Introduction to Robotics
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Lecture 25
Principles of PMSM Control

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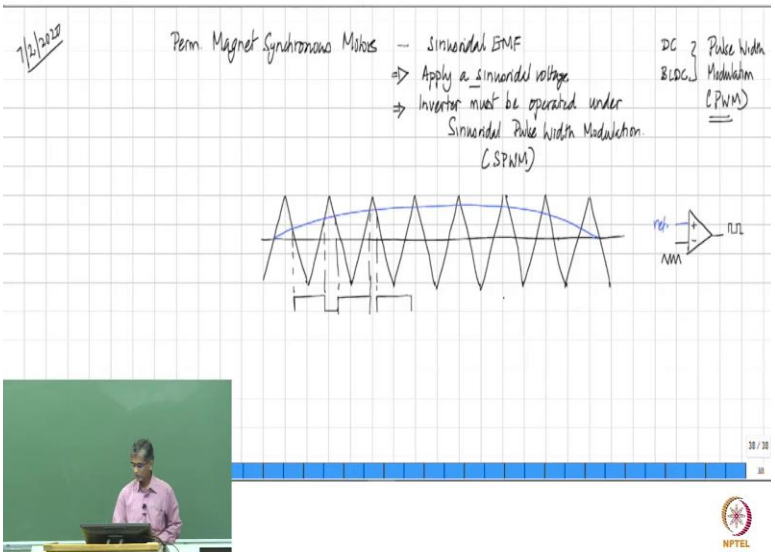

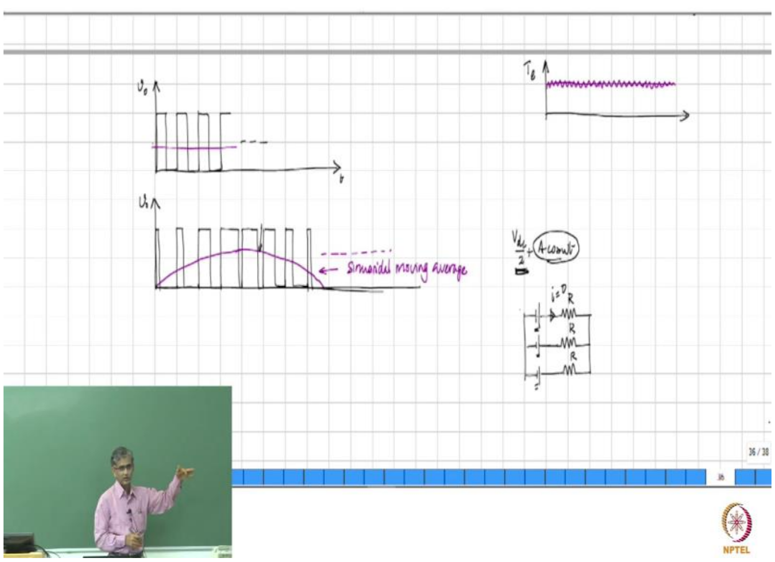

We started looking at Permanent Magnet Synchronous Motors and we said that it is distinguished from the brushless DC motor by having a sinusoidal EMF that will be induced in the rotor, induced in the stator when the rotor begins to rotate. So, we have seen therefore, that this will mean that you need to apply a sinusoidal voltage to it in order that you can have a meaningful interaction on the electrical side.

So, if you need to apply a sinusoidal voltage which needs to come from an inverter then we have seen that the devices, the inverter devices have to be switched in a manner that the duration of on-time of the devices is, it needs to be varied in a way that reflects the variation of the sinusoid amplitude. So this is then called as, that is the inverter must be operated under Sinusoidal Pulse Width Modulation.

In the earlier case where you had DC motors and the brushless DC motor, in these two cases also we had used pulse width as a means of conveying information regarding how much voltage needs to be applied. So, there also we have a control on the width, so this is just pulse width which is being modulated. So, this is called therefore as PWM and this is called as SPWM.

How does one do this? In a manner which is analogous to the way we saw here you have to take, you can take a high frequency waveform like this, triangular waveform and let us say this is your 0 level. What one does is then have a reference sinusoidal waveform, I mean somewhere you will have to have a way of indicating what is the sinusoid you want to reproduce at the inverter output, and therefore you need a reference for that sinusoid.

So, you take that reference for the sinusoid and make a comparison with this waveform and so, in a manner similar to what we have seen earlier, what you do is you have a comparator and to this comparator you give the high frequency waveform here and to the other input you give the reference. And this comparator will then generate an output which is going to switch between 0 and 1 or low and high and that low and high is going to depend on these amplitudes, these intervals.

So, in the way in which we have drawn, this will mean that you will get a high pulse here and then this high pulse will be slightly longer duration, then this will be slightly longer duration so on and it will increase and then decrease.

