Mechatronics
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Lecture - 14
Electrical Actuation Systems - II

I welcome you all to this course on Mechatronics. In this lecture, we are going to talk about Electrical Actuation Systems further. So, I have named it Electrical Actuation System Part II because as I told you in my earlier lecture that electrical actuators are one of the important components of a mechatronic system, that is why I am covering it up in two lectures because these actuators are easy to control.

So, in my lecture on part I, we have seen the relays, solenoids, and DC motors. We have also seen that are permanent magnet type as well as field winding, we have seen the series shunt-wound and the compound wound motors, their characteristics. So, all those things we have seen.

We will be further taking up some of the electrical actuators over here. So, let us begin with a brushless permanent magnet DC motor. So, in the simple DC motor as I told you that we use brushes to reverse the direction of current in the armature conductor.

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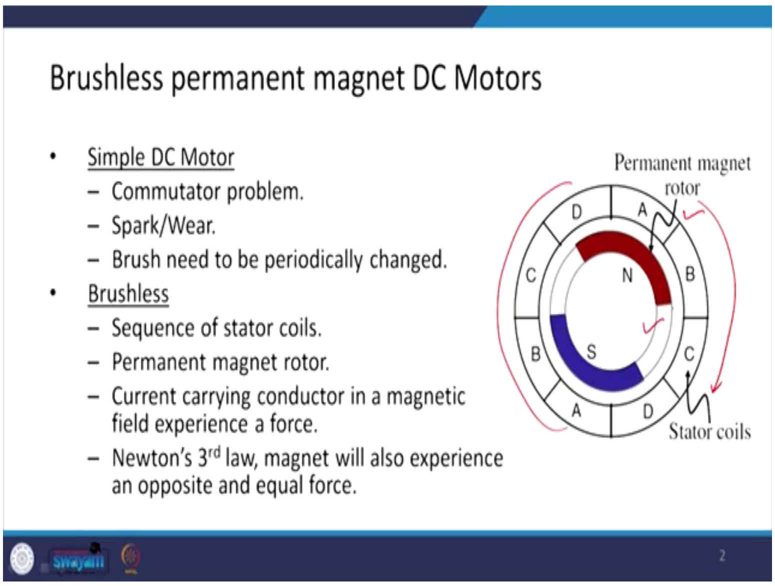

And these brushless because of wear and tear, these brushes have to be periodically changed. So, there is a commutator problem in the case of a simple DC motor. So, people thought about a motor which is brushless permanent magnet DC motor and now, in this case of brushless permanent magnet DC motor, we have their sequence of stator coils you can see A, B, C, D say this sequence and then, you have A, B, C, D, so these are the sequence of stator coils and there is a permanent magnet rotor and you see the current-carrying conductor in the magnetic field experiences a force. So, here the current is carried by the stator, conductor in the stator and it is there in a magnetic field. It experiences a force and from Newton's 3rd law, the magnet will also experience an opposite and equal force and this is the basic principle of the brushless DC motor. So, in the case of a brushless DC motor, the permanent magnet rotor rotates because of the reactive forces which are coming from the stator side. To switch these coils in a sequence, the switching circuits are used and this is provided by output from three sensors operating through a circuit to give appropriate base current, and hall sensors are generally used to sense the position of the rotor and initiate the switching by the transistors and hall sensors are positions around the stated that schematic, I have not included over here. You can see some of the standard textbook, then you can see switching with the help of transistors.

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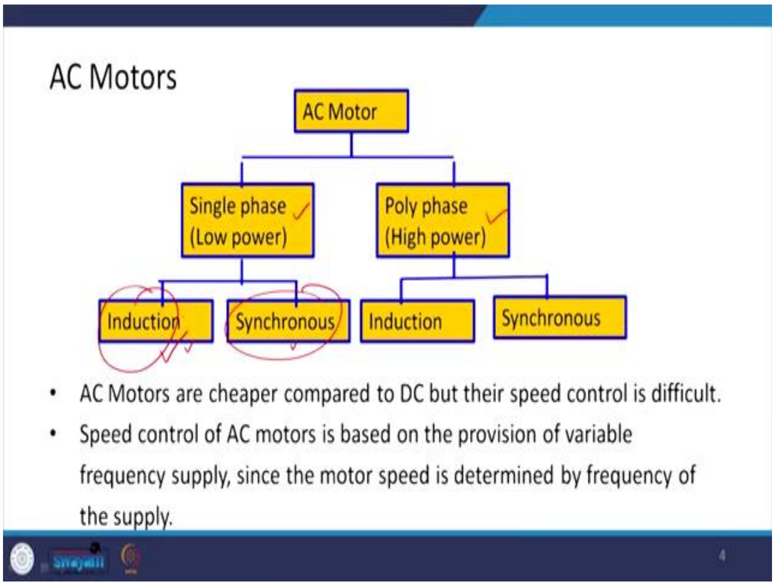

The next motor which I would like to take these are the AC motors and these AC motors are classified as single phase motor and the poly phase motor. Single-phase motors are used for the low power; whereas the poly phase motor is used for the high power and these motor whether it is a single-phase or poly phase, could be further classified as the Induction motor or the synchronous motor based on the principle they use for the operation. So, these AC motors are cheaper compared to DC motors, but their speed control is difficult.

So, you will find that most of the motors which are used in the general smaller applications are the DC motors because it is easy to control them. The speed controller of the AC motor is based on the provision of variable frequency supply since the motor speed is determined by the frequency of the sub power supply. Now, let us lo at the basic induction motor first, then we will be looking at the synchronous motor.

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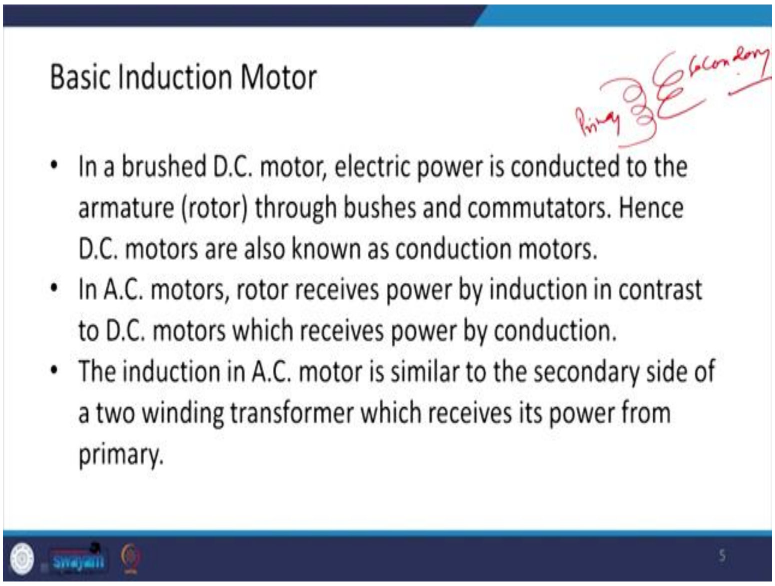

So, in a brushed D.C. motor, you see electric power is conducted to the armature through bushes and the commutators. We have seen in the previous lecture and hence, these DC motors are also known as conduction motors. Because the armature conductor carries the current through them. So, they are called the conduction motor. Whereas an A.C. motor's rotor receives power by induction in contrast to the D.C. motor which receives power by the conduction. In the A.C. motor, the rotor receives power by induction and this induction in the A.C. motor is very similar to the secondary side of a two-winding transformer which receives power from the primary.

