Introduction to Robotics
Professor Krishna Vasudevan
Department of Electrical Engineering
Indian Institute of Technology, Madras
Lecture – 23
Control of the Brushless DC Motor

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In the last class we had started looking at Brushless DC Machine and these varieties of machines belongs to group a called permanent magnet AC Machines, which is PMAC; and this further belong to a group called synchronous motors. So, the brushless DC machines indeed the entire group, which is the synchronous motor variety they are an inverted arrangement as compared to the normal DC machine. The field winding or the field arrangement is on the rotor, while the armature is on the stator. And in view of this arrangement the voltages induced are alternating and hence you cannot connect a DC supply directly to this machine.

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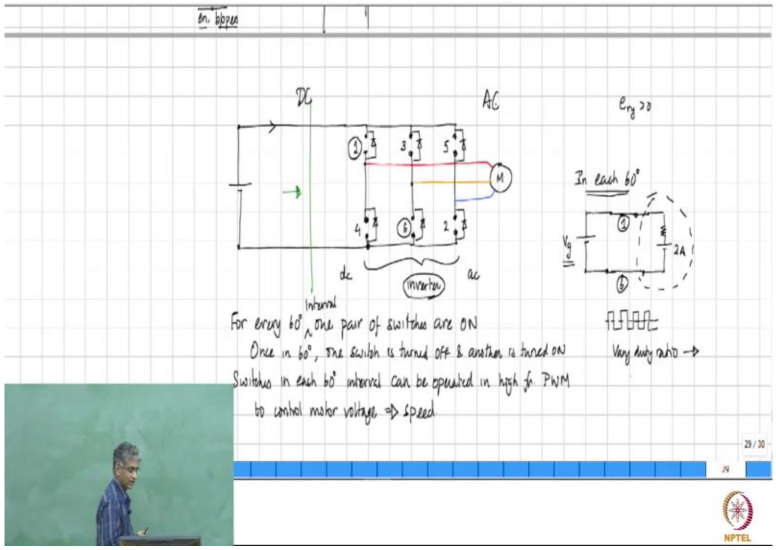

And therefore, you make use of a circuit as we had discussed in the last class that is here. And this is then called as an inverter that accepts DC on the input side, and delivers an alternating AC AC output voltage, which is then the given to the motor. The understanding of how this is supposed to operate was what we discussed in last class.

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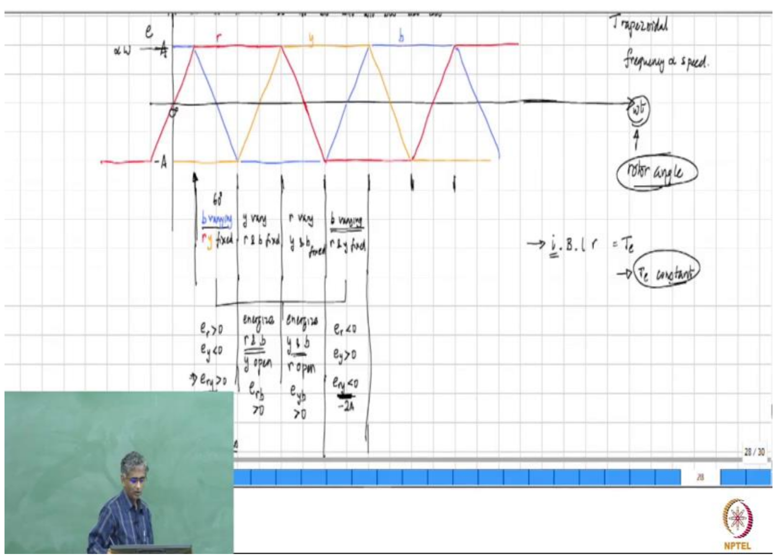

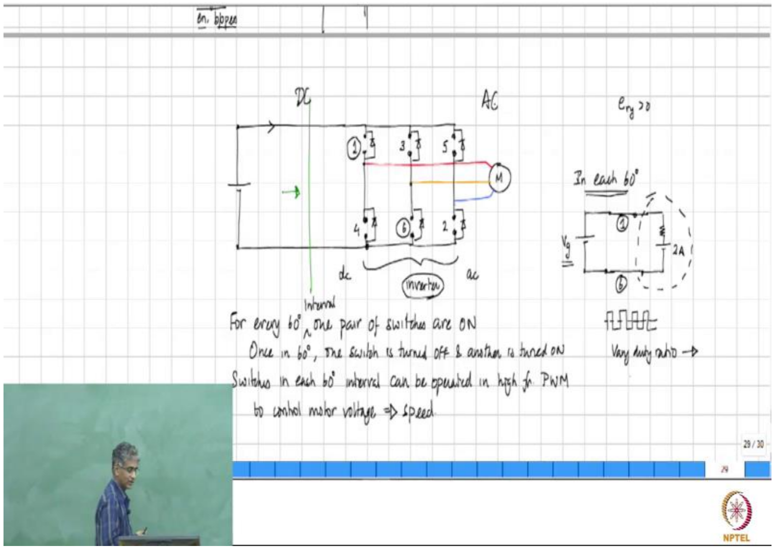

That is depending upon in this case of the BLDC machine; where the induced emf waveform looks like this. Then depending upon which two phases have an induced emf that is flat; you select those two phases to be connected to the DC supply.

The phase that is undergoing an induced emf variation from one level to another; you leave it open, do not do anything to it. If you do it in that manner, this machine then looks like a DC machine at all points of time through the DC supply voltage, to this DC supply. And hence therefore for operational aspects that is to estimate the performance, and decide how much load it can take and so on; in order to design the control look for the motor. You can consider that to be roughly equivalent to DC motor and then you do all your designs. Now, I had asked you to look at how to determine or each interval which of the two switches will be on.

