Advanced Electric Drives
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Lecture – 29

Hello and welcome to this lecture on advance electric drives. In the last lecture we are discussing about the control of switched reluctance motor, we have seen that switched reluctance motor is nothing but a motor in which the torque is produced by variation of reluctance. The stator has got concentric lining, the rotor has got slotted structure and as the rotor rotates, there is variation on inductance seen by each winding of the stator. And hence this variation of inductance is helpful for the torque production. So, we were seeing the close loop speed control of a switched reluctance motor.

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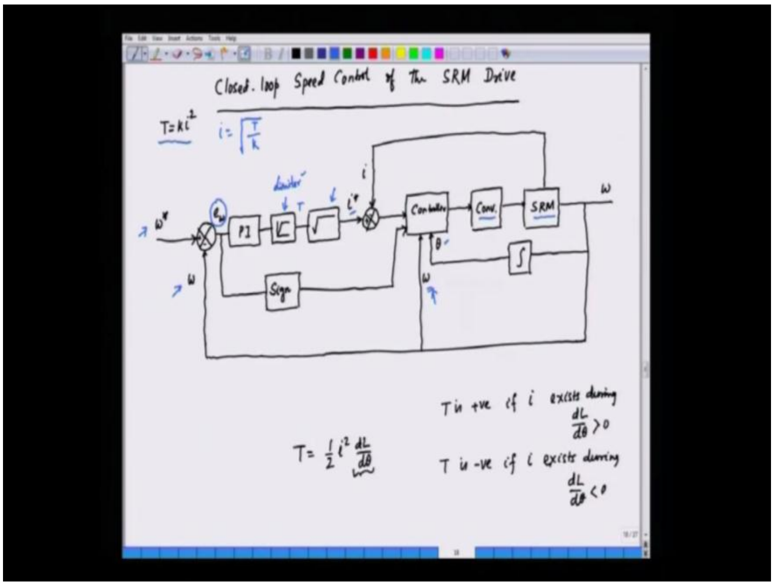

So, this is the block diagram of the close loop speed control, we have the reference speed this is the reference speed and we compare this with actual speed by having a speed set back. And then we have the PI controller the proportional integral controller, which keeps something similar to the torque. We know the torque is given by k into i square so if you want to find out the current currents will be the square root of torque. So, in other words we can say that i is equal to T by k the constant under root, T is the torque, k is the constant. So, we have a square root block here, this is the square root block this is the square root block here and this is the limiter. So, this the limiter that limits the maximum value of torque that can be produced, and this limiter is practically very important because when ever we have a PI controller this controller has the 2 parts, one is the proportional part other is the integral part.

The error is integrated and also the proportional part gives the proportion of the error in the output. Now, if the error is the d c error the integral part sometimes will go and reach very high value, and practically the motor torque is always limited, the motor current is always limited we cannot get infinite amount of torque form a current neither can we inject infinite current into a motor. So, the motor torque and current are limited by the virtue the rating of the motor, so it is practical to limit the value of the PI controller output and that is achieved by limiter.

And then we get something similar to the torque here and we have a square root function and we get the reference current that is i star, and the reference current have to be injected into the windings of the stator. The stator has got many phases we have seen this this current i star has to be injected into the windings of the stator that is achieved by a close loop current control. So, we saves the actual current how the switched reluctance motor or SRM, this currents are same sphere and compared with the reference current, i star. And then the controller is properly designed to inject the current on to the srm.

Now, when we want to inject the current the currents have to be injected in proper phase angel and this phase angle is decide by the rotor position. So, the controller will also have a input of theta and theta is the rotor position and that is obtained by the integration of the speed, we integrate the speed and get the rotor angle and this is i is injected into the srm by means of a converter, and the controller besides the angel depending upon the theta.

And as we know that when we control the switched reluctance motor, it can be operated at a very low speed in chop mode, and then after the base speed it can operate with constant power and then beyond some speed we can go for t omega square constant. And these are the various modes of operation and the modes are decided based on the speed, the speed is also fared as an input to the controller to decide the mode of operation. And we have we have a speed sensor here, the speed sensor senses the speed and hence we have a close loop speed control.

