NPTEL Online Certification Courses
Industrial Robotics: Theories for Implementation
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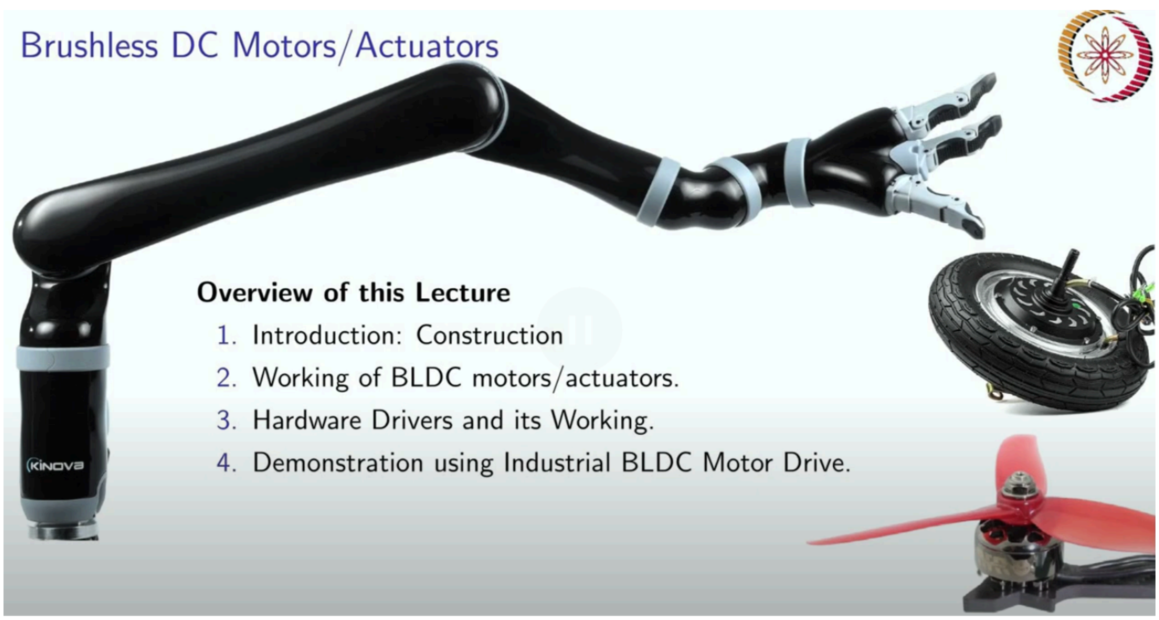
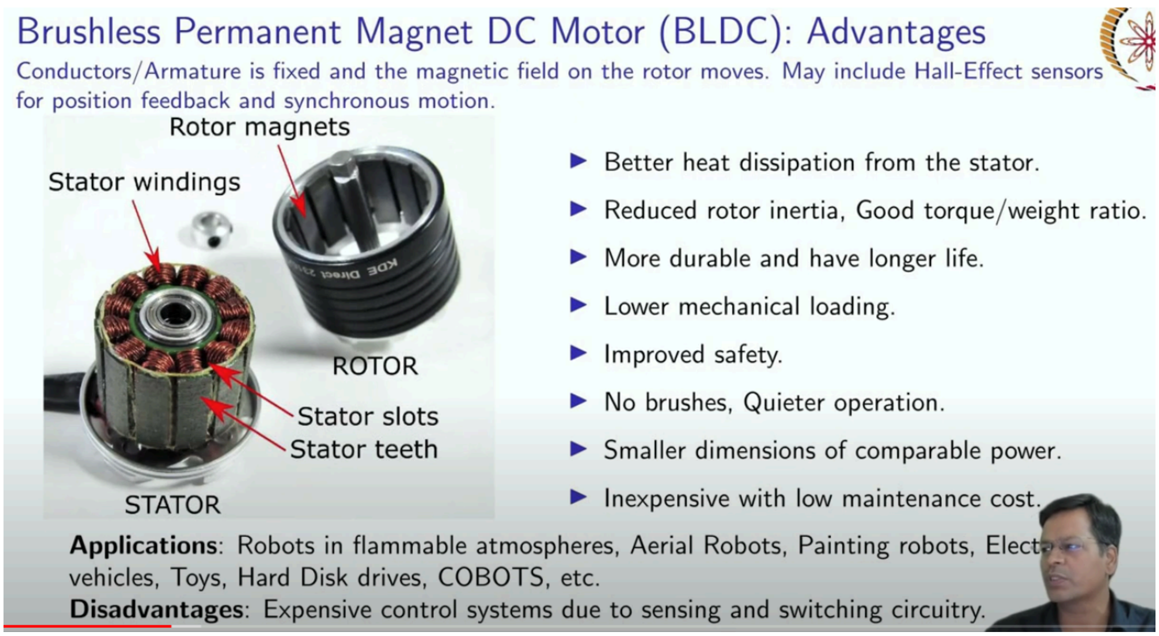
Brushless DC Motors/Actuators

Hello everyone. So, I hope you are enjoying learning actuators, which are mostly a key element in designing or using any robot. So yes, in the last class, we discussed DC motors, different drivers that can run those motors, and embedded drivers that you know already it is an H-bridge drivers and an industrial DC motor driver. So, today, in continuing further, we will learn about BLDC motors. It is a motor of this kind that you can see in my hand. So, it is commonly, nowadays, very widely used to make cobots you see. So, we will learn about this today. So, the outline of today's class will be as follows.



So yes, today I will be discussing the construction of one such motor, which is a BLDC motor working, how it works, and how you can convert it to an actuator. Basically, you know, there is a slight difference between motors and actuators as far as feedback and different types of sensors and transmission, which is concerned with motors, you know. So yes, hardware drivers that can make it work, demonstration using industrial BLDC motor drive.

So, these are some of the pictures that you see. The bigger one is the Kinoa robotic arm. It is one such cobot there are many other cobots which are there in the industry nowadays. So, this is a cobot which is designed using BLDC motors. BLDC servo motors, rather, it is a BLDC motor with feedback also. There are many others like KUKA LVR, IWA robot, UR arms and many, many more; we will discuss them also. Apart from robotics, there are many other industrial automation applications like the one you see here, electric vehicle drives. So, that is a hub motor that also is a BLDC motor, you know and most commonly, it is used like this. So, one which you see here is one of the arms of a quadrotor you commonly call a drone that is that you can see here. So, these are a few applications which are associated with robotics and many other accessories which are there in the industry.