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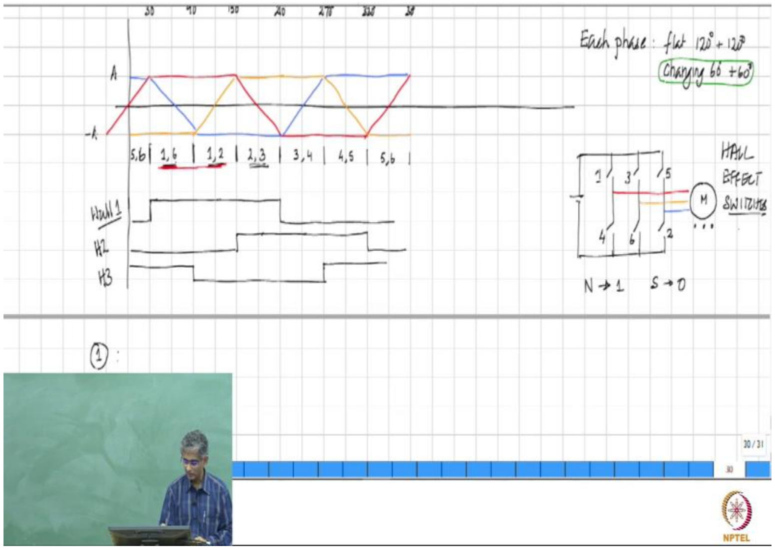

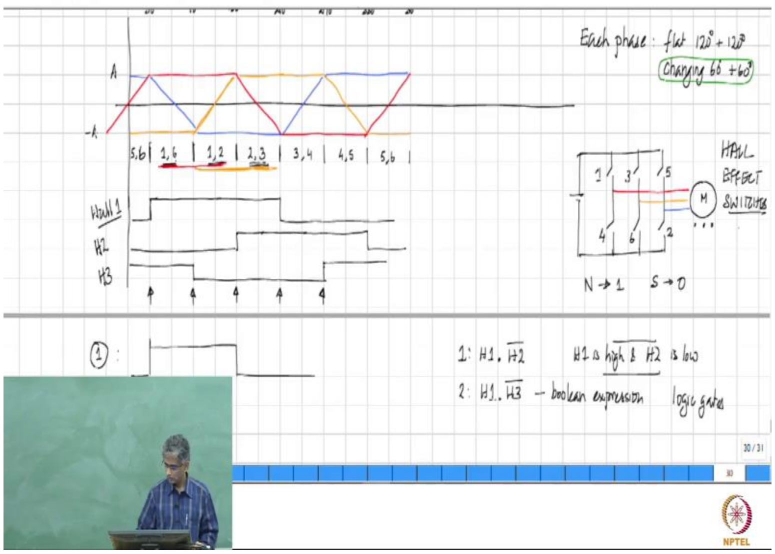

So, let us take this diagram once again, so let us look at this waveform once again; so, this is 30 degree, 60, 90, 120 and 150 degrees and then it is 210, 270, 330, this is 360 and 30. So, here we going to have voltage waveform that looks like this; this is for one phase. Then this phase for y is phase shifted by 120 degrees, and therefore looks like this; and then v is going to be further phase shifted by 120 degree. So, note that each phase is flat for 120 degrees on the higher side and 120 on the lower side. So, we can call this amplitude as A and this is minus A; then it is changing for 60 degree plus 60 degree.

So, we are saying that during the interval when the phase is undergoing a level change from one to the other, do not use that phase whereas, when the level is flat, you use that phase. So, if you look at that then we can see that during this interval, so maybe let me draw quickly the switches. Then you have R, Y and B and the switch numbering is 1, 2, 3, 4, 5 and 6, so in this 60-degree interval that we have marked. You want to make use of the R-phase and the Y-phase and therefore you would keep switch number 1 and 6 to be on. In the next 60 degree you will have switch number 1 and 2 to be on.

In the next 60 degrees, you have 3 2 and 3 to be on; in the next you would have 3 and 4, and here it is 4 and 5. There it is 5 and 1, so this is part of 5 and 1; and then you go back to 1, 6. So, every 60 degrees you have 2 switches that are on and you can see that 1, 6 which goes to 1, 2. That means the instead of 6 you have now 2; which is conducting 1, 2 goes to device number 2 and device 3. So, instead of 1 you now have device 3 and then that goes to 4, 5, 6 and so on; and that is a way in which divide this switch. So, the issue is how are we going to decide how to switch these devices.

So, usually in the motor there are sensors that are put, so these are called as Hall Effect; so those are called as Hall Effect switches, which basically detect the field in under their influenced, under their region of influence. And they give an output that high or low depending on what sort of field you have. So, if the field is N then this gives an output 5; if the field is S to give an output of 0. So, that is a digital output that you get, and therefore if you place Hall 1 around the machine at some particular location such that Hall 1 gives an output of 5.

When the induced emf in phase R starts becoming flat; then it will remain high, so therefore for a duration of 180 degrees. Because, the machine has North Pole for 180 degree and South Pole for 180 degree so, this is how the output of Hall 1 is going to look like. And similarly, H2 if you draw that would be phase shifted by 120 degree, so that goes high exactly when the Y-phase emf starts becoming flat. Therefore, 30, 60, 90 and the 30, 60, 90; and then you have H3 which is also located somewhere in the machine.

The location is such that it starts going high, when the B-phase emf becomes flat so, this is how it is going to be. So, using this three-sensor information, it if it is feasible to determine the instance for the duration; for which for which each device is must be turned on. For example, if you want to consider device number 1, you see that device number 1 is on in this region, this region and here. Sorry this is not correct; this should be 4, 5 and then 5, 6 and then 6, 1 so device number 1 is on during this interval. So, if we are able to implement the algorithm such that for device number 1; I say Hall 1 and Hall 3 bar, Hall 2 bar.

That means whenever Hall 1 is high and Hall 2 is low, turn on device number 1; so, device number 1 will get a switching pulse during this interval. Similarly, you can look at device number 2, device number 2 needs to be turned on in these two intervals. And how do you determine the algorithm then for switching on device number 2; Hall 1 is high and Hall 3 is low.

So, that can be written as a digital expression that Hall 1 or and Hall 3 bar; so this is a Boolean expression. So, the signals to turn the devices on can be obtained by using logic gates appropriate AND, OR, NOT combinations; can be used to arrive at as a simple circuit to switch on the appropriate devices, depending on the rotor angle.

So, you see that this Hall sensor Hall switch information give you information about the rotor angle at 60 degree intervals. That is you get an information about the rotor angle, only when one of the switch is going to change state from one level to another. In between the range you have no idea where the rotor is and you are not really interested to know as well. It sufficient if you know at those instances, because that is going to switch is the turned on or turned off. So…

Professor: During this slope that is you mean during this region.

