Power Electronics

Prof. K. Gopakumar

Centre for Electronics Design and Technology

Indian Institute of Science, Bangalore

Lecture – 16

Dc Motor Speed Control-Introduction

Last class we studied about various phase controlled convertor that is controlled rectification; how we can get variable DC voltage and then variable DC voltage with improved power factor, then finally we come to the front end ac to dc converter with unity power factor and how it can be controlled using sine triangle comparison and also without resorting to high frequency PWM, how we can suppress the low order harmonics.

So now, we know that we can get a variable voltage and as I told, explained before in the case of ac to dc converter, 4 quadrant conversions is possible that is power can flow from ac side to the dc as well as dc side to the ac side. So, four quadrant operations is possible. Now, let us with this one, let us go to our speed controlled system for a motor.

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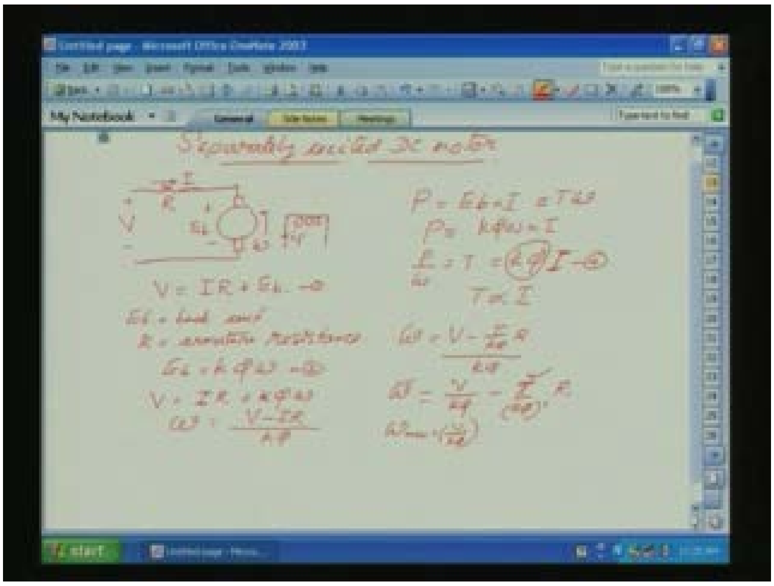

So, here we will take first, separately excited dc motor, separately excited. This is with respect to field winding, excited dc motor; dc motor, speed control. We are going to talk about the dc motor speed control. Separately excited dc motor, we can represent it like this, schematically like this; here you will have the back emf E_b, then the motor, how much the resistance or inductance here and this the applied voltage V, then speed of rotation, here field, field winding, field winding will be excited with the rated field current. So, we will use a separate rectifier, we will rectify the mains with using diode rectifier according to the rated voltage and give it to the field. So, field will be excited.

Now, let us see the motor is running with a speed omega. Now, we are applying dc voltage, so the inductance will not come into picture. We can assume the current through this one is I_A I, dc current. So, if you write the equation for the terminal voltage, it will be V is equal to I into R plus E_b, E_b is the back emf. This, this is the relation between E_b and V. So, this is the R. V is equal to I_R plus E_b and we are going to have a speed control of the dc motor. For speed control, any speed control change that means we want to accelerate the motor, decelerate the motor; we have to give a correct torque applied to the machine. So, what we want? We want the torque, typical torque speed characteristic of the machine.

So, let us start from this equation, V is equal to IR plus E_b, we know E_b is equal to the back emf. So, you have the flux orthogonal to the winding, the construction itself is like that and the windings are because of the rotation, there is a relative motion between the windings and the field and a back emf is generated. So, E is the back emf, R is the armature resistance, resistance.

So now, what is E_b? As I told, E_b is proportional to omega; so proportional to omega means we can write it this E_b is equal to some constant K that depends on the machine and the flux, flux generated due to this field winding, flux and rated flux, we have given the rated flux - K phi and the speed, speed is a function of time. E_b is equal to K phi omega.

Now, we will substitute this equation - 2 into 1. Then, see now we have, we have going to introduce the omega into this equation. Then later we have to introduce the torque. Then from this, we have to get the relation between the torque and speed. Then, we will find the torque speed characteristic of the machine for variable conditions. So, Eb is equal to K phi into omega.

Now, when you substitute this one, this will be equal to V is equal to IR plus K phi into omega. This K phi is the constant for a machine. From this one, what is omega? Omega is equal to V minus IR that is the armature drop that depends on the resistance and the load current, sometimes we can neglect it also. So, V minus IR divided by K phi.

