Introduction to Robotics
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Lecture 26
Encoders for Speed and Position Estimation

In the last class we had looked at the set of machines that we had seen going from BC to BLDC to the synchronous motor with sinusoidal, and we saw what are the advantages and disadvantages of each one.

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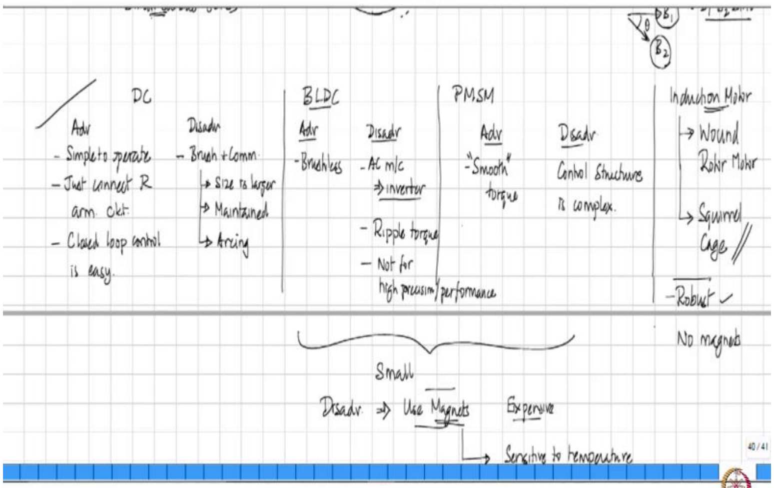

So, apart from this there is one more AC machine which is the induction machine, induction motor. So, the induction motor is an AC motor, it does not have all the disadvantages that the DC motor has, there is you do not have anything like a brush commutator arrangement and therefore, it is definitely of advantage.

The induction motor has these two varieties; one is called the Wound fields motor, I mean Wound rotor motor and the other one is called the Squirrel cage motor. And if one uses this variety then you do not have any electrical circuits to energize from outside on the rotor and therefore it is completely enclosed inside and because of this mechanical design, the induction machine is perhaps the most robust of all the variety.

This has no magnets and therefore heating is not an issue, there is not any sort of concern with respect to the level of demagnetization, etc, all these have no role to play. And therefore, this machine is probably the most robust out of all the different varieties that we have seen.

And industrial applications therefore by and large or larger capacity, this is the machine that they would use and historically what has been used.

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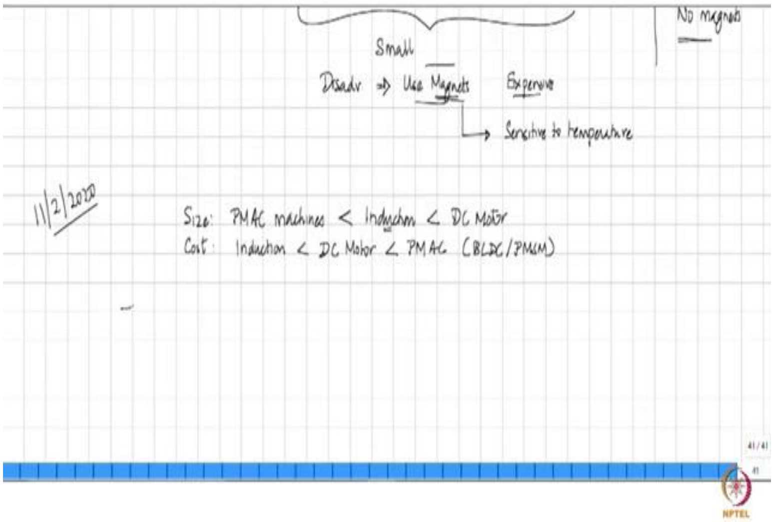

But however now, when you look at this induction machine, so if you look at the size aspect PMAC machines are the smallest and then you have the induction machine and then the DC motor. So, if you are looking at an application need where you really need a smallest electric motor that you can get, then you need to go for the AC machines having magnets.

So, if size is not so much of a restriction you are allowed to have bigger sizes then you would maybe go for an induction machine which is there. So, how to operate the induction machine it is basically the same as the synchronous machine, the loop structure everything remains the same. So, we will not have any more discussion about that, but it is a little more involved to operate the induction machine as compared to the synchronous motor.

Then the other most important thing is how expensive the motor is going to be. In this case, the induction motor most probably is the lowest, is the least expensive and then you have the DC motor and then you have the PMAC machines which include the BLDC or PMSM. Therefore, one would look at all these aspects that is the advantages, disadvantages that we saw, also which one is smaller, which one is larger, which is more expensive, all these will then decide which one you are really going to use in a particular application.

