Introduction to Robotics
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Lecture 19
DC Motor Control Regions and Principles of Power Electronics

In the last class, we talked more about how the DC motors actually works and when we are going to combine it with some sort of load, how do you then determine how or where the system will operate at which speed it will run?

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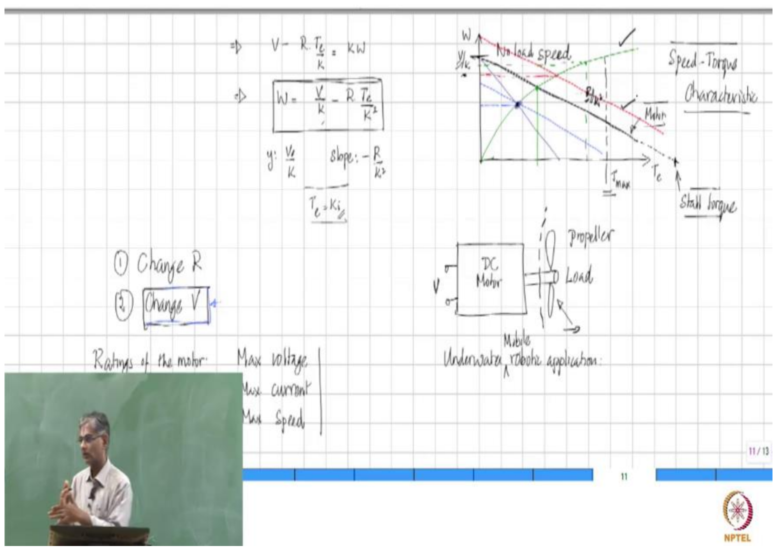

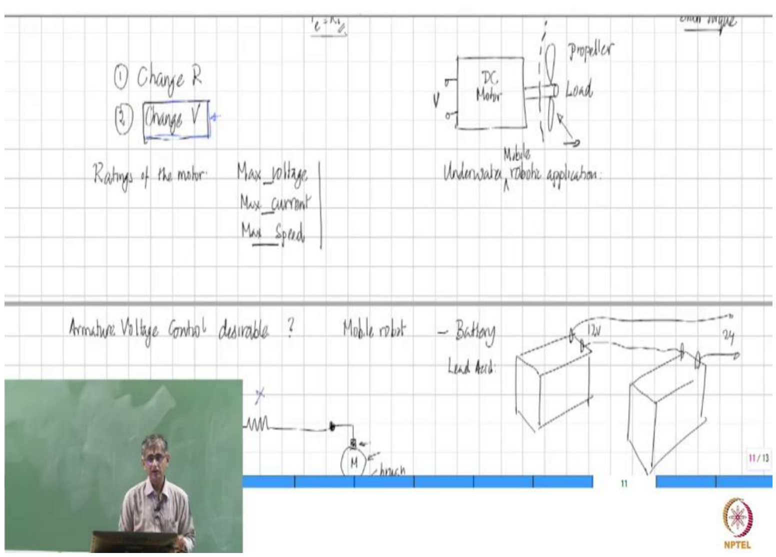

it is determined by this intersection between the speed versus, speed versus torque graph of the motor and the speed versus torque graph of the load. Where they intersect, that is where the system together will operate. So, when I say load, it is everything that is going to be there on this side. In this case, what we have drawn is a simple fan. But in general, it may not be, so it may be some series of mechanical linkages connected with something else, it could be as sophisticated as one can look at it.

But the entire thing how it looks like the motor is this represented by this graph and as far as the motor itself is concerned, that is represented by this graph and therefore, where they intersect is where the system together is going to operate. Now, as I mentioned that there is a certain maximum speed of the motor maximum current and maximum voltage. Those are the limits of operate.

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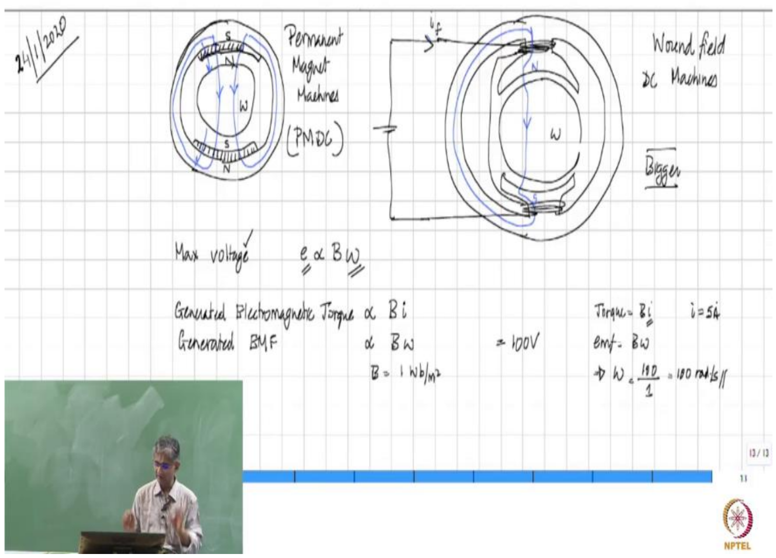