See, we are going to have the control of the machine through V. So, for a speed control omega here, this is the only parameter we can control is the V here, there is an applied voltage, armature voltage. Now, we want the torque speed characteristic. How we find out the torque speed characteristic? We know the power generator in the machine that is P is equal to E_b into I, power generator in the machine; not V into I because there is a loss here in the R, so after that only we are getting a, there is loss and after the loss only, the rest power only going to the machine. So, the machine, the power generator in the machine is equal to E_b into I, V into I that is equal to K phi omega into I.

Now, we know that P is also equal to torque into omega, also proportional to torque into sorry it is also equal to torque into omega. P is also equal to K phi omega into I. So, from this equation, what is P by omega? P by omega is equal to torque that is P by omega is equal to torque is equal to K phi into I. So, P power is equal to K phi omega into I and power is equal to T into omega. So, P by omega is equal to torque is equal to K phi into I.

So, if you see here for a machine, this K phi is a constant. That means torque will be proportional to our input armature current. So, to vary the torque, we have to supply variable I_A depending on the torque. To increase the torque, we have to increase current; to decrease the torque, decrease the current I_A. So T, now this equation, this is the fourth equation; let us substitute this equation to this omega. So, if you do it omega is equal to V minus I is equal to, what is I? I is equal to T by K phi. So, T by K phi V is equal to omega is equal to V minus IR into R divided by K phi. This we can again write it as omega is equal to V by K phi; this is a constant, minus T by K phi whole square into R. So, we got a relation between omega and the torque T, this is this one.

Now, let us take we found the torque is proportional to I and omega also depends on the I here. When we have the maximum speed? Maximum speed is when T is equal to 0 or I is equal to 0. I is equal to 0 means there is no load. So, this is the omega zero, the maximum speed for a particular V is omega maximum; for a particular V is equal to V by K phi. Now, how will, from this one, how we will get the power speed characteristic? Let us see.

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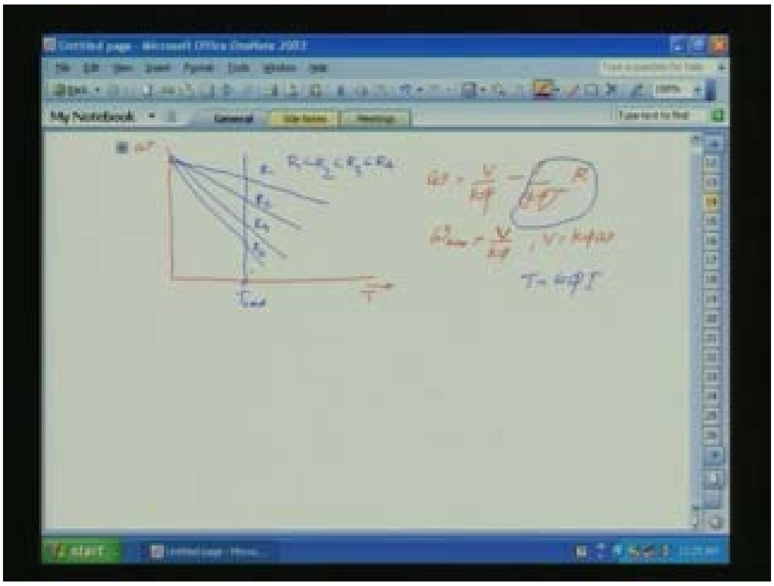

This is our torque and this is our omega. Now, from the previous equation, we will write equation again here for our reference; omega is equal to V by K phi minus I divided by k phi square into R and omega maximum is equal to V by K phi. So, the maximum speed depends on for no with I is equal to 0, it is proportional to V, V by K phi. So, here also if you see, this is also equal to the maximum back emf. When I is 0, VI is equal to 0, IR drop is equal to 0, V is equal to E_b. So, that means this is also equal to, V is equal to K phi into omega. This is the back emf. So, V will be equal to back emf.

Now, let us plot the torque speed characteristic for a particular V. So, we have fixed the V, we have not or once we fix the V and when E_b is equal to V, we have the maximum of speed here. Now, as I increase due to the second time here, as I increase, what will happen? The speed will slowly decrease; speed will decrease this way from the maximum speed. This depends on the R, I into R. See, I depend on the load, so depends on the load that means load means torque demanded by the load. So, I torque is equal to K phi I. So, what is the torque demanded by the load that depends on I.

Now, if you see here, can we have a speed control of the machine? For a let us say torque is fixed, load torque is fixed. This is the load torque what we want, T, T load. Now, so I is fixed; can we have a speed control here? If you see this equation, V is fixed. So, the maximum speed is fixed.

Now, how we can have a speed control? Suppose, we increase the resistance R, R is the armature resistance; if you if I increase the R, this drop will become like this. So, where different R we can have for the same load by introduce more and more armature resistance, we can control the speed. This type of speed control, you have done before where we can see with the lever while we are increasing this armature resistance and decreasing armature resistance. That way we can that way we can increase the speed or decreases the speed by varying the armature resistance.

