Advanced Electric Drives
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Lecture – 30

Hello and welcome to this lecture on advanced electric drives. In the last lecture we are discussing about the stepper motor, more precisely the variable reluctance type stepper motor, where the torque is produced where variation of reluctance or permeance in the air gap. The stator is in fact has silent poles which have got concentric windings, the rotor has got teeth and slots without any winding, and there is no permanent magnet. And here the torque is entirely produced by the reluctance variation. So, in the last lecture we were discussing about a 4 pole stator and a 6 pole rotor variable reluctance type stepper motor let us have a look at it once again.

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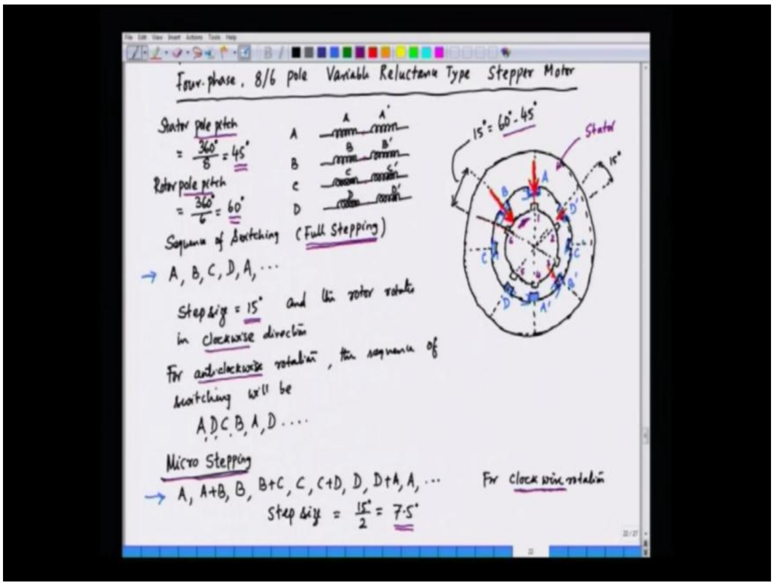

Now this is the stepper motor cross section that we were discussing in the last lecture, this is the stator which has got 8 poles. So, we have the poles are in this case A B C D these are basically the phase windings every pole is wound with a phase winding concentric winding. So, we have A B C and D and then A prime B prime C prime and D prime. So, these are the 8 poles in the stator and out of 8 poles, 2 poles will make a stator phase A and A prime will make a stator phase they are series connected.

Similarly, B and B prime if you see here A and A prime are diagonally opposite and these 2 are series connected in the sense that this is phase A and A prime is series connected here. Similarly, we have the B and B prime they are also diagonally opposite pole having concentric winding, the windings are wound over the stator pole and they are also series connected B and B prime are series connected and we call that to be the phase B.

Similarly C and C prime are the 2 poles and they have 2 windings and they are series connected C and C prime there is a phase C. And then we have D and D prime are the 2 poles and they have got 2 windings and they are also series connected D and D prime winding. So, in fact here we have 4 different phases and we have to switch these 4 phases for the motor to rotate. Now, let us see the pole pitch of the stator and pole pitch of the rotor.

The stator has got 8 poles and hence the stator pole pitch we calculated as 360 by 8 we have got 8 poles and hence that is 45 degree. The rotor pole pitch we have got 6 poles in the rotor and the rotor poles are 1, 2, 3, 4, 5 and 6 they are the certain poles, but the rotor does not have any winding they are just aligned poles. So, we have 6 poles in the rotor and hence the rotor pole pitch is equal to 60 degree 3360 by 6, 60 degrees. So, when we switch various windings we have phase A phase B phase C and phase D. So, when we switch on phase a the mmf will be along this phase A that is basically along the stator mmf. So, this is a mmf which is produced by phase A winding and this mmf will be along phase A and the rotor pole will try to orient itself along that particular mmf the rotor has got aligned poles it will try to align so that the reluctance is minimum. So, one will be aligned along phase A and 4 will be aligned along A prime one and 4 are diagonally opposite the rotor poles. So, this basically establishes a minimum reluctance position for the flux to flow.

