Basic Electrical Technology
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Lecture -36
Induction Motor

Hello everybody, in the last class we had started our discussion on induction machines or the induction motors. Induction motors are very popular; something like 80 percent of the prime movers all over the world use induction motors for various applications so it is important that we learn about the induction machine. So we began our discussion by an initial comparison of the induction motor with the 3 phase transformers.

In the case of 3 phase transformers we had the energy movement from the electrical side into the magnetic domain and then back again into the electrical domain in the secondary. In the case of the induction motor it is also similar in the sense that you have a primary side coil called the stator, the secondary side coil called the rotor plus there is also another domain called the mechanical domain so you have the energy which is moving from the electrical domain into the magnetic domain and you can tap energy in the electrical domain or in the mechanical domain or both depending upon the type of the motor.

So, in the induction motor you have two main categories the squirrel cage induction motor where the rotor is shorted you cannot take any electrical energy from the rotor so all the electrical energy can be taken only from the mechanical domain. So you have the electrical domain magnetic mechanical domain as the path for the energy and in the case of the other category the wound rotor induction motor or the slip ring induction motor you have the electrical domain, energy enters the machine goes into the mechanical domain and the energy can be tapped out either in the electrical domain of the rotor or the mechanical domain of the rotor. And all the working principles operating principles of the transformers are valid even in the case of the induction motor.

We have the Faraday's law of electromagnetic e is equal to Bℓv which induces the voltage on the rotor conductors and thereby a current in the rotor conductors by virtue of the relative motion of the rotor conductors with respect to the field inside the machine. And because there is a current in the rotor conductors and there is a field in the machine, by virtue of the Lorentz law that is force is equal to BIL there is a force which is induced on the rotor conductors and the accumulated force on all the rotor conductors creates a torque and which makes the rotor move. So this is how we get the mechanical motion. We will look into the details of that much later. But the important concept now is that how do we bring about a relative motion between the field in the motor and the rotor conductors.

Now, to achieve that we use the 3 phase source. So in the 3 phase source we have the three sources wherein they have the same effective amplitudes however they are 120 degrees apart in time. Now applying one more constraint that is these the currents from these three sources flow through coils in the stator of the motor wherein the coils are physically located in space 120 degrees apart, a combination of these two produces a rotating magnetic field. So let us now see how this is created. First we shall have the rotor represented as a nice circle here and let me have ……….. the circle is not as nice but let us into the circle and let us have the 3 phase currents flow through three poles electromagnetic poles located 120 degrees spatially apart.

So let us say the A phase current flows through a A phase this is let us say flows through A phase poles set and let me indicate the pole the salient pole in this manner so you have one pole pair per phase as shown here (Refer Slide Time: 6:03) then let us have 120 degrees apart one more set of poles which are like this along this axis as shown, now this is 120 degrees apart 120 degrees. Now along this also I am going to have some fixed stationary poles pole pairs of course, you cannot have single poles; you should always have a south and a north pole. Now one more pole set which is placed 240 degrees with respect to the A axis and this is 240 degrees with respect to A axis 240 degrees, this is the C axis and of course the red one is the B. So on the C axis also we are going to place the stationary poles as shown here shown in this manner you see.

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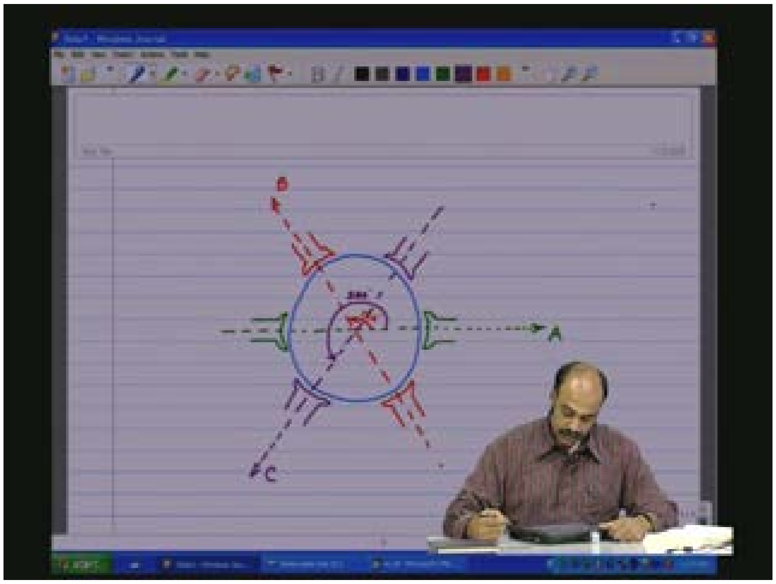

Now we can of course connect all these into the same structure and that structure is called the stator. So all these are connected into the same structure and that structure is called the stator so we have the stator like this as shown with salient poles projected inward and we have the rotor in blue. Now let us say we have the 3 phases and let me take the let me take the A phase and the A phase you have a coil as shown here on the stator and internally the same current whatever is entering here let me call this one as I A from the A phase source. Internally this coil is then brought in and connected wound around the other part of the pole to get the south pole and taken out. And then we have the B phase so I am going to take the B phase part wound wind it around the pole here then bring it to the other side and then take out in this direction. So we have I B which will flow here and then I C so we will take I C which is going to flow like that taken all through like this and goes out.

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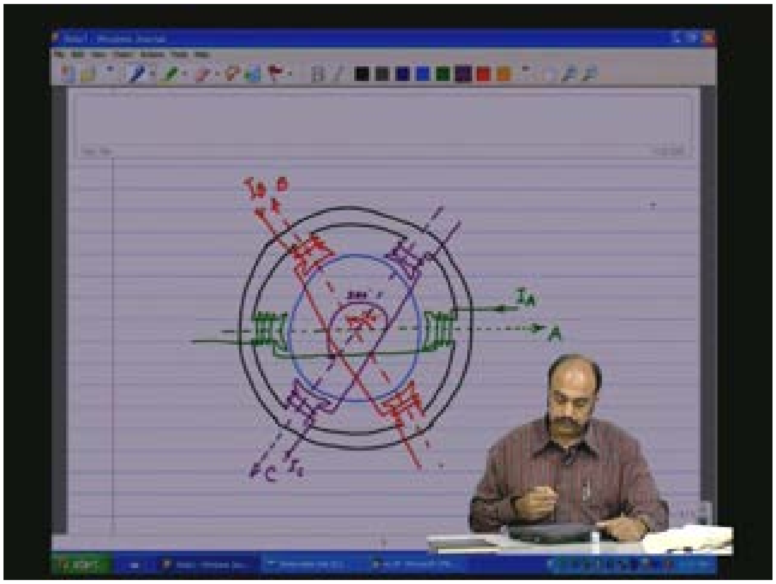

Now the other ends are joined together. So let me join this end, this end and this end (Refer Slide Time: 11:06) and that is called the neutral. So, as the other ends of the coil are joined together that is the neutral so you have the other open end through which the sources are connected and you have the I A I B I C flowing. So I A is flowing through the A phase pole this is stationary fixed and I B is flowing through the B phase pole that is also stationary and fixed in space 120 degrees shifted with respect to the A phase pole and I C is flowing through the C phase pole in the C phase axis and that is also shifted 240 degrees with respect to the A phase this one in this manner. So this is a star connected induction motor where the stator coils are star connected with the currents I A I B I C flowing in this manner. So we have the 3 phase currents 120 degrees electrical in time that is when this is at zero this is negative, this is also negative like in a 3 phase current so the amplitudes here along these three axes vary according to the time. Let us see what happens to the amplitudes of the flux.

