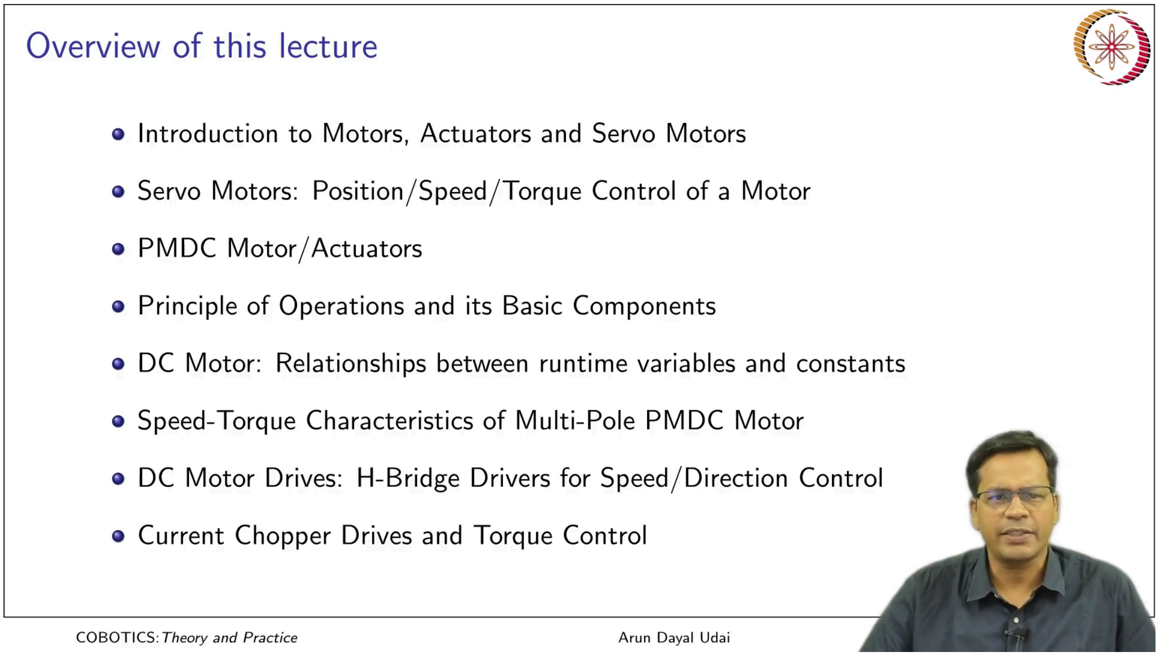
NPTEL Online Certification Courses
COLLABORATIVE ROBOTS (COBOTS): THEORY AND PRACTICE
Dr Arun Dayal Udai
Department of Mechanical Engineering
Indian Institute of Technology (ISM) Dhanbad
Week: 02
Lecture: 06

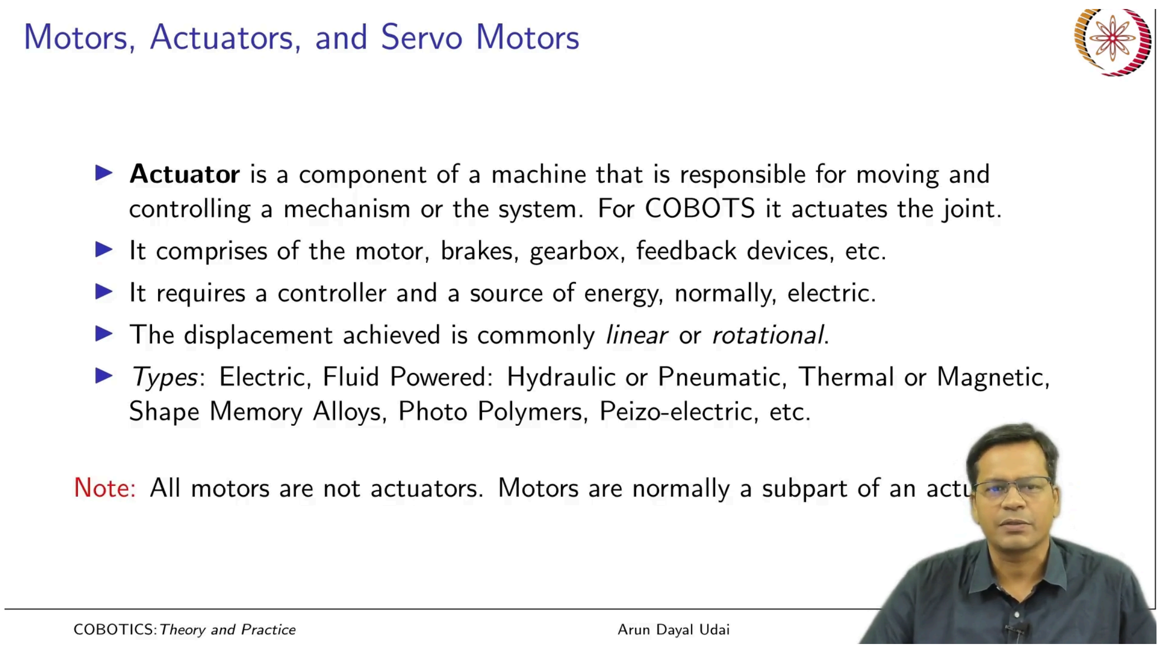
DC Servo Motors, Position, Velocity and Torque Control

Welcome to the second week of the course, Cobotics: Theory and Practice. This week, we will discuss actuators, sensors, and safe workspaces.

The first lecture will cover DC Motors, Position, Velocity, and Torque Control. In the second lecture, I will discuss BLDC motors and PMSM AC Servo Motors. In the third lecture, I will discuss Sensors: Position, Velocity, Acceleration, and Force Measurements. In the fourth lecture, I will discuss in more detail Force and Torque Sensors, Planetary Gearboxes, and Harmonic Drives. In the final one, the fifth lecture, I will discuss Industrial Field Buses, Drives and Devices, Safe Workspaces, Safety Triggers, Workspace Monitoring, and Marking Forbidden Zones. So these will be the five lectures this week.

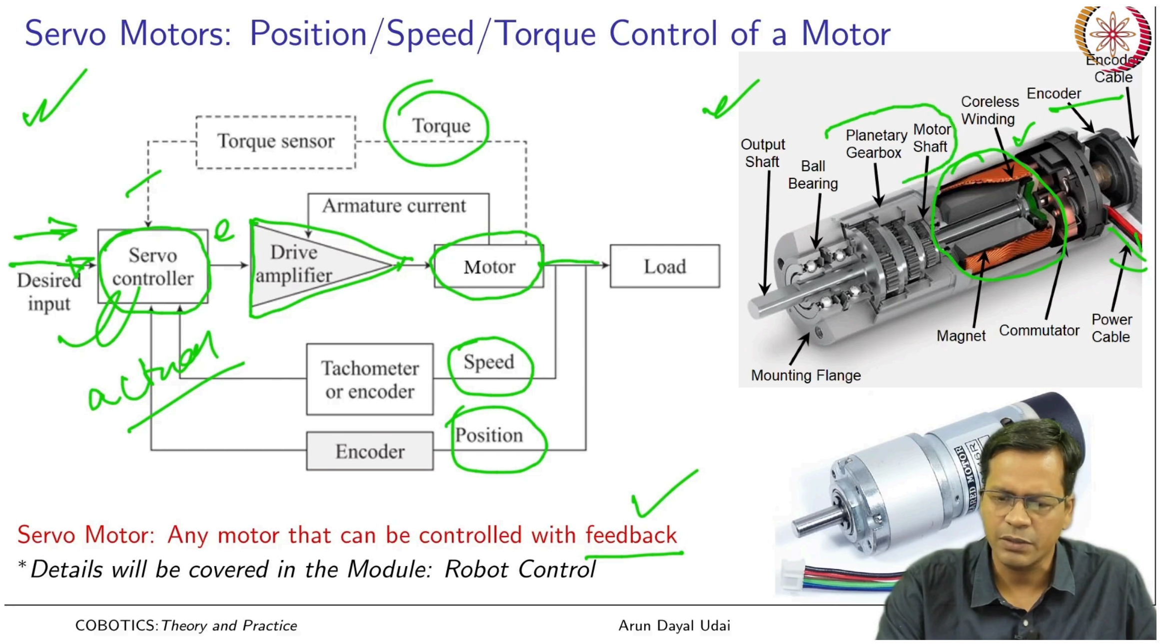


So, let us move to the first lecture of this week. Starting with the first lecture of this week for the course Cobotics: Theory and Practice, which is on actuators, sensors, and safe workspaces, in this lecture, I'll discuss DC motors, position, velocity, and torque control. This is the overview of this lecture. We'll start with an introduction to motors, actuators, servo motors, servo motor position, speed, and torque control. We will discuss PMDC motors and actuators, the principle of operation and its basic components, DC motors, the relationship between the runtime variables and constants, speed and torque characteristics of a multipole DC motor, DC motor drives, H-bridge drives for speed and direction control, and finally, current chopper drives and torque control.



