NPTEL Online Certification Courses
COLLABORATIVE ROBOTS (COBOTS): THEORY AND PRACTICE
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Week: 02
Lecture: 07

BLDC Motors and PMSM AC Servos

Welcome back to the course Cobotics Theory and Practice, Module 2, which is Actuators, Sensors, and Safe Workspaces. In this lecture, we will discuss BLDC motors and Permanent Magnet Synchronous Motors. These are commonly known as AC servo motors.


Overview of this lecture

- Introduction: Construction of a BLDC Motor
- Working of BLDC Motors/Actuators
- BLDC Motor Driver Schematic
- Introduction to AC Motors: Advantages and Disadvantages
- Working Principle of a Synchronous AC Servo Motors
- Synchronous Motor Drive System: Variable Frequency Drive (VFD)
- Position and Speed Control Scheme for PMSM/BLDC Motors
- Torque Control Scheme for PMSM/BLDC Motors

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So, the overview of this lecture is as follows. We will start with an introduction, that is, the construction of a BLDC motor, and the working of a BLDC motor or actuator. We will discuss the BLDC motor driver schematic and how it works. We will have a brief introduction to AC motors, including their advantages and disadvantages. We will see the working principle of a synchronous AC servo motor, synchronous motor drive systems, that is, variable frequency drives, which we will discuss. We will discuss position and

speed control schemes for PMSM or BLDC motors, and torque control schemes for PMSM and BLDC motors.
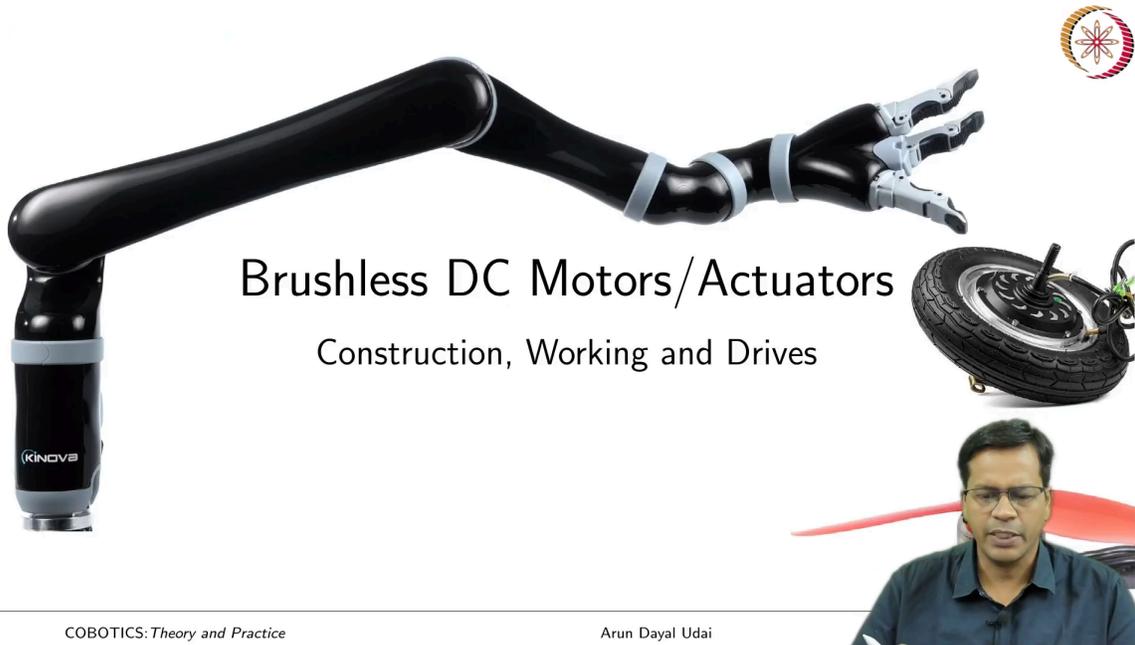
So, let us continue with BLDC motors and actuators. We will discuss construction, working, and drives.

Brushless Permanent Magnet DC Motor (BLDC): Advantages

Conductors/Armature is fixed and the magnetic field on the rotor moves. May include Hall-Effect sensors for position feedback and synchronous motion.

- ► Better heat dissipation from the stator.
- ► Reduced rotor inertia, Good torque/weight ratio.
- ► More durable and have longer life.
- ► Lower mechanical loading.
- ► Improved safety.
- ► No brushes, Quieter operation.
- ► Smaller dimensions of comparable power
- ► Inexpensive with low maintenance cost
- ► Center hollow design possible.

Applications: Robots in flammable atmospheres, Aerial Robots, EVs, COBOTS,
Disadvantages: Expensive control systems due to sensing and switching circui

So, as for BLDC motors, there is a significant difference in the way they are constructed compared to the DC motor that we discussed in the last lecture. So, the conductors and

the armature are fixed. Here you see these are the conductors. These are the copper coils that you can see here that are fixed and stationary, and they are mounted permanently to the station, and you have a rotor here. This is the rotor, that is the armature. That contains the magnets. So, these are the magnets. Magnets are glued all around.

So, the armature is fixed, and the magnetic field on the rotor moves. The centre spindle that you see actually goes inside here. So, it is fitted on top of that. It may include Hall effect sensors to give position feedback and synchronous motion. So, in these motors, because the stator contains all the copper windings, all the heat is generated at the stator and is dissipated out easily. So, there is better heat dissipation from the stator, and you do not need to make and break a kind of commutator arrangement which is there in the armature of a DC motor that you saw. Over here no make-and-break circuit, no commutator is there. Current is directly put to the windings which are creating the magnetic field.