Now, in this case the this switched reluctance motor has to come with a converter without the convertor, the motor cannot be operated. So, the convertor should be able to inject current into the machine winding and also should be able to control the current. So, we were seeing the various topologies of this convertors. Now, let us look again the topology of the converters.

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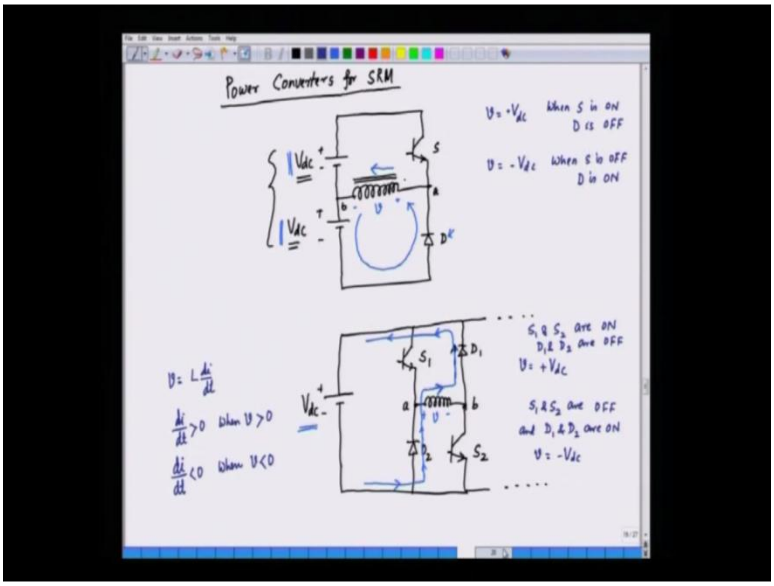

So, this is the convertor topology for the switched reluctance motor. Now, in this case this is one of the windings of the stator and for every winding will have this kind of configuration a transistor and a diode, if the transistor is switched on the current will flow like this through the transistor and through the winding. And what we have here if we if we say that this voltage is weak with this positive and this negative. So, we can say that when the switch is on v is equal to V d c plus V d c when S is on and D is off.

So, we are able to apply positive voltage to the winding by switching on S, S is a transistor switch and when we switch on S naturally the diode will refers by S the diode D will be referred by S at this, this automatically remains in off position. And then if you want to apply negative voltage if you want to apply negative voltage we switch off the switch S. So, what we do here is that V is equal to minus V d c when S is off and it means D is 1. So, it means when we want to apply a negative voltage we switch off S and when we switch off S what happens this current will vanish.

And when this current vanishes, earlier this current was flowing in this direction this path is not there. So, this current will try to maintain in the direction through a alternative path so the path is provided by the diode. So, the earlier path is not present because the switch is off and when the switch is off, the phase being inductant the current has to be maintained. So, this current finds an alternative path to the diode and the diode turns on. And when the diode turns on we can see that positive is applied through V and negative to A which means V becomes minus V d c.

Now, this convertor is can be used, but there is a problem the problem is this that this convertor uses 2 power supplies the power supplies one is this power supply that is V d c plus minus and the other one is plus minus V d c and totally if you see the voltages 2 V d c. So, out of 2 V d c we are only using V d c we are applying plus V d c and minus V d c. So, the first reason is that we need 2 power supplies and second reason is that the power supply is not full utilized. In one mode we are only switching S 1 so the bottom power supply is not used the top power supply is used in the other mode, we are switching off S bottom power supply is used the top power supply is not used. So, the utilization of this 2 power supplies is not hundred percent.

So, we can go to a second topology in which we have we have a single power supply here that is plus V d c and we have the winding and the winding in this case we can we can say this is a voltage here plus minus. So, we have the transistor S 1, S 2 and the diodes D 1 and D 2. Now, what we do here we first turn on S 1 and S 2, S 1 and S 2 are on so if we turn on S 1 and S 2, what happens? The current path is given like this path of the current so the current flows through the switches return back to the source so as a result we can say that V is equal to plus V d c.