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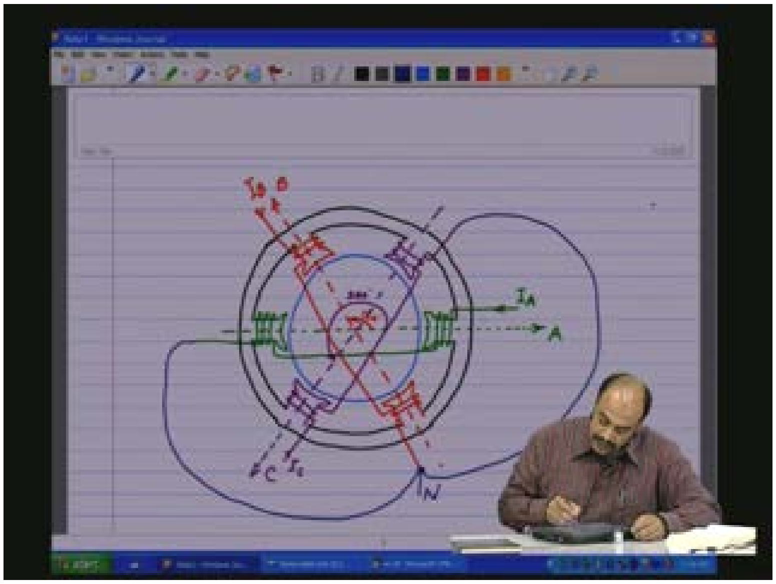

So as a current flows here we have we have a A phase flux in this direction, we have a B phase flux in this direction and we have a C phase flux in this direction with the amplitudes changing according to the instance of time.

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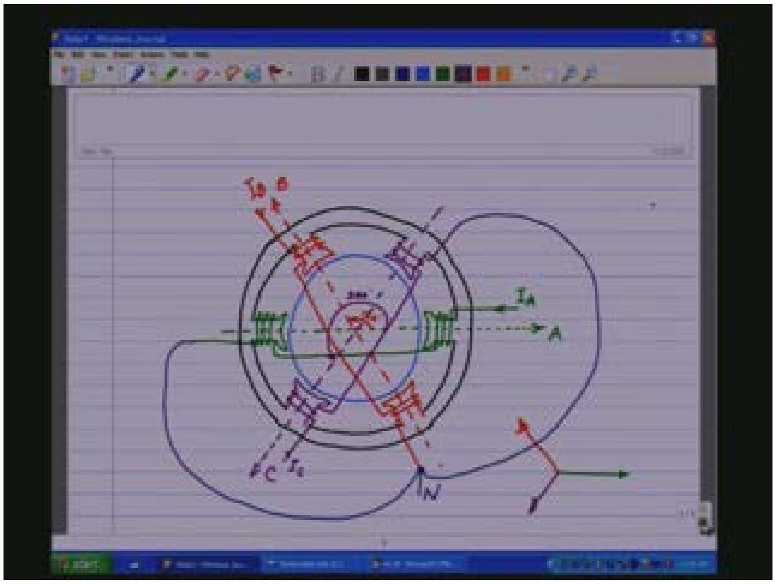

So now let us see, if we apply a 3 phase sinusoidal waveform how does it look. So we generate a 3 phase sinusoidal waveform by the method that we followed before; just draw this triangular wave shape then connect the tops with curves like this as shown, connect the bottoms of the vertices with curved lines like this and you have your 3 phase wave shape with respect to time.

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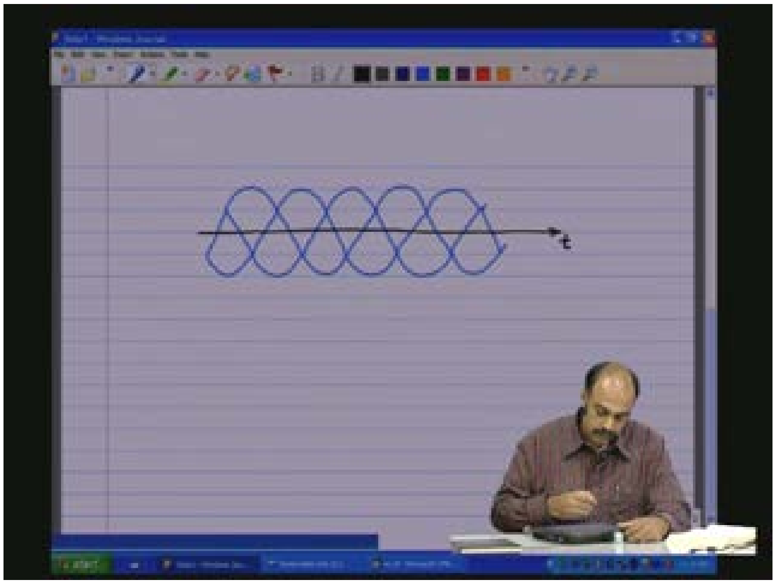

Now let me have the let me have the axis the vertical axis at this point the zero point here. So blue is the A phase and let me call that as I a, 120 degrees phase shifted would be our B phase and I will call that as…… I will use the red colour for that so that is our B phase current I b effective value and then the C phase current is given by the violet so it comes in this fashion which is 240; you see that it is now cutting the zero and going positive 240 degrees with respect to the A phase. So these are the 3 phases I c. Now just we will look at some crucial critical points okay.

So let us have point of interest. Let us say some of these points would be points of interest. Now I could also take a point along this, now let us take this and this is also another point of interest (Refer Slide Time: 16:02) and we have and let us and so on every 60 degrees.

Now let us say when I take a section at that point how does the how does the resultant vector look like or there is going to be a flux along the A phase axis at every instant of time B phase axis, C phase axis. Now if we take at that point of time at this point of time so we have A phase current is maximum positive direction so I will put it as A phase is maximum positive direction, B phase is half negative so this was B phase so B phase negative and half, C phase is also negative and half C phase negative is this direction and half so you have a resultant which is having…….. let me draw a circle so the resultant is having a direction in this that is these two add up and then you have a resultant in this direction.

