NPTEL Online Certification Courses
Industrial Robotics: Theories for Implementation
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Lecture: 07

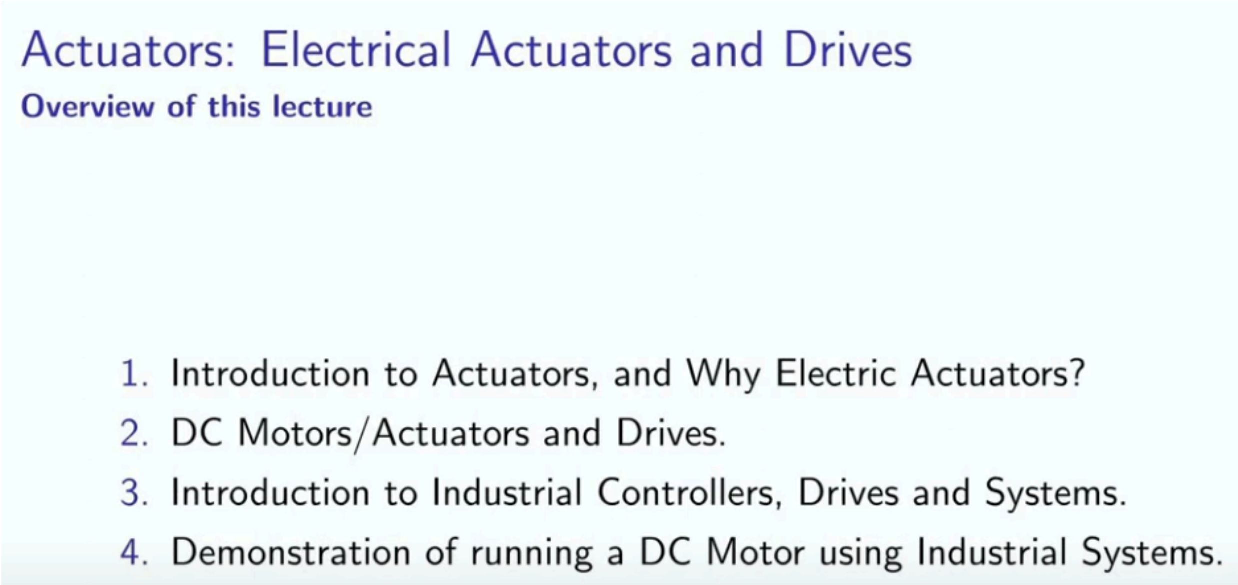
DC Motors/Actuators and Drives

Welcome back. So, in the last module, you saw different types of robots. You were introduced to robots. It's anatomy, and you see various aspects of the robot that make actually a robot. So, what is it made up of? It is made up of actuators, links, different sensors, end-effector grippers, and so on.

So, you now know different things that make up a robot, and you also see how a robot is classified and how technically a robot is specified by its datasheet by the manufacturers. So, one thing that was very, very common in all of them was actuators. Why, you know? When you see a robot is made, that actuator is something that makes a mechanical robot move you know. So that is what.

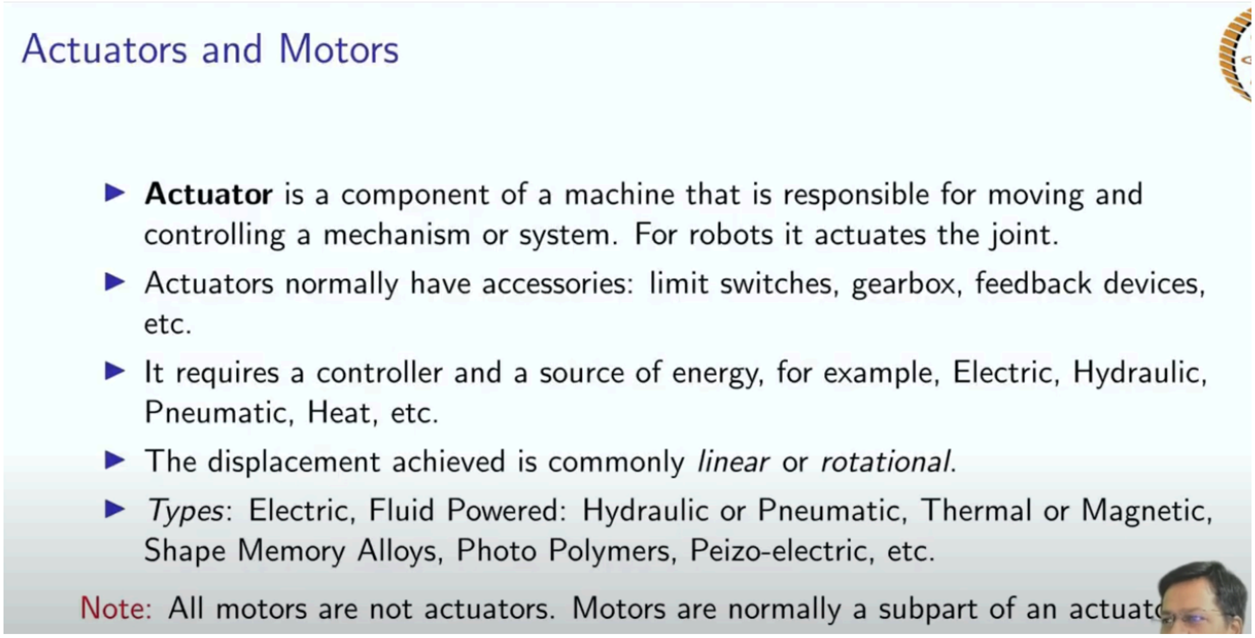
So, even to classify the industrial robot, you require whether it is driven by an electrical actuator, a hydraulic actuator or a pneumatic actuator. So, you know that helped us in classifying the robot; even while specifying the robot, you know how much the speed by which your joint can go and how much the end-effector velocity a robot can achieve. All these things depend on the kind of actuator you have to make that robot. So yes, that is why the actuator has come up as a significant thing that makes up a robot that we should discuss. In the last lecture, I discussed something about industrial electronic hardware, which is there in this type of robot communication interface. You now know how to communicate with these drivers and different sensors which are attached.

Once you are done with your calculations, you want your angles to go to the joints. Yes, how that will go? That will go using the communication interfaces to the drivers. Industrial PC, different systems you now know. In today's lecture, we will discuss about actuators. Yes, actuators are the key to success. It is the tagline that I have been telling my students for a long time. Do you know why? Because the country, the company that you see are developing in robotics they are good in actuators also. We are able to make a good EV if we are able to make a good actuator for its wheels. So, in the case of robotics, you are able to control the joint precisely using these actuators, and then you can make perfect robots. The procedure of the robot and the capability of the robot are defined by the type of actuator it has.



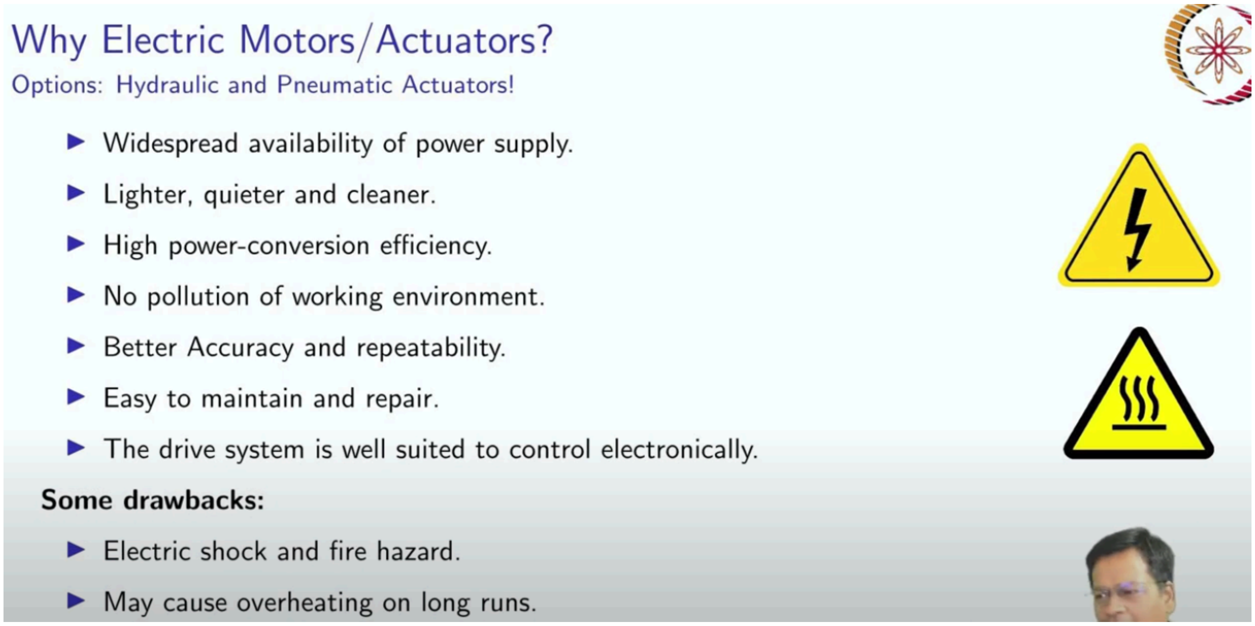
A company which has accessibility to these kinds of actuators at competitive cost are the companies that are successful in making these kinds of robots. So, an engineer is capable if he is able to control these kinds of actuators. So that is an essential aspect of any engineering as such, but yes, in the case of robots also, it is very important. So, in this particular module, we will be discussing about actuators. So yes, coming to this, I will be introducing you to different kinds of actuators, different types of actuators.

Why an electric actuator only? Why not hydraulic? Why not pneumatic? We will discuss them. DC motor as such, I will be discussing in today's lecture and what is the difference between motor and actuator and what drives that drive these kinds of robots. So, the DC motor and its drives we will be discussing today and introduction to different types of controller drive systems we will be doing that are specific to DC motor control. In this lecture, I will also be demonstrating the DC motor using an industrial system. So here we go.



So, yes, actuators; the actuator is a component of a machine that is responsible for moving and controlling a mechanism or a system. For a robot, it actually actuates the joint. So, you got it; it is a joint which is actuated by the kind of actuator it has. The actuator typically has accessories, but it has limit switches. Let us say my joint goes beyond a certain angle; I have to stop. So, it sometimes includes software limits or physical limit switches to stop it once it reaches there. It also has gearboxes so that it can elevate the motor's torque to a given scenario. Let us say if I am to handle the load capabilities of my robot, let us say more torque at one of its joints. So, that actuator may have a gearbox to enhance the torque capability of the motor which goes there. It has some feedback devices to get the precise angle values wherever it is. It requires a controller; normally, a motor can run just by providing electricity, whereas an actuator needs a controller because it has to travel through a path. It has to follow a trajectory while moving through its joint and a source of energy. For example, an electric actuator, hydraulic actuator, pneumatic actuator, or maybe heat is required, so energy is needed. So, the displacement is commonly linear or rotational. So, an actuator can be both, it can be a linear actuator, and it can be a rotational actuator. So, different types of actuators are there. It can be electric or fluid powered like hydraulic or pneumatic, thermal or magnetic, shape memory alloys, photopolymers, and piezoelectric devices, which are also there to move your joints.

So, with all these kinds of actuators, not all motors are actuators. You know, motors are usually a subpart of an actuator that is residing inside the actuator. So, the motor, along with its accessories like limit switches, gearbox, feedback devices, and more, is called an actuator. So now you know the difference here.