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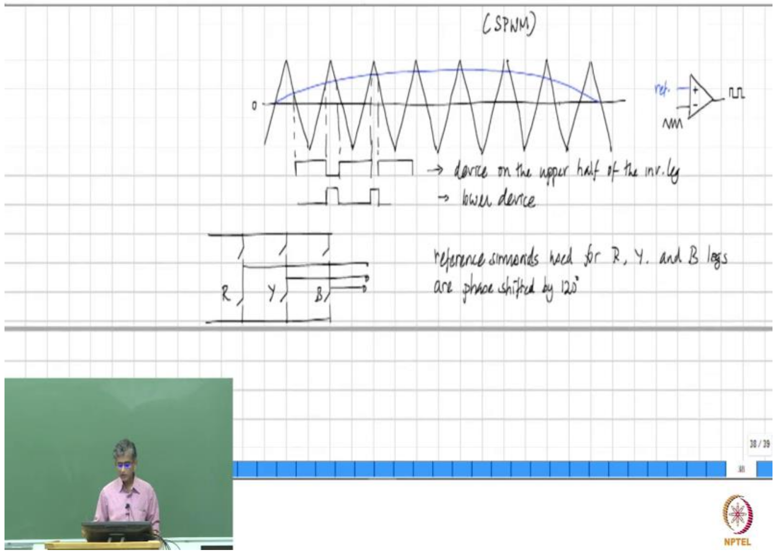
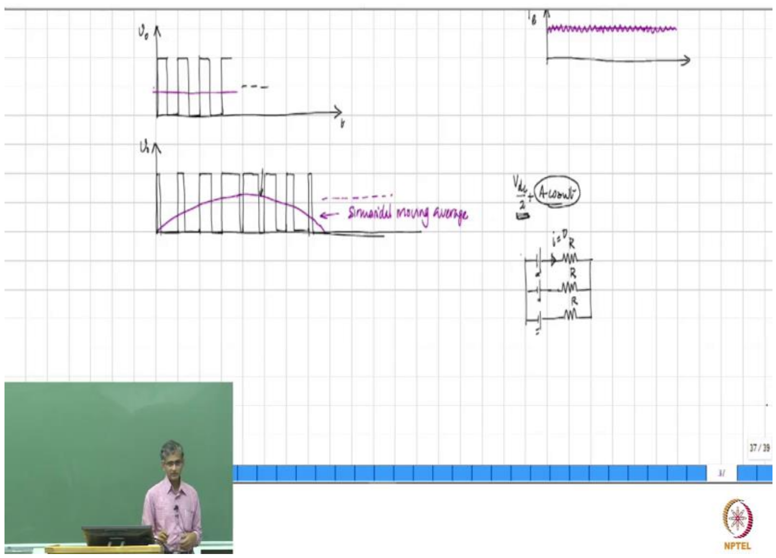

(SPWM)
ref.
0
→ device on the upper half of the inv. leg
→ lower device
R
Y
B
reference sinusoids used for R, Y, and B legs are phase shifted by 120°
38 / 39
NPTEL


← sinusoidal moving average
R
R
R
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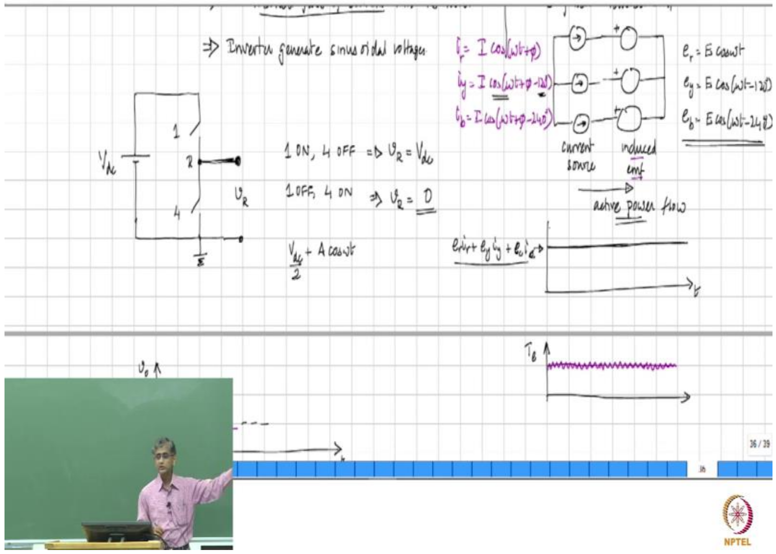

So, this can then be given to the device on the upper half of the inverter leg and then you generate an inverse which is given to the lower device. So, if you do this then you will be able to generate a system that looks like this and therefore you get a sinusoidal moving average and the electric motor responds only to the sinusoidal moving average because the other term which is there which is DC, the motor does not respond to DC because all the phases have the same level of DC so there will be no current flow due to the DC component but you will have current flow due to the sinusoidal component.

And the way it is done is then the inverter has 3 legs. Then you have one phase of the motor, second phase of the motor and third phase of the motor. So, if you call this leg as R, Y and B then the reference sinusoids used for R, Y and B legs are phase shifted by 120 degrees. Therefore, you are able to generate at the output of the inverter effectively 3 sinusoidal supply voltages that are phase shifted by 120 degrees. The motor-induced EMFs are also phase shifted by 120 degrees and therefore there is a meaningful interaction between the output of the inverter and the electric motor.

You need not, because if you do it like this with a 0 and this sinusoid, the very fact that you are going to be switching an inverter leg that looks like this introduces a DC offset because the output from this can only switch between 0 to Vdc. You cannot have a negative, you know, a negative output from the leg.