So, let us move ahead now. So yes, how do you think these motors are constructed? It is not in a conventional way when you have an armature which goes at the centre of a stator and it rotates the way you saw a DC motor is constructed. Over here, it is very much like a ceiling fan that you see at home. You have an armature which is actually rotating from the outer casing of the motor. So, the outer part is there, which rotates. So, that is the armature, whereas the stator, which actually contains the windings, is the stationary part of it. So, this winding now creates the rotating magnetic field, and you see magnets all around. So, these magnets are fitted in the periphery, the inner periphery of your rotor, which actually is going to rotate; that is the armature, and then you have slots where you can have those windings.

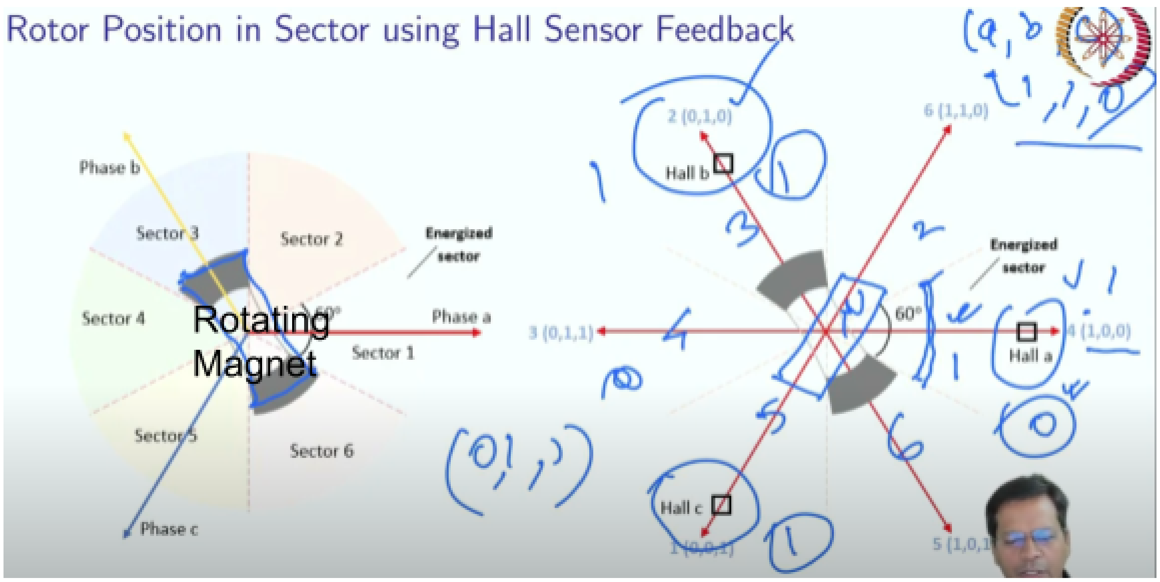
Each of these slots has windings that will create a rotating magnetic field around this one. The stator will be stationary and will carry the rotor magnet along with it. So, that is a standard principle of any motor, not just this one. These types of motors may include a hall effect sensor for position feedback and synchronous motion development. So, you will see very much in detail now that I will be discussing.

Because they are constructed in a way where the electromagnets, which are a source of heat because you know electromagnets are wound, they have a bit of resistance also not just an inductive load, so, they create a lot of heat because that is stationary that can be mounted on top of the heat dissipating element. So, it can very easily dissipate the heat from the stator which is there. And then the reduced rotor inertia because the rotor now carries only the magnets nothing else. Mostly, they are not medium magnets but very high-quality magnets that have very good power as compared to standard magnets.

So, in very compact form, you can get a very good amount of magnetic field out of it. So, they have a very good torque to weight ratio. These types of motors have a very good torque to weight ratio as compared to the similar DC motor or any other motors that you have seen so far. So yes, they are very durable again, you see, because they don't have any commutator or brushes which can wear off. After all, they continuously keep on sliding against the moving rotor. So, that is the reason they require maintenance. DC motors require maintenance. Over here, there is nothing as such; the rotor is only mounted on bearings that are very free to move. So, there is hardly any friction over there, and that is the reason this type of motor is very, very durable and has a very, very long life.

Yes, and the lower mechanical loading: again due to the same reason because the rotor is of very little weight. So, idle run, the rotor is not loaded. So, it can rotate at dangerously high speed, but even when it is loaded, it can the rotation rpm can be controlled, and that rpm will not have much mechanical loading as such due to its mass. And then they are very, very safe with this type of motor because there are no brushes. There is no fire hazard as such. This type of motor can get into atmospheres like inflammable atmospheres like mines or those types of locations where you can have potential areas where there are plenty of methane and inflammable gases all around. So, they don't have any sparks within the motor or the gases cannot enter into a zone which has sparks which can cause a fire. So, they are very, very safe as such and because there are no brushes which are continuously sliding, it is almost noiseless. So, they are very, very quiet in operation also. Smaller dimension as compared to the power that it can deliver. So, similar size DC motor will definitely deliver less amount of power. So yes, and because of all these reasons, the construction is very, very simple. They hardly have anything inside apart from the magnet and the fixed-mounted coils, and they have very little maintenance, very low maintenance, and they are inexpensive as well.

So, these are a few applications you see. Robots in flammable atmospheres. Just now, I gave you an example of mines aerial robots because they are lighter, they are compact, can attain very high rpm and have a very good torque torque-to-weight ratio. It has so you can mount a propeller on these. This is the reason it is mounted on drones that you see nowadays. The painting robots again for the same reason, that is, an explosive atmosphere and electric vehicles. All modern electric vehicles that you see carry this type of motor, which is known as a BLDC motor. They are nowadays, with a digital control system, they can be controlled to a very good extent from low speed to high speed with a good amount of torque that it can deliver. Also, in toys, hard disk drive have been using this type of motor for a long time. Cobots are one of the potential applications which are now coming up widely in the industry also because this type of motor can be mounted directly with harmonic drives with less gear ratio. So, they are sometimes back-drivable, and they allow this type of motor to be fitted directly on cobots. So, these are some of the applications. The disadvantage, yes, because this requires a digital control system. They can be a bit expensive due to the sensing and switching circuitry which is there.