So, let us say this is R_1, this is R_3, this is R_4. So, if you see R_1 less than R_2 less than R_3 less than R_4. So, as R_4 increases, resistance increases, the speed decreases. Now, but these type of speed control system, it is not very, it will not give very good dynamic performance because it have to increase resistance and decrease resistance. It is done manual, it is a slow system.

What exactly we want? We want in a system, especially in a modern electric drive, it is frequently necessary to stop the drive work quickly accelerate or reverse it, so the torque speed characteristic should be noted in this quadrant, it should be in the all four quadrant. That means we have talked about the four quadrant operation.

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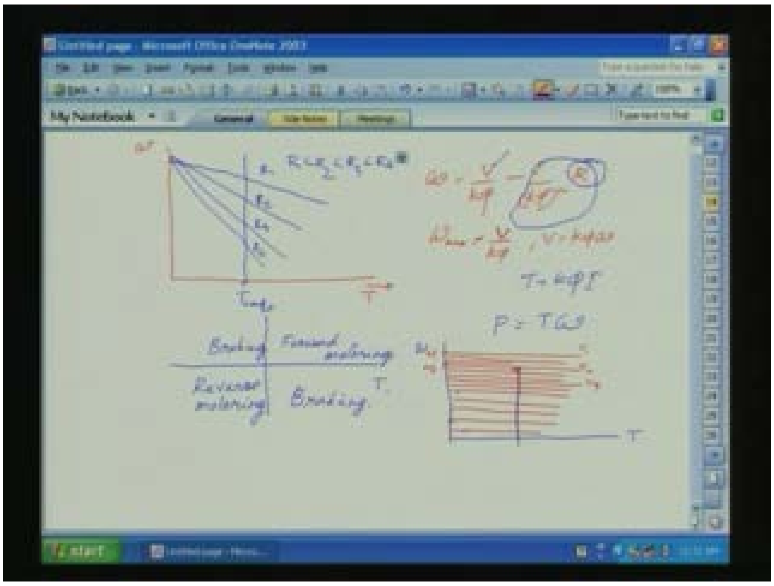

If you write here, see as I told, we want to accelerate, decelerate, speed reversal all those is required. So, if it is omega, this is T. See, this quadrant, let us say forward motoring, now with the same speed; suppose I want to reduce the speed, reduce the speed means what I should do for quickly for reducing the speed, see motor is running, we have to take back the kinetic energy from the system and supply back to the source. That means there should be we should apply, say reverse torque with the same speed. So here, that is called Braking; torque will be negative, speed will be the same direction. This can be also said forward braking.

Then both the omega and torque are negative; omega torque are negative, so what will happen to power? We know P is equal to T into omega. So, when both the torque and omega are negative; the speed is also reverse, torque is also negative if you say, then power is still the positive. That means it is still, it is called reverse motor. Same like our forward motoring, this is called reverse motoring.

Now, in this case, torque is the other direction. So, it is call braking. So, we want all four quadrant operations. So, if you see here, this conversational way of speed control with varying the armature resistance is not required. So, we have already talked about phase controlled converters using thyristors, controllers. So, this will give fast voltage control.

Then instead of controlling the R here; see, the more resistance we include, losses will also be more. So, we do not want to increase the armature resistance other than what is there with the motor design, present design. So, if you see this equation, what way we control the speed? Then the next parameter, we can control is only V that is armature voltage and we have already studied armature voltage that variable dc voltage, how we can control.

So, let us take when the voltage is controlled; how the speed torque characteristic? This is torque, this is speed. So, armature resistance, R is the armature resistance. So, if you take here, let us say for one speed; see, here also as the torque increases because of the armature resistance is there, slight loop will be there. But this is the omega $_1$ due to one V_1.

Now, if you reduce the V_2, omega $_2$ will be varying, so we will get a parallel curve here. Now again, V_2 you change to, see this is for V_1 V_2 V_3; so by varying the applied voltage V, we can have many parallel curve, we can have a fine speed control, this way it is possible, fine speed control is possible. So, by varying the V slowly, go to this one.

Suppose, let us take in our drive scheme. I am, I am running, at present I am running here, now I want to go to this speed that speed has to be reduced. See, if you see here and suppose assuming with the load, we are staying here, somewhere here with the torque, this the load torque. Suppose, this is the case, I have to come here. I have to come here means already motor is running at this speed, whatever the depending on the torque curve here.