So, we can we can write down V in this case so V is equal to plus V d c because a is connected to the positive supply and B is connected to the negative supply and hence the voltage V is plus V d c. And when we turn of the switches lets go a second situation, S 1 and S 2 are off and D 1 and D 2 are on. Normally the diodes remain reversed biased, the diodes you can see that the cathode is connected to the positive and anode is connected to the negative terminal. So, naturally the diodes will be reverse biased and specially when the switches are on S 1 and S 2 are on so D 1 is fully reverse biased it is off D 2 is fully reverse biased and that is also off.

So, we can also say that when S 1 and S 2 are on D 1 and D 2 are off the second situation where S 1 and S 2 are off we are turning on the transistor switches by removing the base drive or the gear drive we are turning on the transistor switches, what happens? The winding was earlier carrying some current and this current has to be maintained and the former path is broken, the current will try to find out an alternative path and the alternative path is provided not through the switch, but through the diodes. So, this path is not there, so this path is broken this path is also not there, but the windings the current is still present and this current is flowing in this direction is original current, but the swithes are turned off, this current will forcible make the diodes on.

So, the diodes will be on and the path of the current will be through the diodes D 1 and D 2 that is why we say that diodes turn on so D 1 and D 2 are on and as a result the current flows like this and fade back to the source. So, the current which is which is present in the inductor, the inductor stored energy is fed back to the source to diodes. And hence we can say here that V is equal to minus V d c, so this is the situation when the transistors are off and the diodes come into conduction. So, we are able to apply plus V d c and minus V d c in this case and when we are applying plus V d c and minus V d c we can control the rate of rise of current because we know that we ignored the inductance we can write down the simple equation that V is equal to L di by dt.

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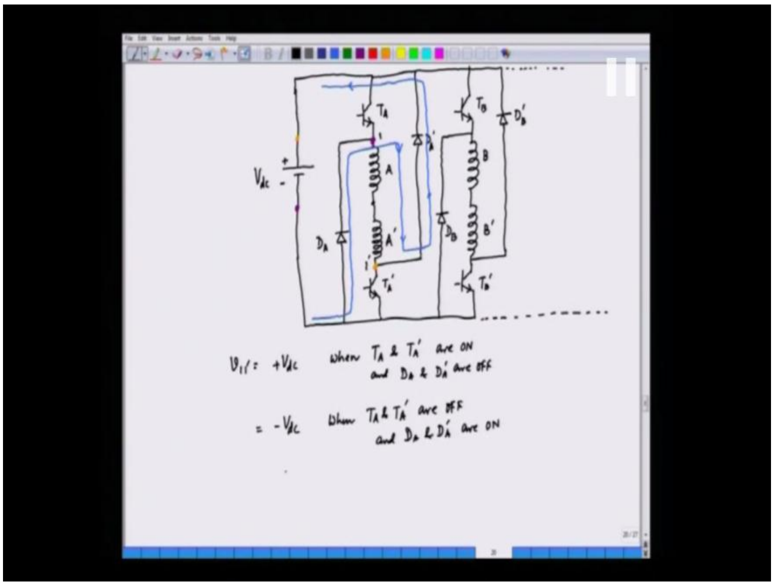

So, the rate of change of current is determined primarily for a constant inductance primarily by the applied voltage. So, by applying a positive voltage, so we can say that di by dt is positive, when V is positive and di by dt is negative when V is negative. So, we can in fact control the current and maintain the current in the winding where it is necessary. Now, we have seen actually that sometimes there are 2 windings for a phase either a 2 windings or a phase we can extend this to 2 winding structure also. So, if you have 2 windings per phase, so we can we can have a structure like this we have.

We have the voltage here that is a dc supply voltage and we can have the transistor switch in this case, and then we have 2 windings per phase, this is one winding may be A other winding may be A prime. So, per phase we have 2 windings and this 2 windings can be series connected so we have 2 transistors here something similar to the previous situation and also we have the diodes. So, these are the 2 transistors and the diodes are present like this, this is one diode and we have other diode which is present like this. So, this is applied voltage V d c so we have the transistors and we have the diodes. Now, this is for one phase.