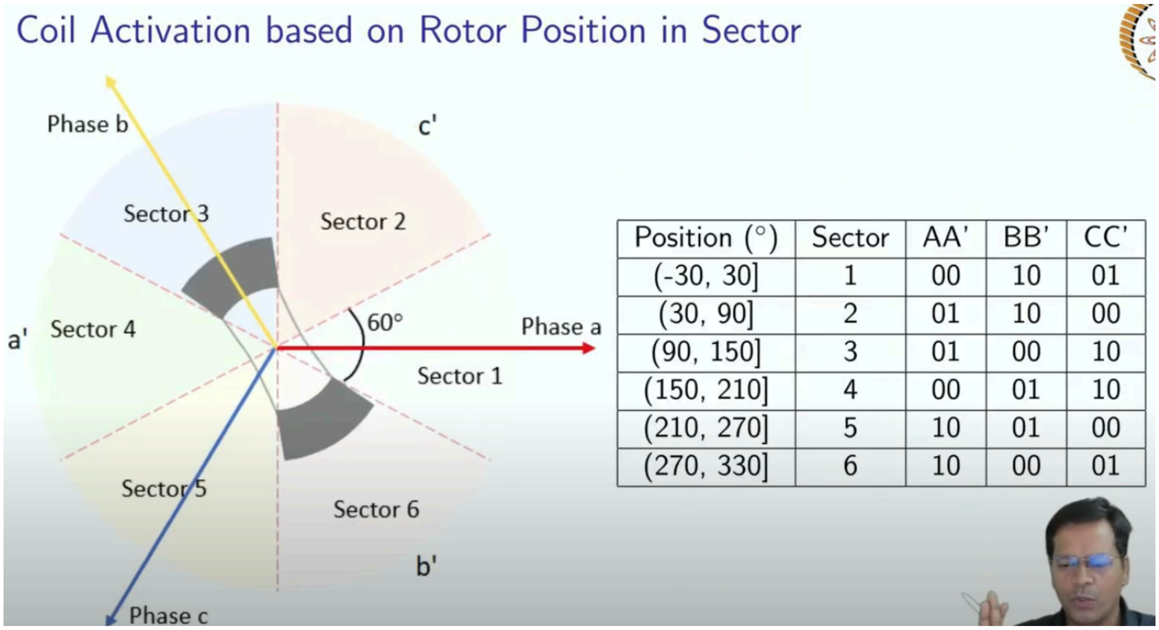
So yes, let us now start going into the theory of how it works. So yes, this is the way how one can detect position in position of the rotor if it is there in one of the sectors using hall sensor feedback. The six zone let me just explain this one how it works.

So yes, this is the rotating magnet which is there. I want to find out where it is using three sensors which are there. One is here (Hall a), one is here (Hall b), and one is here (Hall c). So, what type of signal will it give? Just look very carefully. When there are three bits, it can assign the location of the rotor in one of the six zones. Let us say this is sector one, this is sector two, this is sector three, this is four, this is five, and this is six, got it? So, your three zero to three sixty degrees is now divided into six sectors of six sectors of sixty degrees each, okay, and you have three sensors. The status of each of these is digitally assigned; if your rotor is there, it will tell yes; otherwise, it will say no high or low or true or false zero or one, whatever. So yes, there are three bits, so if your rotor comes within this region. Take one of the reasons, for example, if it is within this region (Sector 1 region), this (Hall a) hall effect is the sensor is turned ON. So, I call it a hall effect sensor: a status, b status and c status. So, what will happen as it comes here in this zone (energised sector)? You see, this (a status) bit goes high. This will tell you yes, I am here (Hall a). This rotor will tell you. This Hall effect sensor will tell you, whereas the Hall b effect sensor is turned as zero. Hall c is turned as zero. So, what you see here is (1,0,0), okay, got it.

Now, when you go here (sector 2). Let us say you are in sector two. You are in sector two, okay. Now, you are in sector two, so what will happen if the nearest region is this one (Hall a) and this one (Hall b) so both will turn high, whereas this is the opposite. So, hall effect sensors are mostly polarity dependent. So, if it sees the north pole of your rotor that turns it high, the south pole will not turn it high. So, they are sometimes directional. So, these are one of them. So yes, if your rotor is something like this or something like this, this is your north pole. So, this will turn. This one 1, this one 1. So, effectively, the bit output that you will get is 1, 1 and zero. That is, for Hall a, Hall b, and Hall c become equal to zero, got it?

Let us come to you, yet another zone. So, this time, let us say it is somewhere over any example you can pick up. Let us say it is at this zone (sector 4). So, what do you see? All hall effect sensors will turn on. So, in this zone effectively, you will see this hall effect sensor. Hall b will turn 1, and Hall c will turn 1, whereas the Hall Effect sensor a will turn 0. So effectively, you will get a bit, which is something like this: zero, 1 and 1.

So, each one of the sectors will return a value. If it is represented in these three bits. So, a total of six combinations is possible when these can reflect the position of your rotor, which actually carries the rotating magnet. So, this will give you feedback on where my rotor is. So, now you got it.



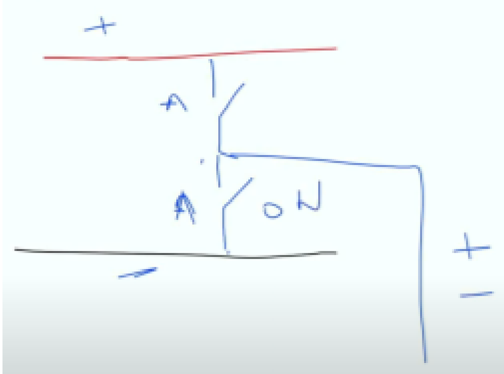
Position (°)	Sector	AA'	BB'	CC'
(-30, 30]	1	00	10	01
(30, 90]	2	01	10	00
(90, 150]	3	01	00	10
(150, 210]	4	00	01	10
(210, 270]	5	10	01	00
(270, 330]	6	10	00	01

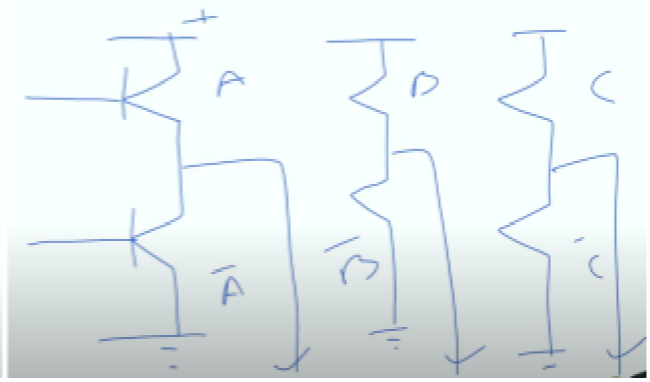
So, if you are at a low position and you are at a location you are alert at a location somewhere here. I will try to energise a location in my field, which is here. So, my rotor will try to align with this okay. If it aligns, I will put another target. I will again align this another target aligned with this and another target, and I'll with this. So, that way, I will keep on rotating my magnetic field based on the current status of my rotating armature, okay? So, wherever it is it will give you a new target in the direction in the direction where I actually want my rotor to move.

