basically that in standstill condition. It is not still it has not started moving as yet.

Please note that the X_m value in a transformer is generally really-really large. Because it consists primarily of only the iron path, there is nothing else. N^2/R is the inductance L_m, where N is the number of turns and R is the reluctance. The reluctance happens to be really-really small in a transformer because of which this X_m value is generally very-very large, whereas in the case of an induction motor the reluctance is somewhat larger because I have an intervening air gap.

Between the primary and secondary or stator and rotor windings the coupling is tight but, not as tight as what I would like it to be or not as tight as what it happens to be in a transformer. So, I will have X_m value to be somewhat smaller as compare to a transformer. If I look at the transformer if I say it is like 1000 ohms, this may be like 800 ohms or 700 ohms or even less that is how it is going to be. X_m value will be smaller. Now, I am going to have actually this EMF what is induced is E_2 and I am going to have, $\frac{E_2}{E_1} = \frac{N_2}{N_1} = \text{Turns ratio}$.

But this is true under standstill condition, and all of you know the equation for E_1 and E_2 also clearly, so I am going to have $E_1 = 4.44 f \phi N_1$. And similarly, $E_2 = 4.44 f \phi N_2$. Assuming that the same flux links both of them, I have neglected leakage this is what is the truth.

Student: How the turns ratio is decided? (42:47)

Professor: See, equivalent calculation exists, basically what we will be looking at this for what current rating I have designed. From the current rating of the secondary side to the primary side, we look at both of them rated currents and then arrive at the number of Turns ratio. So, we design it corresponding to your current and place the number of rotor bars correspondingly and then we calculate the number of turns correspondingly.

So, it is basically a pretty involved design as per as the squirrel cage is concerned. Although it looks very simple, but the Turns ratio in squirrel cage is not a straight forward one, it is very straight forward one in the slip ring rotor, it is pretty simple, whereas in the squirrel cage I have to calculate the equivalence in terms of current, torque and everything, from the torque I will decide, what is the current from the current I decide what is ultimately the Turns ratio. From the primary current to the secondary current. That is how we do it normally.

We are talking about basically per phase how many ever turns I have got, if I am talking about flux as flux per pole then I will also have N_1 as the number of turns per phase per pole. So, depending upon how I am, if I am connecting all of them in series or parallel those things also matter. Sometimes I may still connect some of the windings in parallel or series depending upon whether I want a high torque machine or high speed machine, high power machine depending upon my ratings, I might connect all the windings in series or parallel. Similar to lap and wave what we talk about in the case of DC machines.

So, now, I am going to allow the rotor to rotate, until now I did not even allow it to rotate, I was holding the shaft tightly, it is just, trying to rotate it has not rotated. Now, I am just taking off my hand it has started rotating.

Once it starts rotating, I told you that ω_r is that is the rotor velocity is ω_r, so the rotor velocity is going to be less than ω_s or the synchronous speed. So, we introduce one important term which we use repeatedly in induction motor called slip. Slip is defined as whatever is the difference between the revolving magnetic field speed and the rotor velocity. So, I am going to say slip is equal to $\omega_s - \omega_r$, but generally it is expressed with respect to ω_s because ω_s is a fixed quantity for a given frequency, for a given number of poles.

And I can express it as percentage slip in which case I will say multiplied by 100. When the machine started or it was just in standstill condition, the frequency induced in the rotor circuit is same as that of the stator circuit frequency; because it is like a transformer the rate of change of flux is similar. Exactly, but the moment the rotor starts rotating, the relative velocity is going to decline. Originally the relative velocity if I say that the revolving magnetic field was rotating at 3000 rpm, the rotor was at standstill condition, I was having 3000 rpm as the relative velocity between the rotor and the revolving magnetic field.

Now, the rotor has picked up speed slowly maybe it has come to 2000 rpm. So, this is the 2000 rpm revolving magnetic field is at 3000 rpm, the relative velocity is only 1000. So, obviously the rate of change of the magnetic field that the rotor conductor is going to visualize will also decline. Originally it was looking at the rate of change at the rate of 3000 rpm. Now, the rate of change will correspond to only 1000 rpm.

So, I will have clearly the induced EMF in the rotor that frequency will depend upon the relative velocity. Originally the relative velocity was corresponding to f_1, if I may call the stator frequency as f_1. Now, if the relative velocity has declined, this will correspond to sf_1, because s is the one which is indicative of the difference in the speeds between this particular revolving magnetic speed and the rotor speed.

So, I am going to have the rotor frequency declining as I go to higher and higher speed of the rotor. And the moment I reach synchronous speed there will not be any induction at all. So, the rotor frequency,f_2, will be 0, so there is no induced EMF as well. So, I should say once it starts rotating $f_2 = sf_1$. And E_2 at any ω_r will also become sE_2, because frequency very much comes in the equation of induced EMF.

So, I am going to have this as sE_2, where E_2 is the induced EMF in standstill condition. Are you clear with this? So, the moment the rotor starts rotating I am going to have immediately 2 repercussions, one is, I am going to have the frequency of the rotor circuit declining and the second one is, the overall induced EMF in the rotor circuit also declined. And both of them declined by a factor of s and s is definitely less than 1, you have seen that, because ω_r is also in the same direction so, slip, $s = \frac{\omega_s - \omega_r}{\omega_s}$. I am going to have slip to be very-very small.