Now, we have seen switched reluctance motor which has got 4 phases phase A phase B phase C and phase D phases D. Now, this is for a single phase a phase will be something similar to this phase C will also be something similar to this. So, phase B will be connected to this exactly in the same way we can have phase B here we have B and B prime this is B and B prime these are the transistor switches and this is the diode here is the diode. Similarly, we have another diode here and same thing will be for phase C and D.

So, here what we do in this case that the transistors are switched in pair, now this is we can call this to be T A transistor A and transistor A prime this is T B and B prime this is lets say we can call this to be d A and d A prime this is d B and d B prime and so on. So, we turn on lets us say if we talk about phase a now if we concentrate on phase A when we want to apply positive voltage we turn on s A and s B so when T A and T A prime.

So, in this case what we have here is that if you turn on T A and T A prime the current through the winding would be flowing in the following fashion. This is the current through A and A prime and what is the voltage here if you say this is terminal one and one prime, we can say that V 1 and 1 prime is equal to plus V d c when T A and T A prime are on and d A and d A prime are off. Necessarily when the transistors are on diodes could be off similarly, if you want to apply a negative voltage switch off the transistors, if you switch of the transistors the current will flow through the diode.

So, V 11 prime will be minus V d c when T A and T A prime are off and the diodes d A and d A prime are on. Now, if T and T A prime are turned off what happens now suppose we turn on this 2 transistors current path will not be through the transistors so we can we can remove this path of the current, but the current through the inductor at the phase windings are still present. So, the current through the phase windings will be there so this is the current through the phase windings, but this current does not flow through T A and T A prime it has to flow through some alternative path and the alternative path is provided by the diode.

So, what happens here is that this current will be coming through the diode like this and the diodes will be conducting. So, this current will be flowing like this through the diode and the currents through the windings will be maintained of course, it will decaying, but it is maintained for that time. So, as a result what we have in this case the negative voltage applied across the winding. So, if you see here one, one is now connected to this diode is on so d a is on here so one is connected to negative power supply. So, if you say that this is the one terminal, this terminal is same as this terminal negative, and if you see one prime, one prime is connected to the positive through d A prime.

So, if we say this is this is one prime and the one prime is connected to the positive terminal and hence we have V 1 1 prime is minus V d c and thus this thing can happen for phase A also for phase B and phase C phase D after some phase shift. And thus we able to control the current in each winding of the switched reluctance motor. The switched reluctance motor are used for light weight application, where we need high torque to weighted ratio the rotor inertia is very small, and hence it is popular for those applications where we need high torque to weight ratio.

Now, we will go for another new motor different kind of motor, which are very widely used for control application and also application in robotics and that motor is stepper motor. Stepper motor is very popular for many applications where the power ranges is not very high, may be a few watts maximum few tens of watts not more than that. And examples can be from printer to robotic arm and so on.

So, the uniqueness of stepper stepper motor is that in stepper motor we can do inherently position control with out any close loop feedback. It is basically control in an open loop fashion with out a close loop position feedback and hence the motor control is very simple and this is applied in those applications, where we need a position control. So, let us see some typical stepper motor, which is also based on the principle of variation of reluctance. So, our next discussion will be on the stepper motors.

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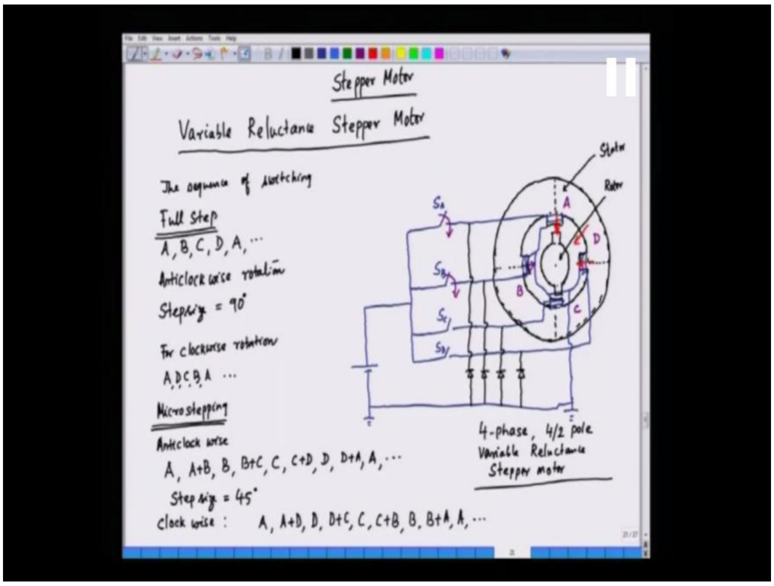