So, I hope you must have studied the transformer, where you have the primary side and we have the second side. So, something like this, it is there. So, here the in case of induction motor the operation is A.C. motor is similar to the secondary side of a two winding transformer.

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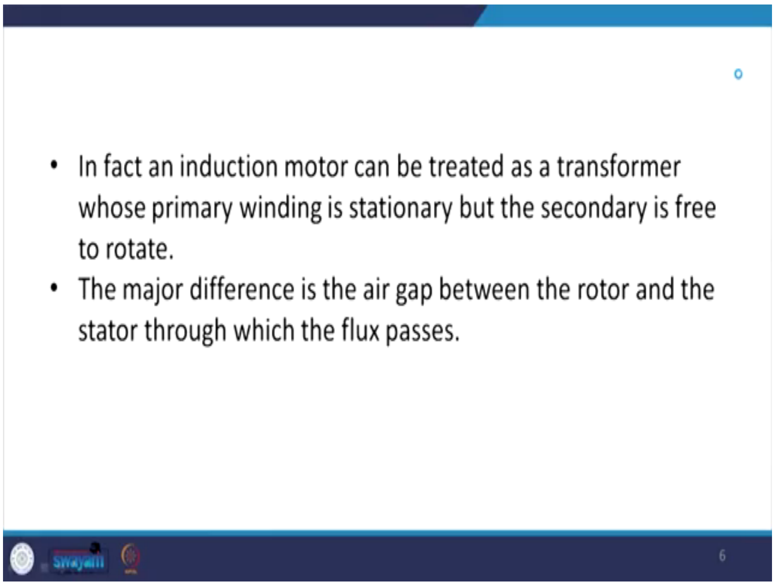

In fact, an induction motor can be treated as a transformer, whose primary binding is stationary; but the secondary is free to rotate. So, this way, we can carry out the treatment of it and the major difference is the air gap between the rotor and the stator through which the flux passes.

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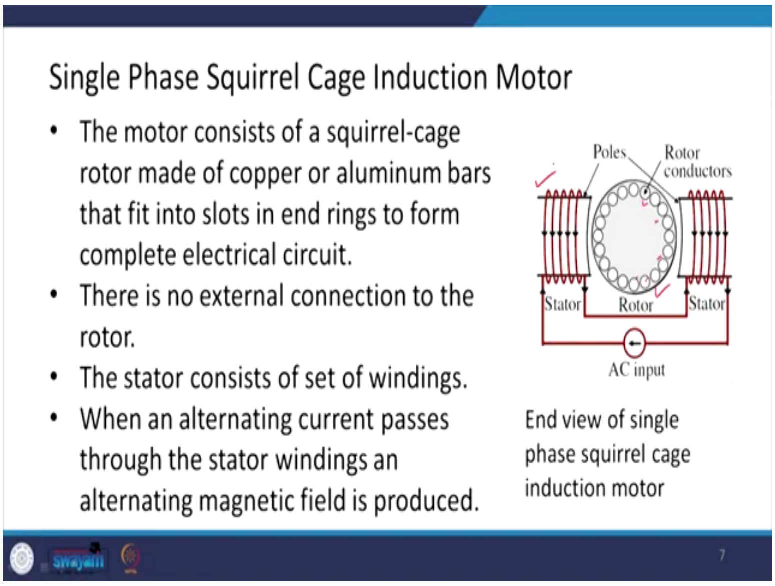

Now, let us see the single-phase squirrel cage induction motor. So, here, you have rotor over here and there are the rotor conductors and you have the poles which form the stator or a stator forms the pole. So, the squirrel cage induction motor consists of a squirrel cage rotor made of copper or aluminum bar and that fits into the slots over here as you can see, in end rings to form a complete electrical circuit, and there is no external connection to the rotor here.

You see I am repeating this again. There is no external connection to the rotor because here we are talking about the AC motor, these conductors are not supplied with the external power supply and the stator consist of a set of windings over here as I said and when the alternating current passes through the stator winding and alternating magnetic field is produced.

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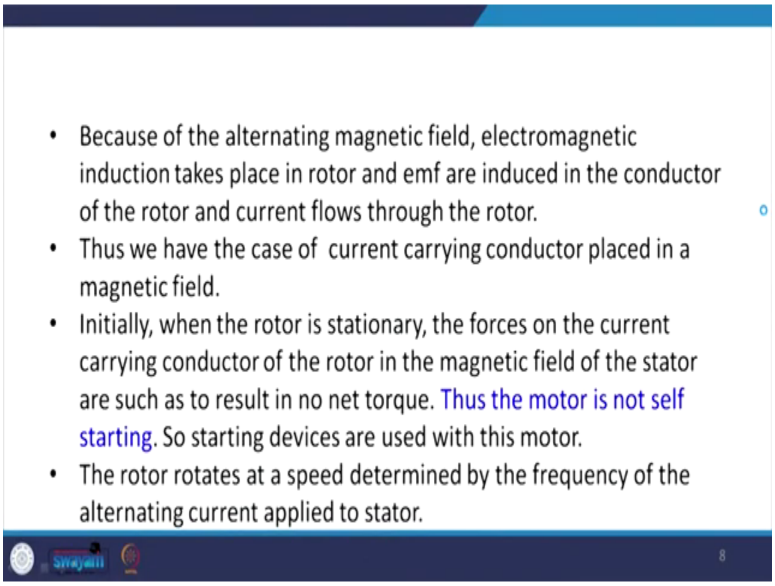

And because of this alternating magnetic field, electromagnetic induction takes place in the rotor and an emf is induced in the conductor of the rotor, and current flows through the rotor.

Thus, we have the case of a current-carrying conductor placed in a magnetic field. This is why how it is done. So, now, with this induction principle, what happens you see initially when the rotor is stationary, the forces on the current-carrying conductor of the rotor in the electromagnetic field of the stator are such that there is no resultant torque.

So, initially, your rotor is not rotating. So, that is why this motor is not self-starting; you need something to start an induction motor. So, devices are used with this motor. Now, the rotor rotates at a speed determined by the frequency of the alternating current which is being applied to the stator.

Next, let us look at the synchronous motor.

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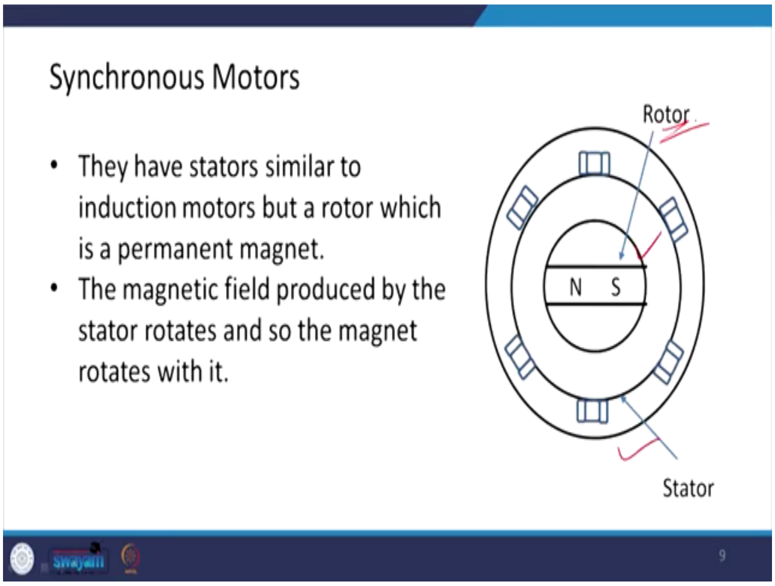

Now, they have a stator similar to the induction motor, but the rotor which is a permanent magnet. In this case, the rotor is a permanent magnet; whereas, in the case of induction motor, the rotor was simple conductors were there. The magnetic field produced by the stator rotates the magnet with it. So, here as you can see that these are the stator and this is the rotor.