And then after some time we excite phase B now when we excite phase B the mmf will shift from phase a to phase B this is that this is the direction of that mmf. So, the mmf is along phase B the nearest pole will try to move and align itself with that particular mmf as the nearest pole here is pole 6. And when pole 6 is attracted and it gets aligned along phase B, what is the distance covered in terms of the angular position? We know that the stator pole pitch is 45 degree the rotor pole pitch is 60 degree, and hence the difference in angle 60 minus 45 is 15 degrees and hence the rotor rotates in the clockwise direction by an angle 15 fifteen degrees. So, 15 degrees is the step size so we say here that the step size in this case is 15 degrees.

But the sequence of switching the sequence of switching is A then A is switched off then B, B is switched off then C, C is switched off then D and so on. So, this actually goes in this cyclic fashion and the sequence of the switching here is A B C D and A again. Now, in variable reluctance type stepper motor, the direction of current does not really matter whether the mmf is upward or downward does not really matter, because it is basically that is that is the minimum reluctance position, and the rotor is trying to align itself with the minimum reluctance position. So, whether the mmf is upward or downward, whether the current is positive or negative, the torque is unidirectional. Torque is in fact is proportional to i square. So, whether is i is positive just like a switch switch reluctance motor whether the current is positive or negative does not really matter.

So, in this case the sequence of switching is in this case A B C D and A and this is called full stepping. The step size is 15 degrees and direction of rotation is clockwise. Now, suppose we want to reverse the direction of rotation now if the direction of rotation needs to be reversed, what we have to do? We have to definitely change the sequence of switching so earlier it was A B C D and A, now we will make it a D C B A D so for the anticlockwise rotation. we will make the sequence as A we switch on a here and then we switch D, this is what is D and D prime they are series connected and we will be switching D.

And when we will be switching D let us say that the mmf is along the phase D and the direction of mmf does not really matter. So, it maybe downward or upward does not matter. So, let us say the mmf is along this particular phase now if that is the situation the nearest pole is 2. So, 2 will be attracted under phase D and hence the moment is by an angle 15 degree, but the direction is anticlockwise so that is how we can refer the direction of rotation the direction of rotation can be reversed by changing the switching sequence.

And the sequence of the switching here is A B C D A and D and so on so this goes in a cyclic fashion. Now, suppose we want to further reduce the step size the step size here we have understood that it is fifteen degrees is there a scope of further reducing the step size without changing the motor, yes it is possible. Now, the sequence that we have just described is called a full stepping, it means the step size is full now we can have a micro stepping in which we can reduce the step size. Now, that is possible by exciting 2 phases at the same time.

Now, in micro stepping what we do here this is called micro stepping, we start with phase a let us say then we do not jump to phase B unlike this, we do not jump to phase B we what we do here a and then A plus B and then B, so when we are exciting A and then A plus B what happens this A and B are excited at the same time. So, this is not excited so right now we are exciting A and B at the same time so A is excited and B is excited. So, if A is energised and B is energised we have 2 mmf's one is along the phase A that is this mmf and the other one is along phase B that is this mmf. So, what is the what is the position of the rotor the rotor will be neither, or this pole one of the rotor is neither under fully A or pole 6 is neither under pole B, they will occupy an intermediate position.

So, in fact what happens here is this that 6 will move towards B and one will move to the right of A. So, we will have 7.5 degrees of rotation, so this is called micro stepping in micro stepping this the step size is 7.5 and the direction is the same clockwise because phase A and phase B are excited at the same time. So, it will be moving still in the clockwise direction, but the movement will be not by a full step that is 15 degrees movement will be in fact by 15 by 2 that is 7.5 degrees. Now let us try to see how we can refer the direction of rotation, the rotation is now in clockwise direction. Now, if we go for anticlockwise, what is the sequence of switching? The sequence of switching would be in that case.