So yes, why are electric motors/actuators? Because there are other options we have, such as hydraulic or pneumatic actuators. So, what is the problem with that? So yes, because in the case of an electrical actuator, you see electricity is available all around your home, in industry, it can even be generated somewhere on the spacecraft using solar energy, using tidal energy you can generate at sea also. So, yes you can generate electricity all around like it can be made portable also. If it is stored in the form of batteries, you can store it in the form of a battery then it can be used on a moving aero vehicle or maybe on a ship somewhere or an underwater vehicle. So, it is widely available. It is lighter; it is very, very light because the source remains somewhere else.

A Hydropower plant or a thermal power station is situated quite far apart. You are getting this electricity from the wires that come to your home. Finally, you are not generating that noise all around. So, it is significantly lighter, it is quieter, it is cleaner at the site. Thermal power stations do generate smoke and all, but that is there at the power plant, not at the site.

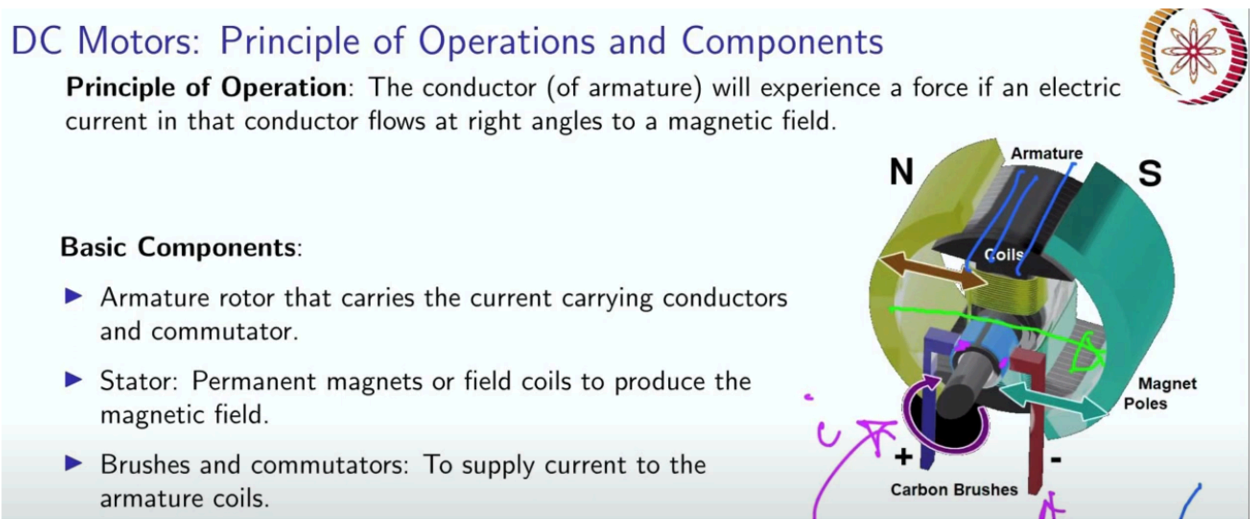
So yes, it has a very high conversion efficiency. If you talk as compared to pneumatic or hydraulic, so you don't waste energy, quite a lot of it is actually converted to the power that you see at its shaft. So, no pollution in the environment, working environment where you are there. And it has better accuracy and repeatability. We will talk about these terms very much in detail.

Repeatability we have already talked about a bit while defining industrial robot specifications. Accuracy and repeatability will be explained very much when we define a few other parameters of the robot in later modules. So yes, it is easy to maintain and repair. Electrical motors are nowadays repaired next to your home. People are there who are repairing your electric fan, your electric motor, washing machine motor, or whatever.

So, it is trained people are around to repair that also. A drive system is well suited to be controlled electronically. You mean electricity is to be controlled by electricity. So, there is no transformation in between. So, you have some controller that generates 0 to 5 volts of current to control, let us say, a current in your motor that varies from 0 to 10 amperes. So, you just need a power amplifier in between. So that transformation is very, very easy.

So, apart from this it has some drawbacks also. Yes, it has some electric shock and fire hazards. If it is in an environment let us say you are inside a mine where mass gas is there, so what will happen? A simple spark can cause a tremendous amount of explosion.

So yes, it has to be shielded to take care of. Yes, electric shock, yes, by proper safety, and all it can be taken care of. It may cause overheating on long runs. Most of the robots that you see at the rear part of it in the motor you sometimes see these symbols which are here. So one of them belongs to, this is for the electric shock hazard, and the other one is for heat, which is the temperature hazard. It may be very, very hot. So those are the warning symbols which is posted at the rear part of your actuators which are placed in the robots. So yes, these are some of them. Yes, you have to take care of it, and then it is okay.



Then, let us come to the PMDC motor or actuator, which is a Permanent Magnet DC motor.

We will talk about motors. Actuators are, along with the motor all the accessories comprise to make it an actuator. So, we will now call it a motor, no issue with that. So yes, the principle of operation is very, very old, and you already know it. So, the conductor of the armature will experience a force if it is a conductor. If it is a conductor, it carries a current. It is placed in a field, in a magnetic field that crosses this. So, this conductor is placed in a field and then it will experience a force which is mutually perpendicular to the field and the current. That is what is given by Fleming's left-hand rule that you probably know through your high school physics also. So, this conductor or the armature will experience the force if an electric current in that conductor flows at right angles to the magnetic field. So fundamental component that this motor includes is the armature.

Armature, you see, has a good amount of conductors. These are all, these are all coils, they are, these are conductors. Conductors are within these slots. It goes within these slots.

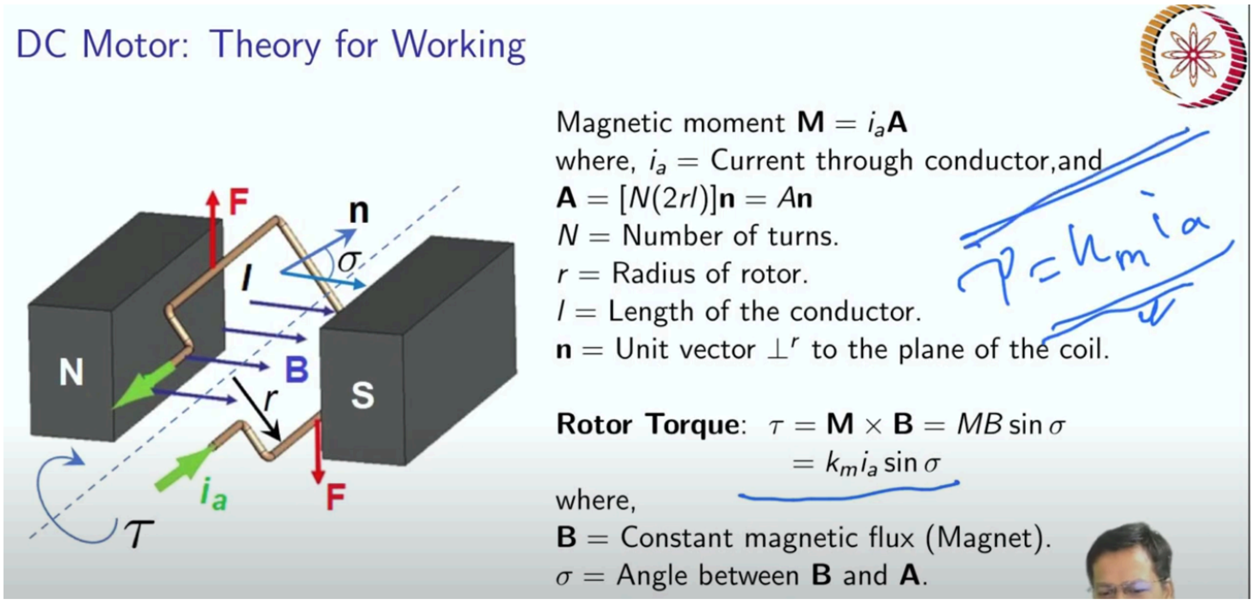
So, they are longitudinal conductors. So, this is a rotating armature. It will rotate like this or otherwise. So, it also has let us say this one, this is known as a commutator. The commutator is to transfer current by having some sort of contact over here. It will transfer current from here to the conductors.

So that is what is an armature and this is mounted on top of bearing on bearing support so that it rotates about its axis. It is supported by two bearings at its end, and it can rotate. So that is what is known as an armature. That is the moving part of a motor.

And then it has a stator. Stator has some permanent magnets, or these magnets are electromagnets that are there to produce the magnetic field. So, you have a magnet here, you have a magnet here, and two opposite magnets will finally create a magnetic field like this. So, you will see a magnetic field that goes like this. So finally, once you place this armature here, armature you see over here, so these are, this will be the direction of your field, and these are the direction of your current carrying conductors. So now you have the picture of how it is going to place Fleming's left-hand rule and create some sort of torque.

You will see very much in detail now. So yes, it also has brushes and a commutator to pass on this. As I have shown you here, these are the commutators. Now you have some sort of brushes that continuously keep in contact with these sorts of commutators so that current can be passed on from the brushes to these copper things, and finally, it will go to the coil and come out. It goes from here; it comes out from here, or it may be otherwise. Yes, this is there. So, each carbon brush is spring-loaded; they are placed in the slots over here. So, as it wears out, it comes closer, closer, closer. Finally, when it is worn out totally, you can simply replace it with a new one. So yes, they continuously keep on swiping across the commutator. Rotating commutator, you have continuous contact so that it rotates and this keeps on slipping.

So yes, this is something that may cause a spark and later on, it requires some sort of maintenance also. Forget about that; let us first learn the principle of operation. So yes, this is to supply the current to the armature coils. So now here it is, so all the particles are mounted here. Now you see the complete picture of this. One of the poles is shown here. You have a pole, which is here, which is the north pole, and you have another pole, which is here, which is the south pole. Finally, this is going to create some sort of magnetic field like this. Ok! Let me draw it with a different colour. Ok! So magnetic field, as I have drawn earlier, so it goes like, goes like this. Ok, so your coil is now placed inside this. Ok, so now you have conductors, conductors will carry the current. So, they are like this: Ok, so once it is here, you see, you have now the commutator which is here, commutator which is here. Ok, so that will transfer the current from here, current from here to the carbon brushes, and finally, these are the points from here it goes to the conductor. It goes to the conductor, which is now orthogonal to the orthogonal to the field. So if you are somewhere in the cleaner space, yes, this is the conductor, this is your field, so finally, this is your field, this is your conductor. Finally, you will see a cross-product of these two. Finally, it will give you a force that is perpendicular to both of them. This force will now create torque. So now let us see.



Ok, going to this picture, yes, this has an isolated picture of one of the conductors that carries the current. See how it is done. So now I will draw this once again. So yes, you have a field; the field is shown in blue over here. This is the field direction that is the blue colour that is the field direction, and these conductors carry current. So, it is shown as a green colour here. So, it carries current; it comes back like this, like this finally, it is out. So, you see, your current is like this: you have a field which is like this. Finally, this is creating some sort of magnetic force. So, this is the force that you see at this end of it where current flows in opposite directions. Ok, here, the current flows in different directions and you have a field which creates a force in this direction.

Ultimately, this creates a couple that rotates the shaft, which can rotate the shaft somewhere like this. This is how it works. Let us say you have now let us see the parameters; let us analyse the physics of it more clearly. So, what is the magnetic moment here? If you remember, your high school physics magnetic moment is given like this. It is nothing but a current into the area vector (Magnetic moment $\mathbf{M} = i_a\mathbf{A}$). The area vector is nothing but if at all you see the area which is inclined like this. Ok, this is your axis, so perpendicular to the plane of this area, you have a normal that comes out of it. So that is your area vector. That is the perpendicular vector. So, the area vector is the magnitude of this area into the vector which is here. So that is what is your A.