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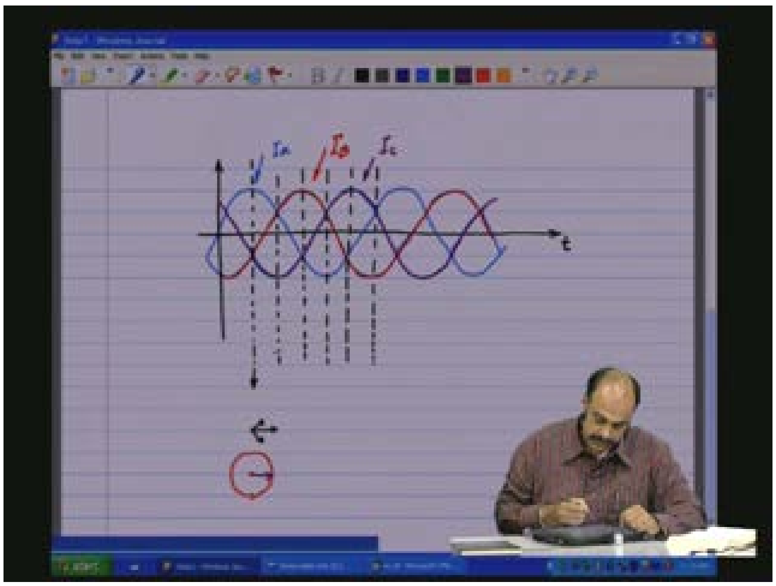

Now if we consider this point now let us say or let us take this point here, now here you have B as maximum so B as maximum positive so I will put it as maximum positive here like that, A is negative half A is negative half and you also have C which is negative half and C negative half, you see that the axes directions are always the same that is the mechanical axis directions are always the same but only that it is positive and negative so which means now the resultant is the resultant flux is now shifted and it is shifted like that. And then if we take a point here, now you will see that I c is maximum positive so you have maximum positive here I a is negative half I a is negative half I b is negative half and that is negative so therefore you will have you will have a flux which is in this direction. So you see that the resultant flux as time progresses it was in this direction then it has rotated in that direction so we have taken some crucial points in between to show that the flux positions is changing. So if we smoothly go along the time you will see that there would be a smooth rotation along this circle and then you will see that the rotating magnetic field has been created. So this is this vector which we are seeing here is rotating smoothly around the circle and that is the rotating magnetic field.

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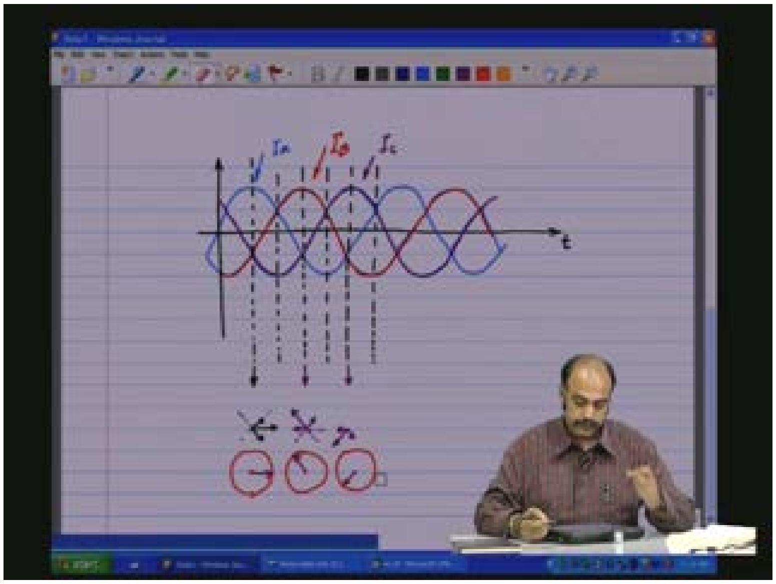

So once we have the rotating magnetic field which is rotating inside the machine in a circular fashion so the magnetic field here is in space it keeps rotating if we apply 120 degrees electrical phase shifted sign waves to the three coils which are also 120 degrees phase shifted in the mechanical that is in the stationary spatial coordinates.

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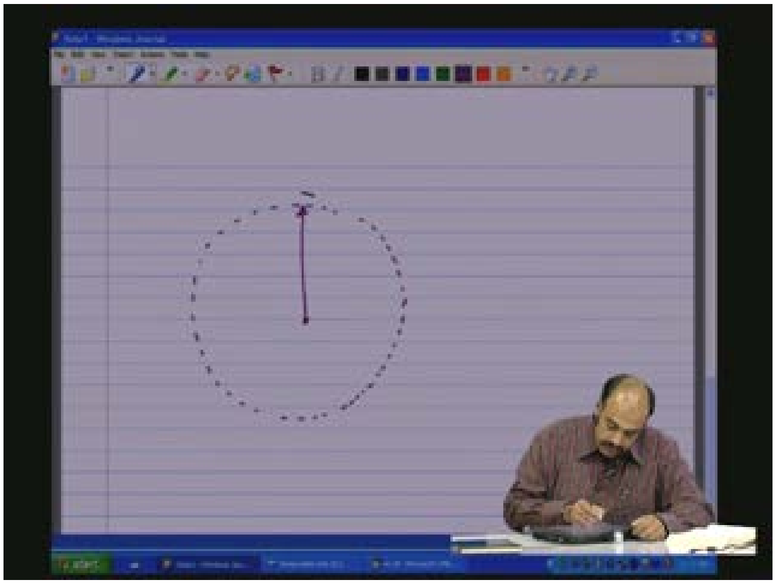

Now as this is rotating and if we have a rotor conductor this magnetic field which is rotating is cutting this rotor conductor and as this is cutting the rotor conductor there is a current which is going to flow through the rotor conductor that is I. There is a length of the conductor L, this magnetic field is having density B so by the Lorentz law you have a force which is BIL that gets reduced which will push the conductor in an orthogonal fashion that is the direction in which the current is flowing and the direction of the field in this case and then you will see the third finger will give you the, the middle finger will give you the direction of the force. So this will cause the conductors to move and it will try to catch up with the field which is already rotating.

Initially when the rotors are not moving the field is rotating at whatever the applied frequency and there is a very large relative speed between the rotating magnetic field and the stationary rotor conductors and therefore that is going to induce a very large current in the rotors which is going to give you a huge torque and then the rotor starts rotating and tries to catch up with the magnetic field and the relative speed starts decreasing. So, as the relative speed starts decreasing the induced current in the rotor also starts decreasing thereby reducing the torque to a steady-state value.

Now suppose let us say that the rotor has caught up with the magnetic field which means the magnetic field and the rotor conductors are rotating at the same speed this means there is no relative speed between the magnetic field and the rotor conductors and therefore there is no cutting effect of the magnetic field and therefore there is no induction of the current in the rotor and as a consequence there is no current in the rotor and therefore there is no force for the rotors to move and therefore it will again lag behind. So the rotors will never catch up, there will always be a slight difference between the magnetic field rotation speed and the speed at which the rotor conductors rotate and this difference is called the slip this difference in speed is called the slip.