Now, I will say you a stepper motor here now this is the stepper motor it is a very small motor, which operates may be on 12 volt, and these are the connection of windings that are brought out of the motor. And if we open this motor this is a motor shaft which is free to rotate. Now, if we open out this motor we will see that this is the motor and this is the stator. The rotor has got lot of corrugations infact we can say the rotor has got the slots and teeth, it is not a smooth rotor and that is how the torque is produced. Similarly, the stator also has the got the winding concentric windings, the stator also has got some corrugations the stator is also having slots and teeth.

Now, this slot and teeth of the rotor and the slot and teeth of the stator help us obtain a torque and the torque is primarily reluctance torque. And also sometimes we can have permanent magnet to also get the permanent magnet torque. So, we will be discussing right now the principle of variable reluctance stepper motor. So, as we can understand that the stepper motor are of various types one type of stepper motor is variable reluctance stepper motor.

Now, here the torque is produced the variance of reluctance, there is a tendency of the rotor to align along the minimum reluctance position. So, if we shift the stator mmf again the orientation of the mmf will change and the rotor is having slots and teeth and the teeth will try to align itself with the minimum reluctance position. Now, let us take an example you will have a simple example, where the stator has got 4 poles and the rotor has got 2 holes. So, we will we will see an example of a stepper motor which is variable reluctance style, this is the stator and we have the rotor.

The stator as I have said has got 4 holes so let's draw the 4 poles of the stator so the 4 poles are equally spaced so this is one pole, the second pole, third pole and the fourth pole. And we can complete intermediate pass, this is the cross sectional view of the stator and the stator code, you can complete the stator code structure, and the stator carries windings and the windings are for every pole, in every pole we have a winding and the windings are placed as follows. This is winding in the phase A and we have phase B winding here and we have phase C winding here and we have phase D winding here.

And this windings can be brought out of this we can call as phase A, this is phase B, this is phase C and this is phase D. And this windings are brought out so we can bring out this winding of phase here and phase C winding is also brought out here, and phase D winging is also brought here. So, we have the terminals which are brought out and these are the 4 phases of the stepper motor and the windings are also connected in neutral point. So, we also have a neutral point which is available to us the neutral point is this so this neutral point is connected with this, this is also connected with this, this neutral point is connected with this, and this neutral point is bought out. So, this is the neural point and usually this point is connected to the negative of the power supply, there is a local ground.

At each phase is connected to a switch a transistor switch, so here we have a transistor switch in phase A, we have a switch in phase B we have a switch in phase C and we have a switch in phase D. And this is connected to a battery, so we can have a battery here, there is a battery, the source is also grounded. So, there is a return path here and the return path is this path. So, we can call this to be switch A this to be switch B this to be switch C and this to be switch D, and what about the rotor? The rotor is also a structure rotor also has got slots and teeth.

Now, here we will consider a 2 pole rotor having only 2 teeth, so in this case we have we have the rotor in which we have only 2 teeth one is like this, 2 poles and the other one is like this and the rotor has that only 2 pole for simplicity of understanding, we have shown this as 2 pole. So, the rotor is here so we have the stator in this case and this is the rotor and the motor is controlled by switching the various phases.

Now, what we do here we switch in a sequence of A B C and D so the sequence of switching is A B C and D. The sequence of switching of switching, we can have 2 types of control first one is a full step control, so for full step control full step we go on switching A then B followed by C then D, then again A and so on. So, what happens when you switch a particular phase only one phase is turn on at a time. Suppose we turn on phase A so this phase is turned on so when we turn on this particular phase, this phase is energized and hence we have we have a flux coming out of this.

