Industrial Automation & Control
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Lecture - 35
Step Motor Drives BLDC Drives

Welcome to lesson 35 of the course Industrial Automation and Control. Today, we will look at the other two kinds of motors, which are used in Industrial Automation, namely step motor drives and BLDC drives, BLDC stands for Brushless DC.

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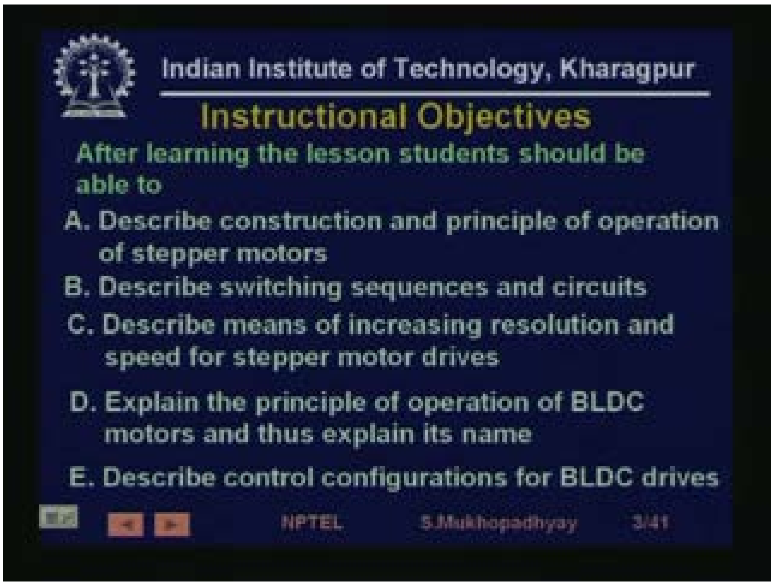

So, looking at the instructional objective, we are going to after this lesson, one should be able to describe constructions and principles of operations of stepper motors, there are interesting constructions. And describe how a motor you know has to be excited in it is stator. So, we will describe, how these are to be excited, they are generally excited in a switched sequence. Then, we will describe means of increasing resolution and speed for stepper motor drives, stepper motor move in discrete steps generally. So, you need to increase it is resolutions, so that it can move in small, small angles and this smaller the better. And it also needs to move fast, when you are trying to move something as fast as possible, so there are certain techniques, which are done to increase the resolution and the speed.

And explain the principle of operation of BLDC motors, then we will come to BLDC motors and explain the principle of operation and we will see interestingly, how by using power electronic switching. We can make DC motor; we can make a motor base, which is basically like a synchronous motor, appear like a DC motor and be controlled like a DC motor. So, we will explain, why it is called a DC motor, although you could say that, it is actually a synchronous motor. Then, we will describe control configurations for the BLDC drives.

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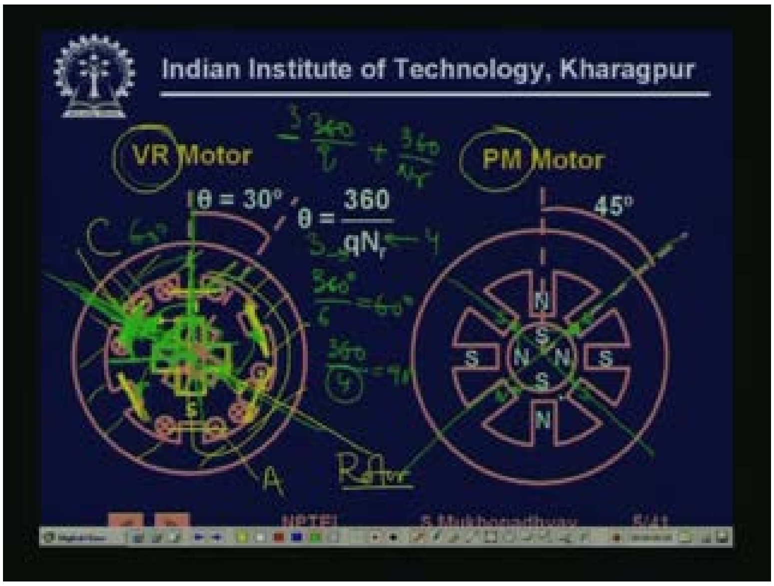

So, we first look at step motor drives, there are generally two kinds of step motors, one are called the Variable Reluctance motors or the VR motors. So, you have this variable reluctance motors, let me choose another pen, so you have this variable reluctance motors and you have this permanent magnet motors. So, this is the motor stator, you know the part, which is stationary and this is the rotor.

Actually, the rotor has many more teeth and it is circular looking, but just to explain the principle, I have drawn it is like a cross. So, that it has 4 teeth and we have also drawn it, so that it appears that, it has 3 phases. So, these two windings and these two windings is one phase and these two windings and these two windings is another phase and here we have not shown coils, they will be another phase.

So, it has 3 phases and it has 4 rotor teeth, now the principle of operation is exactly like that of not a permanent magnet motor, but an electromagnet. So, this rotor, it is made of iron, so when you excite, let us say phase A and you create and let us say, you have N poles here. Suppose, you have created an N pole here and S pole here, that will depend on the on the sense of the current that you are sending.

So, suppose you have created an N pole and an S pole, then what will happen is that, these two magnets will actually attract the rotor and suppose the rotor will be aligned here. So, this yellow position is for a particular case, these two phases A, let us say is excited and so the rotor is now aligned with this. Why is it aligned, because it will align itself, so that there is the least reluctance of the flux path.

So, what happens is that, now as you can see that the reluctance of the flux path for different angles of the rotor is actually different. Say, if the rotor was along just inclined as shown by the pink rotor, then the reluctance of the flux path for this faced by these two coils would have been more. So, the reluctance of this path actually depends on the position of the rotor that is why it is called a variable reluctance motor.

So, for any set of phase is excited, the rotor will assume that position, where the reluctance of the flux path is a least, it will come to that position. So, now suppose phase A is excited and the motor has come, so if the motor previously was rotated in the left position, when you excite phase A and create. Let us say a north pole and in south pole here, then what happens is that the rotor will rotate and will get aligned.

Once, it has got aligned, you can then excite phase B, now again if you excite or may be, what is shown here is that, suppose this is phase C, so you excite phase C. So, when you excite phase C, then look at them, so now this will this is going to be an N pole and this is going to be an S pole here. So, this magnet is now going to be attracted towards this and it will assume this position showed by the pink line, this position let me mark it by green, so it will assume this position.

So, you can understand that by first exciting this and then exciting this, you have turned the rotor by an angle. So, if you go on applying, now after B, if you apply a pulse sequence C, then what will happen is that, this will get pulled toward this and this will get pulled towards that and therefore, it will assume another position, so it will again rotate.

So, you see that every time, if you do it in a sequence, then every time you are exciting another winding, the motor rotor will rotate by a definite angle. That is why; it is called a step motor, because every time you apply a voltage, it is a DC voltage to a winding the motor steps, the motor rotates by one step. And you can easily calculate the angle, by which it will rotate, for example in this case, there are the angle between this and this, axis is 60 degree, while this angle is 90 degree.

So, actually what will happen is that, if this rotor was here, then it will rotate, it was it was previously aligned here, then if you excite this and take off the excitation here, then it will rotate by this angle. So, correct, what will happen is that, you see actually the opposite will happen, what I said is not exactly correct. In the sense that, you see when you excite this, this is an electromagnetic, so when you are exciting this, it is in this position.

So, this and the pole the angle between this and this will be actually 60 degree, while the angle between this axis and this is actually 30 degree, because it is 90 minus 60. So, actually what will happen is that, this pole will get pulled in, so because it is closer. So, this pole will get pulled in and so the motor will actually rotate by 360 degree by 6 is the angle between this phase and this phase and 360 degree by 4, because, there are 4 rotor teeth.

So, each rotor teeth is actually separated from the other, mechanically by 360 by 4 angles, which is 90 degree. So, this motor will actually rotate in the clockwise direction, if you first excite this, then excite this, then the rotor will rotate in the clockwise direction by 30 degree. So, it will rotate 360 by q minus 360 by rather minus 360 by q plus 360 by Nr.

So, in this case it will it will rotate by 30 degree, so in this case what will happen Nr is 4 and q is 3, so it will rotate by 30 degree, now this is the way a variable reluctance motor works. On the other hand, there is another kind of motor, which is called a permanent magnet motor in which the rotor actually has some permanent magnets. So, these permanent magnets will see can be fixed to the rotor in various ways.

But, now previously, this was not a permanent magnet, it was just a soft iron rotor, so it was getting attracted. On the other hand, now you have put magnets here with fixed poles N N, S S, so now, what will happen is that, if you create an N pole here, then obviously the S poles will now get attracted towards it and the rotor will actually assume this position. Now, if you create an N pole here and then S pole, N pole here and so this is N N and this is S S.

Then, what will happen is that, this S pole will get attracted towards this N, this S will get attracted towards this N. Similarly, this N will get attracted towards this and this N will get attracted towards this. And not only that, they will get attracted towards this, they will actually be, if you actually what will happen is that, if you excite it, this will also push it.

So, then what will happen is that this rotor will actually rotate and then this N pole will get aligned with this S pole, while this S pole will get aligned with N pole, so the motor will step by 45 degree. So, this is the way a permanent magnet motor works, basically they are absolutely similar, only thing is that, there are certain advantages and disadvantages between these 2.

For example, it is difficult to create see as we have understood now, that the resolution that is the steep angle, which is the smallest angular resolution that you can have for a step motor. Depends on the number of stator phases you have and the number of rotor teeth or the number of rotor poles that you have. Now, you see how many number of stator phases you can have or how many stator teeth you can have and how many rotor teeth you can have, that actually depends on the motor size.

