Introduction to Robotics
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Lecture No. 20
Power Electronic Switching and Current Ripple

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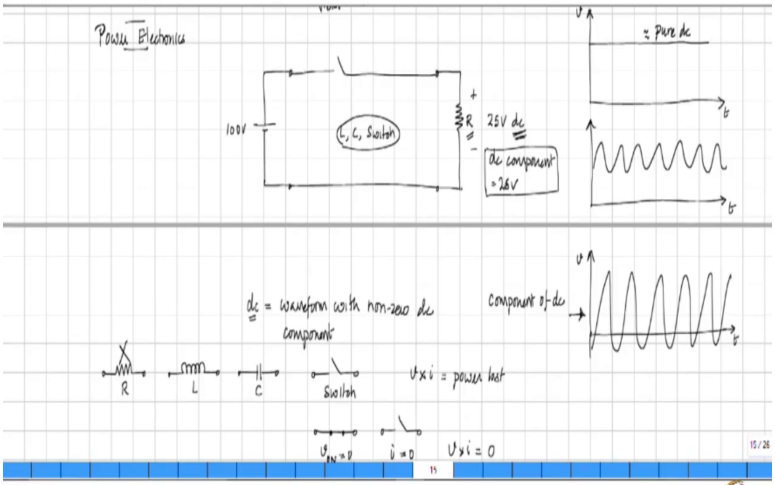

In the last class, were trying to look at how one can generate dc, which is of a different value as compared to what was there in these course.

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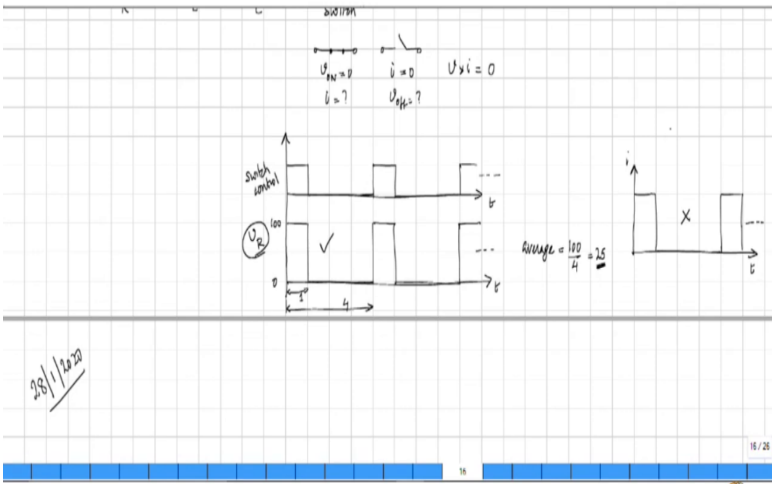

And we saw that you can generate a dc which has a different value that is some 100 volt. If you want a dc of 25 volt, one can generate that by using a switch and operating it in this manner. So, if you keep it on for one fourth of the times and the remaining 75 percent you keep it off then on an average you get the required dc value applied across the resistor. So now, the question is, if you are going to do this then it means that if you plot through the resistance, if you want to look at how much flow of current is there with respect to time, then that is also going to look like this. And this waveform is not accepted.

While the waveform of voltage is all right, we do not really desire that that needs to be smooth for this application. For certain other applications, perhaps you may want the really smooth dc waveform that is okay. But in this particular case, this is not so important, but this is important and not acceptable. Now, the question therefore is, how do you get a smoother waveform for i?

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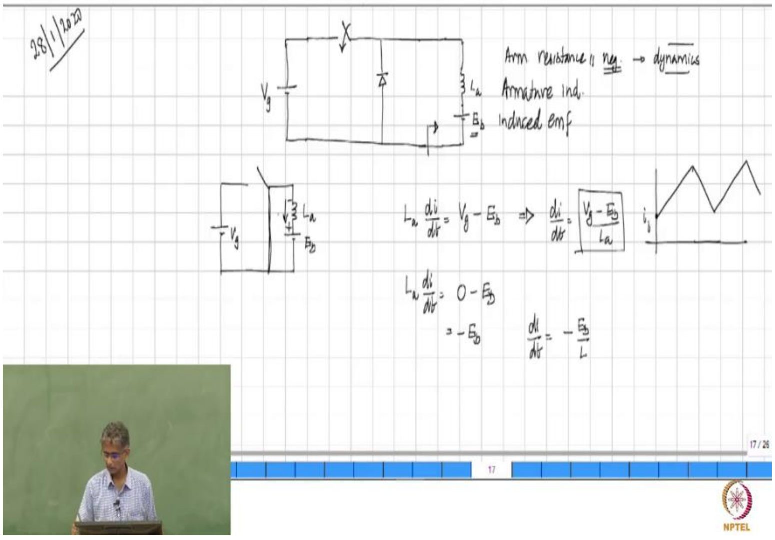