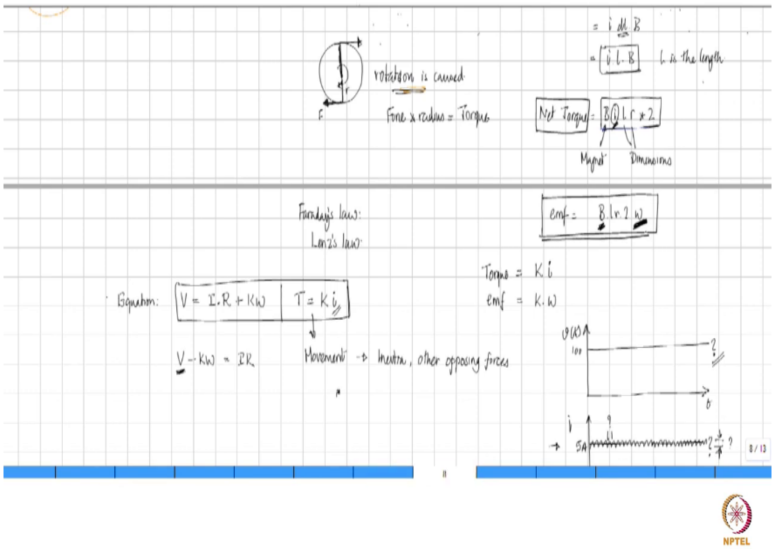

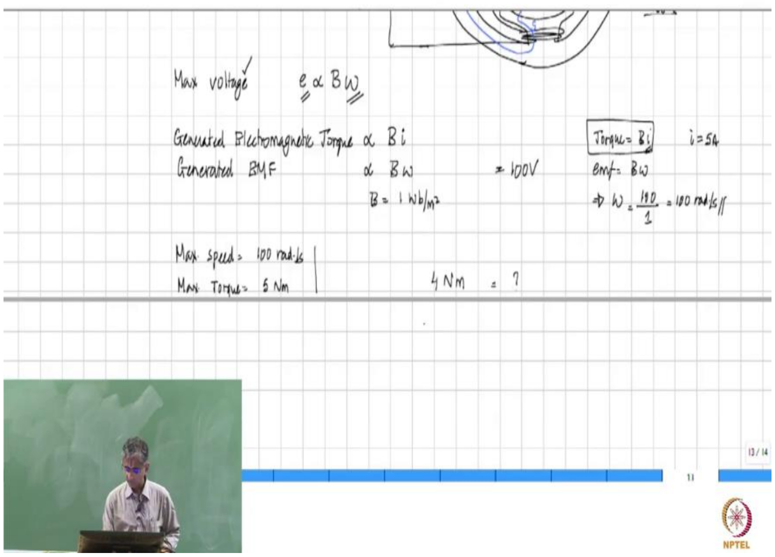

But when you look at electric motors, the operation of electric motors. In this case, we considered that if you look at the stator we have a magnet which is going to produce a magnetic field and here you have a magnet that is going to produce a magnetic field. So, as I mentioned at one point this face of it, if it represents north, then this would represent south. Then this would represent south and this represents north and this is then the outer circumference of the stator itself.

So, the field lines will then come out of this face go into the rotating member that is armature and then come out of this, there would be field lines that form a path here and then there would be field lines that will form a path here. So, this is the way it is going to go and as we said in this particular case, there is no way you can adjust the strength of this magnetic field.

Because you have a fixed magnet and there is no adjustment that you can do to it, it will generate whatever magnetic field will happen, there is no adjustment between the two. But there are machines, where this is not the situation and what you have is let us say the outer surface looks like this of the cylinder in sectional view and then what you have is its structure that roughly would look like this and similarly a structure that roughly look like this and then you have the inner surface of the cylinder and then you have the rotating member sitting here, that is the rotor.

So, here if you want to generate a magnetic field what you can do is put several turns of one conductor, bring this out, put several turns of conductor here bring this out. These two you simply connect in series. So, that whatever current you sent here will be the same current that will flow through this and you can connect a DC source here.

Now, because you have a flow of current in the loop, this then we will be able to generate a magnetic field. So, you can arrange the direction of flow of this current and the winding direction in this such that the magnetic field in this will flow out of this into the rotor and then flow here back through this and then form the loop here. So, this may still look like north, this may look like a south pole as far as the rotor is concerned.

So, these sort of machines are called as wound field machine. Whereas these kind of machines are known as permanent magnet machine. These are sometimes called PMDC machine. These are simply DC machine, wound field machine. So, obviously, you can see that the mechanical arrangement is a little more involved in the second case and this machine will therefore, be bigger than the other one which is quite obvious from the down the figure.

But what is the advantage you get? The advantage is that the strength of the field that is generated in the second case, can now be adjusted by determining the length and breadth of the field. The armature part and whatever is there in the rotating member in both cases is the same there is no difference to that. The only difference is in the second case, you are able to adjust the level of magnetic field. Whereas, in the first case you cannot adjust the level of magnetic field.

Why is this important? We said that if the rotor is going to rotate with a speed of omega, here also you have a rotor that let us say rotate the speed of omega. Some classes ago, we said that there is an induced EMF, which is going to depend upon speed and it depends upon the strength of the magnetic field.