Most of the times if the induction motor is on no-load; it is not loaded at all. The slip will be as meager as 1 percent or 2 percent, nothing more than that.

This one, E_2 at any other speed ω_r will be equal to slip times because the frequency has decreased; the rate of change has been what visualize by the rotor conductors that have declined. So, the frequency will decline, so the magnitude will also decline. So, if this is the standstill rotor induced EMF, it will decline by a factor of s, where s is actually the slip of the induction motor.

I have 2000 rpm as the revolving speed of the rotor; I have 3000 rpm as the revolving speed of the revolving magnetic field. Imagine I am a conductor sitting on the rotor, what will I see as the speed of that revolving magnetic field. That will be 1000. So, the frequency will correspond to 1000, the difference, got it, so that is the reason why it will correspond to the slip. So now, that I have this clear that this is going to be sE_2.

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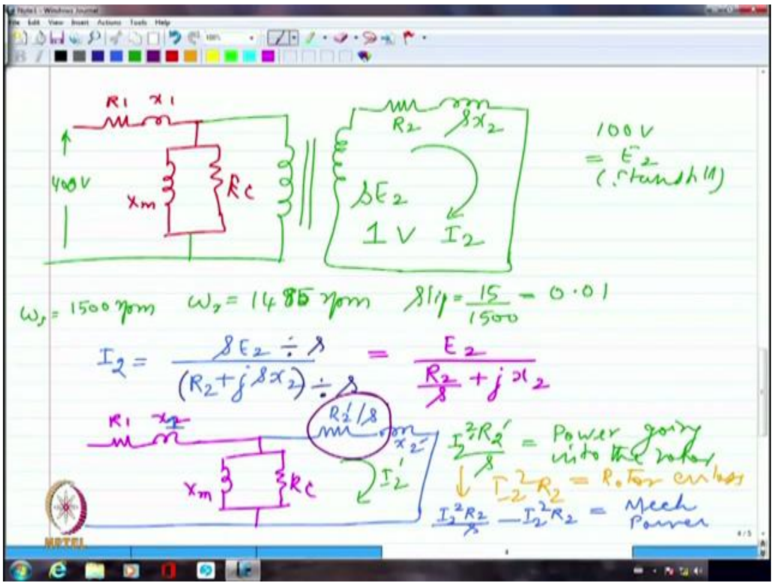

Let me redraw the equivalent circuit again, I have this as R this as X_1, I do have definitely X_m, R_c and I have here, the stator winding. Now, I am going to have the iron core as well, this is now sE_2, it is not E_2 anymore. Because it is in rotating condition, I am not drawing this for stationary condition this is going to be sE_2, I will have R_2, agreed what will happen to X_2, X_2 was originally, $X_2 = 2\pi f_1 L_2$. Now, it is $X_2 = 2\pi f_2 L_2$ because the rotor current is flowing through this leakage.

The rotor current is at a lower frequency. So, obviously the reactance offered by the leakage flux that will also be declining. So, I have to write this as sX_2, where X_2 was the original reactance corresponding to stator frequency f_1. Now sX_2 is the reactance offered by the rotor conductors corresponding to the new rotor frequency which is sf_1 which is f_2. So, now, I am going to have again the short circuit no doubt.

Let me try to talk about some values a little bit, if originally, I had applied may be some 400 volts, arbitrary I am saying, let say I have applied 400 volts and maybe I had gotten 100 volts here, at standstill EMF. Now, maybe I have a 1500 rpm induction motor which is ω_s is 1500, may be ω_r is something like 1490 rpm or 1485, it is easier for calculation 1485 rpm. Right? So, I am going to have the slip to be 15/1500, so that is going to be 0.01.

So, originally I had and induced EMF of 100 volts, now it has become 1 volt, it is a very-very small induced EMF that I am going to get, so this will become 1 volt and 1 volt with whatever is the resistance and leakage reactance has decreased, I agree the current is going to be definitely very-very minimal compare to what I got during starting, that is what you would see when you start an induction motor.

When you start you will see the ammeter shooting up, the current will really go up, and as it gain speed slowly you would see that the ammeter hand, the pointer falls and comes to the minimum, whatever is the minimum current that is needed, first of all, to develop that minimum torque, frictional torque, and also to establish the flux, X_m will require some current to establish the flux.

So, you will see that as the induction motor starts the current falls very rapidly, because of this particular reason. Now, this is I_2, I am calling this as the rotor current. Let me try to write the expression for the rotor current I_2, so I can write, $I_2 = \frac{sE_2}{(R_2 + jsX_2)}$. I have just written the rotor impedance as simple as that. Short circuited, so I do not have anything else. Let me divide the numerator as well as denominator by s. So, I can write this as, $I_2 = \frac{E_2}{(\frac{R_2}{s} + jX_2)}$.

There is no difference mathematically, the magnitudes are the same, but it makes a world of different electrically, because originally, I said that when the frequency of the rotor, was same as that of stator frequency, I had E_2 as the overall voltage. Now, I have come back to the same voltage and I said that previously, the reactance was only X_2. Now, after the rotor has started rotating, I got sX_2 as the reactance, now, I have gotten back to X_2 itself, so this talks about reduced frequency current whereas this talks as though the magnitude is the same but, the frequency is f_1, it is not f_2 anymore.