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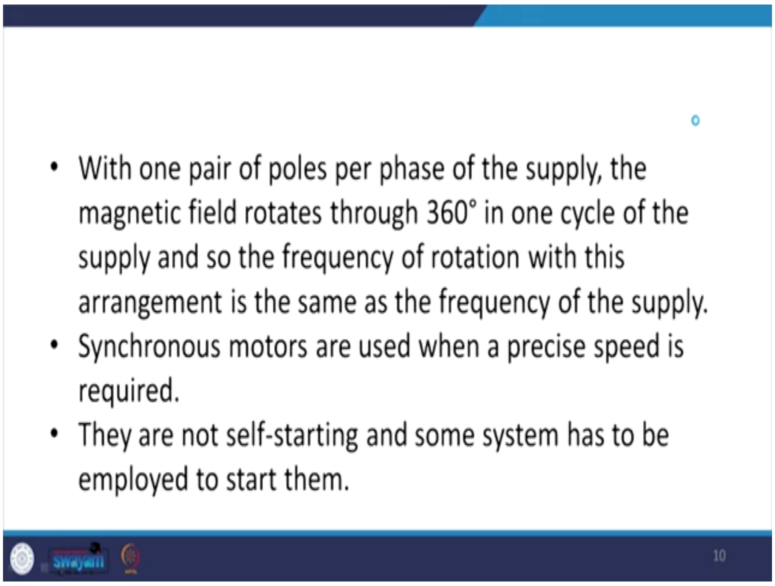

Now, with one pair of poles per phase of supply, the magnetic field rotates through 360 degrees in one cycle of supply and so, the frequency of rotation with this arrangement is the same as the frequency of the supply.

The synchronous motors are used when we need precise speed control. They are not self-starting and some system has to be employed to start them.

Next, let us look at the stepper motor. As the name indicates, these motors move in steps.

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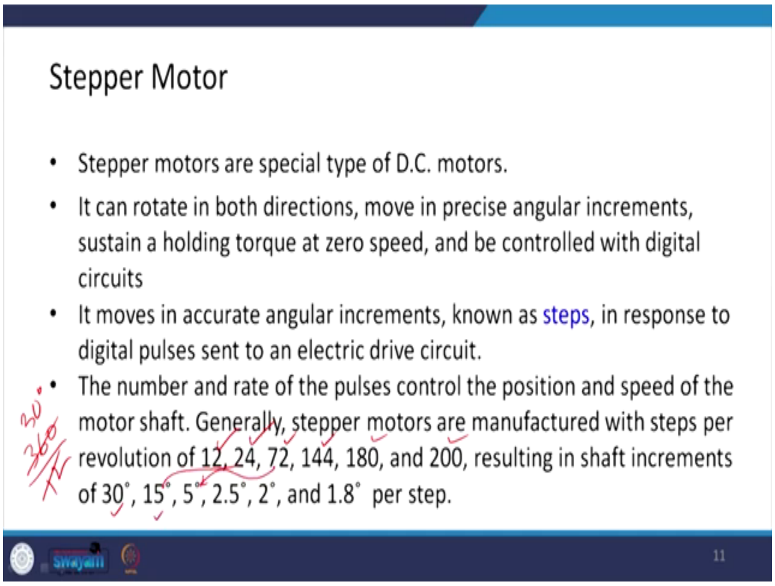

So, they are a special type of D.C. motors and they can rotate in both directions and move in very precise angular increments, sustain a holding torque at zero speed, and be controlled with the digital circuits. It moves in very accurate angular increments known as steps, in response to digital pulses sense sent through an electrical drive circuit. The number and the rate of these pulses control the position and speed of the motor shaft.

Generally, step motors are manufactured with steps for revolution such as say 12, 24, 72, 144, 180, and 220, and this results in say shaft angle of say 30 degrees that is 360 divided by 12. So, this is your 30 degrees; so, 30 degrees, 15 degrees. Corresponding to this 72; 5 degrees corresponding to 72 steps and so on.

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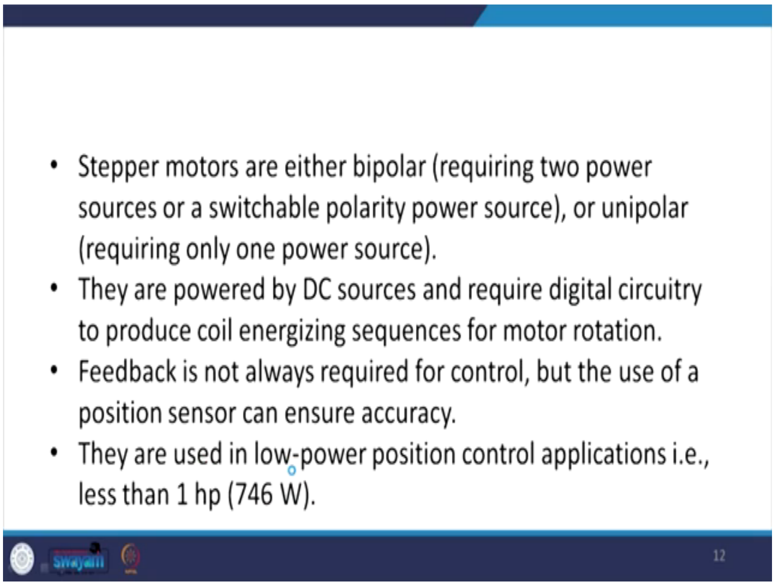

Stepper motors are either bipolar that is they require two power sources or switching or a switchable polarity power source or they are unipolar, requiring only one power source. They are powered by DC sources because they are DC motors and require digital circuitry to produce the coil energizing sequence for the motor rotation. I will explain to you how we get the different steps and, feedback is always not required for control, but why we do not require feedback?

Because here, we make the motor rotate in a step and many times, we know that how many steps it has to rotate and so, how many pulses have to be given. But if you have the provision of position sense, then it can ensure accuracy. They are used in low power position control applications usually less than say 1 hp or say 746 Watt.