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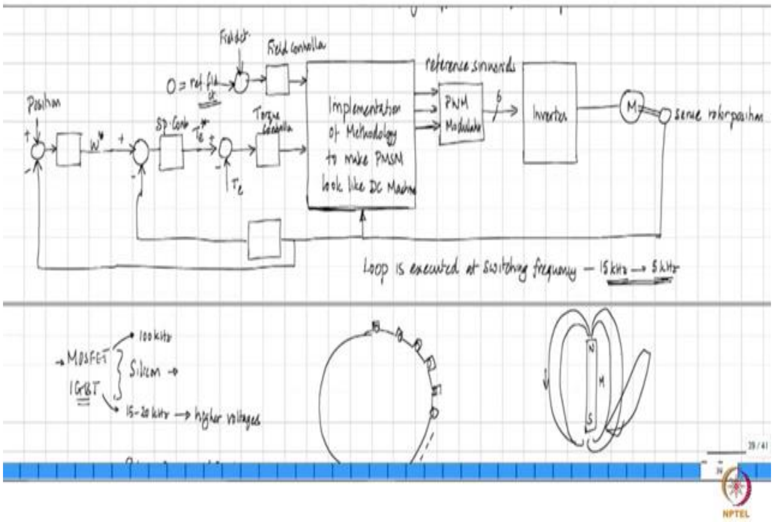

So, we have seen that when you are going to look at the designing of this loop for the AC machine, it is very important to have some kind of mechanism to sense the rotor angle. And of course, you may need to have a mechanism to sense the speed of the rotor as well. Speed of the rotor is then indirectly an indication of how fast your application is going to move, whether it is going to move along the line or whether it is going to be a rotating application whatever it is, speed of the motor is the one that is going to make it happen and therefore, speed of the motor is definitely an important indicator of how we design it. So, you will need to have some kind of a speed sensor.

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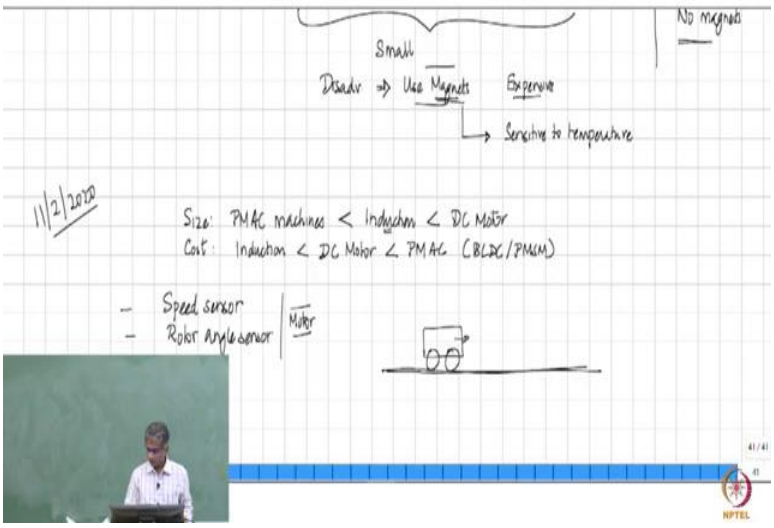

So, you will need to have a speed sensor and in some cases speed sensor alone is not enough, you will need to have a rotor angle sensor. Now, this is what is required for the motor and you may require additional information for your application. For example, now, let us say you are going to have a robot that is going to move, somebody asked me this earlier if this robot is going to move then if you are going to say that I am going to estimate the velocity of this entire vehicle based on the speed of rotation of the motor, yes you can do it provided the wheel does not slip. So, as long as the wheel does not slip then the RPM of the motor is an indicator of the velocity of motion of this.

But if you are going to have a slipping condition then the RPM of the motor is no longer a good enough indicator. Then if you are going to have slipping conditions then you need to have something else which will indicate what the speed of the entire system is. So, you may therefore need to have additional mechanisms to sense the speed which can be done in a variety of ways, so that is a different issue.

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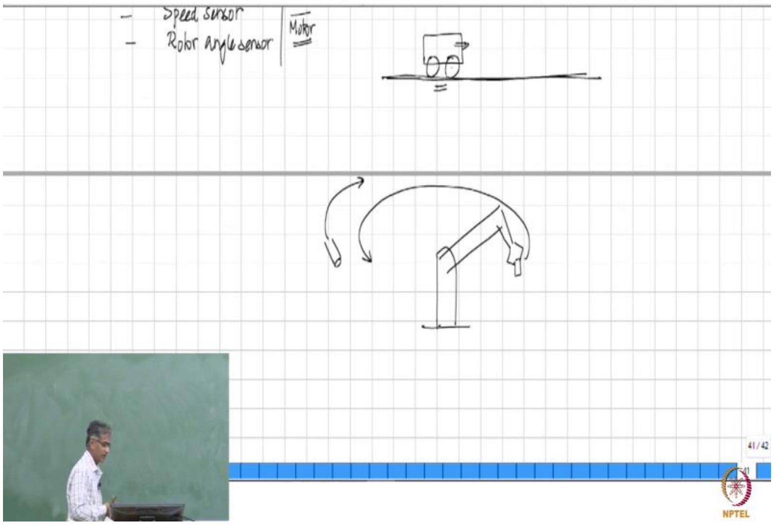