So, simple mathematical modification of dividing the numerator and denominator by s has kind of modified the frequency. It looks as though it has modified the frequency. In the transformer, I could connect the primary and secondary quite easily just by taking in the count the Turns ratio because the frequencies were the same. In this case, I could not have connected unless I convert everything back to f_1.

And this is the mode of operandi I have adopted to convert the rotor frequency also back to stator frequency so that I can interconnect both of them. So, what I am going to do now is, I can write R_1, X_1 and, of course, I can write the X_m and R_c, no problem, but the rotor side I am going to write rather than writing R_2, I am going to write $\frac{R_2'}{s}$, and then I am going to write X_2', and then just short circuit the whole thing. And this is the induction motor equivalent circuit per phase.

What we have done is to convert the rotor frequencies into equivalent stator frequency, only what we have adjusted is the resistance value. And the second thing we have done is transported all the secondary side parameters to the primary side by taking care of the Turns ratio which is not very easy to decide, I agree in a cage induction motor unless we have all the designed parameters.

This is the overall equivalent circuit of the induction motor where the resistance inherently what was there was R_2 or R_2' if I look at it from the stator side, but I have divided that by s to take care of conversion from the rotor frequency into stator frequency. We have a little bit more of work to do on this equivalent circuit.

This is $\frac{R_2'}{s}$ multiplied by $I_2'^2$ this is what is the power going into the rotor ($I_2'^2 \frac{R_2'}{s}$) this is the power that is going into the rotor per phase, of course, everything we are talking about per phase. I_2 is actually the current that is flowing, $I_2'^2 \frac{R_2'}{s}$ will be the overall power that is actually entering into the rotor. There will be definitely dissipation that will be $I_2'^2 R_2'$, that will be the dissipation.

So, whatever is the power that is getting into the rotor part of it will be dissipated in the rotor resistance. Rest of it is the one which is converted into mechanical power. So, we are going to bifurcate this power into 2 portions, so we would say out of this $I_2'^2 R_2'$ is going to be the rotor copper loss. And whatever we get as the, difference between these 2 that is $I_2'^2 \frac{R_2'}{s} - I_2'^2 R_2'$, because otherwise where will the motor get the power to rotate from, it has to get it from here.

I have got this as the total input power to the rotor out of which I know for sure that something has been dissipated as the rotor copper loss. That is $I_2'^2 R_2'$ within the resistance, I know physically the resistance only R_2. But I have represented that by R_2/s so I know that I am probably supplying more amount of power than what is required by the rotor to dissipate that more amount of power is the one which goes towards mechanical power conversion.

From electrical power now that is getting converted into mechanical power which is enabling the motor to rotate. So, I should be able to write this resistance which I got as R_2'/s.

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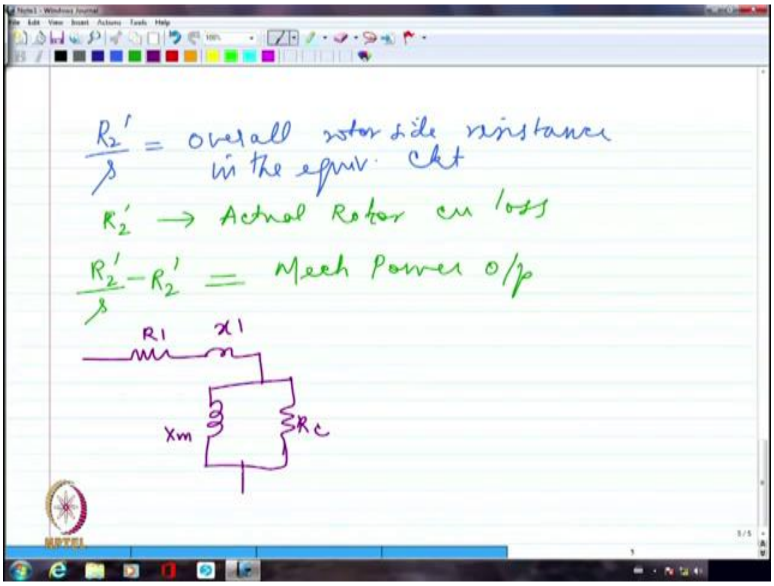

This R_2'/s was the overall rotor side resistance in the equivalent circuit. This I am going to bifurcate into 2 portions, one is R_2' itself which is corresponding to the actual rotor copper loss component. So, I can say $(R_2'/s - R_2')$ is the one which is going to represent the mechanical power output. Of course, I have to multiply everything by $I_2'^2$ I have just eliminated $I_2'^2$ because everywhere that is a common factor. That is all. So, I can draw now the equivalent circuit. Like this, saying that this is R_1, this is X_1, this is X_m, this is R_c.

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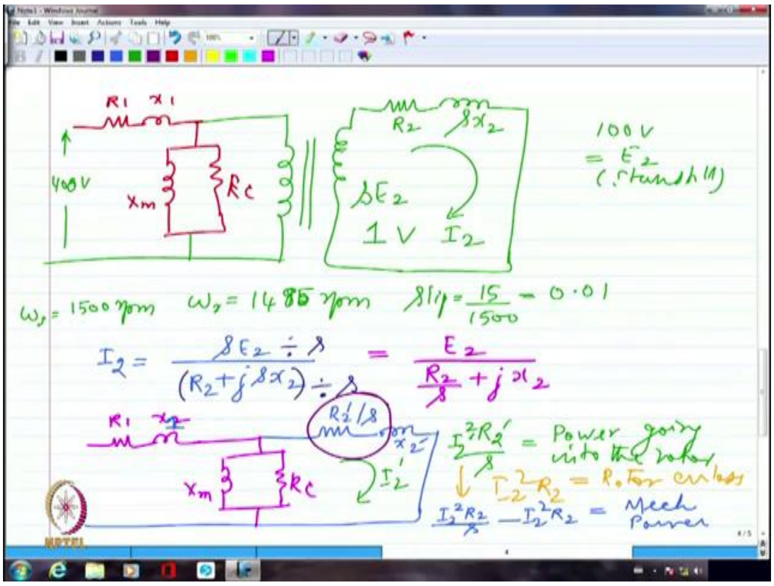