Now, if you take the case of a dc motor, what we really have is, let us say that this is the 100 volt that is available, what you have in the dc motor is a resistance of the armature, call it Ra and then there is an inductance of the armature, call it La and then there is an induced emf. If the motor is rotating at a fixed set speed then the induced emf is simply equal to some gain times the speed from k into omega. And therefore, for a fixed set speed operation, you can represent that by another dc source. This is the induced emf, I will call it Eb. So, this is induced emf, this is armature inductance, this is armature resistance.

Now, normally for reasonably sized machines, this armature resistance is not likely to be very large, I suppose if you take a small motor which you operate from some very low voltage dc, those will have a very high armature resistance, but any dc motor that is of higher output power, you will find that the armature resistance is really small. We would like it to be small because any resistive element is a dissipative element. You do not want to waste loss in a motor, so these are designed so that armature resistance are small. So, for the purpose of analysis, what one can do initially at least is to neglect the armature resistance, say that, that is not there.

Therefore, as far as the motor is concerned, seeing from the outside of the motor, it looks like an inductance in series with its source. Now, I am saying armature resistance is neglected for the purpose of looking at the dynamics of the motor, not for the purpose of V is equal to Ra into i plus k into omega, that is the steady state expression, where you cannot neglect armature resistance and say that V is equal to k into omega. So, one needs to do, one needs to understand where to make what approximations.

Now, if this is the situation, we need to understand what will happen now if you apply this kind of switch control. So, let us say you are having a switch and this is close, what will now happen if you close the switch? So, if you close the switch, basic electrical circuit which I am sure everybody would have done at some stage or the other says that if this is Vg and this is Eb and you close this switch, a very simple circuit is the result, which is your Vg, there is an inductance and then there is Eb. This is all there is in a circuit.

And you want to find out how much current will flow. The equation is very simple, it simply says La into di by dt equals Vg minus Eb, that is all. L di by dt is the voltage across the inductor which you very well know. This is elementary-elementary electric circuit. And therefore, we can easily conclude that di by dt equals Vg minus Eb divided by La, which means that this is a fixed number as far as the motor is operating at a constant speed, it is a fixed number. That means the inductor current will increase with a fixed set slope. That is what it means.

So, you are going to have inductor current from some value. It may not start at 0, of course, if you are going to switch on the motor initially at 0 speed, motor was not at all operating, and you turn the switch on, there was no current flowing, current will increase from 0. But let us say you have done several set switching operations, after that if you see there was some initial current flowing and this current will now go on increasing. That is what is this equation says.

Now, we are going to turn the switch off after some time, and the question is what happens if you switch it off? So, if you turn the switch off, then it means that you are interrupting the circuit. And if you interrupt the circuit, what will happen to this flow of current that was happening?

Professor: What will happen to this current I, if you switch off? It will go to 0. That is very simple. The moment you open the switch, no more circuit is there. There is no no route for this current to flow. You are forcing the current go to 0. But this is not at all a good idea for this circuit. Can anybody guess why?

Student: Half La square will be dissipated, will be gone.

Professor: Half La square will be dissipated, will be gone. It will result in a spark. L da by dt L da by dt di by dt is minus infinity here, you are just switching it off. And L da by dt will generate a huge voltage spike, and that voltage spike will come across the open switch. It will result in a spark if it is a mechanical switch. But we cannot use a mechanical switch here, we will use an electronic switch. And a huge voltage comes across the electronic switch, the switch will burn.

So, that is not at all a good idea to interrupt inductor current like that we need to allow the inductor current to continue flowing, but nevertheless cause the voltage across this as 0. So, one simple solution to that is to put a diode here. How does the diode help? If there was an inductor current flowing and you now switch this off, this inductor is trying to generate a voltage in this manner. And if you have a diode here that attempt to generate the voltage in the negative direction will automatically switch on the diode, because the diode becomes now forward-bias. Therefore, this diode will turn on and a good semiconductor diode is as good as a short circuit.

So now, you go to an equation which says, La into di by dt equals, there VG is no longer there, so instead of Vg, it is now V rho because you have shorted this, V rho minus Eb, which is simply minus Eb. Now, therefore, di by dt has now become minus Eb by L, which now means, instead of this current falling to 0, it will now have a negative slope, which means the current will fall. And after some time, you are going to turn the switch on again, which means the current will increase again and then you are going to switch it off again, so current will fall and so on, like this one can go on and off. So, this current waveform is obviously much better. We saw that right at the beginning, where was that?