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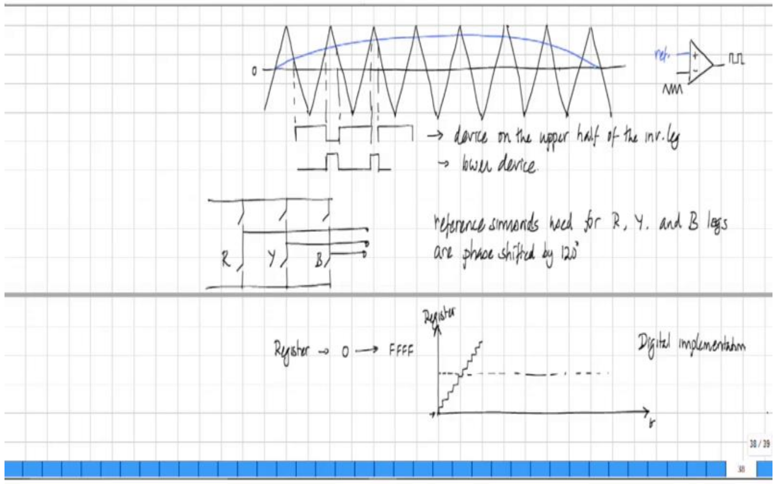
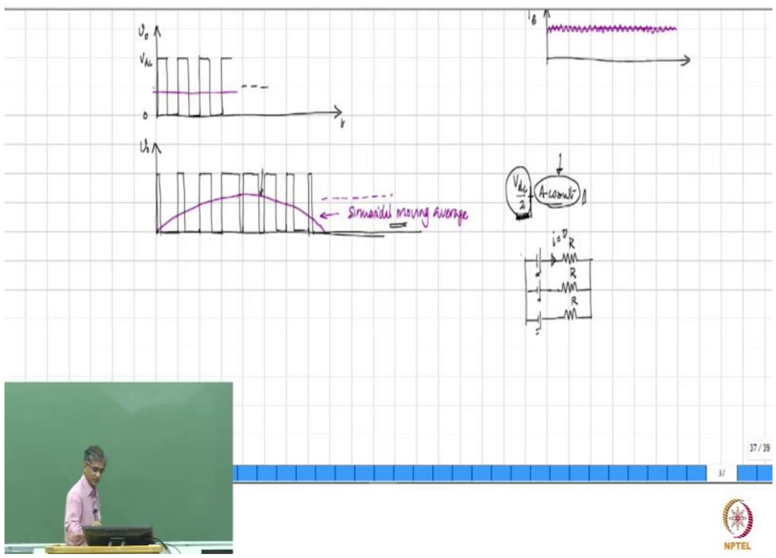
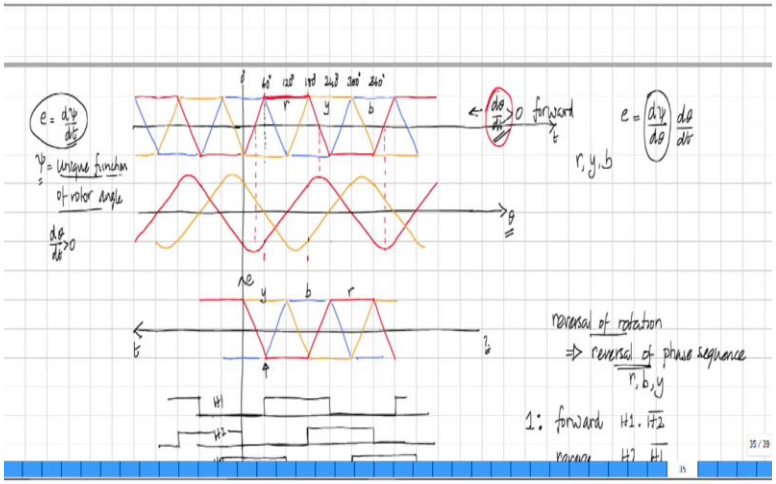

ref
→ device on the upper half of the inv. leg
→ lower device
R
Y
B
reference sinusoids used for R, Y, and B legs are phase shifted by 120°
Register → 0 → FFFF
Register
Digital implementation
38 / 39


V_dc
sinusoidal moving average
A-counter
R
37 / 39



So, this way also can be done but if you look at the actual implementation that happens inside a digital system then in the digital system how this is done is, you have a register which goes, which is incremented from 0 to some high value, let us say FFFF. So, which means that if you are having, this is with respect to time, this is the register number, then the register number goes on shifting from 0 and because of this you cannot have a high frequency waveform that is going to go negative.

So, in a digital implementation, that is exactly what you will do, that you will level shift the AC waveform by half this amplitude and then do a comparison of the numerical value of the amplitude level shifted with this waveform that is also level shifted. So, you still get the same sort of output in any case. So, this would be the manner in which you would do it in a digital implementation.

No, if you look at the induced EMF inside the machine that is going to be alternating. It will go high, it will go high and it will reach back 0 then it will go negative, go to negative maximum and then come back. So, that voltage waveform is going to be alternate and therefore you have to give an input voltage to the motor that is also alternating, it has to go negative.

Now, it has to go negative but, you were not there in yesterday's class, it has to go negative but we are offsetting it and if we offset it, this component does not cause any impact on the machine because all 3 phases have it. Therefore, the motor will respond only to this component which does go negative. It has been level shifted by DC that is all. And that level shifting is harmless to the motor because you are level shifting all the phases. Therefore, the motor does not respond. The motor responds to whatever is alternating and therefore it works.

So, this is fine but we have another difficulty that the induced EMF that is happening inside the motor is going to be dependent on the rotor angle. Just like we drew this waveform for the earlier electric motor, this is for the brushless DC and we said that the induced EMF is going to depend on the angle of the rotor.

Similarly, in this case also, the induced EMF depends on the angle. Therefore, if you are going to generate a sinusoidal waveform from the inverter, that sinusoidal waveform that is generated also has to be dependent on the rotor angle. Otherwise you cannot have a synchronization between the two.