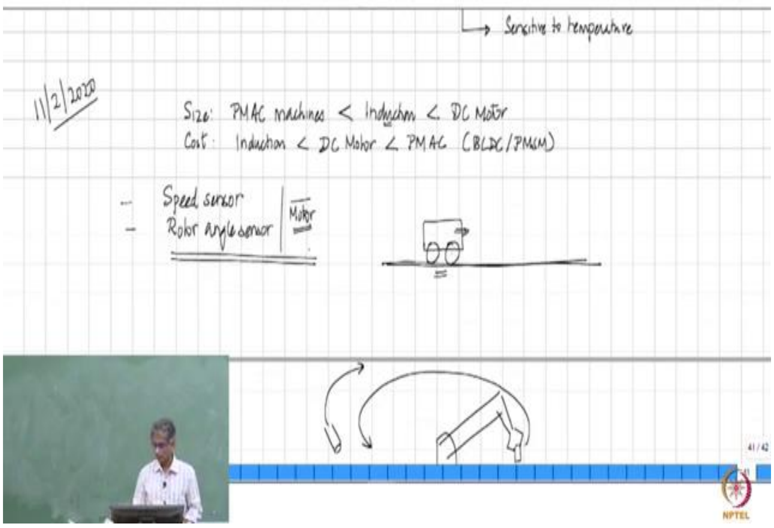

In certain other applications for example, let us say you are going to have a robotic arm which is going to lift some object and put it somewhere then you need to have some kind of arrangement to sense that it has lifted the object, all that is there built into the robot definitely in some way, but how do you know whether this has moved and reached the end position?

You can of course say that I will determine how the robot moves all the while because you know the rotor angle, you know the mechanical arrangement, therefore you can always convert it into some inquisition. But how do you know that no error has happened in between?

So, you may need to then have an additional information regarding maybe you will need to put a sensor somewhere here, which will indicate whether the arm has reached there, and this may need to give information regarding where it is. So, you may therefore require in the overall application perhaps additional sensors depending on the needs of the application.

For automobiles, you cannot depend on an external mechanism to sense, whatever you need to put has to be built in to the automobile. Yeah, so that is then a difficult issue. What you will need to do ideally is you will need to have some other mechanism to sense the velocity, maybe you can use air flow or an alternative will be, you somehow design your electric motor control system to ensure that there is no slip.

So, which is what is usually done in the case of electric locomotives because there estimating the speed is very important because you need to go exactly and stop somewhere, you cannot all the time depend upon the fact that it may not have any slip or it may have slip. So, you have to estimate what the slip is going to be in some way and then you have to control the motor such that that does not happen. So, those are definitely required to be built in but the sensors that we will look through for some time is those that are required for the operation of the motor itself.

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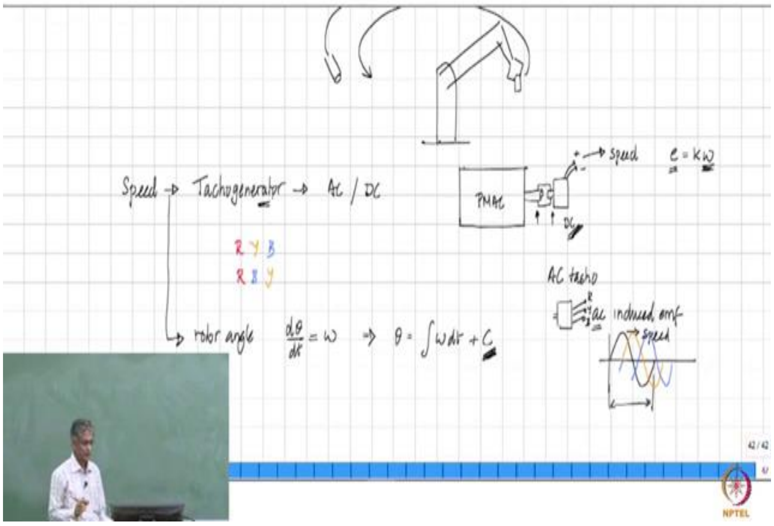

So, if you are going to sense the speed of the motor, the simplest is to have an instrument or an equipment called tachogenerator. So, this by itself is an electric machine, it may be an AC motor, it may be an AC generator or it may be a DC generator, which means that if you are going to have your electric motor sitting here and then you have the shaft of the motor, you then attach another small electric motor to it, electric machine to it and you take its output and you ensure that this is well linked, there is no slip that happen in between.