The rotor now has a reduced moment of inertia. Now, the rotor does not carry the coils, so it is very, very light. So, that is the reason it has a very good torque-to-weight ratio. The torque which it can generate for a comparable size of a DC motor is because it does not have any commutator. So, they are very, very light for the same torque. So, the rotor is light as well because, you see, the rotor has only the magnets, not the commutator, so that is very light. So, it picks up speed very fast. It is more durable and has a longer life because there is no make-and-break circuit. So, there is no arcing, and there are no carbon brushes that get worn out. So, low maintenance is required. So, it has lower mechanical loading because of the low mass of the rotor. It has improved safety because there is no make-and-break circuit. So, there are no electrical sparks. So, they are very, very safe for the environment, inflammable environments like a robot doing some painting operation and those kinds of environments. There are no brushes. So, it is very, very quiet also. There is no noise. Smaller dimensions as compared to comparable power. They are inexpensive and have low maintenance costs because you do not have carbon brushes that are required to be replaced every few running hours.

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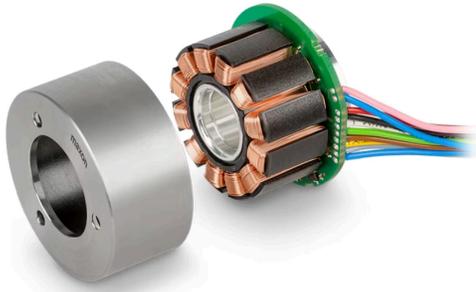
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- ▶ Center hollow design possible.

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A centre hollow design is possible. This is very much required for cobots. Cobots need all the wires to be passed from within the robot, which requires a centre hollow shape, and that is very easily possible with these kinds of motors. So, applications are many: robots in inflammable atmospheres, aerial robots, which need a very high speed to be generated quite quickly, electric vehicles, and cobots. So, these are some of the applications. The disadvantage is only one: they are expensive. Because of its control system, the kind of winding which is there, and the kind of sensing which it has, it has Hall effect sensors at three places, and the switching circuitry is a little bit complex because of the three-phase winding which is there. We will discuss this in detail. So, these arrangements would cause a little higher cost for these motors.

Coil Activation based on Rotor Position in Sector

Position (°)	Sector	AA'	BB'	CC'
(-30, 30]	1	00	10	01
(30, 90]	2	01	10	00
(90, 150]	3	01	00	10
(150, 210]	4	00	01	10
(210, 270]	5	10	01	00
(270, 330]	6	10	00	

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So, let us see how this motor works. Based on the rotor position in the sector, how the Hall effect sensor can give me the position? So, where are the Hall effect sensors located? The whole of the motor, let us say, is divided into 6 sectors. So, every alternate sector has a Hall effect sensor. So, if it is sector 1 here, sector 2, sector 3, sector 4, sector 5, and sector 6. So, there is a Hall effect sensor here which is called A, a Hall effect sensor which is here, Hall effect sensor B, and Hall effect sensor C that lies here.

So, let us see how it can communicate the position of the rotor. Let us say, if at all there is this, this (Setor 6) is your rotor which has a magnet. So, this magnet will energize the Hall effect sensor. How? So, if at all, it is located here 100 percent, let us say your armature is here, this will cause Hall effect sensor A to be completely energized. These three bits will show the state of Hall effect sensors A, B, and C, 1 for active, and 0 for inactive. So, when the rotor is at this location, what happens? Sector A Hall effect sensor is fully energized, whereas B and C are taken as 0. Hall effect is a gradual sensor; it gives you an analog signal that needs a thresholding device to actually convert it to a digital signal. So, based on the signals, this will now give a high signal of 1. So, effectively this gives you 1 0 0. If I convert it from binary to decimal, it is equivalent to 4. So, whenever it is at this location in sector 1, it will give me 4. 3 bits converted to decimal.

What happens when it is here (6(1,1,0) - sector 2)? This energizes Hall effect sensors A and B both. And C, which is quite opposite to it, this remains at 0. So, this will give me 1, 1, 0, and when this is converted to decimal, it is equivalent to 6. Now, when it is at this location (Hall b), So, sector A, this is 0; Hall effect sensor B will give you 1; Hall effect sensor C again gives 0. So, it is 0, 1, 0. So, this, when converted from binary to decimal, is 2.

So, likewise, for each and every position in any of these sectors, it will give a unique value of Hall effect sensors. So, like for example, if it is here, you see because it is 100 percent opposite to Hall effect sensor A, A goes to 0, B and C get energized, and this gives you 0,1,1. Likewise, wherever your armature is lying, this rotor, which has a magnet, lies; accordingly, it can tell you the approximate pose of your Rotor. If it is in any of these sectors, you can get to know. So, depending on that, you energize the next coil. This is a closed-loop kind of operation.

So, what happens? When it is at minus 32 plus 30 degrees, that is in sector 1, sector 1, what do you do? You switch off the coil phase A. A and A bar are made to go to 0. What about B and B bar? You switch on B, and you also switch on the C bar. So, when it is at this location, you switch on this and this so that you get an effective pull along this direction. Got it? So, now, let us say if it is at sector 5, 210 to 270 degrees over here. So, you should energize B bar and A, B bar and A. That means A is energized, A bar is 0, and B bar is 0, 1. That means B is 0, and B bar is 1. So, it effectively gives me A and B bar as high, and because it is in this sector already, that is made to 0. So, what you do actually, wherever your rotor is located in any of the sectors, you energize the next two sector coils so that it gets a pull and finally moves in that particular direction. So, in this case, it will move like this (anticlockwise).

So, in order to rotate it in the opposite direction The reverse thing has to be done. If it is here, you switch on 6 and 5. If it is at 6, switch on 5 and 4, likewise. So, the coil can be energized based on whether you want to take it in a clockwise or counterclockwise direction, accordingly, it is done.

BLDC Six Step Switching based on Rotor Position

3 Phase Trapezoidal Sequence

Refer: https://in.mathworks.com/help/mcb/ref/sixstepcommutation.html

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Sector	6	1	2	3	4	5	6	1	2
Hall states	1	5	4	6	2	3	1	4

So, now how is that effectively implemented here? So, making A or A bar high means that there are three-phase coils that are connected like a star, which is shown here, So, when A is on, A bar is off, so this becomes a positive wire. Similarly, when B is on, and B bar is off, what will happen? This will become positive.