So, now, if it is in sector one, that is here minus thirty degrees to plus thirty degrees (-30° to +30°). So, this one, I am talking about this one. So, what will happen? So, if it is here in this sector, what I am doing is actually making because the rotor is already here. So, this time, switching this one (phase a) ON will not help. I want to move it. Let's say the anticlockwise direction. So, what should I do? I should switch on my electromagnet, which is a pole here, a pole here, opposite poles which are here so that if c is turned ON, c bar is turned OFF. So, in that case, this will be high, and the field will be directed like this. Now, because I want to go to the next location, which is somewhere over, I want to make my rotor something like this. So, what will I do? I will quickly make this one (phase c’) high and this (phase c) one low, okay? So, that my field is directed something like this, okay. So, this will take my rotor in the anticlockwise direction. So, it moves from sector one to sector two got it. So, this is how I can keep on energising. So, what happened? I made this one zero zero a and a bar as zero zero whereas c c bar is made high c bar is made high and c is done low c bar is made high and c is done low c bar is made high and c is done zero got it and I have also made this one high so this time b is high b bar is zero so this is high this is low. So, you have high here. You have high here, you have low, you have low. So effectively, the resultant magnetic field will try to pull this rotor towards sector two and sector three somewhere in between right. So, you try to create a maximum magnetic field where you want to go get it. So, this is from going from sector one to sector two.

Now let us come back, let us come back and see how to go from one of the sectors again to another one. This time, let us say I am somewhere over here where my rotor is shown here, okay. Let us say I am here. You tell me you just analyse by looking at this how should I do my job then okay, now that it is already in this sector, that means it is already seeing this position. So, I should make b and b bar both equal to zero. So, it is in sector three. It is in sector three, which is from 90 to 150 degrees, okay that is another 60-degree sector this sector, okay. So, this time, it is at phase a. So, now, what am I going to do? I will switch on the next pole, okay? The next pole is a dash (a '). a dash (a ') should be high, and a should be low. Why? Because this will create the next target magnetic field, which is like the other one. So yes, this will this will because I am here in sector 1. I am making A bar high and A zero okay. This creates a field which is like this, and I can make this also as high that that means C is high, C bar is low, C is high, C bar is low. So, C is high, C bar is low, got it? So, this is how I am trying to create. So effectively, it will create the next moving target. So, this will create a resultant field, which is somewhere here. So, this will pull my rotor to the next sector, okay? So, this is how I keep on changing my targets you know. So, now you can be somewhere where you don't have any existing field, let us say. So, let me just be in one of those locations now, okay? So, this time let us say I am somewhere in this location already. I am somewhere like this. I am somewhere like this. I am in this sector. So, again, what can you do? So, this sector is represented by 150 to 210. This one is okay. So, if you are already here, that means a bar, and a should go to 0. This is 0, and which one should be high, you should be c and c bar. So, that means C should be high, and C C bar should be low. So, you create a field which is something like this, and you are trying to you have to make this one high as well, that means B bar is high B is low. So, this is high, this is low. You got it. So, that means the B bar is high, B is low, and C is high. The C bar is low. Effectively, it creates a target, which is something like this. So, this will pull my rotor to this field. So, hope you got it. So, based on the location feedback, which you saw here, I can keep switching my coils I can keep energising my coil.

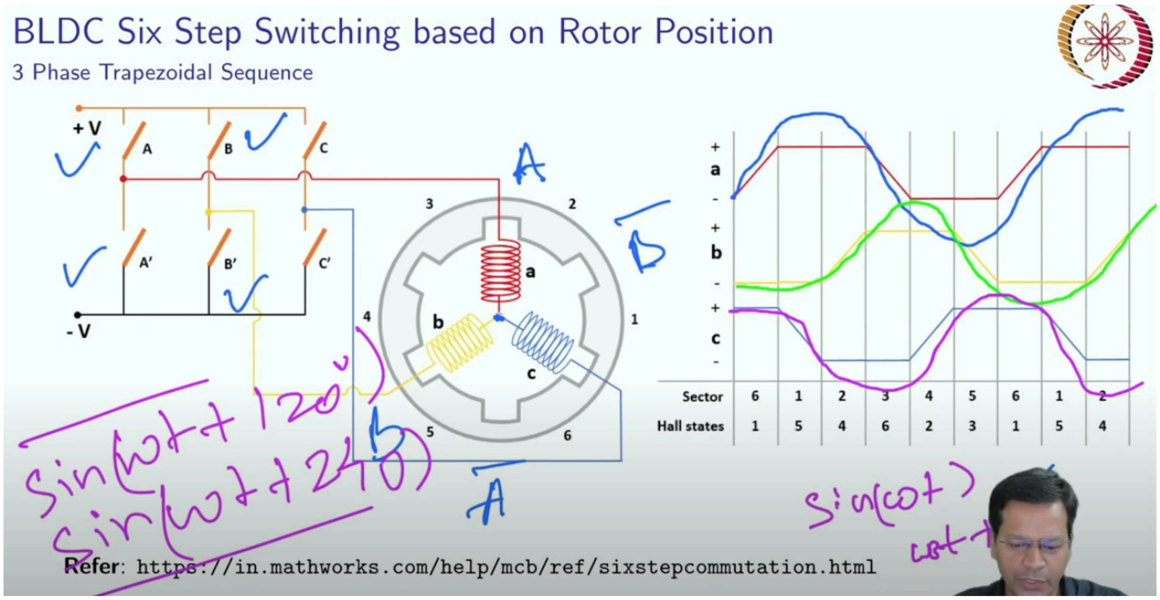
So, are three pairs of poles okay A, B and C. Those are connected in a way I can draw it here, okay. I have a pole which is here. I have the opposite pole, which is here. So, I can directly wound it in a way like. So, effectively, if I pass the current like this. This becomes north, and this becomes south, okay. So, if I pass my current, which is something in a different way. So, if I try to pass current, which goes like this in a reverse way. So, in that case, what will happen is this will become north, and this will become south. So, that is the way you can flip between this C bar and C if it is. So, this we call it. This we call it C. So, this is called C bar, got it. So, this is the way you can switch off all the coils. So, that is how it works.