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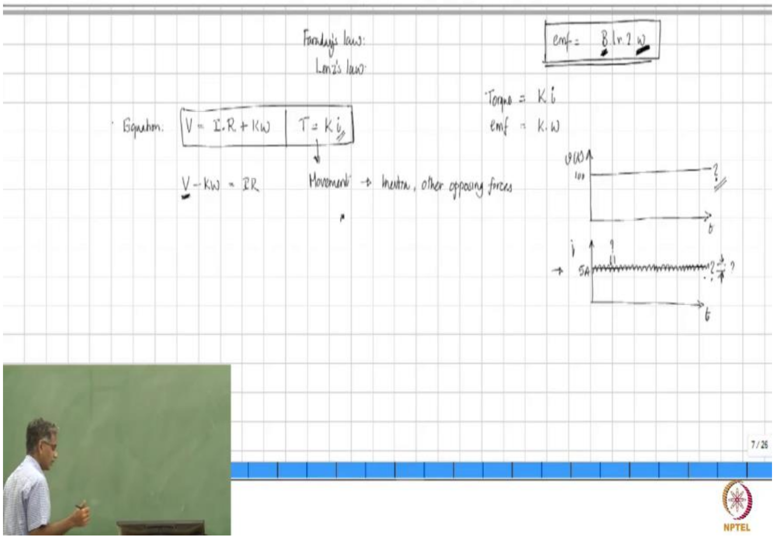

We said whether we can allow this kind of current waveform and we said that yes, you can allow. What are the things you need to look at? Whether the magnitude of the ripple is small enough and the frequency of the ripple is high enough.

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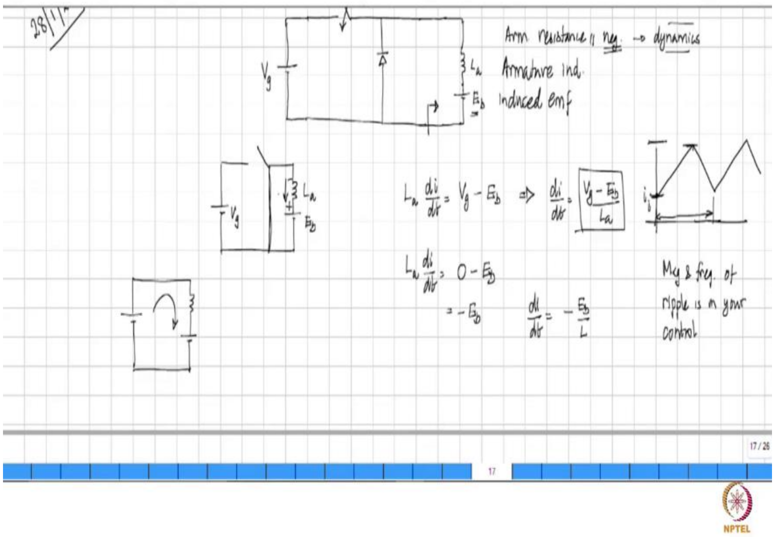

Now, in this case, magnitude of the ripple is certainly under your control, because when you close the switch, the circuit looks like this and this current is going to increase. And therefore, you know how much increase is happening. If it goes beyond a certain value, you can always switch it off, and allow it to fall down. So, magnitude of this ripple is certainly under your control, you can control it to whatever you want.

Similarly, the rate at which you are going to switch this duration, that is also under your control because that is decided by how many times you are switching the switch on and off in a given interval of time. Therefore, if you do this operation, both magnitude and frequency of ripple is in your control.

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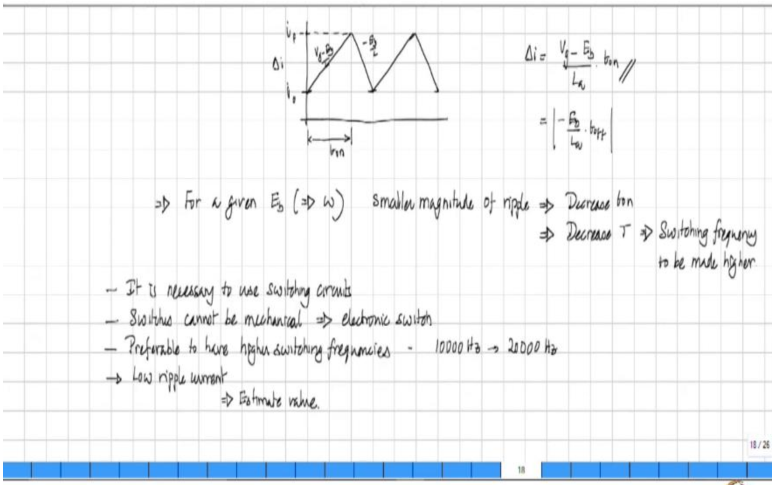

So, in this case, for example, if the motor is going to operate in a steady manner and the circuit is also going to operate in a steady manner, then it means that this waveform has to be in such a way that if it starts from some initial value i naught, and during the time of this switch, it rises to some value, let us say, if, then during the off time of the switch, it has to come back to the same value I knot and repeat in this manner. This is what would then be a stable steady operation.

