Power Electronics

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Lecture - 18

Dc Motor Speed Control Current Control & Speed Control Loop

Today, we will start the DC motor speed control. We will talk about the separately excited DC motor control speed. So, speed control of DC motor.

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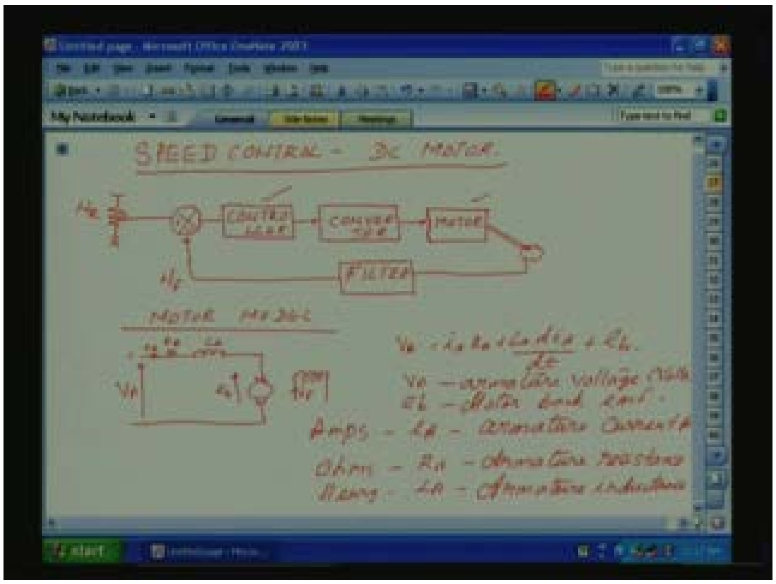

Any speed control requires a reference speed. For last time, when we were talking about the front end AC to DC convertor, the reference was DC link voltage, output DC voltage. Now, the speed is the reference. So, this we will represent it like this; this is our speed reference. So, speed reference, I will put it as N_R speed reference. The moment speed reference means it has to be compared. We have to check whether the system has required the correct speed whenever there is a change in the input reference. That means whether the input is following or the output following the input. So, we require a control. Here is the speed feedback, we will represent as F feedback.

Now, we require a controller. So, we talked about various controllers; classical controllers used P, PI, P, I, PI. So, we will decide which controller is required. So here, we will simply write now, controller; what this controller should do? This controller output will vary whenever there is a mismatch in the speed reference and the speed feedback and we are controlling the DC motor.

So, DC motor speed, we are we are, how we are controlling? We are controlling by controlling the armature voltage, input voltage and this is we are through a convertor. Let us take a phase control convertor, then we have to control the firing angle. So, this output should, if with cosine comparison is the control voltage, it should go to convertor.

See, I am generally saying convertor; we can have phase control converter or front end AC to DC convertor or our four quadrants chop or whatever it is, so converter. This converter output as a variable DC, it will go to our motor. This is our motor and motor will have the tackle. So, from the tackle, we will measure the speed. So, tackle voltage we will not be perfectly DC and it will have repel. So, we require to filter it out and a gain change is required because to bring, have to bring it to the controller level. So, this is feedback signal processing.

So basically, this is a filter, filter with a gain control. So, we have to control the repel also. So, this is signal controller, signal processing. So, we can put it as filter because tackle will not be perfect DC and if it be a DC, this voltage we have to bring it to variable speed; with different sped the voltage is, different variation will be there. So, we have to bring down to the controller level. Controller level as I told before, let us take for with unload controls, we are working with plus 10 and minus 10 and also we want perfect DC here. So, if there is repel is there, we have to filter it. So, we put a filter here.

Now, the question is how to design our controller? We should have an input output relation that is a transfer function, frequency response smaller that frequency dependent model of the system. Then we can based on that one, we can find out the total input output relation, output by input ratio that is a transfer function and from there, we can design our controller so that it will give an optimum response. So, where we will start? Let us start with motor, we have not got the motor model now. So, separately excited motor; so, we will start here, motor model.

Well, this we can represent, this is our armature resistance R_A and leakage resistance L_A. Then here, we have the back emf, back emf E_b here and here also the field winding; we are giving the required field winding, field current, rated field one keeping, we are not disturbing that one. We are only controlling the armature voltage V_A, this is plus minus.

Now, we have to find out the transfer function. So, here V_A, V_A is equal to our I_A armature current I_A, R_A plus L_A into d I_A by dt plus E_b. We know that V_A is armature voltage, armature voltage, armature voltage which we are controlling through our converter and back emf we have studied; it is not in our control, it depends on the speed. This is the back emf, motor back emf, emf, I_A armature current due to our applied voltage current, R_A is the armature resistance, L_A is the armature inductance winding inductance, inductance, should be in Henrys, this should be in volts, this should be in volts, this also in amperes, this is should be amperes, this should be amps, this should be in ohms, this should be in Henry.