For anticlockwise rotation and this is for micro stepping, we are talking about micro stepping here step size is 7.5 degrees. Now, the sequence of switching would be we will start with again phase A and then we will excite phase A and D together. Let us see now if we excite phase A and D we have phase A and then we have we are now exciting phase D this is this is the new phase that we are exciting. So, when phase D and A are excited at the same time the pole 2 will try to move closer to D prime, and pole one will be going to the left of A at this moment, we will by 7.5 degrees because we have now two different m m f's one is along phase A, other is along phase D. So, no single pole will be rotor pole will be lying under a stator pole they will occupy an intermediate position and the movement will be thus by 7.5 degrees.

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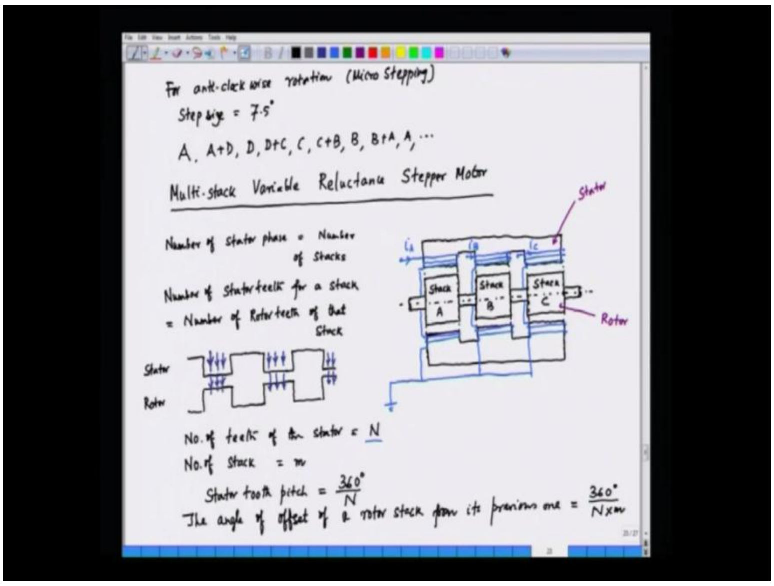

So, the sequence of the switching is A, A plus D then D and then D plus C then C then C plus B then B and then B plus A then A and so on, it continues. So, this is called the micro stepping, now even the 7.5 degrees is a large angle. In stepper motor the objective is that if the angle can be reduced we will have a smooth rotation, but how can we reduce the angle because in this particular case we have 8 stator pole and 6 rotor pole, we cannot go on increasing the number of poles in the stator, there is a limitation, there is a mechanical limitations. So, we cannot infinitely go on increasing the number of poles to reduce the step size, and then what is the solution?

The solution is to go for multi stack stepper motor, here we have seen only one rotor and one stator, but it is possible to have multiple stack of the stator and the rotor. So, that we can reduce the step size further, in multiple stack the stator is more than one stack the rotor is also more than one stack. So, let us take a look at multiple stack variable reluctance type stepper motor.

So, we will be discussing right now about a multiple stack or multi stack variable reluctance stepper motor. Now, how is it constructed, let us first see a longitudinal section of the motor we take a stepper motor and we take a section, all this motors we can analyse by taking a section. Either a transverse section or a longitudinal section, now if this is a motor, this if we cut from this we take a transverse section, this is the transverse and this is the longitudinal section. So, we now analyse by taking a longitudinal section of the variable reluctance stepper motor with multi stack and see how it is constructed.

So, we take a section and we will first draw the stator and say for example, we have 3 stacks here. So, we have 3 stacks in the stator 1, 2, 3 this is the 3 stack we have. So, we have 3 stacks in the stator and then the stator will have the other part also, this is one side of the stator we have the other side also, this is the other side of the stator, this is one stack, second stack the third stack. So, here just draw the various stacks of the stator the other side of the stator is identical to this it is a sectional view, what about the rotor?

Rotor is also having multiple stacks so the stacks of the rotor this is the rotor stack, one stack, the second stack here, and the third stack. And we have we have the shaft here so this is the shaft the rotor shaft here, it is mechanically connecting all the rotor stacks this shaft out. Now, what we have in this case we can we can call this to be stack A, this is one stack, stack A and this is stack B and stack C. So, this is the stator we have this is the continuous stator what have been various stacks, the rotor this is the rotor. And the stator stacks have got windings, have got concentric windings and the windings and energise the stator stacks each stack is having a winding and that is called a phase.