Therefore, if you need to generate a sinusoidal waveform that depends on the rotor angle you must know the value of the rotor angle. Unlike the earlier case, where the induced EMF if you had determined this instant, if you had determined, if you have identified this instant, then from this point onwards the induced EMF is basically flat, leaving aside the phase that is going to vary, the other two EMFs are going to be flat therefore there is not anything that is going to change.

Unlike this case, in the case of the, in the case of the sinusoidal EMF machine, the EMF is going to change instant to instant. As the rotor is going to rotate, the EMF value also goes on becoming different, and therefore you cannot operate this machine without knowledge of the rotor position instant to instant. In the earlier case, it was sufficient to at one instant then you only need to know where the rotor is when the EMF begins to change again. Until that time, you know that it is fixed therefore there is no problem.

But whereas here the EMF is going to change instant to instant and therefore you need to know the rotor position instant to instant so that you can relate if it is at this angle I would expect that much of EMF given the speed.

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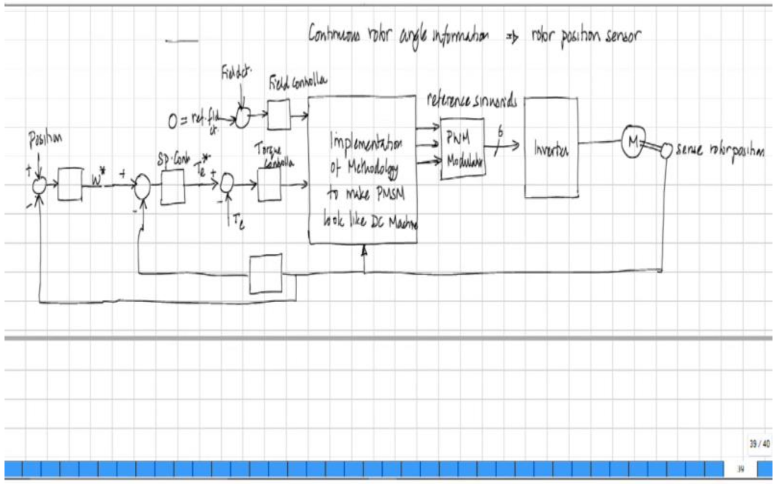

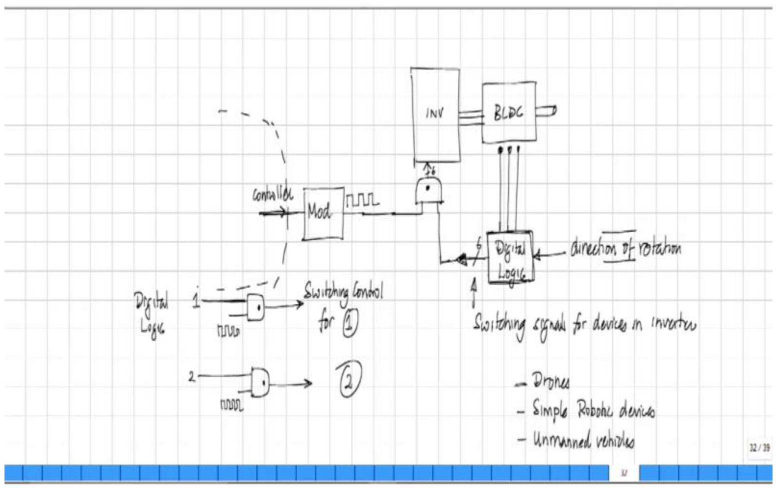

So, therefore you need in this case, continuous rotor angle information. Therefore, it is usually necessary that you put a rotor position sensor in this machine. So, if you really want very high precision operation then it is necessary that you have a rotor position sensor. Without that this motor cannot be used.

So, having said that, however the philosophy of motor control operations will remains the same; in the case of the earlier machine, we did draw the block diagram of control circuit. We said that whatever happens here is still the same as that of the DC machine. The only difference now is that you have a different motor so the inverter has to be controlled by the all switch information. We were able to derive a digital implementation of that.

In this case also what we have is, the same sort of arrangement, that you have maybe a speed reference which may come from angle reference and error and all that but I am just leaving that out. And then you are going to compare the actual speed. Then we need a controller that besides what should be done based on the error and based on the error and speed what the controller will say is how much electromagnetic torque needs to be generated. So, that is then the reference for electromagnetic torque.

This electromagnetic torque has to be then compared with what is the actual torque that is being generated in the motor. This is the actual torque signal and this is then acted upon by a controller which gives an output. This output is going to tell the inverter how much voltage to apply. This is therefore the same as in the case of the DC machine until this point.

But however, here there has to be a difference because the motor is no longer DC and you need to generate a sinusoidal waveform and therefore there is one block that sits here which implements the methodology to make PMSM look like DC machine. So, there is some interface that is going to sit inside your digital system that accepts the signals from the synchronous motor as a output signal and then it implements certain equations that make the whole thing look like a DC machine as far as the closed loop control is concerned.

The motor is not DC motor, and then you get this block then gives as output 3 reference sinusoids which is then given to a PWM modulator which gives all the 6 signals required for switching the inverter. So, this goes to the inverter and this inverter connects to the motor that we have. The motor shaft has a device to sense rotor position. So, this is what is done.

So, this controller is then the torque controller. This is speed controller. Now, nevertheless, this motor is an AC motor and we are going to be generating an AC voltage here. In the case of DC machine we saw that the armature input current that flows will generate its own magnetic field but it does not impact the main magnetic field in the system because they are oriented at different angles. But we cannot ensure that in the case of an AC machine. There is a rotating magnet.