Because, for a given size you cannot create more number of poles, then a certain number, because of mechanical and special constraints. So, it turns out that with variable reluctance motors, you can have more number of rotor teeth, than you can have poles on the rotor. So, therefore, the resolution of permanent magnet motors is generally less, I mean the resolution is less means, it actually step through a larger angle, than in the case of a variable reluctance motor.

But, on the other hand, you can see that, if you do not excite, this motor actually you know, does not have a locking torque. So, generally this motor is free, but here you have NS, NS, so this motor will actually lock to this, even in the unexcited condition, this motor will actually lock to this position. So, therefore, you have a lock torque available and till you get excited till you change your excitation sequence, the motor will not rotate, but will hold the position, so this may be useful in certain applications.

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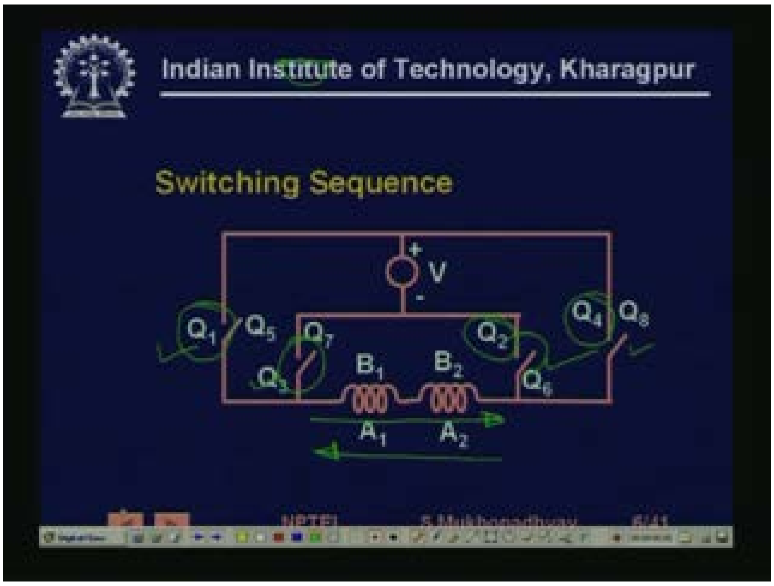

So, moving on now, how do you excite the stator phases, suppose let us take A 2 phase case. So, we have two coils A 1, A 2 and B 1, B 2 and I am showing them, basically you know, you either have, you assume that in the same figure, that either you have Q 1, you have Q 3, you have Q 2 and you have Q 4. So, assume that for the A 1, A 2 coils, you have these 4 switches and similarly you can have another circuit in which you have the B 1, B 2 coils in which you can have Q 5, Q 7, Q 6 and Q 8.

So, now why this switches, because you can see that in the switching sequence, you want to create north and south poles. So, if you want to create north and south poles, you need to see the coils are wound already. So, you need to send currents, once in this direction and the other in another time in another direction, so you need to have a bipolar excitation

So, what we are doing is that we are, so you see if Q 1 is on and if Q 2 is on, then the current plus, so the current will be flowing in this direction and on the other hand, if Q 4 is on and Q 3 is on, then the current will be flowing in the other direction So, with this simple circuit, you can switch on and switch off currents, I mean reverse the sequence of currents to create, either a north pole or a south pole. So, what is the sequence in which we need to drive these.

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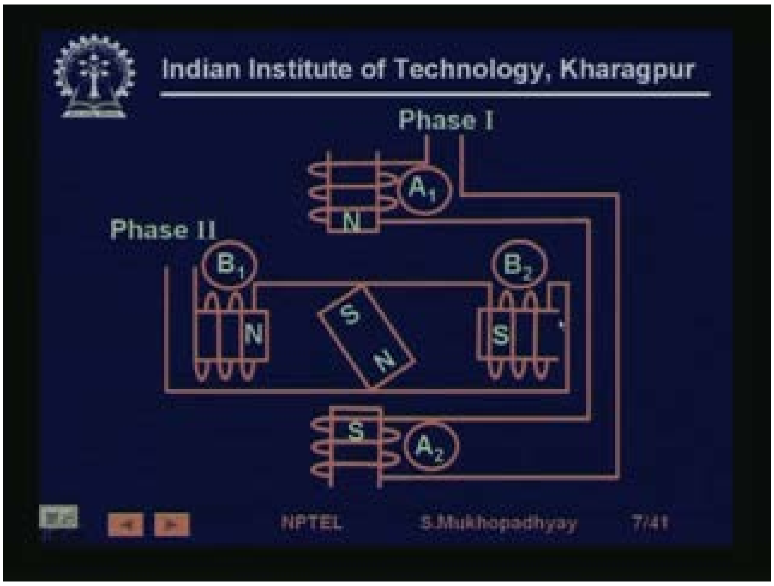

So, imagine this case, that you have these phases A 1, A 2 and you have these phases B 1, B 2 and you have we are just for simplicity, we are assuming that we have only one pair of rotor poles.

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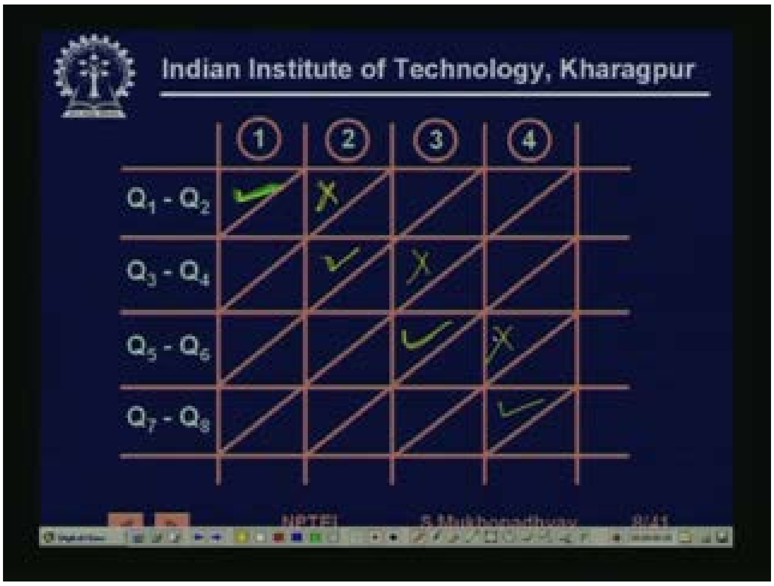

So, what happens is that, so we the switching sequence like for example, first you what you will do is that in the first place, you will sequence switch Q 1, Q 2. So, you will switch Q 1, Q 2 let me change the color, if you switch Q 1, Q 2 then the rotor will get aligned in one direction. Then, in the second step, you will switch off Q 1, Q 2 this you can do, this is one strategy and you switch on Q 3, Q 4.

Similarly, in the next stage, you can switch on, you can switch in the next step, third step, you can switch off Q 3, Q 4 and you can switch on Q 5, Q 6 and in the last stage you can switch on Q 7, Q 8 and switch off Q 5, Q 6. So, then you are the motor rotor as we are saying will rotate. Now, this is called full stepping, where one phase is actually excited at a time, so the motor rotates by one angle. Now, we will see that, we are always interested in trying to be able to make the motor rotate, through smaller and smaller angles.

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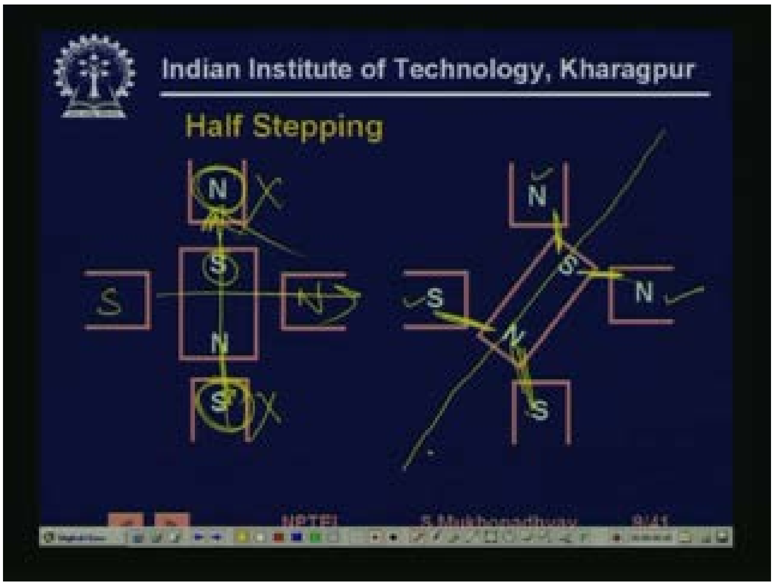

So, what we are doing is now look at this, so there is something that we can do, to make it rotate to a through a smaller angle. So, you see in case of full stepping, we were once making this N, this S and then switching this off and then making this N and this S. So, it will rotate first, it will get aligned through this, then it will get aligned through this. Actually, it gets aligned to a much smaller angle, since we are only drawing two pairs of stator magnets and one rather, two stator magnets and one rotor magnet for simplicity.

So it appears that motor is rotating 90 degree, actually it will not rotate 90 degrees, it will rotate by an angle, which is dependent on the number of rotor teeth and the number of stator teeth which is generally much larger than what is shown here. But, to understand the principle, suppose we from this position that is initially N and then S we make, so this was S attracted to N and this was N attracted to S.

Now, if we make this N, keeping this N and S, if we make this N and this S, then what will happen is that this rotor will assume a position, where it will experience equal pulls from these two sides and this will experience equal two pulls from these two sides. And it will see that, now it has rotated through, so it will assume another equilibrium position, which is midway between the two poles. So, by doing this, we can make it rotate through half the angle, that is why this is called half stepping.

