Introduction to Robotics
Professor. Krishna Vasudevan
Department of Electrical Engineering
Indian Institute of Technology, Madras
Lecture No. 22
The Brushless DC Machine

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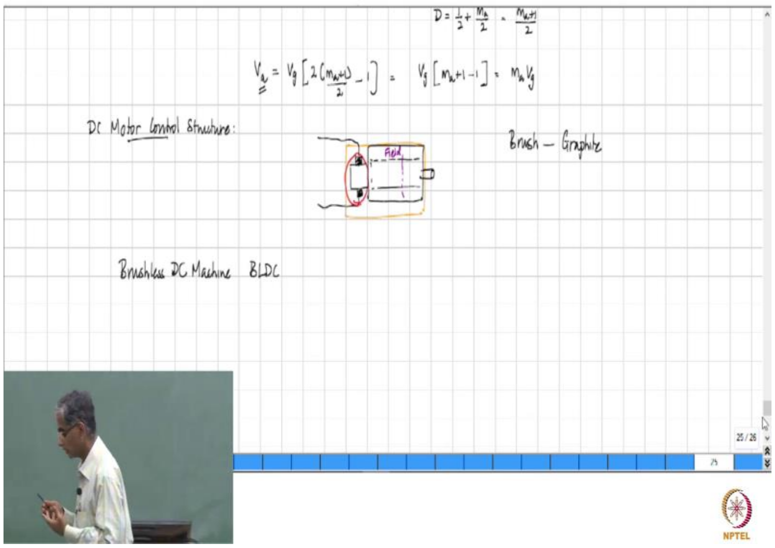

So, we had been looking at the DC motor operation and control and we said that the DC machine has certain difficulties due to which it is not really used much in the field now a days if you want to select a new machine, however the ability remains remains very much there, if you look at tools in your labs, because this is still the simplest machine that you can just take and evaluate some action that you got, you do not require elaborate setups and so on.

If you just want to test something in the lab it is okay to connect a resistor in the armature in external resistance to the armature and attempt to adjust the speed, it will work. We will not be able to have a resistor always connected for the normal operation of the machine because it is inefficient, but if you are just looking at a few hours use in the lab they evaluate something now then it still okay.

So, if you look at it from that part of view then the the machine is would be something definitely a of use, but not in the industry. In the industry where DC machines are used it is used because they have been historically used and we do not want to replace it, so we just go on with such situation, but as I said new installations people would rather go for something else. And the next best option is the one that is called as brushless DC machine. And if you see why brushless have been used in the DC machine at all, the main aspect why brushes have been made necessary is that you have a stationary.

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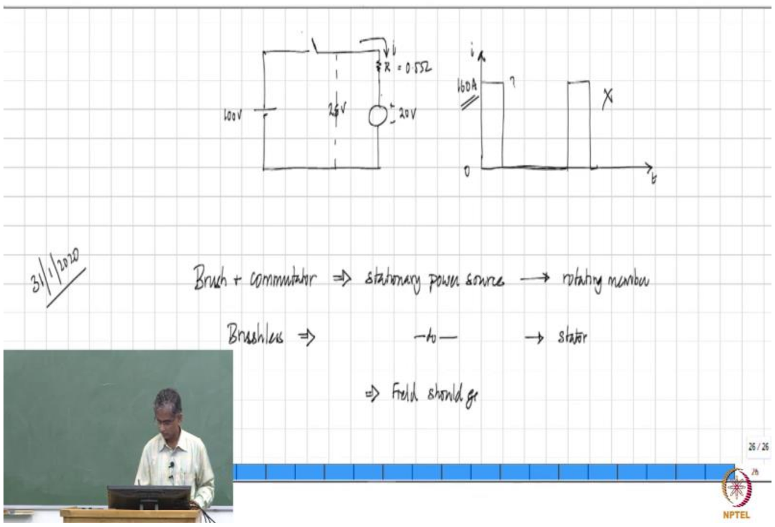

So, you require a brush and the commutator arrangement, because you have a stationary supply, stationary power source, which has to be linked to a rotating member, which has to energize a rotating member and it is the facilitated facilitate that, that you require this arranged. So, if you need to have a brushless DC machine, then it is necessary, so if it has to brushless, then it implies that stationary source is of course that all sources inherently are stationary, you do not have sources that keep rotating by themselfs.