Ok and then so that is i_aA, i.e. the magnetic moment. i_a is the current through the conductor, and A is the area given over here because there is a bunch of coils. If you saw that armature carefully it has not just one wire at a particular place. So you may have a bunch of wire that makes N number of conductors which is taking this current from this loop. Ok, through this loop. So, this is n. This is n over here. 2r is the radius. If this is the radius, it is r, and it has another r. So, r-r, that is the dimension. $\mathbf{A} = [N(2rl)]\mathbf{n} = A\mathbf{n}$

This is your l that is the length of this conductor. 2rl effectively gives you the area that is here. So, n times that area because you have multiple turns of this wire. So n, time that area finally is A and n. A is the number of all those areas, and the number of times added together finally gives you the total area.

It is not just one winding. It has multiple windings. So, this gives you the direction. So, the magnitude is A where, whereas the small n vector is the unit vector, which is orthogonal to this area vector. Ok, so yes, moving ahead. So yes, N is the number of turns of the coil, and r is the radius of the rotor. l is the length of that conductor, so effectively, n is the unit vector, which is perpendicular to the plane of the coil.

Rotor Torque: $$\tau = \mathbf{M} \times \mathbf{B} = MB \sin\sigma = k_m i_a \sin\sigma$$

Rotor torque is given by magnetic moment cross product to the field that is B. OK, so effectively, you will see M into B sin sigma (**σ**). What is sigma here? Sigma is the angle between M and B because it is a cross-product.

So effectively, you will get K_m I_a sin sigma (**σ**). What is K_m? I will tell you. So, B is the constant magnetic flux. So, this is there because these magnets are permanent electromagnets; even if it is an electromagnet, it does not matter; the current is always constant through the excited coils, which makes that electromagnet a constant one. Ok, a constant magnetic flux one.

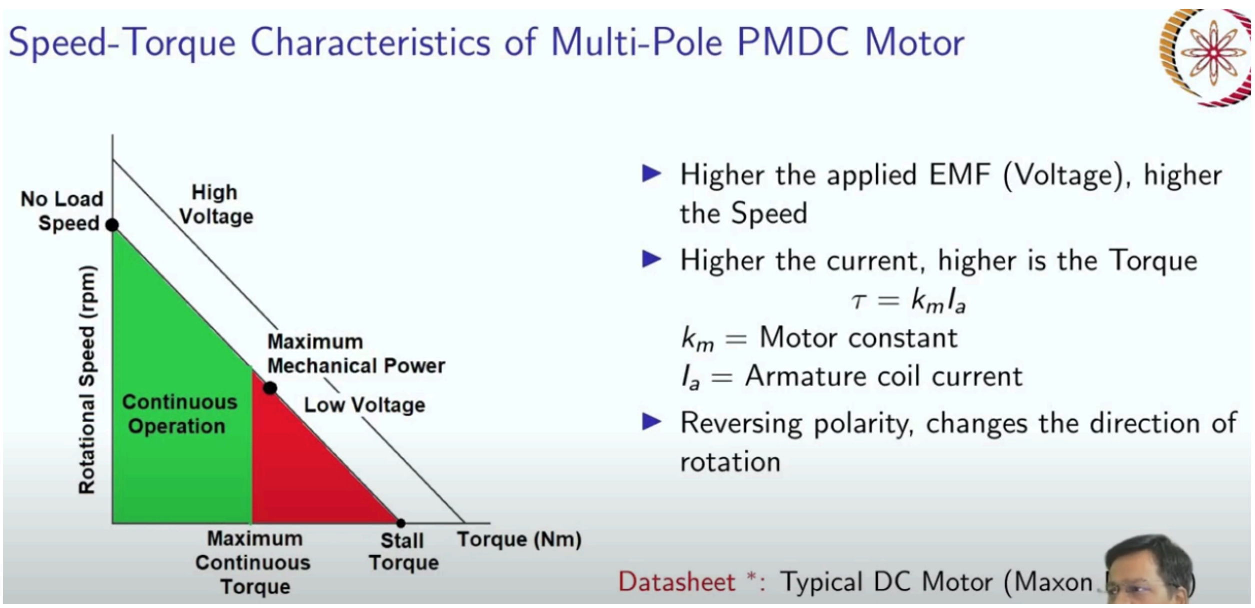
So, the field remains constant. Ok, so yes, sigma is the angle between B and A. So, finally, you got torque, which is equal to K_m I_a sin sigma. This torque is not a uniform one; it depends on the angle as the rotor rotates; torque is a variable. It becomes 0 degrees; it becomes 0 degrees; in that case, you see a 0 torque. So how will it cross? Maybe through inertia, it will cross.

Can it start from that position? No. So, in that case, what you do, you don't just have one single conductor; you have multiple conductors. Now look at your armature once again. Ok, so let us see the armature once again. So how was this? It has multiple commutators, multiple commutators and multiple conductors. So, if one of them crosses that field, another one enters, another one enters, and another one enters.

So, one of them is always getting into the field, and the other one comes out of the field. Ok, so effectively, what you see is a constant torque that is there. So, one of the sigma becomes 0, the other sigma is entering, leaving and entering, and it becomes 90 degrees. So, you see, by increasing the number of poles, you can always make this torque almost a constant. So effectively, what you see is tau is equal to $k_m I_a$. So, sigma no more is a variable if you sum the torque sum of the torques of all those coils which are there so effectively that annul the effect of sigma. So, it becomes almost negligible pulsation in torque. So, almost constant torque, you will see. Combined with the motor inertia rotor inertia almost is not seen even as a mechanical vibration. So, this is a standard equation for any motor, not just a DC motor; this is the basic principle of any motor. It can be a servo motor, it can be a stepper motor it can be anything. So, this is the torque which is created out of a conductor which is carrying a current and is lying in the field. Ok, so this is the torque which is given, and each type of motor, any type of motor, has multiple numbers of poles, so you see a similar equation is there even for servo motors or any kind of motor. So, this is a general equation of motor.

$$k_m = NBA$$

Now k_m is equal to NBA. This is just derived from the variables you have. Ok, that is the motor constant that is known as the motor constant. If it is Tau (τ)/ I_a, the unit is Newton Meter by Current that is ampere.



Ok, so what is this? This is basically the relationship between speed-torque characteristics of a multi-pole DC motor, that is, the PMDC motor. Tau is equal to $k_m I_a$. You can very well notice here that torque is proportional to the current which flows through the armature coil. Ok, so that is always there so if you can relate one of the very standard equations that says torque into omega is the power of a shaft. So, what is this? Because a constant amount of power is fed into this system, if torque increases, angular velocity should decrease, but yes, it should not be in a straight line, so what you see here is a plot between the torque and the rotor speed. Torque and the rotor speed and it is in somewhere like this; it is not like this actual relation is something else. This is the operational diagram of a typical motor DC motor. Ok, so I will show you the correct picture of this also. So yes, the higher the applied EMF, that is, the voltage, the higher the speed. To control the speed of a DC motor, you have to apply more voltage to it. So, the effective voltage should increase. So, the higher the current you can increase the torque so both of them can be controlled. So higher is the torque which means higher current is flowing through your conductor. Reversing the polarity changes the direction, so you see it as a fundamental principle if a conductor is carrying current in this direction. If it considers force like this, if you reverse the polarity, it will see the force which is opposite to it. It is quite easy to understand, so this is what is creating a negative couple and, finally, the negative direction of rotation. Ok, so this DC motor is very well controllable for speed torque and changes it and the direction also.

Position can be controlled if you have a feedback mechanism that checks the position every time, wherever you are, and then you can create a closed loop, and you can control that, which is known as a servo; we will talk about that also. So, how does it look like this type? So you see, there are a few parameters to notice here itself, so this is the stall torque this is the position which is known as stall torque; this is the condition when you completely stop your motor from rotating; this is the maximum torque which is delivered by the motor when it is completely stalled ok and this is the no-load speed when torque effective torque apart from the torque which is there due to friction and all so if it is not loaded this is the maximum rotational speed that you can see. Ok, so you have to run your motor somewhere in between; this is the continuous operation range. Ok, so that is where you should be; so, the higher the voltage, the higher the speed. Every speed line will have a different characteristic curve. So, if at all you increase the voltage, speed also increases so you will see a different line, another line maybe something like this so that also creates different lines; ok, so we will see all these details very much closely in the actual picture that is on the datasheet now.

maxon motor

maxon DC motor – Comments regarding motor data (pages 37-84)

Line 1 **Assigned power rating** P_{2T} [W]

● This figure represents the maximum power output when operating within the recommended output power range. It is dependent on motor type and can be correlated with the presentation in our Selection Guide (Please refer also to pages 37-81 under «Operating Ranges»).

Line 2 **Nominal voltage** U [V]

All nominal values refer to operation at this voltage. It was chosen such as not to exceed the maximum recommended speed in no load condition. Motor application is of course not limited to this voltage. To reach the assigned power rating (Line 1) higher operating voltages are permissible. Maximum power output (Line 12) will increase respectively, (see also page 30 «Important considerations» - bottom of right hand side).

Line 3 **No load speed** n_o [rpm]

This is the speed at which the motor turns at nominal voltage and without load. For practical purposes, this speed is proportional to the voltage applied.

Line 7 **Starting current** I_A [mA], [A]

❍ is the quotient «Voltage at terminals/DC-resistance» and is proportional to stall torque.

Line 8 **Terminal resistance** R [Ohm]

is the resistance at the terminals at 25°C and determines the starting current at a given voltage.
In the case of graphite brushes it must be noted that contact resistance varies depending on the load.

Line 9 **Maximum permissible speed** n_{max} [rpm]

This speed should not be exceeded during normal operation. Commutation problems may be expected at higher speeds, in turn, this could lead to premature motor failure.

Line 10 **Maximum continuous current** $I_{permiss.}$ [mA],[A]

Operating the motor continuously at this current level and at 25°C ambient will cause the winding to ultimately reach the specified max. winding temperature. This

The higher the efficiency, the nearer to no load speed the operating point will be. Maximum efficiency is usually at approximately $^1/_7$th of stall torque.
Operating at this point is not necessarily synonymous to operating at the motor's optimum load point.

Line 14 **Torque constant** k_M [mNm/A]

This may also be referred to as «specific torque» and represents the quotient from generated torque and applicable current.

Line 15 **Speed constant** k_n [rpm/V]

shows the specific speed per volt of applied voltage, disregarding any frictional losses. The reciprocal of the speed constant is known as the voltage constant or back-EMF constant.

Line 16 **Mechanical time constant** τ_m [ms]

is the time required by the rotor to accelerate from standstill to 63% of its no load speed. In 4τ the rotor will have reached more than 99% of no load speed.

Ok, this is a standard data sheet of a motor you see. It says a very good amount of parameters that will let you select a particular kind of motor for your application. So, this is nominal voltage, no load speed. So, this is the speed we are talking about that is no load speed when it is, and this is the stall torque, speed/torque gradient that is the slope of this line; that you see no-load current that is flowing through this motor's maximum power output this continuous torque. Continuous torque is the continuous operation region that I showed in green colour, so the maximum permissible speed, if it goes beyond that, it is dangerous, and you can break your robot. You break your joints, maybe, be your motor over here. Thermal resistance is in ohm. So, these are all helpful in designing the controller for your joint. Ok, that is the joint, so thermal resistance will be useful, and the thermal terminal inductance will be helpful.

