Mechatronics

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Lecture - 13
Electrical Actuation System - I

I welcome you all to today's lecture on the Mechatronics course. Today we are going to discuss the Actuation Systems. You see in a mechatronic system; the actuation system has got a very pivotal role to play. The actuation signals are obtained from the microprocessor and these signals are given to the actuator to perform a specific type of task.

So, in a control system or in a mechatronic system as I said, the actuation system has got a very important task to do. Today we are going to see one of the very important types of actuator, is the Electrical actuator. Why electrical actuators are important? Because these actuators are very easy to control as compared to the hydraulic or pneumatic ones. We will be covering this in two lectures. I will be talking about electrical actuation system 1 and electrical actuation system 2.

Switching devices as I said, in a mechatronic system we require the control signals. And, but these control signals may be switching on and off to some electrical devices. So, what could be these switching devices? These switching devices could be, if it is a mechanical device then it could be a simple relay and if it is a solid-state device then it could be diodes and transistors. The use of diode and transistors or their basic principle I have already discussed with you in our initial lectures.

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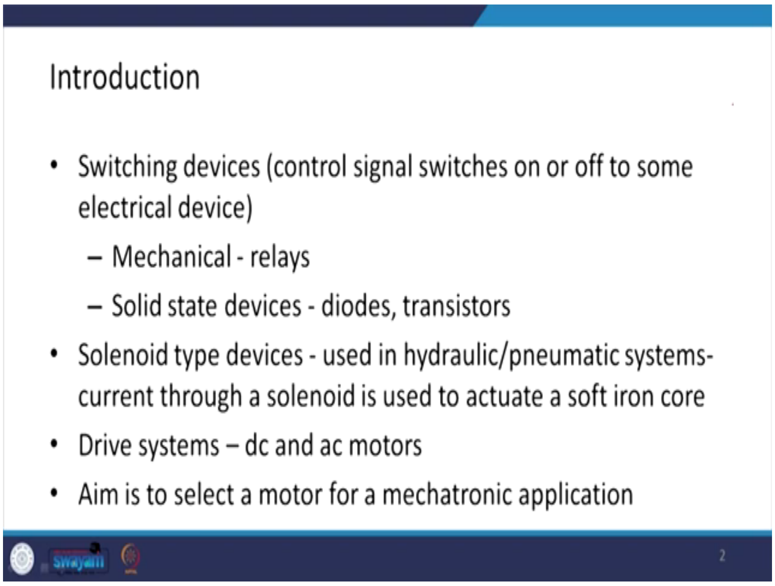

The solenoid type of devices is used in hydraulic and pneumatic systems as I have talked about them in my lecture on the hydraulic and pneumatic system, where we have seen that the solenoid is used to actuate the walls. So, in these solenoid-type devices, the current through a solenoid is used to actuate a soft iron core. The actuating device could be a solenoid type device or it could be a drive system, and in the drive system under electrical actuation, we are using the dc and ac motors. The aim could be to select a motor for a specific type of mechatronic application.

Towards the end of my second lecture in electrical actuation, I will be also talking about how do we select a particular type of motor for a mechatronic application. Let us first begin with electromagnetic principles. Before I go to the different types of actuating devices, let us look at some of the fundamental things.

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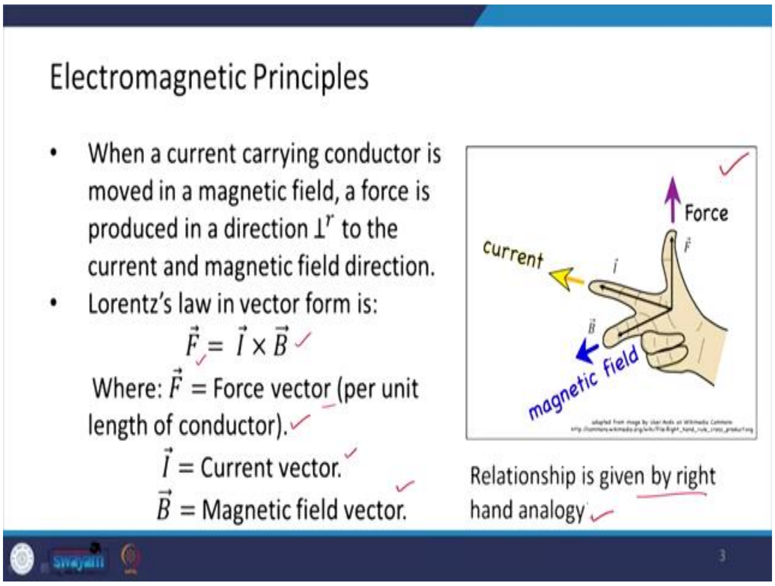

So, Lorentz's law is one of the basic fundamental laws or which basically provides the principle for electromagnetic actuation. The law is that when a current conductor is moved in a magnetic field, a force is produced in a direction perpendicular to the current and the magnetic field. As you can see in this figure, so it is something like this, you have your thumb and you have this finger and the middle finger. So, if this is the direction for the current and this is the direction for the magnetic field, then this is going to be the direction for the force. Lorentz's law in a vector form is represented by,

$$\vec{F} = \vec{I} \times \vec{B}$$

Here, $\vec{F}$ is the force vector expressed per unit length of the conductor and $\vec{I}$ is the current vector and $\vec{B}$ is the magnetic field vector. And this relationship is given by the right-hand analogy as I showed you.

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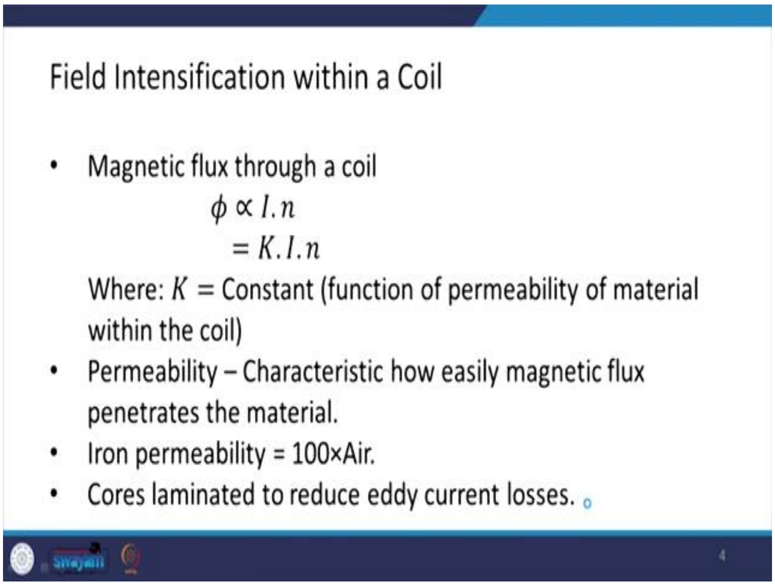

Now, if we talk about the field intensification within a coil, so when a current is passing through a conductor, you see the magnetic flux through a coil is proportional to the current which is passing through the conductor through the coil and the number of turns in it and, if we replace this proportionality sign with an equal to sign,

$$\emptyset = K.I.n$$

I put a constant K and this K is the function of the permeability of material within the coil. The permeability is a property or characteristic, how easily magnetic flux can penetrate the material. To give you some idea about permeability iron permeability is around 100 times that of air permeability. The cores are laminated to reduce the eddy current losses, so that is there.

Now, let us look at the first device that is the relays. It is an example of the electromagnetic switch and it is used in application to turn on or off the circuit by a low power signal.