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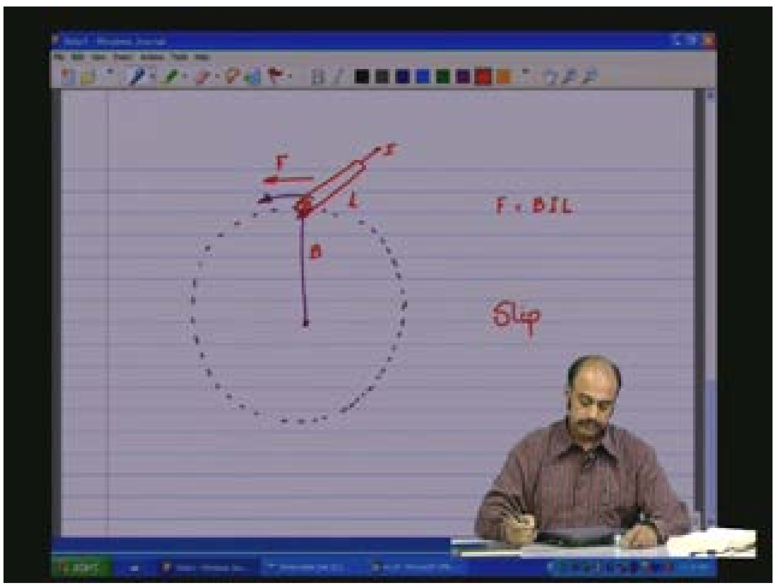

So if the magnetic field is rotating at a speed let us call n s called the synchronous speed synchronous speed in rpm and the rotor conductors are rotating at speed n m this is the mechanical speed of the rotor mechanical speed of the rotor in rpm then slip s is given by n s minus n m by n s and it is a value which ranges from 0 to 1.

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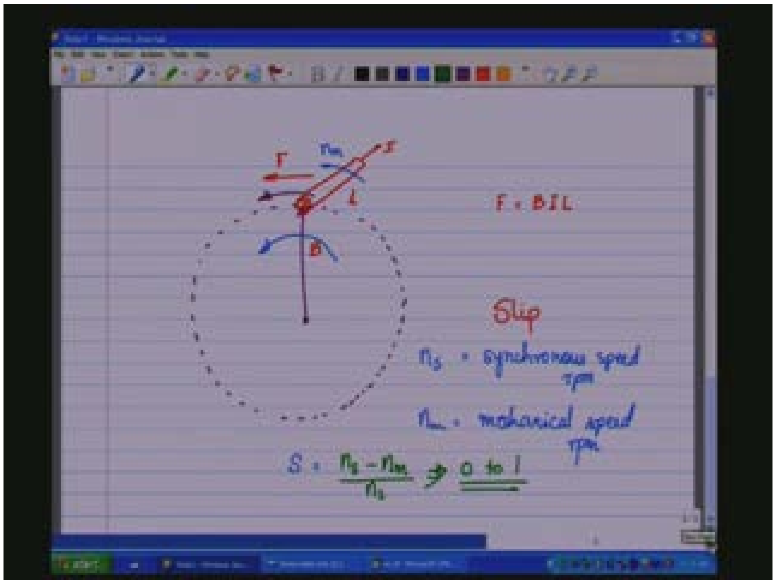

We shall come back to the concept of the slip a bit later again we shall revisit that. But now we should try to understand what happens if we put more number of poles. We saw in the picture here (Refer Slide Time: 25:28) that there is one pole set there is one pole pair per phase. Now, for every phase you could have more than one pole pair. In such a case what happens to the speed what happens to the synchronous speed.

Let me this explain the concept with respect to just one phase that is the A phase, what happens. So let us say we have let us say we have the rotor here and we have one set of fields and that is let us say the A field. So let us explain with respect to just this A field. So we have the A field like that with coils wound and all those things.

Now imagine that inside inside in the rotor imagine there is an imaginary dumbbell there is an imaginary dumbbell, so one is the north pole and then the other is the south pole. So as the coils here are fixed the pole here is fixed this dumbbell does not rotate it only goes shrinks and expands.

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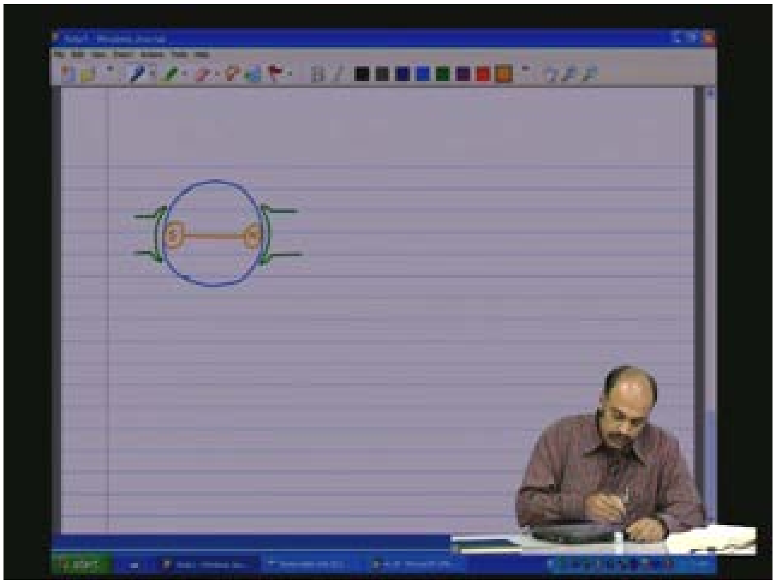

Let me first make a copy of this because I will be using this later, copy. Now let us see what happens to this dumbbell as time progresses and we have a sign wave which is applied to the coils. So let us say this is I a and this is apply to the coils here and then we have also the coils like that, this is connected to the neutral and this is connected to this and you have a passing I a to that. Okay So at this point I a is 0, the flux intensity at that instant is going to be 0 because N I is going to be 0 at that instant so the mmf which is at at this instant is also going to be 0. So the mmf is going to follow more or less this curve because it is N I so what happens to the dumbbell inside; so the dumbbell inside which represents the magnitude of the flux will will be residing here so there is no amplitude because it is 0.

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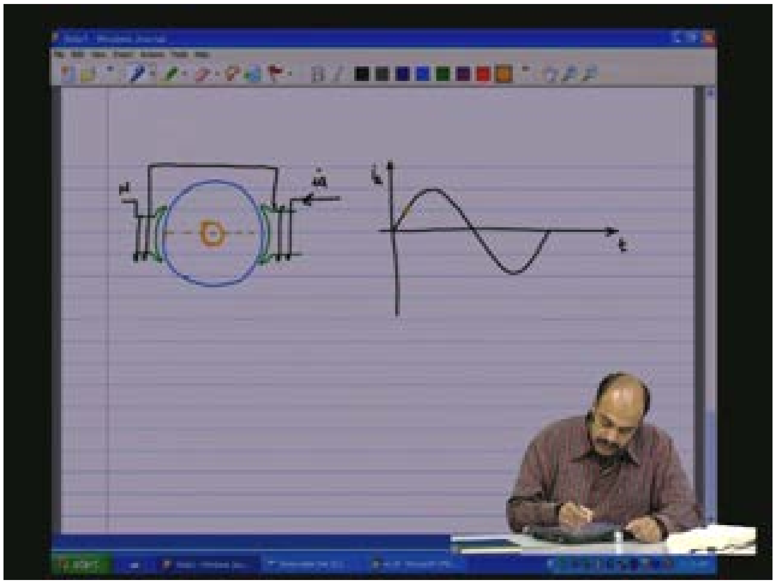