So, this rotor will try to align it self along this particular phase and when phase A is switched off and B is switched on, it means we are turning on phase A. So, this is not on right now so what we do here we now turn on phase B now when we turn on phase B the mmf or the flux of the stator shifts form A to B. So, it shifts form A to B so this is basically the mmf position now to have this smooth transfer of mmf every phase is connected with a free willing diode. So, what we have here each one is connected to a free willing diode so in phase a we connect a free willing diode here phase B, we also connect a free willing diode, phase C we also connect a free willing diode and phase D we also connect a free willing diode.

And when we turn of s A and turn on s B now you are turning on s B and we have already turned off s A now the current in every winding will take some time to die out. So, if the transistor is switched off the current will free will through the respective free willing diode. So, for some time A and B will both carry some current so the mmf from phase A to phase B will shift gradually although quickly the process will be gradual process from phase A the current is decreasing and phase B current is increasing. So, the mmf will change gradually form phase A to phase B and the rotor will try to follow the mmf.

So, when phase A is switched off and then phase B is switched on the rotor moves in anti clock wise direction, the rotation in this case will be anti clock wise, the rotation will be in anti clock wise direction. Now, what is the step angle, the step angle is a angle between 2 subsequent switching we have switched off s A and now we have turned on s B. Now, between this the rotor has moved by 90 degree so form phase A to phase B if you if you see this the step size in this case is 90 degree. So, the step size is equal to 90 degrees and that is called the full step operation by full step we mean the step will be full the full step size is 90 degrees.

Now, what about the direction of rotation can it be reversed, yes the direction of rotation can be reversed if we change the sequence of switching instead of switching A B C D and A and so on, if you switch A D C B A B and so on the direction of rotation will be changed from anti clock wise to clock wise. So, the clock wise rotation for clock wise rotation what we have to do here the sequence of switching will be from A to B it means when we turn on s A the rotor is aligned along phase A and then we turn of phase A s A and turn on s D. So, the mmf will be shifting form A to B and hence the rotor will be rotating in clock wise direction. So, in this case A D C B and again a now this is again the full step operation, but the rotation will be in the clock wise direction.

So, we have already seen full step is there any scope of reducing the step size because of the step size is more the machine will be switching in jerks there will be lot of jerk, while changing from one to the other the mmf is shifting in step which may not be desirable and this can be reduced if step size can be reduced. So, here we have facility for micro stepping in which we switch on phase a then phase A and then phase B then phase B and C and so on.

Now, let’s see how we can reduce the step size the step size can be reduced by micro stepping in which the 2 phases are exited at the same time. So, the sequence of the switching for micro stepping will be as follows, so for micro stepping we first start with the anti clock wise rotation. So, what we do here we excite or energize phase A then energize A and B together and then B then B and C then, C then, C and D then, D then D and A then A and so on. Now, if we do that the mmf will have a intermediate step now when we excite A and then A B mm f was originally in a it was some where here and then we are exciting both A and B if we are exciting both A and B phase s A and s B are closed simultaneously. So, this 2 switches are closed simultaneously so in that case what we have here this mmf is here this mmf is here and the resultant of this 2 will be some where here.

So, this resultant mmf will subtain 45 degree with the phase A axis and the rotor rotate by 45 degree. So, here the step size will be half of the full step and it is 45 degrees so the step size here will be 45. Now, similarly we can have anti clock wise this is anti clock wise rotation similarly, we can have clock wise rotation also. In clock wise rotation we change the sequence in a different fashion, so for clock wise rotation we will go for the following sequence will start with A and then A plus D. So, we are basically shifting in the opposite direction right now we are not exciting A and B now. So, what we are trying to do here we are trying to excite A and B simultaneously.

So, when we excite A and B simultaneously the resultant mmf will be somewhere here and hence the rotator with rotate in the clock wise direction. So, the sequence or switching will be A, A plus D and then D, D plus C then C, C plus B then B B plus A then A and so on. So, this will give us rotation in the clock wise direction with a step size of 45 degrees.