So, so so since sources are necessarily not going to a rotating, it then means they have to energize the stator only, difficulty comes because you have a stationary source and in the DC machine that needs to energize something on the rotor, so if you do not, if you want to avoid this arrangement of brush and all this, then the source must supply the stator, there is no other alternate. So, if the source has to supply the stator that means that the field arrangement should go on to rotor.

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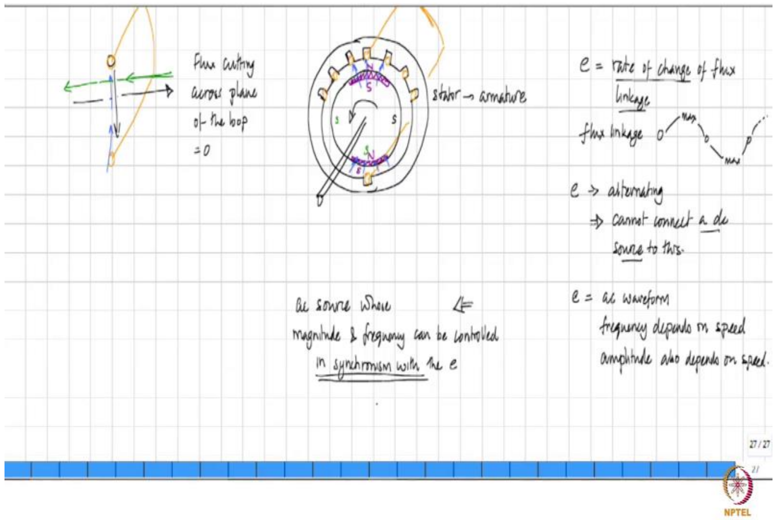

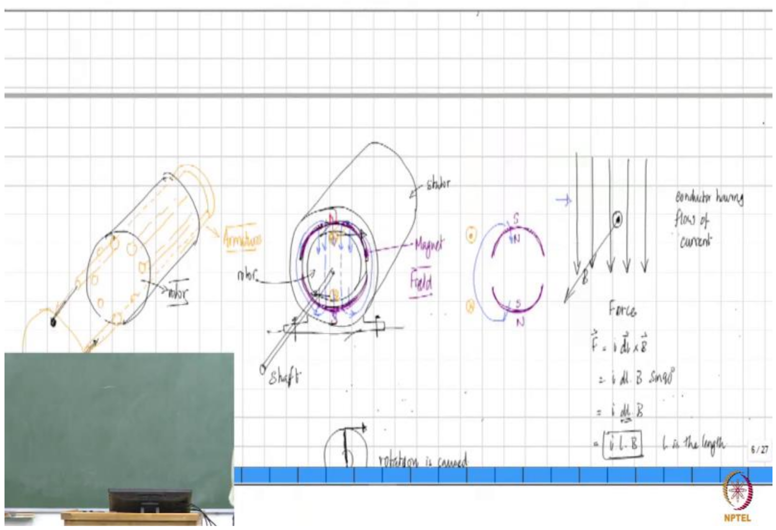

Therefore, what you have is that you have the stator which contains the armature that means you are going to have that is the inner circumference of the stator and in the inner circumference of the stator you will have slots, so I just draw one slot here. And we had earlier for the DC machine we had earlier put we had earlier made an arrangement like this, where the armature conductors were placed around the circumference of the rotor, now instead what happens is that they would be placed around the circumference of the stator.

So, we would now have conductors going into all these things, these slots and you have for example, a conductor here then this conductor goes all along the length, exits out of the cylinder and then it makes a connection with this conductor which similarly runs along the length and then comes up. And then there are interconnections in different ways in order to make flow of current happen through all. And you then have a rotor, you have a rotor and on the surface of the rotor you can put magnets. So, this phase of the magnet maybe north that is south, then this is south and that is north.