Now to reduce it; already there is kinetic energy in the system, we have to take back the energy from the system as fast as possible so that the system can decelerate. Take back the energy means we have to reduce the current to 0 and then back emf should drive the current back to the source. So, the power is reserved such that machine will slowly decelerate. So, our front end converter should be capable of receiving or able to receive the power front end like a phase end phase controlled converter if you use it, it may not be able to take or current may not be able to reverse it. Then what we have to do?

There we have to somehow dissipate it. So, there are different types of braking. Let us talk about different type of braking.

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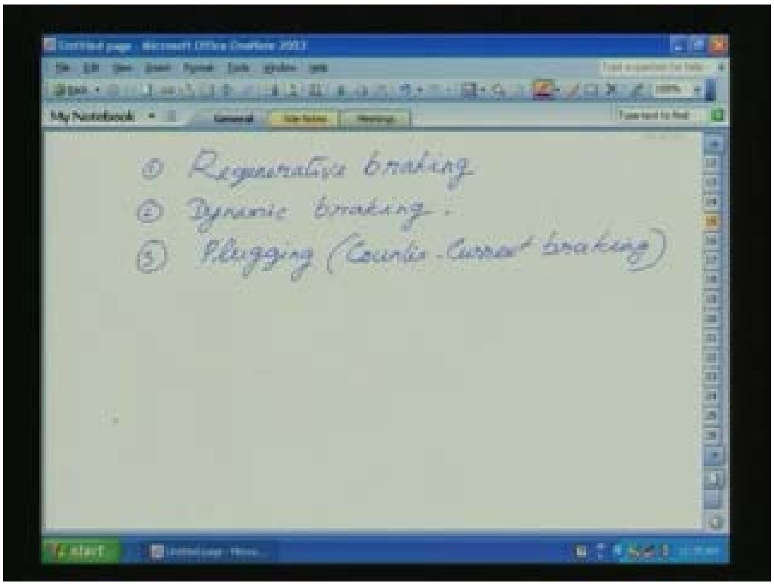

One is regenerative breaking, generative braking; two, dynamic braking; then three, plugging or it is also called counter current braking. During regenerative braking, as I told, the stored kinetic energy in the rotating system will be converted to electrical energy and pump back to the source. So, source should be resistive for that one. So, part of the energy, mechanical energy will be converted to electrical energy and pumped back to the source. So, source should be resistive. Our front end ac to dc converter, the PWM converter is capable of doing that one; power can flow from both sides to the negative with unity power factor.

That means here the alpha should be 180 degree, that firing, the current phase swift between the input current and the input mains should be 180 degree. So, power that means power will be going from the source side to the other, the load side to the source. So, many times we will not be able to have a have a source which we will be able to which is able to receive the power from the source like phase control converter. But then if you want all four quadrant operation and the source is also capable of receiving power; see this all depends on, the choose of the front end converter depends on the cost, what is the cost required and the power load.

So, suppose if we use the regenerative, regenerative is not possible; so, we will use dynamic braking. What is meant by dynamic breaking? In dynamic breaking, instead of regenerating back, the energy is dissipated in a resistor by disconnecting the armature from the source supply and connecting to the resistor. See, here it will, it looks like this.

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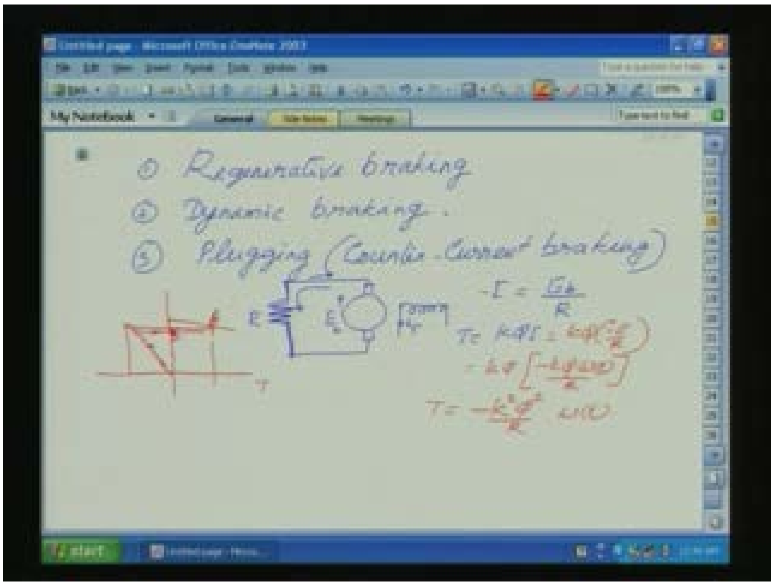

See previously, it was like this; field windings we are not touching, there is a back emf here E_b, machine is still running. Because the inertia of the system is so high, we will not be able to quickly change the speed. But we can change the current direction quickly. That depends on the electrical time constant. Here, back emf depends on the rotation and it depends on the mechanical time constant. So, mechanical time constants will be usually large. So, here we are going to give a resistance here.