How does one ensure that the magnetic field, if you leave it as it is, the magnetic field generated by the flow of current in the stator does not oppose the magnetic field that is generated by the rotor itself. So, that has to be explicitly implemented in this case and therefore there is another input that is given here which is a field controller, and this field controller takes what is the equivalent of field current and then gives a reference field current.

This reference field current is usually 0 in most cases because you do not want the stator to generate any magnetic field. The rotor is doing that job. You do not want to either increase the magnetic field of the rotor or decrease the magnetic field of the rotor under normal operation. So, you say that I do not want the stator to generate any magnetic field that is going to oppose the main magnetic field generated in the rotor. So, you keep that 0 whereas you focus on the other parts alone.

So, this is the way normally the structure is given and in order to do this job of implementing a methodology to make the synchronous motor look like a DC motor this requires the rotor angle information. So, that is used there and once you have the rotor angle information, from that itself one can compute the speed.

After all speed is nothing but the derivative of the angle. Angular velocity is nothing but d by dt of the angle itself. So, if you know the angle, you can get the speed. So, this is the way in which this kind of a motor control system would work, would look like.

Of course as I mentioned you can get speed through another controller if you want to finally give reference position and then you take the reference feedback of the position itself. So, plus, minus, this would be the structure if you want to finally control the rotor position; if that is the variable of interest to us. So, that is why I said, the rotor will produce magnetic field. We do not want the magnetic field produced by the stator to oppose this magnetic field.

[Professor-student conversation starts]

Student: (())(23:29).

Professor: No.

Student: (())(23:36).

Professor: No, not a (())(23:39).

[Professor-student conversation ends]

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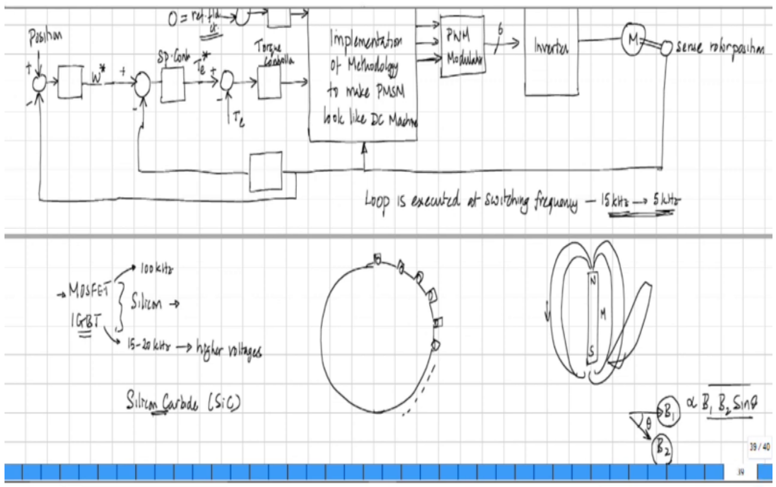

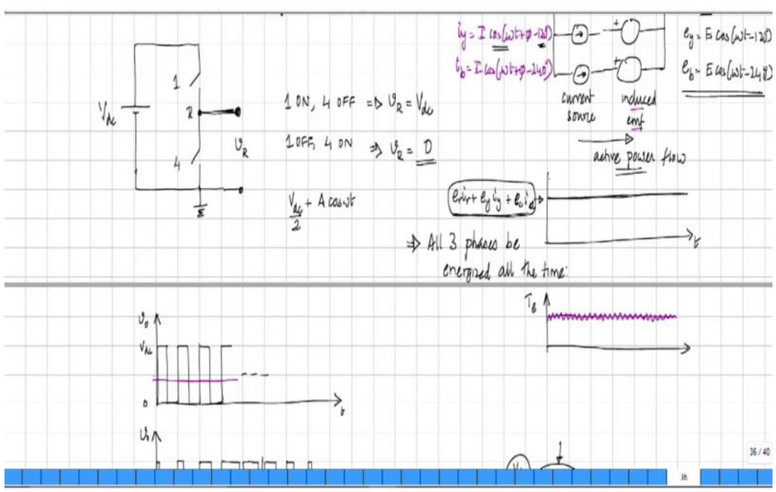

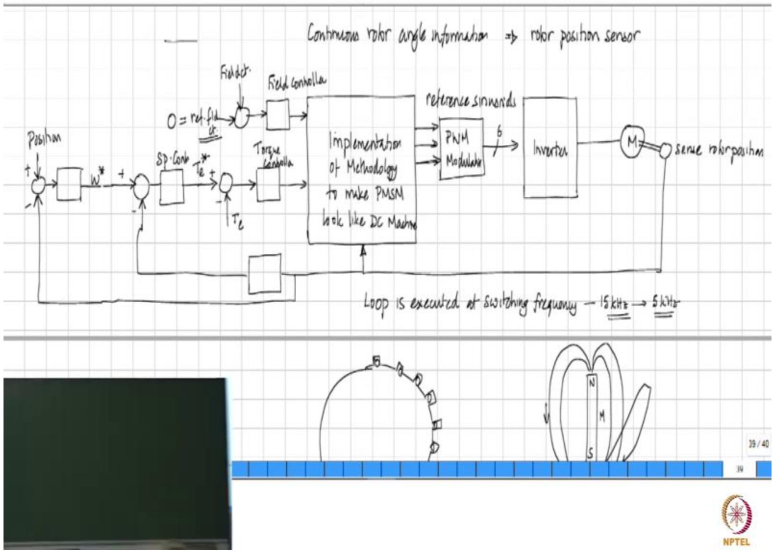

See if you are going, see if you look at the way stator is arranged, stator is a cylinder so stator is a cylinder and it has large number of slots in which lot of conductors are arranged. So, you are going to have, so you have a slot here, you have a slot here, slot, slot like this it is there all around. And then you are going to have some conductors that are placed all in these slots and interconnected in some manner. Let us not get into how that is done.