So, it is then means that the magnetic field lines go out of the North Pole here and enter into the South Pole here and this rotor then contains a shaft which can then be connected to load and you can make the load rotate. So, this is the arrangement and if this is the arrangement what we see is that if this rotor is now going to rotate in some direction, then the field lines which are going to be linking this one turn, for example that is going to vary with respect to time and if it vary be with respect to time you have an induced EMF which is proportional to the rate of change of flux linkage.

And since this rate of change of flux linkage is always going to be there as the rotor keeps rotating, so let us consider for example, you have this conductor which is there here goes along this length you have the return conductor, so this is connected and you have the field like this, at this particular instance when you have a magnetic field going upwards and then returning back like this.

Therefore, in this case, flux cutting across the plane of the loop is equal to 0, because this loop if it has to have flux that is cutting across the loop then it has to flow this way. But in this rotor position, there is no flux flowing in the horizontal direction, all flux is going like this, therefore the flux linkage is 0. But if the rotor is now going to rotate and this S comes over here, then you will have all flux lines going in this direction, no flux lines going in the along the loop itself and therefore you have maximum linkage of field.

And then when the rotor is going to rotate and S is going to come over here, then the field lines would be going like this and then again the linkage is equal to 0. And when S comes over here, then the flux lines will be going like this, then the flux linkage will be highest but in opposite direction. So, you have as the rotor is going to rotate, flux linkage goes from 0, to maximum, 0 to negative maximum, back to 0 and then goes up. Which therefore means that the induced EMF e will be an alternating EMF.

Because d phi by dt is going to change signs, therefore since the induce EMF e is alternating this implies that you cannot connect a DC source to it, it is not feasible you have an alternating source you cannot put a DC source on it and get anything useful out of that. So, if this is an alternating source, then you want to connect an alternating source that is the only way and this alternating source as you can see the rate at which it is going to alternate one full full one full alternating cycle is going to depend on one full rotation of the rotor, what if the rotor is going to rotate by one full 360 degrees, then the flux linkage goes from 0 to maximum, 0 to negative maximum to 0.

And therefore, how many times will it alternate per second? It will depend on the speed of the rotor, if the rotor of rotating slowly, then the number of alternating induced EMF's will over a certain durations will be smaller, if it is rotating at high speed when the number of times it will alternate will be both. So, you also see that since induced EMF is proportional to the rate of change of flux linkage, the EMF will be an AC waveform, frequency depends on speed, higher the speed, higher it is going to be, amplitude also depends on speed, d psi by dt.

So, if the rate at which flux linkage is going to change is more, then the magnitude of induced EMF is also higher. And therefore if these things mean that you have to you cannot put a DC source to this, as we said earlier, what we need to put is an AC source, you have the put such an AC source is that is you need to connect an AC source is magnitude and frequency can be controlled in synchronism with the induced EMF.

It has to be done in synchronism with induced EMF, you cannot supply a voltage of different frequency to this motor, than it will simply not run, in case it is very important to do. And so how does this then work? So, one of the ways of this induce EMF being generated is like this.

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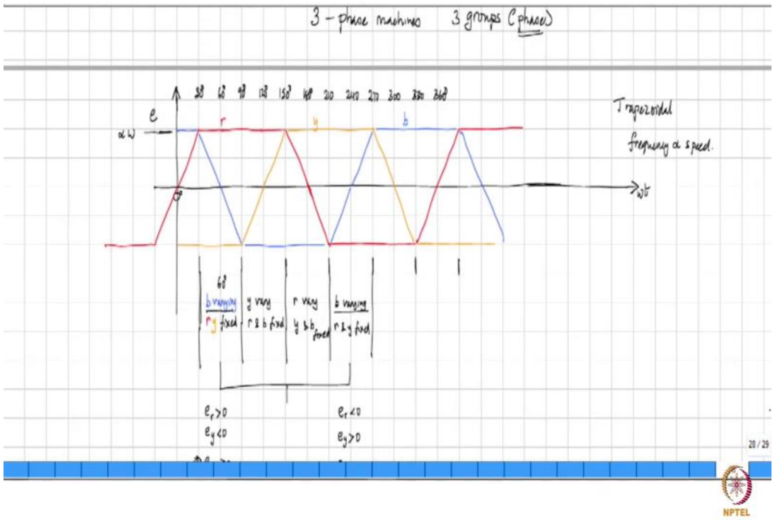