If you see here, previously, we have a voltage source here when the machine was running. Now, we want to reduce the speed or we want to stop the machine, stop the machine; we cannot, immediately we cannot remove the power supply. If we immediately remove the power supply, previously there was a current flowing in this direction, current cannot change instantaneously. So, we have to slowly reduce the V such that when the V slowly reduces, it becomes less than E_b, the current will come to 0, there is a current flowing from the source to the load, comes to 0.

Now, there is a back emf here, now we want the source load to supply current back to the system. So, sensing this zero current, we can we can immediately switch on a resistance here so that current will reserve and this current depends on the maximum rated current. This resistance, we will choose such that see if the resistance is very small, the current would be very large. So, quickly system can come to a zero state. But that is not possible.

For a machine, there is always a rated current because the current value depends on the heat generator on that, the thermal energy or the thermal management of the system. So current, rated current is always specified. So, we have to limit the current flow in and out of the machine within that rate. So, we will choose R such that for the maximum E_b with the maximum speed, this current will not go more than the rated current.

So, once the R is connected here, system will slowly come to 0. So, if you see the top speed characters, if you see here; now I is equal to E_b by R and we are neglecting the armature resistance this R will be much higher than the armature resistance that approximation we can do. Now, T is equal to K phi into I. So, here I, if this current direction we are taking as the positive, this current direction we will take it as negative so that it will show that the power is negative. So, here it is I is equal to minus I, K Phi minus I. So, this will be equal to K phi into minus E by R.

See, this again we can write it K phi into E is equal to also minus K phi. Now, the speed will slowly reduce, so speed is a function of time; we will put it this way, K phi omega T by R. So now, the torque speed equation when the resistance is connected, this will be equal to minus K square phi square R into omega T. So, in the torque speed system if you draw the thing; this is our torque, this is our omega. Previously it was, this was our working point.

Now here, first we have to make the system to come this level, this level means torque is 0, so current will be 0. Then we have to apply the resistance such that large reverse current, rated current will go through this resistance. So, the reverse torque will come here and from there, slowly that means from this point, it will come here.

So, from A to B; speed is the same, speed cannot change instantaneously. A to B if you see this point; A to B, the armature current will come to 0. From this side to this one, quickly because R is connected, so quickly current will go to the negative maximum torque decided by our R. Then from there, it will slowly, it will along this direction, it will slowly come to 0 here. This will move, this path, it will come here and slowly it will come to 0, here. So, why?

As the speed increases, speed decreases; current will decrease, torque will reduce and slowly come to 0. When it comes to 0 here; the back emf will also be 0, speed is also 0. But what we what is not to stop, we want to, see, here also it is dissipating, dynamic braking is dissipating. But many of the medium power applications, the power is very less because this resistance is connected not continuously, only for a small duration during acceleration and during decelerating the machine or trying to stop it. So, momentary dissipation is possible.

Now, another way of doing is as I said, the plugging, it is seldom used. See, plugging means the polarity of some motor is suddenly reversed. If the armature voltage is suddenly reversed, heavy current will flow, reverse current will flow and system will come to stop immediately. But that is seldom used. May be, for low speed, the speed is so low, quickly you want to make it 0, we can momentarily we can reverse the voltage so that with low back emf and this applied voltage till the current is, the quick sudden current is well within the maximum rated current. That is called plugging.

So, what we want in the high dynamic performance application? We will be using, this is best way; regenerator, some of the power is taken back or but this can cost of the system can increase or quick braking by dynamic braking, dissipating. This can be used for speed control also. Not only speed changing the speed, not may change the speed to upto 0, lowering the speed also, it can be done.

So, with voltage control, how effectively with good dynamics, how we can control the speed? That we will study now. Now, let us talk about the how dynamically, how we can control the torque speed characteristics? See here, we have assumed so far the flux is constant. So, with constant flux, what is the speed that we can go? The rated speed; and, is there any way, any other way we can slightly increase the speed above the rated speed?