The total power that had come in was basically $I_2'^2 \frac{R_2'}{s}$. I can write it as $I_2'^2 \frac{R_2'}{s}$ or $I_2^2 \frac{R_2}{s}$ because power is in variant, whether I am looking at it from the primary side or secondary side power is invariant, it is not going to change, that is how we did the conversion also, $R_2' = R_2\left(\frac{N_1}{N_2}\right)^2$. That is what we did.

So, I am inputting a power which is corresponding to $I_2'^2 \frac{R_2'}{s}$ per phase. Out of that $I_2'^2 R_2'$ is the one which is getting dissipated in the actual rotor resistance. There is definitely more excess power, please again think about it. Let us say 100 watts was $I_2'^2 R_2'$, slip is 0.01 or 0.02, so 100 divided by 0.02 is the total power that I have given the rotor circuit. Out of which only 100 watts I have dissipated. What happens to the rest of the power?

The rest of the power is the one which is going toward rotating the mechanism completely otherwise, there is the power coming from, so I have given 100 divided by 0.02 as the total power to the out of which 100 watts has gone dissipated. So, I am going to have rest of the 100 by 0.02 minus 100 as the total power that goes towards mechanical power conversion.

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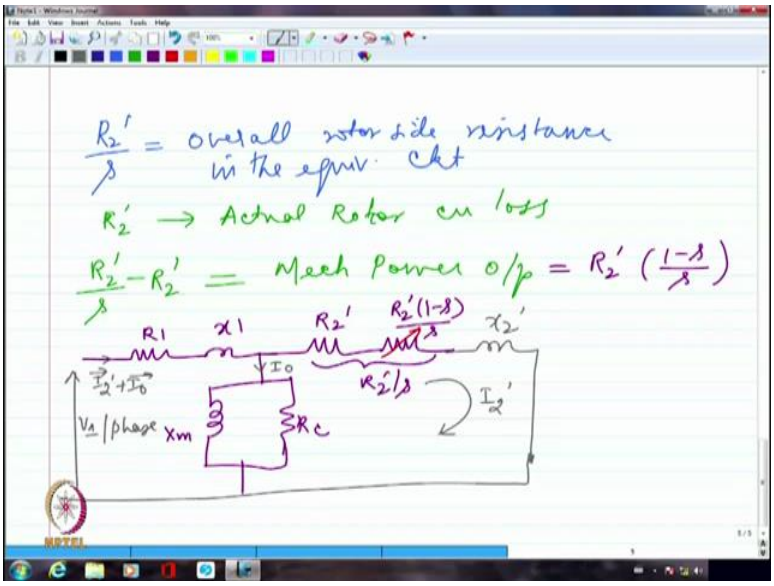

So, I am going to have basically, here I am going to divide this into 2 portions one is going be R_2' which is the inherent resistance of the rotor circuit converted into the primary side this I can write this as $R_2'\left(\frac{1-s}{s}\right)$, this is same as that so I can write here, as $R_2'\left(\frac{1-s}{s}\right)$both these together I am having $\frac{R_2'}{s}$. Originally, I wrote it as $\frac{R_2'}{s}$.

Now, both of them I have bifurcated into 2 different portions, that is all. And please note this is mechanical power, so this can be a variable one depending upon how much of load I am drawing, how much of load power I am drawing, depending upon that it is going to change because the slip will change, the speed will change, if I load the motor more and more the speed will come down, the slip will increase.

So, more power will be actually passed on to the rotor circuit which will be converted into mechanical power. More power will be converted into mechanical power as well, so now, I will have, of course, this will be X_2' and then I am going to complete the circuit here, and this is V_1 per phase. Now, I should be able to write this is I_2', this is I_0 which is the no-load current and this will be the summation of $I_2'+I_0$.

Which is I1, that is $I_1=I_2'+I_0$,is this clear, this is the overall equivalent circuit, per phase equivalent circuit of the 3 phase induction motor from which we will calculate everything for 3 phases by multiplying by 3, but if star connected we will have the line current equal to the phase current, if it is delta connected will have line current equal to $\sqrt{3}$ times the phase current. Whatever we are doing is per phase, everything will be converted into 3 phase line or phase quantities by multiplying by the appropriate factors.

Student: Will X_m and R_c remain the same?(68:46)

Professor: Yes, that will not change because I am looking at the whole thing only from the stator side, no change at all, because it is stator is still at f_1, stator is not rotating, stator conductors are continuously looking at the frequency only as f_1. Yes, because this is essentially carried by the stator winding to establish the flux initially. It is the same thing like transformer, the mutual flux is established initially by the primary or whichever winding I am exiting it is the same thing.