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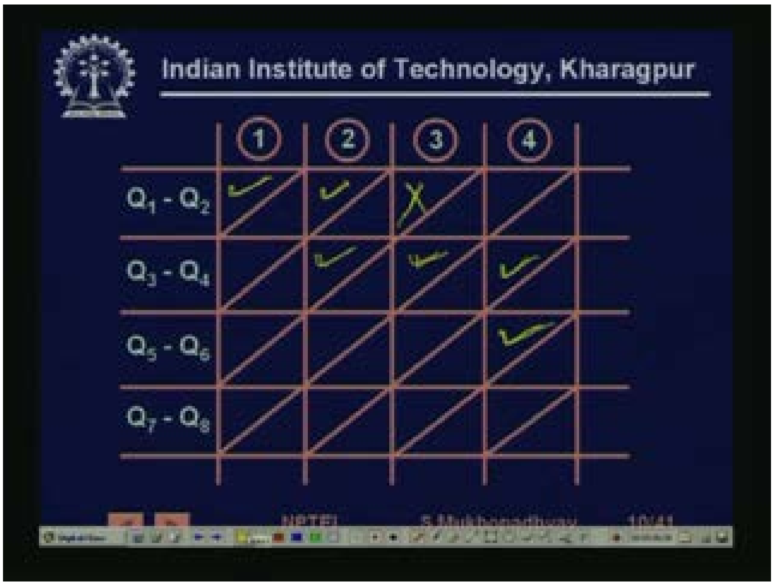

So, for half stepping, what we have to do is, we have first we have Q 1, Q 2 on, next we have Q 1, Q 2 and Q 3, Q 4 on, next we will have Q 3, Q 4 on and then keeping this on, now then we will make only Q 3, Q 4 on. So, in the third cycle, we will have this and we will switch this off, after we switch this off in the 4th cycle, what we are going to do is, that we are going to keep this and we are going to switch Q 5, Q 6 on. So, we are going to have both in this side, so it will rotate by another half.

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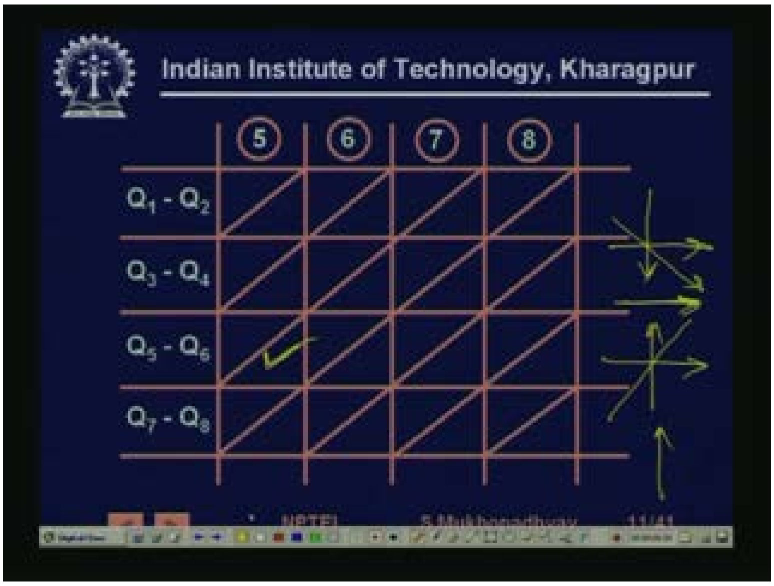

In the next cycle, which is shown in the next diagram, so in the next cycle, which is the fifth step of the cycle, so in the next cycle, what will happen is that, we had Q 3, Q 4. And Q 5, Q 6 on, then we will have only Q 5, Q 6 on, after having Q 5, Q 6 then we will have Q 5, Q 6 and Q 7, Q 8 on. So, you see that, we are actually exciting, this is exactly what we are doing, we are trying to first excite, one coil of one phase only, then we are exciting this and this, so that the rotor moves to 2 halves.

Then, we are switching off this excitation, so that the rotor gets completed aligned with this one, then what we are doing is that, we are changing the polarity of this. So, we are first creating a field like this, then we are creating a field like this and like this. Then, we are creating a field only like this, then we are creating a field which is like this and like this. So, you see first in here, the resultant field is like this, next the resultant field is like this, next the resultant field is like this and then we will keep only this and so on. So, the rotor gets every time aligned with the resultant field of the two stator coils, so basically that is happening very simple.

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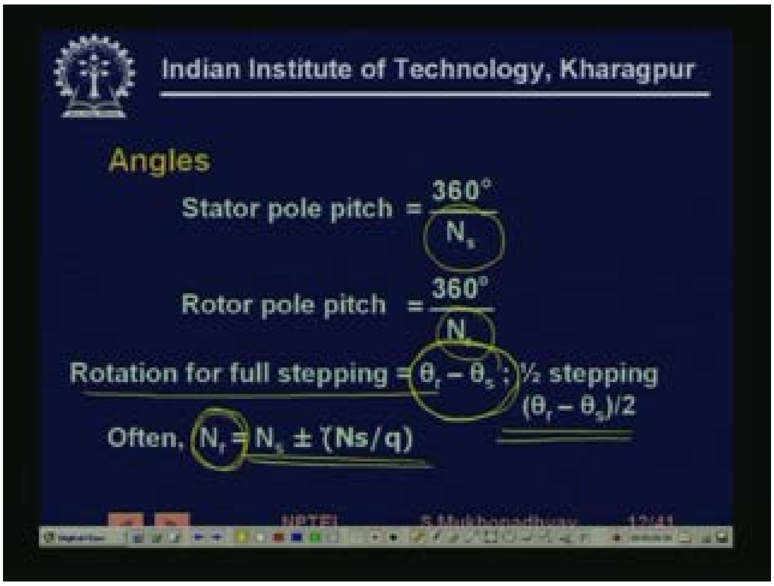

And we can understand that, if you have Ns number of stator teeth, then each phase is separated from the other by 360 degree by Ns. If you have the rotor pole pitch as Nr, then it is 360 degree by Nr, for the rotor tooth pitch and the rotation for full stepping is theta r minus theta s, generally theta r is less than theta s, so because it is a smaller.

So, you have theta r minus theta s and for half stepping, it is theta r minus theta s by 2, so then you will get generally, I mean often Nr is chosen as Ns plus or minus Ns by q. So, if you do that, then you will get Ns by rather 360 degree by q Nr as the pole pitch as the steep angle, so this is the basic principle of operation.

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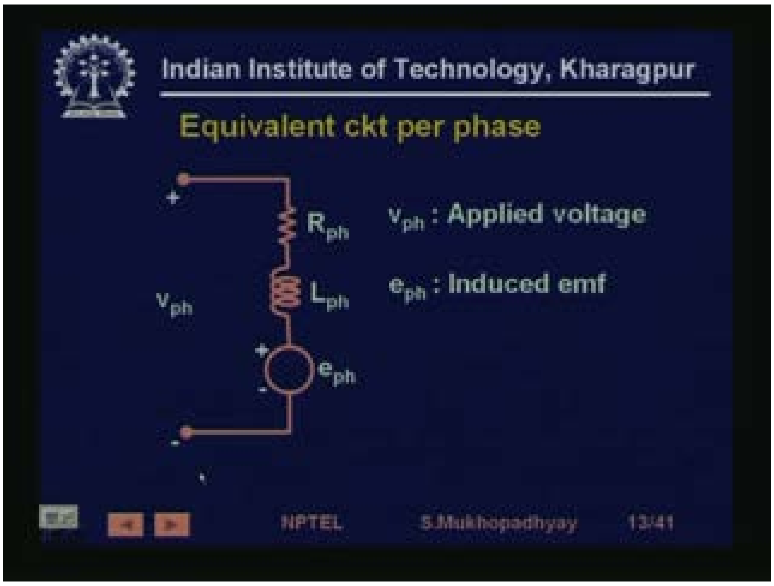

If you look at the equivalent circuit per phase, then it is just a coil, so it has a resistance, so you are exciting it by a phase voltage and there is a resistance, there is an inductance and there is a back here, so that is the induced e m f.

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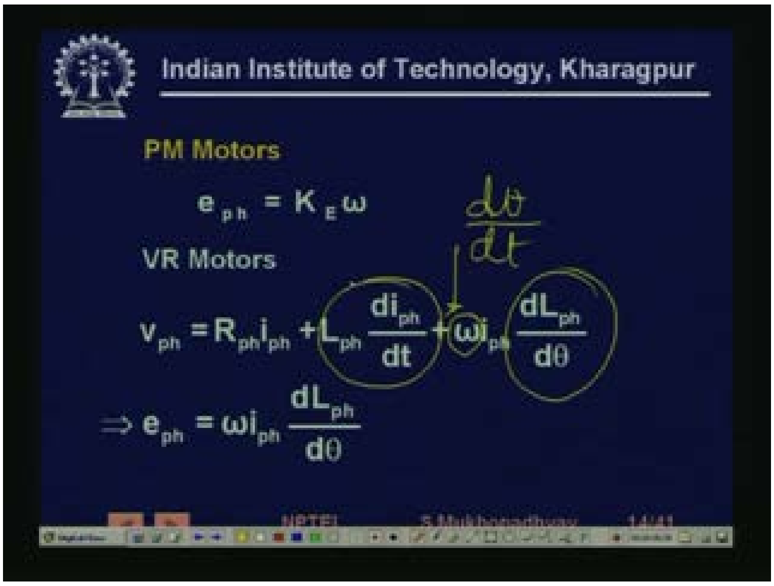

So, if you see the equations, then if the motor is rotating continuously, then this the phase back e m f induced is actually proportional to omega, because the flux, it is a motor. So, when it is crossing the coil, the flux is getting link, so it is K E into omega and for variable reluctance motors, what is happening is that, you see that the rotor is rotating. So, as the rotor is rotating, two things are happening, first the current itself is changing and the inductance is also changing, so both things are happening.