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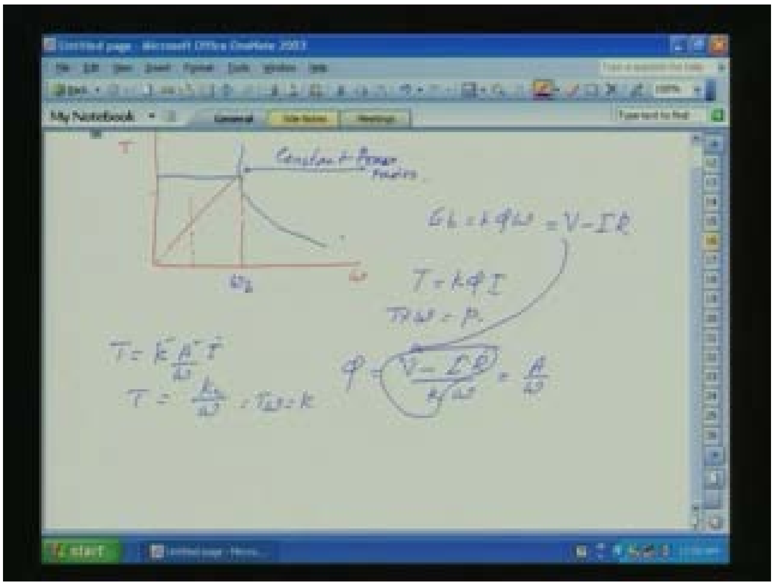

So, let us see the let us see the torque speed character is like this; here axis, I will change it for convenience, this is T. Now, we are controlling the voltage, so slowly voltage we have increasing. So, motor will start from zero speed. So, as the water increase linearly, when it comes to here, the maximum rated voltage; maximum rated voltage means speed as also reached to the maximum rated speed.

Now, in this region, suppose this is torque; depending on the current, depending on the current, the torque region can be anywhere. So, we can have for the same speed, we can have any torque point here depending on the current. So, suppose in this voltage here, omega here, let the machine is taking the maximum torque that means current is maximum. So, torque is also maximum here. We will mark the maximum torque here with different colour. So, machine has gone to the maximum torque here, T.

Then hereafter, we cannot increase the voltage because if we increase the voltage, what will happen? It will, may be going beyond the rating of the machine and voltage and current also, we cannot increase it because we have come to the maximum torque. Suppose, we found again speed control, it is possible. See, we have one more degree of freedom. We can control the flux, we can reduce the flux. So, reduce the flux means we know its E_b is equal to K phi into omega.

So, at this point if you want to again increase the speed means we can reduce the omega phi such that E_b is constant, maximum rated value, we can keep it here. So here, from this region, above this region, this is called the omega base speed; so by E_b is constant that means V is also constant and if it is a current is also constant for the depending on the torque, we will reach the maximum power region but torque is variable. So, from here onwards, this is called constant power region.

See, we have reached the maximum voltage and current, we cannot go beyond this one. So, this power is limited. But the speed, we can change by changing the flux. Now, how it will have or how it will be? Let us say, T we know it is K phi into I, armature current and we know T into omega is equal to P, power and for a separately excited machine, what is back emf? K phi omega is equal to V by I armature. So, from this one; what is phi, from this one? Phi is equal to V minus IR by K omega, R is constant, I is constant depending on the rating, V is also reached the maximum value; so if you see here, all this is a constant value. So, phi will be equal to some constant A by omega.

Now, let us take phi is equal to MI, A by omega. So, what is torque? Torque is equal to K into A by omega into I and K is constant, A is constant, I is also constant, we have reached the maximum level. So, this can be that means T is equal to some constant K_2 by omega. This shows, T omega is equal to constant. This is called constant horsepower. So, whenever we are changing the flux with respect to speed, we are in the constant horsepower region.

Now, if you see here, torque will be inversely proportional to phi. When we slowly change the phi in proportion to omega, torque will be inversely proportional to omega. So, here if you say, the speed torque it will go like this. See, upto how much, we can go? That also depends on the bearing and the mechanical design. Usually 1.5 times, 2 times above base speed, we can go. So, we are using the two degrees of freedom; one is armature control, one is a flux control. So, when we do the flux control, we said it is a constant power region. So here, this region is called constant torque region.

So, constant torque region means full the speed, we can have constant torque irrespective of the speed up to the maximum. But here, above base speed, torque is not constant, we cannot have, the maximum torque available is limited. So, it will go like this. Then how do you have a speed control system like this that which can go above base speed or below? Is it only, is it only possible after the phase control converters or AC to Dc convertor it would realise? Before, it was not possible?

But as engineers, one beauty we well think about engineering is engineers always have a solution for everything that depending on the situation. So, in olden times, the speed control system, this is possible, how you control it. Dynamics may be slightly not as fast as possible but we can have a speed control, all four quadrant. As old regions, variables region means below base speed and above base speed also, it is possible.

So, how it was done and initially, we sort the resistance control but resistance control is not economical, its efficiency will come down. So, we are4 not using resistance for speed control and how it can be done, let us say one of one very famous system. It was introduced around 1890’s, the Ward Leonard system.