Only thing I want you guys to recognize is that the DC machine we had a field system separately armature system separately, here I am having the field also is established by the stator side current, there is no separate current. I am not having a separate field system and the rotor is carrying a current which is producing the torque, but the current is also coming from the stator, where is it coming from? It is like a transformer. So, if I look at the stator current, the stator current will you know contain the magnetizing current as well as the torque producing component of rotor current.

Both will be there so, I will never ever have an induction motor work in unity power factor. I will never ever have an induction motor working on leading power factor; it is an inductive effect always. I will need that current no matter what to establish the flux. And, if I am establishing the flux it is inductive. No way it can be capacitive, no way it can be resistive, so always an induction machine will work at lagging power factor only.

It cannot work in leading power factor, or unity power factor, at any point in time this is one of the major disadvantages of induction motor. We talk about all positive things; of course, this is one of the negative things. So, just to reiterate what we said, we have a rotor input which is corresponding to $I_2^2 R_2 / s$, and rotor output which is corresponding to $I_2^2 R_2 \left(\frac{1-s}{s}\right)$, and the copper loss which is corresponding to $I_2^2 R_2$ let me write it down, again.

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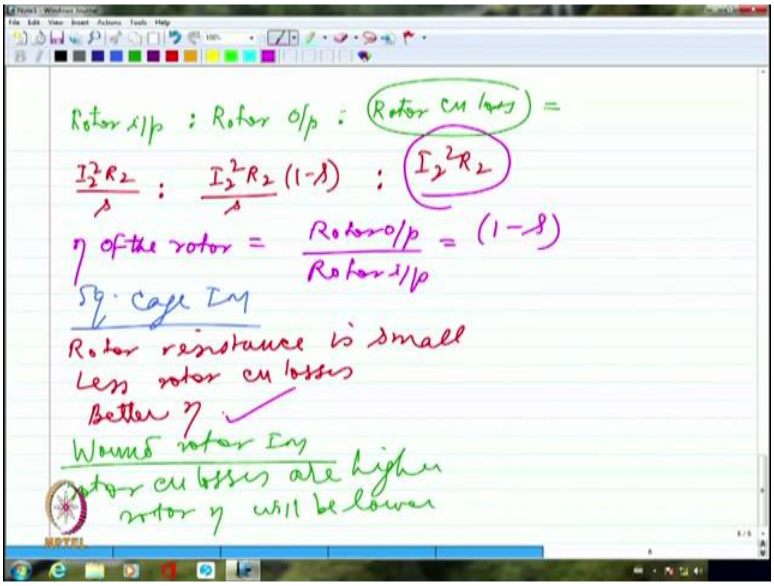

So, I am going to have

the rotor input: rotor output: rotor copper loss.

I am just trying to write it in terms of ratios, so this is going to be

$$I_2^2 \frac{R_2}{s} : I_2^2 R_2\left(\frac{1-s}{s}\right) : I_2^2 R_2$$

So, if I take what is the efficiency of the rotor that is actually rotor output divided by rotor input, so that will be 1-s. So, I am going to have the lower the speed of the induction motor. the lower the speed of the induction motor I am going to have larger and larger slip, if I have larger and larger slip; very clearly $1-s$ is going to be smaller and smaller.

If I have the induction motor, let us see 1500 rpm is my normal synchronous speed, if it is working at 1470 rpm, 30 divided by 1500 is going to be my slip, which is actually 0.02. So, if it is 0.02 is the slip, I am going to have the efficiency to be 98 percent. If rather my motor works only at 1440 rpm lower speed, now 60 is the difference in this speed between the revolving magnetic field and the rotor speed. 60/1500 is my slip, which means that is 4 percent, 6/15, so that is going to be 4 percent.

If 4 percent is the slip, I am going to have the efficiency to be 96 percent. So, lower the speed of the induction motor, more is going to be the losses or less is going to the efficiency. So, if I have a larger rotor resistance for a given current, I will have larger rotor copper losses. For a given chunk of total rotor input power, I will have larger chunk of rotor copper losses, which means I am going to have less and less mechanical power, if I have a less mechanical power in all probably it will be able to rotate only at the lower speed.

So, the slip is going to be larger, so if I look at squirrel cage induction motor which has thick rotor bars, the resistance is small, the rotor resistance is small, the rotor copper losses would be small, normally for a squirrel cage induction motor. So, I can say squirrel cage induction motor, rotor resistance normally will be small, unless I specifically make the rotor bars with some high resistance material, which is very-very unlikely. I, why would I like to have, lower efficiency. So, I better not make it with high resistive conductors, so I will make it with aluminium or copper because of which, the resistance of the rotor bars is going to be small so I will have less rotor copper losses. So, better efficiency.

Student: While writing the expression for efficiency of the motor why are we considering the input to the rotor and why not the input to the stator? (76:19)

Professor: I am currently looking at the rotor, we will definitely have to look at that as well we will have to say $I_1^2 R_1$, I am trying to differentiate between the 2 types of rotor. So, I am specifically orienting my discussion to rotor because I want to differentiate between the 2 types of rotor. That is the only reason.

Student: Efficiency of the machine will depend on the rotor efficiency?

Professor: Absolutely, I am talking only about the efficiency of the rotor which will have at least some amount of repercussion on the overall efficiency.

So, I am looking at only from the rotor side currently we will look at the overall efficiency, of course. On the other hand, if I look at wound rotor induction motor, I will have rotor windings, if I have to have wires going around in the form of winding it has to be any day thinner than my rotor bars. Rotor bars are thick, whereas the wires that are going around in the wound rotor induction motor; they have to bend, they have to be taken round and round.