Line 4 **Stall torque** M_H [mNm]

This is the torque produced by the motor in a standstill condition, also called starting torque. The rapidly rising rotor temperature leads to a corresponding decrease in stall torque (see also «Technology – short and to the point»).

Line 5 **Speed/torque gradient** $\Delta n/\Delta M$ [rpm/mNm]

This gradient says a lot about the power capability of a motor. The flatter the gradient, the less speed variation is experienced during load variations.
The speed/torque gradient is calculated at 25°C winding temperature.

Line 6 **No load current** I_o [mA]

This is the current the unloaded motor draws. It depends on brush and bearing friction and varies slighty with varying speed.

assumes no heat sinking. Depending how the motor is mounted, this value can be increased substantially.

Line 11 **Max. continuous torque** M_{perm} [mNm]

is the torque that can be supplied continuously or on an average, thereby heating up the winding to the maximum permissible temperature; based on an ambient temperature of 25°C.

Line 12 **Maximum power output** P_{max} [mW], [W]

is the theoretical maximum output at 25°C rotor temperature. Permissible limits are frequently below this level (see max. continuous current and max. permissible speed).

Line 13 **Maximum efficiency** η_{max} [%]

Efficiency is derived from the relationship between no load and starting current.

Line 17 **Moment of inertia** J_R [gcm^2]

is the polar mass moment of inertia of the rotor.

Line 18 **Terminal inductance** L [mH]

is the winding inductance when stationary and measured at 1 kHz, sinusoidal.

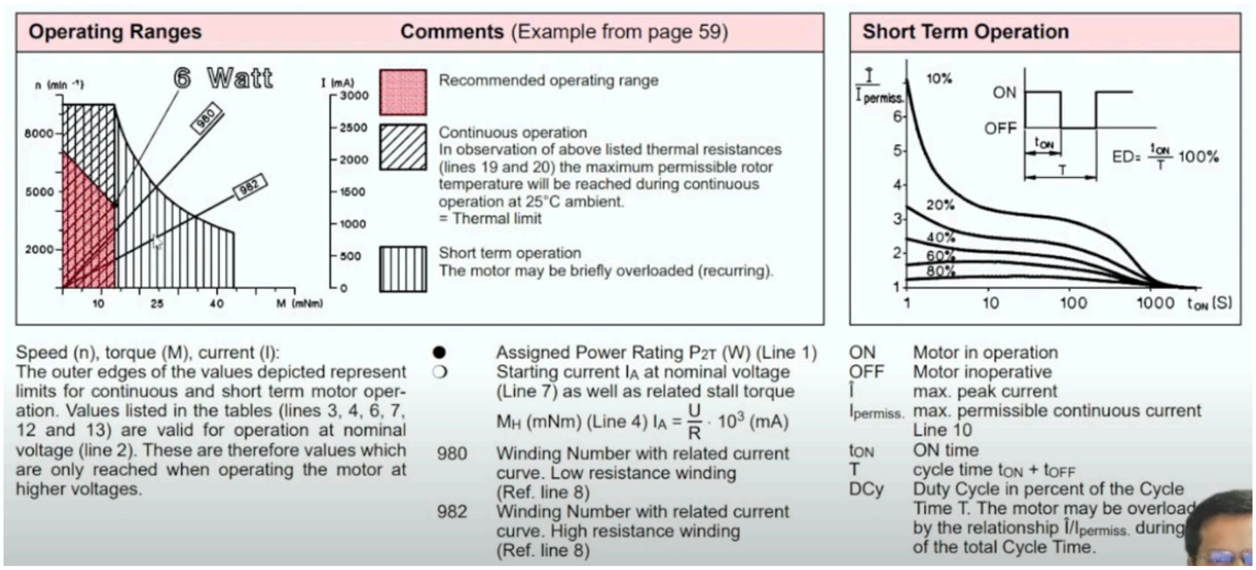
Line 19 **Thermal resistance** R_{th2} [K/W]

from housing to ambient air. Characteristic value of thermal contact resistance without additional heat sinking. The sum of lines 19 and 20 define the max. admissible power loss. Heat sinking may substantially reduce this value.

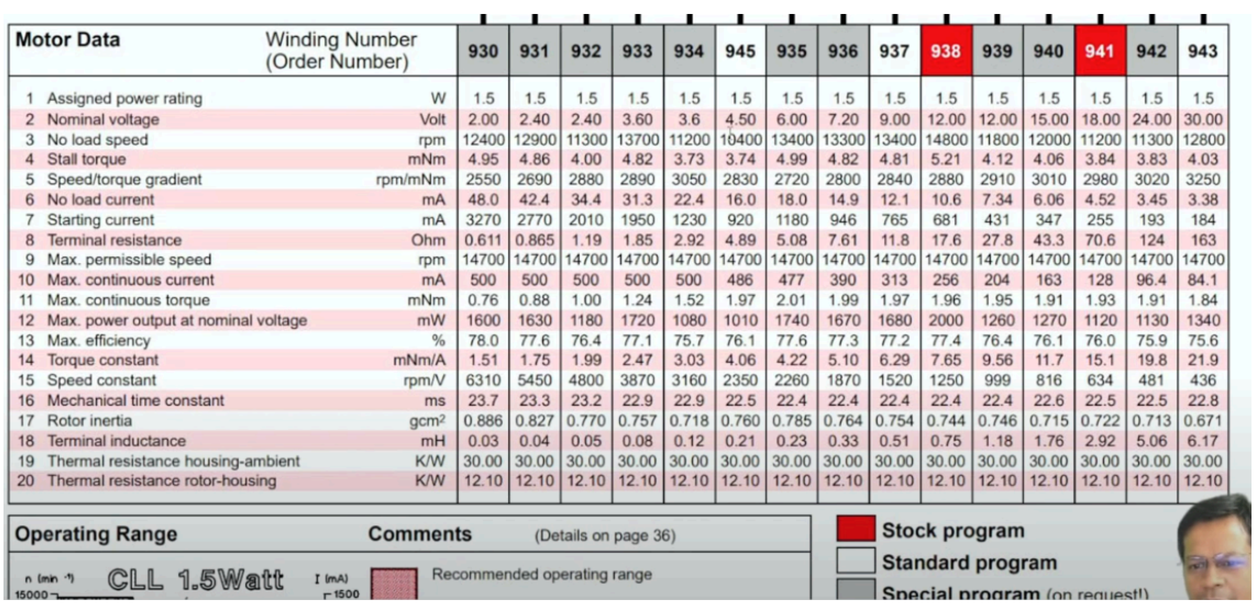
Line 20 **Thermal resistance** R_{th1} [K/W]

from rotor to housing.

We will talk about this motor inertia, which is the armature inertia that also is a mechanical value which will be a very useful torque constant that is your K_m, which is the motor constant you just derived. So, these are some of the parameters which are there. Not all manufacturer will give you this many details because they probably have not tested their motor to this extent.



Ok, this is the actual curve of how it looks, and I will zoom it out to make it clearly visible. So yes, it has different motors of different parameters over here, so this is the operational region recommended operating range, and for continuous operating, you should be somewhere within this area over here, ok, and this is short-term operation, yes you can go here also if it is for short-term operation ok, so this is very, very useful information for the intermittent operation like in case of the robot also you can very well be very safe over here, so let us look closely.



Motor Data	Winding Number (Order Number)	930	931	932	933	934	945	935	936	937	938	939	940	941	942	943
1 Assigned power rating	W	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
2 Nominal voltage	Volt	2.00	2.40	2.40	3.60	3.6	4.50	6.00	7.20	9.00	12.00	12.00	15.00	18.00	24.00	30.00
3 No load speed	rpm	12400	12900	11300	13700	11200	10400	13400	13300	13400	14800	11800	12000	11200	11300	12800
4 Stall torque	mNm	4.95	4.86	4.00	4.82	3.73	3.74	4.99	4.82	4.81	5.21	4.12	4.06	3.84	3.83	4.03
5 Speed/torque gradient	rpm/mNm	2550	2690	2880	2890	3050	2830	2720	2800	2840	2880	2910	3010	2980	3020	3250
6 No load current	mA	48.0	42.4	34.4	31.3	22.4	16.0	18.0	14.9	12.1	10.6	7.34	6.06	4.52	3.45	3.38
7 Starting current	mA	3270	2770	2010	1950	1230	920	1180	946	765	681	431	347	255	193	184
8 Terminal resistance	Ohm	0.611	0.865	1.19	1.85	2.92	4.89	5.08	7.61	11.8	17.6	27.8	43.3	70.6	124	163
9 Max. permissible speed	rpm	14700	14700	14700	14700	14700	14700	14700	14700	14700	14700	14700	14700	14700	14700	14700
10 Max. continuous current	mA	500	500	500	500	500	486	477	390	313	256	204	163	128	96.4	84.1
11 Max. continuous torque	mNm	0.76	0.88	1.00	1.24	1.52	1.97	2.01	1.99	1.97	1.96	1.95	1.91	1.93	1.91	1.84
12 Max. power output at nominal voltage	mW	1600	1630	1180	1720	1080	1010	1740	1670	1680	2000	1260	1270	1120	1130	1340
13 Max. efficiency	%	78.0	77.6	76.4	77.1	75.7	76.1	77.6	77.3	77.2	77.4	76.4	76.1	76.0	75.9	75.6
14 Torque constant	mNm/A	1.51	1.75	1.99	2.47	3.03	4.06	4.22	5.10	6.29	7.65	9.56	11.7	15.1	19.8	21.9
15 Speed constant	rpm/V	6310	5450	4800	3870	3160	2350	2260	1870	1520	1250	999	816	634	481	436
16 Mechanical time constant	ms	23.7	23.3	23.2	22.9	22.9	22.5	22.4	22.4	22.4	22.4	22.4	22.6	22.5	22.5	22.8
17 Rotor inertia	gcm²	0.886	0.827	0.770	0.757	0.718	0.760	0.785	0.764	0.754	0.744	0.746	0.715	0.722	0.713	0.671
18 Terminal inductance	mH	0.03	0.04	0.05	0.08	0.12	0.21	0.23	0.33	0.51	0.75	1.18	1.76	2.92	5.06	6.17
19 Thermal resistance housing-ambient	K/W	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
20 Thermal resistance rotor-housing	K/W	12.10	12.10	12.10	12.10	12.10	12.10	12.10	12.10	12.10	12.10	12.10	12.10	12.10	12.10	12.10

Operating Range Comments (Details on page 36)