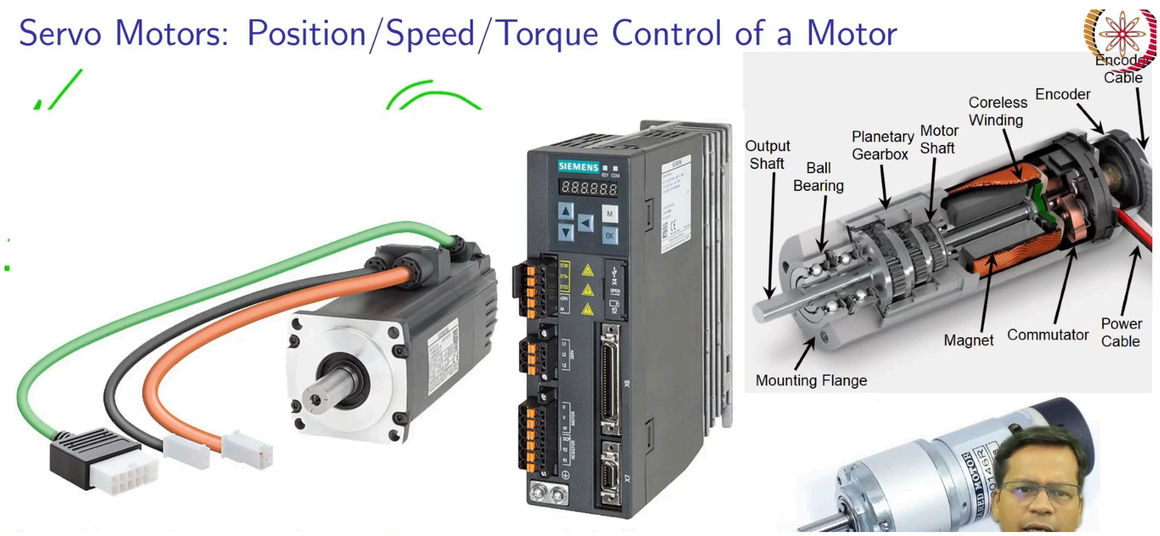
So, let us begin. So, Motors, Actuators, and Servo Motors. These are a few terms that you have heard quite often when dealing with robots. An actuator is a component of a machine that is responsible for moving and controlling a mechanism or a system. For cobots, it actuates the joints. Even for robots, it actuates the joints. It comprises motors, brakes, gearboxes, and feedback devices, all together in a single unit. It requires a controller and a source of energy, normally electric energy. In the case of cobots, most of the joint actuators are electrically driven. The displacement achieved is commonly linear and rotational. Various types include electric, fluid power (that is hydraulic and pneumatic), thermal or magnetic, shape memory alloys, photopolymers, piezoelectric, etc.

Please note that not all motors are actuators. Motors are normally a subpart of an actuator. This we will find in more detail in the next slide.



So, you see a servo motor, which is meant to do position, speed, or torque control of a motor. So, this has a particular layout for its operation. You see here is your motor. This is your motor. It is attached to a load. The load, in the case of robotics, is the links that come next to the link on which this motor is fitted. It gives you feedback on speed, position, and torque. All three combined provide the feedback that goes to the controller here. The controller takes in the desired input for torque, speed, or position. It compares these against the actual values that are fed by the feedback. These are all the actual values that are fed in. This is the desired input. So, it compares and finds out the error. The error goes to the controller, and the controller takes corrective action and sends it to the motor via a drive amplifier. This is the drive amplifier because the signals generated by the controller are not enough to drive the motor, so it finally sends the corrective signal to the amplifier. The amplifier amplifies the power and sends it to the motor. It also has all the interfaces for a particular kind of motor. For a PMSM motor, it may be AC current signals. In the case of a DC motor, there are DC signals in two wires. So this is how all the control loops are in a typical AC or DC servo motor.

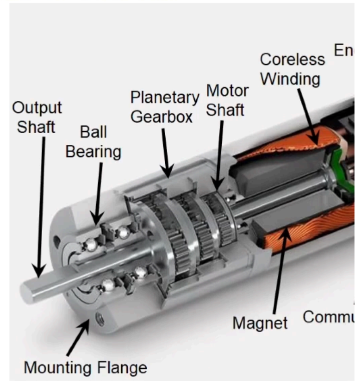
You see, a servo motor is a motor that can be controlled with feedback. It has the provision for feedback, and sometimes the controller also lies on top of the motor.



So, you see, a typical servo motor may look like this when it has three wires: red, black, and green. So these may be for powering the motor. The red and black ones may be for powering this motor, and the green one gives you the feedback. This creates a closed loop in position. So, where is the servo controller that you found here? The servo controller is in the rectangular black cabinet that you have. You can see it here. This attaches this motor and all the closed loops for torque. Position and speed are made within this controller. So, this controller takes in the input and compares it with the feedback given by the motor and all those are taken care of.

So, all the inputs are compared with the actual values from the feedback, and corrective action is sent to the motor. So, how does it look like? See. Over here, you saw the motor and the controller are separate, but there may be a case when they are integrated into a single unit.

Servo Motors: Position/Speed/Torque Control of a Motor

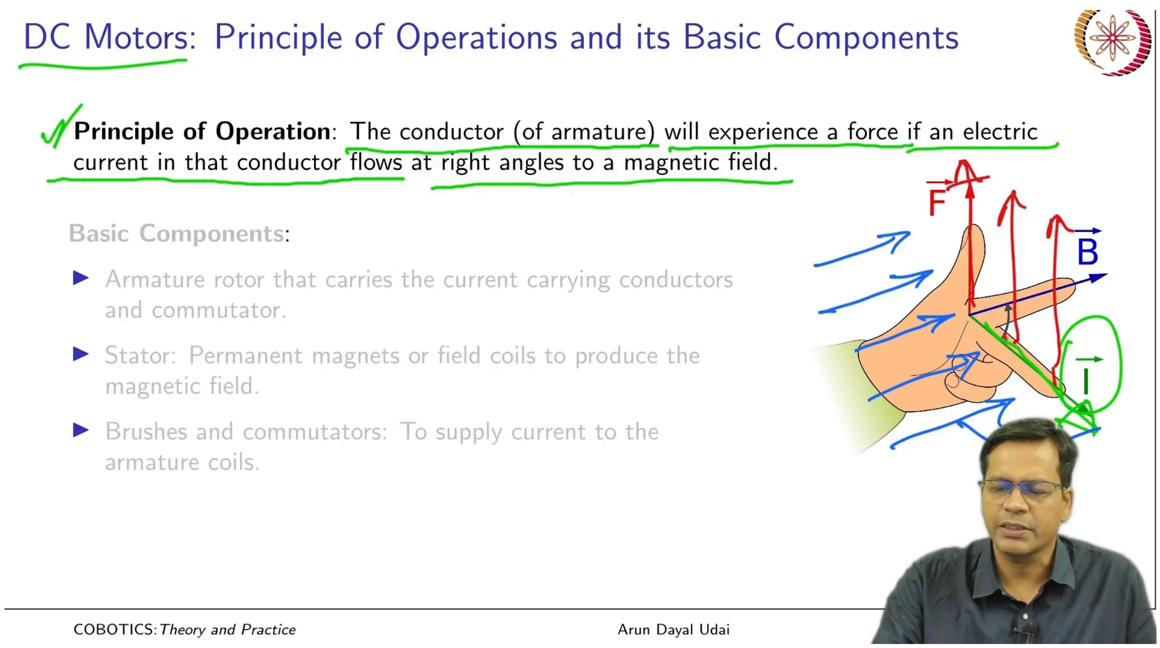


This also is an actuator which includes the controller. So, this forms a small, compact unit where all the feedback wires are not very long. They are on the same platform. So, these feedbacks are very accurate and reliable, making it a very precise motor. In this case, the actuator is not placed quite far off from the controller.