Here, I do not do anything I just put the bars, and 2 end rings I put and short circuit, nothing more than that whereas here I have to go round and round taking the entire winding in the form of not really lap and wave, we call this as the armature winding for the AC machine. So, we will have to go, may be from North Pole to South Pole to North Pole to South Pole, we have to go round and round. Go through the slots and so on, so it has to be somewhat thinner wire otherwise I will not be able to take round and round.

So, generally, slip ring machines will have somewhat higher rotor resistance as compared to the cage machines, squirrel cage machines which are of the same rating, I am talking about similar rating, even if I compare similar ratings if I try to look at the resistive value, resistance value of a slip ring rotors resistance versus what is the resistance of the cage rotor, cage rotor will normally have lower resistance which is definitely good from efficiency view point. So, I would say rotor efficiency or rotor copper losses will be higher here, and so rotor efficiency will be lower.

Student: Ma’am, why lower rotor efficiency? (79:01)

Professor: If I am talking about copper losses to be higher, see I am bifurcating the total rotor input between two components. What are the two components? One is rotor copper loss the other one is mechanical output, so if I increase the rotor copper loss it goes without saying that the mechanical output, has to come down as simple as that. Let us say I am giving totally 400 watts, in the squirrel cage rotor may be 50 watts have gone as copper loss whereas in wound rotor motor 100 watts will go as copper loss.

So, obviously I will have only 300 watts left over as the output in the case of slip ring rotor whereas in the other cases it will be 350 watts so, if I assume that I am giving the same amount of rotor input to both the machines which one will give me a better output. Mechanical, right, even the input depends upon R_2, I agree, but out of $I_2^2 R_2 / s$ how much I am dissipating as the copper loss that determines how much is coming as the output.

So, if I dissipate more and more obviously, I will have only less and less left over. After removing the heat loss exactly, so the heat loss is larger, I will remove more, so what is left over is less.

I am giving 400 volts let’s say it is 50 hertz induction motor 10 ampere of current. $\text{Input} = \sqrt{3} \times 400 \times 10 \times \textit{power factor}$, let us say power factor is 0.8. That is the input that is set in stone, I cannot do anything. From there already $I_1^2 R_1$ is gone, some core losses are gone let us say, those are some factors may be some X and Y.

Now, what is left over is $\sqrt{3} \times 400 \times 10 \times 0.8 - X - Y$. That is available as rotor input, no matter what you put 10 ampere of 10 Ω of resistance 20 Ω of resistance for the rotor, or 5 Ω of resistance for the rotor, it does not mater, this is what is available which is crossing the air gap, and going into the rotor. That we are equating $I_2^2 R_2 / s$ that is it, that is the set in stone.

You got my point it is not being generated by the rotor the power is being given by me not by me 3 phase supply. 3 phase supply is giving the power out of which some chunk has been eaten away by stator copper loss; some chunk has been eaten away by stator core loss. Rest of it goes towards the rotor and I am equating that to $I_2^2 R_2 / s$, it is my fictitious statement, I can write that as $E_2 I_2 \cos\phi_2$, who cares, is also true.

$E_2 I_2 \cos\phi_2$ is the one which is actually the power that is going into the rotor the same thing will come out to be $I_2^2 R_2 / s$ if you actually calculate the whole thing. So now, I can say that squirrel cage definitely is better in terms of efficiency because of these particular reasons, so why not use squirrel cage everywhere, it is fantastic, Right? Might as well use the squirrel cage everywhere, why have another type of induction motor at all. Let me look at the starting current, what happens to the starting current.

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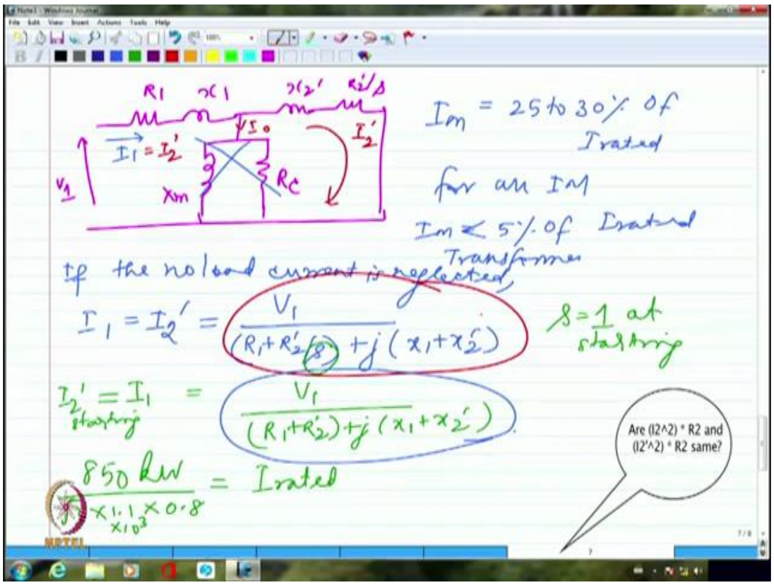

I have R_1 I have X_1, I do have definitely X_m and R_c, I have R_2' this is X_2', this R_2'/s. What I am applying is V_1, for now let me forget about this component although this should not be neglected, I agree it should not be neglected because I am having a good amount of reluctance in the induction motor, the current drawn under no-load condition of an induction motor which is drawn by X_m and R_c is not going to be really-really small, as small as transformer because transformer requires very minimum magnetizing current, very high permeability.