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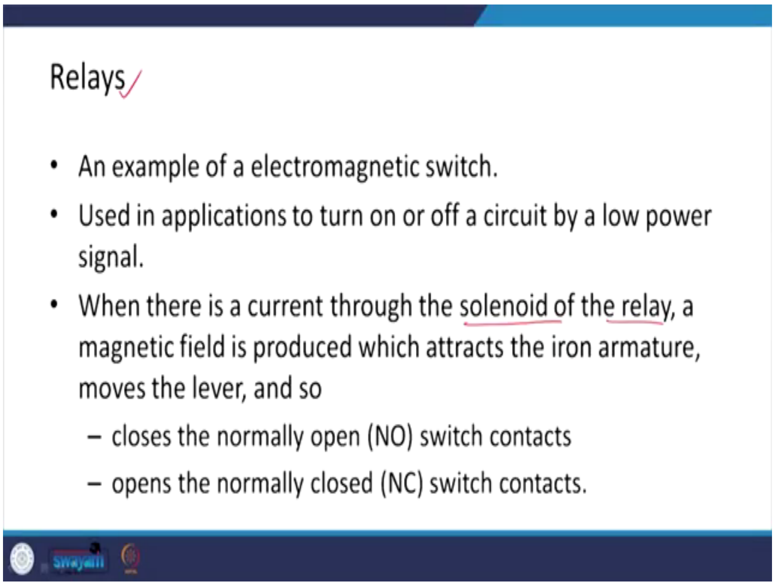

When there is a current through the solenoid of the relay, a magnetic field is produced and which attracts the iron armature and this may move the lever, and so and this moves the lever. So what happens is, that it closes the normally open switch contact and it opens the normally closed switch contact.

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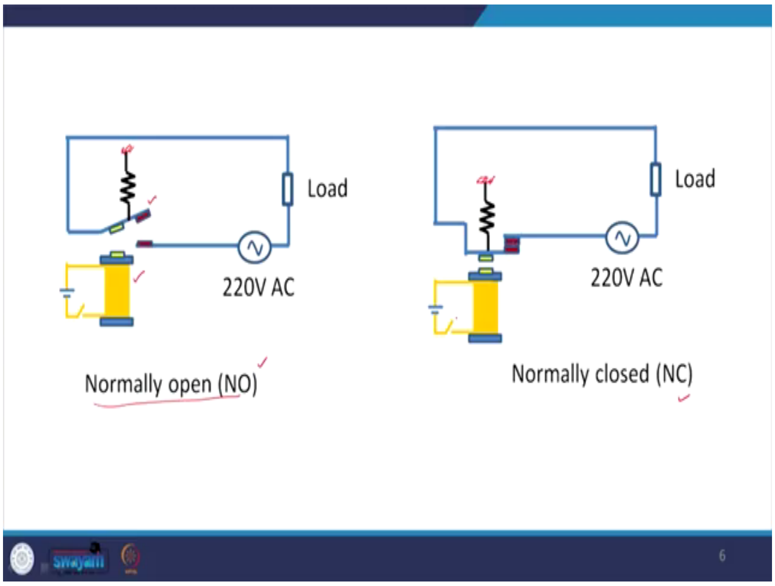

Let me explain this to you further through this schematic figure. So, you see that this figure illustrates the normally open circuit. So, you can see that in this circuit there is a spring put into here and this spring pulls this lever and because of this there is always this contact is open; this contact is open and when the current is supplied to this solenoid a magnetic field is produced, and that because of that this gets attracted over here because of this lever gets attracted over here and this contact closes. So, this is with the normally open switch.

If you look at the normally close switch here, so in the case of a normally close switch this is the normal position you can see if this is the spring that is attached to the lever, so this always pulls towards this end. So, this contact is normally closed. Now, when you pass the current through this solenoid, then what happens? This gets magnetized and in turn, it attracts this lever. There is a magnet over here, so it attracts this, and this way, this circuit opens.

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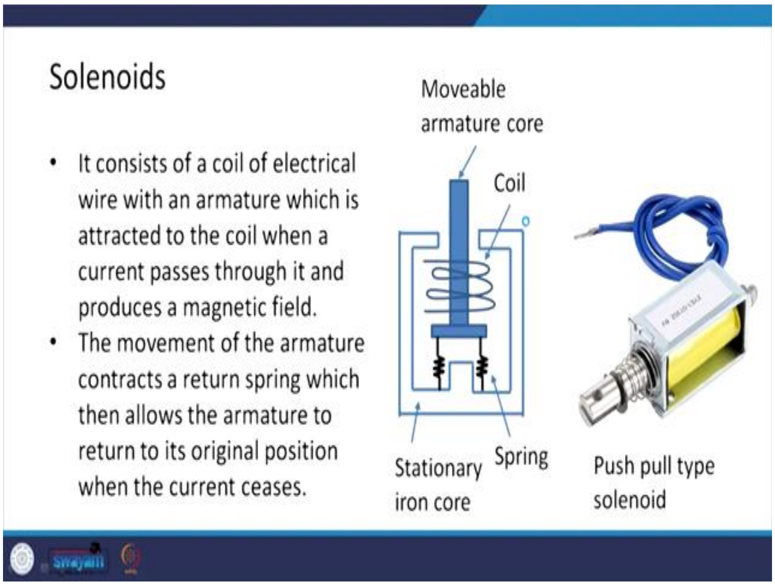

So, let us look at how does the solenoid work. So, the solenoid which we have discussed or explained to you over here, its working principle is something like this. There is a movable armature core as you can see here, there is a coil and there is a stationary iron core over here. Now, what happens? When you supply the current through the coil then a magnetic field is produced and this movable iron core, armature core gets attracted. There is a motion in this movable armature core. And once naturally and when it gets attracted, it presses this compresses these two springs, and when the current supply is switched off, then these two springs expand and this goes back to the movable armature core goes back to its original position. And this is how a push-pull type solenoid is commercially available in the market.

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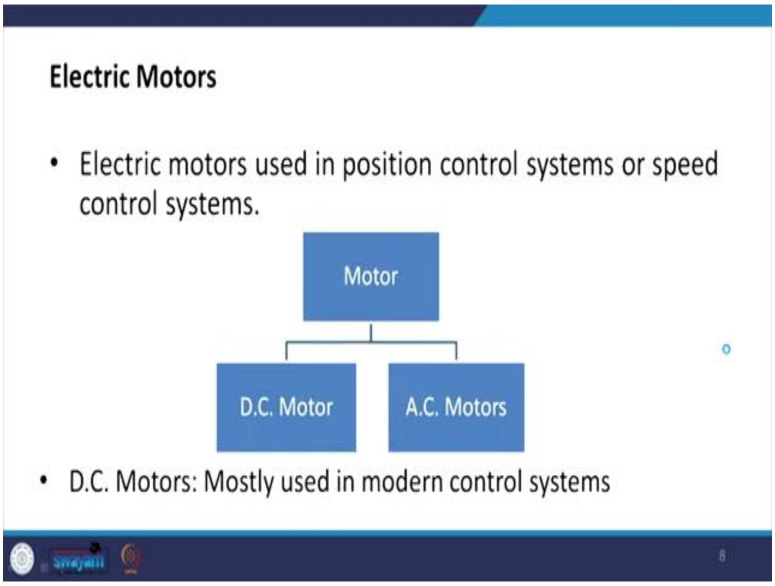

Now, coming to the electrical motors. Electrical motors are used in position control systems or in speed control systems. These motors could be classified as D.C. Motor and A.C. Motors. And the D.C. Motors are mostly used in modern control systems because these motors are easy to control.

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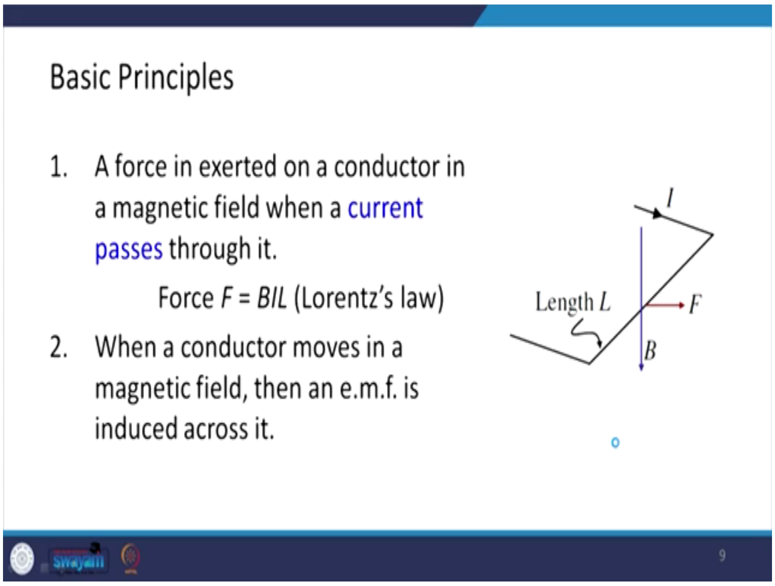

The basic principle which we have seen, the force here you see that if there is a current-carrying conductor placed in a magnetic field and the conduction current through the conductor is I and the field is perpendicular to the current-carrying current direction, then you are going to have,

$$F = BIL$$

, as per Lorentz's law.