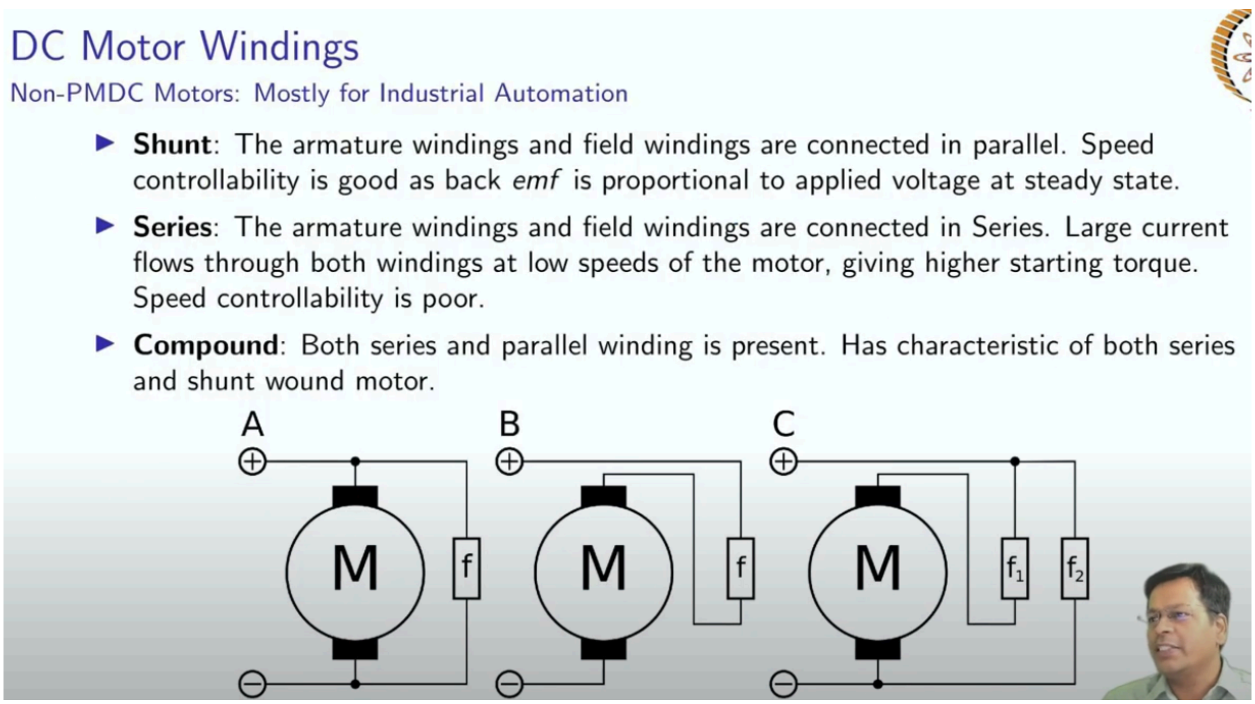
n (min -1) CLL 1.5Watt I (mA) Recommended operating range

Stock program

Standard program

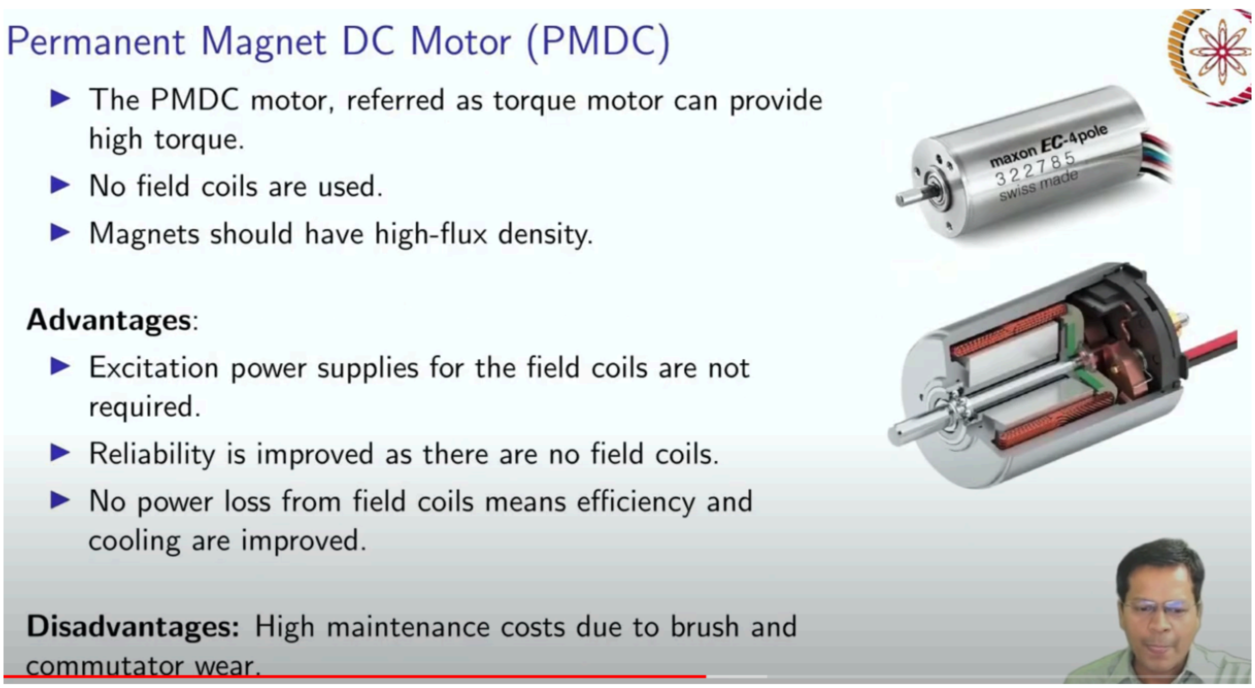
Special program (on request!)

These are the dimensions, so tabular-wise wise, any of the motor kinds is over here. You can simply group one of them. Let us say this motor only this motor only it has all the parameters that were defined earlier here. These will help you to select different robots. So, the maximum torque that it can deliver stall torque right and continuous operation torque is also there; continuous you should not go beyond it is in milli newton meter this is for a small motor, even for the big industrial motor also it will be something like this ok so thermal resistance is there that we will be using later on maximum continuous current. Hence, this is the continuous current that will help you to select a suitable driver to drive this kind of motor; if it is 500 milli amp, a 0.5-ampere driver should be good enough. So, the starting current is intermittent, not an intermittent starting current only, so that you will see it is very, very high. It is going to draw 3.2 amperes while it is starting. So, starting should not take too much time; otherwise, your driver may go bad, so just check the specifications of your driver. Also, no load current; So, this is even without it running freely; it is carrying this much current. So yes, this is all the parameter that is very, very important that you should look for when you select your robot for a particular application. So, this is a typical data sheet that I have shown that shows the characteristics of a multi-pole DC motor.

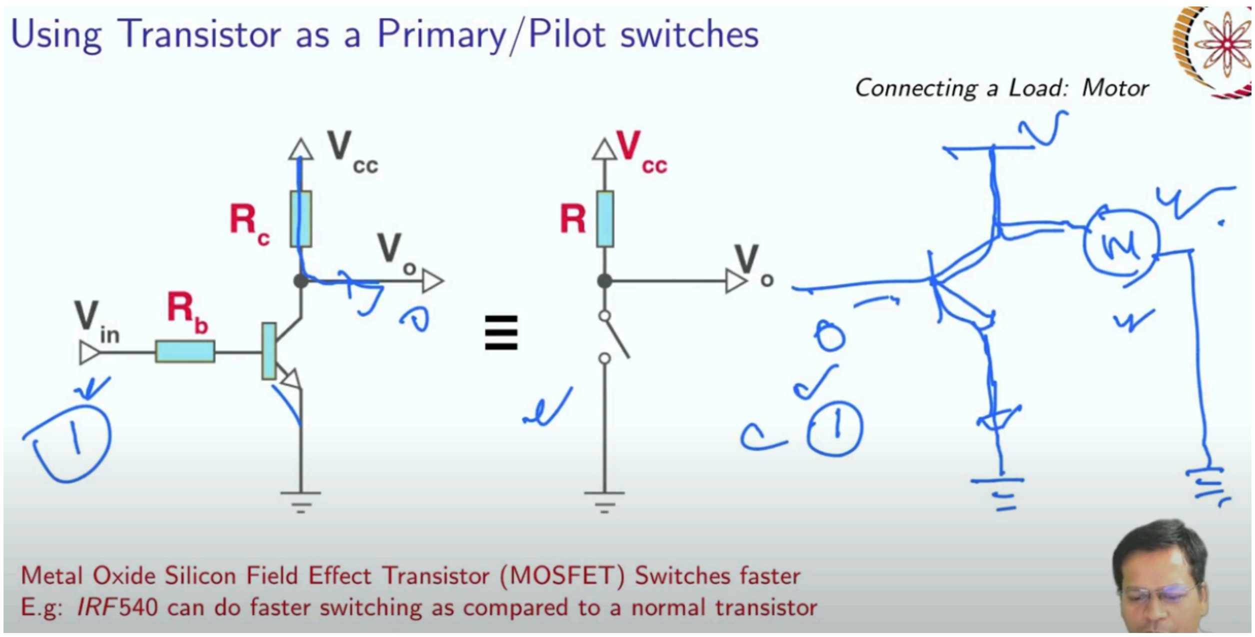


DC motors can also be of various kinds. So, just now, you saw a permanent magnet over there. If that is not a permanent magnet, what is it? It has a field coil, so the field coil will also draw electricity from the source. So, once the current comes, it can be divided into the field as well as this. So, if the field coil and the motor armature are connected parallel to each other, that is known as a shunt DC motor, so the armature winding and the field windings are connected in parallel. Speed controllability is good as back EMF is proportional to the applied voltage at a steady state.

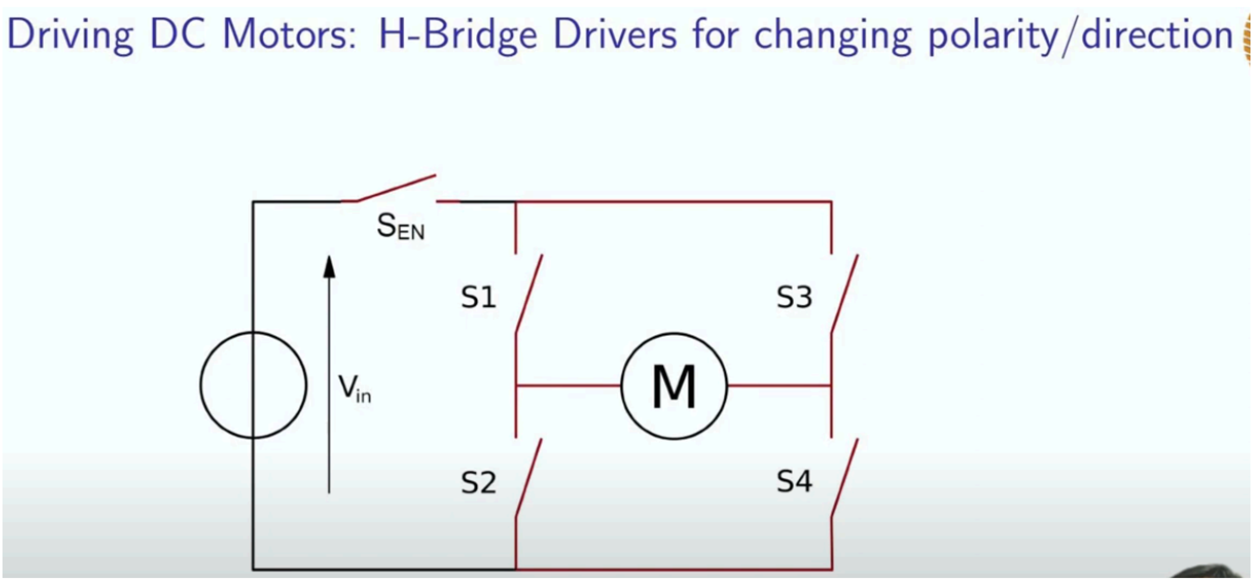
At steady state, Speed controllability is very, very good. Hence, this is a type of motor, and then you have a series type of motor where the field coil and the armature are drawing the same amount of current flows through the field as well as to the armature. So now you know the starting current will be very high to the field, so field windings are large current flows through both the winding at least while starting. So, it will have a very high starting torque. So, speed controllability, however, is very, very poor. Ok, once the rotor takes up the speed, it takes up a small amount of current, so if there is no load, it can draw less current. So, this type of characteristic is also useful. Let us say you want to have a starting motor for your car. May be starting current is required to be very, very high, but in that case, usually PMDC motor is there. So, that is there. In the case of a compound DC motor, a part of the coil is connected in series, whereas the other one is connected in a parallel way. So, it has a joint characteristic of both series and shunt wound motor. These individually may be suitable not just for robots. It may be for other automatic equipment which is around, maybe for a conveyor, maybe for a rotary table and other parameters other equipment which is around.