If the B bar is on, what will happen? If the B bar is on, if this is on, This will become negative. So, any single wire can be made positive or negative depending on A, A bar, B or B bar, C or C bar, whichever is connected. So, these 6 switches can control the polarity of the 3 wires which are here. So, the effective state, if you can see, is a 3-phase trapezoidal sequence. So, all these 3 phases of the BLDC motor will have a voltage that very much looks like a sinusoidal signal. So, this can be equivalent to a sinusoidal signal. It is near to sinusoidal. It is a Trapezoidal signal with a phase difference of 120 degrees. So, if this has a phase of 5, this has a phase of 5 plus 120, and this has a phase of 5 minus 120 or plus 240. Got it? So, this is how these three phases will create a rotating magnetic field in the coil and that ultimately leads to the rotor following the rotating magnetic field, and ultimately, it rotates. Got it? This switching of the coil is done based on the Hall effect feedback because if your rotor is stuck somewhere due to the load, you should not rotate the pole, or else it will miss the cycle and slipping will happen. So, if it is stuck, the coil is no longer rotating the magnetic field. If the rotor is stuck, your rotating

magnetic field is stopped as long as it does not cross through that. It comes to the next sector, and the next two are energized. If it comes to the next sector, another two will be energized, likewise. So, that is the closed-loop kind of operation based on the Hall effect sensor. So, depending on the Hall states, you switch on the sectors.

So, this gives rise to a rotating magnetic field. So, this is how your rotor rotates. And the coil is stationary. The coil remains stationary. This is not rotating. This is fixed to the body of the motor.

BLDC Motor Driver Schematic (HIP4086 3-Phase MOSFET Driver)

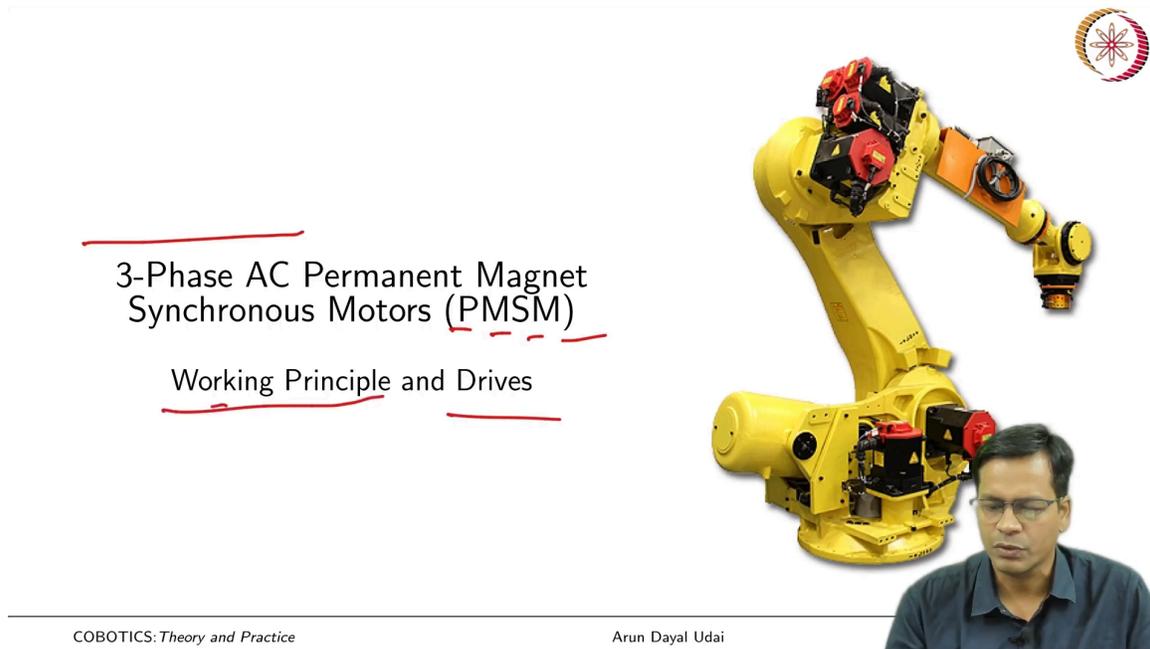COBOTICS: *Theory and Practice*   Arun Dayal Udai
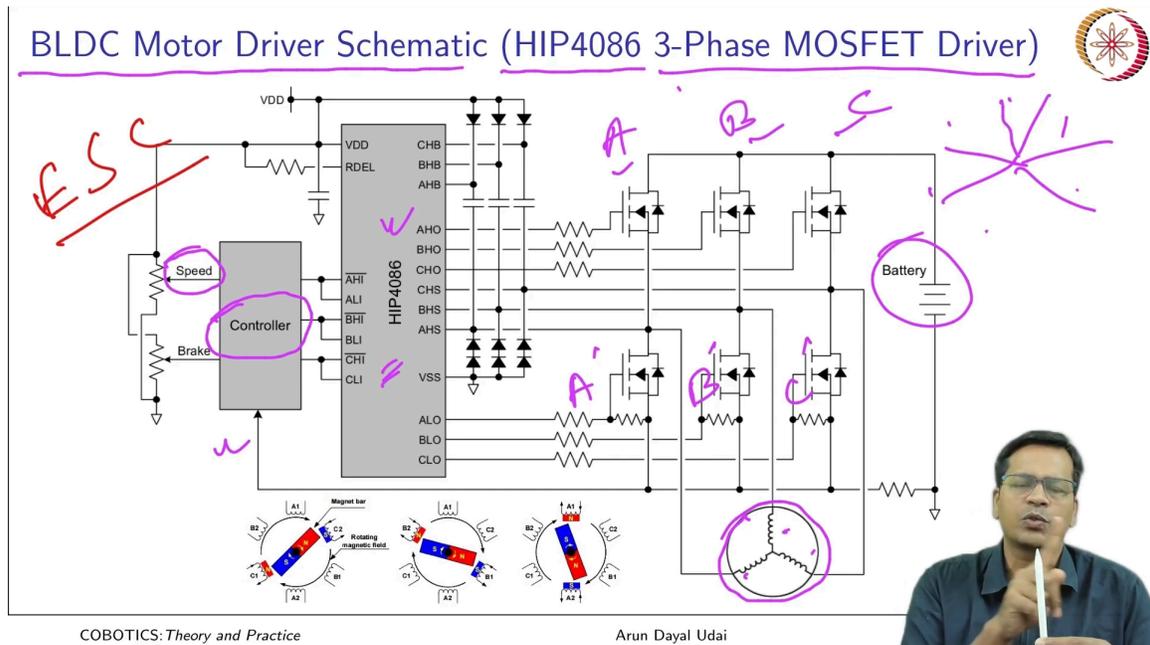
Now, How that is implemented on a circuit, you see here, I have shown the HIP4086 chip, which is a three-phase MOSFET driver. So, this is nothing but a MOSFET driver. These are the MOSFETs that are placed outside the chip. This creates the switches: one, two, three. 1 bar, 2 bar, and 3 bar, or A, B, C, and A bar, B bar, and C bar. So, these are the three wires, and this is your motor, which contains the coil. These are the coils that are star-connected, as shown here, and finally, it is controlled by a controller, which is here, that takes in the signals from all the Hall effects. The Hall effect signals are sent to this, the controller converts which one is to be energized: A, B, or C, or A bar, B bar, or C bar. Accordingly, it sends the signal. This is the external battery that is used to supply the controller as well as this chip. So, this is how it is completely made. The whole scheme goes like this. So, you can control the speed depending on the Hall effect feedback or