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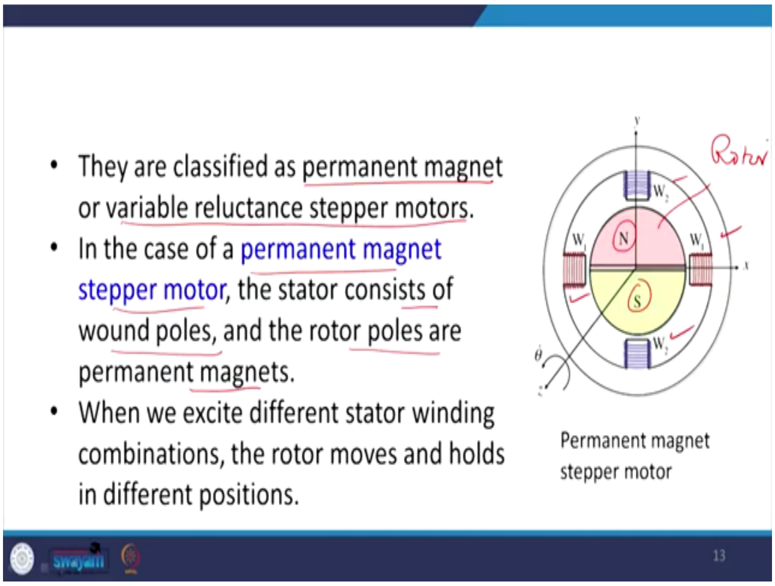

They are classified as a permanent magnet or the variable reluctance stepper motor. In the case of a permanent magnet stepper motor, the stator consists of wound poles. As you can see over here, these are the wound poles and the rotor poles are the permanent magnet here. So, this is your rotor and when we excite stator winding combination, the rotor moves and holds in a different position. As we supply the power to the different windings, this motor rotor rotates and, in the avoidable reluctance type stepper motor, the working principle is that there is a ferromagnetic rotor rather than the permanent magnet motor. So, this is your Ferro ferromagnetic rotor is there.

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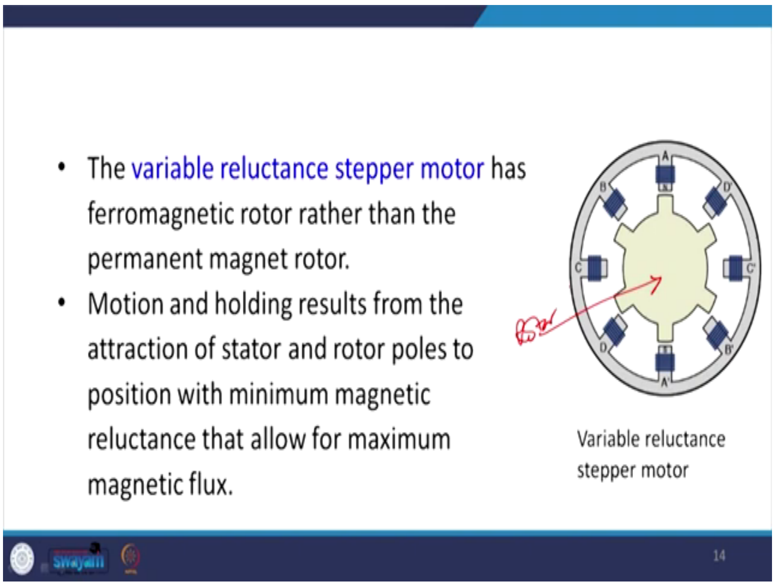

The motion and holding results from the attraction of stator and rotor poles to position with minimum magnetic reluctance, which allows for the maximum magnetic flux.

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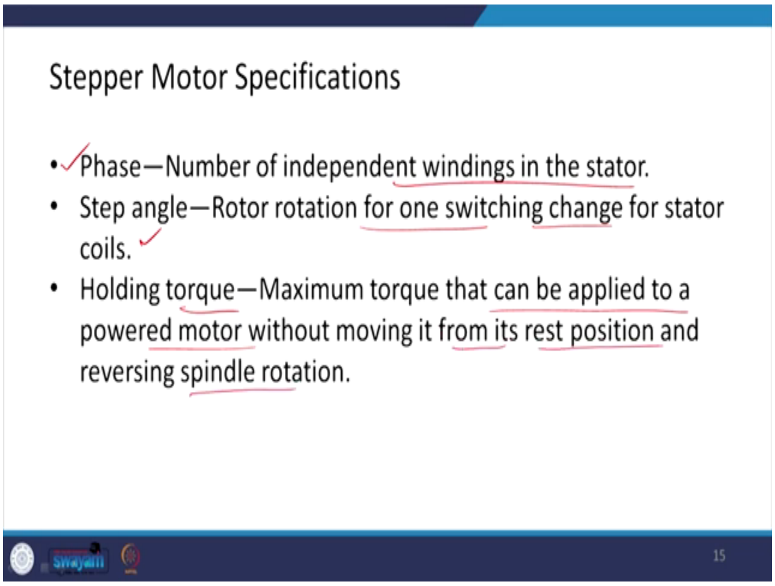

These stepper motors can be specified by phase, that is the number of independent winding in the stator; step angles, that is the rotor rotation for one switching change for the stator coil and the holding torque, that is the maximum torque that can be applied to a powered motor without moving it from its rest position and reversing spindle rotation.

Let us see the working principle of the permanent magnet stepper motor.

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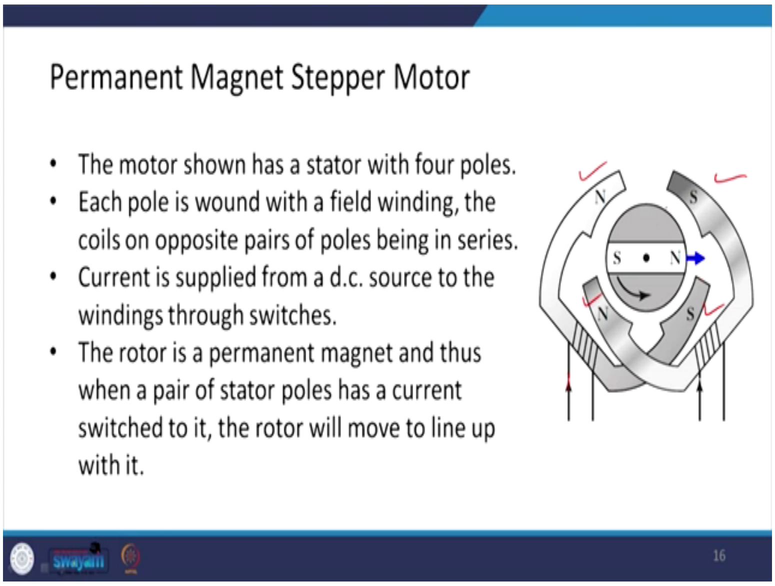

The motor shown has a stator with four poles. So, you can see one, two, three and four. These are the four poles and hereby, changing the direction of the current, we can change these poles. Each pole is wound with field winding, the coil on opposite pair of poles being in the series, and current is supplied from a D.C. source to the winding through the switches and the rotor is a permanent magnet and thus, when a pair of stator poles has a current switched on it, the rotor will move to line up with it.

Let me explain this further over here.