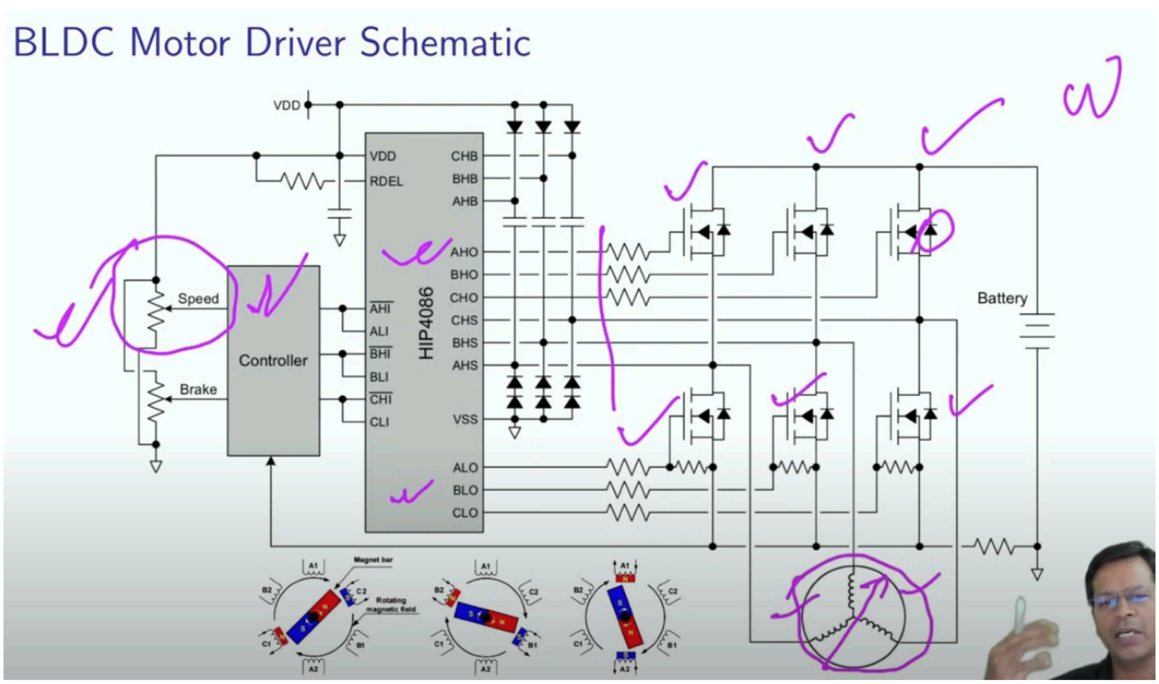
So, how these types of motors are connected? Let me just show you how you can make one wire, which is there positive as well as negative. A single wire. So, there is an arrangement to switch arrangements. So, let us say you connect it like this. So, this is your high line and then you have a ground wire which is over here that wire okay. So, now I want to have some arrangement where my single output, which is here, is to be made high or low. So, there is a way to do it. So, if you have an alternative which is like this. There is a switch here. There is another switch which is here, okay. So, you may call it as A and A bar, okay? A and A bar. So, what will happen, you see? So, if you switch this one on what will happen, okay? So, this is your positive line this is your negative line. It is your positive line. It is the negative line. So, if you connect, make this on this becomes positive, got it? So, if you if you turn this one off and make this one on this one on, what will happen? It will become a negative one. So, this is how. So, now you have an arrangement here. You have a very good arrangement here. Instead of switching on and off, you have two transistors.

As you know, transistors can be used as switches. So, you have transistor one, you have another transistor which is connected to ground this is connected to supply. Let me wipe off the rest of the things, okay? So, this time, what will I do? I have a control wire that can trigger this switch on this circuit, transistors one and two. So, this is a transistor, this is a bar transistor. Okay, now your wire is connected from here, okay? So, what will happen if A high becomes positive? If you switch A bar high, this will become negative okay, and then you have three such arrangements. So, you have one more transistor pair, which is here, okay? That is connected to the ground. You have yet another one that is connected like this, okay, and you have this wire, this wire and this wire. Three different wires. So, this is known as B, this is C, this is B bar, and this is C bar. So, you see what we can achieve by doing this. So, each of these wires one this one and this one can be made high or low okay. Now, you look at this figure. What this is trying to do now is you have three different coils. So, how were you switching each of the wires' polarity? As you know, you require somewhere here, okay? You needed A and A bar to be high and low or low or high, whatever. So, that is what is done using this.