Now, for a particular design of the armature, when it has a certain number of electrical conductors connected in a certain fashion and so, on as the speed is going to increase the induced EMF will obviously increase and the machine is designed to withstand a certain maximum level of voltage and the induced EMF is going to be simply proportional to B multiplied by omega.

So, as the level as the speed of the machine increases, the induced EMF increases and at a certain value of speed, it will equal the maximum voltage that the machine is designed to withstand, which means you cannot go beyond that value or speed for operating the machine. If magnetic field is kept the same. So, in the first case of the machine, there is no way to adjust the magnetic field and therefore, that decide what is the maximum speed limit that you can operate this motor.

But however, in the second case, you have a mechanism to adjust the magnetic field. Usually you operate the machine with the maximum magnetic field that you can allow, why? Again, we need to go back to those equations that we wrote. You will see that the electromagnetic forces that are produced inside the machine also depend on the level of magnetic field and in operation, you would like to see that you generate the required amount of electromagnetic force by the smallest amount of amperes that you are sending.

Which means that you would like to operate the machine with the maximum magnetic field that the machine is designed to handle. But however, having reached a value of speed, that will generate an induced EMF equal to the maximum voltage the machine can withstand. If you now want to go beyond that speed for some reason, usually machines are designed such that the mechanical system the integrity of the mechanical system is valid for much more than the speed at which the induced EMF is equal to the applied voltage or induced EMF is equal to the maximum voltage, a machine can withstand.

You can still go for higher value of speed and therefore, if you do want to go for higher value of speed, then the only way is looking at this equation. The only way you can do it is by reducing the level of magnetic fields, because you cannot violate the condition that the machine can withstand only so much voltage.

Student: (())(10:46)

Professor: Yeah. See, let me rewrite those equations here. The generated electromagnetic torque is simply proportional to B multiplied by i. The generated EMF is proportional to B multiplied by omega. There is a certain maximum applied voltage the machine can withstand. Let us assume that the machine you have is designed to withstand an applied voltage or a maximum voltage is equal to 100 volts. B, let us say B equal to 1 weber per meter square, which then means for simplicity I am assuming that EMF is equal to B into omega and therefore, the generated electromagnetic torque is equal to B into i.

Then this mean that the maximum speed to which the machine can go is 100 divided by 1. Which is 100 radian per second. That is the speed to which you can run the machine. At that speed how much input amperes it will draw is a separate question that is not bothered about that. You can go up to 100, 100 radians per second. The machine is also designed to take a certain amount of amperes that also we have seen in the last class that is the maximum size of the conductors inside the machine if somebody has designed it to be so much it can take only so many amperes.

And let us say the maximum flow of current is i equals 5 amperes, arbitrarily I am just saying. Which now mean that maximum speed is equal to 100 radian per second. Maximum torque is equal to 5 Newton meters. Now, this expression says that the developed electromagnetic torque is simply being too high and for the usage purposes, when I want to, when I need the machine to develop an electromagnetic torque, I need to send flow of current.

Now, if I need an electromagnetic, electromagnetic torque equal to let us say I am looking at I want to develop 4 Newton meter. I want to develop 4 Newton meter and the question is how do I do it? I can do it in many different ways.

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Max voltage ✓ $e \propto B\omega$

Generated Electromagnetic Torque $\propto Bi$

Generated EMF $\propto B\omega$ $= 100V$

$B = 1\ Wb/m^2$

Torque $= Bi$ $i = 5A$

emf $= B\omega$

$\Rightarrow \omega = \frac{100}{1} = 100$ rad/s

Max speed = 100 rad/s

Max Torque = 5 Nm

4 Nm = ?

$B = B_{max}$

$\Rightarrow i_{min}$ for a required Torque generated

~~$B = 2\ Wb/m^2$~~ $i = 2$

$B = 0.5$ $i = 8$

$B = 0.25$ $i = 16$

300 rad/s ? Higher speeds are possible if magnetic field is reduced.

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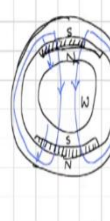
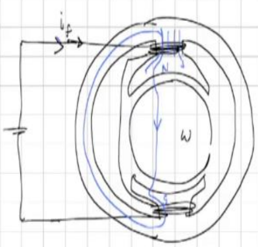


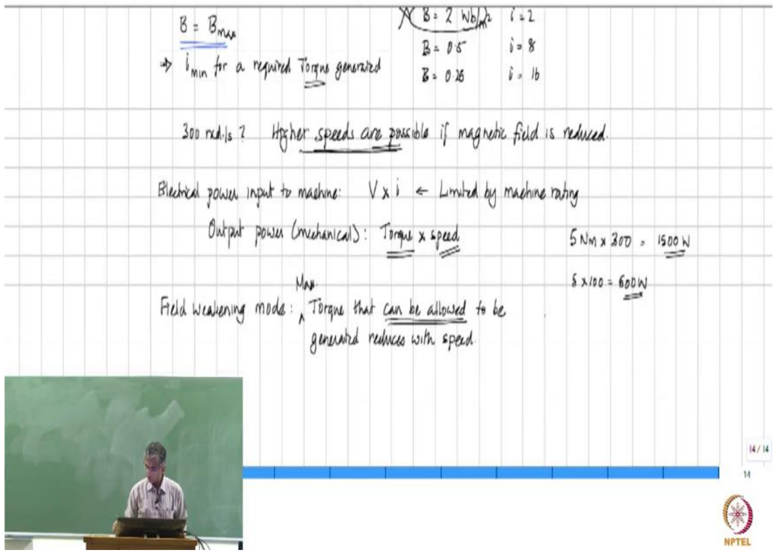
Permanent Magnet Machines (PMDC)