So, therefore, you have this is the normal resistive drop, p phase equal to r phase into I phase, plus you have an L d i by d t term and you have a I d L by d t term, because L is also changing, I is also changing. So, it is basically d d t or flux linkage, flux linkage is Li, so it is d d t of L I, so that is I d L d t plus L d i by d t. So, it turns out, that d L by d t, you can write as d L by d theta into omega is d theta by d. So, then you have L d i d t and then I d L by d t and this is the drop in the inductance and this is the induced e m f in the coil.

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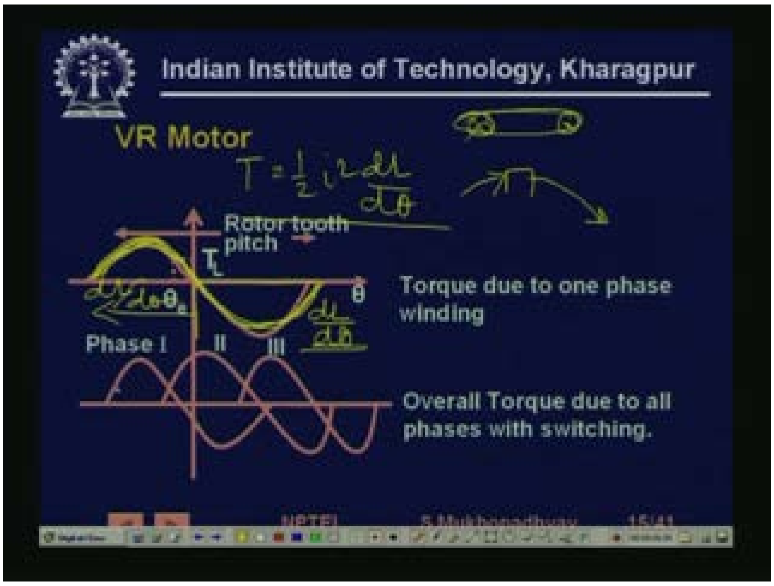

Now, what happens is that, now in a variable reluctance motor, you see that the d L by d theta is between 2 rotors, suppose you have a rotor tooth pitch and you have a stator coil here, so you have a stator coil here. So, what happens is that as the rotor is rotating, suppose the tooth was here, so coming back. So, what happens is that, you see as it is rotating this way, initially d L by d theta is positive, because inductance is increasing and as and after one rotor pole pitch d L by d theta will be decreasing.

So, you have d L by d theta, during this phase d L by d theta is positive and during this phase d L by d theta is negative. So, the torque is half I square d L by d theta. So, you see that the torque and d L by d theta actually changes, d L by d theta is positive, but it is not constant, so first starts increasing slowly, then it increases at a high rate, then it falls. So, the over a rotor pole tooth pitch, the torque generated varies like this.

So, now what is going to happen is that, how are you going to switch the phases, when, so you see that initially you switch phase 1, so this rotor torque is positive, so the rotor moves. Now, and then the rotor torque will fall, so unless you change the excitation to now to phase 2, the rotor torque will actually turn negative. And if you maintain the phase excitation, then the rotator will rotate and then will come back, because it has a negative torque.

But, by the time, this torque falls, you have switched on phase 2, so now with respect to phase 2, the same rotators tooth with respect to phase 2, now has a positive torque. So, now it will switch on to phase 2 and will traverse, when this one will tend to be negative, then you switch on phase 3 and then now with the same tooth with respect to phase 3 will again have positive torque.

So, as the rotor torque tries to reverse, you are switching on another phase, so that with respect to that phase, this rotor tooth has a positive torque and this is happening to all the rotor teeth. So, therefore you are maintaining an average positive torque and your motor is rotating. So, this decides that at what should be your switching frequency, so the principle is that the rotor torque on the rotor tooth should not become negative.

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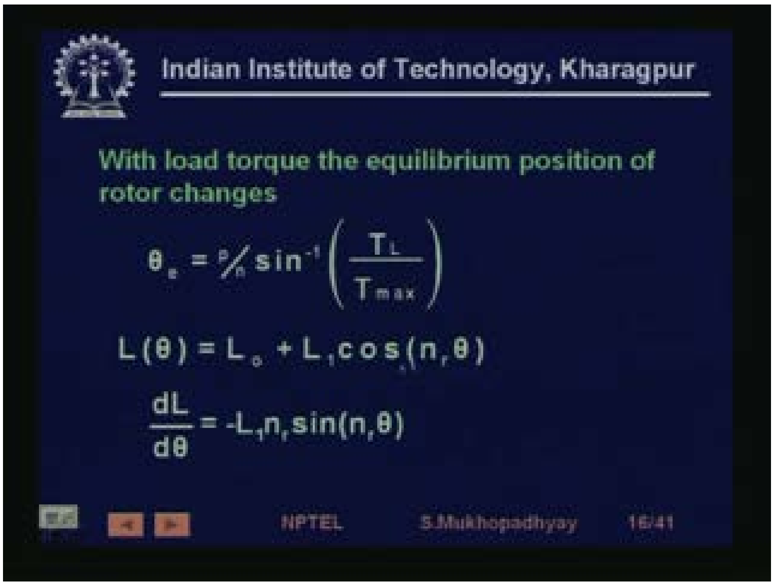

$$\theta_e = {}^p/_n \sin^{-1}\left(\frac{T_L}{T_{max}}\right)$$

$$L(\theta) = L_0 + L_1 \cos(n_r\theta)$$

$$\frac{dL}{d\theta} = -L_1 n_r \sin(n_r\theta)$$

So, this is some expression, which shows that the inductance is varying as there is a DC component and there is a pulsating component, like I was showing. And then d L d theta is actually is a sinusoid, so the torque is also is a sinusoid.

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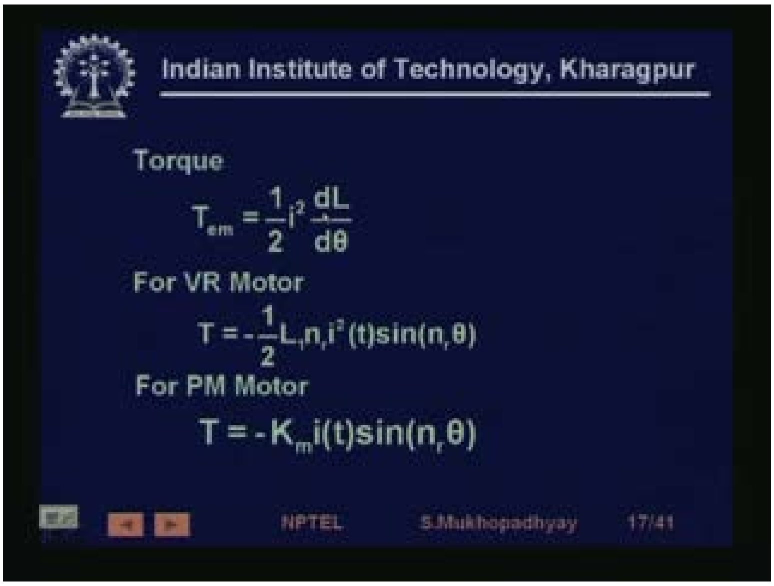

And you determined will be the torque is half I square d L d theta, so it turns out that, these are expressions for the permanent magnet and why this happened. So, these are the torques generated by the permanent magnet motor, in the permanent magnet motor flux is constant. So, this the torque generated on the permanent magnet motor and this is the torque generated on the variable reluctance motor and finally, what will be the torque generated.

So, total torque is T which is electromagnetic torque generated like we discussed and that has to be balanced by the load torque and the difference in this 2 torques will actually accelerate or decelerate the machine or get some of some of it will actually get absorbed in the friction. So, you can see that, this torque itself is actually a function of theta, so this is actually a non-linear differential equation. And therefore, this system is actually non-linear, but anyway we are not getting into the exactly the design of a controller.

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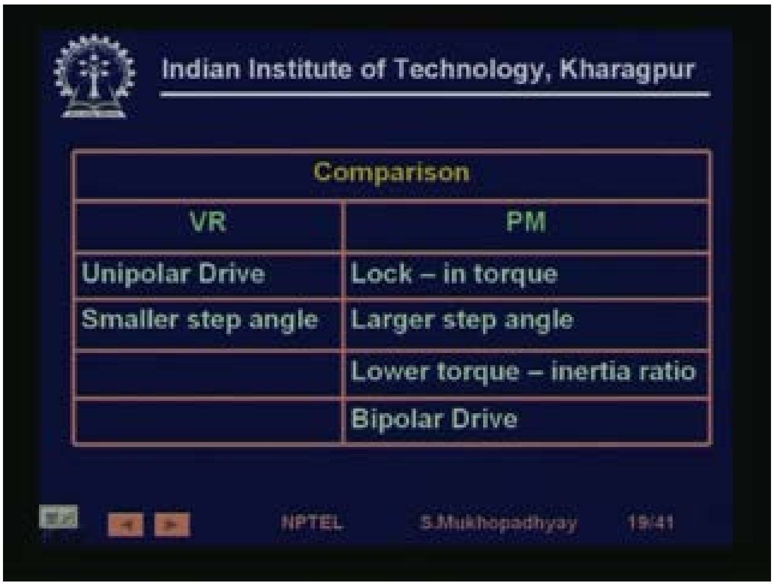

So, this just shows that, how the motor, it is principle of operation, so you know variable reluctance machine, since it is an electromagnet. So, we do not need to and it is always on the principle of the attraction, because the rotor is actually an iron. So, therefore, with you can do with an Unipolar drive and you can achieve smaller step angles, because you can have more number of rotor teeth. On the other hand, with permanent magnet machines, you have a locking torque as we said, but you tend to have a larger step angle and you also have a lower torque to inertia rating and you require a bipolar drive.