So, for stack A we have we have the windings here, so this is basically the windings which is for stack A. Then similarly, we have stack B or the stator is having a winding and the other windings are also here. So, we have the windings for the stator on the other side. So, this is for the other side and for stack C we have the windings here and these are all series connected the stator windings of a particular stack is series connected here so also is series connected, so this is also series connected these are the windings. And since we have 3 stacks we will call this to be i A the phase current i A similarly, here it is i B and similarly, in phase C we have i C and this stacks are actually excited at the same I mean the phase A is excited at the same time. So, here the stack is also known as a phase the stator has got also 3 stacks we can call stack A of the stator, stack B of the stator, stack C of the stator and the stators also have windings. So, the stack of the stator is also known as phase so in fact we can say the stator has got 3 phases, phase A, phase B and phase C and phase A will carry the current i A phase B will carry the current i B, and phase C will carry the current i C as we have shown here.

And we have a neutral point and a star point all these are connected here and have we have the ground in this case and we have switches for phase A, phase B and phase C. So, we can excite the corresponding stacks, so here we can say that the number of phase is equal to the number of stack. So, we can say that number of stator phase is equal to number of stacks, this is one thing and what about the stator teeth and the rotor teeth, this is also a variable reluctance type stepper motor and the torque has to be produced by the variation of reluctance. And hence the stator and the rotor must be having teeth and slots.

In fact here the stator teeth and the rotor teeth are exactly same they are in fact aligned in a way. So, if we see the stator and stack a of the rotor the stator teeth and rotor teeth are aligned in a way. So, we can say that the number of stator teeth for a stack is equal to number of rotor teeth of that stack. And they are aligned in the sense that if this is the stator tooth and slot like this, this is the stator. The rotor will have the teeth and slot and they will be aligned in this case so this is the rotor structure.

So, the idea is this that when we excite the stator by passing current through the winding, the mmf will be produced like this these are the mmf's. So, this mmf's or the flux lines will attract the rotor teeth. Similarly, here also we have the mmf's produced by the stator and this will be attracting this particular tooth of the rotor and so on. So, they are aligned. And the subsequent stack rotor is offset from the previous stack by an angle that we will just try to see. Now, if there are n stack and if there are n teeth we have a formula which will give us the offset. So, suppose we say that the number of teeth of the stator is equal to let us say N and number of stack is equal to m.

So, what is the stator tooth pitch, we can say that the stator tooth pitch stator tooth pitch is equal to 360 degree divided by N because we have N teeth in the stator and one mechanical revolution is 360 degree the stator tooth piece is 360 by N. And if we have m stacks the next stack is offset from the previous stack the next stack of the rotor is offset from the previous stack of the rotor by an angle 360 by N by m. So, the angle of offset we can say the angle of offset of a rotor stack rotor stack from its previous one is equal to 360 divided by N into m so that is how the stacks are offset.

The stator stacks are all aligned we have the stators here phase A, phase B and phase C the stator teeth are aligned, but the rotor teeth are offset. So, if we have 3 stacks here how are they how are they placed the stator will have the same orientation, but the rotor stacks will be offset by an angle that we given by 360 by N into m. So, we will we will just have a view of how the stator and the rotor are placed with respect to each other.