Then the shaft of this motor will rotate at the same speed as the shaft of the other motor which you are attempting to control, and if this is going to be a DC machine for example, as the shaft is going to rotate you will get a DC voltage induced in it.

So, this can then be sensed and this is an indication of speed, we have already seen that for the case of DC motor the induced EMF is K times speed and therefore, as speed increases, so will induce EMF and therefore it gives an accurate indication of speed all the time, if the shaft is going to rotate in the opposite direction, then omega is reversing and therefore induced EMF will reverse and therefore you can also detect which direction the motor is operating.

So, this is something that can be used always, but the difficulty here is that it is still a DC machine therefore, even if this is an AC machine, you are having a DC machine there which means that you have to replace the brushes, service it. So, all those requirements will be there to ensure that the machine operates the way you want it to be.

So, though this is a very good mechanism to sense the speed, because you get instantaneous velocity either direction, there is sometimes hesitation to use this for actually sensing the speed. The other option is one can use an AC tacho, which means that this is an AC generator that you are going to connect which means that the induced EMF will be AC and this means that you will get an alternating waveform, whose amplitude depends upon speed and also frequency will depend upon speed. So, both of them are going to be speed dependent and therefore you can choose to detect in your circuitry either the amplitude or you can detect how frequently the AC cycle is going to change, anyone will indicate what is the speed.

But if you want to also sense the direction of rotation, then it is not sufficient to have a single phase AC, you will need to have R, Y and B and if you have this, then you will have the other phase like that and the third phase will go like this. If you are going to rotate in the opposite direction, then instead of what you have as R, Y and B, which comes one after the other, what will happen when the direction of rotation reverses is you will have R first and then B and then you will get y.

So, if you are able to detect the sequence in which the induced EMF occur that will give you an indication of what is the direction of rotation whereas, simply being able to detect the amplitude will tell you what is the speed at which it is going to be rotated so in this way one can detect the speed.

And from speed you can get a sense of the rotor angle as well, how can you get that after all d theta by dt if this is the rotor angle, this gives you the mechanical speed and therefore, if you want to get the rotor angle itself, you simply integrate the detected value of speed. So, that will give you where the rotor is at any given instant provided where it is initially.

So, if you know the initial position then from there knowing speed, you can always integrate and get what the rotor angle is, but the difficulty is going to be how to get the initial position. So, that is really not one cannot get initial position in these cases so these approaches can be used only if you are interested in speed and not in the rotor angle.

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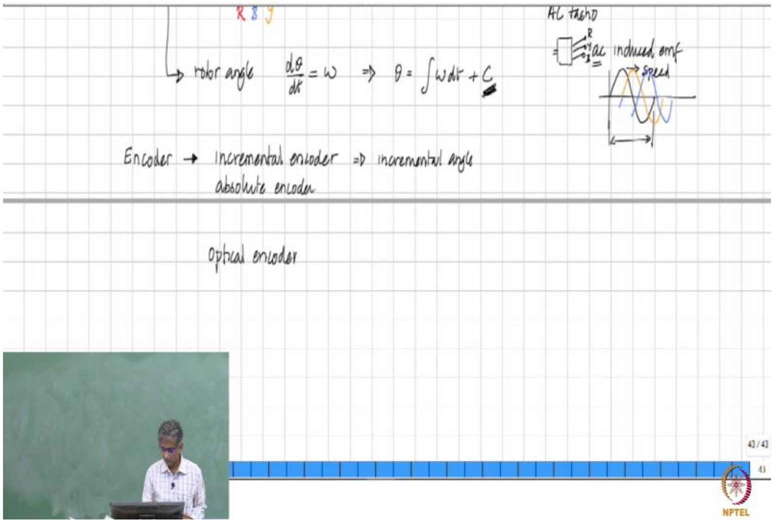