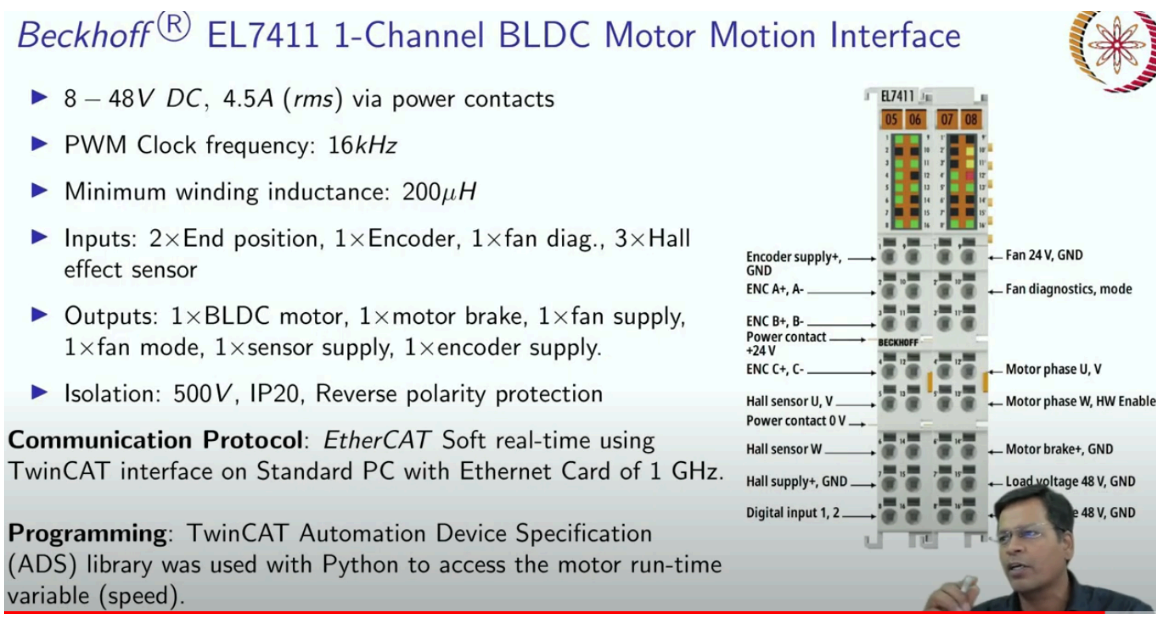


So, if you mean A is high, if you want to make A high, you have to make A high, so you have to make A switch high. So, if you want to make A bar high, you have to make A` switch high, got it? So, A and A bar are oppositely placed, and you know this. This type of winding is done using a star-phase star wiring connection. So, you have at the centre all the coils are connected here, and you can feed in from different directions. So now, if you want to make coil B and B bar are there. So, if you want mean B high you have to make B switch high. If you mean B bar high, you have to make B` switch one high. Okay, B and B bar both cannot be one at a time. Yes, both can be zero at a time. Okay, both but both cannot be one. So, this creates a waveform, which is very much like this, but yes. Now let me give you one another very good example here. Let me go to my whiteboard once again. You see this this all the three wires are connected like this. Your first wire is connected like this. You have another wire which is connected like this. You have yet another wire which is connected like this. You see what is what is going to happen. If the current comes to one of those, okay. It has to go out from the remaining two. Okay, it has to go out from the remaining two, okay? So, it can also happen. Normally, in a star phase winding a star winding you have you have connections which can create something like this, okay? So, if one of them is sinusoidal like this, another one could be if B is equal to zero sin omega t. So, what could be the other one other one is V0 V sin omega t plus 120 degrees. Effectively, it should create a shifted waveform by 120 degrees so that the resultant of sum of all three currents is always equal to the actual supply, which is okay. That is the maximum value which can be there. So, some of those will always be. So, that means if it is going from here, so equal amount may be distributed to both of them so that outgoing from this junction should be equal to incoming to this junction. You remember your Kirchhoff's law also. So yes, that is how it works. So, this is how it works. So, effectively, it will create a field in one of the directions right. So, this is how it is connected. So, it is effectively trying to simulate a three-phase winding a three-phase winding to all these coils okay. So, this is equal to this is equivalent to, let's say, a sinusoidal figure. So, another one another one is trying to create another sinusoidal figure which is something like this.

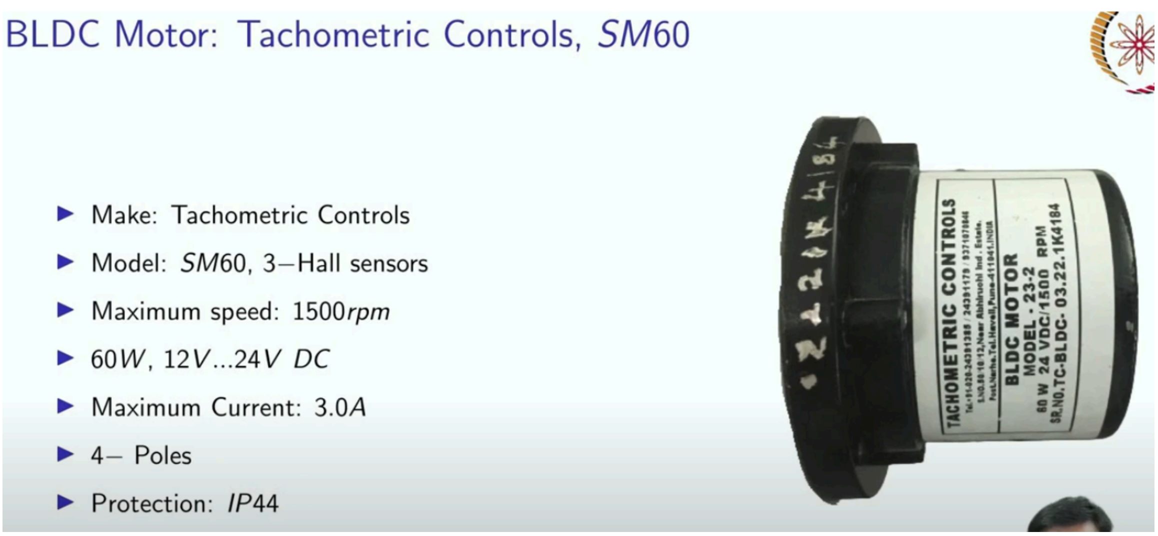
Another yet another one that is trying to create here another sinusoidal figure. They overlap together. They are sine omega t, and one of them is sine omega t. Next is omega t plus. The next one will be sine omega t plus 120 degrees, third one will be sine omega t plus 240 degrees got it. So, effectively, these are the three wires that are to be there. So, we cannot generate this kind of signal for a DC motor. So, the best way to do that is a trapezoidal way, that is what you have seen here. So, the best way to do that is the trapezoidal way is the nearest one to the sinusoidal way. So, this is how these switches are done. Yes, these switches are not just switches. They are transistors. So, they can use MOSFET or transistors, which can gradually take it to this level. So, negative to plus stable there come down gradually be there come up gradually be there like that. So, it is nearest to the sinusoidal waveform. So, each of these has three phases. So, the vector sum of all these should be equal to a constant, okay, that is, the constant field. So, that keeps on rotating. So, that creates a rotating magnetic field. So, if you provide a three-phase. It is not exactly a constant rotating field. It is there is a bit of a hump because of DC characteristics here, okay. So, I hope you know how to create a rotating magnetic field.



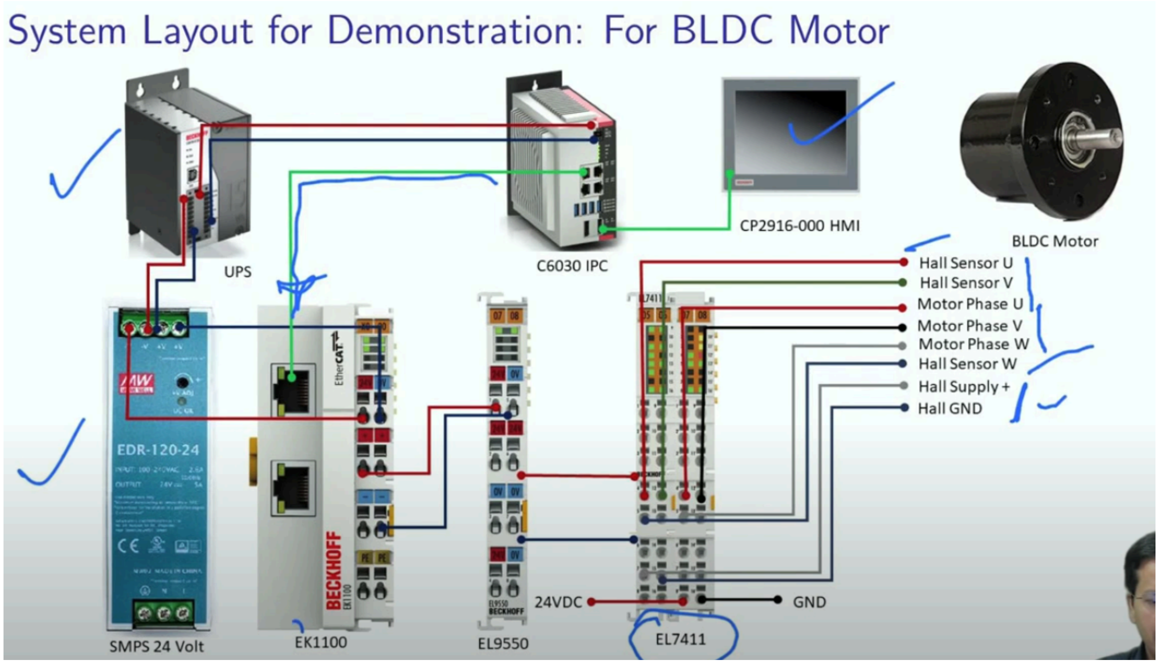
So, this is what goes. So, there is there are many dedicated chips one of them is a HIP 4086. So, it has a similar connection. So, it can trigger the switches which are there you see. You have one switch, A, B and C. You have A bar, B bar and C bar, okay. It is to check any reverse polarity which is happening okay. So, all these are connected by the six wires which are coming from the controller which is here. So, they can easily control the three-phase current which goes to the winding of these coils okay. So, that is what is creating a rotating magnetic field, and finally your rotor is following the rotating magnetic field okay. So, there is there are there are many controls. This controller has an input which can come that is through a potentiometer, you see. So, this potentiometer gives you a voltage signal to this controller finally. So, that is finally controlling the speed with which that actually determines the Omega. So, if I say sine Omega t plus whatever angle is there. So, Omega is controlled. So, the rate at which this field rotates depends on this. So, speed can be controlled and you can even make your field go counterclockwise direction. If you are moving clockwise, you can also go the counterclockwise direction. So, both the direction and the speed are easily controlled. In order to control raw position, at least you can just take the feedback from the sector region that you saw in our initial slide somewhere over here. Using hall effect feedback, you can very well get the sector feedback where my rotor is there. Also, if you take analog readings from your hall effect sensor, you can not do that precisely, but you can get an estimate of where my rotor is okay. You can make a feedback control system to stop your rotor exactly at the place where you want to go. So, you can also do position control based on the Hall effect sensor, but yes, they are very, very coarse. They are not very precise. In order to make it very, very precise, you need to have a dedicated feedback mechanism like a potentiometer or maybe a magnetic encoder or maybe an optical encoder or that kind of stuff, okay? So, that will give you precise feedback and precise positioning control as well apart from this.