So, these are the you know the tradeoffs, only good thing is that you know nowadays very good permanent magnets are actually being available. So, you can have very high field strength on in this machine, these are some common, but probably during that time they used to use, you know alnico or something like you know iron magnets, but now people use rare earth magnets. So, you know this lower torque inertia rating concept may be is probably not valid.

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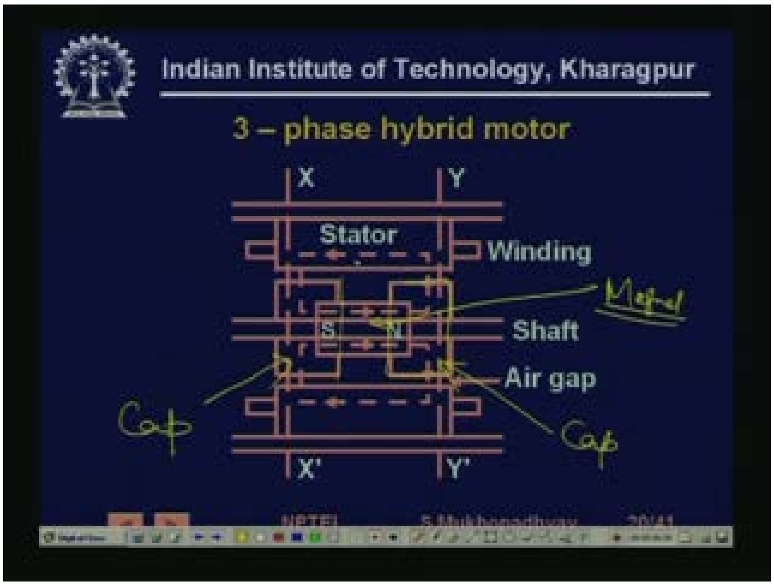

Now, we worry about, what else we can do, increase the resolution further, so we have seen that, the resolution is depending on the stator pitch and the rotor pitch and the difference in that. So, now there are actually various concepts, so one of the concepts is to have, what is known as a hybrid motor. So, in a hybrid motor, you see these are the two caps, you know this is one cap and you have another cap at the two ends and in between you have a magnet, so these are you know iron caps.

So, this thing itself acts like a pole shoe with some teeth and then you have a stator, now you see what happens, if you see the end views, then you will find that. So, if you see from one end, this is one cap and then this is the other cap. So, you have the two caps and on the on two caps you have rotor teeth, so let us go to the next diagram. So, on and you have two caps with rotor teeth and you have equal number of rotor teeth on both the caps, only thing is that there are slightly offset, you know why they are offset.

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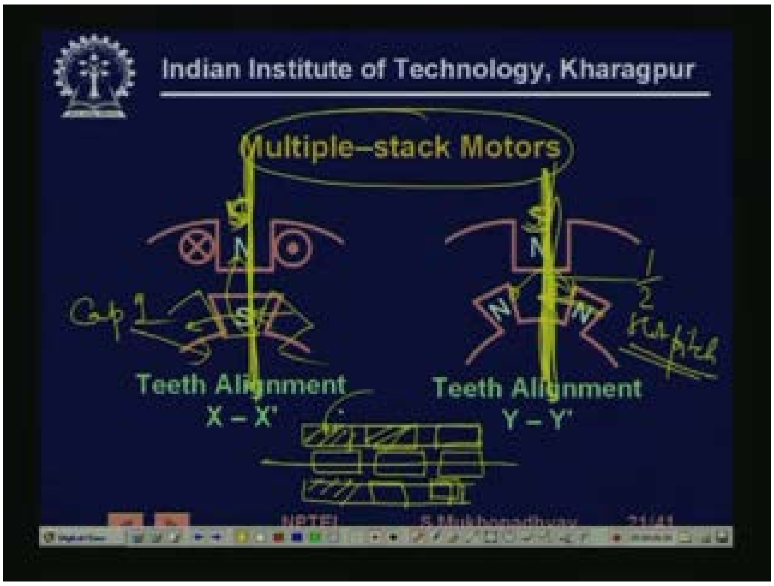

So, what happens is that, so there are the same number of teeth, but they are slightly offset, in such a way that when one tooth, this is for one cap, say cap 1, when one tooth will align with the stator tooth at one end, the other teeth will actually align with the slot. So, this aligns with tooth and this aligns with slot, so what happens and you see this is S and this is N, because there is an internal electromagnet in that.

So, now what you do is that when you the first time that is, so you make it N and S, then the S pole will align with it and this will be in the middle and they will repel each other. So, they will try to be at the maximum possible distance, so it will align with the slot, next time you make this one S and this one N, just opposite will happen. This N will get pulled in and this N will get align with the tooth and this S, when you make this N, this is N and this is N.

So, when you make this is S and this is S, because they are in the same phase, see the stator is only one winding, so then this S will now rotate and will get aligned with this slot, this will be assumed in this position. So, in effect the rotor has moved by half the slot pitch, so you have the same kind of you know excitation, but you can just by having a hybrid motor, which utilizes both the principles of you know rotor slots.

And one strong electromagnets, so you do not have so many magnets, so you can half the phase angle and this is one principle, the same principle similar principle occurs actually in multiple stack motors, which is written here. In a multiple stack motor, actually what happens is that the stator has multiple windings. So, it has one stack, which is one set of stator windings, then you have another stack, which is another set of stator windings, then you have another stack.

So, the motor tends to be long, now what happens is that and you this rotor slots, so you are going to have some rotor slots here and some rotor slots here and some rotor slots here and the shaft. And these rotor slots are actually slightly offset from each other, so the rotor teeth on first rotor stack and the rotor stitch on the second rotor stack are slightly offset.

So, when you excite the first stack, the teeth get aligned with the first set of stator coils, then you switch it off or if you are doing half stepping, you can also keep them on. Then, after you have excited this stack, now you excite the other stack, so now, since these are slightly offset, so then now they will further rotate and they will get aligned. Then, you excite the other stack, so you see actually the by creating multiple stacks and multiple rotors, you are actually dividing the overall angular resolution into the further dividing it into the number of stacks.

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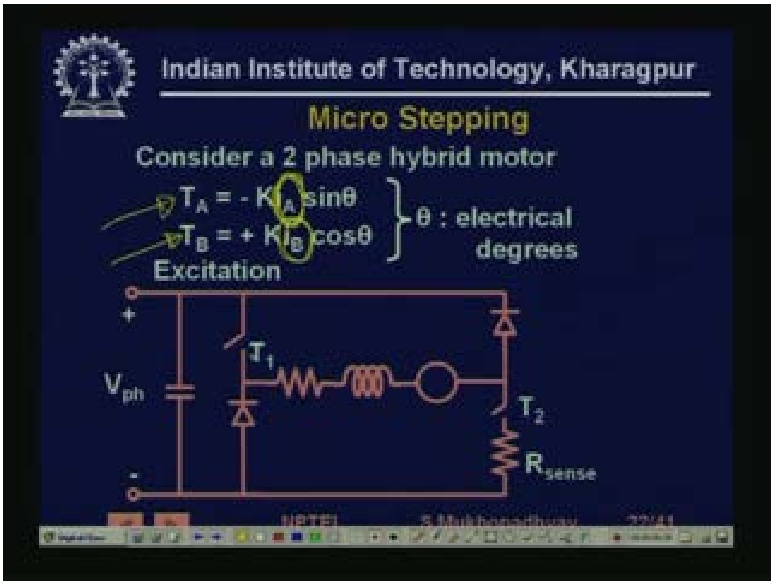

So, this is happening, similarly you can do a similar thing by doing, what is known as a micro stepping, this is you know another technique, where you can actually do current control. So, if you have A 2 phase hybrid motor, then you can actually simultaneously excite for example, you can send a current I A through the first phase and create a torque T A and create a torque T B through by sending current I B and you can control this currents, but by a simple switching mechanism.

So, if you control this currents change this currents, then the angle will get actually that is the torques generated on the two sides will get generated by this angle theta. And then the motor will rotate will rotate by an angle, which can be controlled by these currents I A and I B. So, by having more complex switching you can actually create, even smaller degree motion, but it requires precise control, that why it is called micro stepping.

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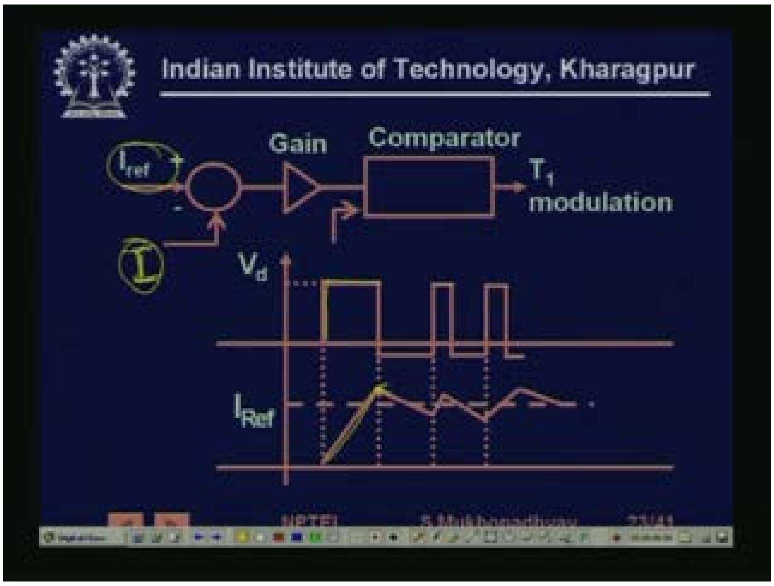

So, this is the current I, so you see you do not want to current to increase by more than I, so whenever this is your reference current, where you want to maintain the current in a phase, this is a actual current, this current whenever you switch it on, the current starts to build up, whenever you switch it off, the current starts to fall.