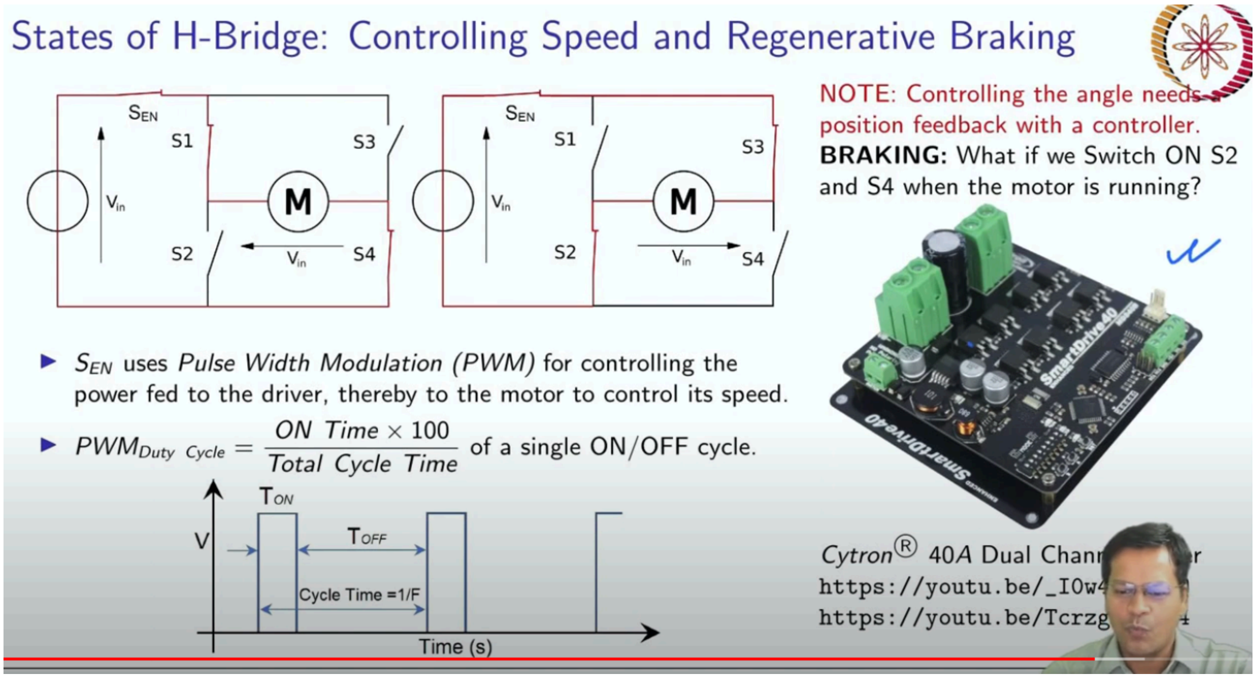
So yes, now what you saw with the permanent magnet DC motor is referred to as a torque motor because it can provide you with very high torque. That is the reason it is used as a starter for a scooter, right? That is the IC engine-driven scooter, right, and then you have magnets that should have a very high flux density; your PMDC motor, your magnets usually a no medium magnet which has a very powerful field which can create a very powerful field. No field coils are used in the case of PMDC motors. Yes, they are very, very advantageous in a way; excitation power supplies for the field coils are not required. So, it does not draw your energy over there, right? Reliability is improved as there is no field coil, less number of parts so that cannot go wrong so that it is permanently there right, and power loss from the field coils means efficiency and cooling are improved, right? So yes, it does not need further cooling of the field coils, but DC motors have brushes. As you know, it is continuously in friction, and that wear will occur over time; it needs some sort of maintenance so that that cost will go high, but still, it is it can provide a very good amount of torque; that is the takeaway of this kind of motor.



Now, to drive this motor, let us first introduce you to a transistor switch. Hopefully, you know this from your basic electronics course. If you had any, so, this is a typical transistor that is biased in a way using these two resistances, and it is connected. So, if it is in a switching mode, not an amplification zone, it has already been saturated. In that case, it is just about to be saturated by even a small amount of current if it is fed from Vin. So, if you apply a small amount of current from Vin, it will get biased, and it goes from Vcc to ground, and the current flows ok. That is the gate type of operation. So, if you do not apply current from here, if no current is there from Vin; so, the current will not flow through this transistor, and finally, it will go all from Vcc to Vo direction. So, it is just like a NOT gate. If you provide 1 over Vin, you see 0 over Vo, so if you provide 0 over Vin, you see 1 Vo. If you provide 1 Vin, you see 0 Vo, so this is just a NOT gate operation. Anyway, I am not here to talk about NOT gate operation, but yes, this is very, very helpful in making your load connected like this, so it becomes very much like a switch. You can connect your motor like this, so if you have a transistor right, you can connect your, so this is your supply. It is your controlling current, which is here. So, if your motor is here right, as soon as you provide current to this line, the transistor is working ok, so now the current comes to the motor, and the motor starts running. A small amount of current can now control a huge amount of current from here, so this is just a switching operation how it is useful, but there is another way of running it and also this kind of motor. This time, what will I do? I will connect this transistor to the ground. Ok, and this time, I have fitted this motor over here. Ok, so now what will happen as soon as I provide 0 over here, that is, connect this to the ground? What will happen is that all the current from here will flow through the motor, and the motor will start so 0 to run the motor. If you provide 1, that is logic value 1; that is, the control signal is here, so in that case, the transistor opens up, and current flows from here to the ground; in that case, the motor is off. It is another way of connecting it, so these are the two methods of how to control a DC motor using a standard transistor. So yes, but then there are other ways of controlling this, also you. Instead of using a transistor as a switch, you can also use MOSFET, that is metal oxide silicon field effect transistor. FET switches are faster in response, and they also can carry a huge amount of current as compared to a transistor.



Now, if you see standard H-bridge drivers, they are used to control the DC motor. Now, let us look at this very carefully. It has the capability to change the direction of your current that is flowing through the motor right as well as you can switch on and off your circuit closely.



Now, let us look at what is happening in this case: the S_{EN} switch is closed; that is enabled switch is closed. Okay, so whatever potential you are applying over Vin. It creates a current. The S1 switch is closed from the motor. It goes to S4 because these two switches, S1 and S4, were closed. These two switches S2 and S3 are open. Okay, finally, the current will go back. So, this is how to make the current flow in that direction, okay? But what is happening over here in this one? You have closed S2, S3 is closed, S1 is open, S4 is open. In this case, you have a current that flows like this. Okay, finally, it goes back. So, in this case, you have a current that flows like this, so you see, you can very well reverse the polarity that is across the motor terminal.

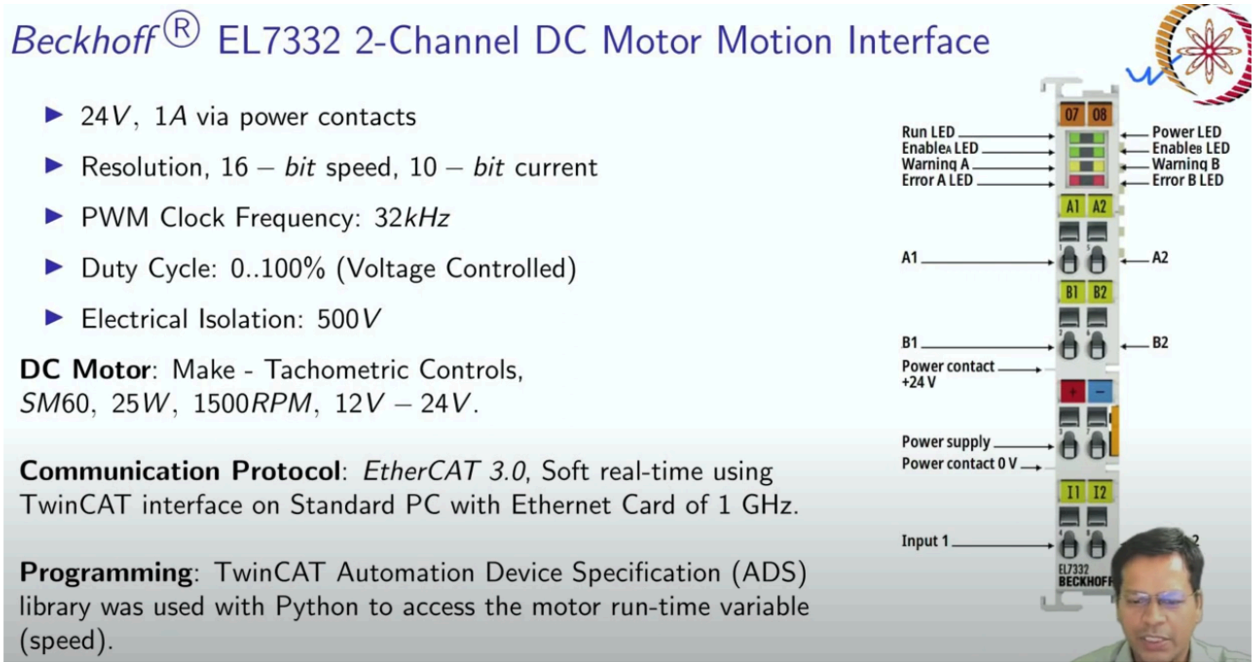
Ok, in this way, you can clearly change the rotation direction immediately using the H-bridge. Now, you need to know how to control the speed of your DC motor. In this case, what you can do is use the S-enable (S_{EN}) switch. The S-enable switch uses PWM to control the power that is fed to the driver. Okay, you know you can; if you can reduce the voltage across your terminal, that can reduce the speed of your motor, but yes, that has a problem. That problem may be at a minimal amount of voltage, the motor is not running, and the current keeps on flowing through your coil. So, if it stays there for a longer period, what will happen is it will finally create a huge amount of thermal load on that, and finally, it can go bad. Okay, so that is the reason. you should avoid that. So, what can we do? Let us say, you are just switching on and off your switch. So, instead of you switching it on, the motor starts moving by the time it picks up, and you switch it off. By doing a high-frequency switching on and off, you can limit the amount of power that goes into the system. Okay, so you can limit the amount of power that goes into the system. Finally, it will be if the power input to the system is low, so in that case, what will happen is it will create. So, you know power is equal to torque into Omega, so torque is constant over here because the voltage is constant, constant current that will prove that will effectively change the speed of your motor. This is how current, which is the effective voltage across the signal, is changed, so how does it look? A PWM waveform looks like this. So, you have an on time, your waveform is like this: you have an on time, it is on for a particular duration, and then it goes back to zero, and this so it remains off; again, it is on so it keeps on going doing. So, for a particular cycle, this is the on-time this is the off-time. So, what will happen?

$$PWM_{Duty\ Cycle} = \frac{ON\ Time \times 100}{Total\ Cycle\ Time} \text{ of a single ON/OFF cycle.}$$

Total on time by total time, which is here; that is the duty cycle of the PWM waveform. PWM waveform is on time by total time, and it is expressed as a percentage, so you just multiply it by 100, and that is the percentage duty cycle. So, the percentage is from 0 to 100 per cent. If I say 0 per cent on time, that means it is off forever, and then, in that case, the motor will stop. If it is a 50 per cent duty cycle, that means 50 per cent of the time it is on and 50 per cent of the time it is off. So, that is how it is done. So, this is known as a PWM waveform or pulse width modulation. It is used to control the effective power that goes into your motor, which can finally control the speed. And how is that done? So, you already know you have a switch over here you have a switch over here. So, whatever direction your motor is rotating, you can have a transistor switch we can feed in with this much of this type of control signal to it. So, that will continuously switch on and off the whole of the H-bridge. The motor as a whole can be switched on and off using this enabling switch. So, PWM switches on and off this particular S enable switch. Okay, the switch is here. So, that is the way you can control the speed. So, now you are ready with the system of H bridge with which you can go velocity that can vary from 0 to maximum in one direction to 0 to maximum in the other direction, right? So, if this is the velocity that is 0 to the maximum in one direction to 0 to the maximum in the other direction. It is how you can control the speed direction, right? So, in order to control the current, maybe you can have a DC chopper drive, which can control the current and can effectively control the current flowing through the armature coil. Finally, the torque can be controlled. That is altogether a different story over here. Controlling the angle needs position feedback with a controller, so you need to have a servo mechanism over here servo means of feedback. We will talk about that later on. But yes, using this, at least you can now you are ready to control the direction. You are ready to control the velocity, Direction-velocity. If you can control the current, you can also control the torque. What is remaining here is just controlling the position that needs a feedback device.