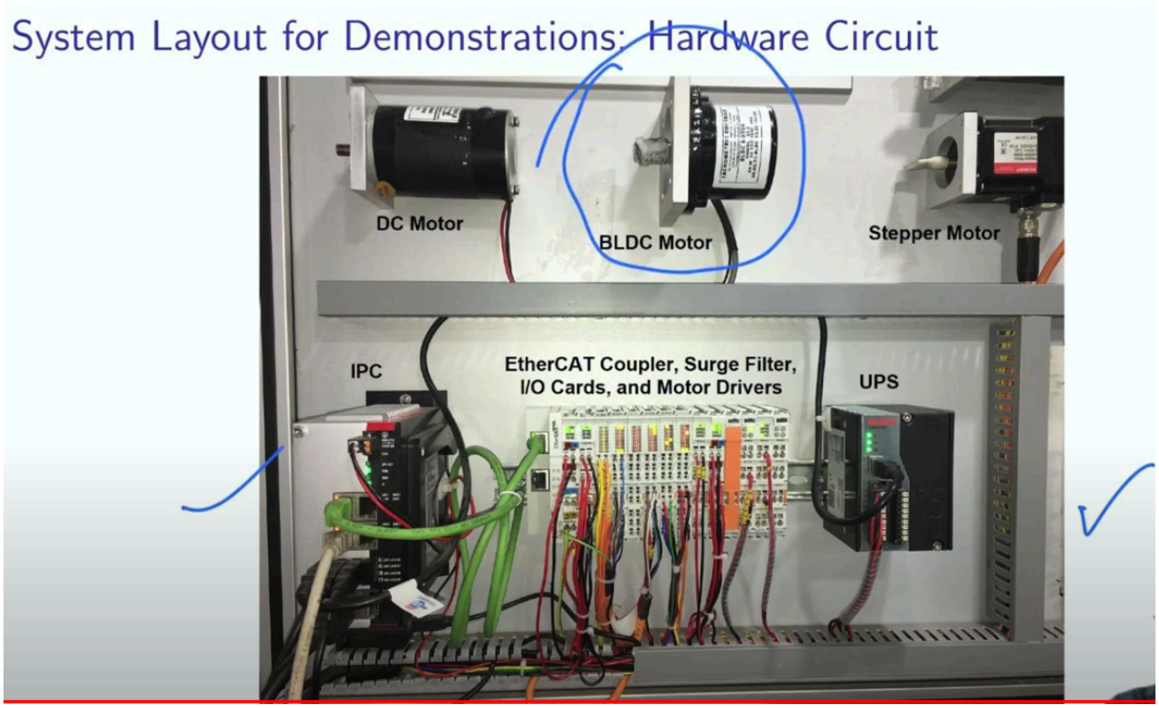
So yes, I have. I have this Beckhoff EL7411 BLDC motion interface that is the driver which can do this task for you. In industry, these kinds of controllers are there. So, this can run at 8 to 48 volt DC with a maximum RMS current that it can give is 4.5 ampere via power contacts, which it has. It is the power contact which is here. PWM clock frequency, that is, the frequency at which it can do all sorts of control, is 16 kilo Hertz, which is quite high. So, you hardly see any hum or noise over there, and they are very, very precise. That is the reason and minimum winding inductance which the kind of motors should not have more than this inductance. So, you see, you have inputs for various reasons. You can have an end sensor. So, the end position can be taken up. You can have feedback from the encoder, that is hall effect sensor or from the encoder, you can take up and have a fan diagnostic. There are fans which are fitted somewhere in this location that will cool up this one if any defect goes with those kinds of fans. So, it will give you feedback. So yes, now I am faulty. Don't feed me with too much of a signal; I may fail. So, you have three for hall effect sensors. You have three fall hall effect sensors that you can feed in. So, this is an encoder, which is an externally mount encoder for precise control, whereas these three are dedicated sector sensors that are hall effect feedback of the inbuilt, which is there in your this kind of motors. So yes, output output, so it is one for BLDC motor that is a phase all the phase wires all the phase wires which are there okay three U V W phase wire and then you have one for fan mode, one for sensor supply, one for encoder supply. So, all the outputs go to the different attachments which are there in the motor that make it an actuator you know. So yes, isolation has 500-volt isolation IP20 reverse polarity production and so on and so forth. It is the same configuration which I have used for my other driving tests. So yes, I will follow this one for this driver.