Wound field DC Machines

Bigger

Max voltage ✓ $e \propto B\omega$



I can say that my value of B will be equal to be equal to this much complete, simply you know equal to 2 and then i equal to 2. I can say B equal to 0.5 and then i equal to 8. I can say B equal to 0.25 then i equal to 16. Which combination will you use? In the first machine that we do you have no option. There is simply no option, there is a given B there is no way of adjusting it, you have to live with whatever B it generates and so much current you have to send. So our first case, this issue does not arise at all. The issue arises only in the second case where you have a facility to adjust the magnetic field.

So, if you have a facility to adjust the magnetic field and you want to generate 4 Newton meter of electromagnetic torque, out of these 3 which option will choose, you will choose the first option going by this, because?

Student: less than 5 ampere

Professor: That results in less than 5 ampere that is the least among all these current. But then the issue is that the machine is also designed to withstand only a certain maximum strength of magnetic fields. You cannot go beyond that and therefore. B equal to 2 Tesla itself will ruled out this is not possible.

We said that B is only equal to 1 Webber per meter square. So, that option is rulled up. Now, given that, which one will you choose? You will not choose either of the two, you want to B equal to 0.5 or B equal to 0.25. Because you can go up to B equal to 1 and if you go to B equal to 1 i required is only 4 ampere and therefore, it makes sense for you to operate the machine at the maximum level of flux density or maximum magnetic fields then, that the machine is designed for.

So, you will choose therefore, under most operating condition B is equal to B maximum of the machine. Which will then result in i minimum for a required level of torque to be generated. We are not talking about load torque. Load torque you can apply whatever you want that is an external phenomenon, we are only talking about what the motor can generate.

Student: (())(17:45)

Professor: Yes. So, there are different restrictions to the level of magnetic field. One is what is the maximum current that this conductor can take, that is one restriction. Second is that magnetic field has to flow through this arrangement of all this stator and it has to be flowing through all these regions everywhere.

So, if that field has to go through all those regions, you do not want iron to go deep into deep into saturation. So, you need to look at whether the material is going into saturation and whether it can handle that flux density. So, if you require an unnatural level of B, perhaps it may not be feasible to generate it inside that iron arrangement at all. So, 1 has to look at what is the maximum fields meant that the geometry can support and what is the maximum flow of current that can generate that kind of magnetic field.

So, all those together has to be considered in order to decide what is the value of the B equal to B max? How much it is. So, for a given machine, somebody has designed it and given it to you, then he will then say what maximum flux density you can have and therefore, of course, having designed the machine he will not say explicitly, what is the maximum flux density he will then say, what is the maximum flow of if that you can allow because that is what you can do outside.

For a given if machine will generate so much magnetic field that is by design. But however, therefore there are application requirement, where you will need to go beyond the maximum speed of 100 radian per second in this example. Let us now say that you want to go to a speed of 300 radians per second. How do you? How can you do that? You can do 300 radians per second, if you look at this equation, you can do 300 radians per second only if you reduce the magnetic field, there is no other go.

Because the machine cannot take more than that EMF. There are some other elements in the machine, which will decide what is the maximum voltage the machine can withstand and therefore, you can go to higher speed, higher speeds are possible if magnetic field is reduced. As I said this is an option available only in the second case. In the first case, where magnets are used it is not at all an option, in this particular machine.

It is feasible if magnetic fields can be reduced. However, if you look at electrical power input to the machine, how do you determine that electrical power input is applied voltage V multiplied by the flow of current i? You can apply a certain maximum voltage V and the machine can take a certain maximum input current i and therefore, maximum input electrical supply, that is this is limited by machine rating V max into iMax.

Output mechanical power output power which is mechanical, how much is that? Torque multiplied by speed. Now, going to higher speeds therefore, mean that if you want speed to be greater than the rated speed the machine cannot deliver a mechanical torque that is equal to the rated level of mechanical torque. Let us say that in this condition, we said that the maximum torque that the machine can generate at 5 Newton meters.

If you want the machine to still generate 5 Newton meter at a speed equal to a value of 300, you are looking at 1500 watts of output delivered from the machine. Whereas, input power is limited, input power can only be equal to 100 volts multiplied by how many ampere did we say? 100 into 5, 5 into 100 is only 500 watt input. This is impossible you cannot supply 500 watt input and get 1500 watt output.

So, the only way to manage this, if you want to go to higher speed is derate the level of mechanical torque the machine can generate, which means since we have said that the mechanical torque the machine will generate should be equal to the load torque that is demanded by the load. It only means therefore, that if you want to go the higher speed you must ensure that the load torque applied on the machine is reduced as the speed increase.

So, this kind of operation is called as the field weakening operation. So, in field weakening mode torque that can be allowed to be generated reduces with speed. Note that it is torque that can be allowed to be generated or I should more specifically say maximum torque that can be allowed to be generated and could be decreased as the speed goes on increasing, you can operate the machine with a level of torque that is lower than that maximum torque that is okay. But you cannot go higher than the reduced value of torque.