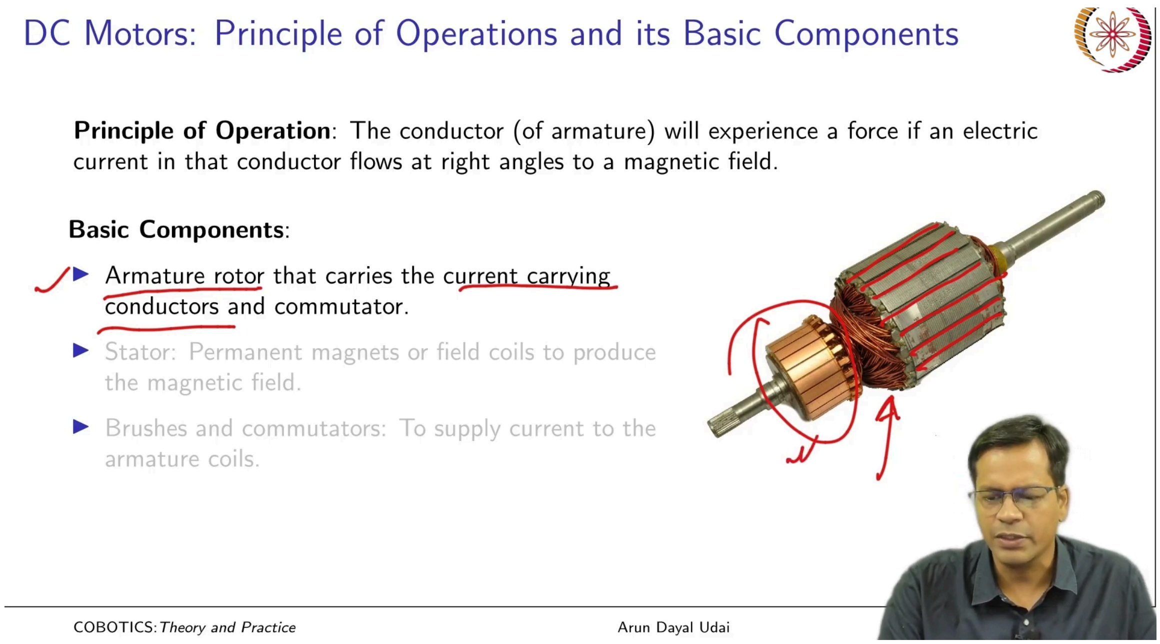
Servo Motors: Position/Speed/Torque Control of a Motor

So, you see there may be a situation like this, which is commonly used in a cobot, where you have all the devices that you have seen: the motor, the gearbox that is the transmission, the servo controller which takes in the input and sends out the corrective signal through the power amplifier to the motor. So, the power amplifier is also on the same compact joint. So, everything is compacted together in the joint which includes the feedback mechanism, the actuation, and the transmission. So, this is very, very complex in the case of a cobot.

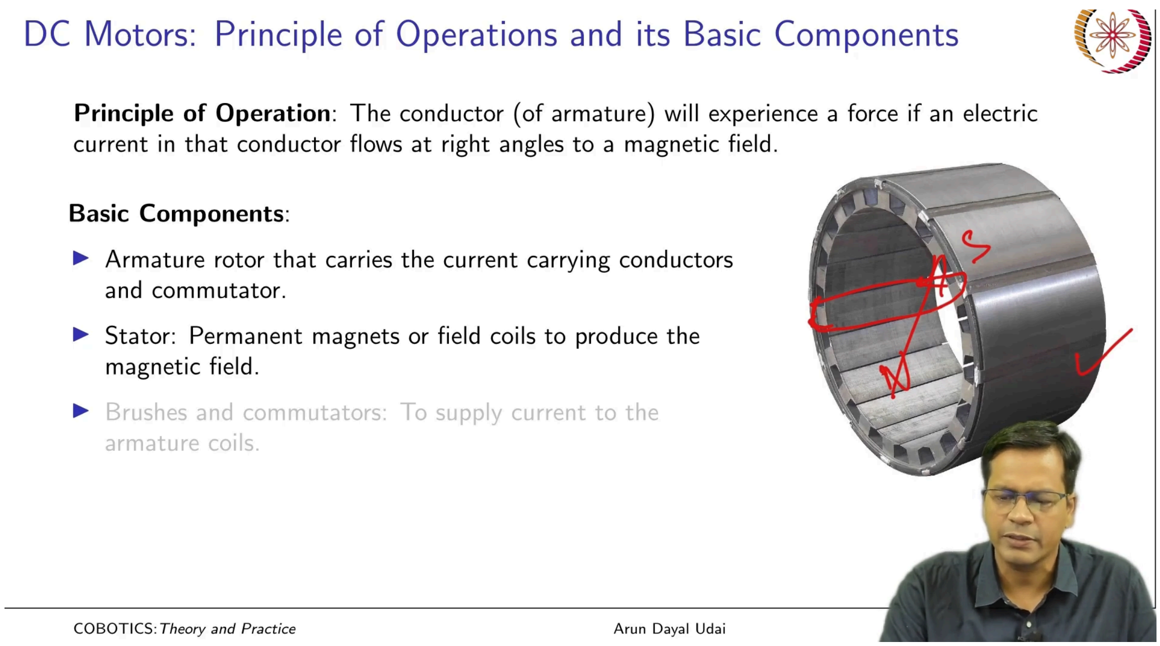
So, a servo motor, you see, is any motor that can be controlled with feedback. This you have already seen earlier over here; this again is a DC motor. The motor comes here; there is a commutator here. There is an encoder; the encoder sends you the feedback of position. So, this can be a position-controlled servo, provided it has a servo controller and a power system connected to it. There is a transmission system here, which is a planetary gearbox, and finally, the output shaft. So, all together in compact, it looks like this.



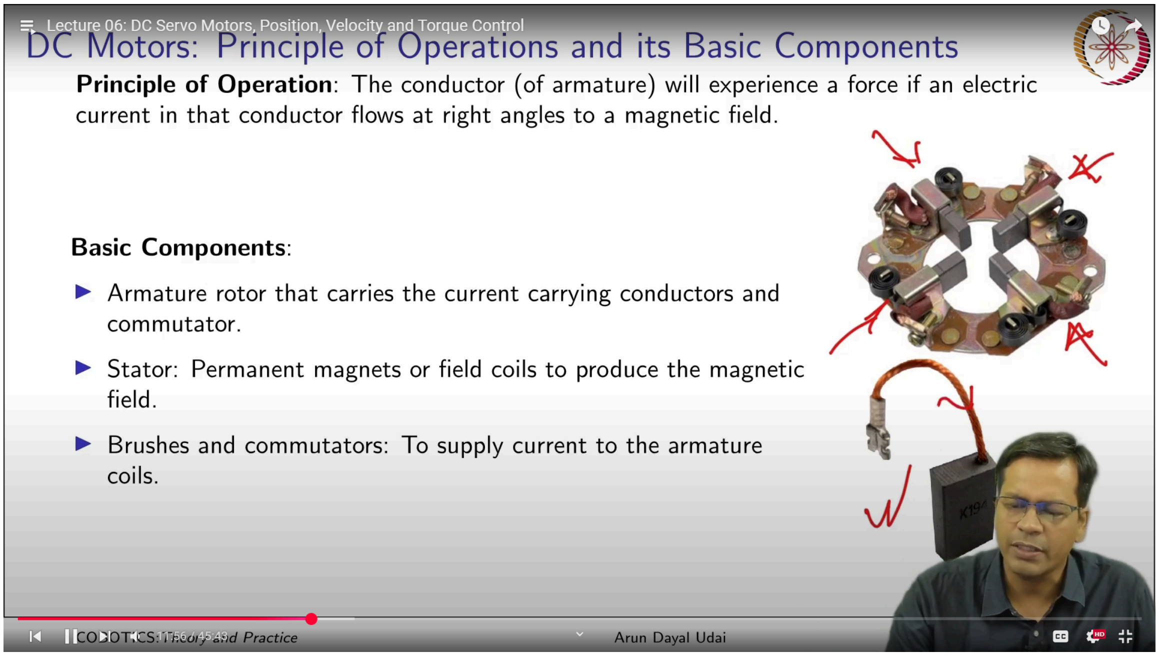
So, let us talk in detail about what a Permanent Magnet DC motor and actuator are. So, in principle, all the motors that we will be covering in actuators will have the same principle, which I am going to discuss next. So, this principle is for all kinds of motors, not just a DC motor. It carries current in the conductor, the conductor of the armature that experiences force if an electric current flows through it and that is oriented at a right angle to the magnetic field. So, where are they, you see? So, this is the current-carrying conductor; I is the current that flows through it. It is lying in the magnetic field like this. So, that is orthogonal to the current, and finally, this conductor will experience a force that is perpendicular to the direction of the Field and the Current, so all three are mutually perpendicular. So, this conductor finally experiences a force that is perpendicular to the direction of the current. This conductor lies in the magnetic field, so this is the standard principle that is applied to the motor.