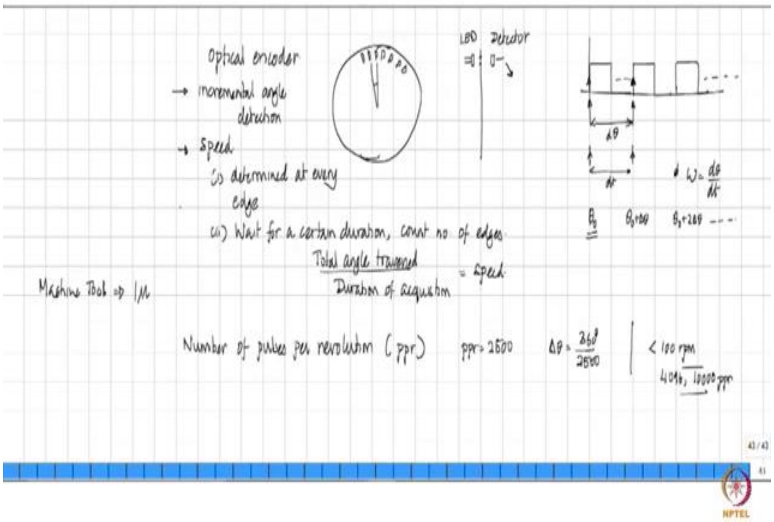

So, the next most frequently used mechanism to sense the speed is what is called as an encoder. So, an encoder is of these two varieties; one is called as a incremental encoder, another is called absolute encoder. An incremental encoder can give indication as to what is the incremental angle over which the rotor is going to rotate, that means from now to the next instant, what is the incremental increase or decrease in the rotor angle but whereas, the absolute encoder is another instrument, another means to sense which at every given instance says what is the absolute angle of the rotor.

That means, as soon as you energize the system if you switch on the supply, the absolute encoder says this is where the rotor is at an angle of 60 degrees or at an angle of 50.5 degrees whatever, but from the incremental encoder as soon as you switch it on you do not get anything.

So, how does the incremental encoder work? Incremental encoders are again of different varieties, the most frequently used one is the one called as optical encoder. The optical encoder basically contains a disk having large number of slots around the circumference, and if you have a slot here and then you have also an LED positioned on this side and you have a detector.

So, this is an LED and here you have a detector which means that in between if you are going to have a slot that is going to be located then the detector will be able to see the LED emitted by the LED, but if the rotor is going to rotate a little bit and the slot goes away, then the emission from the LED is not allowed to reach the other side and therefore, the detector does not see anything. So, if you look at the output then from this side as the rotor is going to rotate, you will get a high when the LED is able to be seen and when the LED becomes invisible because the disk has moved, then you get a low pulse, then you get high low and so on, it just goes on.

So, you know the angle by which the different slots are distributed and because of that, when you get a signal, high level signal between that and the next high level signal you know precisely what is the angle through which the rotor has rotated. And if you know the interval between this height from low to high instant and you know the instant at which the next high edge occurs, then if you know this instant DT and let us say this is equal to D theta, then speed is given by D theta divided by DT, this is one way of doing it. If you know this angle let us say this is the initial angle, if you know this angle then because you know the incremental angle through which the rotor would have moved when the next edge arises therefore, you know what the next angle is?

Therefore, if you know this angle, you know that the next angle must be equal to this plus the delta theta and then at the next stage it is equal to theta naught plus double of delta theta and so on. Therefore, if the initial angle is known, at every edge you know where exactly the rotor is.

Therefore, this mechanism can be used as an incremental angle detection and it can also be used to detect speed. So, speed for example, you can detect for every edge let us say high going edges between this edge and this edge you know the angle, you determine the speed. Alternatively, you can now anything that you make has errors.

So, if you say that the angle between one slot and the next slot, you want it to be equal to this much and somebody has made the encoder and given it to you, you can be absolutely sure that this angle is equal to that much, there is always an error that is going to be there. So, in order to overcome the effects of this error, you do not determine the speed with respect to every edge, but rather you accumulate the number of edges and say that one is determined at every edge.

The other way is, wait for a certain duration, count the number of edges. So, you know that so many edges have occurred, and on an average you hope that the errors that are there in the actual locating of the slots are averaged out and they go to 0, so on an average from this instant to that instant if so many edges are there then you know that it must have gone through certain number of angles.

Then, you have therefore the total angle traversed divided by the duration of acquisition will then give you speed. If you want to locate the rotor angle of course, then you take the speed and integrate so that is the other way. So, if you have this kind of an encoder, speed information can at the earliest be obtained when the next edge occurs. If you have located this edge then until the next edge occurs, you do not know what the speed is.

So, for example, if you are going to have a very slow speed of rotation for some robotic application, let us say you want the rotor to rotate at very low speed, therefore if you use this encoder you have detected one edge and then by the time the next edge comes, so much time would have gone by and in between that time you do not know what the rotor is doing, you do not know what speed it is rotating in and therefore, it may be in error.

So, if you want to have accurate control of speed for slow rotations then it is required therefore, the number of slots in this should be higher so that even at low rotations you get reasonable number of edges, I mean you get edges at reasonable intervals. So, the number of pulses per revolution which is called as PPR, this is one important index of how good an encoder is going to be or how well it can be used or for which speed ranges it is applicable.

So, for example, you have encoders that have PPR equal to 2500. So, it means you will have to look at it, the implication of this. So, this means that the angle resolution that it is going to have is 360 degrees divided by 2500, this is the minimum angle which you can minimum movement which you can detect and then you have speed. So, speed is going to determine how long it is going to take in order to go through this angle. And if the speed is too low and you are not satisfied with that, then it means that you cannot use this encoder, you will have to go for something that is higher.