whatever speed you desire, you can precisely control it. So, using that, you can control the speed. If you have a joint angle sensor, apart from the encoders and Hall effect sensors which are there, it can give you a rough estimate of your state: 1, 2, 3, 4, 5, 6.

So, whatever state it is. That is the gross position of your rotor. You can also have precise angular feedback using some kind of sensor, and you can make the control very, very precise, so this is how a typical BLDC motor driver works and this is implemented over here in this circuit. This is Intersil. This is the company which makes such. There are many similar companies that implement the HRP4086 driver, a three-phase MOSFET driver. So, you see this is the programming port that is used to program the microcontroller which is here. So, this is the microcontroller and peripherals which are here. There is also a current sense circuit which is here, which can control the current. These are the power MOSFETs: three-phase, 1, 2, 3, 4, 5, 6. So, 6 MOSFETs are here, that is creating the three-phase bridge. This is the HIP4086 MOSFET driver that is there. This is a buck regulator that communicates all the required voltages to the driver chips and the microcontroller. This is for the Hall effect supply, which is a 5-volt supply that goes to the Hall effect sensor. Then you have phase A, this is for phase B, and this is for phase C. Three different phases are connected here. This is for the external power source, which is the real power source, not for the control that is to drive the coils. So, the whole implementation that I showed here is made here. And ultimately, you get your BLDC motor driver. This is a closed-loop operation because it also uses the Hall effect sensor as a position feedback. It can just run the way it is used in quadrotors, and there is no feedback kind of BLDC motor drive. So, these are known as ESCs, electronic speed controllers. They have just three wires to trigger the three phases. That is all. It does not have Feedback from the Hall effect sensor, so those actuators don't have feedback. They run on an open loop because the load is not variable. In the case of quadrotors, the load is not variable. You precisely know how much load is going to come, and accordingly, you select the motor with precise torque, slightly higher torque actually, so that it never fails or slips. Whatever the angular velocity you command, it goes there. You don't need feedback. Because your rotor does not get stuck anywhere. It is not overloaded at any time. But in the case of cobots, you also need a Hall effect sensor. Where is your rotor? You need precise feedback before you switch on the next two coils. Accordingly, it is

made to run. It also has a precise angular feedback sensor, which will give you precise angular control as well.

Now, let us come to PMSM, that is, the permanent magnet synchronous motor. It is a three-phase AC motor. Let us see the working principle and the drives that go into these kinds of motors. Whatever motor is there in a standard industrial motor, they are normally PMSM kind.

AC Motors and its Advantages

Operation: AC supply is directly connected to the electromagnets that creates an alternating poles. The magnetic field generated due to set of stator coils appear to rotate.

Design Advantages:
- ▶ Inexpensive due to less number of parts.
- ▶ Convenient power supply.
- ▶ No commutator/brushes, and its associated problems of arcing and wear.
- ▶ Low power dissipation
- ▶ Low rotor inertia making it responsive
- ▶ High reliability, robustness, easy maintenance, and long life.
- ▶ Availability of a wide range of Variable Frequency Drives

NOTE: Due to its simplicity, ease of use and low cost,
it is widely used in all modern industrial robots of different capacities.

Now, the operation goes as the AC supply is directly connected to the electromagnets, which creates alternating poles. The magnetic field is generated due to the set of stator coils. Again, over here, the stator coils are outside, and your rotor, which has permanent magnets, lies inside. So, this is not like your BLDC motor. The BLDC motor has a stator that has coils that are stationary. Over here, you have coils that are again stationary, but the coils are outside, and you have a permanent magnet rotor that is inside.

So, the main design is inexpensive due to a fewer number of parts, just like a BLDC motor. It has a convenient power supply because, as you know, AC supply is readily available anywhere. You just need a transformer to step it down. At least 50 hertz is easily available. There is no commutator and brushes like in DC motors, and associated problems of arcing and wear, which require quite frequent maintenance. It takes up less power because power is not dissipated at the commutator. Rotor inertia, low rotor inertia, makes it responsive. This time, the rotor does not have the coil, just like a DC motor. This does not have a coil on the rotor. So, what happens? The rotor has a magnet. The only difference that I see is the rotor has a magnet that was outside in the case of a BLDC motor over here. The rotor is inside, and that also has a magnet. In both cases, you have an equivalent three-phase supply, which creates a rotating magnetic field. So, PMSM is very much similar to a BLDC motor. The only thing is you have a rotor which is placed inside here. In the case of a BLDC, it was outside.