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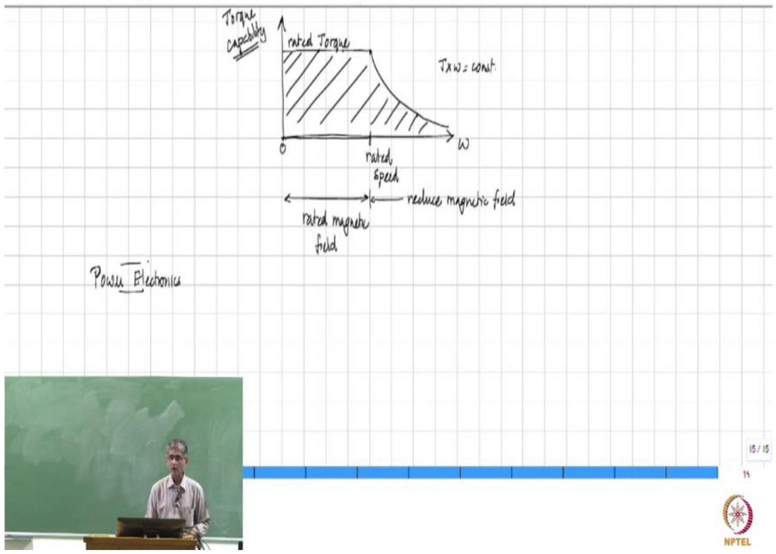

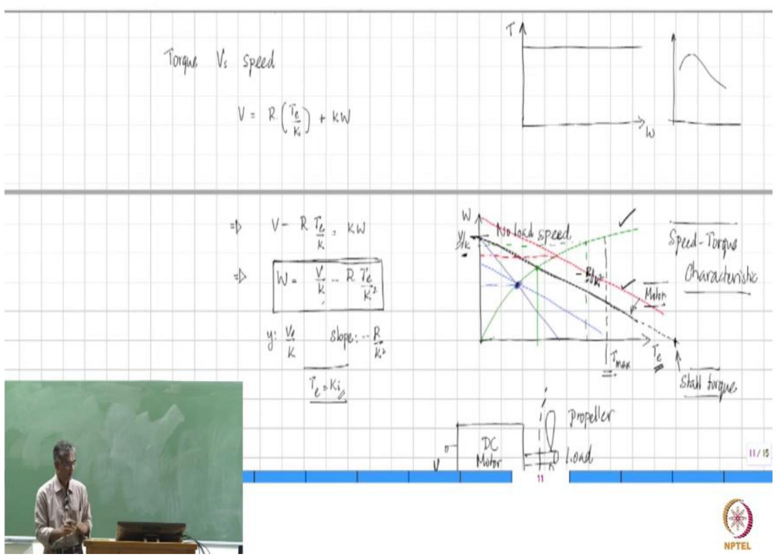

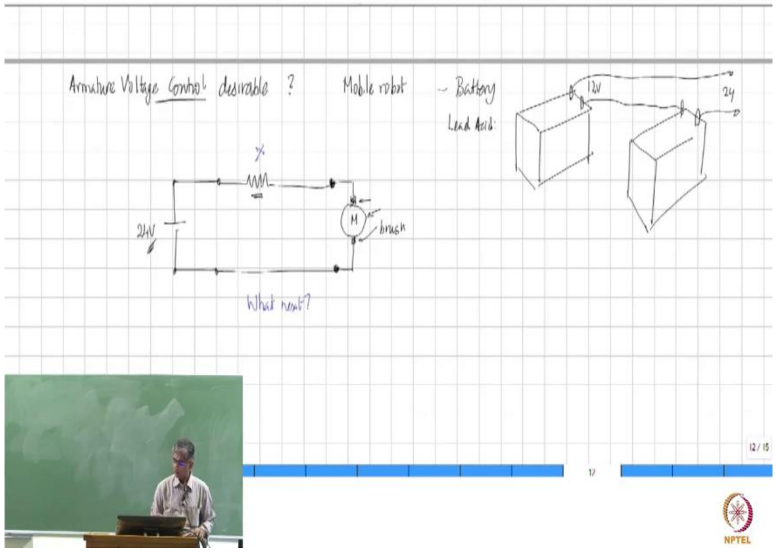

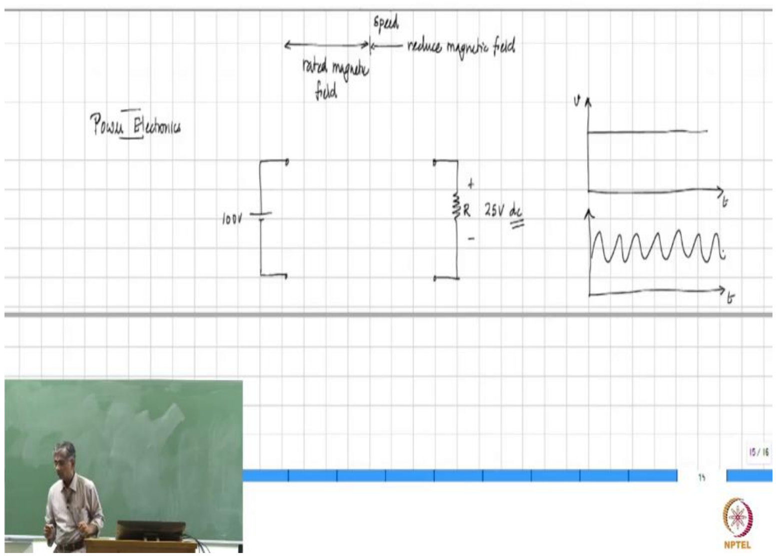

So, if you then look at a graph that can be drawn between torque capability of the machine and speed. Note that it is torque capability, how much you can allow to be generated. The earlier graph that we do, this graph speaks about what is the torque that will be generated for a particular value of speed, when you apply a certain voltage to it.