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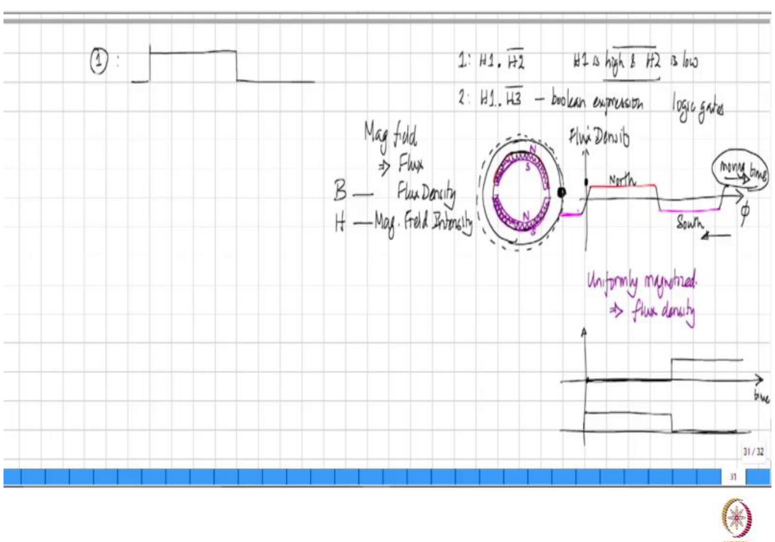

So, let us say that you have the stator of the machine and then you have rotor; and on the rotor you have placed one magnet here another magnet here. So, this is full of magnet material; this is also filled with magnet material. Then this phase is North and this phase is designated South; and here this is North, here is South. Under this condition suppose the rotor is like this at given some instance in the rotation of the rotor; you freeze it at one instance. And what you do is you walk around the rotor, let us you start it at this point.

And you walk around the circumference of the stator and you comeback here. If you do that what do you think will be the wave shape of the… so let me just field. I want to draw the magnetic field that you will encounter, as you go from one point to around the circumference of the stator and comeback to same point. What do you think will be the variation of magnetic field, sine wave; why should it be a sine wave? Anything that vary is a sine wave. Now, this is normally if you look at this magnet and this magnet; they are uniformly magnetized. Which, means that which means that flux density anywhere on the surface of the magnet.

Professor: No, the flux density anywhere on the surface of the magnet is the same; that is what you meant by uniformly magnetized. Now, as far as air gap is concerned between you know if you look at air gap which is intervening here; that air gap is the one that is going to see the magnetic field that is going to come out. And as long as the magnet air gap is small in length, whatever is the magnetic field that is magnetic flux density at the surface of the magnet. That is what is going to be seen by the air gap, and the person is moving around as well.

So, if you move around and then measure the magnetic field; by measuring magnetic field means which quantity you measure. You measure the flux density, if you recall that if you want to describe the magnetic field. How do you describe the magnetic field? Either you can talk about flux or you can talk about flux density or you can talk about magnetic field intensity. So, if you recall high school physics or your physics might you have done in first year; this is given usually the symbol B. And this is given the symbol H, and B and H are linked by one term; what is that called permeability of the material, B by mu this H.

So, when you say that you want to measure the magnetic field; you have to measure one of these things. And usually what is a good indicator of magnetic field is the magnetic flux density. So, when you are having a uniformly magnetized ring, what it means is that if you draw the magnetic flux density; this will in in the region that is here. It is by and large going to be flat and, in the region, here; it is again by and large going to be flat. And in between it has it has to go from one sine of the flux density to another; and therefore, there will be a region where the flux density reverse.

So, that is going to be the shape roughly of the flux density in the air gap. And you are going to place this Hall switch, let us say that the Hall switch is placed here; which means it is placed at this point. This variation is with respect to an angle that you are going to travel around the air gap. Now, if you are located there it means that at that instance at that location, you say that flux density is zero. Now, as the rotor begins to move either little bit that side or little this side; then this Hall switch will encounter two different varieties of magnetic field.

In one case there is flux going from the rotor to the Hall switch, and in the other case it is going from Hall switch the rotor; because the sine of the magnetic field reverses. So, that means if this rotor is now going to move; this magnetic field distribution will either move this side or little move that side, depending on the direction of rotation. So, let us say assume that this magnetic field is going to be moving in this direction with respect to time, moving with respect to time. That means if you draw the output of the Hall switch with respect to time; how is it going to be. As this flux density pattern moves to the right; this Hall switch which is located there will start seeing field which is negative.

And therefore, this switch output will remain 0; for how long will it remain 0, as long as the rotor rotates by 180 degrees. If this if this wave so if this wave begins to move to the right side; then this point will be seen flux density is that then is where here. And so the imagine entire waveform is moving to the right, and therefore it will see negative flux density for 180 degrees of angular rotation. And therefore, it will remain 0 for 180 degrees and then it will again reverse flux direction; so it will go high, this is what will happen.

If on the other hand the rotor was rotating in this direction, then what will happen to this? It will be high for 180 degrees first; then it will go low. Are you able to imagine that? Are you able to imagine? It is not related to the induced emf at all; that is what I was attempting to get that. You are asking what will happen to the Hall state, when the induced emf is moving; it is not related to that at all.

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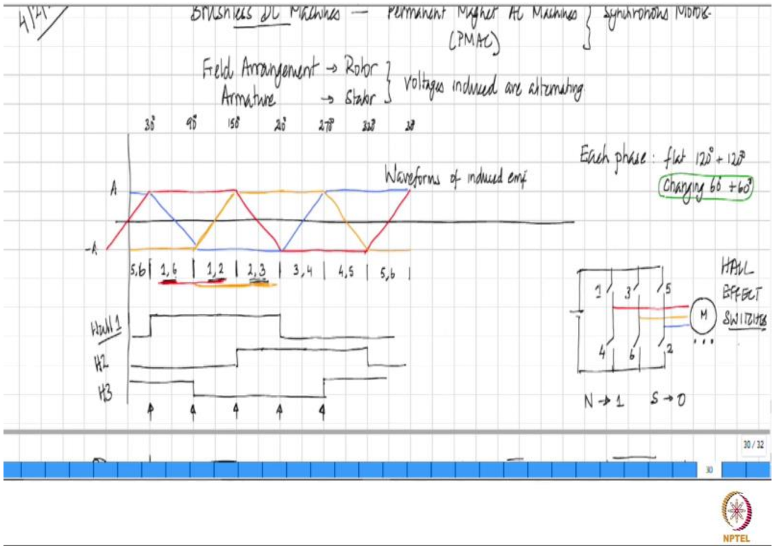