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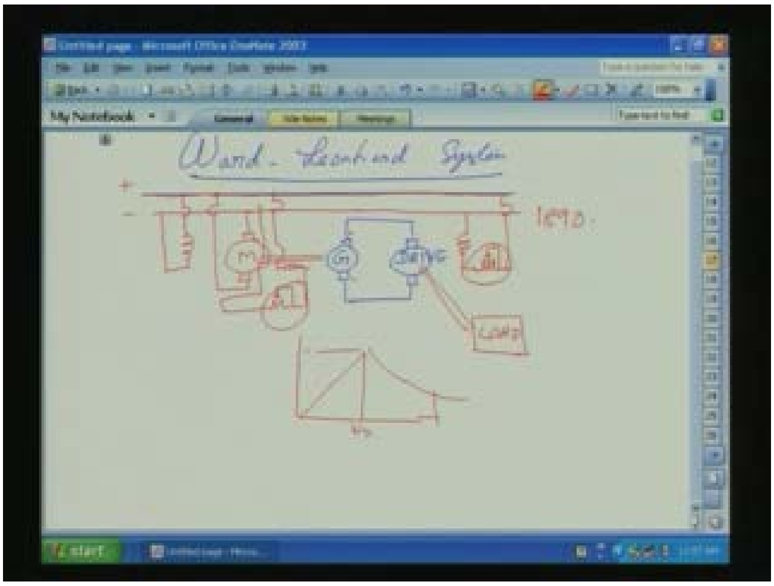

See, we have a motor; this is our motor which you have to run below base speed or above base speed. So, we will require a voltage control. So, what we will give? We will use, this our drive motor, I will say drive. This we will give it another separately excited motor working as a generator. So, I will put generator here. We have a DC line here, DC line we will draw with different colour. This is the positive side, negative side.

So, this machine has our field winding. So, field winding, we have connected here through a rheostat, we will connect it to the positive cycle. So, this shows by varying this resistance, we can have the field voltage also is in our control. So, that also we are going to use it.

Now, to this machine, the load is connected, load for variable speed; we have this generator. This generator is mechanically coupled to another motor. All these show the mechanical coupling. So, we have another motor. This motor is directly connected to our DC supply and the field winding and the field winding for this motor also directly connected here. That means the motor, this motor runs at constant speed because it is directly connected to V. V is not in our control.

Now, there is a generator, this generator supplies the variable voltage to drive. So, how do you get a variable voltage here? See, for this one, this generator field again, we can control through our resistance, we will connect it here. So, the machine is running our motor generator set, this one, motor and generator, this motor is running at constant speed.

Now, by controlling the excitation, excitation of the generator, motor generator field excitation, variable armature voltage can be given to our drive motor. So, this machine will work in the constant, now it will be working in the constant torque region that is this region armature voltage is controlled, we can have constant torque depending on the load here.

So, slowly we are increasing the armature excited that means we have slowly cutting down the resistance. When it comes to the, this resistance is zero that means this field excitation come to the full field excitation, excitation of the generator or slight that is a rated excitation. So, machine has come to the, drive has come to the full speed omega B, our drive motor. That means armature voltage has come to the full. Now, here after above the speed, what we will do? By controlling the field winding, you have to drive motor.

Now, this drive motor field winding will slowly, we will slowly introduce the resistance so that the excitation voltage will reduce and flux will reduce and from here the system will go this way, inversely proportional torque, this. So, we can have variable speed operation. This way, we will do it. So, speed control is possible here.

But this is not, for the, in the modern drive control, this is somewhere 1890’s I think, it is introduced. This is not the one we are using because this dynamics is very poor, mechanically we are doing it and there is a lot of dissipation is there, below resistance in volt field, in the field circuit. So, efficiency of the system will come but it is a reliable system. We can work, we can have variable speed operation of the machine and this is if you want to implement this one, we require lot, it is very expensive. For the drive motor, we require another generator and another motor.

So, three and, 3 motors are required for to control one motor but this also, this way also we can do the thing. But what we want for high dynamic performance application? We want to control through our phase controlled convertors or variable voltage control using PWM convertor so that fast control is possible and we are not going to introduce any resistance, so dissipation should be less, so efficiency should be maximum. That means fast dynamics and maximum efficiency.

How it can be done? See, let us again go back to the torque speed characteristics. So, how it can be done? How it is done with the voltage control using our controlled convertors? Let us take the torque speed characteristics again.