So, the rotor has low inertia, and that makes it responsive, just like a BLDC motor. They are very reliable, robust, and easy to maintain, and they have a long life. The availability of a wide range of variable frequency drives is there. What you need here is a variable frequency drive, which is what we will discuss now. Due to its simplicity, ease of use, and low cost, it is widely used in all modern industrial robots.

Working Principle of a Synchronous AC Servo Motors
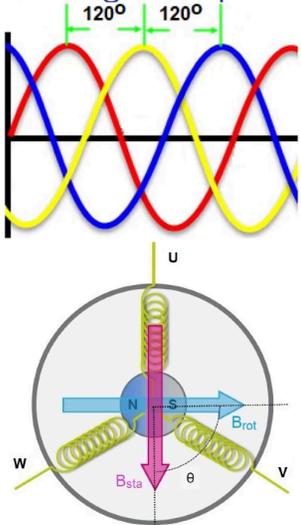
▶ The 3-phase stator winding carrying 3-phase currents produces 3-phase rotating magnetic flux (and therefore a rotating magnetic field).

▶ The rotor is provided with a DC supply/PM, locks in with the rotating magnetic field and rotate synchronous along with it.

▶ Once the motor is in operation, the speed of the motor is dependent only on the supply frequency.

Disadvantages:

▶ Can overheat on long operation.

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So now, how it works, let us see. Three-phase is directly supplied to the coils, which are stator coils, if three-phase is supplied to this if this has a phase of psi, this has phase psi plus 120, and this has phase psi plus 240, so what happens? It creates a three-phase supply like this, and this will gradually rotate the magnetic field like this.

So, if this coil is energized, this coil is fully energized after 120 degrees. That means this magnetic field rotates at the frequency of the electricity, the three-phase electricity that is supplied. So, the supply voltages may be written as V is equal to V0 sin omega t plus phi. Phi is the phase.

$$V = V_0 \, sin(\omega t + \phi)$$

The phase angle is 0 degrees, 120 degrees, and 240 degrees for each one of them. Those are fixed and omega is the frequency of rotation of the magnetic field. V is the peak voltage that each of the coils would see. So, this three-phase stator winding carries a

three-phase current that produces a three-phase rotating magnetic flux and, therefore, the rotating magnetic field.

The rotor is provided with a DC supply or it has a permanent magnet that locks in with the rotating magnetic field and they rotate with the synchronous speed of the rotating magnetic field. Got it? So, whatever the speed of the rotating magnetic field, that becomes the speed of the locked-in armature, which has a permanent magnet. So, permanent magnets get locked to the rotating magnetic field and it rotates at the same speed. Once the rotor is in operation, the speed of the motor is dependent only on the supply frequency. So, whatever is the frequency that is there for the rotating magnetic field, that becomes the speed of the rotor.

So, yes, there are many disadvantages also. It can overheat on long operations. If you rotate it a little slower, it may not pull up that much air inside or there may be a little bit of overheating which can accumulate and make the motor a little hot. In the case of industrial robots, you have very good heat dissipation. But in the case of cobots, the whole of the rotor is cased inside. So, heat may not dissipate so well. So, normally BLDC motors are preferred in those cases. It can overheat in long operations. So, they are normally used in industrial robots where you see a sign that it may get overheated. So, a heat symbol is there.

Synchronous Motor Drive System: Variable Frequency Drive (VFD)
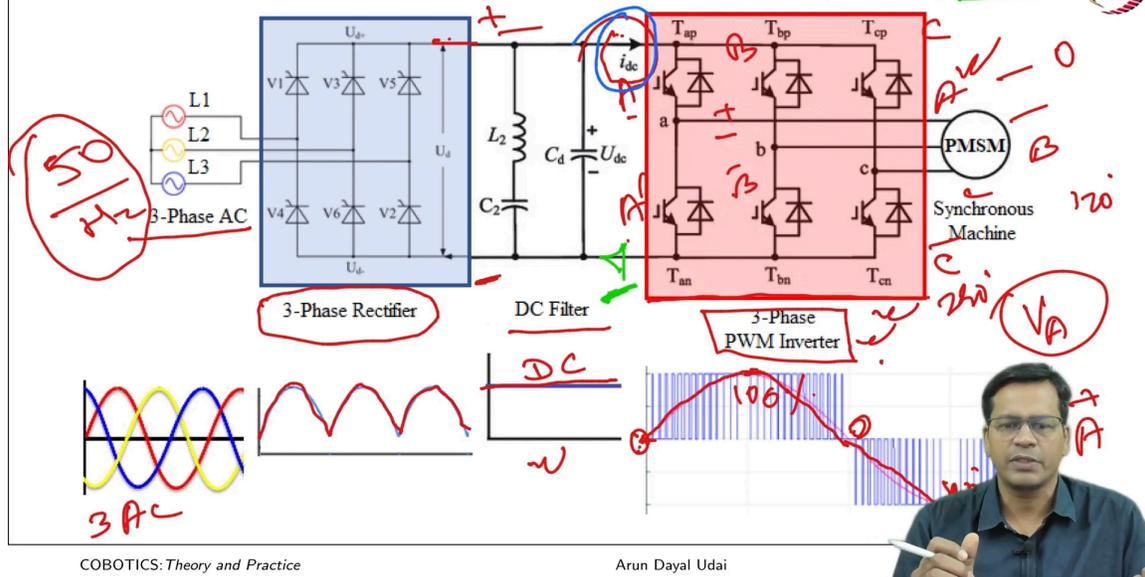
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So, now let us look at the whole driving system. How to change the frequency? Because you see, whatever is the three-phase AC frequency that becomes the speed of the synchronous machine, which is the PMSM motor here? So, you have to input the three-phase AC supply, which is 50 hertz in India. Three-phase AC is inputted. You have a three-phase Rectifier, which is nothing but a bridge rectifier, and finally, you get a positive over here and a negative over here. So, you have from the three-phase AC signal, you have converted it to a DC signal, a DC signal with a ripple. These are the ripples. That is bound to happen because you see, you have just mirrored the low side to the higher side. So, you see only the higher side of it. So, all those are here. You see continuous positive here and negative here. Then it is filtered, and a pure DC kind of power is generated here. So, till here, it is nothing but a rectifier. Now, what is done? You have a three-phase PWM inverter. So, this is nothing but an inverter. What is its role, basically? It has again three-phase bridges, the way you saw it in the case of three-phase switches. So, you have A, A bar, B, B bar, C, and C bar switches. So, if you switch on A, This wire will go positive if you switch on A bar; the same wire will become negative. So, accordingly, each one of these wires can be made positive or negative for the A, B, or C phases of the PMSM machine.