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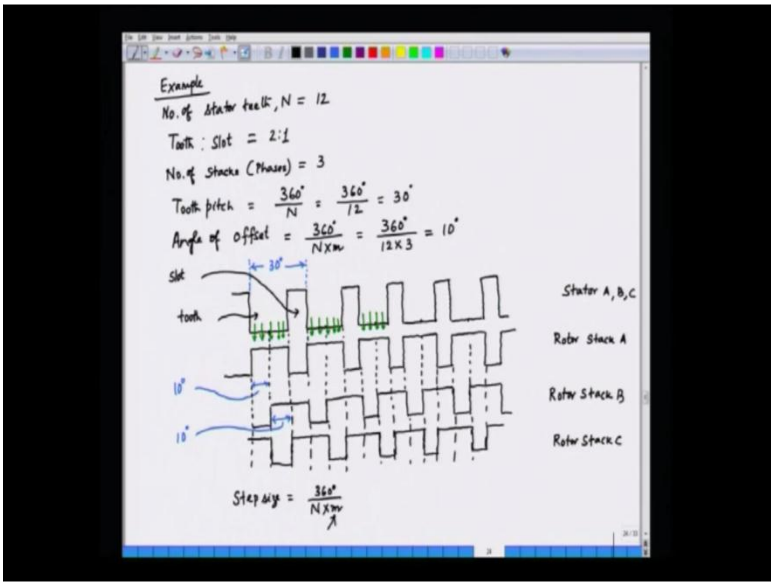

So, let us say that we take an example here and in this example we take the number of stator teeth that is N is equal to 12, say we have N stator teeth that is equal to 12. And also we can we define that tooth angle tooth by slot basically the tooth angle by the slot angle, we have a ratio here that is equal to 2 is to 1. It means tooth is little wider than the slot, now if this is the situation and again we have 3 stacks. Number of stacks or the phases is equal to 3, so what is the tooth pitch here tooth pitch is equal to 360 by N, N is 12 here, so we will have 360 by 12 that is equal to 30 degree. So, the tooth pitch in this case is 30 degree, what is the angle of offset? Angle of offset is 360 by N into m, m is the number of stack and here m is equal to 3. So, in fact if we divide 360 by 12 into 3 we get 10 degrees.

So the angle of offset here angle of offset is equal to 360 divided by N into m that is 360 divided by 12 into m is number of edges or the number of stacks 3. So, what you obtain here is 10 degrees. So, let us see how with respect to the stator teeth the rotors are placed. So, we will just draw a few teeth of the stator, so let us say that we have the stator teeth like this, this is the stator teeth. So, approximately the tooth piece is 30 degree that we have to keep in mind and draw the diagram accordingly. So, this is 10, 10, 20 the slot is also 10. So, this is how the stator teeth look like we have the stator teeth here this is the slot and teeth. So, this is the stator so we can say we have the stator here and this angle or the tooth pitch in this case, this is the tooth and this is the slot. So, this is the stator, stator surface is this so this angle we have is the tooth pitch and this angle is 30 degree.

What about the rotor? The rotor is facing the stator when the rotor is facing the stator and we already said that for a stack the stator teeth and the rotor teeth are exactly the same. And they are aligned along each other so that there as there will be perfect locking between the stator mmf and the rotor teeth. So, the rotor is facing the stator and having the same number of teeth and we have 3 stacks here phase A, phase B and phase C we will draw one stack by one stack first of all we will start with phase A. And let us say that phase A is now aligned along phase A of the stator. So, this is this is phase A so this is how the thing is aligned here. So, this is the rotor it is fully aligned along the stator so the rotor is developed and shown here. So, I would like this to be called stator phase A in fact stator phase A and, B, and C are all aligned. So, this is stator phase A also B and also C now this is rotor stack A.

Now, what about the rotor stack B, rotor stack B is offset from the previous stack by an angle which is equal to the offset angle and the offset angle here is 10 degrees. So, if we say this is the teeth of the stator rotor stack A, this angle we have all 10 degrees here. So, we have to offset for the phase or the stack B by an angle which is 10 degrees. So, we can draw the stack B of the rotor like the following, this is the stack B, which is offset from the previous stack by 10 degrees. Now, this angle is 10 degrees.

So, we can complete this drawing this stack B of the rotor, this is the slot and then teeth then we have slot and tooth here, slot and a tooth continues like this. So, this is the rotor stack B, rotor stack B, what about the rotor stack C? We can draw the stack C of the rotor in a similar way, these are the lines which will help us draw the next rotor stack. Stack C is shifted from stack D again by 10 degrees, so this is stack C we have the tooth and then the slot, the tooth and then the slot tooth and the slot in the following fashion. And again we have we have the slot here then the tooth here this angle is again 10 degrees and this is for rotor stack C.