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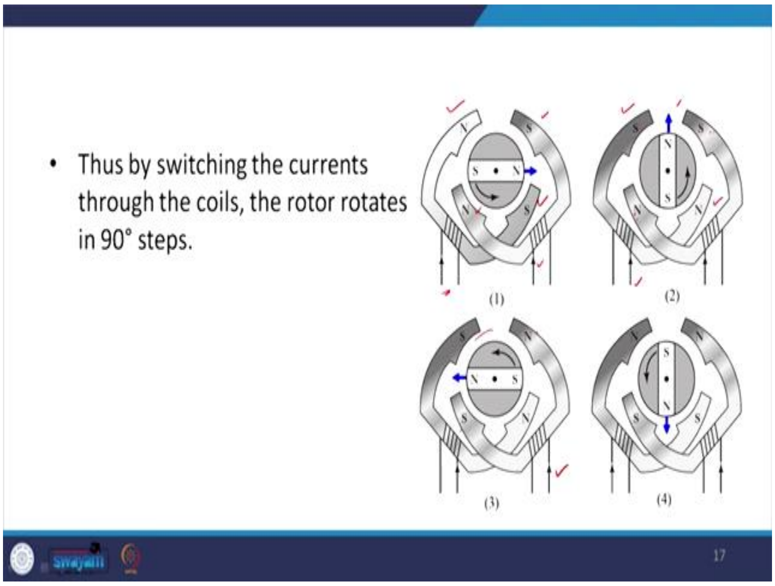

So, as we can see in this figure. Suppose, in this one, this is the direction of current over here. So, this pole is north, this pole is south and this is my permanent magnet rotor over here and in this one, this is the direction of the current. So, this is north and this is the south Pole. Now, what happens if I change this direction of current over here. This is the configuration that is this becomes south and this becomes north. Then, what will happen?

This south and this north will try to align and so, the rotor will be turning like this and it will be moving to this position and in the next turn, what we can do that we change the polarity of saying these poles by changing the direction of current over here. So, this becomes north and this becomes south. So, this was the earlier condition and so, this will be attracted over here.

This is already south. So, this north will be attracted over here and there is going to be a full 90-degree rotation over here and then, further, if again we change the polarity like this, this becomes north, and this becomes south. This was the earlier one.

So, again, we see that this turns further from here. This being converting into the south, this will be turning over here and it will train to or try to align it. So, thus, the rotor rotates here. In one step, you can see that there is a rotation of 90 degrees.

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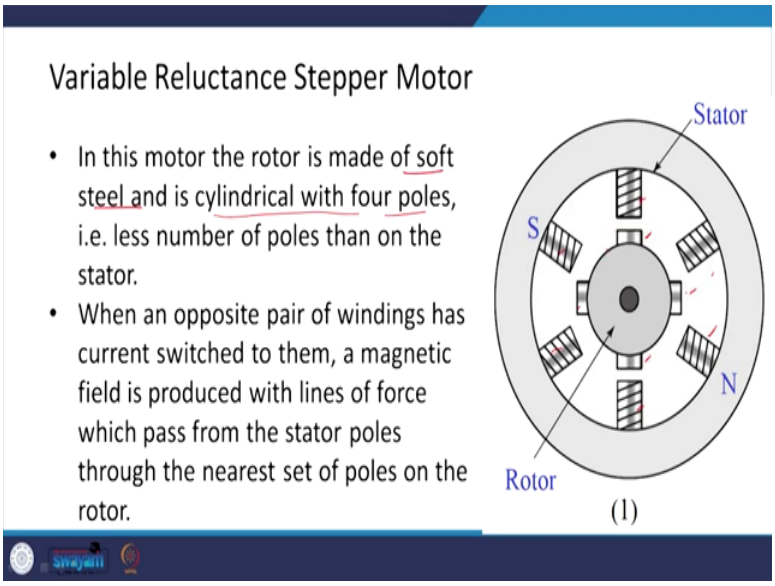

Now, let us see the variable reluctance stepper motor. As I said in the case of variable reluctance stepper motor, here in place of a permanent magnet, we have the rotor is made of soft steel and it is cylindrical say with four poles. So, there are four poles and a lesser number of poles than in the stator. So, here you can see in this stator as one, two, three, four, five, six poles and the rotor has got say four poles.

Now, when an opposite pair of winding has currently switched to them, the field is produced with lines of force that pass from the stator pole through the nearest set of poles on the rotor. So, it is something like your stretching of the thread.

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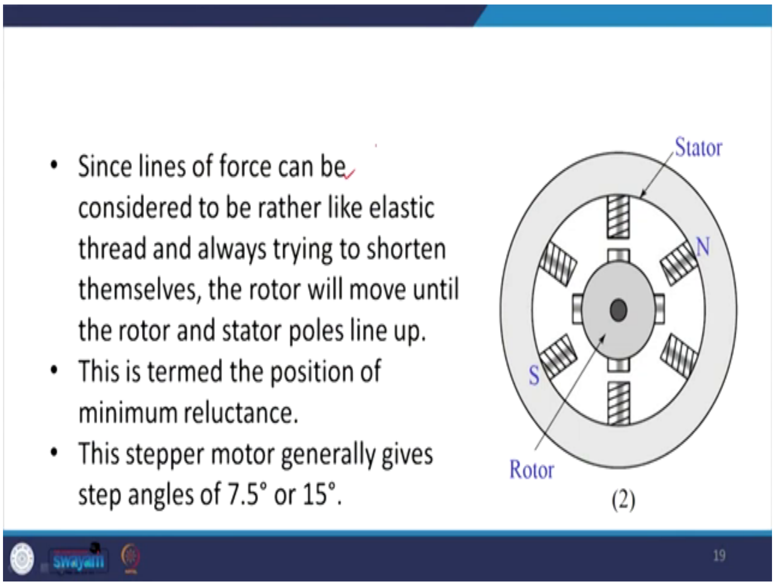

So, the lines of force can be considered to be rather like an elastic thread as I said, and always trying to shorten themselves and this way the rotor will move until the rotor and a stator poles line up. So, that way we get the rotation of the rotor, and this is termed the position of the minimum reluctance and that is where the shortest path is there and this stepper motor generally gives a step angle of 7.5 degrees or 15 degrees.

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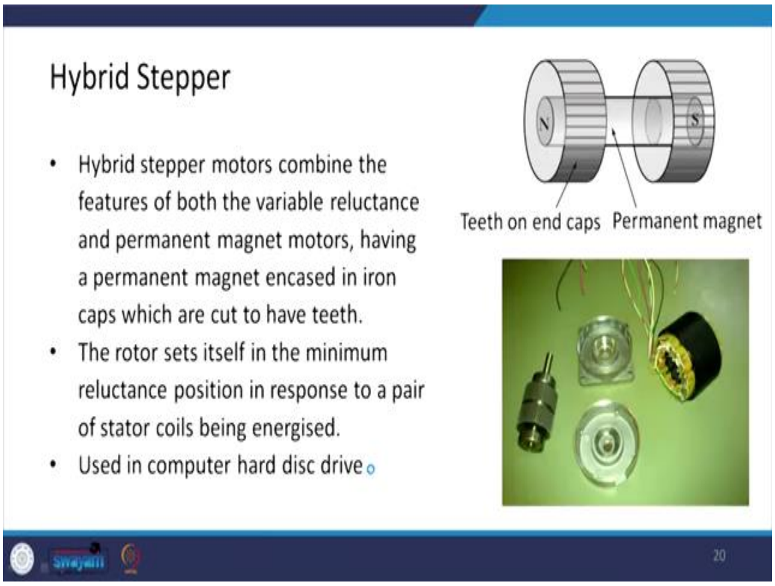

Now, there is a hybrid stepper motor which is a combination of the permanent magnet and the variable reluctance. So, you can see it here there are teeth in the caps to provide the variable reluctance. The same principle is used as the variable reluctance over here and this is you can see the exploded view here. So, this is the rotor. So, you can see the end caps over here and there are teeth's over there. This is the hybrid stepper motor and this combines the features of both variable reluctance and the permanent magnet motor. So, the rotor sets itself in the minimum reluctance position in response to the pair of stator coils being energized and this is used in your computer hard disk drive.