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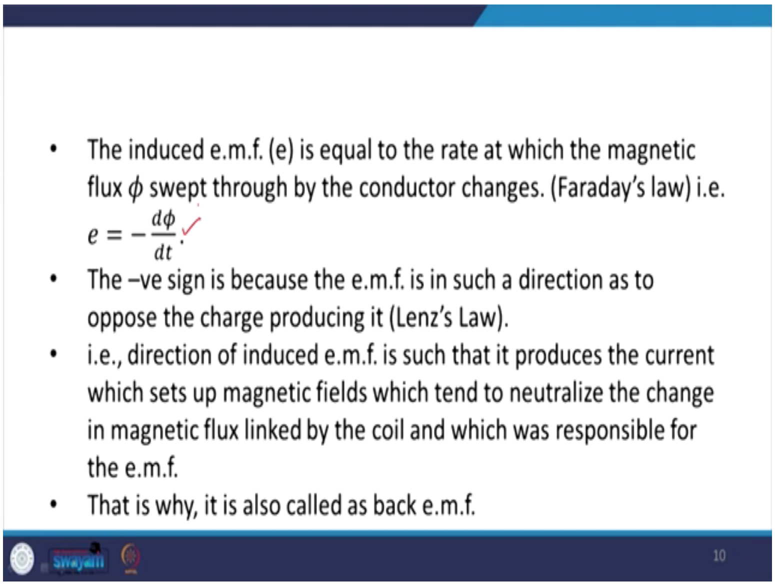

When this conductor moves in a magnetic field then an e.m.f. is induced across it. I will be talking a little more about this and this induced e.m.f. as per Faraday's law is given by,

$$e = -\frac{d\emptyset}{dt}$$

where $\emptyset$ is the flux linkage through the conductor. This negative sign indicates that e.m.f induced is in opposite direction to the charge producing it. This is popularly known as Lenz's law. This you must have studied in your intermediate classes. This direction of induced e.m.f is such that it produces the current which sets up a magnetic field, and that magnetic field tends to neutralize the change in the magnetic flux linked by the coil and which was responsible for that particular e.m.f. That is why we also call it the back e.m.f.

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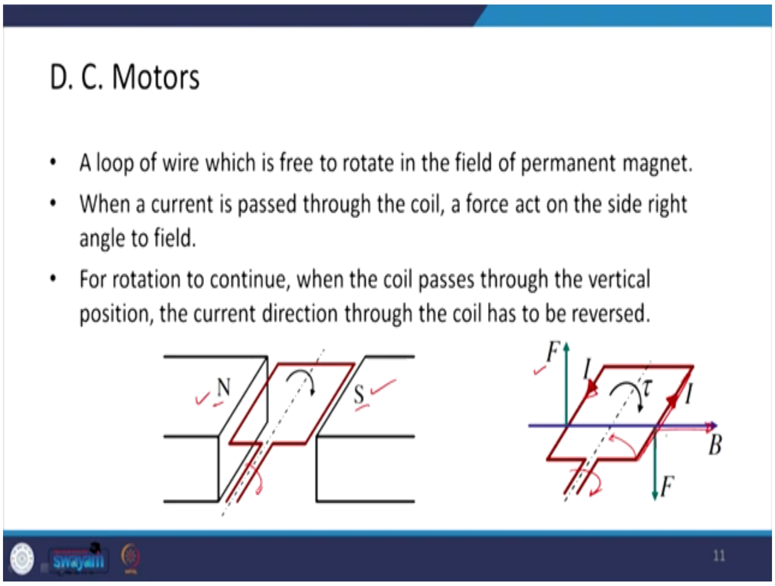

Now, after looking at this principle let us see the D.C Motor. In D.C motor as you see that we have a magnet. The magnetic field is being produced by the magnet and there is a current-carrying coil that is being placed over here. A loop of wire which is free to rotate in the field of the permanent magnet is there. When a current is passed through the coil, a force acts on the right angle to the field. And you see that for this rotation to continue, for this rotation to continue, we need to change the current direction. So for example, here you see that in this conductor this is your I this is your B, so this is your F; and whereas, in this conductor current is in this direction in this side the current is in the reverse direction. So, you have the force F is acting in this direction and this force forms a couple and it tries to rotate this about this axis. You see that for this rotation to continue when it reaches this position there has to be some switching mechanism to reverse the direction of the current so that it keeps on rotating.

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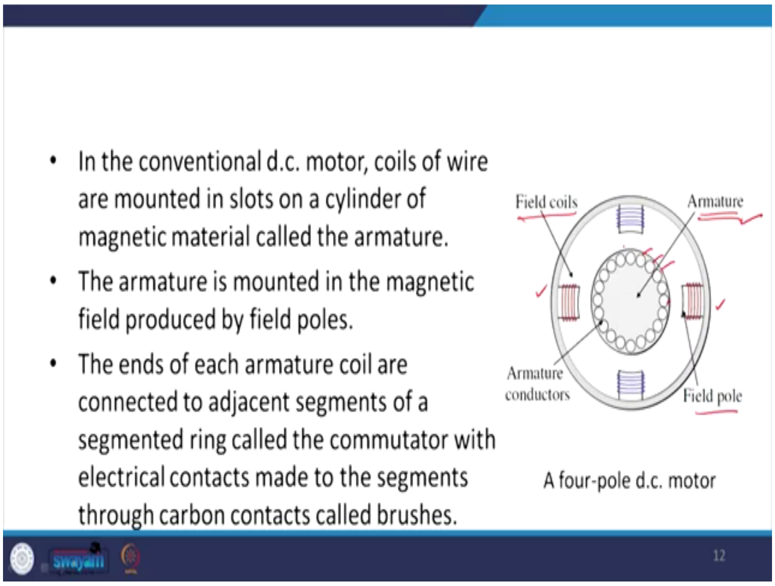

So, in the conventional DC motors, coils of wire are mounted in the slots, as you can see these are the slots where the coils of wire are mounted on a cylinder of magnetic material which we call the armature. And this armature is mounted in the magnetic field produced by the field coil. Instead of the permanent magnet here, we could have the field coil and which generates the magnetic field. At the ends of the armature coils are connected to adjacent a segment of a segment rings a segmented ring which we call a commutator with electrical contact made to the segments through carbon contact usually called as bushes. This is done for changing the sign of the current in the conductor. As the armature rotates, the commutator reverses the current in each coil as it moves between the field poles. This is necessary if the forces acting on the coil are to remain acting in the same direction, and if the rotation has to be continued.

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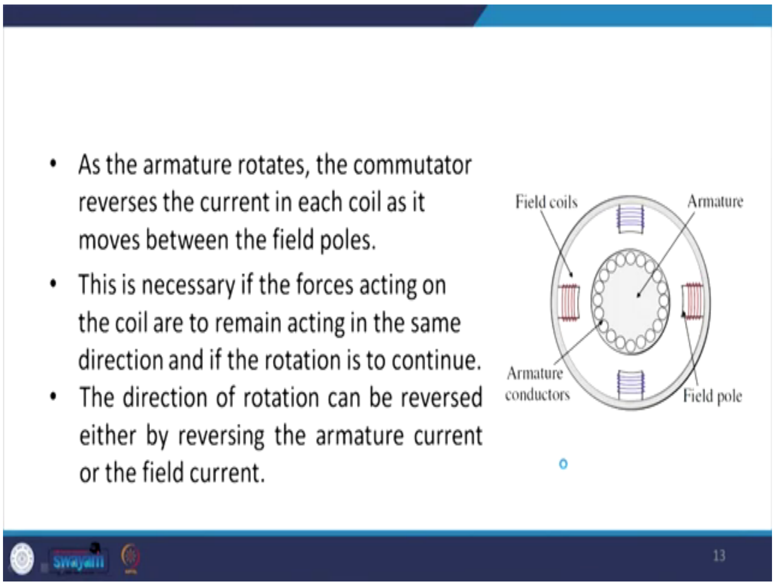

The direction of rotation can be reversed either by reversing the armature current or the field current in this case.