And therefore, if this ripple is delta I, how do you compute delta i? Delta i is then equal to Vg minus Eb divided by La multiplied by the on time, where this is then the on time, this is delta I, it should also be equal to minus Eb by La into t off magnitude of that, because during this time the slope is minus Eb by L, during this time the slope is minus Vg minus Eb by L.

So, it means, for a given Eb, which implies for a given speed of operation. If you want smaller ripple, smaller magnitude of ripple, how can you achieve smaller magnitude of ripple? If you look at this expression, either you have to decrease t on or increase La. That is the simplest trick. So, you can choose to do either of them. Either you can choose to decrease t on or you can increase La.

How can you increase La? La is the armature inductance, you cannot go inside and modify the machine, so what you can do is put an inductance outside the machine. That is one way. The other way is to decrease the value of t on. So normally, what you do is, you do not put an inductance outside because that is extra cost, it may be big depending on how much inductance we want. So, the best way to do it is to decrease the value of the t on.

But you cannot just decrease the value of t on, why? Because you want a certain armature voltage. And the value of armature voltage is Vg multiplied by t on divided by t. If you simply decrease the value of t on and keep the overall duration same, then it means the average voltage will come down, that is what I am talking about is, if you look at the circuit here, how do you get the average voltage?

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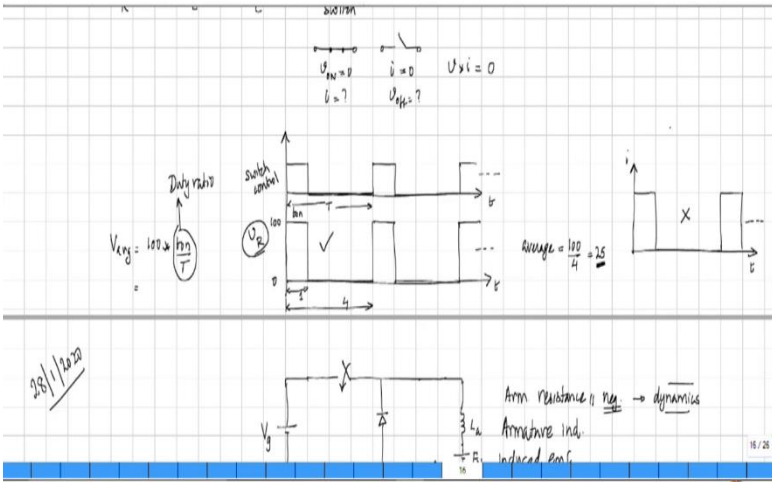

V average is equal to 100 multiplied by if this is the on time t on and if this overall duration is capital T, this is multiplied by t on divided by T. You do not want this to change. You want 25 volt average applied to the motor. And therefore, if you want smaller ripple and you want to decrease the value of t on in order to keep the average voltage same, you have to decrease the value of capital T as well. So, this ratio of t on divided by T, this ratio is called as Duty ratio. So, you need to keep the duty ratio fixed in order to get a certain voltage.

And therefore, if you want to decrease t on decrease t on, which therefore means decrease capital T, which implies therefore, switching frequency to be made higher. So, important thing is that the major conclusions that we have are, it is necessary to use switching circuits. Why it is necessary to use these kinds of circuits with switching things?

Students: to maintain average voltage.

Professor: You want to maintain average voltage but you could have got an average voltage by putting a series resistor as well.

Student: keep the efficiency high.

Professor: To keep the efficiency high, to keep the losses low. So, it is necessary to use these kind of switching circuits. Switches cannot be mechanical. You cannot use a mechanical switch what you see here. Then you will have to put somebody there to switch it on and off at some frequency. Nobody will do their job for you. You cannot use any automatic mechanical switch also. Mechanical switches cannot really be switched at great speeds.

So, you will have to go necessarily for electronic switches, electronic switch. Preferable to have higher switching frequencies. How high is a high switching frequency? What is high for you may not be high for me, what is high for me may not be high for somebody else. So, you will have to look at what is the switching frequency, which this electronic switch can handle. Any electronic switch will have to go from on state to off state and off state to on state again, that is the switching action.