Now as the amplitude starts rising so let us say at some point here the corresponding flux here would be somewhere would result in a dumbbell which is of this size north and south and then at some points here the peak amplitude the dumbbell would have length end and you will have the maximum peak amplitude of the dumbbell like that. And as it starts coming down the dumbbell shrinks and then at this point again comes to 0, at this point (Refer Slide Time: 30:21) it would again come to 0 and then further when the current starts going negative what happens is……… now the dumbbell sorry dumbbell reverses polarity that is you will have a dumbbell which is half the size, now this is south and this is north note the change in polarity and then a corresponding value negative peak it would reach the negative maximum. So what would happen is that you would have a dumbbell which would reach the negative maximum that is this is south pole and north pole. So like that you will see the dumbbell which is swinging along that axis depending upon the amplitude of the current.

Now let us take just the two crucial points that is this point this and this point that is the positive max and the negative max so at these two points we will see that the dumbbell size or the length will be the same maximum except that during the positive max it is going to be it is going to be north on this side, south on this side and during the negative max the dumbbell length is going to be the same except that it is going to be south on this side and north on this side. That is in a half cycle in a half cycle the dumbbell has rotated and shifted by 180 degrees. So inside if we take the imaginary dumbbell which is on the rotor rotating it means it means that the flux mmf inside has rotated 180 degrees for a half cycle traversal of I a and it would have rotated full 360 degrees for a complete full cycle traversal or two half cycle traversal of A that is for a two pole system that is…… this is two pole pole 1 pole 2 so you have a two pole per phase so you have two poles per phase system. Now in this two pole two pole per phase system 360 degrees is traversed by the dumbbell by the mmf dumbbell in two half cycles of the two half cycles of the I a or the current wave.

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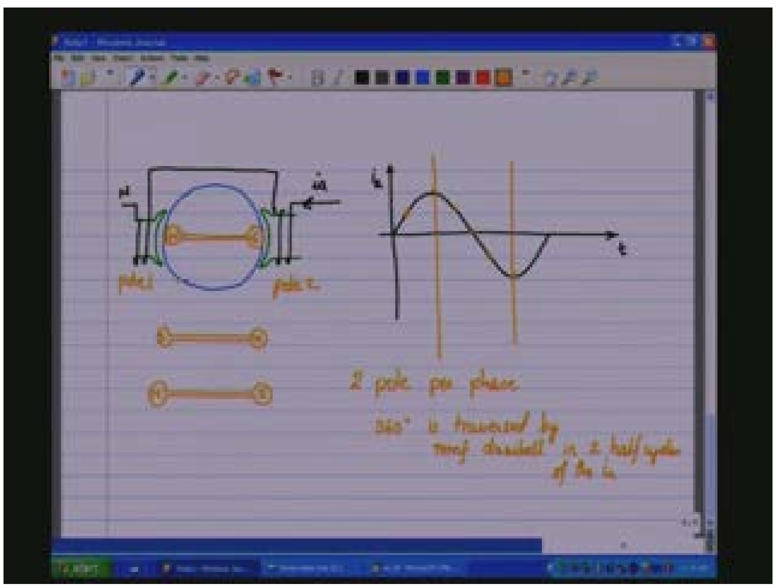

So now let us say the current wave has a frequency f that is this current wave here (Refer Slide Time: 34:17) has a time period of T and the frequency f is equal to 1 by T. So in our case f is equal to 50 hertz because it is a 50 hertz mains in our country so f is the frequency of the sign wave. So it makes full 360 degrees, dumbbell makes full 360 degrees or let us say 1 revolution in T seconds or 1 by f seconds. So in 60 seconds for a minute in 60 seconds that is 1 minute how many revolutions does it make. So it is 60 by 1 by f or we should say 60 f is the revolutions per minute and this is your n s okay this is your n s. This is for one pole pair one pole pair or per phase or should we say there are two poles per phase. So if we use to use this notation that is instead of saying pole pair rather than poles then we say it is 60 f by pole pair. If it is two poles then let us say P is the number of poles number of poles per phase then n s will be 60 into f let us say into 2 by 2 this should be for two poles so that you still have the same result, this will be 120 f by 2 where two indicates number of poles number of poles.

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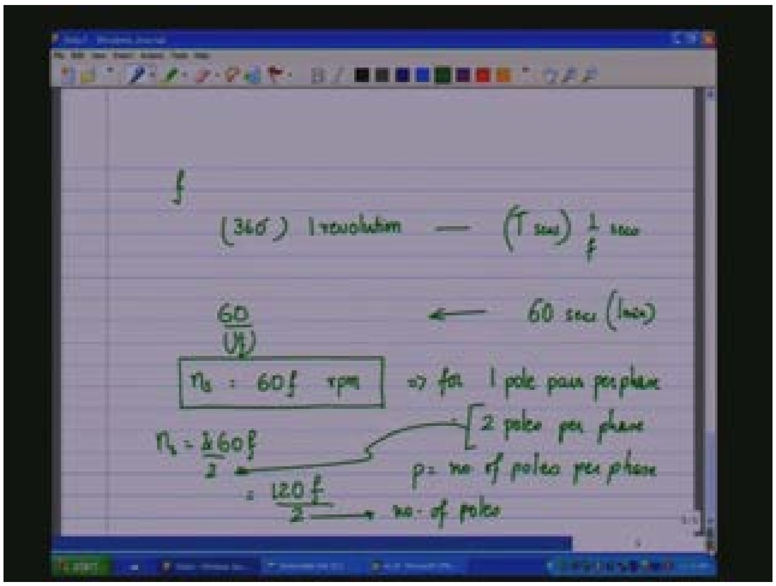

And in general if there are P number of poles n s is equal to 120 f by P where P is the number of poles per phase. What does it say? As the number of poles this is always an even number because you cannot have single poles, this means that as the frequency increases the synchronous frequency increases as the number of poles increases the synchronous frequency decreases. Let us see how this happens.