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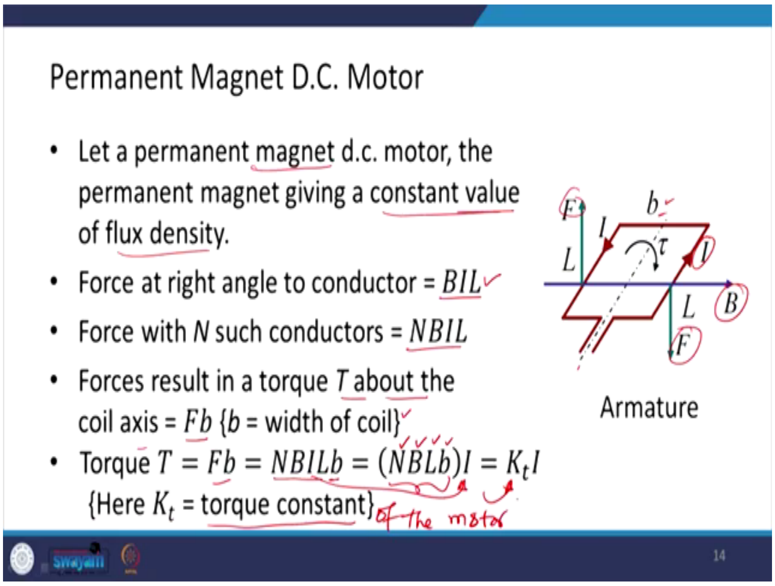

Now, let us look at the permanent magnet D.C. motor. Here, the permanent magnets give a constant value of the flux density.

And, you see that the here this is that constant value of the flux density *b*, and if we supply current *I* through this one, then the force acting on the conductor right angle to a conductor = BIL.

And if we have N such conductors, this force = NBIL. The force results in a torque T about the coil axis.

This force forms a couple and this moment is given by,

$$T = Fb = NBILb = (NBLb)I = K_t I$$

where b is the width of the coil. What is the constant over here?

This N is the number of turns, it is constant, B is the field strength we have already assumed that the permanent magnet is giving the constant value of flux density, so you have the constant field strength; L is the length of the conductor so, this is constant and this b this value is also constant. And I rename this constant K_t, and this K_t is popularly called the torque constant of the motor.

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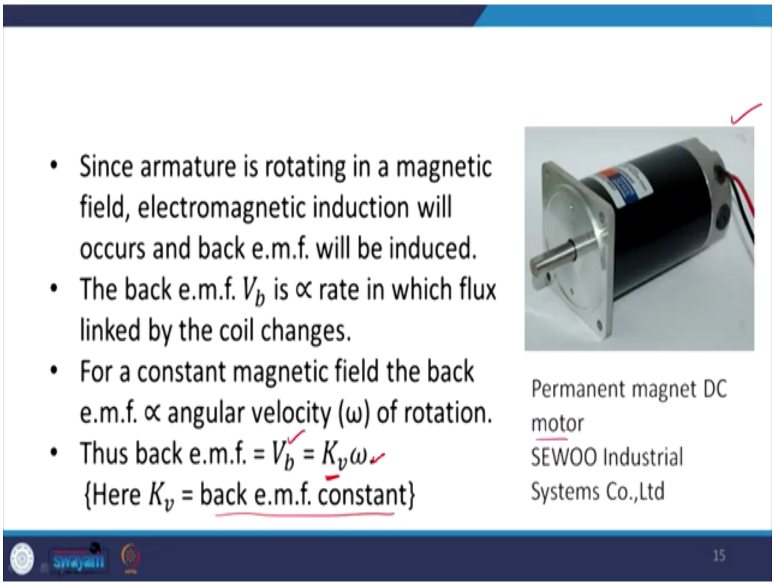

Since the armature is rotating in a magnetic field, electromagnetic induction will occur and the back e.m.f. will be induced which I have talked about in my previous slides. This induced back e.m.f. is proportional to the rate at which the flux is linked by the coil changes.

For a constant magnetic field, the back e.m.f. is proportional to the angular velocity of the rotation ω. If I replace that proportionality with a proportionality sign, I can write this,

$$\text{back e.m.f.} = V_b = K_v\omega$$

This K_v is back e.m.f. constant.

This is how a commercially available permanent magnet D.C. motor looks like. This is a product of SEWOO industrial systems company limited.

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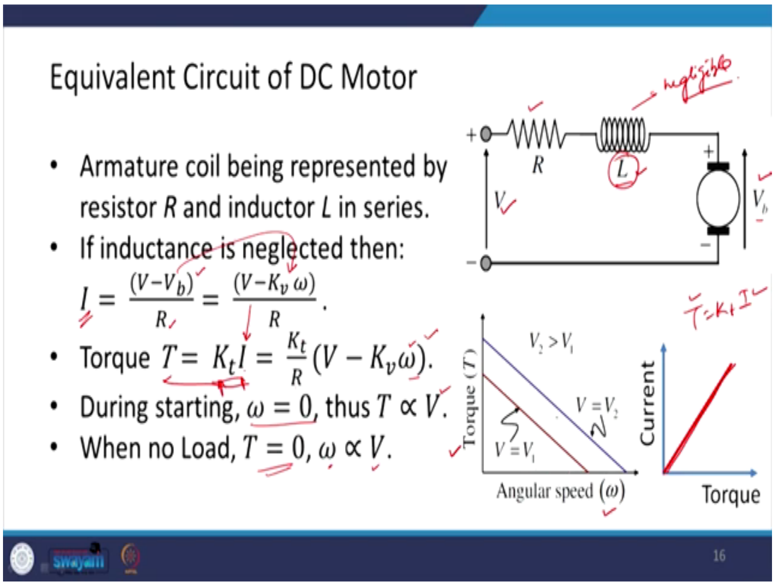

Let us look at the equivalent circuit of the DC motor. The armature coil is represented by a register and an inductor in series. To represent the armature coil it has got a certain resistance and it has got a certain inductance. So, I can represent this resistance and inductance in series for this. You have a motor here this V_b is the back e.m.f. and this V is the voltage supplied. Now to simplify the analysis let us assume that this L is negligible. So, if this L is negligible, then what are the voltages here;

$$I = \frac{V - V_b}{R} = \frac{V - K_v\omega}{R}$$

So, I am now replacing this V_b with $K_v\omega$.

$$\text{Torque } (T) = K_t I$$

So now substitute for this I over here. So I have,

$$T = K_t I = \frac{K_t(V - K_v \omega)}{R}$$

Now, what happens during starting, when the motor starts then at the time initially at $\omega = 0$. Torque is proportional to V. And, if there is no load that is if I keep the torque is equal to 0 in this equation, then what happens? I can see that ω is going to be proportional to the voltage.

Let us see how these variations look like. So, you see that our equation for torque and the current is T is equal to K_t times I. So, as that current increases the torque increases. So, you can see the linear relationship over here. And if I plot the torque versus angular speed, you see that as the voltage increases its keeps on shifting. There is a parallel shift in this characteristic curve, and you see that when we have angular speed (ω) is 0 we have the maximum torque which we also called as the starting torque and when there is no load, that is when torque requirement is 0 we have the maximum angular speed. So, this is the characteristic for corresponding to voltage V_1, corresponding to voltage V_2, and if V_2 is greater than V_1 naturally then here its torque is going to be more.