So, usually, if one wants a speed of less than about 100 RPM for industrial application you need at least 4096 or probably 10,000 PPR encoders. These will give you very accurate ability to control the speed because you have more frequent information regarding speed, the higher the number is the better your loop will perform, but then the more expensive it is going to be as well. So, you have to take a call regarding what is the accuracy requirement you have as again how much money you need to sink in for this.

At very high RPM is not an issue because you are going to get pulses. It will not be an issue because this is going to be handled by electronics. These output signals that are going to become high low signals are going to be given to some electronic circuits. And usually electronic circuits will not face a difficulty with high frequency. Yeah, that is true. So, you have to do your system design appropriately. I am not saying that any circuit will be able to handle anything. All I am saying is normally electronic circuits can handle high frequencies without any issue and therefore you can go for high PPR.

No, You can. Usually if you look at very high accuracy applications for example, if you take machine tool applications, these are some of the most demanding accuracy needs. And here you have a requirement to make a step of 1 micron, which means that you are really looking at the angle of the rotor moving by a very-very small angle and then you want to stop. So, the motor energization is only for that much time and in that much manner, so that the rotor just moves by a small angle so you will need encoders that are very high accuracy in such cases.

So, it is not well usually these kind of requirements high precision requirements arise only for a proper industrial application. So, yes as you go for higher accuracy industrial applications you will need, but there may be several applications where angle resolution is not so important, speed is what is important and you may not be operating at low speeds in all applications, 100 RPM is a very low speed usually, because I mentioned about how big the motors are going to be.

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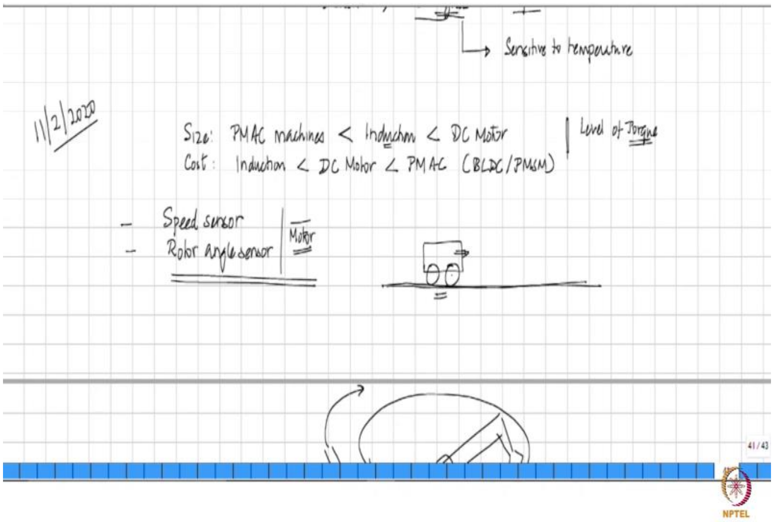

Now, one important thing that is going to determine how big an electric motor is going to be is the level of torque. So, if you are going to look at a high torque motor then it means that more amperes has to flow through it which can be accommodated only if you have large armature conductors, which means the motor size will have to be big.

So, if you are looking at a particular application and which says that in order to move my robotic arm let us say I require to have this much torque. So, the issue is whether you will have an electric motor that generates that much torque as such or you can choose a motor that will generate lower torque but step it up using some mechanism.

So, usually you do not want to have an electric motor that is a high torque motor, because if you are going to use a high torque motor it is usually bigger and more expensive. So, you will choose a motor that is lower torque and usually as you go to high torque the RPM requirements are not so high. So, you will then choose a motor that is low torque but high speed and therefore the motor will be small, it will be lower cost and then you will use some mechanism to step up the torque and reduce the speed as well.

So, this is what one would use and therefore when you say that you want a certain speed and a certain amount of load torque, one has to look at whether you want that speed at the load end or at the motor end. So, even if the load is going to be for example a very, very low RPM load, you may not want to use a motor rotating at that speed, I will give you an example.