So, these machines are best design as 3-phase machines that means all the different conductors that are put around the circumference of the stator are split into groups, 3 groups, each group is than called as one phase. And therefore, we then talk of induced EMF in each phase. So, one of the ways in which that can be done is like this, the induced EMF can be made to look like this. So, this is a trapezoidal EMF and not a sinusoidal induced EMF.

And I have drawn it that is why if you so this axis is with respect to time, this is induced EMF and this happens as the rotor rotates that is with respect to time it is understood that the rotor is rotating at a fixed speed and as the rotor therefore gets moving there is an induced EMF on the stator phase. And since the rotor is moving at a fixed speed we are drawing with respect to time, you can also scale this in terms of omega into time, which then means the angle through which the rotor more.

So, if that is then the case I can draw this to be 0 degrees and then this is 30 degrees 60, 90, 120, 150, this is 180 degrees, 210, 240, 300, 340 and 360. So, I am drawing this at intervals equal to 40 degrees, then the next phase is design to start 120 degree later that means this way, so this is waveform that goes on continuing, it would have existed here then, so this waveform then looks like this and then there is one more phase which is phase shifted further by 120 degrees, this machine is interesting if this is the way the waveform is going to behave we said that this magnitude, magnitude of the induced EMF is simply proportional to speed, frequency is also proportional to speed, both are proportional to speed.

So, we have drawn this waveform for a particular speed of operation. Now, the nice thing about machine is that if you look at let us say this interval, this is a 60 degree interval, in that 60 degree interval you find that one phase is going from one amplitude level to the negative amplitude level whereas this phase and this phase are at fixed level of amplitude, when if you consider the next 60 degrees one of the phases that was at a fixed amplitude level now begins to change and the other two phases are at a fixed amplitude level.

So, in this manner if you look at 60 degree blocks, so take the first that 60 degree mark, then the next 60 degree, next 60 degrees, so let us call this as r phase, call this as y phase and call this b phase, then in the first 60 degrees we have b varying, r and y are fixed. In the next 60 degrees we have y varying,, r and b fixed. In the next 60 degrees we have r varying y and b fixed. Further, let us write this again in this 60 degrees we have b varying, r and y fixed.

So, it is quite evident therefore that in every 60 degrees that we select like this one of the phase EMF varies with respect to time, the other two remaining are remaining fixed.

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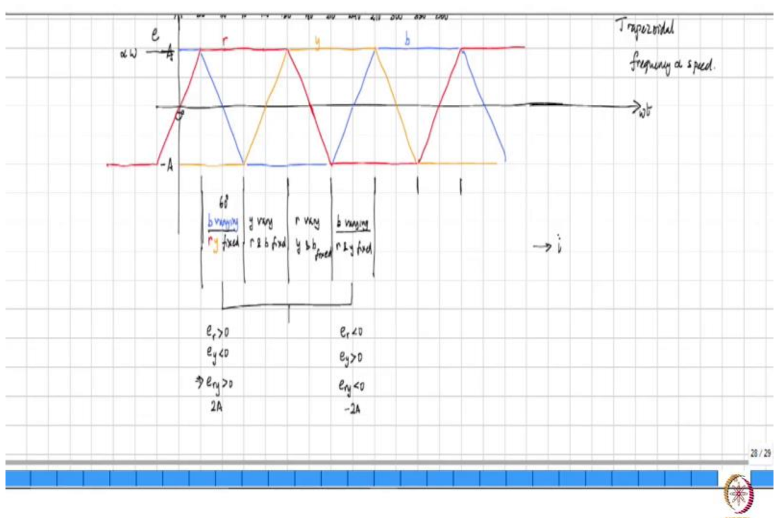

Now, if you look at these two intervals, in both these two intervals you have b varying, r and y are fixed, but what is the difference? The difference is in this interval the potential of r is greater than 0, the potential of y is less than 0, in this case the potential of r is less than 0 the potential of y is greater than 0. Which than means that in this interval if you take the difference e r y that means the potential difference between r phase and y phase if you take this will be greater than 0 and this potential difference e r y will be less than 0.