Professor: Not at all, these are these are waveforms of induced emf, not flow of current. The induced emf waveform is purely dependant on rotor angle, and the Hall switch output is also purely dependant on the rotor angle. What we are attempting to do is place a Hall switch at a suitable position around the circumference; such that this Hall switch going high synchronizes with this position that is all. You could have placed anywhere on the circumference, it is a circular stator; you can put it where ever you want. We are choosing the to put it at a particular place, such that this goes high when that becomes flat that is all. Why we are doing that? Is just for ease of operation; just to get some simple expression here; otherwise it is not going to be easy. So…

Professor: Yes, so this is if you say that this is North Pole flux density, this is South Pole flux density.

Professor: No, in the first case if the flux density pattern is moving. See if the ro… you are standing at this point, the rotor is going to rotate; which means that this flux density distribution that we have drawn, is a distribution in a space at a given instance. If the rotor rotates then the flux density distribution itself moves, is it no? So, if the distribution is going to move to the right; then that point will see the negative flux first. Now, it is seen 0 flux density, if the distribution move that side; what we will be see is what it will be see is flux density, that is here.

So, if you start giving 0 output first and then after the rotor is rotated by 180 degree; it will see flux density reversed, and therefore it will give high output. So, like this one can go on and determine the functions for all the six devices.

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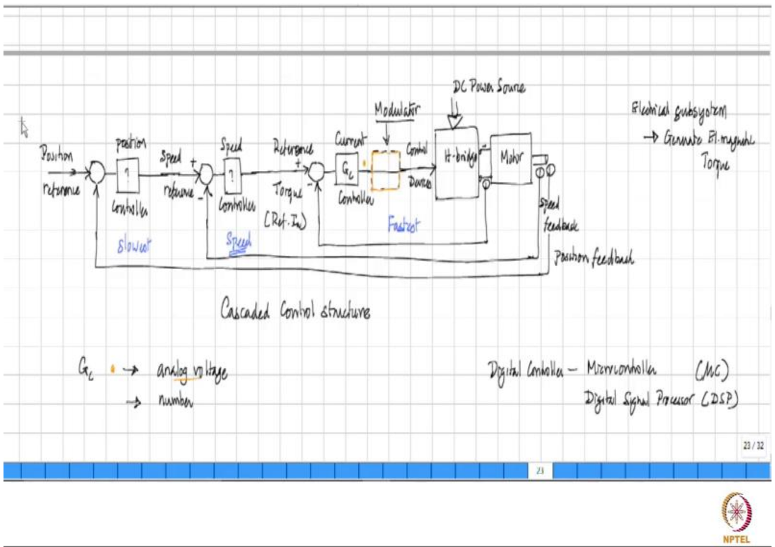

So, as I had mentioned earlier, we had looked at the DC motors speed control; so, this is the same sort of structure that will be used even now. But what is the difference, so let us go I need to copy this, now let me copy this.

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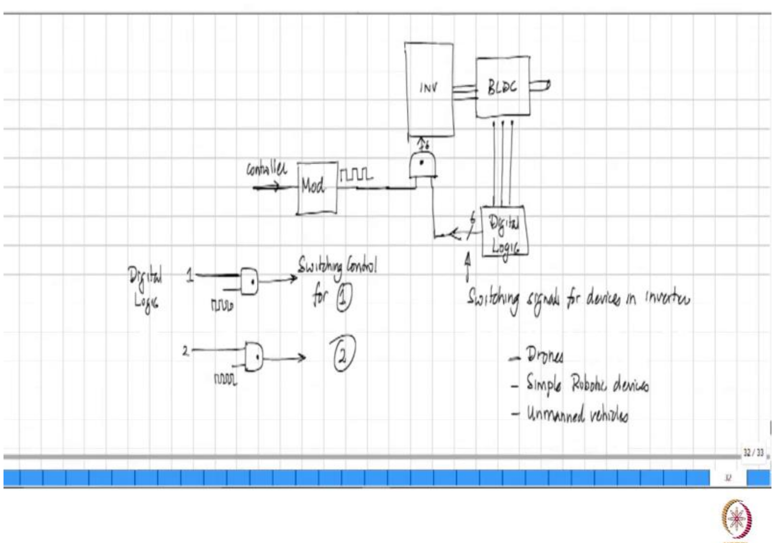

So, what we will do now is then you have the BLDC motors here, and BLDC motor is connected to the inverter. And then you have the shaft and then you have Hall sen… switches that are placed here. You take the output from the Hall switches, and then you have a digital logic that is placed here. This digital logic in turned gives you six signals; each of which determines when a particular device is going to be on or off.

So, these are the switching signals for devices in inverter, and these six switching signals are to be given to the inverter for operation. The rest of the circuit is then going to be the same as the rest of the closed look structure, is going to be the same as earlier. So, there is no difference, you have a opposition reference and then you have a speed loops; and then the loops for flow of current, all that is going to be there.

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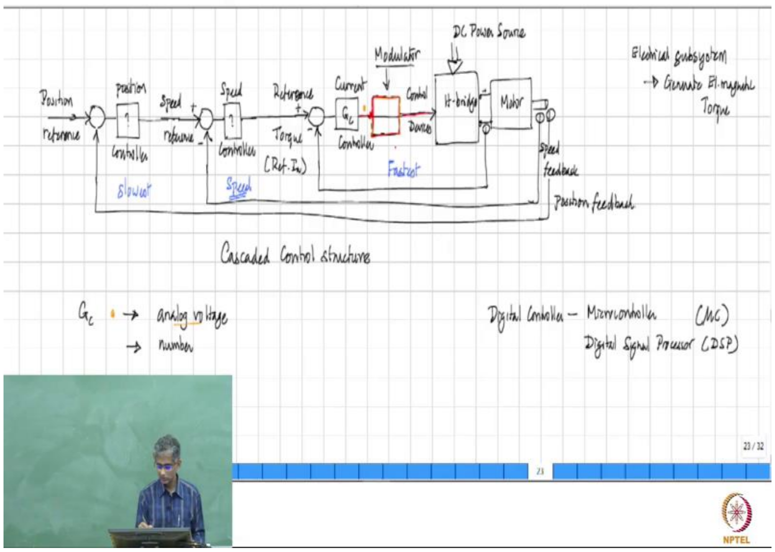

But, when it comes to the final stage that is here, this block which we said is going to is going to take the output of this controller. And then convert it to switching control signals.