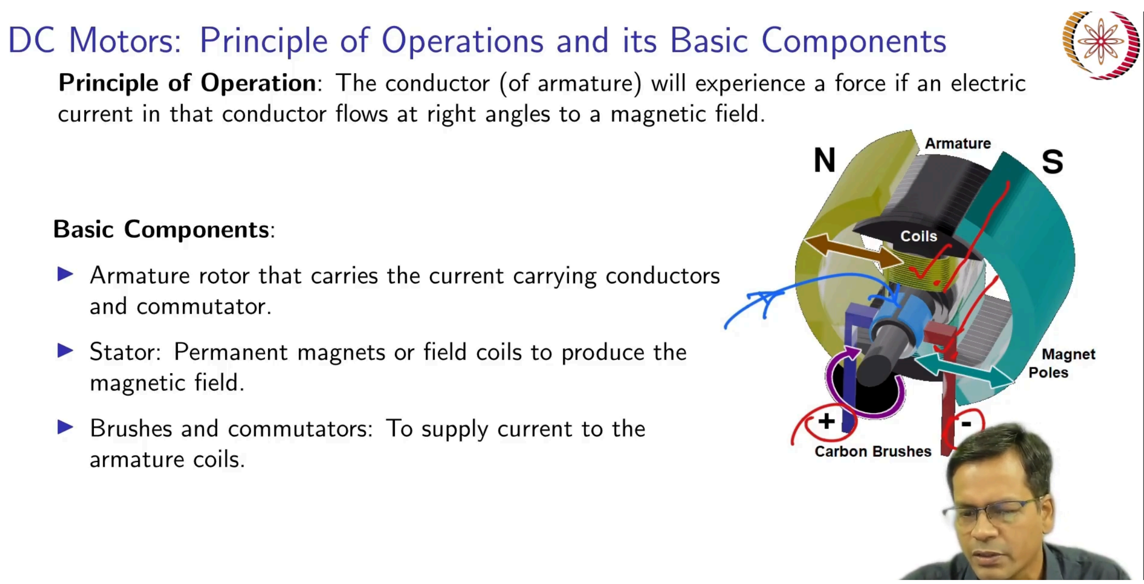
So, the basic component is the armature. That is the rotor that carries the current-carrying conductors and the commutators. So, here is the commutator, and you see there are many current-carrying conductors. They are copper-wound. So, you see these slots are filled with many such conductors. So, they are wound over here. These are laminated copper wires. This commutator transfers the electricity from the shaft to the running conductors.



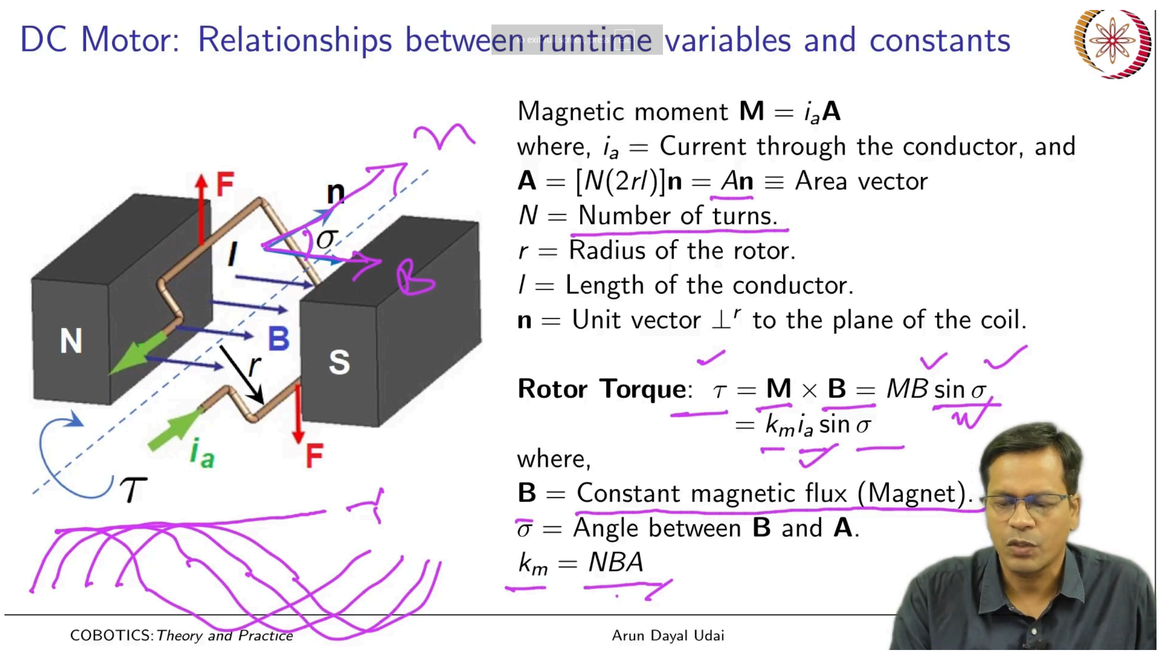
The stator- The stator has permanent magnets over here, north and south like that, so that this creates the field within the cage. All these opposite poles will create a field. Okay, so this may be a permanent magnet, or they may be coils again, coils within these slots, so that they create magnets over here. Okay, so this is the stator which carries current so as to create a magnetic field, or they carry the set of magnets all around and create a magnetic field that is perpendicular to the direction of the conductor.



Finally the brushes and the commutator. So, this is a carbon brush that is inserted within these pockets from all around, so that it makes continuous contact with the commutator, and current from here is finally transferred to the motor commutator, and the commutator sends it to the conductors.



So, all together when assembled, it looks like this. So, if you have carbon brushes that carry current, send it to the conductors that are here. Okay, the conductor takes up the current and makes it flow in the conductors which are here, this one and this one. So, they are conductors, and you have magnetic fields within this space that are like this. So all the magnetic fields are like this, from north to south, and mind it, there is not just one pole, one pole north and south that is creating the field. There are multiple poles all around and wherever this conductor goes, in all directions, there are magnetic fields. This armature, a rotating armature, will have conductors that will always be perpendicular to those magnetic fields. This is how it creates motion.



So, let us just look inside again to see how it is. You see, it takes in the current from the commutator and makes it pass through this. Coil, one of the coils, is isolated and shown here. So, current passes like this, like this, and it comes out. So, overall, this is the current-carrying conductor. And you see, you have a magnetic field like this, that is B, which is shown here. Magnetic field, and ultimately, this will lead to the forces on this conductor. So, these are the forces F. Finally, both ends of this coil loop have force on it. This finally creates a torque, which is finally picked up by the armature, which holds all these coils together, multiple numbers of such coils, and takes it out from the output shaft.

So, now let us look at the parameters that are there and some relationships. So, the magnetic moment is given by M, which is i_a into A.

$$M = i_a A$$

What is it? i_a is the current through the conductor. A is the area vector. What is the area vector? If this is the surface area of the coil, that is nothing but 2r, that is 2r, r is the radius of the rotor, l is the length of this. So, 2r into l is the total area of one single loop, and if there are N turns, so it makes it N times of 2rl.

$$A = [N(2rl)]n$$

So, that is the magnitude of the area, and n is nothing but the surface normal, normal to the surface. That is given by the n vector over here. So, A into n is the area vector. A is the magnitude, and n is the unit vector which is perpendicular to this area.

So, now this rotor torque, rotor torque is given by magnetic moment (M) into B. B is the constant magnetic flux due to the magnet or due to the field coils. So, this is the torque.

$$\tau = M \times B = MBsin\sigma$$

If you take the cross product, there is sin sigma. What is sigma? Sigma is the angle between the magnetic field B and the area vector n. So, that is sin sigma. This is for a unit coil.