If you call this amplitude as A when this amplitude is minus A, then this potential difference e r y is 2 times A, whereas it is minus 2 times A here. Similarly, you can work out for all the intervals. Now, we have seen that if there is going to be a flow of current i into the machine. Now, in the case of DC machine, in the case of DC machine, we said that if there is going to be a magnetic field that is going to be there at the place of the rotor conductor, the conductor carries a certain direction of current and there is a magnetic field.

Then there is a force that is exerted on the conductor, which is given by this ideal cross B and therefore this conductor tend to move. Now, you look at this situation now you have the exact inverse of this, by row of physical arrangement, never the less. You are having a same situation here as well that there is a magnetic field that is going to go, like this and there is a conductor which can carries some current you can supply some current it is now on the stator you can connect what you want with it.

So, will this conductor experience the force? Will it experience? It has to, I mean that is the law of physics, there is a magnetic field, there is a conductor, there is a current, there has to be a force. But now the difference is this is in the stator and what is the meaning of stator? The stator means you are not going to allow it to rotate, you are going to prepare bolt and bolt it to the base plate, bolt it towards, so what is going to remain fixed, than what will be the effect of this force? It will attempt to make this it will attempt to make this move but it is not going to move it is going to be fixed. But every force has an equal and opposite force which will now be felt by the one that is generating the magnetic field.

And therefore the reaction force the rotor will now going to rotate. If you allow it rotate, if you are going to put a clamp on it and rotate that also, then it will not rotated, but nobody will do that, the whole idea is to get something to move and therefore you are behaving the rotor free to rotate, therefore we are keeping this fixed and the reaction force now causes this fellow to rotate. So, the the first magnitude is still the same, why? Newton's law says, it is an equal and opposite force.

So, the first magnitude that is felt by the rotor will still be the same, but it will now start rotating the rotor instead of the stator because you have chosen to put the stator fixed. However, if somebody is going to ask what will happen if I leave the rotor free and I leave the leave the stator free, then both will start rotating, one will be rotated in one direction, one will rotate in other direction, that is all difference.

In the other machine also the same thing would have happened, the stator would have rotated in one direction, rotor would have rotated in other direction, after all the laws of physics are still the same. But there also keeping the stator fixed here also the stator is fixed, the stator happened to be the member generating the field in the earlier case we use the rotor is the one that has generating the field that is all the difference. So, in both cases the stator is fixed and therefore the rotor begins to move.

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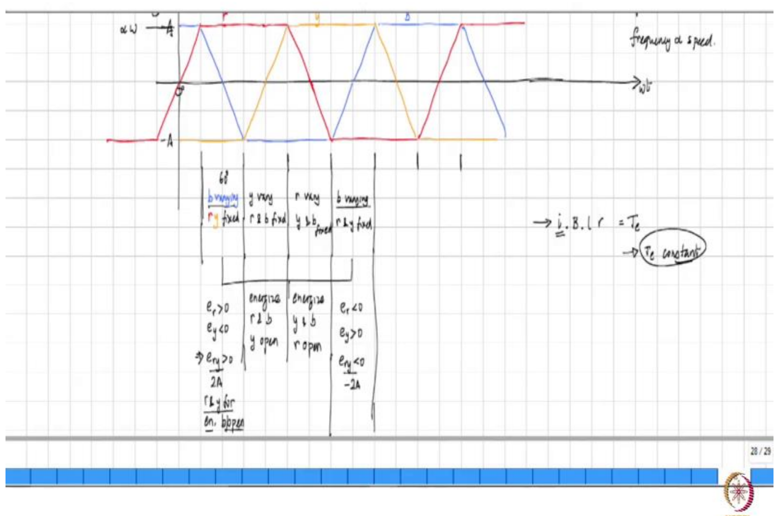

So, now it is still the flow of current i which is the cause of the movement, the same expressions as we had derived earlier still continue to hold that means i is going to add along with this vector B and along the length of the cylinder l and multiplied by the radius of the cylinder is going to give the electromagnetic torque.