Next, let us take up the DC motor with the field coils. The DC motor with field coils as you see that, the rotor is placed in a magnetic field produced by the field coils. So, this is the case for the one which I was talking to you about. So, you have the field coils over here, and here is your armature. Now the thing is that how these field coils are connected with the help of armature based on that we can have the different types of classification and we can have the different types of characteristics of the motor.

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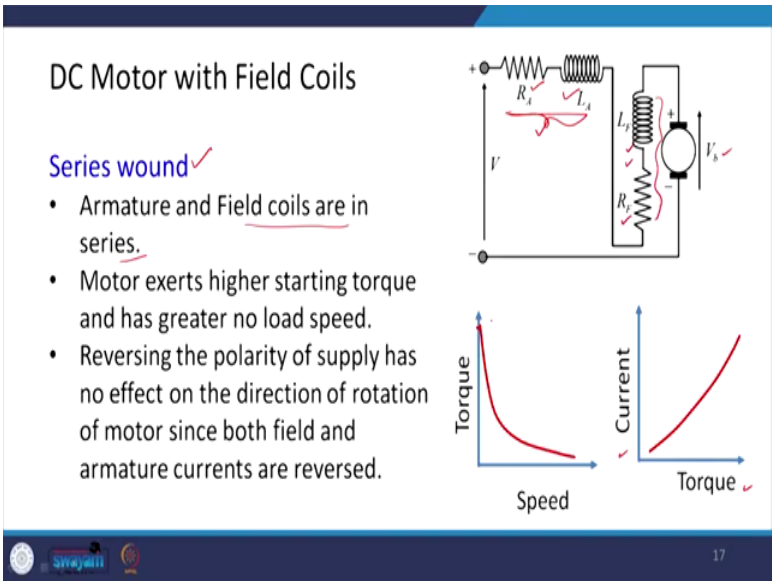

Suppose I have the armature here, represented by its resistance and inductance, and the field coil again represented by its resistance and inductance. Now, if they are connected in series, what we get is as the series wound DC motor. So, that is there V_b is the back e.m.f. here. In the series wound DC motor, the armature, and field coils are in series. Motor exerts higher starting torque and has greater no-load speed. This is the case of a DC motor with a series wind field coil. Here, you see that since armature and field coil they are in series if you reverse the polarity of the supply you are not going to have any effect on the direction of rotation of the motor since both are connected in the series This is because we are going to have changed in the current direction in the both. In this case, the torque and current characteristic is going to be like this, and the torque and speed characteristic in the case of the series wound motor is like this, and this value the starting torque as I said motor exerts higher starting torque.

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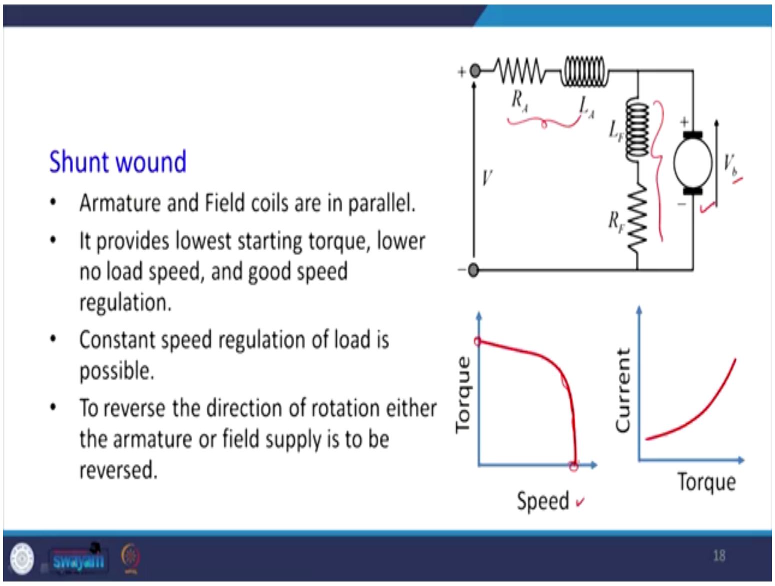

Now, let us look at the shunt wound. In case of a shunt-wound what happens? This armature coil and the field coil, are in parallel, they are shunted. So, and this is the motor; V_b is the back e.m.f. which is being generated. So, here the armature and field coils are in parallel and it provides lower starting torque, lower no-load speed, and good speed regulation. This starting torque is lower, this no-load speed, this is also lower and you can see that this portion is almost a straight line. So, it has good speed regulation. It could maintain a constant speed as you can see. So, the constant speed regulation of load is possible with the help of the shunt-wound motor. To reverse the direction of rotation either the armature or field supply can be reversed and we could change the direction of rotation of the motor. This is the characteristic for the torque and current, as current increases, the torque is going to increase.

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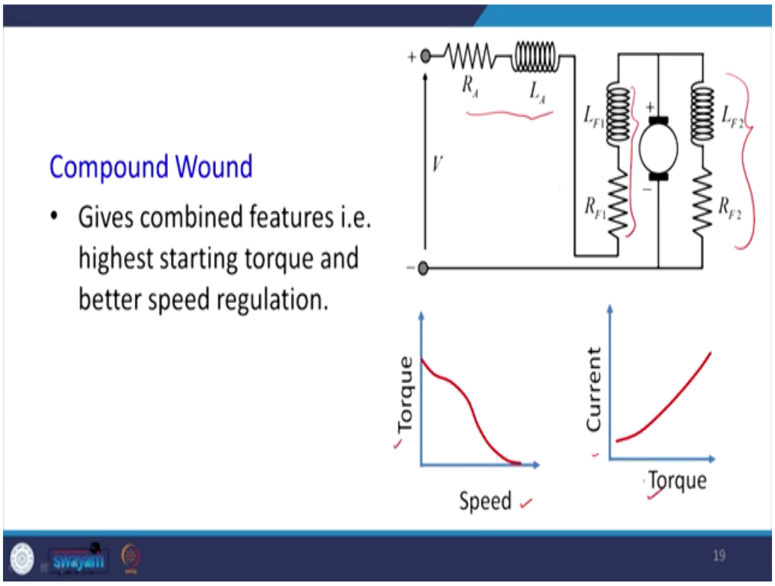

Then we have the case of the compound wound. Compound wound, a field winding part of the field winding, is in series with the armature winding and the part is in parallel with your armature winding. This type of one is called the compound wound and this gives the combined feature that is the higher starting torque and the better speed regulation. So the best of both series wound and shunt-wound you get in this case of the compound wound motor. This is the torque-speed characteristic which looks like and this is the current and torque characteristic which the motor has.

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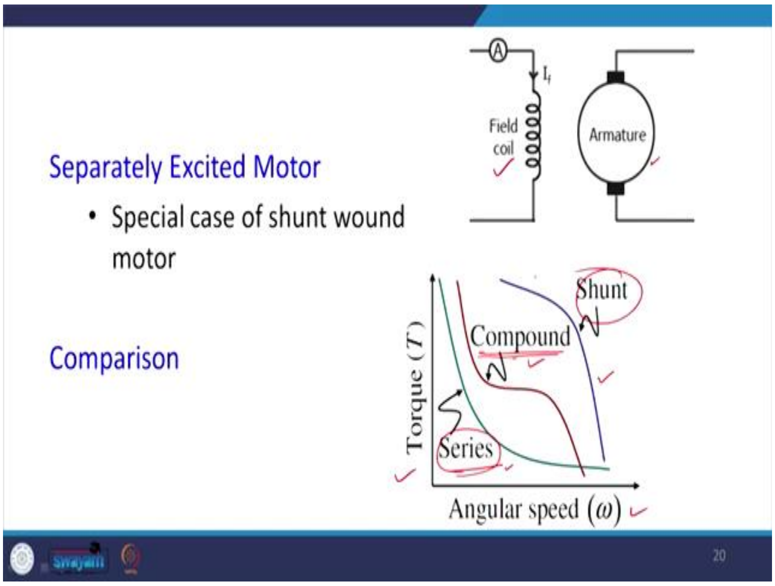

Then we could have a situation where we could have the separately excited motor. So, this is a special case of the shunt wound motor where we have the field coil which is not having contact with the armature coil and they are separately excited. Also, it is we can deal with this type of condition as a special case of the shunt-wound motor.