Now, let us write down the equation between V_A input and the motor parameter.

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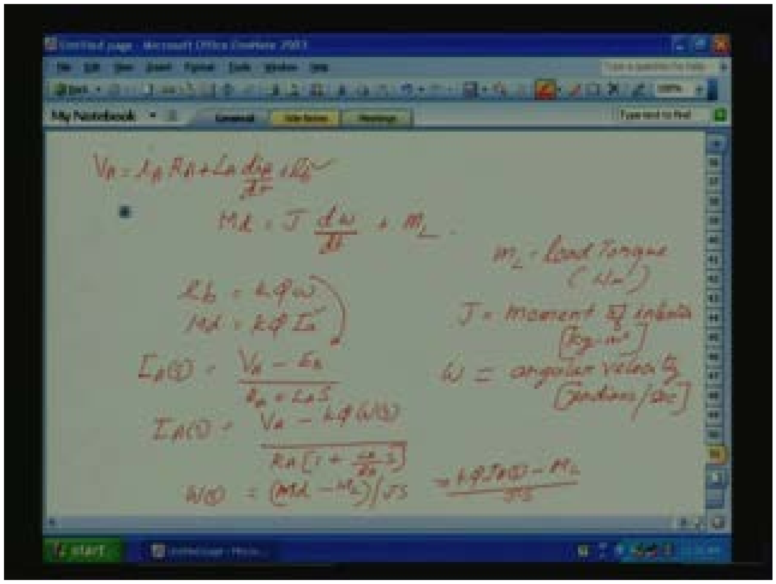

Now, we are basically controlling the speed. So, in the previous equation, speed we have not brought in. So here, we have to bring the torque. So, the driving torque which is supplied from the input from the input power divided by speed; so, driving torque M_d is equal to J into d omega by dt that is angular speed in radians per second plus our load torque that is our load torque. So, here J is the M_L is, if you see, M_L is the low torque in Newton meter, is in Newton meter unit. J, how to find out the J we have? Studied the initial classes; moment of inertia of the whole system. J is equal to moment of inertia, moment including the load, the complete system; this will be kilogram meter square unit. Omega, angular velocity in radians per second per second, this is M_d.

Now, the back emf E_b we know it, K phi into omega. Omega is, phi is the flux. For a machine, this is constant K phi. So, K phi, we can also, phi we are keeping it constant by fielding the giving the correct excitation winding and K depends on the machine parameter. This we have talked about in the last class, how to find out.

Now, the driving torque M_d, M_d is also equal to K phi into our I_A in Newton meter. So from these two relations, we can bring in the speed into our original equation and we can find out. Because that is speed is our output, input is the armature voltage. So, we should have a relation between these two. How to find out? Now, let us take the pervious equation, armature voltage equation. That also we will write it here for clarity so that again we can refer it; V_A is I_A R_A plus L_A d I_A by dt plus E_b back emf.

Now, let us take, let us write in time domain to the Laplace domain this one; so, that will take care of the frequency part. So, this will be equal to our armature current I_A (s) is equal to V_A minus E_b divided by R_A plus L_A into S, d by dt we represent in the S. So, this can be again rewritten, modified. So, from this one, again we can modify this equation. That is I_A (s) is equal to V_A; now we will bring the E_b, this one we will bring it here, E_b is equal to K phi omega into S divided by R_A into 1 plus L_A by R_A into S. So, this is in the time constant form, 1 plus S t, that form.

Now, omega m s, omega (s) is equal to our M_d minus M_L divided by JS. This also we can write M_d is equal to K phi into I_A, here this we can bring it here, this K phi I_A. So, this will be K phi into I_A (s) minus our load torque divided by J into S, this is our Laplace. Now, based on these equations, let us see whether we can write down the input output transfer function or the block diagram of our DC motor. So, let us go to the next page.

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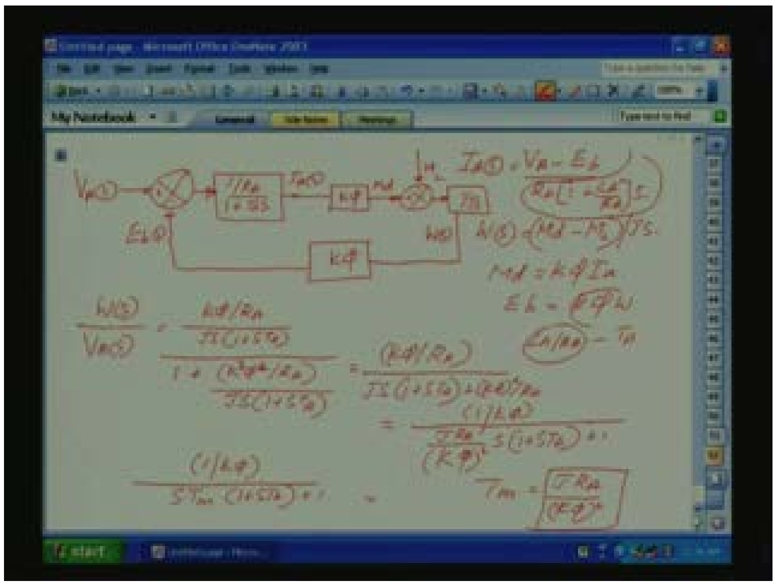