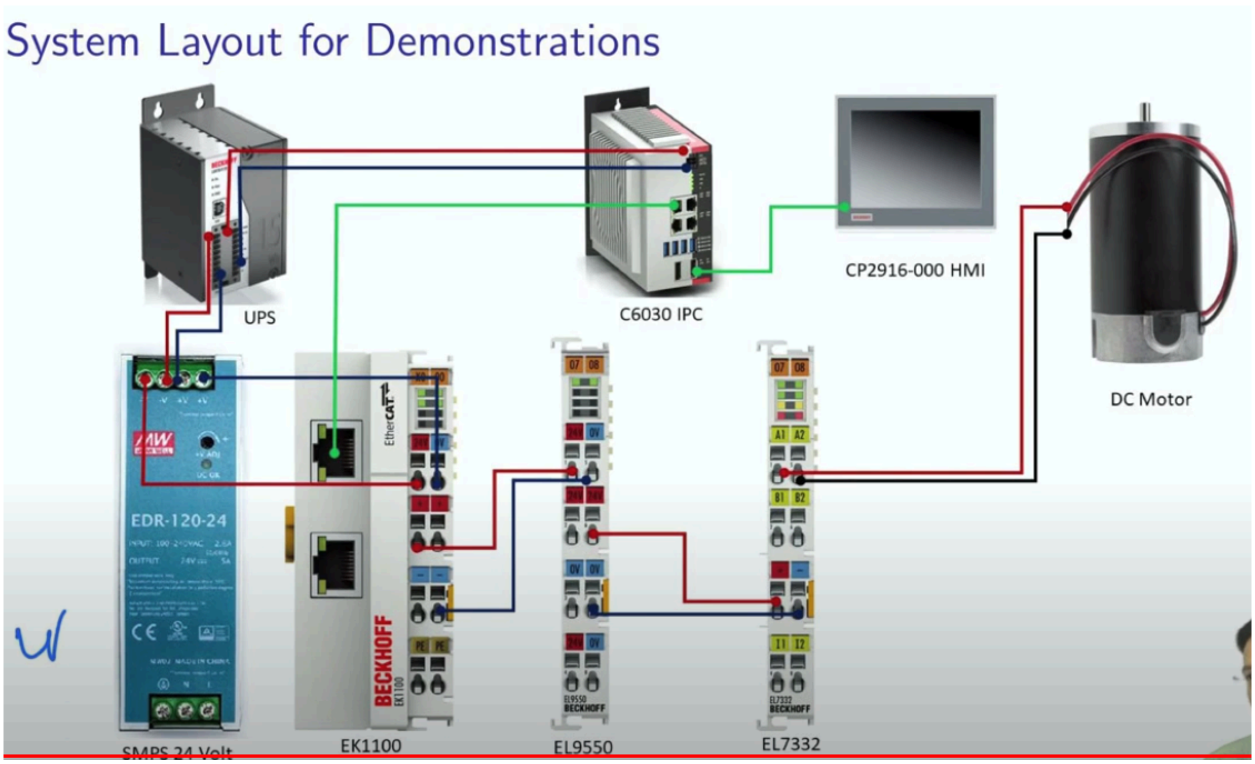
It is now braking. How can you achieve braking using such a system? Now, can you imagine if you could close the S2 switch and the S4 switch close and keep S1 and S3 open? So, what will happen? If the motor is continuously running, it behaves like a generator. If you don't provide power to it by switching off these two switches, S1 and S3, it is not supplied with current. So, what it is now is it is already running, and what you have done here by closing these two switches, S2 and S4, is you have short-circuited this running generator, so you will have a huge amount of loop current that will flow through it right and that will create a back EMF and the reverse torque.

EMF will be short-circuited, and finally, it creates a reverse torque, which tends to stop this motor. However, it cannot bring it to zero because when it comes closer to zero, hardly any EMF is generated and is not sorted. Finally, it cannot bring it to the zero situation, but yes, it can bring it very, very close to the stopping speed of the motor when you can physically apply the brake. Right now, and more so, let us ask you if you can use this motor to generate electricity when you are not supplying it with power. Right? By opening this, too. You can have a battery which is here which can be charged by having motor running in idle condition. Let us say your robot is going downward on a slope. Now, you can use that power; you are not supplying it with the power you need. Instead, that motor has become your wheel motor, which has become a generator. Now, it is like a charger for this motor, so where it can charge the battery right, so that is what is known as a regenerative type of driver that is there. So, yes, a very commonly used type of driver is this, which probably you have used in your hobby electronics and that kind of stuff during your school days or maybe in your intermediate. So, this type of driver is common here. So, you see, it has 1,2,3,4. These 4 make up an H-bridge over. Here, it has another H-bridge, which is here, so two sets of H bridges are clearly visible, and it can run the first motor from here and the second motor from here. This is a direction control bit where you can supply. The power comes in from here. So, one of them may be supplying to control the velocity, and the other one is for the direction. Again, for velocity and direction for the first motor and the second motor. For both the motors, velocity and direction wave can be given from here. Power is inputted from here, and this is there, so this is a commonly used H-bridge driver. It is quite suitable for small robots but not definitely suited for a big robot like an industrial robot or like that which is required to have other compliances as well.



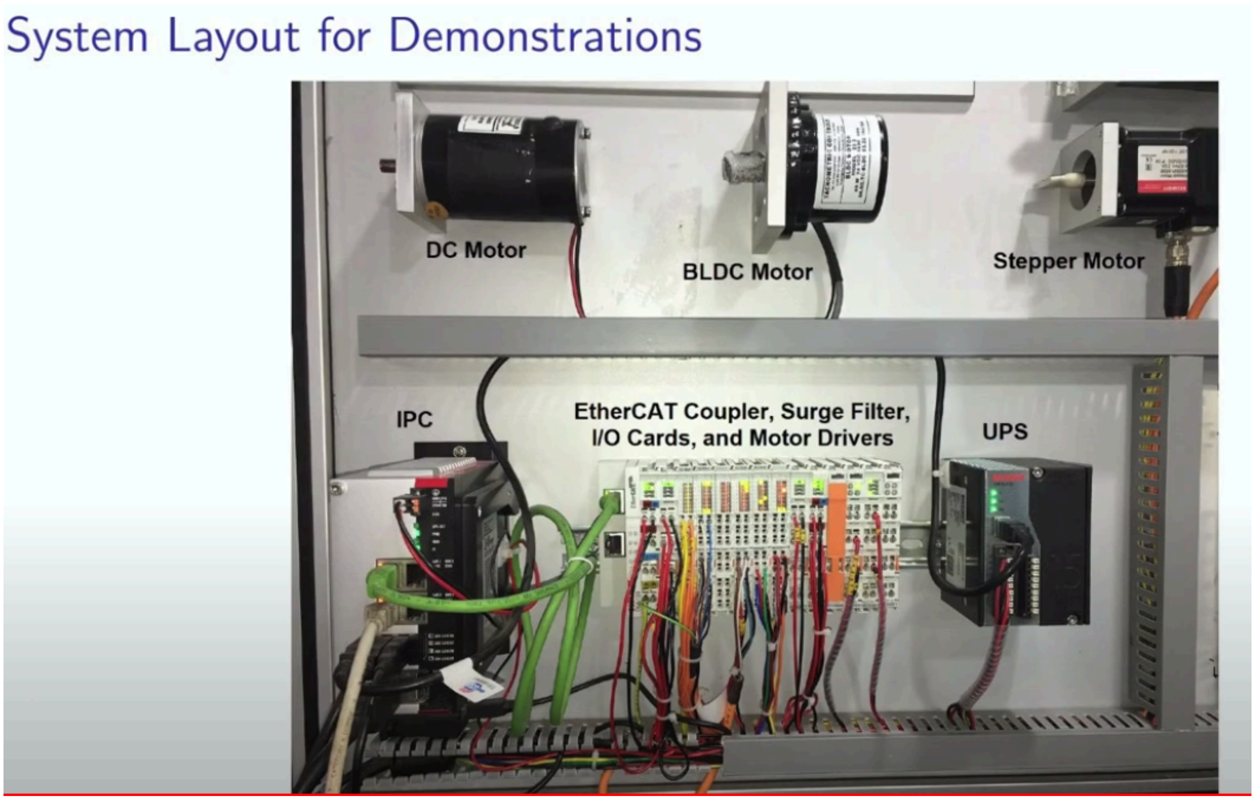
So, let us now have a demonstration of DC motor driving using industrial hardware. Okay, so now look closely at the parameters of what this driver can do. It has an inbuilt DC motor driver, not like this one. This is also a driver. So, this is an industrial driver that you have seen. It also can run the first motor from A1 and A2 and the second motor from B1 and B2 that has to be powered from 24 V port. It can drive a 24-volt 1 amp motor, and input power to this can be given from a Power port that is 0. The power is given from the port, and there are two inputs, which are also there as I1 and I2. So, now you look closely, it can have speed control up to 16-bit.

What does it mean? Actually, 0 to 100% of the PWM cycle, this duty cycle can have a resolution of 16 bits. 2 to the power 16 means so precisely you can increase the speed; so, this is there, and then it has some electrical isolation because it is an industrial driver it has to have this sort of safety inbuilt so that is there. Okay, so you see, this PWM crop frequency is very, very high. It is 32 kilohertz. So, you can imagine you won't feel the switching on and off of your PWM cycle. If you switch it on and off at a very small frequency, you will see a hum in your motor that noise will come. So, with such a high frequency, there is no noise. With such good precision, so this is what is an industrial DC motor motion interface. It is known as a motion interface. The communication protocol that I have used over here to drive this kind of driver is EtherCAT. EtherCAT, not 3.0, is the communication interface so soft in real-time that I have used it as a TwinCat 3.0 interface on a standard PC I have used. So, TwinCat is a proprietary software layer over a standard Windows PC that allows you to do some real-time communication. That is a software layer. Okay, that can do EtherCAT communication to its drivers to couplers; okay, with the couplers, I can communicate using TwinCat ADS using EtherCAT, okay so it just requires a standard Ethernet card of 1 gigahertz or so. Okay, so that is necessary for it to be implemented to do some real kind communication. So, what I have used here for programming is the TwinCat automation device specification. ADS TwinCat, ADS library I have used the library that you can import to the Python environment, which allows you to access the motor runtime variable once you have declared those variables in Twincat okay and made it available as an environment to the external TwinCat ADS driver, so this driver can take that variable directly from memory and do read and write operation to that memory location okay. So, your Python code can now read and write to the TwinCat interface. TwinCat finally sends it in real-time to the external driver.