But if there are a large number of conductors which are interconnected in some manner and you are going to send a certain flow of amperes through these conductors it will generate a magnetic field. You cannot avoid it. Basic physics cannot be avoided. You are going to have certain conductors, they are going to have some current and therefore they will produce a magnetic field.

At the same time you have a rotor which is also producing its own magnetic field. Now, the question is, will the magnetic field produced by this, by the flow of amperes in these conductors, how does it look like when seen from the rotor? I mean is it opposing that magnetic field or is it at an angle 90 degrees to that magnetic field? Or is it at some arbitrary angle so that some part of it opposes the main field, some part does not? So, this is something one has to do, I mean you have the option to arrange the magnetic field whichever way want it because you are controlling the flow of stator current.

So, now let us say that you have a magnet. So, this is north and south, it generates a magnetic field. Now, it can be shown that if you have a magnetic field oriented in one direction in this case, depending on where you are the magnetic field has a certain orientation. And if you are going to have another magnetic field, this is, let me call B1 and B2, if you have another magnetic field oriented in some other direction and there is certain angle between them then there is a force that is generated which you obviously must have seen, you take, you have this magnet, if you put another one here, then it gets attracted.

So, when you have a magnetic field and you have another magnetic field there is a force of attraction or repulsion as the case may be, and that force of attraction or repulsion depends on the angle between them. If the fields are completely aligned then there is no force which will make them move. If there is a force it should move. If they are completely aligned there is nothing to move, so no force is generated. So, as you separate them then there is a force tending to attract them to each other. So, one can, with the analysis, one can then see this is proportional to B1 into B2 into sine of the angle between them.

So, now the issue is, if you have the rotor that is generating a particular magnetic field and then you have a stator that is generating a particular magnetic field the question is how should you orient the stator field with respect to what is generated by the rotor. If you orient them in the same direction, then there is no force produced on the rotor to rotate and therefore electromagnetic torque is 0.

Whereas if you can orient it at an angle 90 degrees to B1, then you get maximum torque because B1 into B2 into sine of 90 degrees is 1, therefore all the flow of current that you send into the stator is useful to produce torque. Whereas if you have a certain angle between them then all the current that is sending, that is being sent in is not useful to generate electromagnetic toque because it is diminished by the factor which is sine of the angle. You understand? So, we need to do something to say what should be the nature of the magnetic field that is generated by the stator?

[Professor-student conversation starts]

Professor: No?

Student: (())(29:24).

Professor: No, oh okey.

[Professor-student conversation ends]

In this case therefore if you remember I said that er into ir plus ey into iy plus ec into ic is what gives you a fixed output power, correct? You can, if you take these two equations, er, ir, ey, iy, we just do er into ir plus ey into iy, you will find that the result is a fixed number. Now, er exists because the motor is going to be rotating, there is an induced EMF whether you want it or not.

In the earlier case we did not energize one phase because the EMF in that was varying while the other two EMFs were not varying, and if it is not varying it looks like DC and therefore if you give a DC excitation, DC current flows, so er into ir plus ey into iy is already a fixed number. Whereas in this case if you do not energize one phase and you consider er into ir plus ey into iy is eb, do not energize, then you will not get it as constant.

So, in this case, all three phases must be energized all the time and with a sinusoidal voltage applied so that a sinusoidal current flows. So, you cannot say that I will ignore one phase and energize the other two. I forgot to mention that. Good that you brought it out.

So, here, this requires that all 3 phases be energized all the time. So, now if all 3 phases are to be energized all the time, then comes question of how much current at what phase angle it should flow. Now, how much current decides the strength of the magnetic field, at what phase angle it should flow decides the orientation of the magnetic field, and therefore you have an option how you want to do it.

And that is what is going to determine whether you are going to have the field generated by the stator opposing any part of the field generated by the stator opposes the rotor field or does not oppose the rotor field. So, you generally say that you do not want to oppose the rotor field because why, it simply does not make sense at least at the first look. There is already a magnetic field. Why do you want to diminish that magnetic field and send extra current to generate the required amount of electromagnetic torque. So, you leave that field as it is and then do it.

This control ideally if done in analog domain should be instantaneous. It should be done all the time because rotor position is going to be changing. But that is not feasible in an actual system so usually the control loop is executed at, loop is executed at switching frequency which may be probably 15 kilo Hertz all the way down to may be about 5 kilo Hertz depending on what switching frequency you choose.

We have already seen what are the considerations for switching frequency. You would all the time like to have as high a switching frequency as you can. You want to go to 100 kilo Hertz then it is very good. But there are certain other problems. If you want to switch at very high frequencies then the losses in the inverter start increasing.

Therefore, the efficiency of the system starts coming down. So, you cannot really afford to go to high, how high you can go depends on the hardware that you have. So, we discussed about devices. So, we said there are different varieties of devices. One is called as MOSFET, another is IGBT, so these are generally made of silicon and these devices therefore you can switch at certain rates.

For example FET, if you are going to use a MOSFET, then it can accommodate even up to 100 kilo Hertz without generating too much of losses. Whereas if you use IGBTs then 100 kilo Hertz is little too high because these devices have more loss associated, one can go to switching frequencies of 15 to 20 kilo Hertz, 15 to 20 kilo Hertz.