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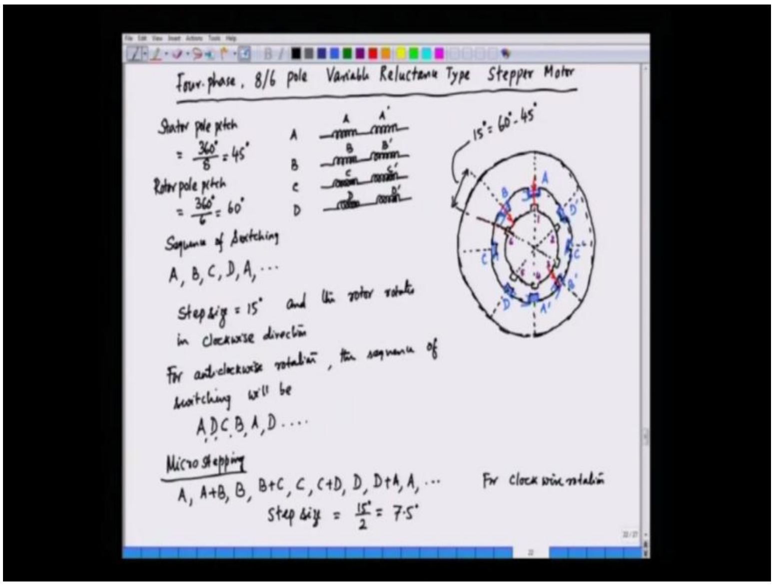

Now, this stepper motor is called 4 phased 4 by 2 pole variable reluctance stepper motor so we can write the name here this is called 4 phased because this are the 4 different phases A B C and D. So, we call this to be 4 phase 4 by 2 pole variable reluctance stepper motor. So, if we want to say suppose we need to have a reduced step size so the step size to be reduced we can go for different configuration. We will now see a configuration where the stator has got 8 poles and the rotor has got 6 poles, they are the step size is reduced and we will see how it is reduced by going for higher number of stator pole or rotor pole.

So, we will be discussing about a 4 phase we have 4 different phases 4 phase 8 by 6 pole variable reluctance type stepper motor. Now, let us see how this motor looks like again we will be making a transverse section and trying to see the orientation of the stator and the rotor with respect to each other. The stator has got 8 poles, so we will draw this once again stator is a cylindrical structure, the rotor is also a cylindrical structure. And we have the stator core and the stator core here and the stator has got 8 different poles. So, we have 8 pole structure this is one pole, this is second pole third pole the 4th pole 5th pole 6th pole the 7th pole and the 8th pole.

So, these are the stator poles so we can complete this whole structure of the stator, and what about the rotor? The rotor has got only 6 poles. So, the rotor poles will be as follows this is basically 60 degree shifted so 6 means 360 by 6 the distance between 2 poles will be 360 by 6 that is 60 degrees so this is 60 degrees here and then 60 plus 60 will be 120 it will be something like this. So, we have the rotor poles which will be from the following fashion. So, this is a rotor structure.

Now, we can we can name the rotor poles also, we call this to be 1, 2, 3, 4, 5 and 6 this is pole 1, pole 2, pole 3, pole 4, pole 5 and pole 6. So, we can complete the rotor complete structure here, the rotor structure the stators boundary the stator cores and the stator cores carry windings. So, we have windings in the stator and the windings are concentric winding, each pole is having its own winding. So, we can have the windings for lets say this pole and this are the windings here, this pole we can we can call it to be phase A and the diametrically opposite will be A prime. So, each phase has got 2 windings A and A prime so this is A prime which may be series connected.

Similarly, we have phase B here and this is B prime and so on, so we have phase C here and this is C prime and we have phase D here, and this will be D prime this all this will be carrying windings this will be carrying some winding D will also be carrying some winding same as D prime. So, A and A prime could be series connected B and B prime could be series connected and so on.

Now, what we do here we in the same way excite first phase A then phase B then phase C and phase D. So, each phase now has got 2 windings so each phase will have windings like this phase A will have 2 windings and we can call this combined and phase A and A prime A phase A. Similarly, phase B will have 2 windings and they are series connected so this is B and B prime, we call it as phase B phase C will have 2 windings here. So, we have C and C prime we call that to be C and D again will have 2 windings D and D prime we call that to be D.