Now, instead of making it continuously high or continuously low, you create an equivalent voltage signal. That means what is done here is, to regulate the level of

voltage on the positive side of A, what do you do? You create a PWM with a 0 to 100 percent duty cycle from here to here so that you see an equivalent voltage rise that is there in the A wire. Let us say it is A only. So, each of them will carry a PWM that creates an equivalent voltage ranging from 0 to 100 percent duty cycle, 100 percent to 0 again duty cycle, and again A bar is switched on, and you do the same thing: 0 to 100 percent duty cycle and 100 percent to 0 percent. That means in both the positive half and the negative half, you make a 0 to 100 percent sinusoidal wave. So, effectively, this creates a field of a complete sinusoidal wave. So, this is how equivalent voltage is generated in phase A, which is equivalent to the signal that you want. So, each signal should be at a phase of A; if it is 0 0-degree phase, this one should be at a phase of 120 degrees, and C should be at 240 degrees. So, three different sinusoidal waves are created using a three-phase PWM inverter, which effectively goes to the PMSM motor.

So, what happens? This is the three-phase signal for which the frequency you can control based on the inverter frequency. So, now a constant frequency is converted to a variable frequency, which is the reason it is known as a variable frequency drive.

So, you saw how a rotor gets locked to the rotating magnetic field and how a variable frequency can be used to create a magnetic field with different rotation frequencies. So, this is how the motor speed can be controlled. Now, if you can control the current that effectively goes here—let me use a different color—so this is it. If you can control the current which is actually flowing through this wire, then you can control the torque as well. So, there is a DC chopper drive again. A chopper drive, which is here, can control the torque of this PMSM machine. So, you can have a similar type of chopper drive which can control the torque. Speed can be controlled by controlling the frequency of the variable frequency drive, and direction can be reversed by reversing the direction of omega, which is the cyclic frequency of the three-phase motor. The direction can be reversed. So, this is the way you can control the speed, as well as torque and direction. If you have position feedback, then you can have an external controller which can create a closed loop and can control the precise position of these kinds of motors. So, this is how the position, velocity, and torque of such motors can be controlled.

Synchronous AC Motors: Special Features, Types, and Applications

Especially useful in applications requiring precise speed and/or position control.

▶ Speed is independent of the load over the operating range of the motor.

▶ Speed and position may be accurately controlled using open loop controls.

▶ It can hold its position with static magnetic field.

▶ Increased efficiency in low-speed applications (e.g., ball mills).

Application: Low-power precise robot actuators, turn-tables, linear-rails, CNC, etc.

Types of VFD: Voltage or Current Source Inverter is common to robotics.

Controller Types: PWM Scalar Control, Field Oriented Control (or Vector Control), Direct Torque Control.

So, now synchronous AC machines have some Special Features, Various Types, and Applications. Especially useful in applications that require precise speed or position control, such as robots. So, speed is independent of the load, you see. Whatever the load, your rotor will rotate at the locked-in frequency along with the frequency of the rotating magnetic field over the entire operating range of the motor. So, speed is independent of the load.

Speed and position may be accurately controlled using open-loop control. So, you see whatever the the frequency of the rotating magnetic field becomes the speed of the rotor also. So, speed can be precisely controlled even in an open loop. You do not need to have a closed loop. There is no slip, you see. Why? Because the load is predetermined and it is well calculated before selecting this motor.

It can hold its position with a static magnetic field. Let us say each of the poles has got fixed magnets, and electromagnets with the current that is coming to it. So, it will create a resultant magnetic field that is in a particular direction, and the rotor will align itself to that particular direction. So, it can hold its position also. So, omega can also become equal to 0, the frequency of rotation of the magnetic field. If that is static, that goes to 0, and the rotor gets locked.

Increased efficiency in low-speed applications also, like in the case of ball mills, but yes, at low frequency, the motor has a tendency to get heated up.

So, applications are many. It is mostly low-power precise robot actuators, turntables, linear rails, and CNC machines. They require such kind of precise speed and position control. Types of variable frequency drives, it can be voltage-controlled or it can be a current source inverter. These are very common in robotics, depending on whether you want to control just the speed or also the current, which is to control the torque of the motor.

So, the controller types are PWM scalar control and field-oriented control, which is the vector control. This is the most common one in robotics and direct torque control.