Now, if I look at the torque and angular speed of characteristics of these three motors, then this is what we see as the behavior for the series wound, this is the behavior for the compound wound and this is the behavior for the shunt wound. So, you can see that the compound wound characteristic is in between that of the series and shunt-wound motors.

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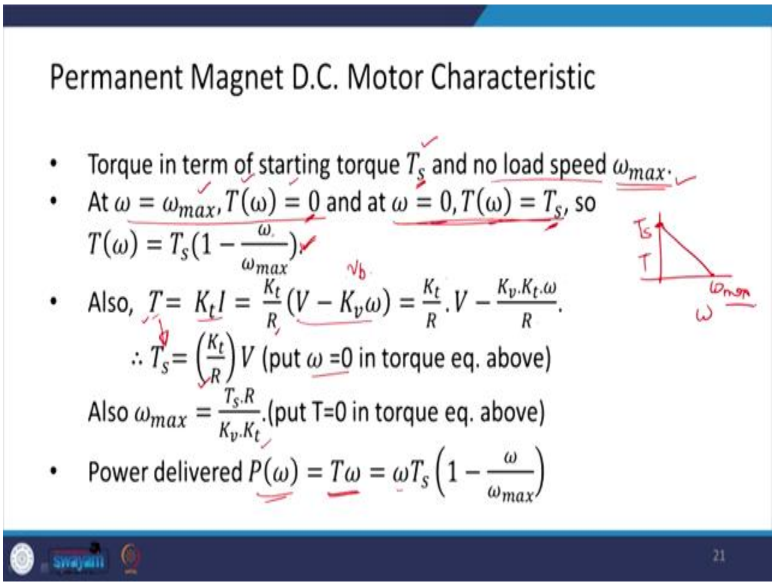

Next, let us look at the permanent magnet DC motor characteristic. So, if I talk in terms of starting torque T_s, subscript s I am using to indicate its starting and no-load speed and you know the no-load speed is going to be the maximum speed. So, I am representing the no-load speed as the ω_{max}.

Now you see, at $\omega = \omega_{max}$, when there is no load the torque requirement is naturally going to be 0. And, at $\omega = 0$ that is when the motor is not starting or about to start, that time this $T(\omega) = T_s$. This is what had we had this is T_s and this is the ω_{max}.

Now, you see I can represent this relationship with the help of a single equation,

$$T(\omega) = T_s(1 - \frac{\omega}{\omega_{max}})$$

So you see, if I put $\omega = \omega_{max}$ in this equation, So, I will be having T is equal to 0.

So the first part I will be getting. And, if I am putting ω =0 in this one, then my torque is going to be T_s. So I am getting the second part. So, this way this equation generalizes or depicts the relationship for both these parts.

Now, the torque requirement or the torque,

$$T = K_t I = \frac{K_t(V - K_v\omega)}{R}$$

So,

$$T = \frac{K_t}{R}V - \frac{K_t K_v \omega}{R}$$

And so, you see if we put $\omega = 0$ in this torque equation then what I get T, this is T_s at $\omega = 0$ and this is what I get as $\frac{K_t}{R}V$.

And, also I can get the ω_{max},

$$\omega_{max} = \frac{T_s R}{K_t K_v}$$

so, that I can get from over here.

So, The power delivered will be,

$$P(\omega) = T\omega = \omega T_s(1 - \frac{\omega}{\omega_{max}})$$

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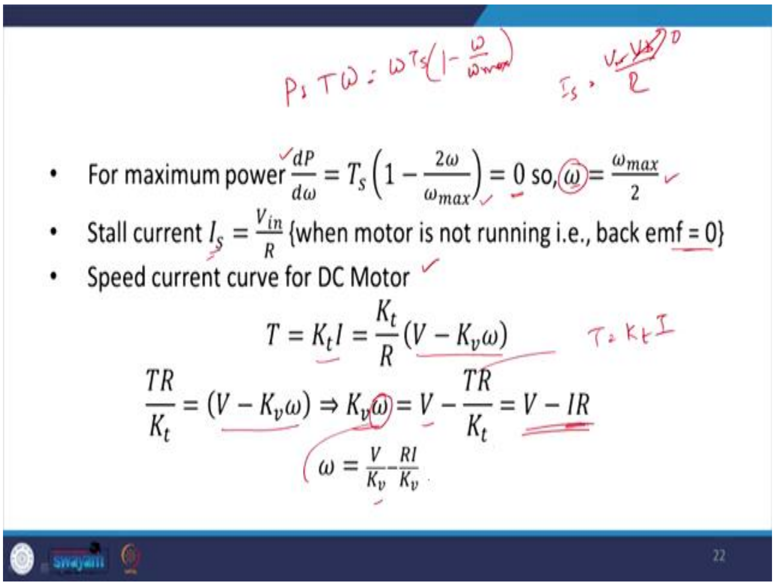

Now, what I can do is that, for maximum torque I can differentiate this expression with respect to ω. Now, if I differentiate this then I can take what I get over here,

$$\frac{dP}{d\omega} = T_s(1 - \frac{2\omega}{\omega_{max}})$$

If I equate this 0, then what I will be getting is

$$\omega = \frac{\omega_{max}}{2}$$

So, for maximum power, the speed of the motor has to be equal to half of the maximum speed. I can also get the stall current that will be when the motor is not running that is the back e.m.f. is going to be equal to 0, so a stall current,

$$I_s = \frac{V_{in}}{R}$$

The T is equal to,

$$T = K_t I = \frac{K_t(V - K_v\omega)}{R}$$

Further,

$$\frac{TR}{K_t} = V - K_v\omega$$

The $K_v\omega$ is going to be equal to V. And we get,

$$\omega = \frac{V}{K_v} - \frac{RI}{K_v}$$

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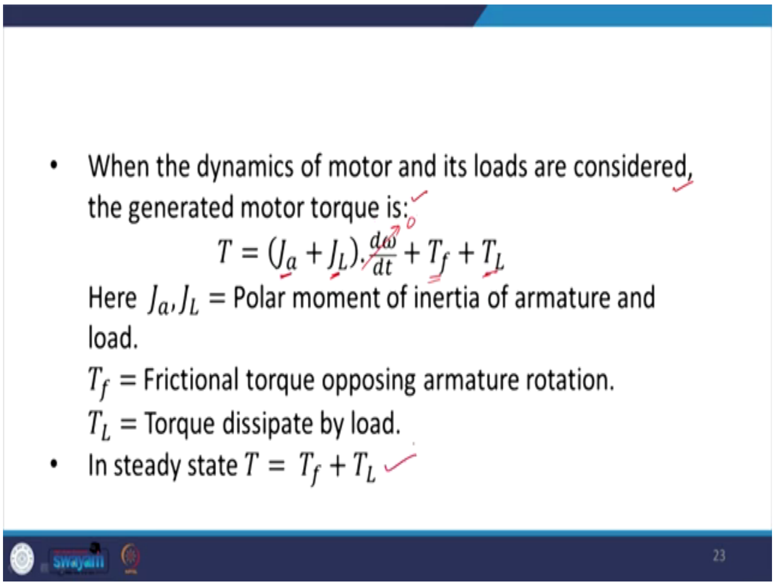

So, and when the dynamics of the motor and its load both is considered, then the generated motor torque,

$$T = (J_a + J_L).\frac{d\omega}{dt} + T_f + T_L$$

And for the steady-state condition, you see that this portion is going to be 0 because your ω is going to be constant.