But the difficulty is that IGBTs are the ones that are available for higher voltage levels. So, if you want to operate your electric motor from a DC bus, DC input voltage or let us say 600 Volt then you have to go for IGBT because at 600 Volt if you select a suitable FET it will have more loss than the IGBT.

So, now only nobody selects FETs for high voltage applications. Whereas if you are going to look at low voltage application, let us say you are going to be operating a small robotic contraction which is going to operate from a DC voltage of let us say, 50 Volts, then you will not choose an IGBT, you will go for FETs.

At the same time there are also newer devices that are appearing, for example devices made of silicon carbide that is SiC it is called. These devices have much lower losses than the other two and therefore if you are going to be using SiC you can operate higher voltages at 100 kilo Hertz. So, it is a question of what sort of device you are going to use, what voltage levels are involved?

SiC devices are of course as of today more expensive than the other two. So, you will have to take a call, what is that one wants to use?

[Professor-student conversation starts]

Student: why magnetic fields are at all being generated.

Professor: Yes, so the ultimate explanation of why magnetic fields are at all being generated is because there is some internal flow of current, electrons moving around the atoms is what generates magnetic fields. That is a final physics which is understood as of now I think. Tomorrow somebody might come and upset the whole thing saying it is a new phenomenon.

[Professor-student conversation ends]

So yes, so why fields are getting attracted itself? I think, I do not think there is an intuition behind it. It is an observed phenomenon that if you have magnetic fields it attempts to attract. And if you, by analysis inside the machine one can show that the electromagnetic force is then given by this expression.

But I will not be able give you an intuitive answer as to why magnetic fields attract or repel. I do not, I am not aware of any such explanation also that is been given. It is a observed phenomenon. You just have to take it, I think axiomatically that magnetic fields have the ability to attract or repel. So, this is then what happens. So, the loop is executed at this kind of speeds.

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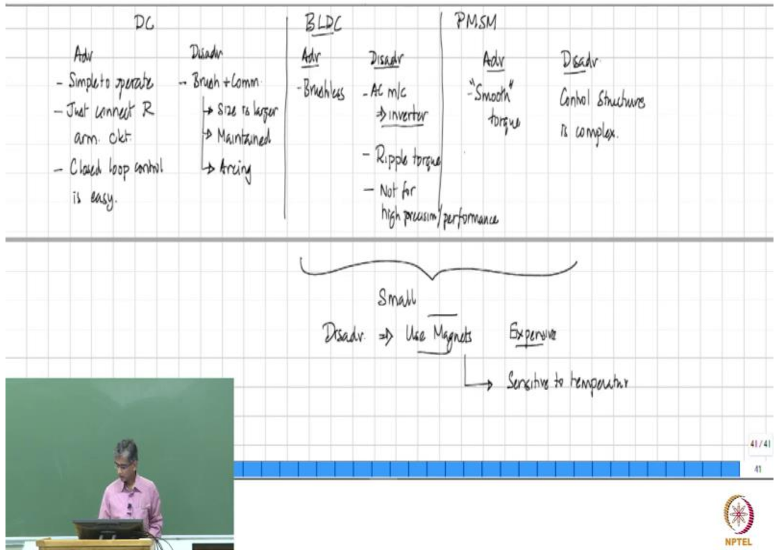

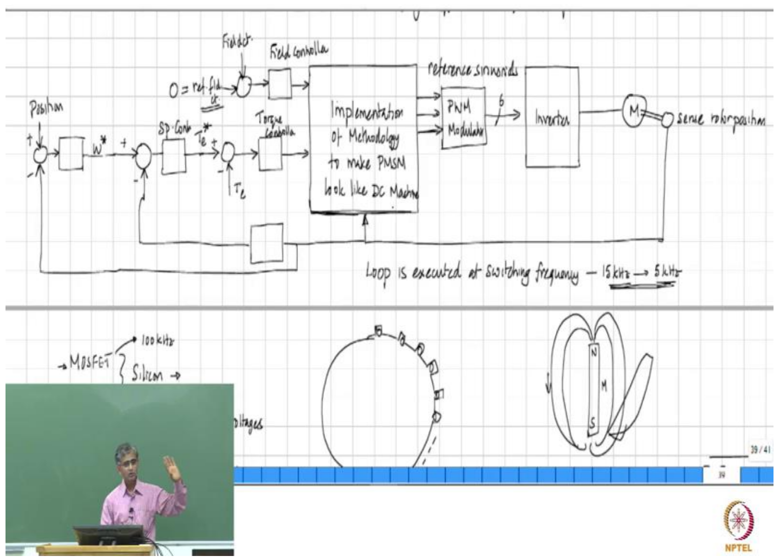

Now, there are, there is the, so we have seen so far the DC machine and then we saw that, we saw a brushless DC machine and then we have seen a PMSM, at least since that we have seen 3 motors then the question that will arise is, if you want to choose a motor for a given application, which one do you choose out of the three.

So, let us look at the advantages and disadvantages of the motors as we have seen until now. This motor, the advantage of this motor is that it is simple to operate. It is very easy. All you need to do is connect a DC voltage to it and then you are done. If you are not really too much concerned about speed and accuracy, position and all that, all you need to do is just take a DC voltage, connect to it, it will work. You do not have to do anything at all other than this.

If you want to have some minimal amount of speed control in the lab, you just want to run something, you want to adjust the speed etc, it is very simple again. Just connect a resistor to it, just connect a resistance in the armature circuit and your job is done. You can vary that resistance a little bit, you are there and then you can get whatever speed you want.