Position and Speed Control Scheme for PMSM/BLDC Motors
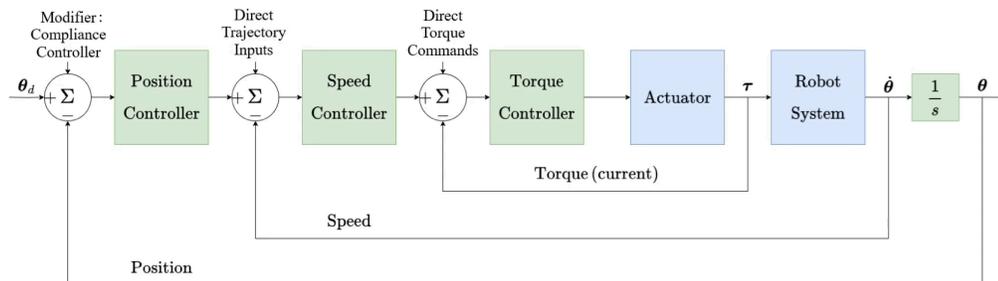
Synchronous speed: $N_s = 120\dfrac{f}{p}\ rpm$
where, $p =$Number of poles and $f =$Frequency of AC supply
Slip rate in Synchronous Motor $S = \dfrac{N_s - N_r}{N_s}$, where $N_r =$Rotor Speed.

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So, yes, the whole control loop looks like this when you have to control torque, speed, as well as position. So, the control loop looks like this: this is your robot system, which has nothing but motors within. That actually runs the links and finally gives you the joint rates and the position. So, both of them can be obtained from the same kind of sensor. A position can be differentiated to get the velocity, the angular velocity. So, it gives you the velocity feedback and the position feedback. That is compared against the desired position. The desired position and the actual position are compared, and the error is calculated. So, you have a position controller which goes in here, normally a PID

controller, that generates the reference speed, which is theta desired dot, that is theta desired dot, which is the rate of change of the joint angle that is required here, and this is the actual rate of the motors which you are controlling. So, the desired velocity and the actual velocity take the difference, which will create a reference error here. This error is put into the speed controller here. This again is a kind of PID controller. This generates the commanded torque which is the desired torque that has to come here. Now again, you may have a current sensor that gives you the calculated torque over here, which is the actual torque based on the current sense. This can be compared with the desired torque. So, the actual torque here and the desired torque here can be compared and that goes to the torque controller here and finally, the current goes to the actuator, which controls the robot. So, this is a closed-loop scheme, which can control the position of the robot joints.

So, actually, at each stage, there is an additional input. You see, this is a desired trajectory input from here. You can directly feed in even if it has achieved the desired position. You want to go at a certain velocity, so direct velocity input can be fed here at this location. Direct torque commands can be given here. So, even with the balanced torque of the desired and the actual you want to run the motor directly with the torques. So, you can directly feed in the torque here, and torque is inputted directly to the torque controller, and it goes to the actuator. So, you can make the motor run in position mode or in torque mode, depending on where you are feeding in the inputs.
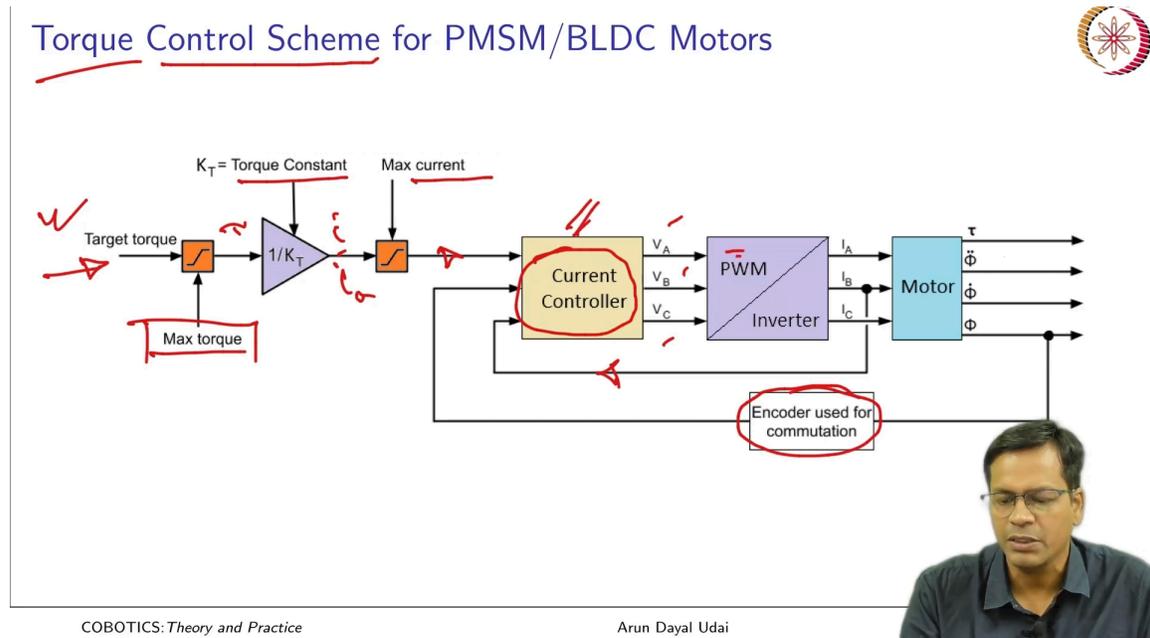
So, the synchronous speed is 120 f by p.

$$N_s = 120\frac{f}{p}\, rms$$

You see, these motors do not just have three poles; they have multiple poles. So, if f is the frequency of the AC supply, which is the inverter supply, and p is the number of poles, then the synchronous speed in that case would become 120 f by p revolutions per minute, where p is the number of poles.