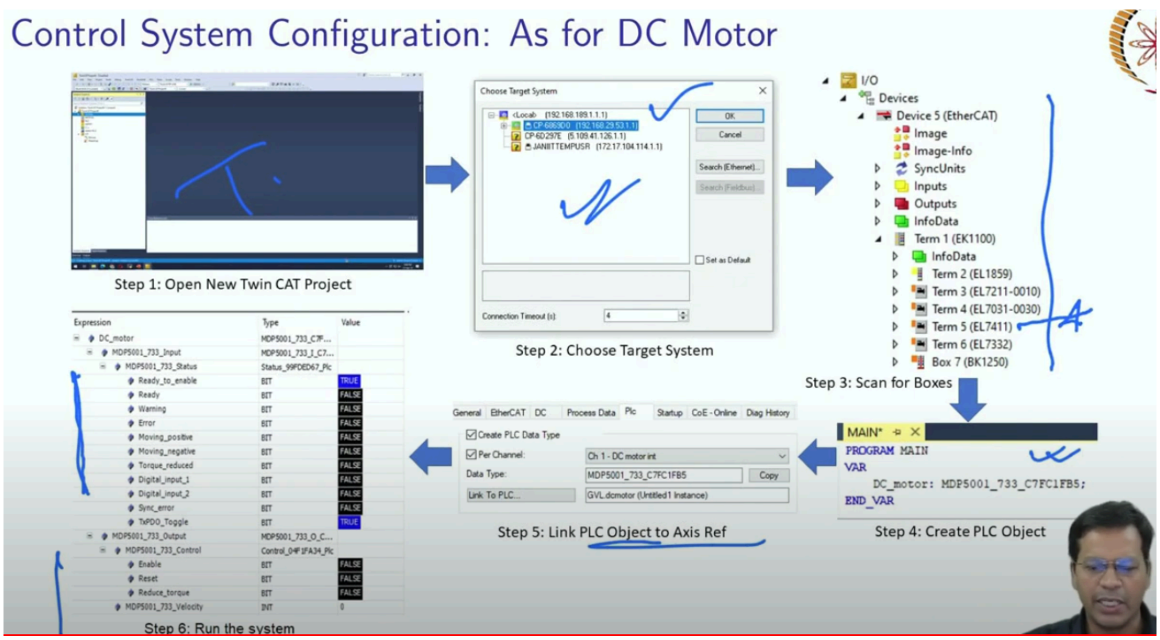
It is the motor which is not a very good one. It doesn't have an external encoder here. It only has Hall effect sensors, made by tacho-metric control sm60. The data sheet is online. You can see I will share it with you. It also has three hall sensor outputs. Maximum speed, it has 60-watt 12 to 24-volt DC 3, ampere current, 4 poles IP44, and so IP44 is the type of protection it has.



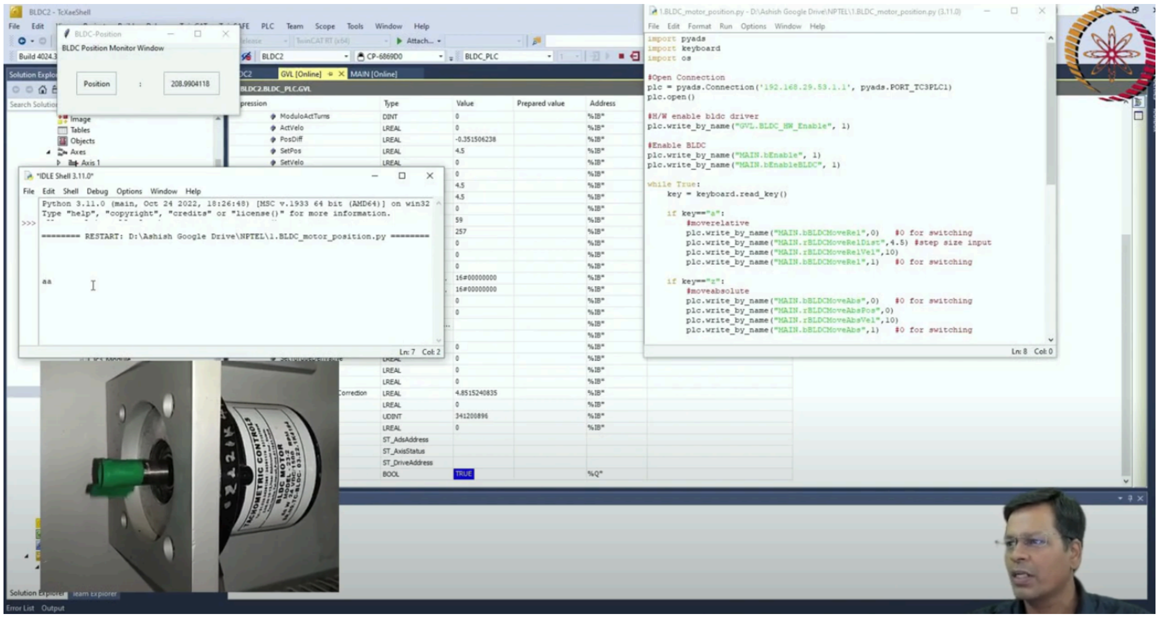
Now, it is connected like this. So, the whole of the system is very much the way I have used for a stepper motor and DC motor you have seen already. This is the only change which is here that is EL7411, the one which you saw here. El7411, the same one goes here, okay. So, that is the additional stuff. So, here are all the kinds of U V W phase wires. Sorry over here, U V W for the hall effect sensors is okay, and then you have motor phases, which is uvw here. Hall W is here. Hall supply is there, and hall effect sensors. They need supply also that comes from here okay and rest everything is the same. It is your TwinCAT communication, which is happening from your PC. It is your HMI. This is your UPS. It is the power supply. It is the EtherCAT coupler here, and this is your filter.



It is the real hardware layout. So, this is the motor which I want to run. Everything is similar to the one we have seen already.



The configuration is very, very similar to the way you have to have a TwinCAT system here. So, you open a new project you search your system from here. Select your system and search for the connected IO boxes. So, here you have your motor driver, which is the one I could find out. I have declared an object with one of the variables which I want to change. I have connected this object to the axis, and this is the parameter that it can give you as feedback as a status, whereas these are some which I can control okay. So, this object has some variables which can be accessed from the external environment. I have used Python. So, let me just run that Python code here, and you will see it running.



So, you see how it is run. So, you see, I am trying to do some course position control. Even with the course position control, it is almost accurate. You see, it is trying to go to exact positions like 90 degrees, 0 degrees, 180 degrees and so on and so forth. So, it is it is able to go to different locations almost not exactly, but yes it is able to do such controls, even with the Hall effect sensor feedback. Hall effect is digital. I can use it as high or low to sense my location, but sometimes, Hall effect sensor values let you know the precise location based on the analog input from all three directions got it. So, that is how it is made to run. So, positioning is done. You can also do velocity. There are inputs for velocity, also you can see in this code. So yes, that velocity is also fed. So, I won't go to a position with this much velocity. So, I get continuous feedback on position and rate of change. That is the Omega that I told you. So, that is what is changing the speed, okay? So, speed and position are both controlled here, okay? So, you can repeat it later on. So, that's all. Thank you for this lecture. In the next class, I will be discussing AC servo motors, which really go on to industrial robots. That's all, thanks a lot.