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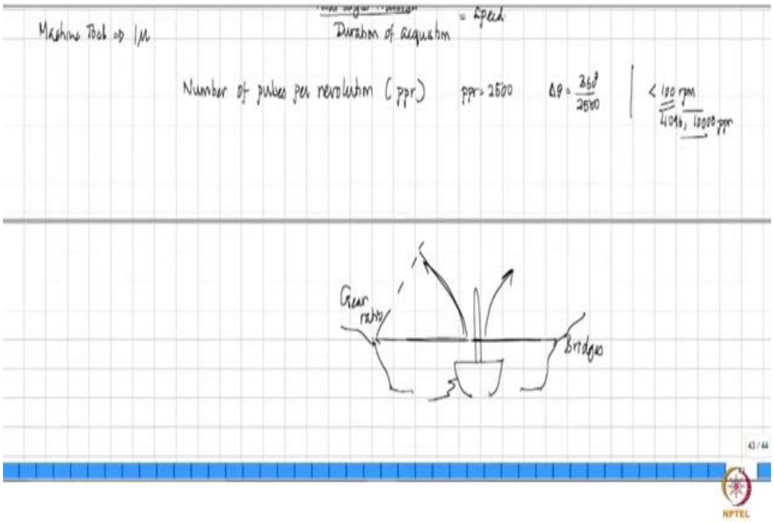

You have when you look at operation of bridges, there are different ways I mean let us say for example, you have a river that is going there, you have a hillside and you need to have a bridge and the river is in a way such that you need to allow some chips to go through, which means that this bridge has to be somehow let us say opened up.

So, you will then do the design such that this is you are able to split it and this part can rotate this way, this part can rotate this way so the bridge opens up and the ship will go through and then you can close the bridge, so this is one way of having the arrangement. There are other ways of doing this as well.

Now, the bridge when it is going to rotate, how fast do you think it will move? It is not going to you know, the angular speed would not be something like 1500 RPM. It is a huge mass that is going to move and therefore it will move at a very, very slow speed maybe to go from horizontal all the way to some particular angle, it may take 6, 7 minutes.

So, that is a very low speed requiring huge torque, because that is a big iron, hopefully it is iron and that is going to be moving, it is a huge torque requirement on the motor and you will not have an electric motor that will generate that much torque, you can make it if you want but it will be a huge motor, very expensive, so, nobody will do that.

Instead and if you see if it is going to move from this angle to this angle, it is not even going to complete one rotation, it is only going to go from 0 to maybe 45 degrees that is all. But the electric motor that is operating it would have finished many, many times rotating in order that this fellow goes from here to there.

So, you are going to have a large gear ratio which will step down your motor speed and will reflect that the speed of the load. So, by the time the motor has done innumerable number of rotations, this bridge has only moved by that much. So, the motor therefore will be smaller and therefore, the motor may not really require to rotate at low speeds in most applications, there are certain applications where you do not want gears due to various reasons and you may want to have a motor that can rotate at low speed by itself.

But one has to look at the economics of the whole thing and which one works out better for you. So, not many applications would be there where you really need to go to very low speeds and therefore you do not really need high PPR encoders all the time, it will be by and large sufficient to use an encoder like 2500 PPR or maybe even lower can survive.

So, in this way then one can find out what is the angle and what is the speed. But then the question is, how do you get this initial angle? There must be some way to get the initial angle otherwise, you still do not know, you can get speed information nevertheless, because you know the incremental angles and you know the duration, you can get the speed. But if you want to get the actual angle, then there is another facility, there is another slot that is given in this, which is only one single slot in the region where it is located. So, you will have a mechanism to sense that as well.

And therefore, this will detect the slot only once per rotation and that is then known as index pulse. So, this index pulse occurs once per revolution and you can therefore use that as an indicator of a reference angle because the encoder is physically fixed to the rotor of the motor which you want to control, it will always occur when the rotor goes at when the rotation goes to a particular angle because it is fixed, and therefore you can use these index pulse as an indicator of saying that is what I will consider the rotor angle 0 to be. And then from then on you can determine where the angles increase or decrease so this can be used as angle 0.

Yeah, you can always detect this angle. But how do you know where to start? No, you really have a difficulty. Let us say my robotic arm is there, and the earlier instant when I operated it, it had moved all this while and I have stopped it at this point so I know where I have stopped it. I know in the sense the electronics inside the software that you have written knows where it is.

But before I switch it on for the next time you enter the lab and you start discussing with all the people who are there and you lean on this arm while discussing and this arm moves a little. So, next time when you come and switch it on, this movement is not recorded by the electronic because it is deenergized. So, now how do you know where it is? Yes, so that is an uncertainty. But that is going to happen in one rotation, within one rotation of the rotor you will get an index plus.

Now, if your application mechanical design is such that within one rotation of the rotor the arm is not going to move by a large distance, you may say it is okay. But if that is also an issue for you, then this cannot be used or you can use encoder only in those applications where you do not want the instantaneous position to be controlled, but it is enough if you know the incremental angle, it is enough if you know the speed, if there are such applications, then this absolute encoder can be used.

That is more difficult to build, you can do that, you are essentially you are saying that it is equivalent to saying all these are not spaced uniformly, but you can have a difference and because you know where the difference is, how you have designed it you know where the rotor is going to be. Yes, but it is then going to be a non uniform split and it will give you difficulty when estimating the speed, you are not going to be waiting for the same angle all the time.