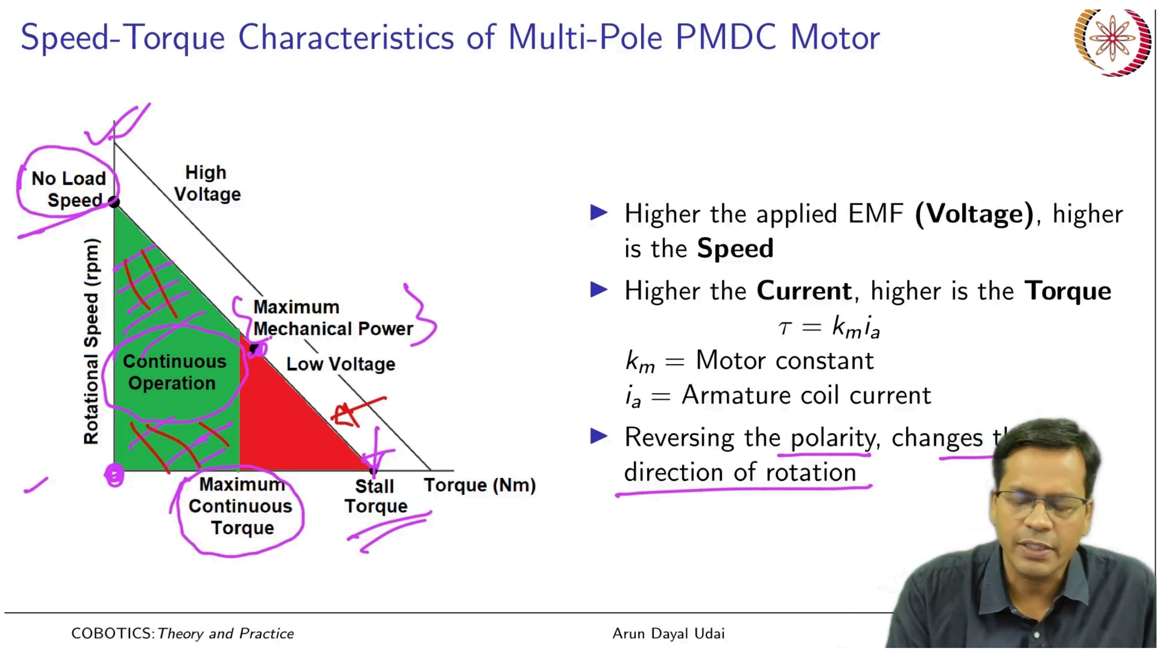
But when there is multiple number of coils all over, the effect of this sinusoidal variation goes off. It averages out with a uniform torque. So, then you can write this as tau is equal to Km into i_a. Sin sigma is evened out by a multiple number of coils.

$$\tau = k_m i_a sin\sigma$$

So, there are multiple sinusoidal torque variations. If you see the torque, it is like this. So, torque varies like this for a single pole, and single coil, but there are multiple coils. So, each one of them produces combined torque together, and this becomes the Combined torque, and that torque is having Km into i_a. What is Km? Km is equal to NBA.

$$k_m = NBA$$

N is the number of turns. B is the magnitude of the field. A is the area of the coil. The area is N into 2rl. So, this is the general equation of a motor that relates current to the torque.



So, now, let us see the speed-torque characteristics of a PMDC motor, a permanent magnet DC motor. So, you see, the higher the EMF, that is the voltage, the higher the speed. Why is this so? You see in the last slide, what you saw here, higher EMF will cause higher current. The current remains proportional to the voltage that is applied. So, the higher the current, the higher the force. So, effectively, the higher the voltage that comes here, the higher the current, and thereby the higher the force that this wire would experience. So, the higher the force, again, the higher the torque. So, effectively, torque is proportional to the current that flows to the armature, which is proportional to the applied EMF across the coil. So, what you see here is, that the higher the EMF, that is the applied voltage across the armature coil, the higher the speed of the armature because higher EMF would cause higher current in the armature coil, and finally, it will lead to higher speed. So, in order to regulate the speed, you can directly regulate the effective voltage that goes across the terminals of the armature.

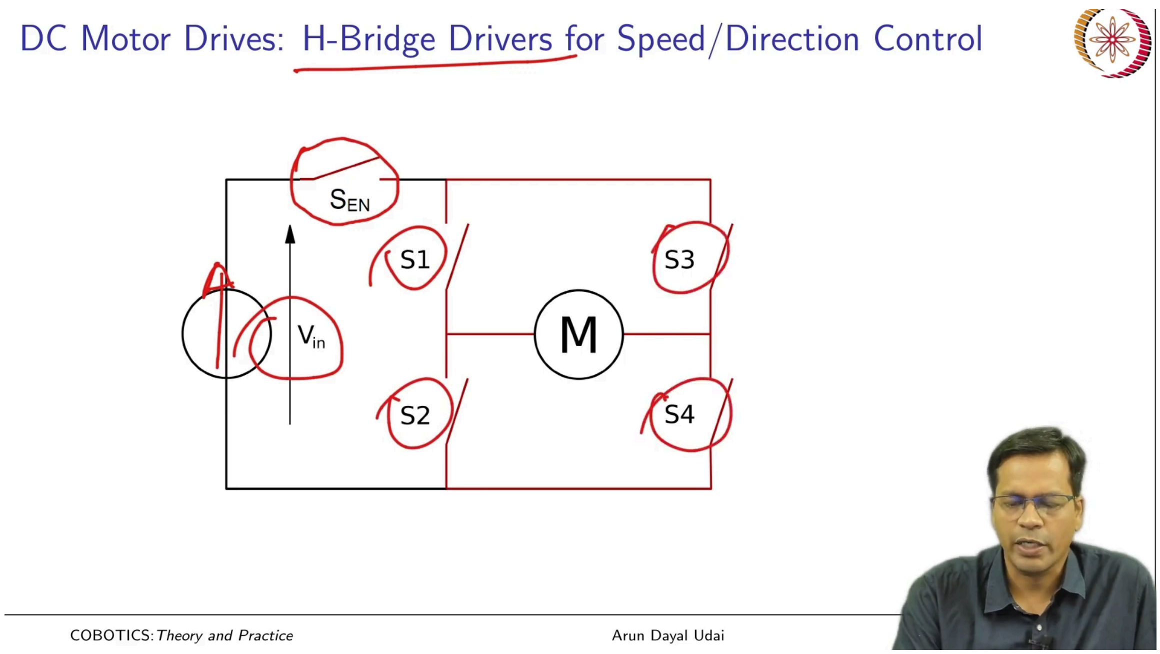
Now, the higher the current, the higher the torque. You saw it is directly proportional, tau is equal to Km into i_a in the last slide.

$$\tau = k_m i_a$$

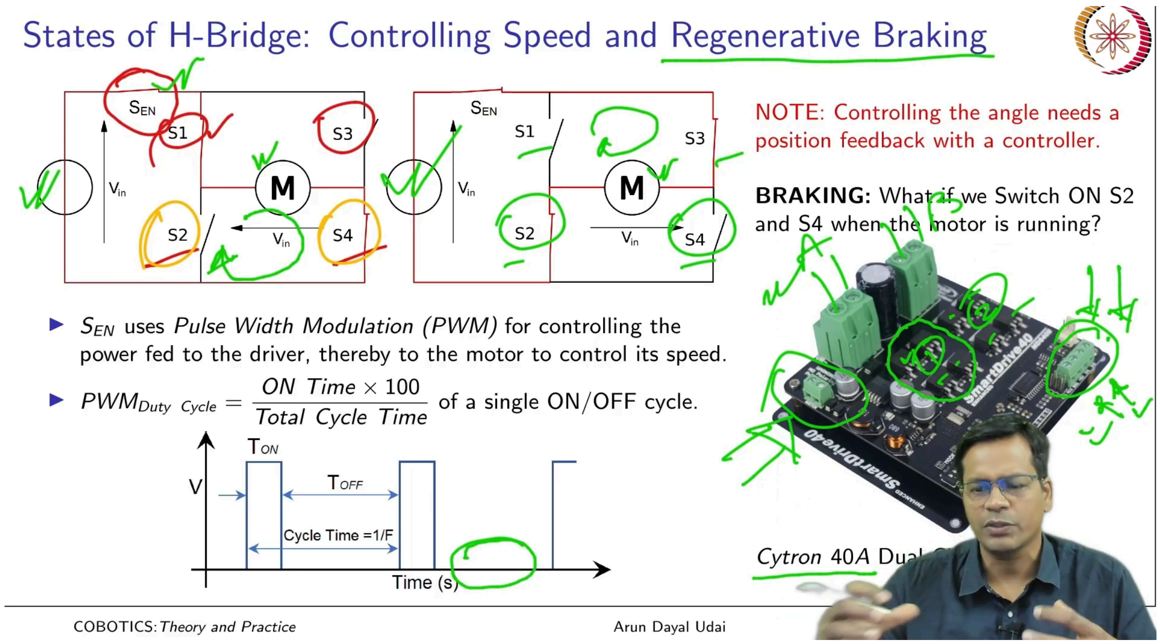
So, k_m is the motor constant, i_a is the armature coil current. So, if you have to control the torque, you have to control the current flowing through this armature. If you have to control the Angular velocity of this armature. So, what do you have to do? You have to control the effective voltage across this armature. So, reversing the polarity would change the direction of rotation. Why? Because reversing the polarity will create forces in the opposite direction and finally the torque in the opposite direction.