Now, what we do here we again excite phase A followed by phase B followed by phase C and then phase D and again A. So, the sequence of switching here in this case the sequence of switching is A B C D and again A and so on. Now, if we do that how does the rotor respond to the sequence of switching. Now, if A is switched on A is excited the mmf is along phase A, so the mmf will be along phase A means it is something along this. So, this is the direction of mmf and the rotor orients its pole along the stator mmf. So, this 1 and 4, 1 is diametrically opposite to 4 so 1 and 4 will be aligned along that mmf. So, it is stable position so the rotor will be held at that particular position.

Now, when we switch off phase A and switch on phase B so we will be switching off phase A and then switching on phase B so phase B is this one this one is phase B and here we have also that diametrical opposite which is here. So, if phase B is switched off, what happens? Phase A is no longer excited so we can we can de energize phase A this also de energized. So, we have energized phase B, how does the route respond? The rotor rotates in such a direction so to align its pole along the mmf.

So, the rotor pole closes to this particular excited phase is basically is 6 and 3. So, 6 will be moving under phase B and 3 will be moving under B prime. So, what is the angle that angle can be determined, if we extend this and try to calculate this angle this angle by which the rotor will move the stator reaches 45 degrees. Stator is actually having 8 poles stator pole pitch is 45 so we can say that the stator pole pitch stator pole pitch is equal to 360 dived by 8 that is 45 what about the rotor pole pitch, the rotor pole pitch is 360 by 6 that is 45 degree. The rotor pole pitch is rotor pole pitch is equal to 360 by 6 is 60 degree. So, this angle the differential angle is basically 60 degree minus 45 degree so this angel is nothing but 15 degrees is equal to 60 minus 45 that is why it is calculated.

So, this from 1 to 60 degree from phase A to phase B of the stator is 45 degree so if you subtract 45 form 60 you get 15 degrees. So, this 15 degrees is a step by which the rotor will move so, here we can say that the step size is 15 degree. So, in this case what we obtain here is that the step size is 15 degree and the rotor rotates in clock wise direction clock wise direction. The rotor is rotating in the clock wise direction 6 is coming under phase B, 3 is coming under B prime. So, the rotation is clock wise.

Now, suppose we would like to have anti clock wise rotation in that case we can go for the other sequence, phase A and phase D and so on. So, for the anti clock wise rotation we can we can go for, for anti clock wise rotation the sequence of switching will be earlier we had A B C D and A. Now, we will have A D B C and so on, so we have A D C B and then A and then D and so on.

Now, in this case also we can have micro stepping by micro stepping we mean the 2 phases will be excited at a same time. So, that we have a reduced step size. So, in this case the micro stepping can be done by exciting phase A then by exciting phase A and B like this. So, for the micro stepping we can have the following sequence will have A then A plus B then B then B plus C then C then C plus D then D D plus A then A and so on.

So, what happens in micro stepping we are first energizing phase a rotor aligns along phase A, we are energizing both phase A and B. So, when we energize both phase A and B this is energized and also this is energized, now in this situation the router will try to occupy an intermediate position. Here the pole will not be aligned fully along the stator mmf. So, it will be occupying a intermediate position, so here the intermediate position is 15 degrees by 2. So, in fact what happens here is that this 6 tries to come with in or below phase B and 1 tries to go little away from phase A and this angle is 7.5 degrees.

So, the step size in this case we have the size here 15 degrees by 2 is 7.5 degrees and this is for the same clock wise rotation. For the anti clock wise we can have similarly, the sequence of switching so this is for clock wise. And what about for the anti clock wise rotation? For the anti clock wise rotation we will do the following way that A then A plus B, and then D, and then D plus C then C then C plus B, so the mm f will be changing from A to A and D then D to D and C, and so on and the rotation in that case will be anti clock wise.

So, in the next lecture we will be discussing more about this variable reluctance stepper motor, and we will see how this step size can be reduced. Actually if the step size reduced we have an advantage that we can have finer stepings the motion will be almost continuous and that is basically desirable in many applications. So, if we can reduce the step size we can have better application with stepper motor, that we will be discussing in the next lecture.