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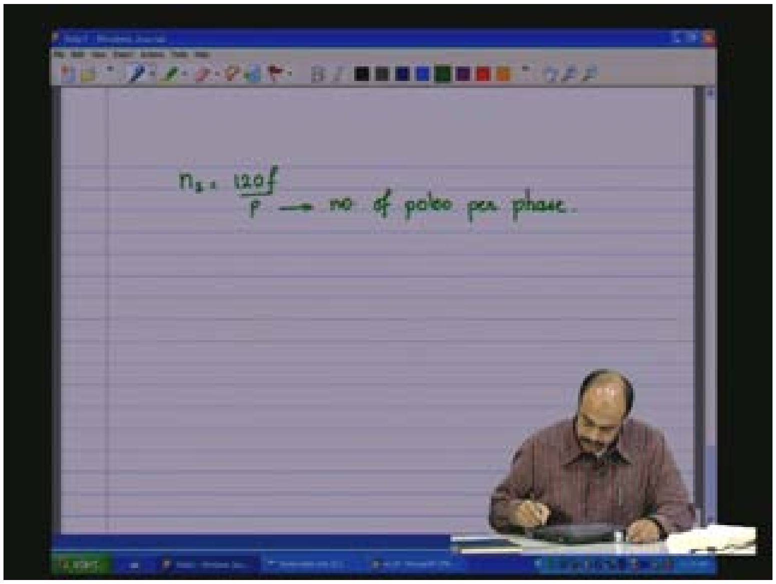

Now of course I will explain it again only with respect to the A phase. Let me have this figure. So here we have just one pole pair or two poles here P is equal to 2. Now let me have two more poles in the A phase all A phase and the windings are so the windings are so done such that the north and south poles alternate; all the currents flowing through this and then this and then this and then this; they are all I a I a I a I a and I a is flowing through all these poles. Then there are four sets of other B phase which are tilted and shifted 120 that is 120 degrees axis and then another four sets for the C phase so they are shifted and placed in such a manner meaning just to indicate…….. so we have let us say the rotor so let me say this is the A pole set that is at the A phase and the B phase let us say is shifted 120 degrees, you have one here see like that and like that and the C pole set is again shifted 120 degrees and it will be in this manner. Only it is minus 120 degrees the winding sense is just changed from clockwise to anti-clockwise to obtain the 3 phases.

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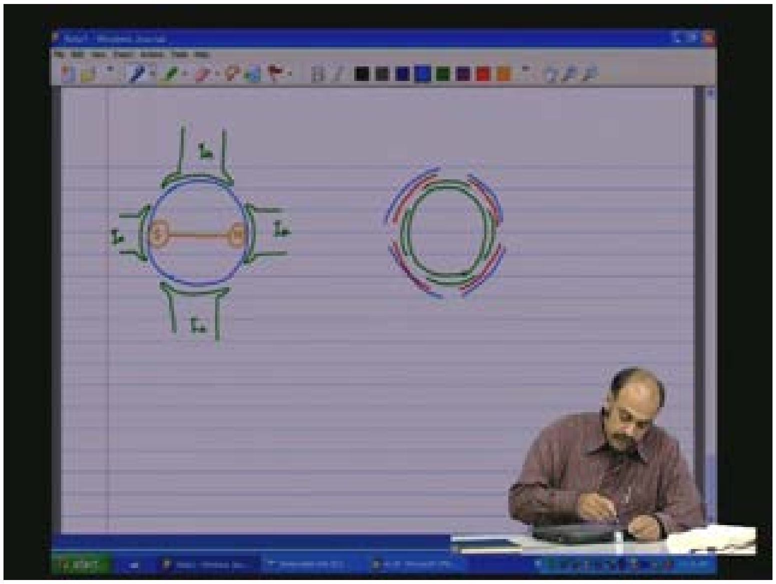

So anyway let me explain with respect to only one phase to get to give you the idea of how the synchronous frequency changes with the number of poles. Now we have four poles. So at any given point of time we will be having two dumbbells imaginary dumbbells which are like that. So we have these two imaginary dumbbells and let us say this is north, this is south, this is south so north south north south it alternates throughout the whole circumference.

Now let us have the let us have the I a current also this is I a current at this point. let me copy this whole portion, copy and let me also paste it and have a duplicate here (Refer Slide Time: 41:49). Let me shift this above, make some space so that you will be able to include this here.

So now let us see what happens at these two critical points that is one point is the positive max and the negative max so what is happening. Now let us say at this point okay I a is positive max, let us say this is the position I a is positive max. Now you have I a is negative max. So, between the positive max and the negative max there should be a 180 degrees that is the north and south poles should interchange. So here we have the north north south south so that is at the positive max. At the negative max north and south poles should interchange so we shall interchange the north and the south poles here and see the north and south so south becomes this and this becomes north so which means there is a movement of……… between this and this it looks as though the mmf has rotated by 90 degrees between this and this the mmf has rotated by a 90 degrees mechanical. But however, here you have one complete half cycle T by 2 that is one half cycle. So one half cycle makes the mmf rotate by 90 degrees and to get 260 degrees you need four half cycles or two cycles to complete one complete revolution of this so which means if there are two pole pairs that is n s we saw was 60 f if there are two pole pairs that is if there is one pole pair it is just 60 f by 1, if there are two pole pairs it has become 1 has become…….. two cycles of this one is needed to make one complete mechanical revolution so the mechanical speed the mech one complete the mechanical synchronous speed is 60 f by 2 and if there are three pole pairs it becomes 60 f by 3.

Now if you want express in terms of number of poles rather than pole pairs then you have to multiply this and this by 2 which means you are talking of 120 f by two poles in the earlier case and then in the case of this four pole machine n s is equal to 120 f by four poles per phase and so on. So if you have p poles it becomes 120 f by p poles so you see that it actually slows down the system if you have more number of poles.

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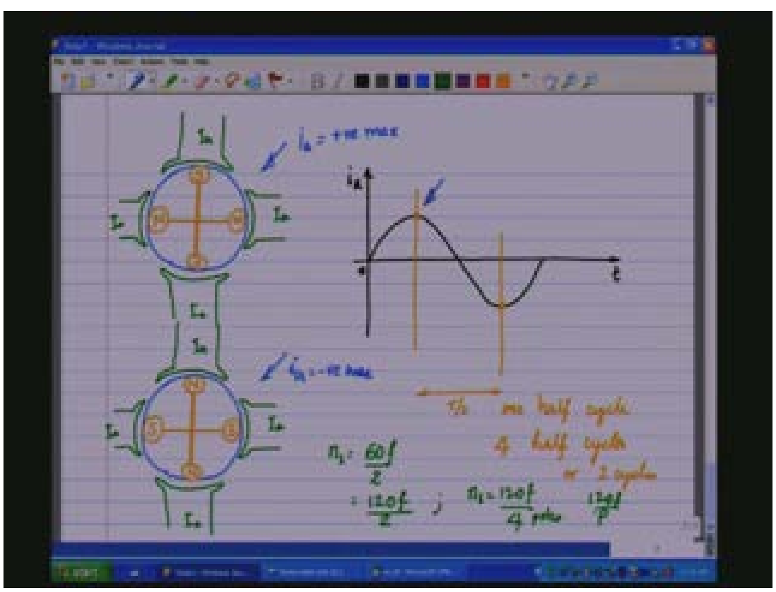

So the n s the synchronous speed of the flux is 120 f by P; here P is number of poles per phase so be careful about this. Now here you can also have 60 f by P p where P p is number of pole pairs per phase because these are various formulas that you will find in different literature it is better you know the nomenclature and P p is always P by 2 number of poles by 2 and n s this is in rpm this is in rpm.