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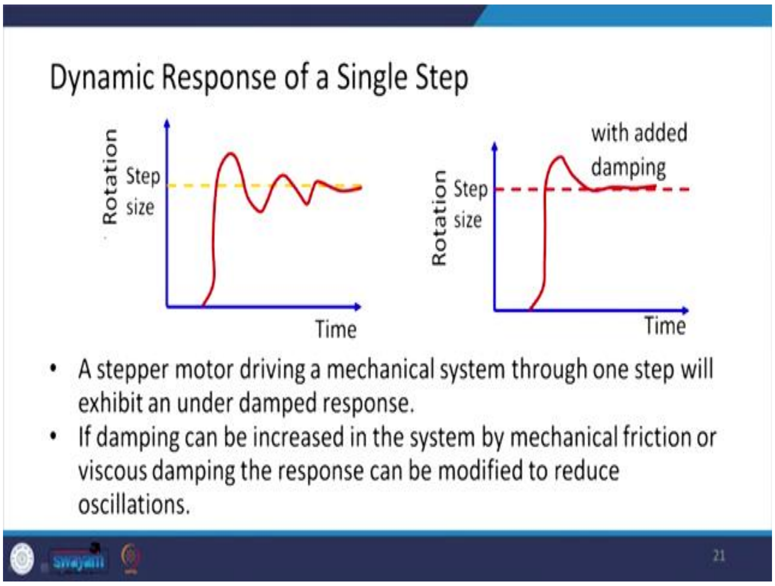

Now, let us look at the dynamic response of a single step of the stepper motor. So, if I plot the rotation versus times. If this is the step size, naturally, my motor will not directly jump into this step rather it follows this path and it tries to settle after sometimes on the step size. If I aid some damping to it, then these oscillations can be reduced and so, with aided damping this is the behavior that can be obtained.

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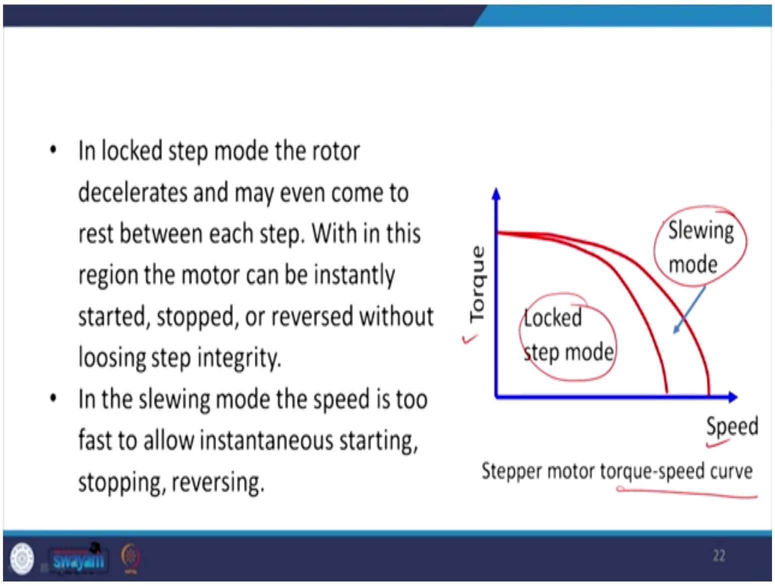

Now, these stepper motor torque-speed curves, if we look, there are two modes; one is called the locked step mode and the other is called the slewing mode. In locked step mode, the rotor decelerates and may even come to the rest between each step and within this region, the motor can be instantly started, stopped, reversed without losing step integrity, and in the slewing mode, the speed is too fast to allow the instantaneous starting, stopping and reversing because you see that this is obtained at a greater speed range.

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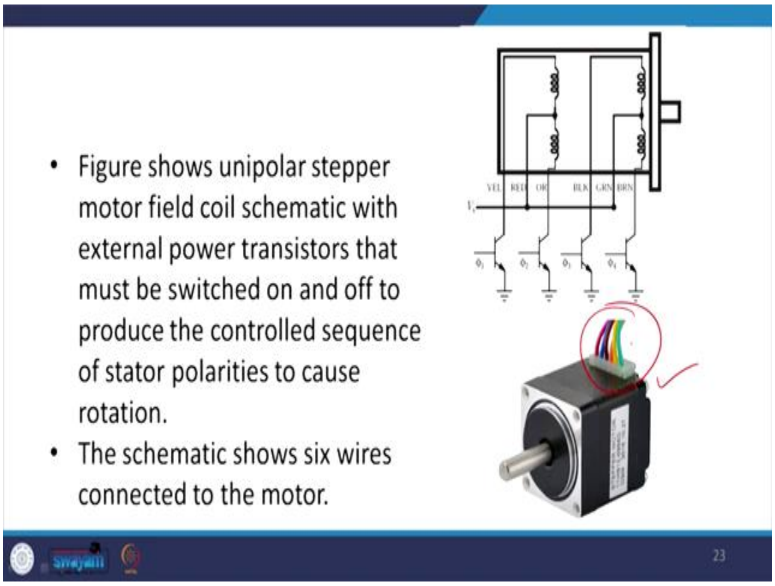

This is how this commercially available stepper motor looks like. One can usually identify the stepper motor with so many wires over here. So, these wires usually have a certain color coding. This figure shows a unipolar stepper motor field coil, schemed with external power transistors as you can see over here. That must be switched on and off to produce a controlled sequence of its stator polarities to cause the rotation and this schematic response to the six wires connected to the motor. As you can see that we have one, two, three, four, five, six; so, yellow, red, orange, black, green, and brown. So, this is the color-coding done over here. Usually, the second and fifth, are usually joined together internally.

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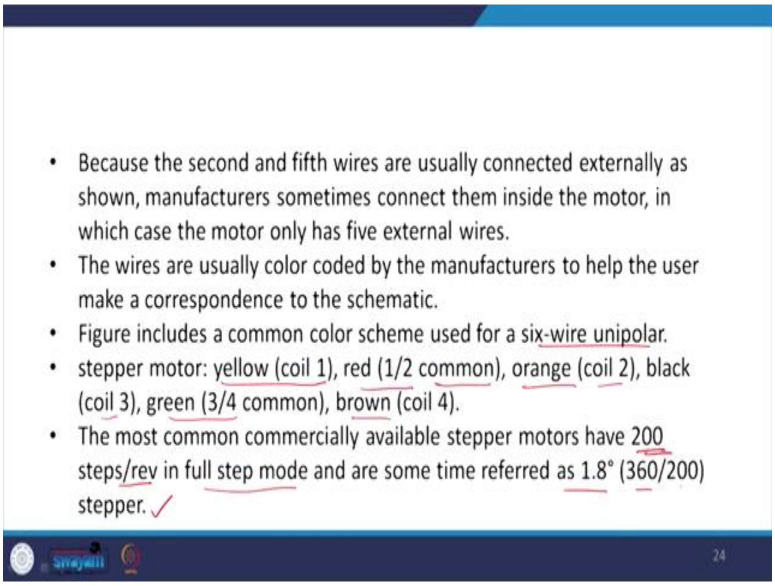

So, the second and fifth wires are usually connected externally as shown and manufacturers sometimes connect them inside the motor also, in which case the motor only has the five external wires. The wires are usually color-coded by the manufacturer to help the user make correspondence to the schematic and figures include common color schemes used for six-wire unipolar. Stepper motor yellow is coil 1, red is 1 or 2 common, orange is coil 2, black is coil 3, green 3 or 4 common, and brown is coil 4.