So, overall, all of this can be represented using this picture which is here. So, no-load speed is the speed when there is no additional load apart from the armature load, which is the only load. So, this is the speed at very low torque, which is the added torque. So, this creates a very low Torque and very high rotational speed, so this torque is very low because there is no load, and in this case, you see the speed is maximum. And there is a stall torque over here, which is the maximum torque this motor can deliver when the motor is stationary. It is not moving at all. It has 0 rpm. So, in between, it looks like a straight line. It is a part of a curve. The whole of the curve that this motor can take in. So, this is the continuous operation region. This is where you should make your robot work. Your motor should work in this region. Within that, there is the maximum continuous torque this motor can deliver. And you have the maximum mechanical power that is somewhere over here, a little above the maximum continuous torque region. You see it is in the red region. So, you should not run your motor in the red region. Why? Because it carries a lot of current in the conductors, and there is no balance between the heat dissipation, which is dissipated out of the motor, and the heat generation because of the current in the coils. And then, the motor gradually gets heated up, and it may go bad. So, it should run in a continuous operation region where there is a heat balance. The heat generated is equal to the heat dissipated, and that balance is there, and the motor works in the green region most of the time.

So, this is what this curve tells you, and this curve can be found in the datasheet of a motor, any motor, not just a DC motor. It looks like this.



Now, let us look at the DC motor drives. In the case of a DC motor, we use H-bridge drives for speed and direction control. So, this is how a typical H-bridge would look like. It consists of Five switches, one over here, that is known as the enabling switch. The enabling switch, if this is on, the motor is on. If this is off, no current will flow through the motor, and the motor will be off. So, this is the applied EMF, which is the voltage over here. So, these are the four switches: S1, S2, S3, and S4. Accordingly, if you switch on and off each one of them, it does something.



So, let us look at that. So, first, S is enabled, and S1 is on, and S4 is on. So, what happens? Current from here comes like this, goes like this through the motor in this direction, and it comes back. So, this, let us say, makes the motor move in a clockwise manner. So, in the next case, when S enable is on, and you have switched on this and this, S2 and S3, the current goes like this. It follows this path, and in this case, the current from the motor goes in a reverse way, and the motor rotates in a counterclockwise direction. So, you see, these four switches can be used to reverse the polarity across the motor, and the motor can be made to run in opposite directions, clockwise or counterclockwise. So, what is this S-enabled switch doing here? S-enabled uses a Pulse Width Modulation for controlling the power that is fed to the driver, thereby the motor speed can be controlled. How? A high-frequency switching is done over here. This switch is made to switch on and off, on and off. Instead of continuously maintaining an on status or off status, it is made to go on and off.

So, the higher the duration, the switch remains on at a high frequency. The motor does not detect high-frequency switching. Effectively, it keeps rotating at a constant speed due to inertia. Okay, due to its inertia, so that on and off effectively is doing what? So, the PWM duty cycle is given as on-time divided by total time. So, if the motor is kept ON, then off, again ON, then off, there is some off time from here to here, and then you have ON time. So, on time divided by total time. Multiplied by 100, this is effectively the percentage of time the motor is kept on from here. Okay, otherwise, it is off during the off cycle of this PWM wave.

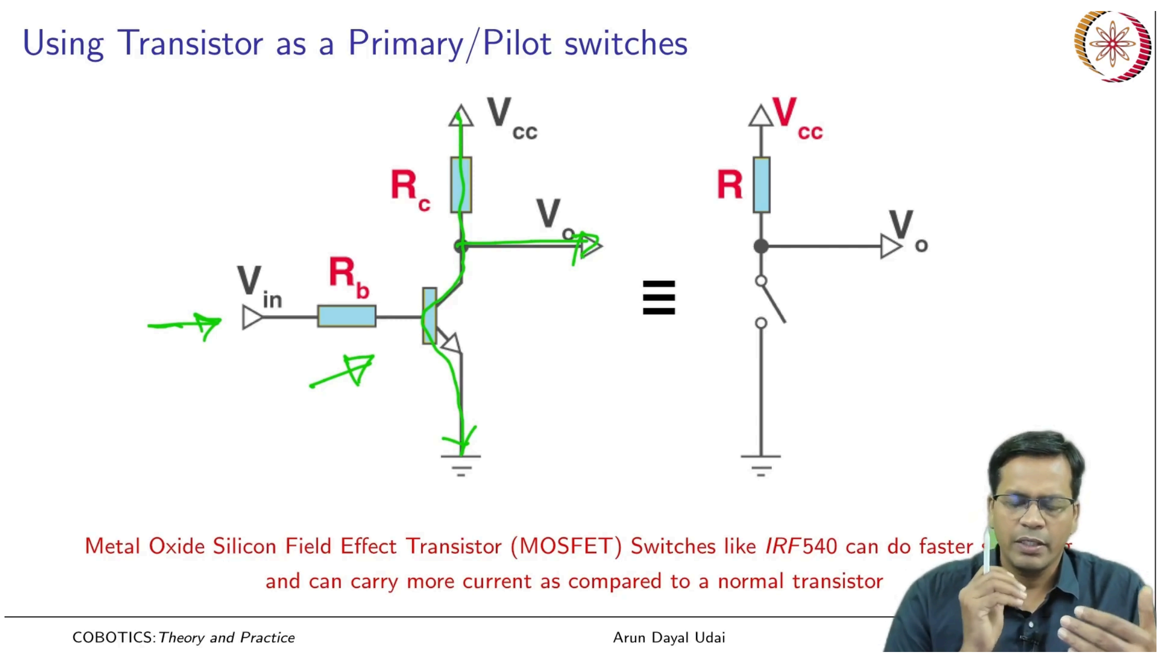
Now, let us say if the duty cycle is 100 percent. What has happened? The motor is on for 100 percent of the time, and the motor picks up the maximum speed. But let us say if it is switched on and off with a 50 percent duty cycle, so 50 percent of the time, the motor is off for the total time. So, less amount of power is fed to the motor. The motor picks up speed, but by the time it reaches full speed, it is off. So, the ON and off cycle will maintain an average speed for this motor. So, this is all. This is able to control the speed of the motor. So, the S enable switch, which is here, may be used to control the speed of the motor.

So, now, controlling the angle. If you want to control the angle of this motor, you would require angle feedback from this motor, and you would also need a controller that can compare the desired inputs to the actual input of the position controller. Okay, the state of the position is compared, and accordingly, the direction and speed are controlled, finally making it stop at a particular place. So, all of that will be done by the controller using the feedback, joint angle feedback.