So, the actual current in the winding is actually always increasing or decreasing and when it increases by a certain amount, when you have switched on, the winding voltage, so the current stats building. And then when it crosses a certain limit, then you switch off one of the one of the switches, so T 1.

So, you can if you can see T 1 by seeing the previous one, initially you keep T 1, T 2 both on and then you switch off T 1. The moment you switch off T 1 the inductor will start driving current through this loop for some time. Because, it has a magnetic energy and it does not allow in an instant reversal of current through itself. So, therefore the current will continue for some time, but it will fall in magnitude and therefore the current will fall.

So, you switch on T 1 and T 2 and then you switch off T 1, the moment you switch off T 1, current will fall, again when the current falls too much, then you again switch on T 1. So, when you switch on T 1, current will fall, then again current will rise. Then again, by doing this continues switching, you can actually maintain a particular current in a phase. And then as we have seen that you can make the motor rotate by a certain angle by controlling the currents in the phases, so this is the basic idea of micro stepping.

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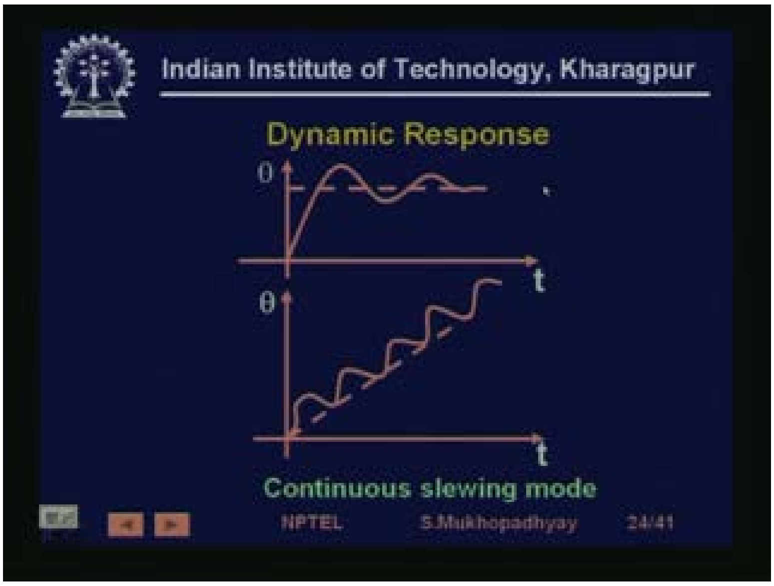

Now, it turns out, generally when we are using a motor, we want to move it as fast as possible. So, if you are giving pulses slowly, then what will happen is that, you excite one phase motor rotor will come and will stand still. So, it will actually stop at that position, it might excite, because of it is inertia, it might give us a little overshoot. So, it might give a little overshoot, but it will stop, but if you let it stop and then excite, then you are taking more time.

So, you do not let it stop, but you rather, when it has come to a certain point, when it when it is and the position from that position, it can be pulled in by the next phase, then you excite the next phase. So, even before it stops, it actually moves to the next position, so this is called slewing. So, the, the rotor never comes to stop, but continuously starts rotating, this is called the continuous slewing mode. So, you actually little bit advance your pulses to the phases, so that the rotor does not come to a stop.

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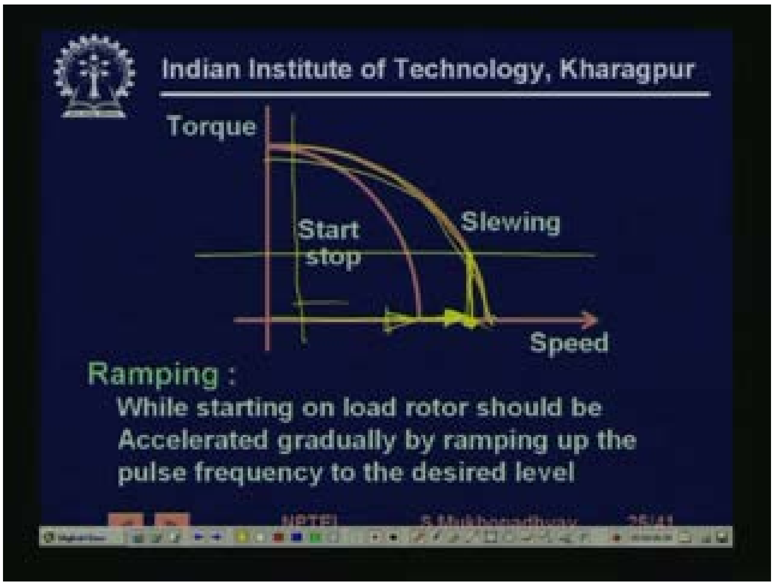

So, if you see the torque speed characteristic will see that, when one is trying to start the motor, when the motor has no inertia, it is not moving, it is actually at rest, then initially you have to start it, you cannot give very high frequency pulses, because if you increase the pulse frequencies, then actually what will happen. If you increase pulse frequency too much, that before the rotor can move another phase will be excited.

So, with respect to since the rotator has not moved, so with respect to that phase, it is torque will not be enough to move the rotor. So, therefore, we cannot just have more and more speed just by increasing the switching frequency of the phases that is not possible. So, it turns out, that while we are trying to start the motor, we have to start it slow, when you are starting it, when you are giving pulses at lower frequency.

So, initially it will come and then it will stop, then you will get the next pulse, so it is again starts moving. So, you slowly start increasing your pulse frequency, so that the motor gradually starts slewing and you will find that, so it is speed is increasing and while for it, you see for starting a motor, you need a larger starting torque. So, for starting a motor, you have to start from low value and then gradually ramp the pulse frequency.

But, once it reaches a certain speed, then slewing will start and it has it is own inertia, so it can move a certain extent by it is own inertia. So, therefore, you can increase the speed further and your torque requirement has also come down to some extent. So, you can increase it further by actually increasing the speed by doing slewing, but if you increase it beyond this slew torque speed characteristics. So, if your load torque is here, then you can only excite it by a frequency up to this.

If you give excite the stator phase at higher frequency, then this motor will actually stop, because it will it will actually come down to a lower speed, so you cannot you cannot increase it is speed just by increasing the stator frequency arbitrarily. So, this phenomenon is called ramping, while starting on load rotor should be accelerated gradually by ramping of the pulse frequency to the desired level.

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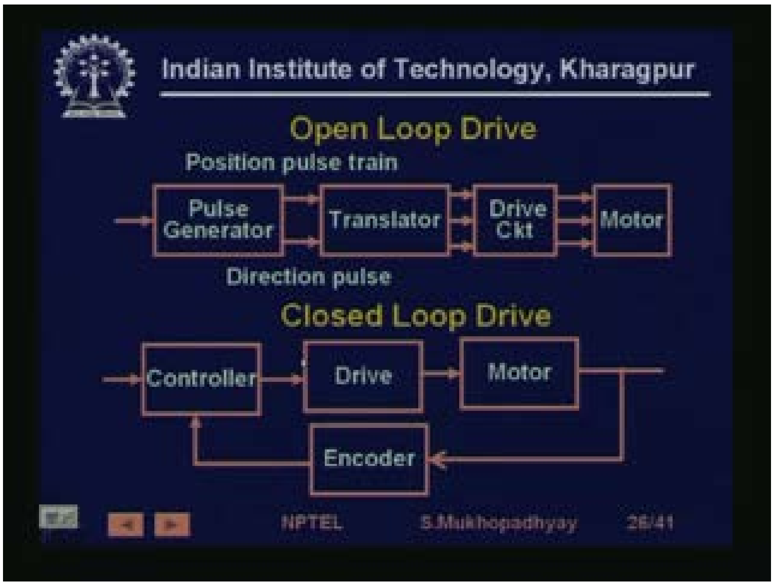

So, you can have two kinds of drives for stepper motors, either open loop or closed loop, in open loop drive, we are not taking any feedback. So, you are kind of assuming that every pulse, that you have given has been executed by the motor; obviously to this assumption will be satisfied, when your pulse frequency is low. So, you are moving slowly this can be satisfied, provided the load torque is not too much.

On the other hand, if you want to really move it fast, then you need to know whether the pulses that your are sending have actually been executed by the motors, so you need to take a speed feedback. So, you can have two kinds of drives, for more precision drives, people uses a speed feedback.

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So, the advantages are that you have simple feedback control, position feedback may or may not be needed, you can even do without it and it is cheap, this is the biggest advantage. And disadvantage is that you have step, you have limited resolution, you have limited torque, you have limited speed, so these are it is limitations. So, typically these are used in applications, such as computer peripherals and let us say the textile industry, so high resolution is not required of motion and the loads are not high, so torque is lower. Similarly, some small writing machine tools small robots etcetera use step motors, but for the most demanding motion control applications you need BLDC drives. Because, this can give you very high torque, this can give you infinite resolution and can give you very high speed drives.

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So, we will first see, how, why BLDC drives are called BLDC drives, this is a very important concept to understand. So, in a DC machine, you have the poles are fixed. So, the poles are fixed on the stator, it does not move, so you have fixed, so the field m m f is fixed in space, it does not move. Now, the armature is excited, so the armature is a coil, it is excited by current, so that also creates an m m f.

Now, these two m m f s, must be perpendicular to generate maximum torque, but the rotor is rotating. So, as the rotor is rotating, it is coils are on the rotor, so therefore, that will also rotate. So, then what will happen, if you did not have brush and commutator, then what would have happened is that the rotor would have come and been become aligned with the stator poles.