Now the synchronous speed is also expressed in radians per second because radians per second is the SI system of units so you should know how it is converted. So in this SI system if you say synchronous speed is given as omega s is the synchronous speed synchronous speed in radians per second, so to convert something to radians per second that is 60 let us use 60 f by P p this is in rpm and we want to convert in radians per second it becomes 2 pi by 60. So this we saw while doing the DC machines; conversion from rpm to radians per second, you multiply by a fact of 2 pi by 60 and therefore you have 2 pi f by P p and this is the applied frequency.

So omega synchronous is equal to omega applied by P p. Or if you want to express it in terms of this one it is 2 omega applied by the number of poles. So this is also something that you should know how to express it in radians radian terms.

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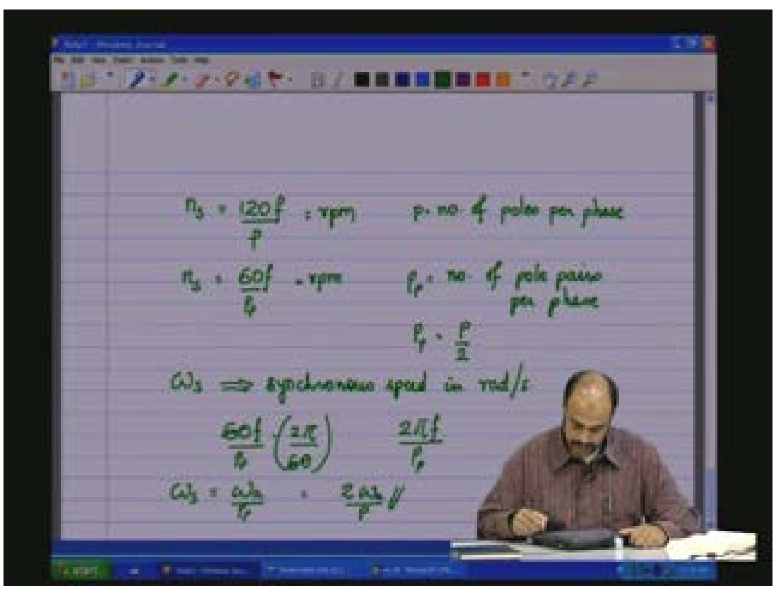

Now let us just have a small example from the book. Okay Let us say we have a 3 phase induction motor 3 phase induction motor which has 20 poles per phase and it is operated from and operated from a 50 hertz 3 phase source. Now what is the synchronous speed. So we know that n s in rpm is given by 120 applied frequency by P where P is the number of poles per phase. So this will be 120 into 50 divided by 20 so that is 300 rpm revolutions per minute.

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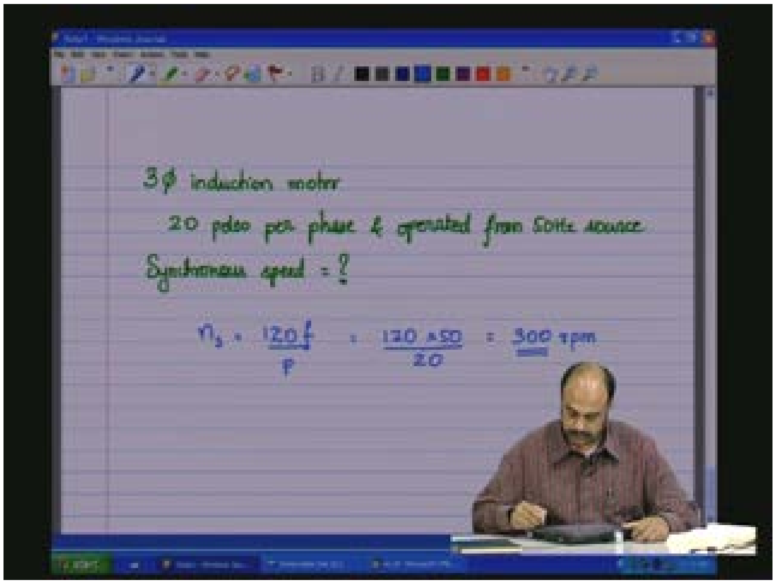

Now we have also defined the slip. the slip which is s is given by n s minus n m that is the rotor speed mechanical speed by n s and this is something always less than 1 because n s is always greater than n m; it could also be written as omega s in radians per second, omega m in radians per second divided by omega s where this is in rpm and this is in radians per second. So this is the slip. Let us take a simple exercise on this from the book.

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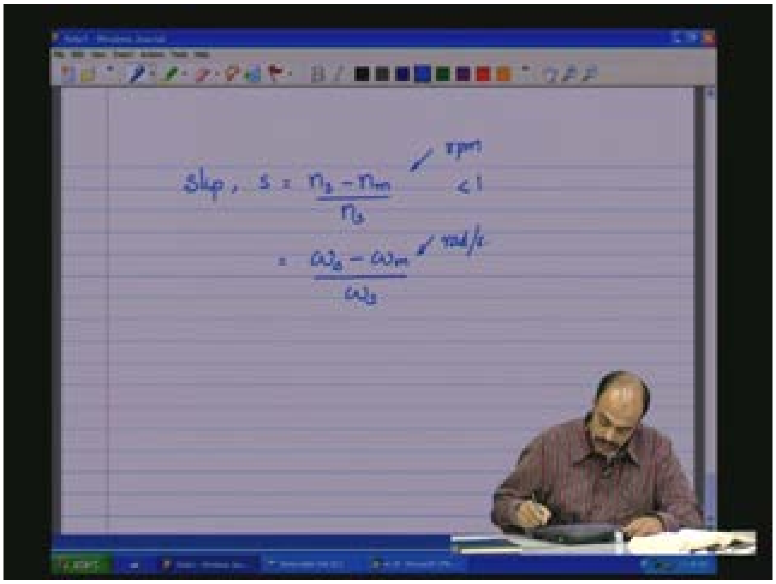

So we have a 6 pole induction motor and this is excited by a 3 phase 60 hertz source, the full load rpm is 1140 revolutions per minute, calculate the slip. So first let us say what is n s. n s is 120 f by P which is given by 120 into 60 divided by 6 poles which is equal to 1200 rpm 1200 rpm. Now slip s equals 1200 minus the full load motor rpm divided by 1200 and this is equal to 60 by 1200 and in terms of percentage this is equal to 0.05 and this is something like 5 percent in terms of percentage. So this is how one calculates the slip.