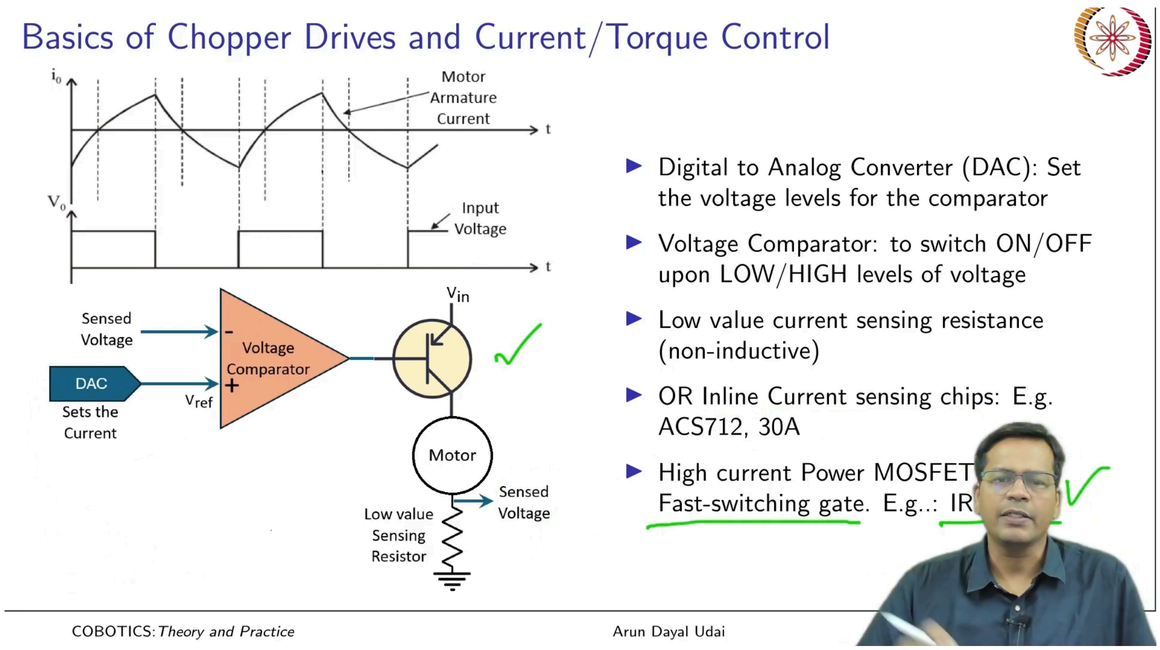
How Braking can be done? So, when you switch this ON, okay, and you haven't switched ON any of the switches S1 or S3, . What you can do here is you just switch ON S2 and S4. So, what happens? This motor is continuously running. You want to do braking, and you have switched ON this one and this one. So, what will happen? A current, which is generated by the motor when it is running and it is not connected to the terminal, becomes like a dynamo. It creates electricity. So, that will create a loop current over here, and it is short-circuited. So, that will apply a huge amount of electrical loading on the motor, and the motor will eventually come to rest. So, this is known as regenerative braking. So, what you have done? The motor was running, and you just made two of the switches on together, S2 and S4, or S1 and S3 together. So, what would happen? A loop current flows, and that short-circuits the motor. Finally, the motor is overly loaded, and it finally stops. Mind it, it cannot bring the motor to a dead stop because when it is dead stop, it is not generating any current, and any further braking cannot be applied. So, in order to completely make it immobile, you have to apply external brakes as well.

This is how a standard motor driver looks. So, you see it has H-bridges which are here. You see four switches here: 1, 2, 3, 4, and another four switches here. This is a dual motor controller for Cytron, a 40-ampere controller. So, these are the two H-bridges which are here, one and two. These are the connections for two motors: motor A and motor B can go here. These are the wires from where you can feed in the speed signal, PWM for both motors, that is for speed and two for the direction: clockwise, counterclockwise for the first motor, and clockwise, counterclockwise for the second motor. Altogether, four wires are here. This is the connection for power input, so this is the power that is fed here and here. So altogether, this is a set which can make a loop here and put the motor somewhere over here, and you can control the speed. Speed control is not just the PWM input; you would also need a speed sensor.

Speed can be sensed by measuring the voltages when this motor is in the off cycle. So, that you can do, or you can have a physical tachometer fitted at the motor so that you take the feedback, create a closed loop, and adjust the PWM accordingly. PWM that goes at the S enable pins. S enabled.



So, all the switches are not just physical switches; they are switches like this. This may be a transistor; it can be a MOSFET which can do faster switching and carry much more current as compared to a normal transistor. So, if you feed in from here (Vin), a voltage signal if you feed in here, the current from here goes like this, and here is the output (Vo). So, this transistor can become a pilot switch for switching the MOSFET switches. Because, you see, normally these transistors cannot carry a huge amount of current. So, it cannot run the motor directly. So, a microcontroller can directly command the MOSFET if it is a small MOSFET, or you can have these transistors in between, which can be just like a pilot switch that further switches on and off the high-value MOSFET.



So, current and chopper drives, let us talk about that. That is normally used to control the current and, finally, the torque of a DC motor.

So, here are the basics for this. So, when you switch ON a motor, current starts building up within the motor. As long as it is on, it will keep on increasing up to the maximum value. As soon as you switch it off, what happens? Current starts dropping, dropping. Again, if you switch it on, it will increase. Again, if you switch it off, it will decrease. So, there is an average value between these two, high and low, that is maintained across the motor wires, and motor winding. So what you can do is switch it on and off, just like the way you did it earlier. This ON-and-OFF is based on the current feedback. If you want to go a little higher, so accordingly, when you reach the high value above the desired current, if this is the desired current, this is the desired current, so a little above that, you switch off the motor. You switch it off, let it come down, come down, a little below the desired, that is the threshold, and you again switch it on.

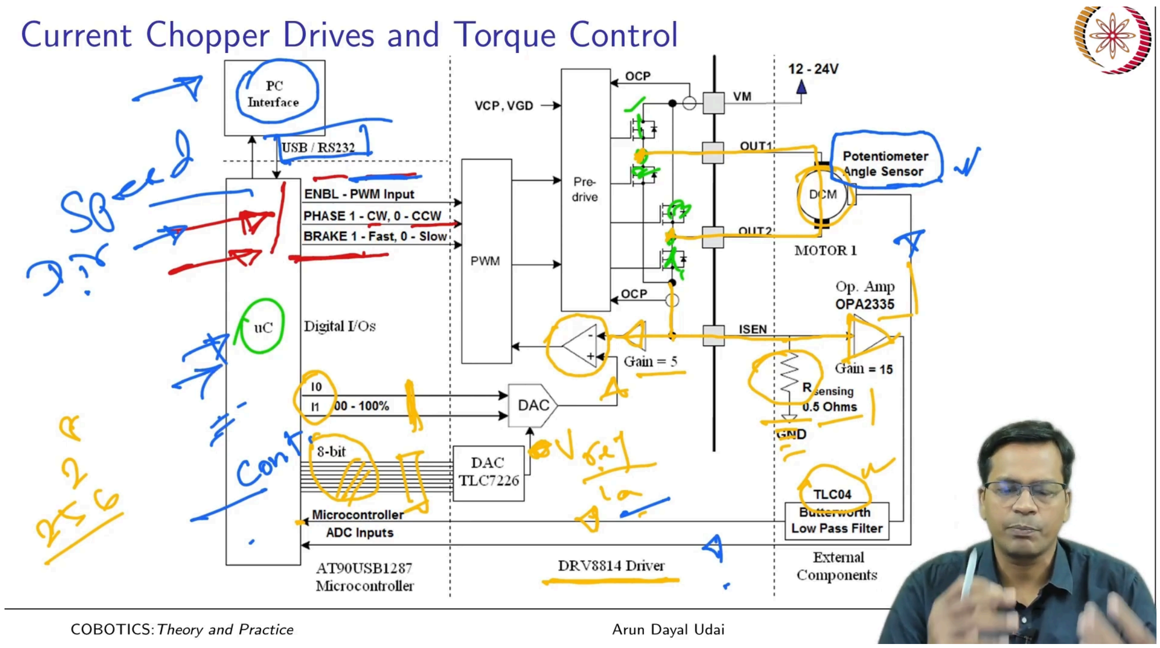
So, switching on and off can be done, let us say, 0.5 percent above and below this desired current. So, this is an automatic switching based on the current that goes to the armature coils. This is how you can control the current. And finally, controlling the current means you are controlling the torque. Torque is equal to Km into i_a. i_a is current.

So, you see how it is done. So, you can measure current across any wire using a low-value resistance. Low value. It may be just 1 ohm here. This does not affect much the current that is flowing through the armature coils. So, this current is the same as that of the armature current. So, it is in a series. This motor and the low-value resistance are in series. So, the higher the current, the higher the voltage over here. So, this is the sensed voltage, which is proportional to the current that flows through this resistance or through the wires and conductors which are there within the motor. So, this is what you want to control.

So, you have to give this feedback. This can be used as feedback for the current that is flowing through the motor. This is put here. Now, there is a digital-to-analog converter. So, this digital signal is setting an analog reference for this comparator.

This is a comparator. So, it compares with the sensed voltage, which is the sensed voltage for the current. So, this is the sensed signal for the current, and you have set the reference from the digital-to-analogue converter. So, it will compare the actual value of the current and the desired value of the current. If the actual value exceeds the value that is somewhere over here, it automatically switches off the transistor gate, which finally allows this current to flow through the motor. So, this voltage, which is here Vin, is switched off as soon as the comparator sees that the sensed value is higher than the threshold value, the high threshold value which was here, and if it goes low beyond the threshold, you again switch it on. So, this automatic switching on and off is done by the comparator. So, what all things go into creating a chopper drive? This is known as a chopper drive system. It requires a digital-to-analog converter, which will set the reference for the comparator. That is, the desired current value is set in the form of voltage over here.