Now, does not happen you have the brushes and commutator, so as the rotor rotates, since there are brushes and commutator, so the resultant armature m m f is kept perpendicular to the field m m f. So, the rotor is moving, it is running fast to catch up with the stator, but because of the brush and commutator arrangement, it is m m f is slipping out and it is staying perpendicular.

This is the principle of the rotor and stator m m f are fixed in space see, but you will realize that for generating torque, you do not need to keep it fixed in space, you need to keep it always perpendicular. They both of them may be actually rotating, it does not matter, exactly this principle is used in the brushless DC motor.

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So, in the brushless DC moto,r that is why it is called a DC motor, because here the field and the armature m m f's are kept perpendicular, nearly perpendicular, but the field m m f is rotating at synchronous speed with the rotor. See the rotor is rotating and you do not have any brush, so the rotor m m f is rotating. So, to keep them perpendicular, what you do is that you sense the rotor position.

And you also make the field m m f on the stator rotate, along with the in synchronism with the rotor, so that they always maintain 90 degree. So, that is the essence, so your field m m f rotating at synchronous speed with rotor and stator field also rotating at synchronous speed and this is achieved by switching and the angle between the fields can be controlled.

And therefore, you do not need any brush and commutator, but you need to see, when you will switch which stator phase, that depends on the rotor position, because you want to keep 90 degree. So, you need to sense rotor position, so you do not need a brush and commutator, but you need to sense the rotor position.

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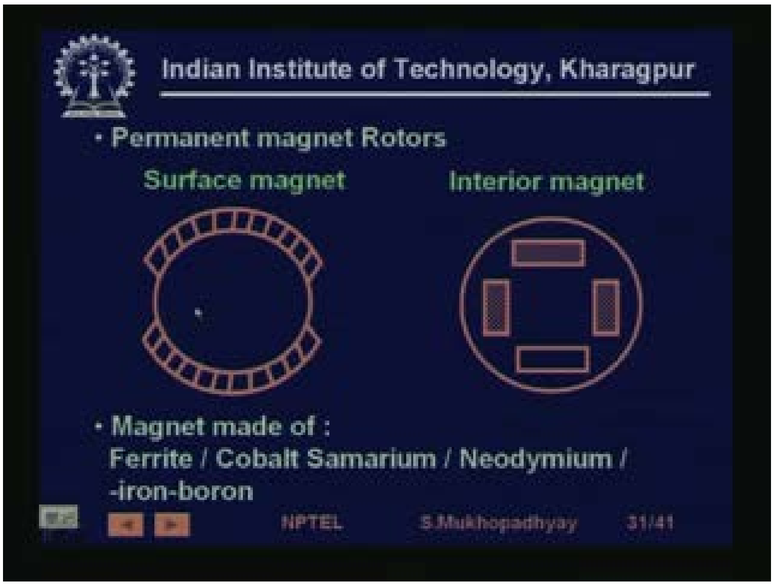

So, the principle is very simple and you have permanent magnet rotors of various kinds, so you have either surface magnets, where the magnets are several magnets are you know stuck by some means glue or something. Or sometimes, you put them, if you have this, then there is a chance for high speed cases, because of centrifugal forces. They tend to you know get dislodged, while if you have an interior magnet, then you put it inside the rotor iron and therefore, it can rotate at much higher speed. They now a days they are very important, because the magnets are made of ferrite, cobalt samarium and neodymium, iron boron and can create very high flux densities.

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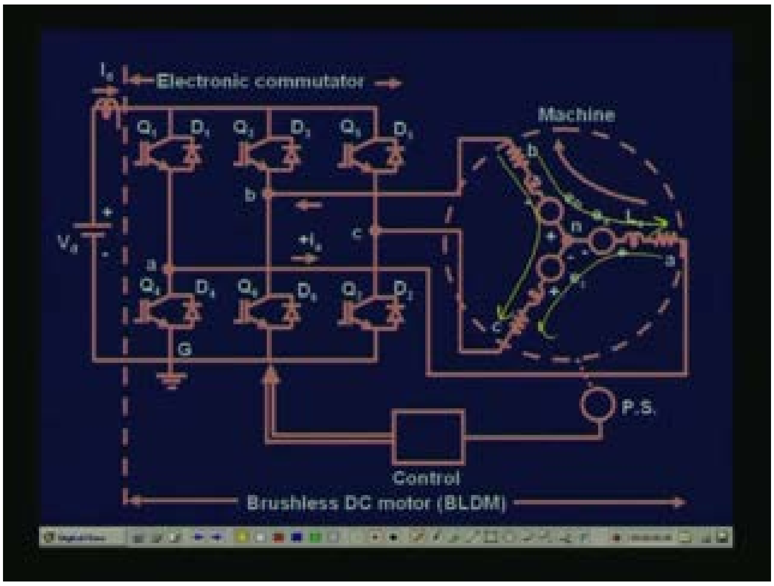

So, that is the basic idea without going into too much, we will see that, these are the 3 you know stator phases and they are actually excited by these, what is known as the this inverter. So, you see sometimes what is happening, if there sometimes current is flowing through this, sometimes current is flowing through this, sometimes current is flowing through this, that depends on which inverter legs, you are you are keeping on. So, you see that, if you see the next diagram, you will understand that when in the next diagram, you will understand.

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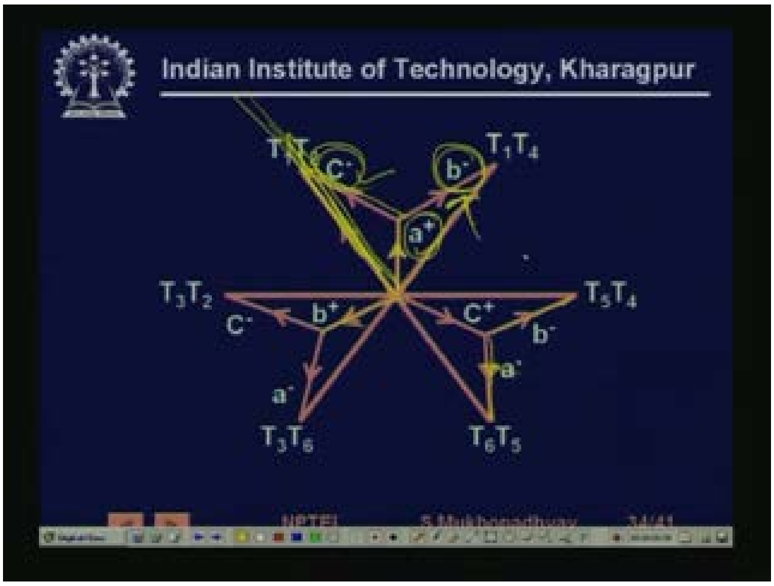

We will go to the next diagram, so in the next diagram you will understand that how the stator m m f direction is changed. So, if you have the coil a in a certain directions, say one terminal positive and the other terminal negative, we call it a plus. So, the m m f is in this direction, if you change the polarities, it will be a minus, this is in the opposite direction, similarly you have b plus and b minus and you have c plus and c minus.

So, when you connect a plus and c minus, because current is flowing in through 1 and then going out through the other, then that then the net m m f is actually along this direction. If you now switch off c minus and you excite b minus, keeping a plus on, then the m m f will switch in this direction, so you have made the mmf switch. So, as the rotor is rotating, you also make this switching, such that this stator m m f, previously, it was in this direction, when the rotor has moved you make this switching.

So, that the stator m m f will now going to the other direction, so using this switching you are actually rotating the stator condition and then it becomes like a DC motor with both stator and the rotor m m f rotating. So, this is the basic idea.

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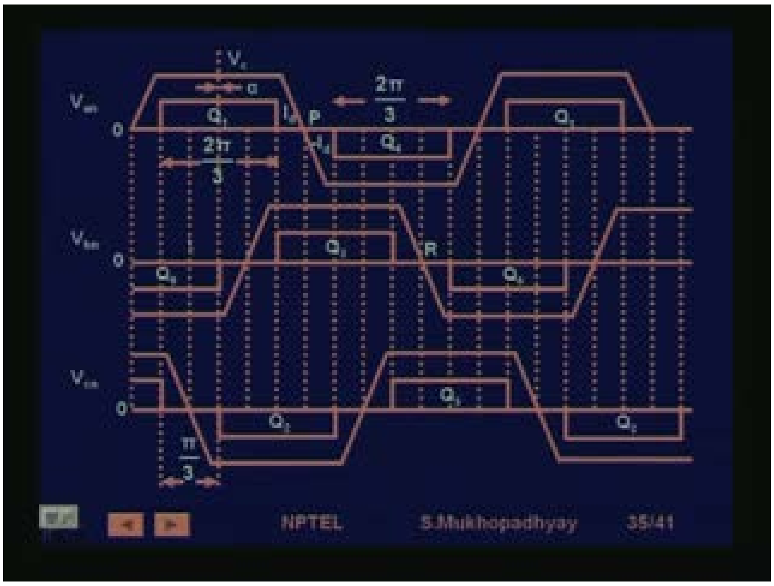

So, we will switch these transistors Q 1, Q 2, Q 3, Q 4 in such a manner, that whenever the induced e m f is positive in that phase, we will try to drive current through it. Because, we know that we can generate positive torque, if we drive a positive current for a positive voltage. So, we will be delivering power into that phase and that phase will experience a torque and the machine can move.

So, we are switching these transistors Q 1, Q 2, Q 3, Q 4 in such a manner, that they always at some interval Q 1 and Q 6 are on, then in this interval also Q 1 and Q 6 are on and this is off and in the next interval Q 1 and Q 2 are on, so Q 6 has been switched off. So, in this way, we are actually switching the stator m m f's and keeping always the torque positive.