And every switching action results in a certain loss, every time the switch is turned on, there is a certain loss, when the switch is off there is a certain loss. One has to make an assessment of what is the loss that is happening as you increase the switching frequency and what is acceptable to you. So, one has to make that assessment to decide what kind of switching frequencies are admissible. In the systems that are implemented today, what you will find is frequency is in the range of in the range of 10000 hertz to about up to 20000 hertz are widely used.

So, if you do all this then you can get a low ripple current, which might satisfy your need. But nevertheless, you have to estimate, “What is the ripple current?” How to estimate the ripple current? This is the way to estimate the ripple current, where you have seen an example of how that can be done. Now, in reality, there is an armature resistance. So, what is the difference that armature resistance will bring about?

The armature resistance, if you have it then during the on time instead of the equation that we have here, we will have a slightly modified equation.

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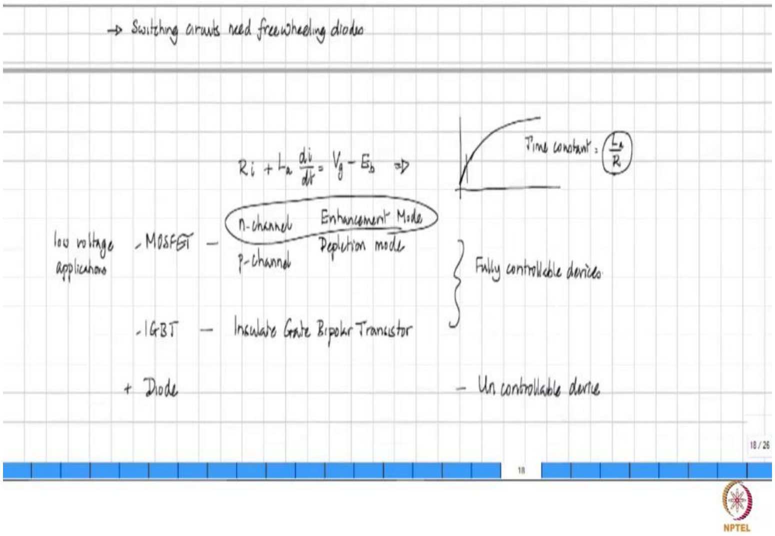

So, this is the equation that we saw, if there is no an armature resistance, you have one more term which is plus R into i. This will mean that it is a simple first order equation, we do not need specific knowledge of electrical engineering to solve it. So, let us not get into a solution therefore, but now there is, you know what a first order equation solution looks like. This is going to go like that. Earlier, we had a simple linear increase of inductor current.

Now, it is not going to linearly increase, it is going to slowly increase. So, if you arrive at the mathematical expression for this, the slope initial slope is equal to this Vg minus Eb divided by L that is what you will find is the slope at start. So, it is going to increase much more slowly as compared to what we thought was the case without the resistance. Now, as the value of the resistance becomes smaller then this is going to be determined by the time constant of the circuit, and that is La by R. If the time constant is larger, then it is going to take a longer time to reach the final value. So, this is what is going to happen and therefore, this rate of rise may be actually a little slower than what we want.

But in any case, if this number is going to be large, we are not going to wait until that time to switch it off, you want high switching frequencies. So, it is very-very likely that you will be switching off somewhere here itself. So, you are not going to wait till it reaches the steady value of some level. So, in view of the fact that you are going to switch off very fast, again the approximation that we have made by neglecting the resistance is a good enough approximation in order to determine this.

So, this, the semiconductor diode that goes here is called as a Freewheeling diode, because it allows the inductor current to freely circulate when the main switch is off. So, one important another inference is that switching circuits need freewheeling diode. So, what are the electronic switches that are used for this? MOSFET is one. What is the expansion of MOSFET? Metal Oxide Semiconductor Field Effect Transistor. MOSFETs are of various variety. Do you know what are the varieties of MOSFETs?

Student: N-Channel and P-Channel

Professor: N-Channel and P-Channel MOSFETs. Then there are sub-classification within that, what is that?

Student: enhancement mode MOSFET or depletion mode MOSFET

Professor: Each of them is, can be either enhancement mode MOSFET or depletion mode MOSFET. So, what is normally used is the N-Channel enhancement mode MOSFET in these applications. It is just a name just to be aware of such name. But as far as the circuit operation is concerned, it acts like a switch or it is made to act like a switch. So, this is used usually in low voltage applications. Low voltage applications meaning, if you are going to have a circuit, which is going to operate from a dc voltage of let us say about 100 volts, MOSFET is a good choice or less.