So, we have we have drawn here the stator stack and the rotor stacks and we see that when we are having multiple stacks, when you have 3 stacks here stack B is shifted from stack A by the offset angle in this case that is 10 degrees. Stack C is shifted from stack B by the offset angle which is 10 degrees here and so on. And hence when we change the switching from phase A to phase B of the stator all stators are aligned. So, when we de energise phase a at any time only one phase is aligned energised so initially let us say phase A is energised then we will energise phase B, and then we will energise phase C. So, we will be energising the various phases of the stator in this particular sequence.

So, we have seen how the stator and the rotor teeth are organised here now we will be switching from phase A to phase B to phase C. Now, when we switch phase A the mmf will be along the phase A only in phase A. So, in fact what we see here is that the mmf in this case is if we see the mmf's the mmf's or the flux lines will be in phase A this is and the tooth and so on. So, the stator stack a teeth are aligned along that particular flux lines or the mmf's.

Now, we de energise phase A and energise phase B now when we energise phase B all the stator phases are aligned. So, the same thing will be happening for phase B also, when we are aligning phase B stator so phase B will be moving towards the tooth of the stator slot. And hence the movement will be by an angle offset that angle is 10 degrees. So, the step size here is same as offset angle so we can we can say here that the step size in this case is equal to 360 degree divided by the number of teeth into the number of stack.

So, in fact we can reduce the step size by increasing the number of stacks. So, if we increase the number of stack that is m, we can reduce the step size and when we again excite phase C, phase C will be moving the phase c of the rotor or the stator of the stator is excited in phase C the corresponding rotor stack will move and align itself along the stator and this movement will be again by 10 degrees. So, thus the step size here is 10 degrees so the formula is the step size is 360 by N into m that we can increase m and thereby we can reduce the step size. So, this is the principle of multiple stack variable reluctance type stepper motor.

Now is there any other type of stepper motor that exists, yes we have another class of stepper motor called permanent magnet stepper motor, in which the rotor has got permanent magnets. And permanent magnets has a one advantage is that the torque in that case will be more, if the permanent magnet strength is more. So, we can have a very good permanent magnet in the rotor so that the strength will be more, the strength of the magnet is more. And hence we can have little higher torque so we will be discussing about the permanent magnet stepper motor.

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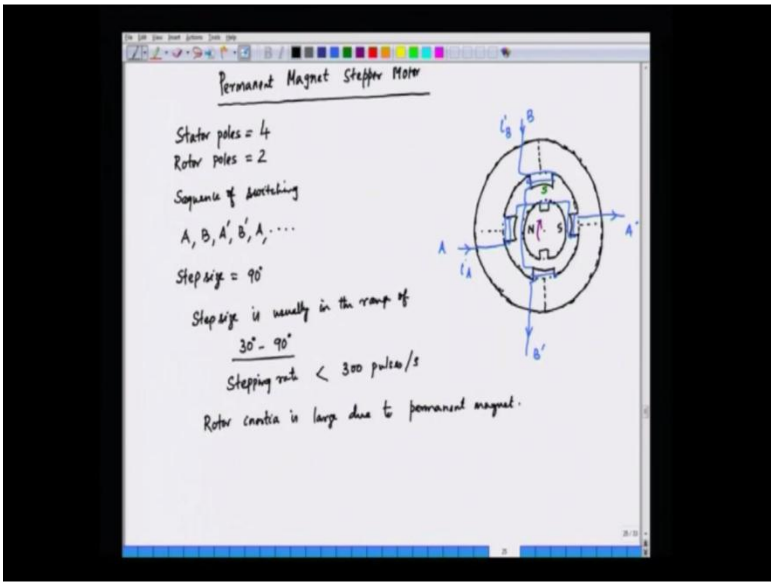

So to take an example, initially what we will do we will take a simple 4 pole stator and 2 pole rotor, the rotor has got permanent magnet and only 2 poles are there in the rotor, but the stator has got 4 poles and will also carry concentric winding. So, let us draw the cross sectional view of the motor, so we have we have the stator here, these are the stator periphery and we have 4 poles on the stator. So, the stator number of poles is 4 stator pole poles equal to 4 rotor poles is equal to 2. So, we have 4 poles in the stator, so we can have one pole here second pole here the third pole here and the 4th pole here.