Next, a voltage comparator that can compare and switch on and off based on low and high levels of the voltage signal sensed here. And a low-value current sensing resistance. So, this is the low-value resistance. Mind it, this is a non-inductive type because you know you are switching on and off. PWM kind of. So, switching on and off with an inductor will create a back EMF also across the resistance. So, it should be purely resistive. It cannot be an inductive resistor. Those who are wire-wound resistors, they are also inductors. They are not just resistors. Such resistors are not considered here. They are low-value resistors, maybe microfilm type or maybe just a wire strip of low value. So, low-value current sensing resistance which is non-inductive is used, or as a current sensor, you can also use inline current sensing chips like ACS712 which can sense up to 30 amps, or there are many such chips that can sense current and give you voltages. These voltage signals can be fed and create a Closed loop within the system. So, this is to set the current. This is the feedback, . So, you can create a feedback control loop within the microcontroller somewhere. There may be a microcontroller that controls the DAC and takes in the data of the current. High current power MOSFETs, so not just transistors, they are MOSFETs that can do fast switching. Like IRF3205, apart from carrying high current.



So, overall, if I configure everything all together, this is the microcontroller that takes in the signal. So, where is everything here? Just try to locate it here. So, one, two, three, four, these four are H-bridge gates. Okay, switches. So, these are the switches, and you see the motor is tapped from these two locations, from here and here. The motor is connected. This is your DC motor. And from here, after the H-bridge, you see it is passed like this to the sensing resistance of 0.5 ohms, and finally, it is ground, that is here. The sense signal, that is the current signal, is picked up and amplified using the operational amplifier OPA2335. And it is filtered because the current signal carries a huge amount of noise quite a lot of the time. So, before feeding it to the microcontroller as feedback of current, you filter it here, and a smooth current value is fed to the microcontroller as the feedback.

So, let us finish the closed loop for the current first. So, when it receives the current signal. The microcontroller receives the current signal, and it can control the current using these eight wires. This is going to the 8-bit DAC. So, based on the signal that is sent here as a bunch of 8-bit signals, that is two to the power eight, 256 different levels of current, I can set it to the DAC. This is setting the reference voltage to the comparator which is here. So, I am setting the comparator levels using this. What is this? These two wires are internal DAC wires which are there in the driver DRV8814. It is a Texas Instruments driver. So, it can control only in four levels: 00, 01, 10, 11, and two wires.

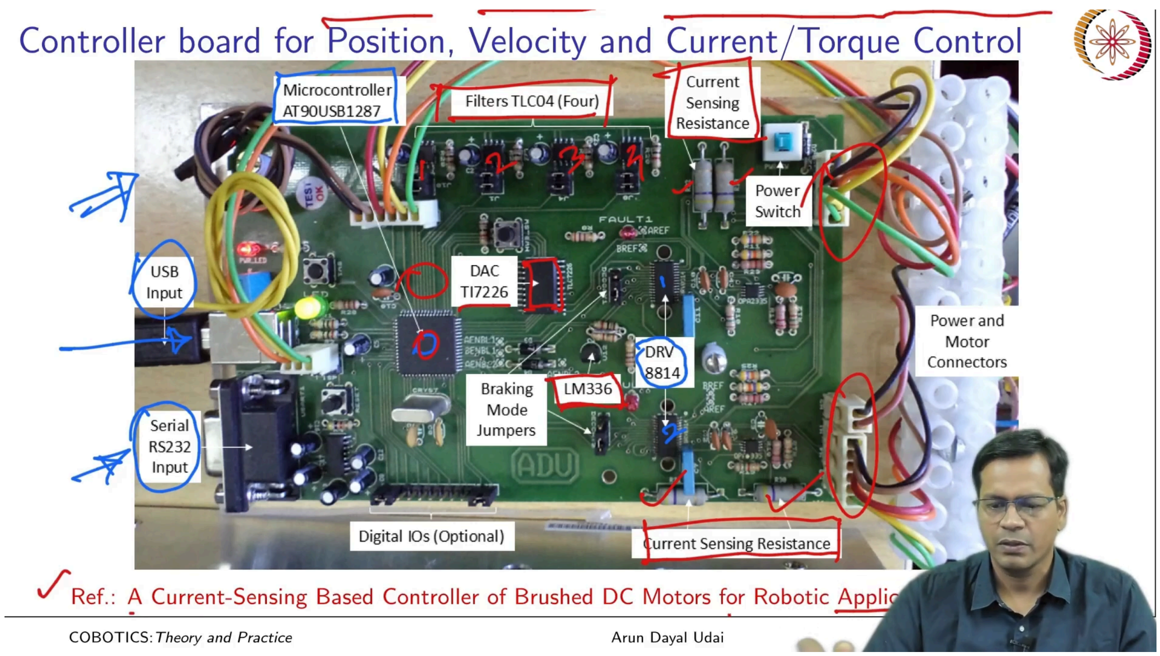
So, instead of using these two wires, you can have an external DAC like TLC7226, which is an 8-bit DAC signal, and control the reference voltage. So, here comes your reference voltage. Here goes your sensed signal after the internal gain of 5 and they compare and do the thresholding, that is cutting in and cutting off. So, overall, this is controlling the current that is going to the DC motor.

Now, you have additional wires here, you see, you have to enable wire, PWM input, and phase wire that is to make the motor go clockwise and counterclockwise. Now, it can switch on and off the H-bridge switches 1, 2, 3, and 4 like that. So, based on that, it can do phase changes clockwise and counterclockwise. It can also apply a brake, that is Switching on two transistors together and making the current go in a closed loop and short-circuiting the motor, that also can be done, that is regenerative braking. So, it can do all kinds of things.

So, enabling, you can control the speed from here. Speed can be controlled using the PWM input. Making a closed loop with the current, you can do a controller, you can build a controller for the current. You can change the direction. Direction can be controlled using this. So, speed, direction, and current. Current means torque. So, everything can be done. Now, what about the position?

You have an angle sensor over here, which is a potentiometer angle sensor. This value, which corresponds to the angle, joint angle value, and some voltage signal is fed back to the microcontroller. The microcontroller takes in the feedback, creates a closed loop, switches ON, controls the velocity, and gradually stops wherever it is required, depending on the input to the position controller. So, all the controllers can be built within this microcontroller. So, this is how it is done. So, you see, this is the signal for the position. This is the signal for the current. So, everything can be done.

So, now, what is this PC interface doing here? This is holding all the robot kinematics, doing forward kinematics, inverse kinematics, commanding the motor joint angles, and commanding the different joint angles and torques, which are required at each joint. So, those calculations are done over here on the PC using USB or RS232, which is shown here. It may be some other interface also. So, it is transmitted to the microcontroller. The microcontroller has three closed loops, as it was shown in the servo control diagram. So, all the closed loops are done here on the microcontroller which is for position, speed, and the torque closed loop. So everything is done here.



So, when this is all implemented on the chip, it looks like this. This is a board that has all the implementations. So the microcontroller that was shown here is sitting here. That is microcontroller AT90USB1287. This is a pure USB chip. So it is communicating all the data from the PC using USB communication. There is the option for RS232, which is serial here, but that is not used, and then you have DRV8814. You have two of them, one and two, which are here. So these two chips are motor drivers. Each one of them can drive two motors, so a total of four motors can be controlled here. So you see, you have Butterworth filters, which are to filter out the noise in the current sense signals. So one, two, three, and four Butterworth filters are there before feeding it back to the microcontroller. So it is filtered.

Where are the pickups? These are current sensing resistors. These are current sensing resistors for all four: one, two, three, and four. So, current sensing resistors are here. That is taking up the current value and feeding it to the microcontroller after doing the filtration over here. Then you have LM336. What is this? This is a reference signal generator for the TLC7226 DAC. This is the digital-to-analog converter. This needs a constant voltage source that is generated using the LM336 chip. This is a constant voltage source that is used as a reference for the DAC. The DAC takes the data from the microcontroller and generates the reference voltages for the current comparators. So, everything is implemented out here, and all the motors are connected from here. Four motors. So, the whole of this circuit can be found here. I have done the current sensing-based controller for brush DC motors for robotic applications. So, this is a publication that I have noted here. It is an ISRM 2013. So, that you can just find it out and use such a thing.

So, now we are ready with the position, velocity, and torque control of a DC motor. Torque control can be done using chopper drives, not just for DC motors; it applies well to other kinds of DC motors also. So, it is a general approach that can be applied to many other motors.

So, that is all for this lecture. In the next lecture, we will discuss Brushless DC motors and Permanent Magnet Synchronous Motors AC servo motors. We will see. That is all.

Thanks a lot.