$$T = T_f + T_L$$

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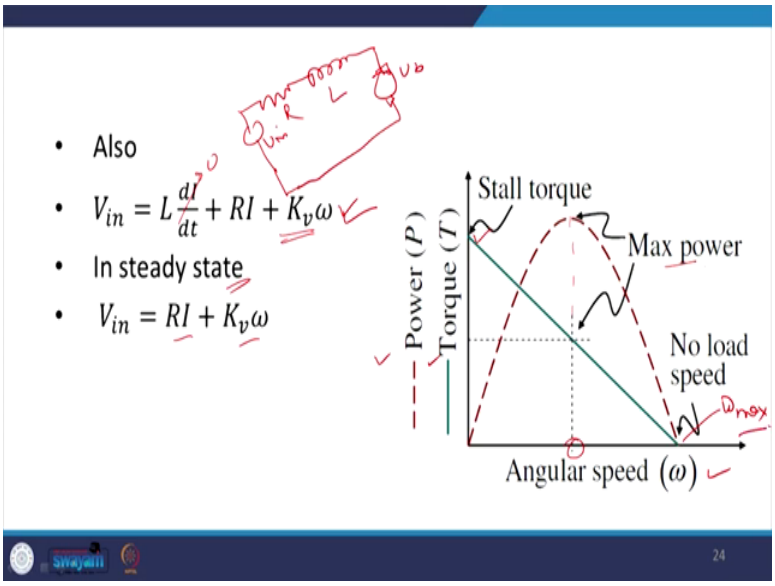

And also, the

$$V_{in} = L\frac{dI}{dt} + RI + K_v\omega$$

This is because you see that we have model the armature as a resistor and inductor here. So this V_b and you have here V_{in} , this is your R, this is your L. So if you apply Kirchhoff's law over here, you will be getting this equation. And again, for steady-state,

$$V_{in} = RI + K_v\omega$$

So, if I could plot the power and the torque versus angular speed, so you see that this power is going to become maximum at half of the maximum speed over here and this is my torque-speed characteristic. So this is the torque which I have been talking to you about that is the stall torque and this is the no-load speed which is the maximum speed. Now the question is that, how do we control these DC motors? So, the control of these DC motors depends on the current through the armature coil.

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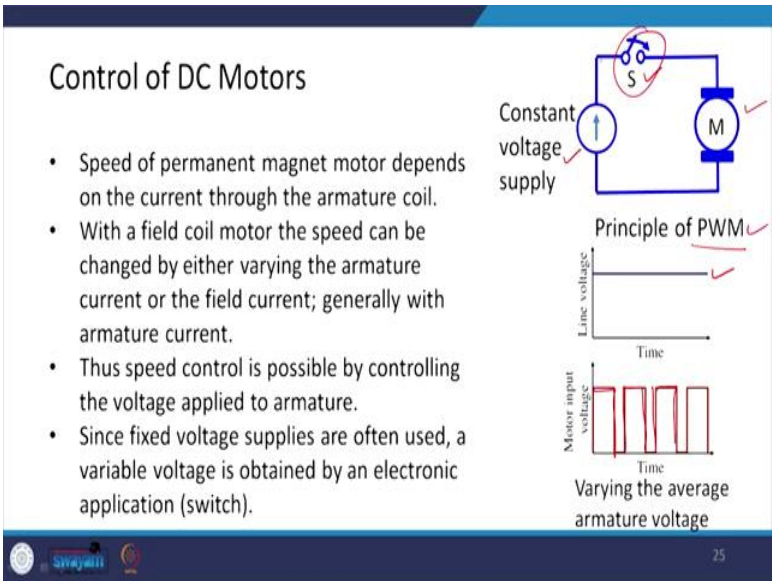

And with a field coil motor, the speed can be changed by either varying the armature current or the field current. Generally, we do with the armature current. If it is a permanent magnet motor, then you have to do with the current through the armature and if it is a field winding then you can do with either the field current or with the armature current you can try to control it.

Thus speed control is possible by controlling the voltage which is applied to the armature. And since fixed voltage supplies are often used, a variable voltage is obtained with the help of an electronic circuit or switch and this forms the basic principle of what we call the PWM or the pulse width modulation.

So, you have a motor, you have a voltage source and there is a switch. With the help of this switch, we try to supply the variable voltage. So, this is the line voltage which is a constant which is available, and with the help of PWM, this is the variable voltage we try to supply and try to control the motor.

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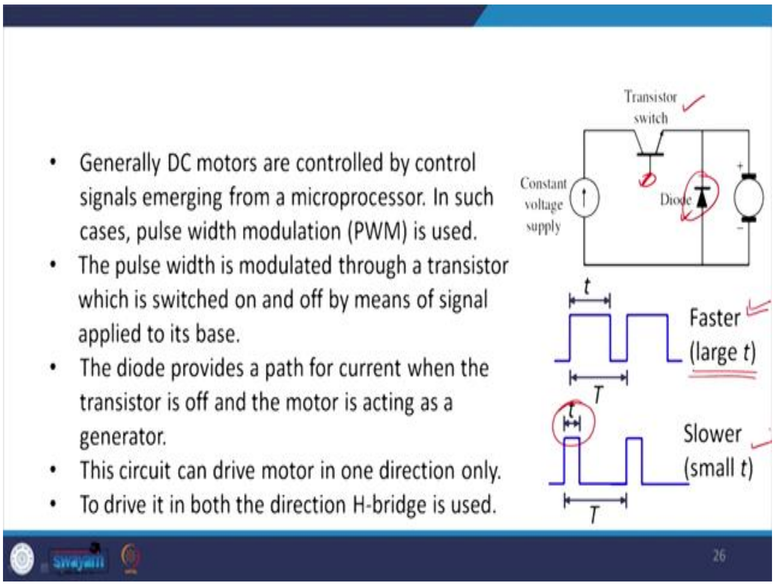

Now, this switch I just gave a mechanical example, but this switch could be an electronic switch consisting of a transistor and the diode. And, generally these DC motors are controlled by a control signal emerging from the microprocessor, and in such cases, we are using the pulse width modulation. The pulse width is modulated through the transistor which is switched on and off by means of a signal applied to its base, which is over here. A diode is provided here which provides a path for current when the transistor is off and the motor is acting as a generator. So, in that case, it provides a path for the current when the transistor is off. And this circuit can drive the motor in one direction only.

And this is how we could have a faster that is in this pulse width modulation if we have a large *t* over here, that is the voltage is there for a large portion of time, so this is the faster one and if the voltage is supplied for a small duration, then this is going to be the slower one. But, as I was telling you this circuit can drive motor in one direction only. So, what if you want to use a motor that can run in both directions? So for that, we need to use the H bridge circuit.

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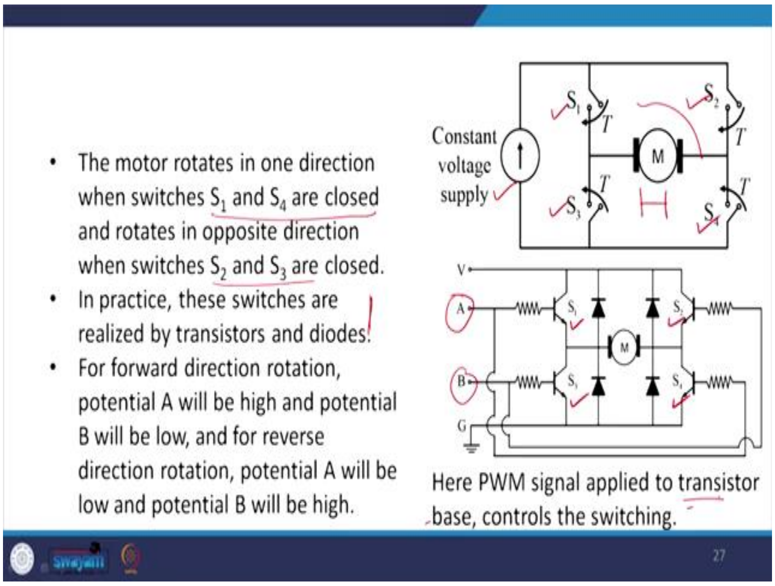

The H bridge circuit looks something like this of the shape of the H over here as you can see that is why it is called the H bridge circuit. So, there is a constant supply voltage here. There are four switches you can see, S_1, S_2, S_3 and S_4. These are the mechanical switches. You have the electronic switches and that switching is done with the help of transistors S_1, S_2, S_3 and S_4. Here motor rotates in one direction when switches S_1 and S_4 are closed and rotates in the opposite direction when S_2 and S_3 are closed. So, that is in this direction one rotation when this end is closed and in opposite one when the other two are closed. And, as I said, in practice these switches actions are realized with the help of the transistor and the diode. For forwarding direction rotation, the potential A over here will be high and the potential B will be low, and for the reverse direction potential A will be low and potential B will be high. And here you see that as I discussed in the previous slide, the PWM signal is applied to the transistor base and that controls the switching.