And what we want is we want by electromagnetic torque to be something that does not vary with respect to time, we want if you send a fixed current, we want the fixed torque and not something that is going to vary respect to time because we want to rotate a load with the smooth torque, smooth within cotes we have already seen, therefore if torque we wanted to remain fixed and we find that the induced EMF in this blue phase in the first 60 degree interval is changing with respect to time, then it does not make sense to energize that phase.

Whereas the phase's r and y are having a fixed induce EMF, so if you send a flow of current into that then that is likely the generator fixed it up. Therefore, what you do is, in this 60 degrees you select r and y for energization, keep b phase open do not do anything to leave it open. In the next 60 degrees interval you have r and b is fixed, so energise r and b keep y open, in the third 60 degrees energise y and b keep r open when you come to this point again you have to select r and y for energization and keep b open, but what is the difference because the induced EMF sign is going to change you have to energize it in the opposite sense. So, how does one do this?

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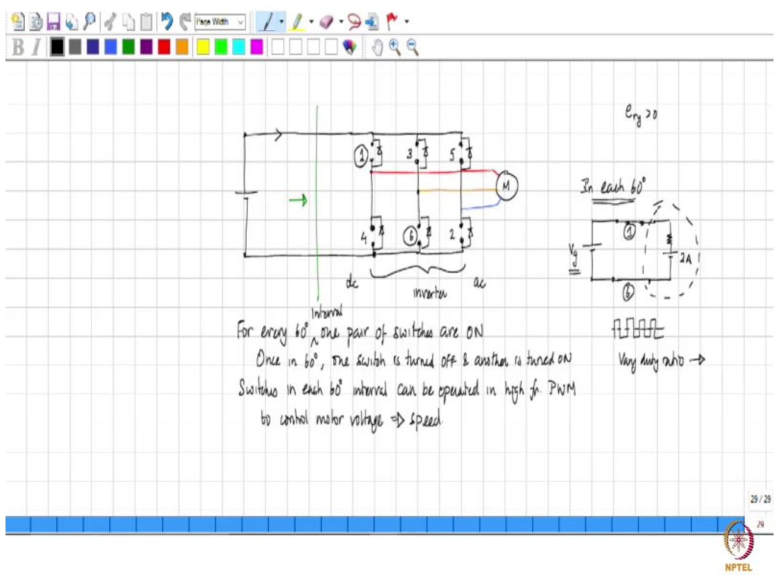

So, if you say that this is your motor and you are having r phase y phase and then the b phase and then what you have is a DC supply since the first 60 degrees you want to connect r and y, such that e r y is greater than 0, so that means this terminal of vg can be connected to the r phase, through a switch and you connect here through switch, so in the first 60 degrees e r y is greater than 0 and we are connecting vg in the same sign and therefore flow of current into this will be opposed by the induced EMF that is there and therefore it will result in active flow of electrical power from the source to the motor.

Now, in the next 60 degrees you want to energize r and b keeping y open, so in the next 60 degrees, what you do is you will keep y open and what is the nature of the voltage e r b, r b is still greater than 0, so e r b is greater than 0, so you want to connect r like this and then you need to connect b here. So, e r b is greater than 0, you are connecting vg greater than 0, so induced EMF is still opposing the applied voltage, there will be a flow of current and active power flow can be there.