It speaks about a particular operating situation. Whereas, now what we are drawing is a different graph that speaks about what is the ability of the machine, maximum ability of the machine to do something. So, under that condition, if you say that this is the value of rated speed, which is determined by induced EMF consideration, then from 0 to rated speed you can operate in this region with the rated magnetic field.

Beyond this region, you have to reduce the magnetic field. Therefore, until this region you, I mean everywhere, you can supply the machine with the rated flow of armature input current and since in the first portion you are having the rated value of magnetic field up to this point the machine is able to generate the rated value of torque. But beyond this point, the machine will not be able to generate the rated value of torque you will have to derate the machine in accordance with the fact that mechanical torque multiplied by the speed must be equal to a fixed number.

And therefore, if you draw a graph of the ability of machines to generate torque versus speed, this graph will be a hyperbola which is determined by the fact that torque into omega is equal to a fixed number. You can operate the machine anywhere inside this graph. This is the operating region feasible for the machine. Inside this region, where exactly the machine will operate is going to be decided by the actual load that is there the amount of voltage that you apply and all that, that is determined by the earlier graph.

Now, having said all this and having come to an understanding in the last class that armature voltage control is a desirable mode for controlling the speed and in most cases you do not have a voltage source that is automatically variable, you have only a fixed voltage source available and from that fixed voltage source you have to generate a variable voltage for running the motor under various condition, the question is how to do it and we found that putting a resistance is not the best way to do things.

So, then the question is what else you can do? So, that is where the field of our electronics enters the picture. It is important therefore, to understand how the philosophy of operation goes. So, let us take a simple example, that you have a DC source of 100 volts and you want to connect it to a load which is let us say a resistor. You want this resistor to be supplied with a voltage of 25 volts DC.

This is the goal. Now, as we said earlier what can be done as you can simply connect another resistor in series and you know the value of this resistance. So, the other resistor can be very easily you know determined a simple law of potential division will tell you what should be the value but it is a hopeless exercise because it will be highly inefficient circuit. In order to supply so much to this register you will dissipate much more into other resistor and this is useless situation.

Now, the question is we need to understand certain things. What you mean by DC?. So, let us say you take the voltage across this and let us say I draw a graph of this with respect to time and this is the voltage and the voltage waveform looks like this. So, is this DC? Yes, it is no questions about it. It is obviously DC because there is no change in the voltage. Now I draw another graph, is this DC?

Why do you say that?

Student: it does not change polarity

Professor: It does not change polarity.

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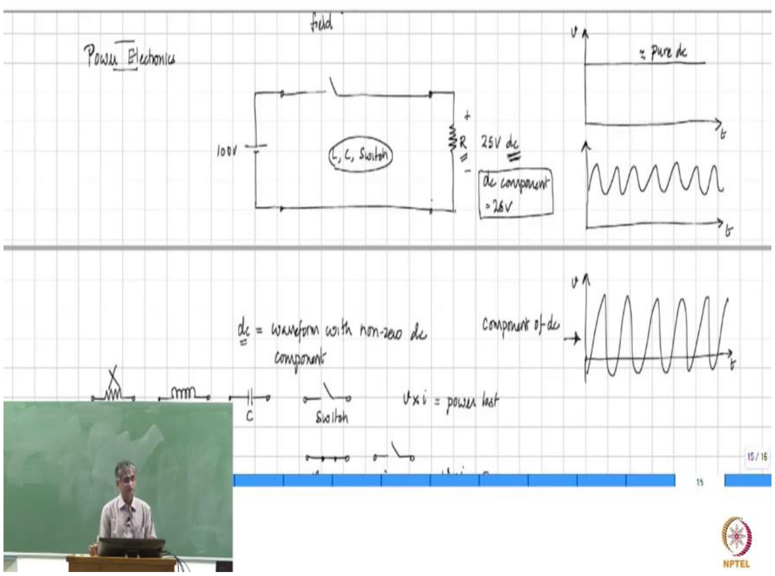