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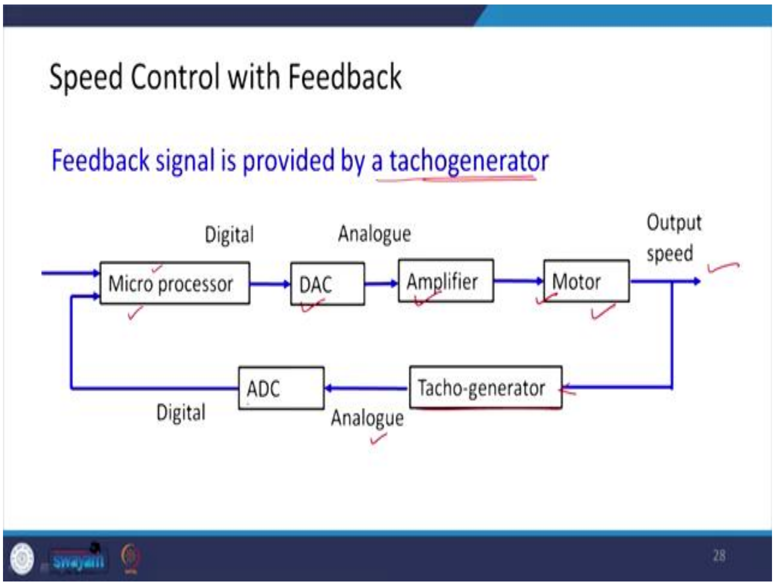

Let us see the speed control with feedback. In case of feedback, suppose I am providing the feedback signal with the help of a tachogenerator. So, suppose this is my motor, there is an output speed, I take out this output speed give it to drive a tachogenerator. Now, you see that this tachogenerator gives you a voltage that is we are getting the analog signal, so I need to convert this analog signal to a digital signal because this signal has to be sent to a microprocessor and microprocessor cannot take an analog signal, it takes an only digital signal. So I supply this digital signal to the microprocessor, and then this signal has to be fed to the motor and the motor accepts the analog signal. So we do a digital to analog conversion here, amplify that signal, and then send it to the motor and this is how the feedback signal is provided with the help of a tachogenerator.

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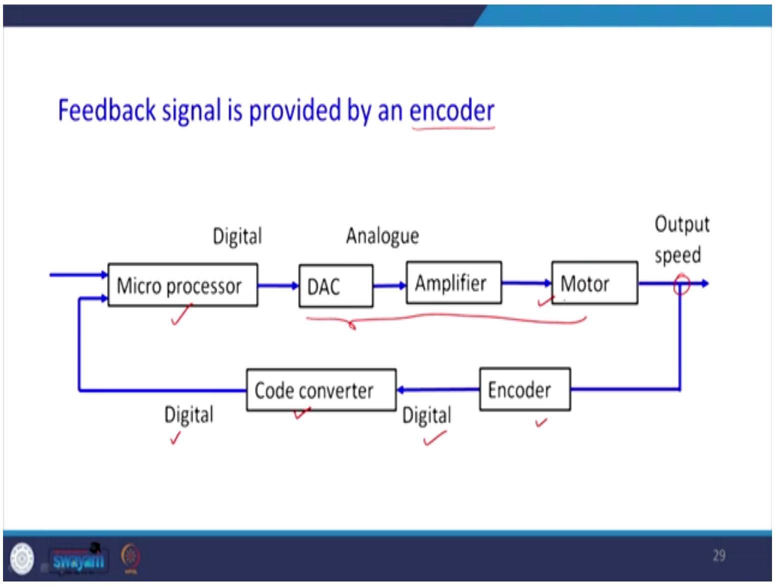

Then, we could also have the feedback signal provided by an encoder. So in that case what is done is that, there is a connection of the output shaft with the encoder shaft. This encoder gives you the digital signal, and as I talk to you about encoders we need to have a code converter over here to convert the encoder codes and this converted digital signal will be sent to the microprocessor. And then again rest of the things are the same, that is we have the digital to analog converter, amplifier and then this signal is given to the motor and this drives your circuit.

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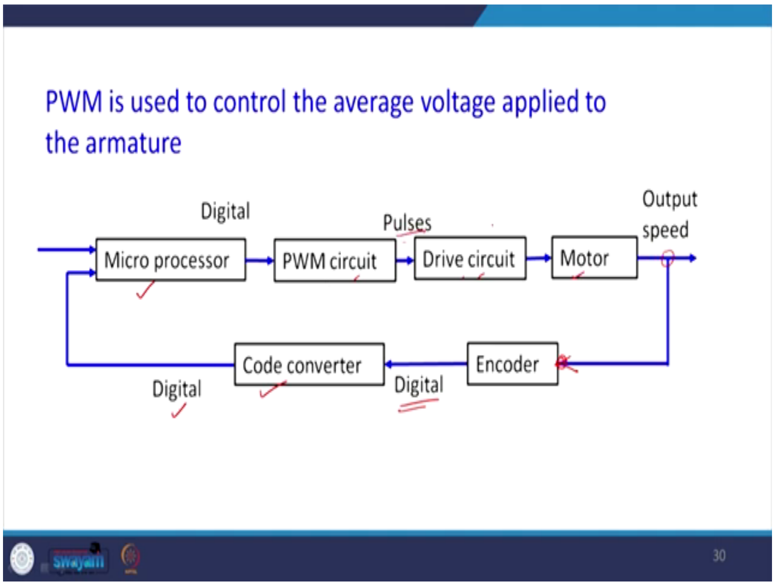

And, if we have PWM used to control the average velocity for the armature, so if we are using the PWM, then in that case what happens? You have the motor output shaft connected through the encoder shaft, here. And this digital signal with the help of the code converter is converted again, the conversion of the code for the encoder rotation is done and this is sent to the microprocessor and from here we have the PWM circuit and the drive circuit. This PWM circuit and drive circuit drive the motor and that is how the PWM control of the motor is done.

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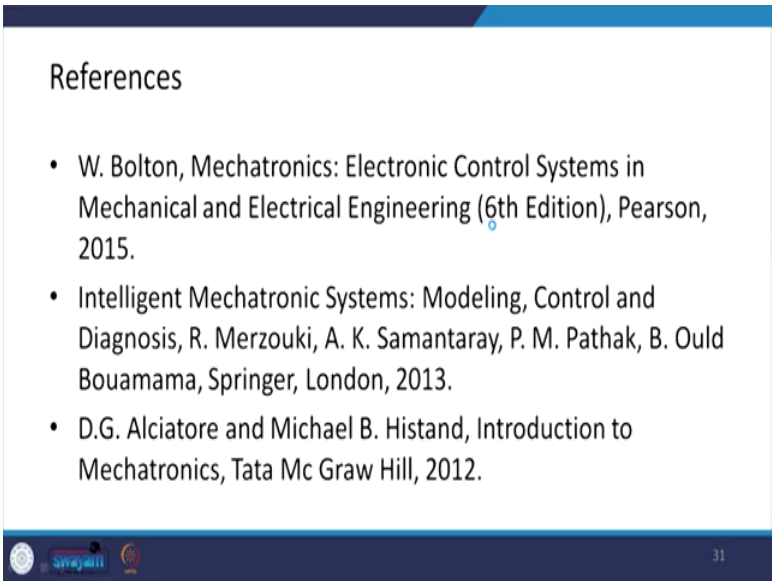

Here are the references. If you want to read further you can go through either through Bolton Mechatronics or our book on Intelligent Mechatronic Systems or The Mechatronics Introduction to Mechatronics by Alciatore and Histand.

Thank you.