So, before coming a block, let us again for our reference, let us write down our voltage; I_A (s) is equal to V_A minus E_b divided by 1 plus R_A into 1 plus L_A by R_A into S, that is one equation. Omega S is equal to M_d minus M_L by JS and M_d is equal to K phi I_A and E_b is equal to K phi omega, omega. So, let us write down our transfer function, how do you do it, no sorry the block diagram.

So, we have V_A (s), we are giving here and if you see, V_A minus E_b; so this is plus, this is our E_b, E_a minus E_b, this has to be multiplied by 1 by this one. So, this we can write it like this; 1 by R_A divided by 1 plus what is L_A by R_A? L_A by R_A is the armature time constant. This, we can write as T_A, it has a unit of seconds; so, 1 plus T_A into S, 1 plus S T form.

Now, what is this output? This output is our current I_A (s). So, this I_A (s) into K phi, so gain function into K phi, this our machine, will give our driving torque M_d. So, M_d minus M_L, M_d minus M_L multiplied by 1 by JS; 1 by JS, this gives our speed omega here. So, this is our omega S; this omega again multiplied by this K phi, your back emf. So, this is our motor model.

Now, what we want the transfer function? Input output relation, we want the omega S speed, our control variable is V_A (s), so we want a relation between omega S and V_A (s). Let us write down the omega S by V_A (s) of the form G(S) by 1 plus G(S) H(S). So, what is G(S) here? G(S) is equal to K phi divided by R_A plus K (S) into 1 plus S T_A divided by 1 plus G(S) H(S), H (S) is only K phi.

So here, if you see here, 1 plus G(S) H(S), here it will come, K square Phi square divided by R_A. Then again divided by JS into 1 plus S T_A, so this we again, we can simplify and this we will get also equal to we can bring this one up. So, this will be K Phi by R_A divided by, this one multiplied by 1, JS into 1 plus S T_A plus K phi square divided by R_A. So again, we can we can bring into the standard form if you take the denominator that is 1 plus S square S, that time. If that form if you want to bring it, this can again we can write it as this is equal to we are dividing the whole thing by R_A by, K phi square by R_A, we are dividing that one.

So, this will be equal to when we divide this one, the numerator will be 1 divided by K phi. This the numerator, denominator will be J R_A by J R_A by K phi square into S into 1 plus S T_A plus 1, 1 plus S T_A. So, this one, what is the unit or can we write, is it, this will have a time constant of seconds, this also another time constant and it is called electromechanical time constant. So, final transfer function will be final transfer will be 1 by K phi divided by S T_m into 1 plus S T_A plus 1.

So T_m, our T_m is equal to electromechanical time constant J R_A by K phi square. How to find out? We can put the values, the units here and we can find out this as a, this unit of seconds and we can hold electromechanical time constant because electrical side, R I is there and J is there that is due to the mechanical moment of inertia. So, that is called electromechanical time constant. This also we can verify, how electromechanical time constant.

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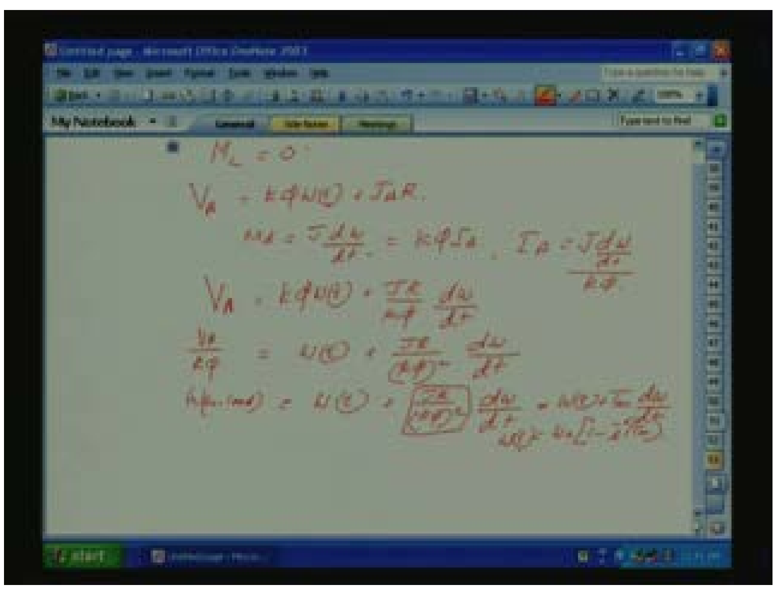