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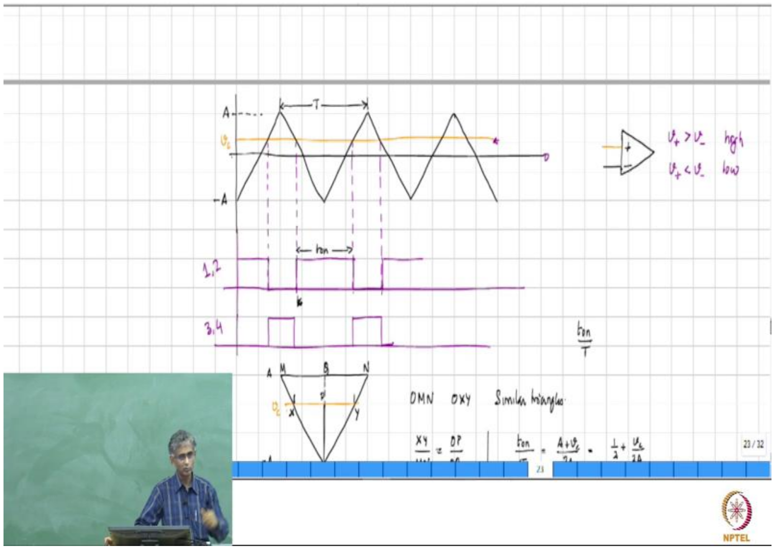

So, this we implemented by means of having a high frequency ramp signal; and comparing it with the output of the controller to generate this kind of a waveform, switching waveform. So, here also we do the same thing.

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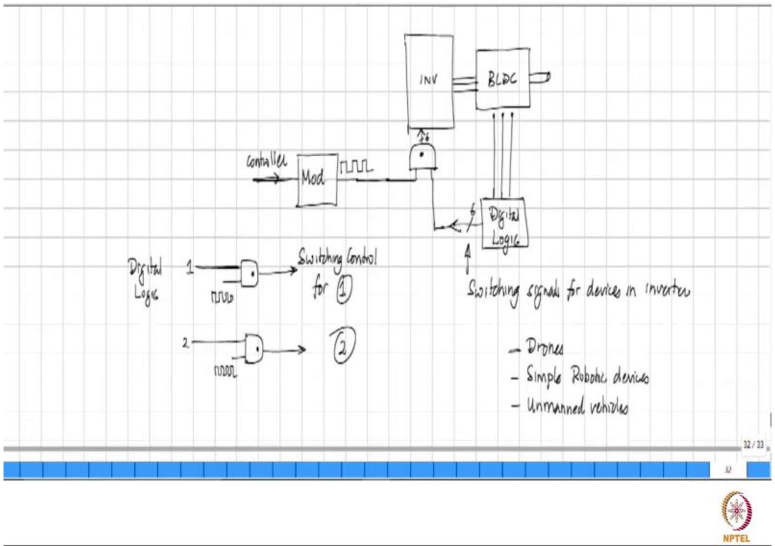

But what we can do is at this point instead of giving this directly through the inverter devices. What we do is take this output from the controller that is a controller output, and then you pass this through modulator; then you get a high frequency on off signal. This simply says that in order to apply the voltage that the controller is asking, you cannot allow the devices to be on all the time.

But rather you have to switch it to the certain duty ratio, so that you apply a lesser voltage; that is the meaning of what the output of the controller is. So, what we can do is simply take this signal and to each of the each of the signal given by the digital logic. You AND it with this signal and give it to the inverter; so, there are six signals that again here. I mean for example, if you take the signal generated by the digital logic, so digital logic for the device number 1; so, that is going to give you a signal.

This signal you simply AND it with this on off signal, and this goes as switching control signal, switching control for device number 1. Similarly, you take the switching control signal for device 2, again combine it with AND gate using the same signal. That goes as switching control for device number 2 and so on. So, this means that even though the digital logic is going to say that in this region; I want device number 2 say to be on. You are not allowing it to be on all the time; but rather that is dictated by how much voltage you want to apply, as per the dictates of the of the signal that is coming there.

That is off this signal which is going to be there from the last controller in the loop. So, by doing this then we are able to con…we have a speed control of the brushless DC motor. Now, this is the sort of motor that is usually used in the drones, simple robotic devices, unmanned vehicles and so on.

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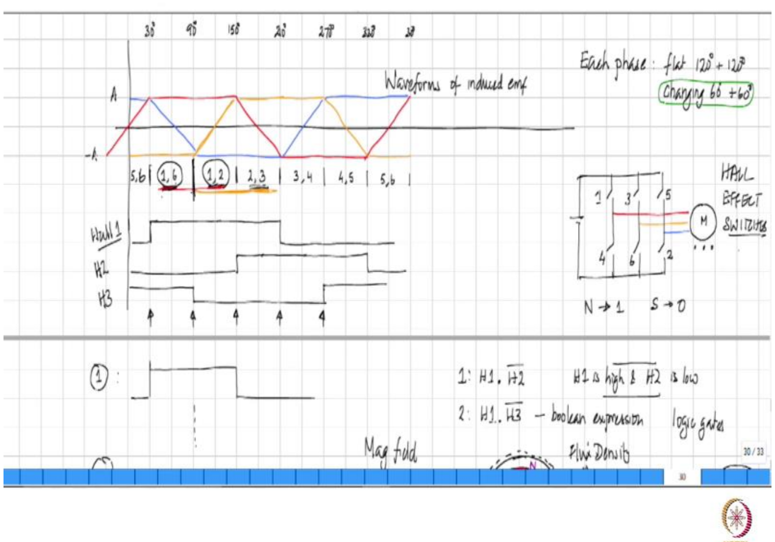

There are certain limitations of this kind of motor, the limitation is that we are going to be operating the switches; that is switch number 1 is let us say operate is meant to be operated in this region. Whether it is kept on or kept off is going to be dependant upon the high frequency signal; that is going to come up as comparing with the RAM and output of the controller.