But if you are going to go to higher voltages, normally when you look at heavy duty electric motors, which are going to be operated directly from mains, this is not a device that you will use because the voltage levels are much higher. There, you would use a device called as the IGBT. Do you know what that expansion is? Insulated Gate Bipolar Transistor. So, mostly, these are the 2 devices that are used. These two devices are what are called as Fully Controllable Switches, Fully Controllable Devices, that means you can decide when you want to turn on this device and when you want to turn off that device, completely both operations are in your hand.

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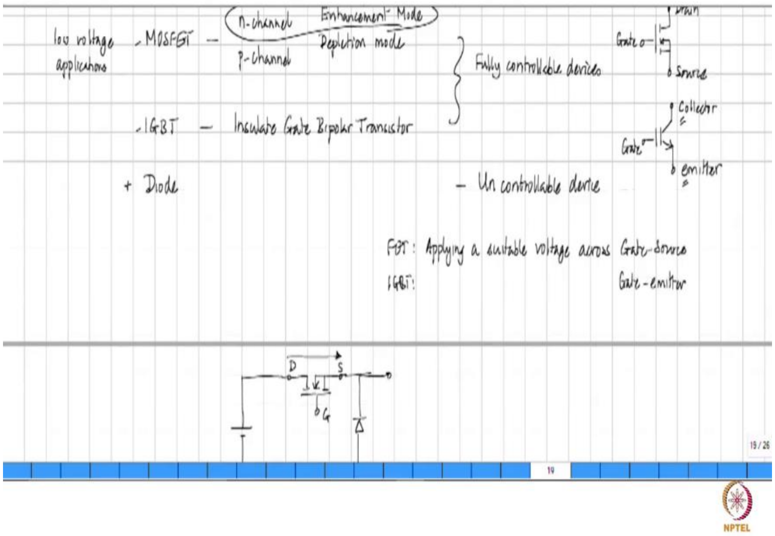

The other most frequent semiconductor device that is used is the Diode. And the diode is not a fully controllable device, in fact, it is a uncontrollable device. Why it is uncontrollable? You cannot decide when you have to turn it on, when you want it to turn on and you cannot decide when you want it to turn off. The circuit conditions decide when it will turn on and when it will turn off. So, every circuit that you are going to have in order to operate the electric motor will comprise of either the MOSFET or IGBT and the diode just like what we have seen here.

So, there is a diode and there is another switch, that switch will then be replaced by an appropriate mechanical switch, the enhancement mode N-Channel effect is represented by a symbol like this. And this terminal is called as Gate, this terminal is called as Brain, and this is called Source. The IGBT is represented by a symbol like that. So, this is called Collector, Emitter and Gate.

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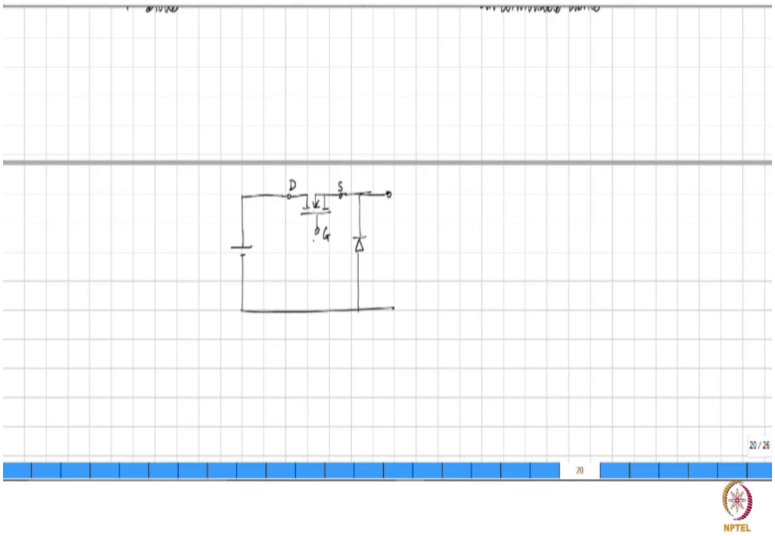

So, when it is going to be used in the circuit, the device will be used as follows. Let us say if it is defect, then you have the drain. So, this is drain terminal, this is source terminal and then you have the gate, and then you have the diode and whatever else comes on the other side. So, defect is operated by both the affect and, defect is operated by applying applying a suitable voltage across gate and source. The IGBT is operated by applying a suitable voltage across gate and emitter.