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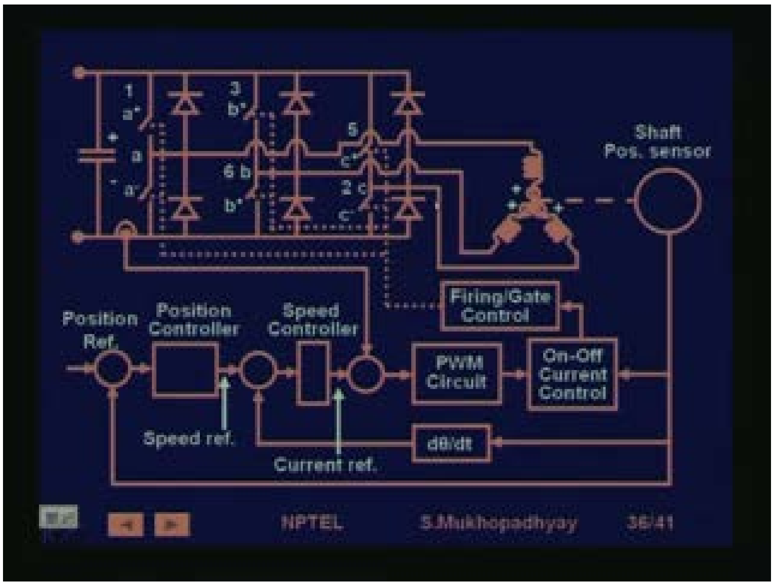

So, we come to a control scheme, so what we are basically doing is that, we want do just like in a DC motor, we want to torque control. So, we have seen in the case of DC motors, this is absolutely similar, in the sense that, if you have a position control loop, then we have a position reference and we give a position feedback, then we have a position controller, which gives a speed reference. So, it is actually a cascade loop, this we have seen in the case of the DC motor.

So, now the speed reference is now compared with the speed feedback and we have seen that the speed feedback actually adds damping and gives very good motion characteristics Then, the speed controller will actually generate a current reference, now the current reference is similar to the torque reference, because the flux is constant and because it is always maintaining nearly perpendicular.

So, now based on the current reference, there is a PWM circuit, which will actually switch on these invertors to actually maintain a certain amount of current. And that current maintaining strategy is actually very much like our micro stepping strategy, that we whenever the current will switch, so we will actually switch off. And we have seen, how we can do this torque control in the case of AC motors, also using a using invertors, so we are exactly similar current control is also applied here.

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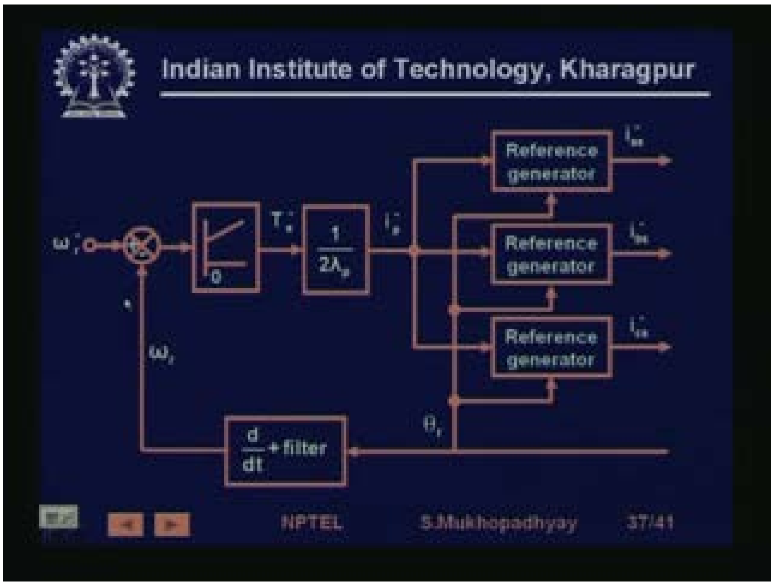

So, this is exactly the same thing, that we are taking, this is just a speed control loop, so the speed reference is there, real speed, then T i control. Then, this is at a proportional controller and then you generate the current references.

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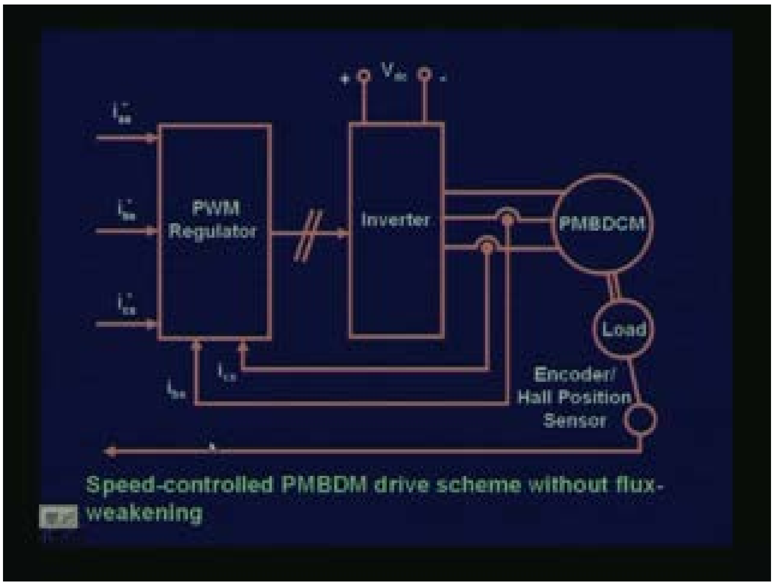

And then this current reference, will actually go to a PWM regulator, which will really create the switching not only to have the current at certain level, we will also have the sense of switching, such that the m m f's rotate in the proper direction. So, this is we did it in a fast manner, but you can understand that this is exactly similar and the main key concept is that the m m f's are rotating and you need to keep them rotating as the rotator rotates.

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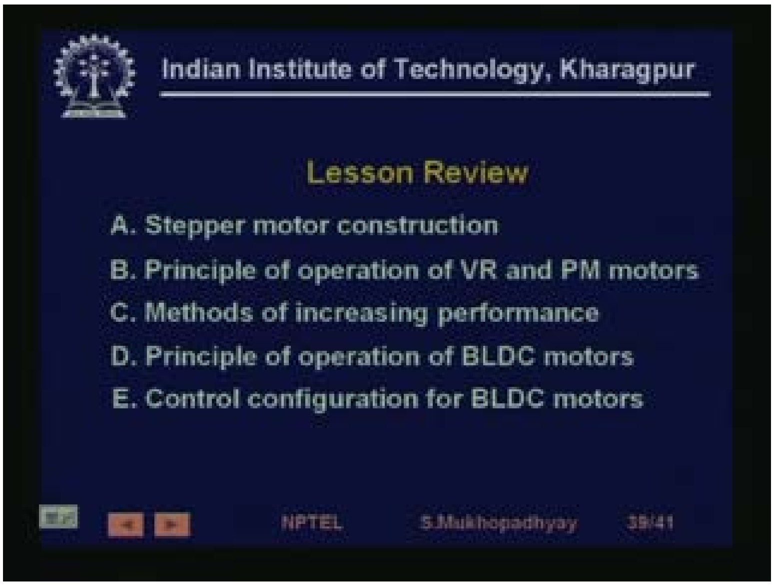

So, coming to the end of the lesson, we have seen stepper motor construction principle of operation of variable reluctance and permanent magnet motors and methods of increasing their resolution and speed of rotation by slewing. And we have also seen the basic principle of operation of the BLDC motor and we have seen one control configuration of BLDC motor and seen that it is just like a DC motor, except for that PWM switching, which creates the stator phase to rotate.

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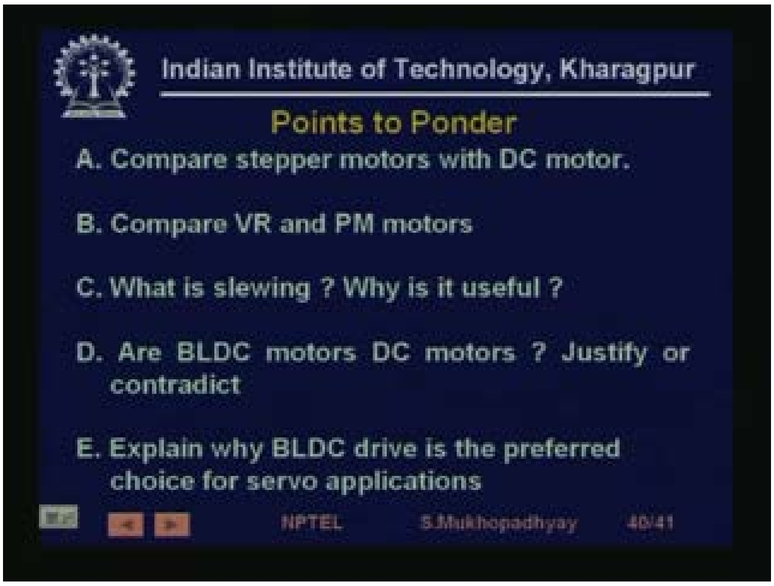

Coming to the points to ponder, you can compare stepper motors with DC motors and see why one is better than the other and compare variable reluctance and permanent magnet motors also. What is slewing, so we have discussed this and why is it useful and obviously, for having more speed.

Are BLDC motors DC motors by construction they are not, but by operation, they are made to behave, but by behavior, they are like DC motors, so you can either justify or contradict. And explain why BLDC drive is a preferred choice for servo applications, because you can have performance like a DC motor without the problem of the commutator and the brush, you can get very good torque, because you get very good magnets. So, that is all for today, we have looked at the various motor drives and from the next lessons, we will move on to a new topic. So, we have seen the electric actuators for use for industrial automation.

Thank you very much.