So, during this region device number 1 will be operated, maybe you are operating with on and off on and off and like that. But, during this 60-degree interval you do not know what is happening to the rotor; in the sense you do not know where the rotor angle is. The information is just not available, because rotor angle information is known only when the switch is going to change state. Either it goes from low to high or high to low; you know where the rotor is at that instance, in between you do not know. When this kind of an operation happens, the difficulty is that the graph of electromagnetic forces that is generated electromagnetic torque; that is going to be generated. Every time you have a switching the device, switching in the sense you go from 1, 6 here operation of one switch, you go to 1, 2.

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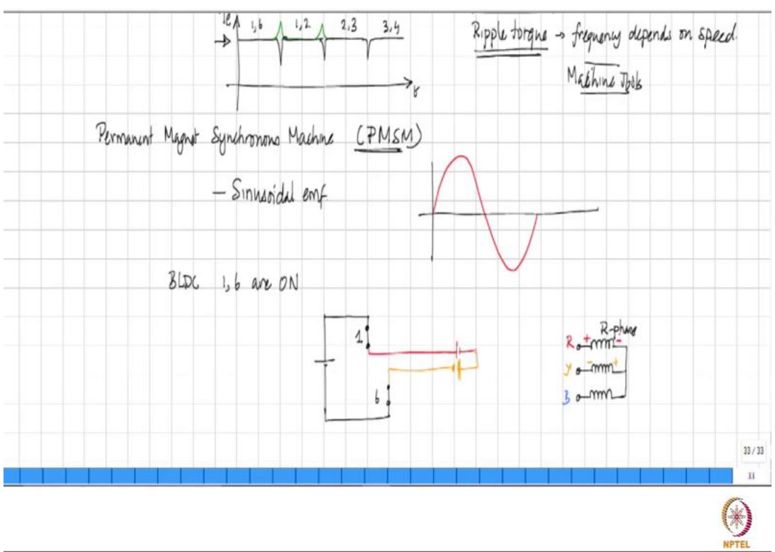

At this instance or around that interval around that instance; what you will have is if you plot the electromagnetic torque versus time let us say. And during this region device is 1 and 6 were on, and then it has to go to 1, 2. It will not go smoothly like this, what will happen is invariably there is likely to be a dip. Similarly, after device number 1, 2 finished, you go to device number 2, 3;

and here there will be a dip and then it goes. Then it goes to 3, 4 then there will be a dip and it goes on.

In some cases it is a dip, at some other space you may field; you may see the torque rise like that. That depends upon the speed and therefore what you have is a ripple torque, whose frequency depends on speed. So, this is one difficulty with this motor that you cannot avoid this ripple torque at top. It happens because one phase is being switch out and a new phase is being brought in. When one phase is goes out and next phase is entering; there is likely to be a disturbance in the load torque. So, if this restriction is not going to cause any difficulty, because this is just a ripple in the generated electromagnetic torque.

It may not have an impact on the speed and on the rotor position, depending on what inertia is connected to it, what kind of system is that. So, maybe it is acceptable; for low performance application it is just alright. But, when you go to really high-performance application, where acurate rotor angle the rotor angle need to be controlled accurately. Then this sort of ripple will really cause a deter in the load angle, in the angle of the rotor; and may not be very desirable at all. In such cases what you may have to do is not go for this machine; but you will have to go for a Permanent Magnet Synchronous Machine, which is generally abbreviated as PMSM.

Because BLDC motor has a repel torque and if you have a if you have a repel torque like this; it may have an impact on the accuracy of the rotor angle. Because, you are going to apply force to the rotor which is going like this; all of a sudden there is a decrease in the torque. And then it moves again with the load torque, with the same amount of torque. When there is decrease in the load torque, you are not able to rotate the load with the same amount effort that you are doing; which means that the rotor angle will not increase its same level; there maybe a sudden lag in the rotor angle.

If that is going to be an issue for the particular application at hand; then this motor is not suitable. If it is not going to be an issue, because whether the rotor is slows down during that time or not; depends upon what is the moment of inertia that is rotating. If you have huge enough moment of inertia, the small difference of load torque will not be felt at all; the inertia will simply continue. So, if there is a large inertia, there is nothing wrong with having this kind of a system; or if you do not mind the speed dip that is going to come, then also there is no problem. So, for simple low precision application like for example drone; the fan has to rotate at by enlarge a fixed speed.

If you are going to experiences, slight lag for a short few millisecond of interval; it may not matter at all for the drone. But, if you look at certain other application let us say that you are going to look at applications you know like machine tools. In the area of machine tool, you are required to accurately locate the job; if you I mean if I am sure all of you have cell phones. The way the outer box of the cell phone which is made up of aluminum. Aluminum box, aluminum shelf is made by having an aluminum block and removing the aluminum that is unwanted; to make the shape that is required.

So, the metal is being removed and for for having that sort of an operation; you need to be locating the aluminum block. You will have a tool which is going to cut metal and remove it, and for that this block has to be move. And the accuracy of the locating with block is very very important; in order that the financial move and the the shape is very exact. In such a situation if you are going to have a dip in the electromagnetic forces, electromagnetic field that is generated like this; then this will have an impact on the dimensioning of the output of the job. So, in those kinds of situation this is definitely not acceptable. So, one needs to go for higher accuracy system, and the higher accuracy system is this kind of machine. So, behaviorally or the way it is built, it is the same as this variety.