So, if you apply a voltage that is high enough, it will turn on, behave like an on switch, it will behave like an on switch between the terminal's brain and so. So, current will flow that way. The IGBT will behave like an on switch between the 2 terminals C and D. That is how one can make this circuit operate. So, having understood that you can have a switching circuit in order to generate whatever be the average voltage you want, you can always adjust the duty ratio in order to get whatever armature voltage you want to apply to the motor. So, when we drew this figure some classes ago.

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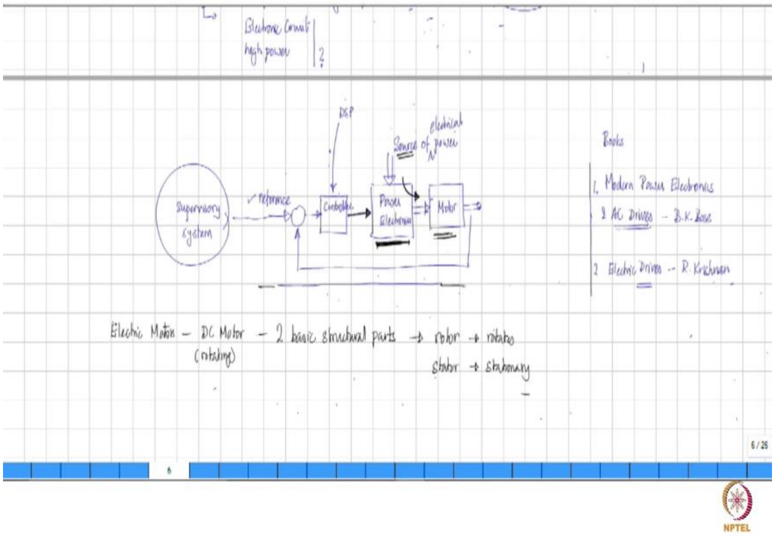

Yeah. So, you had the motor, which we know is the dc motor, and then this block is what we have now been speaking about that there is a higher, high power electronic switch based electric circuit that is accepting a source of electrical input power. And this signal, whatever goes here, this signal is a signal that says, how the switches are to operate. So, depending on the instructions given by that signal, this block then delivers a suitable output power to the motor.

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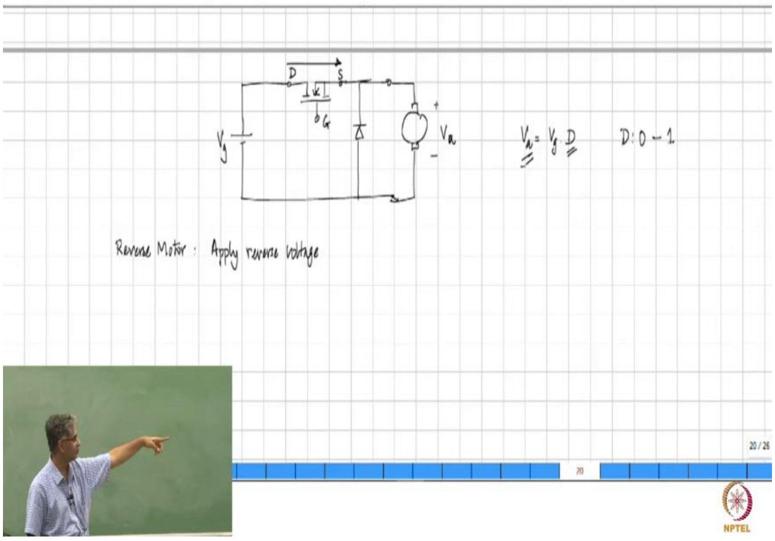

Now, having understood that if you are going to connect a motor here with a suitable high frequency of switching, you can adjust the speed of the a motor to whatever level you want. But now, the question comes, there are a few more things we need to look at, that is "What will you do if you want to reverse the motor?" If you have a robotic arm, that is going to pick up an object and place it somewhere, that arm has to go back, otherwise it cannot take the next job. If it has to go back then all the operations will have to reverse, which means, the, all motors have to perform exactly opposite of whatever they did. And which means that they now have to rotate in the opposite direction. So, how do you make this motor rotate in the opposite direction?

Student: Apply reverse voltage.

Professor: Apply reverse voltage. So, to reverse the motor what you need to do for the dc motor, apply reverse voltage. And how do you apply reverse voltage here?

Professor: If you have the output voltage here, V knot, which is the voltage applied across the motor or Va, V armature and this is Vg, we have derived an expression that Va equals Vg multiplied by duty ratio. And what can be the maximum value of duty ratio?

Student: 1.