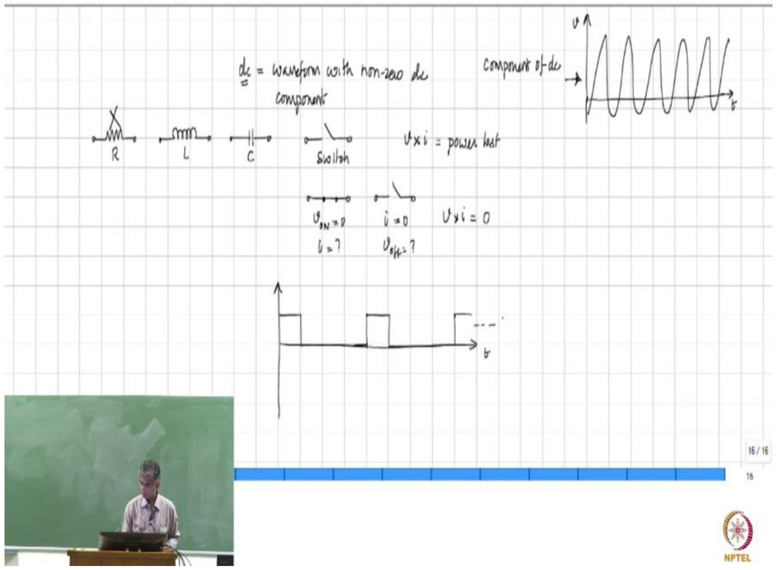

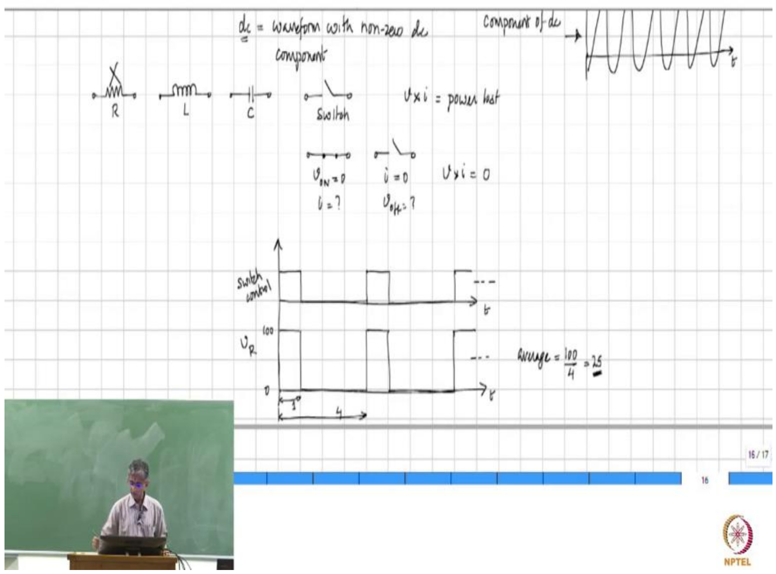

Now I draw another graph, is this DC? It has a component of, how do you determine that DC component? Average value of this waveform represents the DC component that is contained in them. So, we define DC as a waveform with a non-zero DC component. This waveform, on the first waveform on the other hand, we call it as pure DC. Whereas this waveform is not pure DC it contains a DC component, but it is also polluted with so many other things.

Now therefore, when I say that I want the supply 25 volt DC to that resistance and the question is what form of DC? Do you require a pure DC or can you do with some you know, maybe not so undesirable, but need not be eliminated. So, those kinds of impurities whether you can allow or whether you really need a pure DC. Now for example, let us assume that you want to supply this DC to some integrated circuit.

You have seen DC. So, you want to apply DC to integrated circuit. Now the requirement of those normally of integrated circuits is that, if you see the datasheet and it says that this IC is the to accept an input voltage of 14 volts and they will say 15 volts with allowable disturbance limit of 15.1 to maybe 14.9 that is the kind of allowable band that they will have.

So, in such kind of IC you cannot allow this kind of huge disturbance that we have drawn in the last graph. So, it really means that you require a voltage which is very-very close to pure DC and that is what you have delivered, you have to generate that kind of supply with high quality DC voltage. Now, there may be other systems where you may want to supply DC but it can accept all kinds of junk as long as there is a non-zero average value.

So, if you are looking at a resistor, the resistor simply does not care, only thing that resistor is going to do is dissipate electrical power, you really do not care whether it is AC or DC, resistor behave the same way to either of them. So, for a resistor is really immaterial. So, just for argument's sake therefore, we are saying that we want 25 volt DC. When we say 25 volt DC, what do we mean therefore, we want the DC part of the waveform that is applied across it to be further 25 volts.

So, this means that the DC component is equal to 25. So, having understood this then the question arises, is there a circuitry that I can put in between that gives me 100 percent efficient therefore a question arises whether we can have a circuit which means, you can put in between that gives you 100 percent efficient. So, if you look at elements that you can have in an electrical circuit, you would have seen that circuit elements are 1 is a resistor then you have an inductor and then you have a capacitor.

These are three circuit elements that you are definitely familiar with and you would have seen this in some electrical codes or nowadays it is there in high school physics as well. So, resistors are denoted by the symbol R, this is L and this is C. Now of these three elements, which are the ones that have dissipation associated with it? Resistor is a dissipative element. Whereas, the inductor and capacitor are energy storage element.

So, if you send the flow of current i through an inductor L that flow of electric current generates a magnetic field and energy is stored in the form of magnetic fields it is not lost. If you reverse the flow of electricity, that is i through it that electric that the field that is there decreases and you can get it back. Similarly, if you apply a DC voltage of V across the capacitor apply any voltage of V across the capacitor, half CV squared is the electric field energy that is stored in the capacitor and if you reduce the supply voltage you can take that field energy back.