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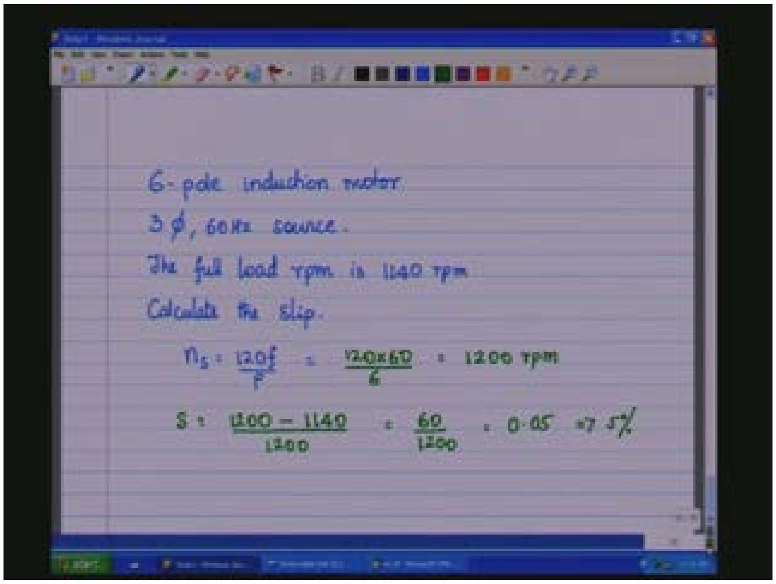

Now there is one important thing that you should know. We saw that there are machines with different number of poles; you have the 2 pole machine, the 4 pole machine, the 6 pole machine, 8 pole machine, 20 pole machine and so on for different applications. What is the maximum speed that one can achieve that is maximum synchronous speed that one can achieve for a given frequency source and that is at 2 pole. That is if we have just two poles per phase that is the maximum frequency that you could get which means n s is equal to 120 f by 2 or which is 60 f is the maximum synchronous synchronous n o u s frequency for a machine that is operated or exited from a f hertz source.

So in India f is 50 hertz so therefore the maximum synchronous speed can be 60 into 50 which is equal to 3000 rpm and many of the machines which are there in the market are 4 pole machines 4 pole machines which means the n s typically of all these 4 pole machines in our country you will see there are 1500 rpm which will be on the name plate, so keep that in mind.

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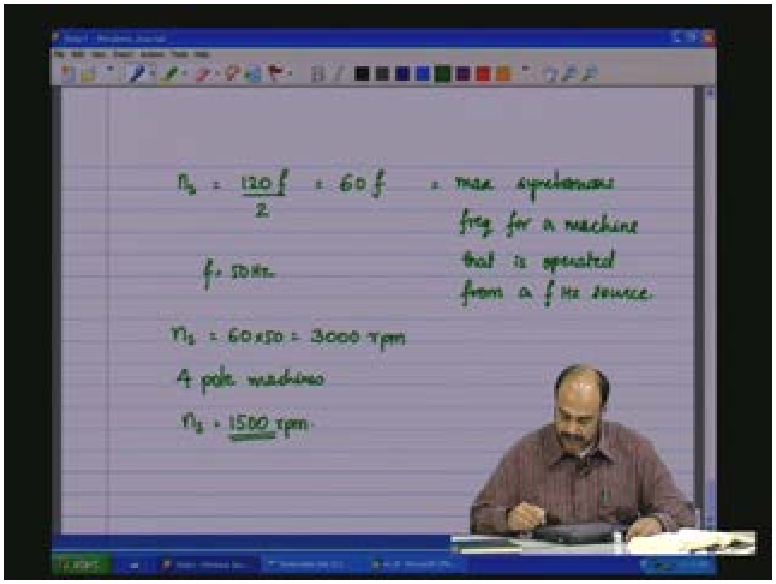
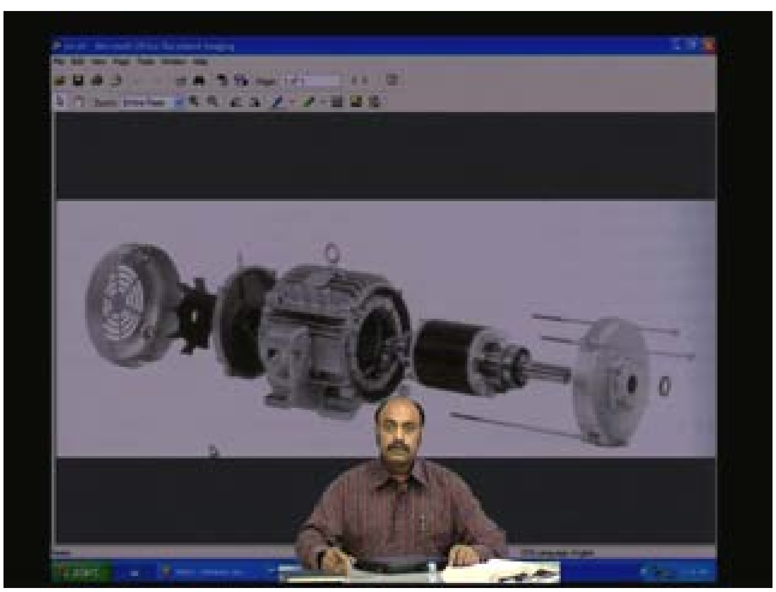


Now there is one thing that I have to show you and that is a picture an exploded picture of an induction motor taken from one of the textbooks that I have referred and I have also introduced during the introduction class.

(Refer Slide Time: 56:40)



So let us see this picture. So you see that this is a picture of an induction motor that is broken apart that is split apart this called the exploded view of the induction motor. Now look at the various parts. Now let me move the cursor here on this part (Refer Slide Time: 57:04), this is the rotor, this is the shaft and this is the rotor and the rotor is die cast it is aluminium die cast and it is shorted at both the ends.

You see this aluminium ring here shorts all the coils all the coils are shorted and that is why it looks like a.......... they say it is a squirrel cage. So this is a rotor and then inside here you see some coils or windings and that is the stator windings which form the various poles the A phase poles, the B phase poles, C phase poles so on which are wound on the circumference of this stationary system and that is called the stator. So this whole coil is wound on the stationary system. This yoke, this is called the yoke and that is the stator that is anchored on to the ground through these foot plates and that does not know........ so that is why we say that once the poles are fixed in space they are fixed in space they do not rotate and what makes the flux to rotate is basically by virtue of the 3 phase source that you supply which are 120 degrees apart. And this rotor is inserted into it and then you have the end phasing plates. These are the end plates here, this is one end plate and this is one end plate that is fitted in through these holes (Refer Slide Time: 58:40) and then there is bearing which you see also the bearing here which is fixed to this thing and that will cause a full smooth rotation of the shaft here. And here you could also see.... beyond this face plate there is something mounted on the shaft and that is a fan and beyond that there is another enclosure a covering for the fan, so this fan is to provide cooling for the machine that is this is an air cooled enclosed air cooled induction machine. So this is how the various parts of the induction motor would look like this is a squirrel cage induction motor.

Now all these windings here (Refer Slide Time: 59:28) are brought out; there are three so all these windings are clubbed together and brought out as three terminal points here A phase, B phase, C phase and also the neutral; you saw that we connected all neutrals together for one or other end of the coil of the various phases. The neutral and A B and C phases are brought out as terminal inside this box here through which the connection to the external source is done. okay so this is how an induction motor a typical induction motor would look like for a given rating. Of course for various ratings the sizes will be different. So this is for all for now for this particular class. We shall continue in the next class with more details on the slip, the formulas, the torque speed characteristics and the equivalent circuits and so on and so forth.

Thank you for now.