Very-very small reluctance that is the reasons why magnetizing current of the transformer is only less that 5 percent, less than 2 percent in most of the cases whereas in an induction motor the magnetizing current generally is almost 25 to 30 percent of I_{rated}, for an induction motor. Whereas in the case of transformer, I_m is only less than 5 percent of I_{rated}, for a transformer this we talked about repeatedly when we were discussing transformers.

Look at the difference very clearly, I cannot neglect but for the heck of it right now I am neglecting. So, if I look at the current I_1 if the no load current is neglected, I can write $I_1 = I_2' = \dfrac{V_1}{(R_1 + R_2'/s) + j(X_1 + X_2')}$. What I have written is the overall impedance of the induction motor, $R_1 + \dfrac{R_2'}{s}$ is the real part of the impedance.

$X_1 + X_2'$ is the imaginary part of impedance. Now, during staring if I look at what is slip,

$s = \frac{\omega_s - \omega_r}{\omega_s} = \frac{\omega_s - 0}{\omega_s} = 1$; ω_r,=0. So, slip s=1 at starting. So, what I am going to get is,

$I_{1(starting)} = I_2'(starting) = \frac{V_1}{(R_1 + R_2') + j(X_1 + X_2')}$. That is the starting current. R_2' is really-really small for a cage induction motor.

Whereas R_2' is probably not so small for slip ring induction motor and one more advantage I have, slip ring induction motor I have brought out all the terminals. I can always attach some resistance; I can attach 3 phase resistance, increase the overall resistance of the rotor. If I want, R_2' is the inherent rotor resistance, I can always add an external resistance and increase the overall resistance of the induction motor to start with.

Which means I will definitely get a reduction in the current I told you, that induction motors are at very-very high rating also if it is the 850 kilowatt induction motor and if it is working at 11 kV or 1.1 kV or whatever, you can calculate for an 850 kilowatt induction motor what is the rated current. $I_{rated} = \frac{850kW}{\sqrt{3} \times 1.1 \times 10^3 \times 0.8}$

So, this is going to be, I_{rated} for this induction motor which will be of the order of 1000 of amperes in all probability. So, I am going to have may be some 1000 of amperes of current. Starting current will be 6 to 8 times, normally. So, I am going to draw 8000 amperes of current. The power system authorities will come and disconnect my power supply immediately.

So, including a rotor resistance in the induction motor external to the rotor circuit is possible only in slip ring rotor induction motor, it cannot be done in the case of a squirrel cage induction motor. This including a resistance will help me actually improve the starting performance at least by reducing the current. So, I will not be able to start an induction motor, which is rated for extremely large values without including a rotor resistance or without including any other starting means.

I have to include some kind of starting techniques in my induction motor, actually the power system authorities generally put up a rule, it is there in India also people flout the rule here and there, but, if an induction motor is rated for more than 50 kilowatts you cannot start it directly without including any other starting methods. If you try to start an induction motor beyond 50 kilowatt capacity directly by connecting it to the 3 phase supply, you can be penalized.

This rule is there because the induction motors take heavy starting current, you will see at dip in the voltage normally, you will see like a welding equipment if you connect directly to the supply you will see all the light going very low, the same thing you can observe if you are starting a very large capacity induction motors because the voltages will really sink, it will become very low normally, for a short while until the machine get started that is the reason. So, slip ring induction motor comes in really-really handy when you want to tamper and somewhat modify the characteristics of the induction motor.

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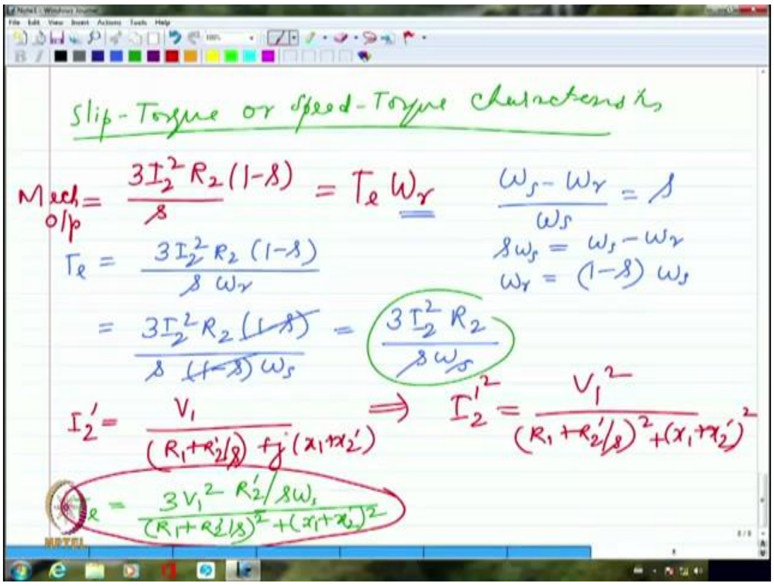

So, that leads us to the discussion on slip torque characteristic or speed torque characteristics. So, let us try to first of all just like how we saw for the DC machine speed torque characteristics, let us try to take a look at the speed torque characteristics of the induction motor.