So, if you want to get, I mean for example you have an idea and you just want to evaluate the idea to see whether it works or not, the best way is to take a DC motor, connect a supply to it, adjust the voltage if necessary if you have the control or put a resistor in series, operate your system whatever you want to operate, you can verify whether it is working or not working.

So, from that point of view this is really a very simple machine to use and do in the lab. Even if you want to do more sophisticated control operation, let us say you want very accurate positioning etc etc, then it is still closed loop implementations is easy. It is not a very difficult motor to do control on. So, these are all advantages of the DC motor.

What are the disadvantages? The major disadvantage is that it has a brush and commutator. This arrangement means that size is larger for the motor than the other two varieties, plus it requires to be maintained because there is a moving part and there is a fixed part, there is bound to be friction. You cannot avoid it. And if there is going to be friction there is going to be material wear. You cannot avoid it. And if there is material wear the material will erode after some time. There will be no material left. So, you have to replace it. That is something that is unavoidable and therefore it has to be done.

Then the other difficulty with the brush commutator arrangement is that there is likely to be arcing. If you open up an electric, if you open up a small machine which is going to take half an ampere or less and then see whether there is arcing, it may not happen. If you are going to take a larger machine where several amperes are going to flow and it is going to be broken I mean you are going to have a commutator action, then there may be arcing. The arcing phenomenon also depends upon how much load is being operated on, at what speed the motor is running, so it is not a simple operation and it depends. So, arcing is going to be there.

There are no other major disadvantages with the DC machine. But this disadvantage is enough to say that I do not want to use. Because the very fact that arcing is going to be there on the one hand restricts the domain of usage of the DC machine. You cannot use it in environments where spark can be hazardous. And you cannot use it therefore in environments where you find it difficult to access, that how will you go and replace all these things that are going to be eroded?

That you need access for doing repair, for doing maintenance, so if it is going to be located in some place where you cannot even reach then there is no use of having this motor. And secondly we have seen that it is slightly larger because that entire arrangement has to be accommodated, so you cannot say that I have only this much space. Somehow can I fit my DC machine here? You may not be able to make a DC machine to fit there.

On the other hand if you go to brushless DC machines the advantage that the brushless DC machine has is that it is brushless; so all the drawbacks that are associated with the brush commutator arrangement in the earlier case are simply not there now. But the disadvantage is that, being an AC machine it requires an inverter.

So, if you have a electric motor like this in the lab and you say that well I want to do some experiment, let me just take this machine and see if I can connect it and use it, unfortunately you cannot. It is not like a DC machine where you simply take the DC voltage and connect to it, it will run.

It requires an inverter, it requires all position switches, so basic semblance of control circuitry must be there, so rigging up that control circuitry, getting into work and all that will require some effort. Not that it is impossible but it requires some effort so this very fact that it is an AC machine makes it very difficult to use under very simple situation. You need the required setup for operating this machine.

Yeah I am talking about motor being available, control not being available. If you are going to go to a vendor and buy a motor, it is quite likely that the vendor will only give brushless DC motor today. He may not possibly get a DC motor at all. There may be some cases where DC motor is sold.

So, if you are going to get a motor plus controller everything available then there is no problem. You just connect the DC supply as it is and it works. But you must be aware that this has more sophistication as compared to the DC motor. There is, in order to make it operate you need some basic sensors, you need an inverter that is going to switch and some control logic must be there.

There are many occasions where people have come to me and asked, I have obtained this from something and it is not working. It is making noise. Can you tell me how it is, how we can set it right? I have no clue because I do not know what is there inside. So, if you are going to go with a electric motor and a drive that you purchase as a whole, as a block, you have to live with what you get. You have already given the money; you got it.

So, if it is not working, well you try to see why it cannot be working, do this, do that and all that but you cannot repair it. Whereas if you are going to take the motor, you are going to build all these things then you know what is happening inside. If you who have designed it, you can do something about it.

So, yes if you are going to buy the motor plus controller which will be the case if you buy it along with an application then yes you do not have to bother about it, you just give supply and get it work, that is all. The disadvantage also is that you have a ripple torque. Whether the ripple torque is a serious disadvantage or not depends on the application. I am not saying that ripple torque is always a issue. It may not be an issue under some case. So, that needs to be evaluated.

So, these are generally used for, not used for high precision stroke performance applications. And this motor also requires to be specially designed. If you really want a nice trapisoidal induced EMF one has to take care to design this appropriately, whereas if you go for this, the advantage is that you get smooth torque.

Smooth within quotes because you are going to be giving a switching waveform, there will be some high frequency ripple; you cannot avoid it. So, within that constraint, yes you have a fairly smooth torque that can be generated and therefore it is very suitable for high performance applications.

The disadvantage, and these two machines are small, they are the smallest among all the motor types that are known and available today for use. The disadvantage is that the control structure is complex. It is fairly complex because of this block which is used to make the motor look like a DC motor. But these two machine varieties have another big disadvantage is that they use magnets.

That is a disadvantage because magnets are expensive. So, these motors are definitely more expensive than DC motors. So, if you are going to look at a low cost motor you will probably not go with BLDC or synchronous motors, you will use a DC motor if you want only low cost as the main objective. So, these are expensive.

Further, because magnets are used these are sensitive to temperature. If your application requires operation in a high ambient temperature environment then you have to think really whether this motor is the right one. That needs to be appropriately designed if you want to use the high temperature, if you want to use it in a high temperature environment. If you lose the ability to generate a magnetic field then the motor is as good as dead. So, we will stop here and look at it in the next class.