So, the slip rate, if at all slip is occurring, in that case, the slip rate is there, which is synchronous speed minus rotary speed divided by synchronous speed. So, this is the slip

rate, which normally should be equal to 0 in the case of completely synchronous machines like robots. So, you do not expect a slip to happen.

$$S \;=\; \frac{N_s - N_r}{N_s}$$

Torque Control Scheme for PMSM/BLDC Motors

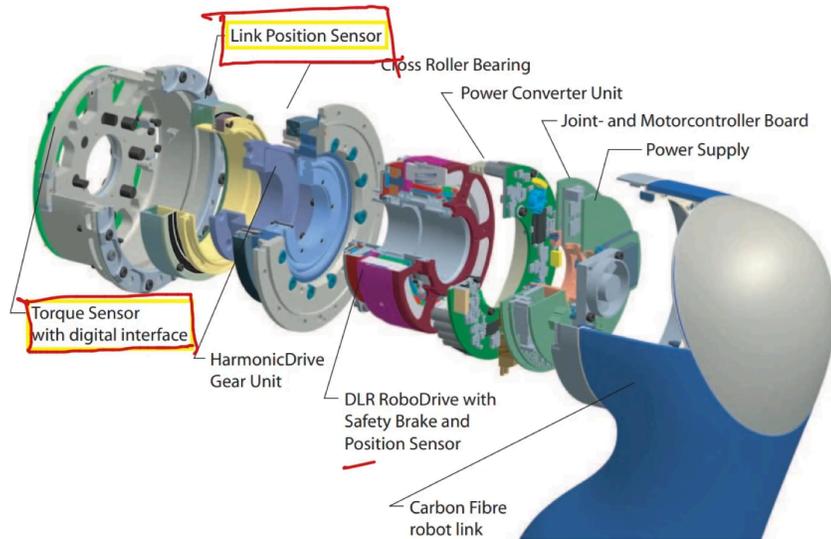COBOTICS: *Theory and Practice*   Arun Dayal Udai

If at all you have to run in a control scheme that can control torque, In that case, you can simply trim off everything that is here, and this is an equivalent circuit for that. In this case, you can directly feed in torque here, torque should be clamped based on the maximum torque that is achievable by the motor. Use the torque constant to convert it to an equivalent current signal, that is Km, if you remember. Km into i_a is equal to torque. So, you do the other side of it. If you want the torque, you divide by the torque constant Km. What you get is i_a. So, this is the desired current to achieve this torque. This current again is clamped based on the maximum current that this controller can take, that goes here. So, again you have feedback for the position encoder used over here to take in the position feedback as well as the current feedback, to control the current. So, this is the combined controller for the internal current loop that can control the current precisely. Finally, this voltage goes to the PWM inverter, which is a three-phase inverter that can control the rotating magnetic field speed that generates the three-phase currents to the motor, and the motor runs. It creates the torque that goes to the joint. So, this is the

control scheme for torque control of a Permanent magnet synchronous motor or a BLDC motor. Both use a kind of inverter-based circuit to run.
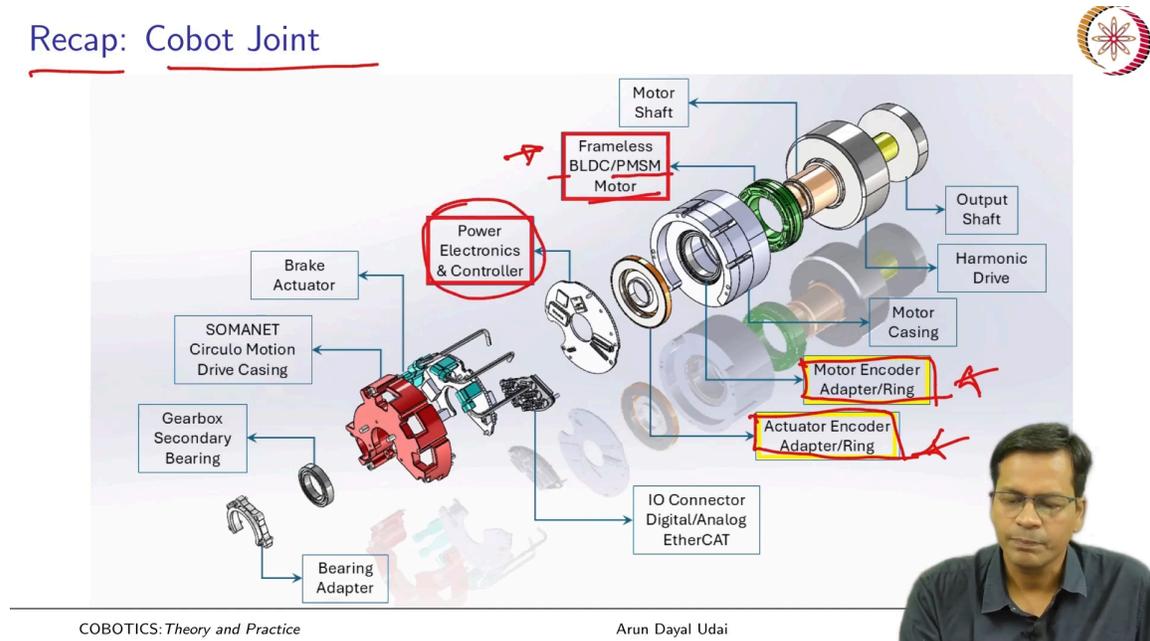
So, overall, let us just recap for the cobot joint, and the actuator encoder ring which is here, these two we will be discussing in the next lecture, that is the sensors, frameless that are the BLDC motor or permanent magnet synchronous motor with the kind of electronics which goes in. So, a few things are covered, and a few are remaining that we will be doing next. Accordingly, we will, in the end, fulfil everything that is Harmonic Drive, sensors and actuators, and some mechanical design also we will discuss and we will complete this.

Link Position Sensor
Cross Roller Bearing
Power Converter Unit
Joint- and Motorcontroller Board
Power Supply
Torque Sensor with digital interface
HarmonicDrive Gear Unit
DLR RoboDrive with Safety Brake and Position Sensor
Carbon Fibre robot link

Albu-Schäffer, A. et al. "The DLR lightweight robot: design and control concepts for robots in human environments." Ind. Robot 34 (2007): 376-385.

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So, this is what we will be discussing next. Torque sensor with digital interface and link position sensor. We have just covered the drives that are there to run two different kinds of motors.

So, in the next lecture, we will be covering sensors, position sensors, velocity sensors, acceleration sensors, and different kinds of sensors that are used for force measurements. That is all.

Thanks a lot.