In the next 60 degrees you want to energize y and b keeping r open, what is the potential difference e y b greater than 0 that means you now have keep r open to connect y here then now you have e y v being greater than 0 again induced EMF opposes the source voltage flow of current will happen. In the next 60 degrees b is going to vary therefore you want to keep it open and you want e r y to be less than 0, so what does it you can do? So, you want to keep b open and e r y is less than 0 that means you can take this and connect it here.

Now, you have e r y less than 0, because vg is connected to this point, r is connected to this point, so r y is now less than 0. And by now you get a hang of it, that you put one more switch here, so if you have a circuit that looks like this, then you can generate all the possible sequences that you want. And these are all then your semiconductor switches may be MOSFET's, maybe IGBT's and as before you need to put a freewheeling diode across each one of them in order to ensure that flow of current is not interrupted.

And this circuit is called as an inverter, because it takes DC on one side and delivers an AC waveform on the other side. Why is it delivering AC waveform? Obviously, you can see that this voltage that needs to be applied is reversing. So, that is the functionality achieved by this circuit. So, the operation then is that in each 60 degrees the circuit of the machine is always going to look like this, you have the DC source and then you have the armature of the machine which could be picturized as a resistance.

And the another DC EMF whose magnitude is 2 times A, this is vg and you can connect. In every 60 degree that is how it looks and therefore as far as the DC source is concerned the motor looks like a DC motor. If in every 60 degrees that is going to be the equivalent circuit, the DC source does not see any change that all from the conventional DC machine. What we have now done is by flipping the arrangement of the DC machine field and armature and putting an inverter here we have made that entire set look like a DC machine to the source. And that is why this is called as a brushless DC machine.

The only drawback is that you are now applying a fixed voltage vg to this so called look alike DC machine and we know that if you apply a fixed voltage to the so called DC machine it will run at a fixed speed depending on the load and some load characters will be there and depending on what it demands, it will run at some state. Now, if you need to control it what we have seen earlier is that you have to reduce the voltage to that is applied to the DC machine, how do you reduce the voltage use the same methodology that we used earlier that is in this case the full DC voltage is applied to the machine, but if you have a switch here you can now switch it at some rate and operate at some ON time and OFF time, therefore the reduced value of DC voltage will be applied.

So, it means that during each 60 degrees you want for example, let us call this is switch number 1 and switch number 2, in this case in the first 60 degree switch 2, let us say 3, 4, 5 and 6 that is the numbering I am giving, so in the first 60 degrees r and y, so 1 and 6 were turned on, so what it would mean is that this switch was switched 1, this switch was switch number 6. So, what do you do is do not keep them ON all the time, in this 60 degree interval itself you operate it at some rate such that they are kept ON and OFF repeatedly.

Then you get only the average voltage for which the motor will respond and therefore by varying the duty ratio vary duty ratio, you can change the average voltage applied to the motor. And thereby, you can control the speed of the motor. We require you to spend a little bit of time with this, you see what exactly is happening. So, essentially for every 60 degrees, one pair of switches are ON, every 60 degree interval once in 60 degrees one switch is turned OFF and another is turned ON, switches in each 60 degree interval can be operated in high frequency PWM to control motor voltage and hence the speed.

So, this is the manner in which this circuit can be operated in order to control the motor speed. So, one can then figure out I will leave it to you as an exercise to figure out in each 60 degree interval which we have already seen we discuss this, go back and put down in each 60 degree interval, which of the switches will be ON? And which switch will be OFF? Which are always obviously two switches are going to be ON, which are the case which is that will be ON every 60 degrees? And the others therefore OFF?

Now, obviously the switches that are ON are going to depend upon which parts which are the EMF better flat and which is varying? And which is a EMF that is flat and which is varying depends upon this omega t, it is a function of the X axis variable omega t. And therefore, this omega t is nothing but the rotor angle, it means that the switches that are to be kept ON are dependent upon the rotor angle.

So, you need to get the rotor angle information at every instant or once in 160 degrees to decide which switch you will turn ON, which switch you will turn OFF, you need to know what are to be kept on each 60 degrees and when does the 60 degree interval start, so that you can turn the switch ON. How to do that? We will see in the next class.