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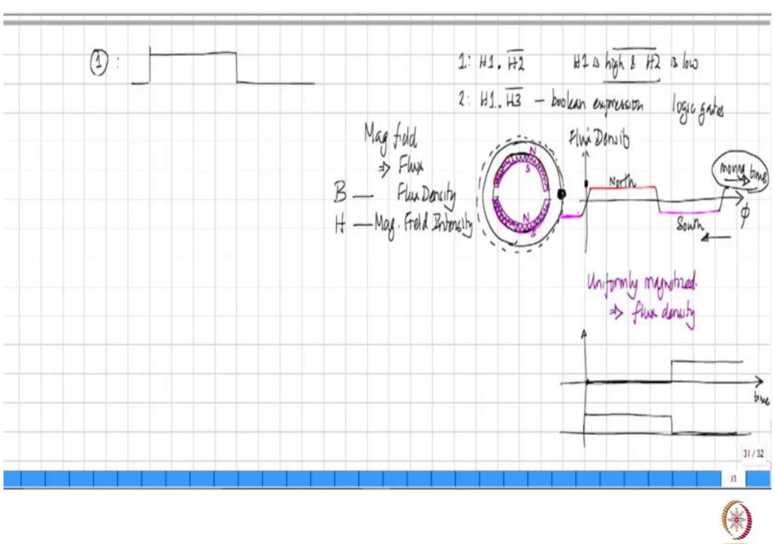

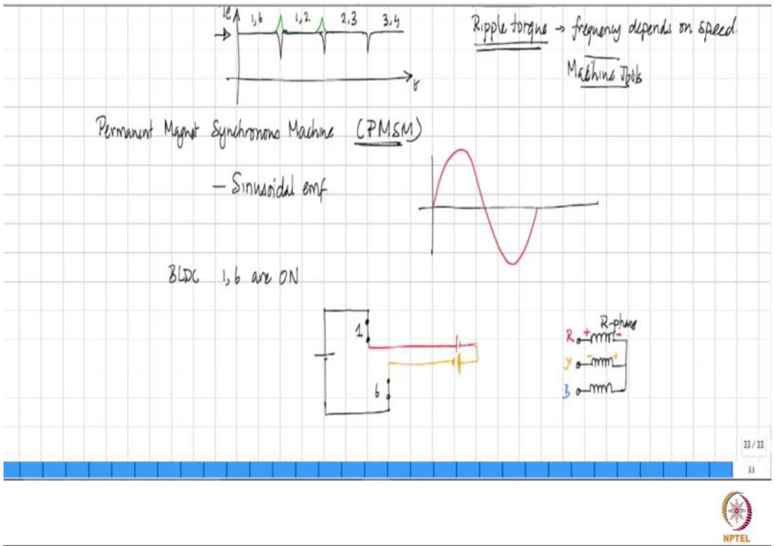

So, the machine looks very much similar to this in the sense that the field arrangement is put on the rotor, the armature placed on the stator. No change in that, but the induced emf in the first case was a flat top emf; whereas in this case the induced emf will be sinusoidal. You will have a sinusoidal emf, so you are going to have a sine wave that is vary respect to time; now, this bring about more difficulty in operating the machine.

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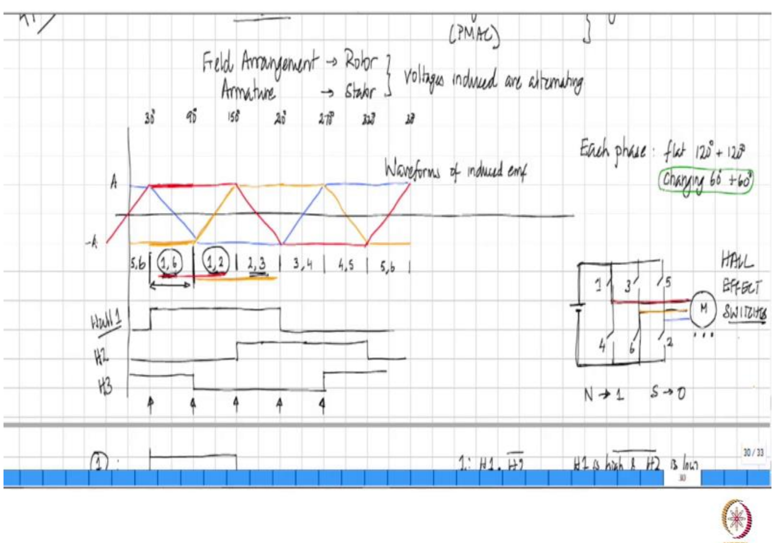

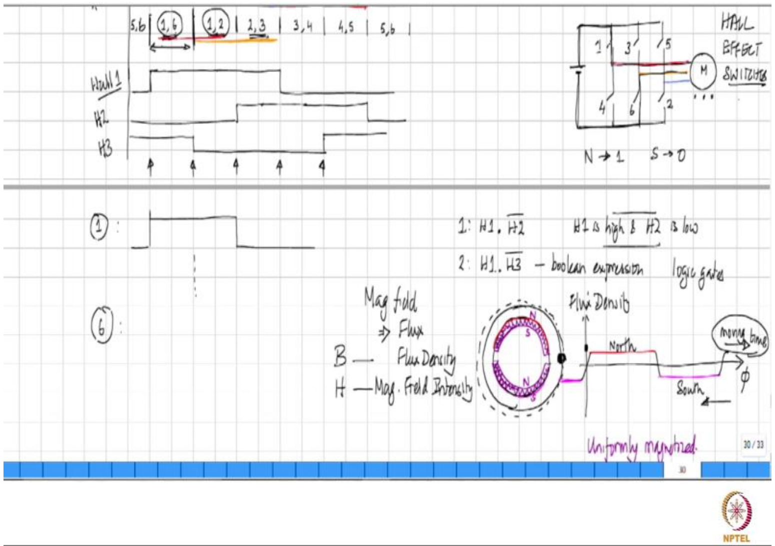

To understand that we need to go back to this kind of machine, and then look at let us say this particular interval; where 1 and 6 are on. So, if 1 and 6 are on, how does the machine look like? So you have the DC source, the circuit goes like this. Device number 1 is on and then this is connected through this phase, goes into the machine, and then comes out 6 is on. So, this is the circuit that is complete. Device all other devices are off, so it means that the blue phase is completely open.