So, the most commercially available stepper motor has 200 stepper revolution in the full step mode and is sometimes referred to as a 1.8-degree stepper that is 360 divided by 200. There is a drive circuit for these stepper motors and this drive circuit comes in a single monolithic IC.

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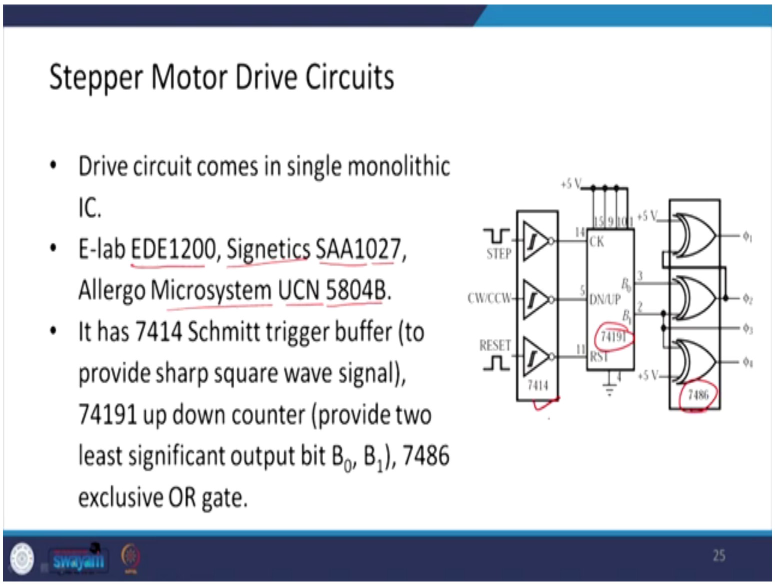

There are various brands of these drive circuits. For example, E-lab has got EDE1200 as Signetics has got SAA1027 and Allegro Microsystem has got UCN5804B and this these have circuits have the 7414 Schmitt Trigger, this one, buffer to provide sharp square wave signal that is and 74191 up-down counter this one which provides two least significant output bit B 0 and B 1 and 7486 exclusive OR gates are there. So, some of these things, I will be taking up in my coming lectures.

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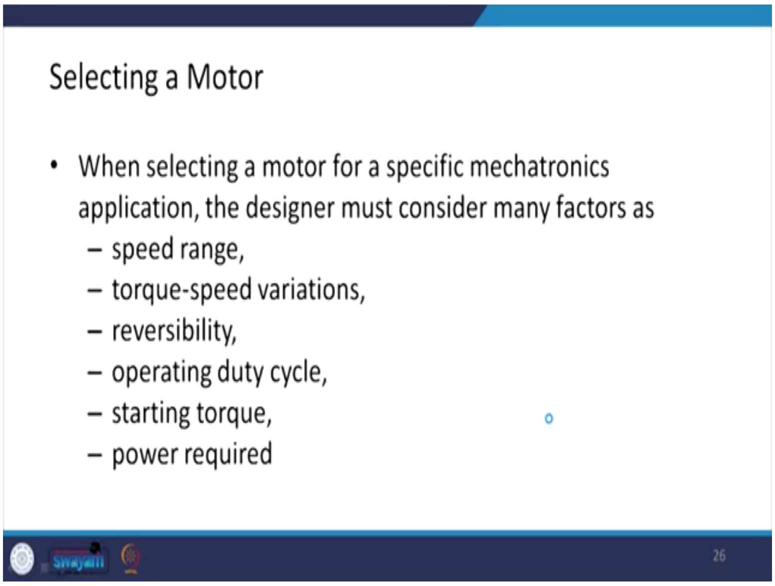

Now, let us after seeing these many motors, various types of motors we have seen. So, in this lecture, we have seen the AC motors and we have seen the stepper motors. So, the question is how do we select a motor? So, when we are selecting a motor for a specific mechatronic application, the designer must consider many factors. What are these factors?

What speed range, I am going to use for the motor; what is the torque-speed variation or torque-speed characteristic; my requirement is that whether I want a motor that should be reversible and what should be the operating duty cycle for the motor; what is the starting torque for the motor and what is the power required for the motor?

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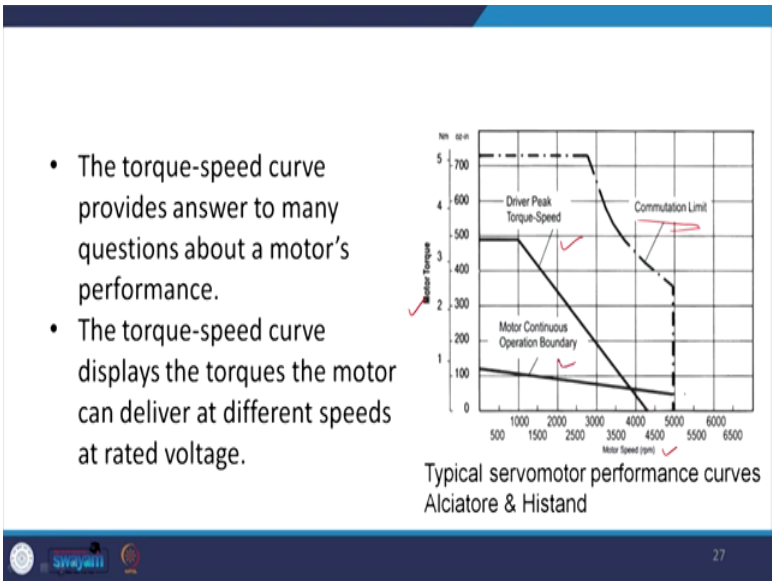

Now, the torque-speed curve provides answers to many questions about a motor's performance and most of the manufacturers provide this torque-speed characteristic with the motor. The torque-speed curve displays the torques, the motor can deliver at different speeds at a rated voltage. So, for example, here, the motor torque and motor speed, this limit provide the commutation limit. Driver torque speed is here and motor continuous operation boundary, these curves provide or that.

Then, there is a list of questions that designers must consider when selecting and sizing a motor in consultation with a motor manufacturer. What could be these questions; will the motor start and accelerate fast enough, what is the maximum speed the motor can produce, what is the operating duty cycle, how much power does the load requirement, what power source is available, and what is the load inertia which is permissible?