The rotor is a permanent magnet and it carries 2 poles only, so we can draw the rotor structure also rotor has got permanent magnet. So, we have we have the rotor, in this case and we have a permanent magnet structure having pole shoes, this is the north pole and we have south pole here, and the stator structure has got 4 different poles and this is the stator periphery here.

The stator in this case will carry the windings and say for example, this could be phase A here and this is connected to the other pole structure and this is we can call to be A and A prime, we have a single phase having 2 different poles. And similarly, we have phase B here and then this is connected to this pole and we can call this to be B and B prime. And the direction of the current here is i A the direction of current and here the direction of current is i B.

Now, when I when we excite a particular phase A let us say A and A prime we have one phase which will have 2 different poles. Now, under that phase we will create a south pole. So, in fact when we excite this we will be creating a south pole here the south pole in this case and here this is the current is going out in this case, this is entering A and leaving A prime. Similarly, entering B and leaving B prime this is our convention so when we excite phase A a south pole is created. So, when a south pole is created the south pole will attract north pole of the rotor, the rotor pole moves and aligns itself in such a way that the north pole of the rotor faces the south pole of the electromagnet that in the stator. So, this is the position of the equilibrium north pole of the rotor is attracted by the south pole of the stator.

Now, what we do our sequence of switching will be as follows so we will have the sequence of switching, we will start with A and then we will move to B. Now, when we will move to B we will de-energise phase A and we will energise phase B we will be injecting a current into phase B. So, when we will be injecting a current into phase B again under phase B we will be creating a south pole the north pole of the rotor will be again attracted to the south pole of the stator. So, the rotor will be rotating in the clockwise direction so this will be the motion of the rotor. So, this north pole will be under again the south pole, south pole will be now here under phase B. So, this is now de-energised, so ace is not there. So, this is this is the stator pole here and we have the phase B connection and this is this is the south pole and hence the rotor will be rotating by 90 degree in the clockwise direction.

The step size in this case would be 90 degree, so we can say that the step size is 90 degree and the sequence of switching will be A, B. And then we will be changing the direction of current A prime then B prime and so on then A. So, this is how the rotor rotates so the step size can be reduced by increasing the number of poles, so we can have 45 degrees again less than that and so on by increasing the number of rotor poles. But there is a limitation, since we have permanent magnets in the rotor we have a mechanical constraints we cannot go beyond certain number of poles in the rotor.

So, here in the permanent magnet stepper motor the step size cannot be reduced beyond a certain point and hence this type of motor are used for larger step size, where step size is to be larger. So, in fact the range is in the range of 30 degrees to 60 to 90 degrees. So, we cannot go to the step size below 30 degree if you if we want to go to a reduced step size we have to choose a different type of stepper motor.

So, in this case the step size the step size is usually in the range of 30 degrees to 90 degrees. And furthermore when we have a rotor and the rotor will have the permanent magnet, the rotor inertia becomes large when we are inserting the permanent magnet the rotor the inertia of rotor also becomes large. And hence this type of motor will have poor speed response and therefore, we cannot have a very high stepping rate, the stepping rate for this kind of motor is usually limited to less than 300 pulses per second. So, we have a limitation on the stepping rate also, here the stepping rate is usually less than 300 pulses per second the rotor inertia is high due to permanent magnets.

Now, we have a third type of a motor, which is a combination of the two we have already seen the variable reluctance type stepper motor, we have also seen permanent magnet stepper motor. So, if we combine this two the objective is to have a reduced step size a reduced rotor inertia and overall compactness. And we have a third type of stepper motor which is called a hybrid stepper motor, this is an example of a hybrid stepper motor, if you see this stepper motor this stepper motor is a hybrid stepper motor. This is the rotor the rotor has got the teeth in this case teeth and the slots and this is a permanent magnet.