Professor: 100 percent, 1. So, D is a variable that goes up to 1. And what is the minimum value? 0. So, D varies only between 0 to 1. If you want negative voltage here, you have to apply negative duty ratio which is just not possible. Duty ratio cannot be negative, it only lies between 0 and 1. So, what else can you do to apply negative voltage?

Student: Put another circuit.

Professor: Yes?

Student: Put another circuit.

Professor: Put another circuit. This circuit is incapable of giving negative voltage to you. Please note that you cannot say, “I will reverse Vg”. That would not work. Why it would not work? Why can you not just slip Vg and apply to this?

Student: The diode will short circuit the whole thing.

Professor: The diode will short circuit the whole thing. The moment you turn the switch on, both the switch and the diode will blast in your face because you are short circuiting the voltage source using those switches. So, you cannot say I will reverse the supply voltage and then attempt to get negative voltage across the motor. So, that is not going to be this easy. So, in reality, therefore, you apply a modified version of the circuit.

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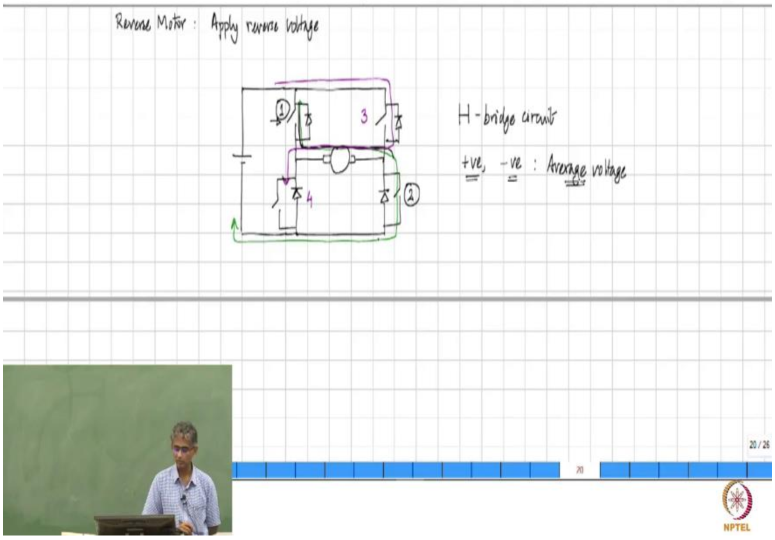

That circuit looks like this. So, you have the dc voltage, and what we did was we had a switch and then we had a freewheeling diode. And from this point, we connected the motor. I am just redrawing whatever we did earlier. And this motor was connected at this point, it was the connection. It is just now as such, it is a same circuit redrawn in a different manner. Now, if you want to apply negative voltage, what one can do is take this and put a switch here, and then convert this path to a diode.

So, if you want to operate it in one direction, where you want to control this switch, then you want current to flow like this. When the switch is on, see here, when the switch is on, you had the current flowing like this through the motor, it comes here. So, in a similar fashion you want the current to flow, so the current flows like this through the motor, and it has to flow back like this. But unfortunately, the diode blocks you cannot allow this current. Therefore, what you do is you put another switch across this and turn that also on.

Therefore, if you operate for example, switch number 1 and switch number 2 together, then it will allow current flow from 1 through the motor through switch number 2. And it will close the path. So, you have this current flowing here, coming here flowing through this switch and then coming back that closes the path. This is for the mode of operation as we had seen earlier. Now, if you want to reverse the direction, what should you do? You need to apply negative voltage to the motor. Negative voltage means, whatever out of the 2 terminals of the motor, whichever was being applied to Vg on the higher side, that has to go to the opposite side now.

So, what one can do is instead of operating switch number 1 and 2, you operate 3 and 4. So, which means that current will have to flow like this through the switch number 3, come back here and you want to flow here, but this diode is now blocking. And therefore, what you do is you add another switch across this. So, by this manner, one can attempt to get the motor rotating in the opposite direction also. But it so happens that, that alone is not sufficient, you will need diodes across this as well. Let us not get into reasons, why you need a diode, you need a diode.

So, ultimately therefore, you have a nice-looking arrangement consisting of 4 switches and 4 diodes. This is called as a H-bridge circuits. So, using this kind of arrangement then you can apply voltage that is positive or you can apply voltage that is negative to the motor. When we say you can apply voltages in both directions, what we mean is average voltage across the motor. Not the instantaneous voltage. Instantaneous will also be negative. But what is more important is that we need to control the average voltage across the motor.

So, it is important to therefore know how you will determine the average voltage and why is it that it will cause reversal of the motor, how is it that it is going to cause reversal of the motor. I think, we will see that in the next class. We will stop here.