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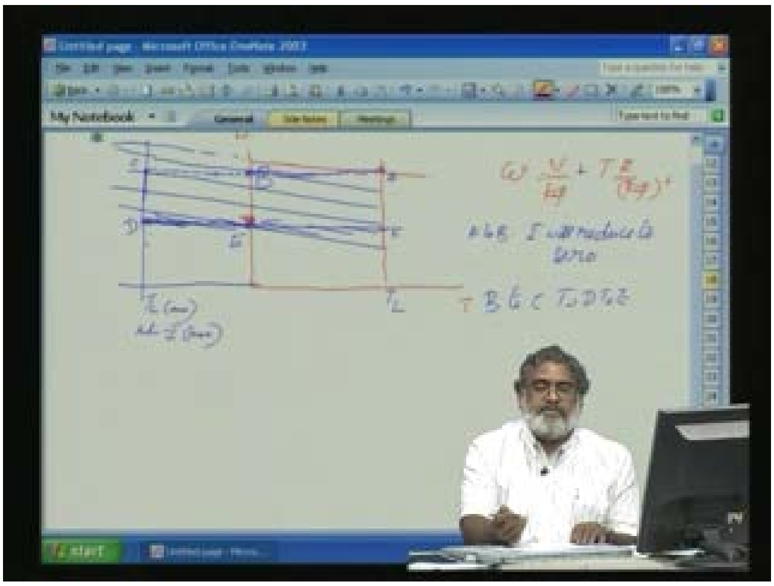

This is our T, this our omega, the system is running like this. Now, our pervious equation, omega, with respective to T, omega is equal to V by K phi minus T into R by K phi square. So, this is, we got this one. Now, let us say our system is running at this speed for a torque, it is the low torque. Now, I want to reduce the speed to this one, this point sorry, I want to reduce the speed to this point, this is here. So now, we are working at this speed here no sorry at this speed, because of the load, speed is here, I will go for a different colour. Now, this is our present speed.

Now, I want to go from this to this speed. So, system is running, what we have to do? We have to make the current supply to the machine to zero using our controlled convertors, we will slowly reduce the firing angle such that quickly current will come to zero. Now, current will come to zero and again what we will do? When the current will come to zero when the applied voltage is equal to E_b, again we slightly reduce the voltage. The current E_b will supply a current back to the source assuming the source is capable of taking this one.

Now, we will again slowly reduce the voltage so that we want to take them, draw the maximum current from the machine such that the maximum negative torque is applied. So, with maximum negative torque, the system will be able to decelerate very fast. So, if you see the curve, system is running. Because of the mechanical time constant, the speed cannot change instantaneously. So, speed is still constant. So, when the current is when the current, maximum current depending on the T_L to 0, we will be going from this speed to this is the region, we will go from A to B, A to B. I will reduce to 0.

Then as the current increases, now the torque is negative. So, this equation instead of negative, it will become positive. So, this curve that means curves we can extend at, extend this region, all these parallel curves, we can extend to this side. So, this is during the regeneration period. Now, but the speed cannot change it so system will go to many parallel through various parallel curves and come to the maximum torque, negative torque depending on the machine rating that is the T_L maximum where I is equal to maximum negative maximum negative. Now, what happens?

So, from here to here, the regeneration starts. This is B, it will come to C, regeneration starts. So, in this region, torque is negative. So, load is supplying power to the machine. Now, what happens? Now, the regeneration starts, machine will slowly decelerate; so A to B to C, the current changes, it is very fast. Now see, now the mechanical time constant will come into picture and this will slowly reduce.

Now, this is our rated speed. We want the rated speed we want the next speed is somewhere here. So, machine will come to this speed, slowly slow down regenerating. Now, we want to, now the back emf has the speed has come to our rated speed. Here again, we do not want the rated speed to go down. So, we will send this one, the convertor voltage we will slowly increase such that slowly increase means these are the curves. The machine will slowly go from this region.

So, the speed is constant so that, what we are doing? We are going in this direction that means the regenerative power, we are reducing. So, that way the regenerative torque, negative torque slowly will reduce and quickly the system will come here. That means it will go to various parallel path. So, DC DE, DC DE that is during their path through BC,

C to D, D to E that means B to C to D to E, it will be regenerating. From here onwards, current will increase. The positive direction machines will, we will try power to the machine and machine will quickly come to this region.
So, A to B, current decreases, B to C is the electrical time constant. Then from C to D, C to D, it is a slow process that is the mechanical time process and machine has come to the required speed. Then from D to E, E to F, we are adjusting the current, driving current or the current from the machine such that we are controlling so that machine will quickly come to the stable state. So, there are electrical time constant and mechanical time constant involved.

So, this we have to properly sense it up and control so that machine should come to the proper speed with without any over suit or without any over suit in current and current should not go beyond the rated value, at the same time any regeneration, we should take the maximum torque, we should develop maximum negative torque from the machine so that the machine will accelerate or decelerate with a maximum time constant possible.

Now, this is from the torque speed curve; from the time domain, how it should work? How a typical response curve for the torque speed characteristic and the voltage characteristic and also the E_b with respect to time, we will study in the next class.