So, this rotor is a permanent magnet in addition to that we have also having variation of reluctance due to the slot and teeth. The stator here carries a concentric windings, if you see the stator in this case we have the various stators in this case. So, we have in fact here 8 stator poles 1, 2, 3, 4, 5, 6, 7, and 8 and each pole is containing concentric winding and the stator poles are also curve gated, we see that the surface the inner surface is not smooth. In fact the inner surface has got again teeth and slots, so this is to increase the torque of the motor.

So, here the torque is produced by two means by the variation of reluctance as we have seen in case of a variable reluctance type stepper motor. Also due to the permanent magnet rotor we have we have the torque production and hence the torque is better here.

So, torque is produced both by permanent magnet also by variable reluctance and hence this is called a hybrid stepper motor. So, we will be discussing about a hybrid stepper motor.

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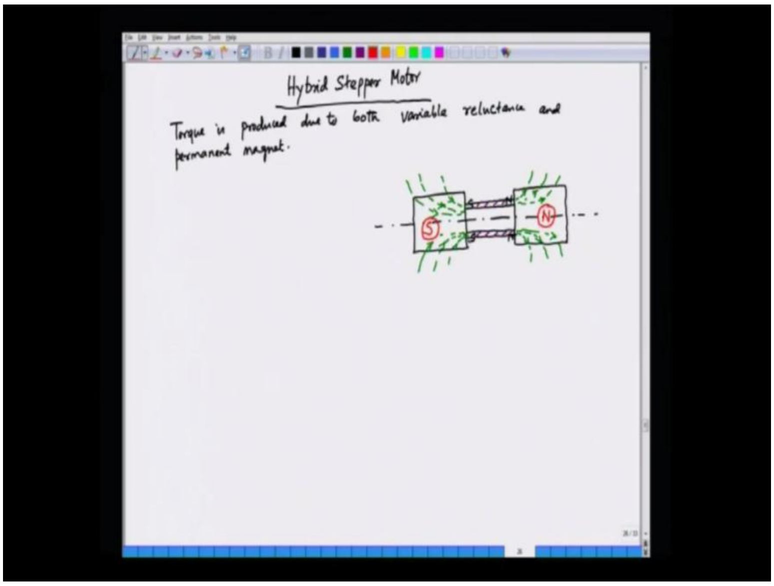

As we seen here in hybrid stepper motor the torque is produced by the combination of variable reluctance type torque, and also permanent magnet torque, and the step size is also quite reasonably small. So, the torque is produced due to both variable reluctance and permanent magnet just to give you an idea that if we see this motor, this motor is little different from the other motor. In the sense that this motor is an axially polarised motor, a hybrid stepper motor is an axially polarised motor in which the permanent magnet is kept or placed axially.

So, which means what we have here we have we have rotor in this case, this is the rotor this is another rotor. So, we have basically two rotor sections and this is the shaft which is connecting the two and in this case the permanent magnet here is placed axially, this is the south pole and this is the north pole and there is a south pole and there is a north pole this is the permanent magnet this is the magnet which is placed axially. As a result the flux lines will be going from the rotor in the following fashion this will be all emanating like this, this is the south pole. So, flux entering the south pole here also the flux will enter the south pole and then we have the north pole here. So, this is the north pole structure, so we have we have the north pole the flux is coming out of the north pole like this.

So, as a result the left side block is completely a south pole structure and the right side block is completely a north pole structure. Now, the advantage in this case is here is that we do not have to place tiny permanent magnets, we are just placing one axial magnet in a such a fashion that half the side of the rotor is a south pole, and half the side of the rotor is a north pole.

We will be discussing more about this in the next lecture where you have this kind of structure this is called a homo polar structure. Usually when we talk about poles we talk about alternate poles a south pole and north pole, the south pole and north pole aligns aligns like this, but in this case due to the special placement of this magnet the entire block is south pole. So, this is called a homo polar structure, similarly entire right half is a north pole this is also a homo polar structure. So, this is very convenient because we can have as many number of teeth as we want, but the entire block is a north pole and the entire block is a south pole. So, we will be discuss discussing more about this in the next lecture.