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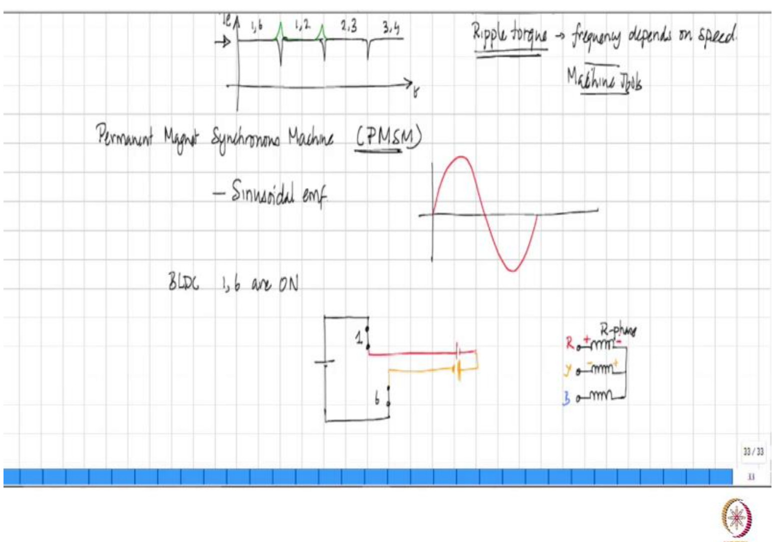

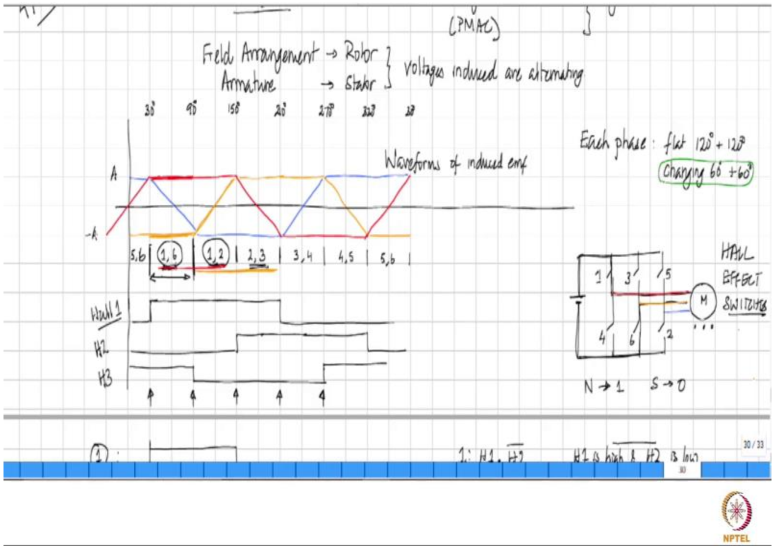

So, if you draw the circuit in that case, so the BLDC when 1 and 6 are on; looks like the DC source. When it comes over here, device number 1 is on and then you have the R-phase, and then device number 6 is on. So, you have the Y- phase and then this switch is on; go here this is 1, this is 6 and then you have induced emf. In this region the induced emf in the R-phase is greater than 0, the induced emf in the Y-phase is less than 0. That means that in the circuit we can represent the induced emf as plus here and then minus here; this is connected. So, this is a simple equivalent circuit of the inverter machine system, during that particular interval.

Student: are the two emf’s are same direction?

Professor: Pardon, the two emf’s are same direction

Student: are the two emf’s are same direction?

Professor: Yes, it is so because here you see this is negative voltage. How do you how do you interpret that this is negative voltage? It is negative because and because it is negative, is why we are drawing negative plate here and plus here, understand. So, if it does not clear, let us say that the machine has one phase winding; this is R-phase, in the armature so many turns of wire et-cetera are there. And the Y-phase also has those many turns of wire, and they are usually this is B-phase. The way the machine is arranged is such that one end of all these three phases is shorted inside the machine.

The other end is what is available to you as R, Y and then B. You can connect inputs into these three locations, these three input points to the machine; now, these phases are going to have induced emf. So, when we say that induced emf is negative, we mean that this is positive with respect to this terminal. When we mean that induced emf is greater than zero; it means that this is positive with respect to this terminal; and that is exactly what I have drawn. So, if you have this circuit then whatever flow of current going to be there; this source is DC source, and these two together is another DC here. And you will certainly have a resistance that is intervening due to the several loads of wire and all that is there in the armature. And therefore you can expect that the flow of current here is also DC. It is this DC voltage minus this DC voltage, divided by the total resistance is the flow of current.

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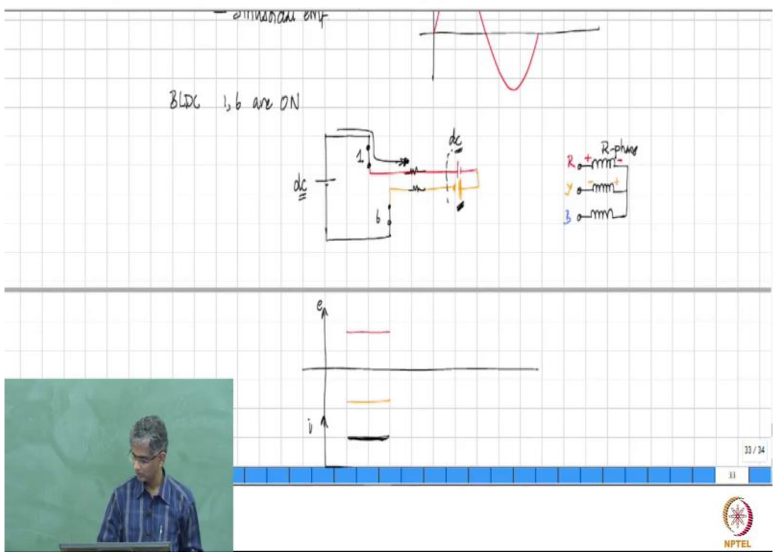

And therefore, what will happen is in the first 60 degree interval; when you are having the voltage of the R-phase is high and the voltage of the Y-phase is low. This is emf plot if I draw the flow of current I, then during this interval the current is also flat; current meaning this current that is going in. So, the fact that flow of current is steady ideally is ensured by the fact that the circuit is a DC circuit.

That it is a DC circuit ensure that the flow of current is flat because it is DC. There is nothing there is not anything that is undergoing a change. That is one of the reason why it is looks like a DC motor; but when you come to a sinusoidal emf, this no longer applied. You are not going to have a DC voltage here, but you are going to have sinusoidal voltage. That then brings about certain other differences in operation which we will briefly see in the next class.