So, we said that $\text{Mechanical power output} = \frac{3I_2^2 R_2(1-s)}{s} = T_e\omega_r$ Please, see the 3, never forget the 3 when you are doing the induction motor problems, we do everything per phase multiplied by 3, so this is going to be the mechanical output.

That has to be clearly equal to the torque that is generated multiplied by the speed of the induction motor. Now, we also said slip, $s = \frac{\omega_s - \omega_r}{\omega_s}$. So, I can write always from here $s\omega_s = \omega_s - \omega_r$ which means I can say $\omega_r = (1-s)\omega_s$. So, let me put this here, this ω_r, let me try to substitute here, so from which I can write

$$T_e = 3I_2^2 R_2 \frac{(1-s)}{s\omega_r}$$

$$= 3I_2^2 R_2 \frac{(1-s)}{s(1-s)\omega_s} = \frac{3I_2^2 R_2}{s\omega_s}$$

So, this gives me the expression for torque, so what I get here will be the torque in newton meters.

Now, we just neglected the parallel component of current or the no load current let me do the same thing. What we wrote as I_2, we wrote it here, Right? this is what was our I_2, right, in starting we neglected s, which is equal to 1 at starting, so we just removed that otherwise I have to include that as well, so this is my current actually I should have rounded this expression, this is what is actually my expression for the current, let me substitute that here.

Let me write first of all what is I_2', $I_2' = \frac{V_1}{(R_1 + R_2'/s) + j(X_1 + X_2')}$, from which I can write, $I_2'^2 = \frac{V_1^2}{(R_1 + R_2'/s)^2 + (X_1 + X_2')^2}$ Just substitute that in the torque expression. So I get $T_e = \frac{3V_1^2 R_2'/s\omega_s}{(R_1 + R_2'/s)^2 + (X_1 + X_2')^2}$.

That is the expression for torque when I neglect the no-load current, which is again a pretty important expression in an induction motor, this one of the most important expressions. So, there are some important expressions one of them is here, the other one is here. So, these 2 are quite important as far as the induction motor is concerned.

Student: What is I_2'?

Professor: I_2 is the rotor current, I_2' is the rotor current visualized from the stator side neglecting the no-load current.

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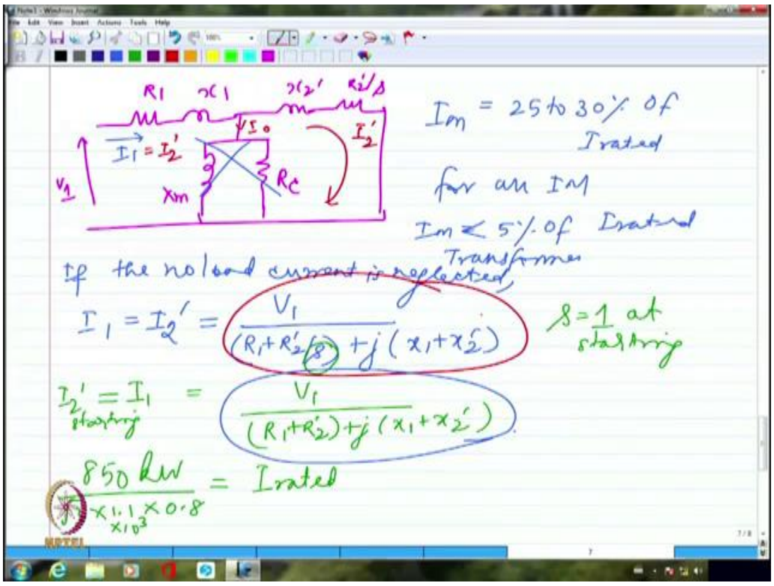

This is the no-load current; I just said forget about the no-load current, this is I_2'. So, I will get $I_1 = I_2'$, if I neglect the no load current.

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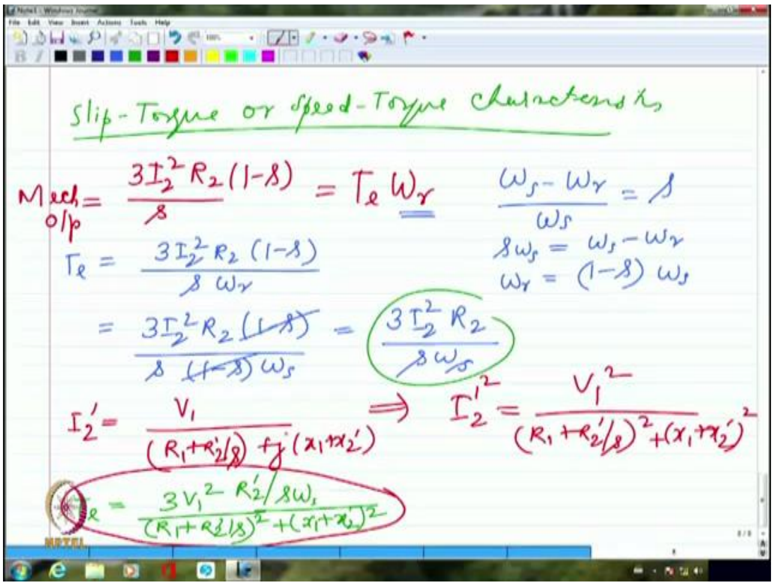

So, I told you that power is in variant $I_2^2 R_2 = I_2'^2 R_2'$. So, I replace R_2 also by R_2' so I do not think there is any mistake.