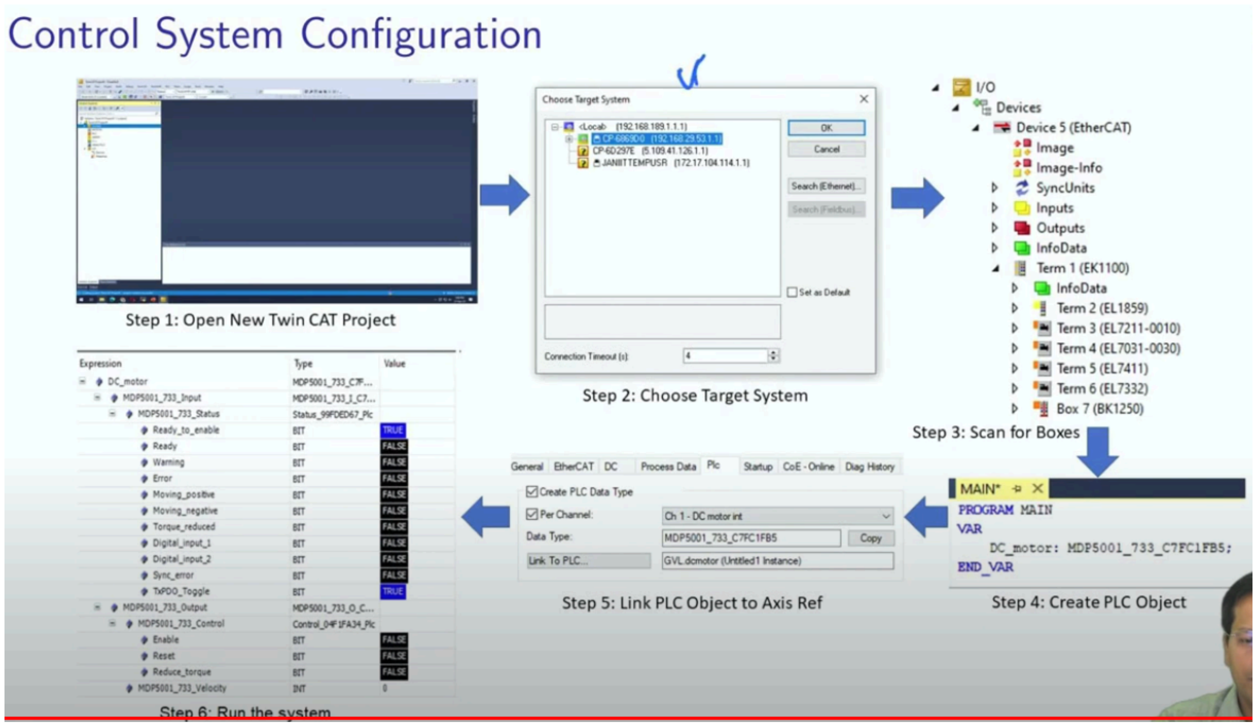


Now, We will see how it is all connected. So, it is the system. So, SMS 24 Volt is the power supply for everything. It is for the motor driver also. It is EL7332, that is the same one that you saw just now, so this is the motor driver. It takes in power from your surge filter, which is El9550. Surge filter to avoid any kind of jitter electrical noise from the main power supply right. So, that is there. It also supplies current to the Beckhoff couplers. So, EK1100 is the Beckhoff coupler. So, finally, this coupler takes in data from your industrial PC, which is C6030 IPC, and the PC has the Python program with TwinCat running. Okay, so it has a TwinCAT that is the application layer over the Windows IoT version that I had. Okay, it can also be installed on Windows CE. So finally, this is the communication that is the etherCAD communication that is provided to that is coming to this device, which is the coupler. It finally transfers this to the through ether CAD bus, which is here provided to the driver, and the driver finally takes in the data variables process variables to the motor. So, this is the driver, okay, so I hope you got this system right, so you have a program. Let me just repeat: you have a program; okay, you also have a software layer which is the TwinCAT, where you will define all the process variables.

TwinCAD is a real-time IO system that can communicate with external devices, whatever devices are there. It can talk to that, it can take in data, it can feed in data. Right and finally, it can make variables accessible to another programming environment. So, over here, this programming environment is Python. So, that is what is changing the process variable.

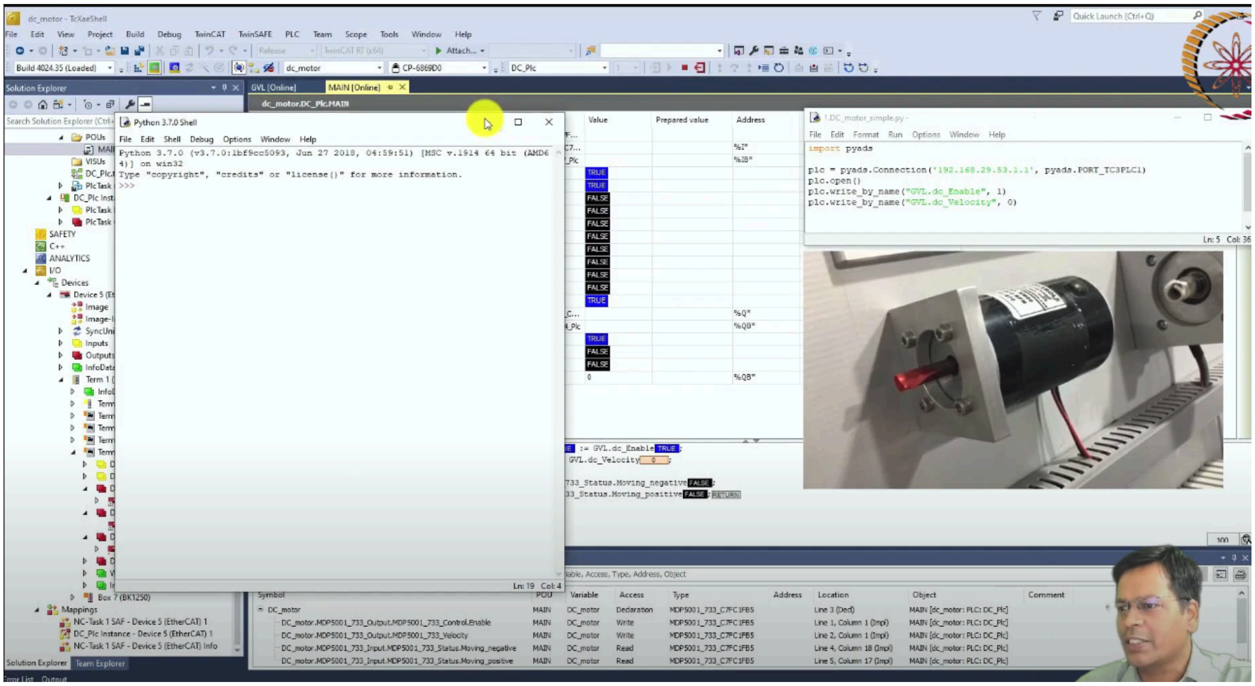


Now, go to the actual system. What does it look like? So it is your industrial IPC, UPS, EtherCAT coupler with a surge filter with input-output cards and motor drivers. Here is the DC motor that I am using today. Okay, so this is the DC motor. Forget about the other motors. I am NOT using this. Hence, the hardware is rigged up like this.



Finally, let me just show you how the settings are done. So, in step 1, you just have to open the TwinCAT project in the TwinCAT new environment, and then in step 2, choose the target. You have to create the target over here. Let me just see if I can show you somewhere from here is your system. You see, What does it look like? So it is your environment. So you can now choose the target. Now it is detecting all your external IPC which is there. So, IPC has different IOs which are connected. So, it has different terminals; you see input, you have terminals, you have motor drivers, you have other terminals, other motor drivers, everything can be seen which is here.

In step 3, scan for boxes. So now let me just take it to a little below. Now, in step 4, I will set the process variable to create a PLC object, so once you have this terminal is detected here. Now you can define and select the target system here and then you scan for all the boxes which are attached to that CPU. This industrial PC is integrated with different IO boxes. One of them is your motor. So, those boxes will have an object. If it is a DC motor, it has a DC motor object with different process variables. So, in step 5, you have to link the PLC object to the axis reference. So, I have just an axis for this PLC object. The object selected has an axis reference, one of which is velocity. So, that it can be accessed, this object has a process variable, that is, velocity. Okay, that is to be accessed from your environment. So, here you see so this is having this object has got multiple process variables. So you have to enable reset; you have torque and velocity also. Reduce the torque true and false so you see this is the actual variable that I have to modify. This is my complete DC motor object. So, it has all sorts of different process variables. Okay so once I select define this process variable. Okay, so yes, now this is access accessible to different external programming environments. So, in step 6, run the system.



Now, let me just run this video and define and show you very clearly. Okay, so this is just an example; when I will show you very much in detail over here. So, what you see here is defining a PyADS. PyADS is the twincat library. Okay, that is imported here in the environment that is imported here, and then PyADS is now able to connect to the external IP address that is to the port through the TCP port that is there so that it is connected. So, you have created an object over here; after once it is connected, the object is created by the name PLC. Now that object is open. Once it is open, you can write to a PLC variable 0, 1; whatever the value you can write. So, one of the variables is enabling, so once I write it 1, that means that the motor is enabled. Now, you can change the process variable of that motor, and that is known as velocity. Now, velocity can be changed by changing the values. So, very simple code; it is just in Python. So, now let me run. Now, you see what I am doing; I am just changing the process variable over here. Do you know what will happen? Let me just go back to this so now, when this was 0, you see in your velocity, the process variable is 0 over here velocity is 0. Once I change it, make it 5000, and run this, it immediately changes the velocity variable to 5000, and that goes to the motor, which is connected to the external driver. Okay, so that gives you some value of velocity. Now I have made it 10,000 motor runs at a higher speed, you can see. Again, I have made it 15,000 it runs at an even higher speed. Yes, now I will make it 0 again. Okay, the motor immediately stops. Now, I will try to feed some negative values. Let us let me provide it minus 5000 velocities. It runs at a slower speed, right? I get it minus 10,000. It has picked up a speed in the reverse direction with a little more value. Minus 15,000, it goes at a little higher velocity again, okay. So, this is how you can go from maximum velocity in one direction to maximum velocity in the other direction. You can stop the motor also. It is what, yes, so this was this was the video demonstration. With this, I will stop here and hope you have learnt the DC motor and how it is constructed? What is the principle behind and how a DC motor can be made to run using an H-bridge driver? You have learnt about industrial systems how it can be rigged up how they can be rigged up using a standard ether CAT system; no worries if you have a Modbus interface system, you can also access the process variable correctly, and you are required to have a Modbus IO interface that can be connected through Ethernet to your PC right. Then, you can access the Modbus variable, and the Modbus interface card will have a motor driver card. You can have an IO card that controls the relays, which is finally controlling the motor, so all the process variables are now accessible using Modbus. So you can have various other interfaces, not just the Backhoff TwinCAT-based system, which is really very expensive. I would suggest you start with a Modbus-based system Modbus IO card and motor driver card if it is possible; otherwise you can have a standard IO card. It can run a standard H bridge, and you can make your motor run okay. So that's all. In the next class, I will be talking about stepper motor what are stepper motors and stepper motors. So I hope you, if you remember your printer faxes, try to get all the all these pictures that you can see. All the motors which are there somewhere you must have seen it right. so try to bring up your memories and we'll talk about this later in the next class that's all thanks a lot.