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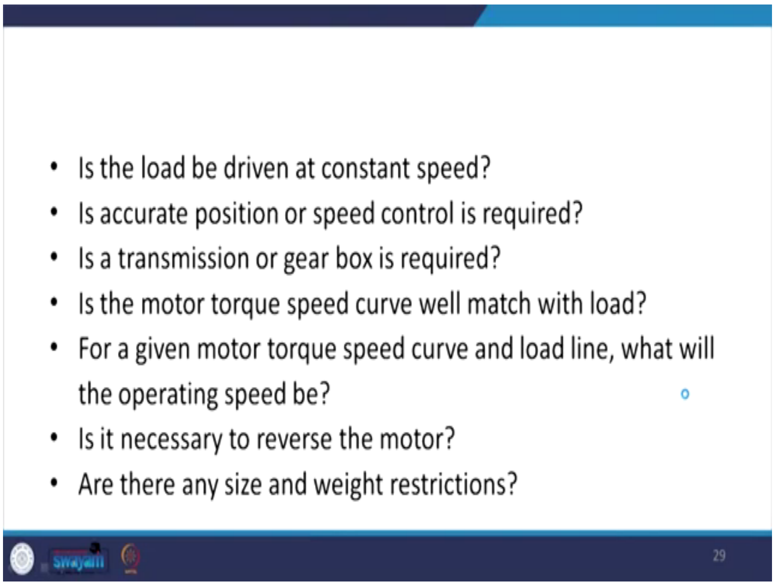

Is the load be driven at a constant speed? Is accurate position or speed control is required? Is the transmission or gearbox is required? Why transmission or gearbox may be needed? Many times, we have high-speed motors are available, but our speed requirement may be low or torque required may be high. So, we need the gearbox and the transmission system such as a gear or belt you may require if the actuator is not at that particular position.

For example, in the case of robots, many times your actuator is not at the robot joint it is at far of place. So, you require the power to be transmitted from the distance placed to that particular joint. So, you require a transmission system. The next question would be the motor torque-speed curve will match with the load speed curve and for a given motor torque-speed curve and load line, what will be the operating speed?

Is it necessary to reverse the motor? Are there any size and weight restrictions? Many times, we may have size and weight restrictions. You see in robotic application because when we are talking about the manipulator’s arm, the arms have to carry the motor weight. So, naturally, in one way the motor weight is going to be added to the arm weight.

So, we have the weight restriction. We may also have a size restriction depending on the space available. So, these are some of the questions which the designer of the mechatronic system has to ask the motor supplier.

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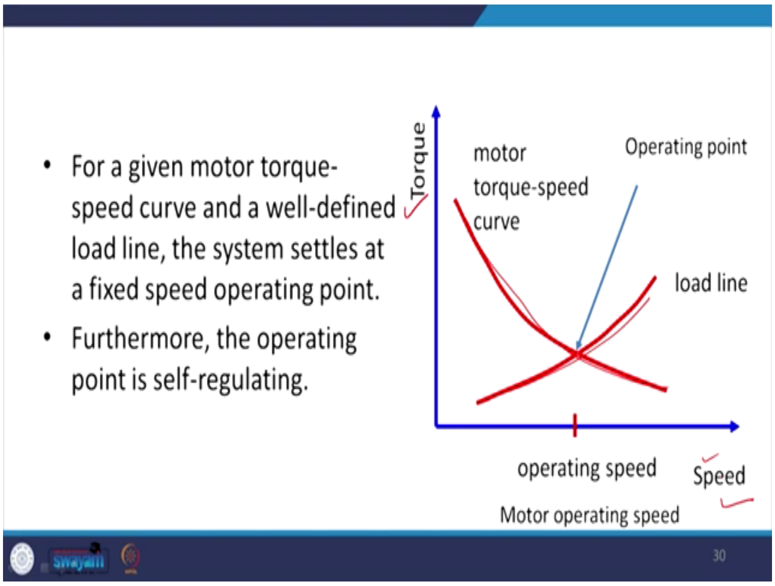

Now, for a given motor torque speed curve and a well-defined load line, the system settles at a fixed speed operating point. If I talk about the torque-speed curve like this. So, this is the motor torque-speed curve and this is my load line that is how my load varies with the operating load varies with the speed. So, now, we can see that there is an intersection point and this intersection point is what we call it has an operating point and this operating point as will see is self-regulating. How it is self-regulating, let us see that.

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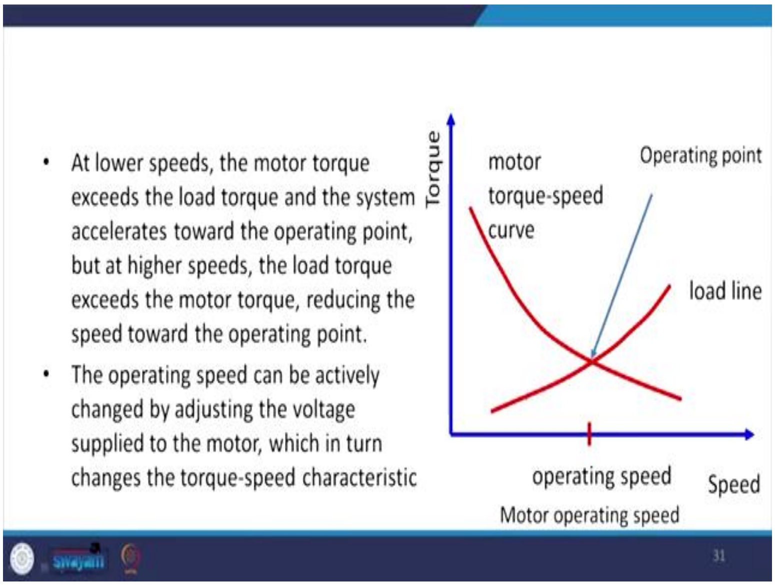

So, at a lower speed, the motor torque exceeds the load torque and so, what will happen? The system will accelerate towards the operating point; but at a higher speed, if we are talking about at higher speed, the load torque exceeds the torque supplied by the motor. That reduces the speeds towards the operating point. So, this operating point is self-regulating. So, the operating speed can be actively changed by adjusting the voltage supplied to the motor which in turn changes the torque-speed characteristic.

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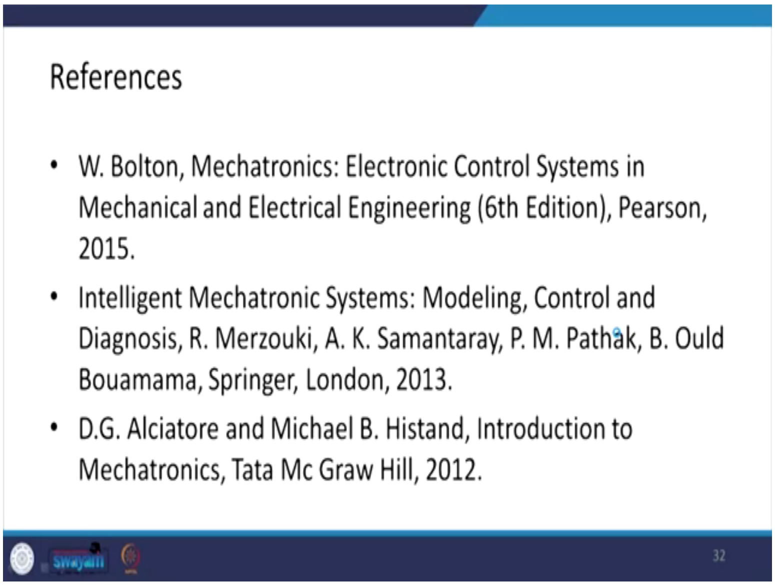

So, if you want further read, refer; please refer to again the very good resource available in Bolton and Intelligent Mechatronic System, that is our book and the one Introduction to Mechatronics by Alciatore and Histand.

Thank you very much.