And therefore, when you want to estimate speed, you will really have to wait for one full rotation to complete before you get a speed estimate. So, you have difficulties either way so I have seen an application where you know they have overcome this in some way that is the electronics even if you switch off there is an internal energy storage that have given which will store all the data.

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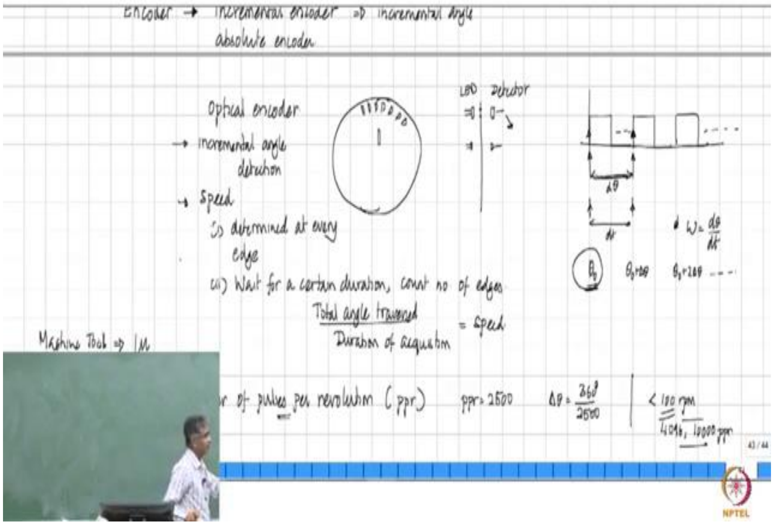

So, that when you start next time assuming nobody has hand moved it, you know where the system is and you can start directly that is one approach provided nobody can hand move the system, nobody can upset alter the system in between. So, the other difficulty however, this does not give an indication as to what is the direction in which it has moved, because anyway you will get this kind of on-off signal, whether it was in one direction or the other direction. Therefore, in order to detect that as well you have one more set of slots, which are placed midway between this.

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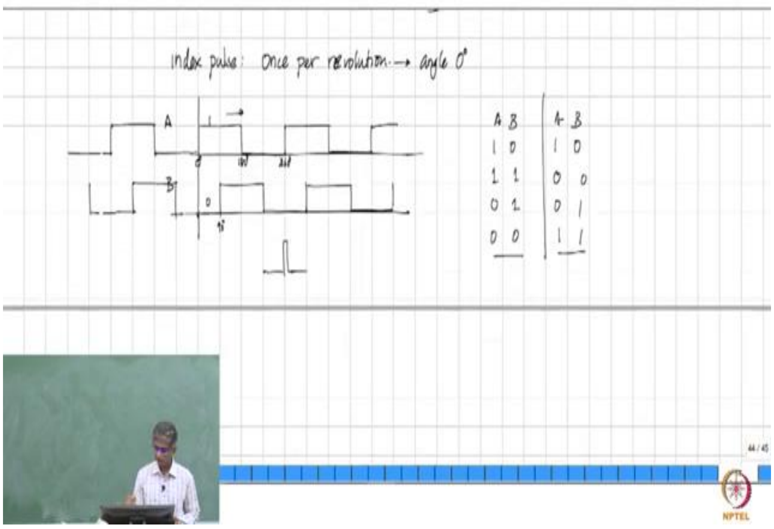

Therefore, you get from the encoder a channel A output and then a channel B output as well which would look like this. If this is A then B would look like this which is phase shifted from A by an angle of 90 degrees.

So, if this is 0 degree and 180 degrees and 360 degrees of the encoder pulse, it is not 360 degrees of rotation of the rotor, then this angle is going to be 90 degrees and therefore if you are now going to be moving in this direction, then you see that for A and B, at the first instance you have 1 and 0, and then you have 1 and 1, and then you have 0 and 1 and then you have 0 0, this is the sequence in which you are going to be detecting the edges, if the motion is such that your encounter edges encounter levels this way.

If you are rotating in the opposite direction, then you will encounter it in a different direction that means, let us say we draw this further. So, if you are going to rotate in the reverse direction, then you start with 1 0 here then the next one will be 0 0 and then it is 0 1 and then 1 1. So, you see that the sequence of occurrence of the levels, whether it is 1 or 0 is altered depending upon the direction of rotation and therefore, if you detect an appropriate thing, you know which direction you are rotating so, this is A and B again.

And together with the index pulse occurring somewhere you have to have a means to say that I know what the absolute angle of the rotor is also, provided this operation is admissible that is one rotation in either direction should not cause any difficulty with your application. Then you can detect the index pulse and then from then on you can do the control as you want. So, we will stop here and then continue in the next class.