Whereas, in a resistor if you tend the flow of current i, i squared into R loss 1. Therefore, if we are looking at a circuit with high efficiency, certainly this is not admissible, you cannot use resistors in the circuit. Now, one other element which is there is a switch, right. How do you decide the dissipation in a particular element? Voltage multiplied by flow of current. So, voltage across the element multiplied by the flow of current in the element will be dissipation.

If you take a switch, the switch may be either on or it can be off, there are no other positions that are there for the switch. So, if the switch is on the voltage across the switch is equal to 0 and some current will flow through the switch which is decided by the rest of the circuit, which does not decide how much flow of current will there it is just switched it on. Other circuit elements will decide how much current flows through it.

If the switch is off, flow of current is equal to 0, how much voltage is applied after the switch will be decided by the rest of the circuit. But nevertheless, in either K, V into i is 0. Whether the switch is on or whether the switch is off volt, the dissipation across in the switch is equal to 0 because one of the quantities will be 0. Which means that high efficiency electrical circuit that we want to put in between the admissible elements are L, C and switch.

Now, we come to the philosophy of how you can design such a circuit. We have said that what we want is a DC component of 25 volt, we are not saying it is a pure DC and you can use these switch, these element. Therefore, the simplest way one can design this is to put a switch here and then do it. So, how does this give you a DC voltage of 25? What you can do is you operate the switch such that it is on for this much duration and off for this much duration.

On, off, on, off. So, if you do that this is switch control. So, when the switch control signal is high we understand that the switch is turned on. When the switch control signal is low, we understand that the switch is off. If this is what happens, what can we say about the voltage across the resistor? This is the circuit. If the switch is on what is the voltage across the resistor? 100 volt and if the switch is off, what is the voltage across the resistor? 0.

Therefore, the voltage across the resistor will be 100, 0, 100, 0, 100 and so on. What is the average value of this? So, this is 1 division and this is 4 divisions and therefore average value is 1 fourth of this, this is 100 by 4, this is 25. So, we got what wanted. You were having waveform which has an average of 25 volt and that is what we want. So, a simple switch will be able to give the kind of voltage that is required. But the problem is that if you do not have a resistor, we are talking about DC motors.

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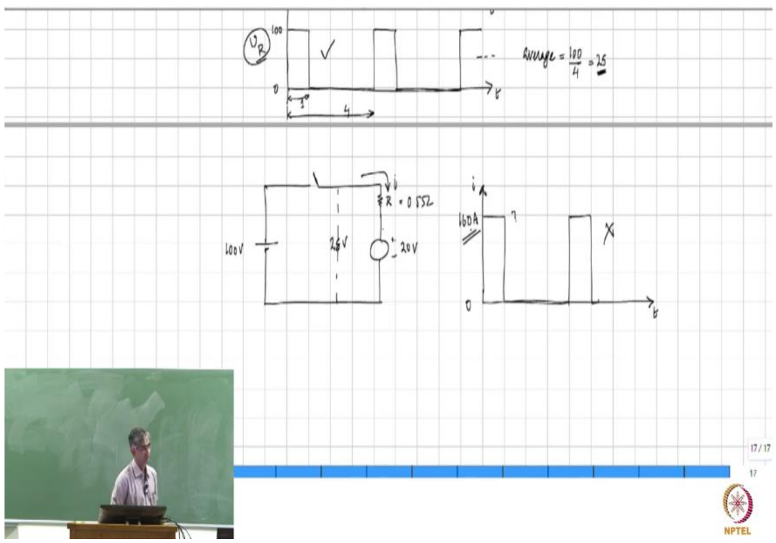

You put a DC motor there and then let us assume that the DC motor is equivalent to. So, let us say that you have this DC. Then you put a switch here and then let us say the DC motor is equivalent to armature resistance and then an induced EMF from induced EMF here. If this is the model, whether is this a model is a separate question.

But if this is the modal and you have 100 volt here and you want a voltage of 25 volt at this point which is what we have designed and there is resistance and this is the DC voltage because T it is a constant speed. So, K into omega will be a constant voltage and therefore that voltage inside the circle is pure DC. So, if that is the case what will be the waveform of armature input current that flows?

So, let us say that this is equal to a voltage of 20 volts and my armature resistance is equal to 0.5 ohm. So, if I want to draw the waveform of i, how will it look like? Same as, same as the voltage waveform, it will look like this, it will look like this and what will be this amplitude? 100 minus 20 is 80 divided by 0.5 is 160 ampere. This will be the wave form of i. The question is, is this desirable? It is not desirable. Why?

Student: (())(46:32)

Professor: This particular case we said earlier that you can take 5 ampere. So, let us say that is not the motor and motor can take 160 ampere. If motor can take 160 ampere, is this desirable?

Student: we want constant current

Professor: We want constant current, why do we want constant current? Motor will generate an electromagnetic torque which is dependent on this waveform. A scaled value of this waveform is electromagnetic torque and you do not want to apply this kind of torque to the load, it is a huge ripple torque, you do not know what the load will do.

Therefore, this waveform is not acceptable. This voltage maybe acceptable. If this voltage is going to result in this current then it is not acceptable. If this voltage can somehow be made to result in smoother current then it is. So, the question really is not about this voltage that is generated; the question is about what can we do to this waveform. That we will see in next class.