Let us assume the load torque M_L is 0 and let us say, we are applying the full voltage V_A to the machine and let us also assume, we are giving the full current, controlling the current so that always it is in the maximum torque to accelerate. So, V_A is equal to then it will be K phi, back emf, it is a function of omega T, function of T plus I_A R. So here, we have the L part we have and inductance part we have removed because we are through controller, we are giving full current; we are controlling the current I_A and applying the V_A, full DC we are applying that one assuming the leakage inductance is negligible.

Now, L is equal to 0, the L. So, the torque driving torque M_d is equal to for acceleration, J into d omega by dt. This is equal to K phi into I_A, K phi is constant; this is our driving torque. Now, substitute this one to the equation, V_A is equal to K phi omega T plus, now let us take what is this I_A? I_A is equal to J into d omega by dt. From this equation I_A is equal to J into d omega by dt divided by K phi. So, when we substitute here, this will be equal to JR by K phi into d omega by dt.

So, we are applying the voltage and leakage inductance, we are neglecting and we are giving the nearly constant current. So, full driving torque, we are given and the machine is accelerating. Once the speed reaches the full speed, let us divide this one by V_A by K phi. V_A by K phi is equal to omega T plus JR by K phi square into d omega by dt. What is V_A by K phi square? When d omega by dt will be 0, then the machine has reached the no load speed, full speed. Then omega T that no load speed V_A by K phi, that we have derived in the last class.

So, V_A by K phi K phi is equal to omega no load that for applied voltage. What is the maximum speed it can go? Omega no load is equal to omega T plus JR by K phi square into d omega by dt. So, this is of the form, omega T plus time constant T_m into d omega by dt. So, the solution will be omega T will be equal to omega $_0$ into 1 minus e raised to minus T by T_m. So, this is the time constant. So, this is called the electromechanical time constant. So, let us introduce the electromechanical time constant into our system and then modify our equation.

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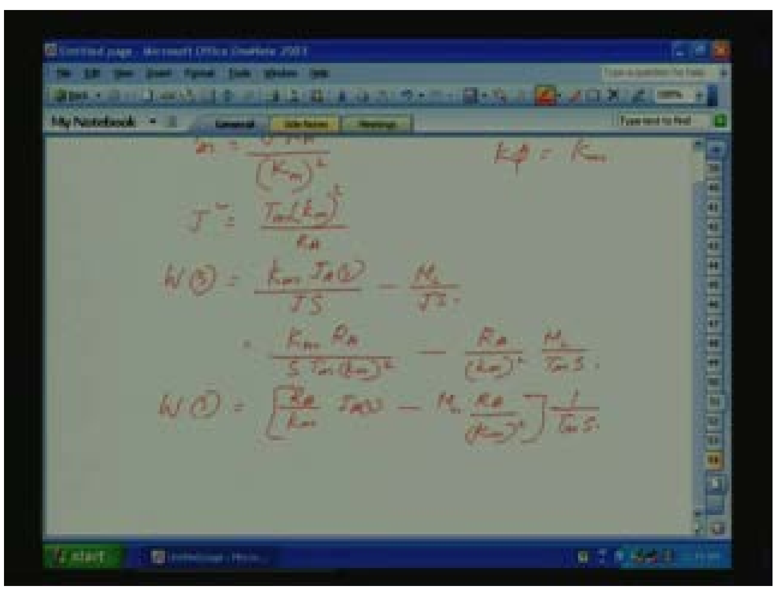

Now, we know its T_m is equal to J R_A by K phi that K phi we have taken as machine constant, we will take as K_m. We will simplify; so, J R_A by K_m square. So, we want to introduce a T_m here. So, J we can write in terms of electromechanical time constant, K_m square divided by R_A. We know that omega S is equal to K phi, K phi is equal to K_m into I_A (s) divided by JS minus that is M_d

minus M_L by JS. The moment introduced J here, this J here. So, this will be K_m I_A (s) is equal to we are trying to introduce this one, J here. So, this will be K_m into R_A by S into T_m into K_m square. This is we must substitute J from here, minus R_A by K_m square into M_L minus T_m into S. So finally, the omega S is equal to R_A by K_m into I_A (s) minus M_L into R_A by, this K_m and K_m goes, that is why K_m here R_A by K_m square into 1 by T_m. So, with this one, so the whole purpose was to introduce the electromechanical time constant, the J factor is also inside this T_m. Now, let us rewrite our block diagram and modify and find out our transfer function.

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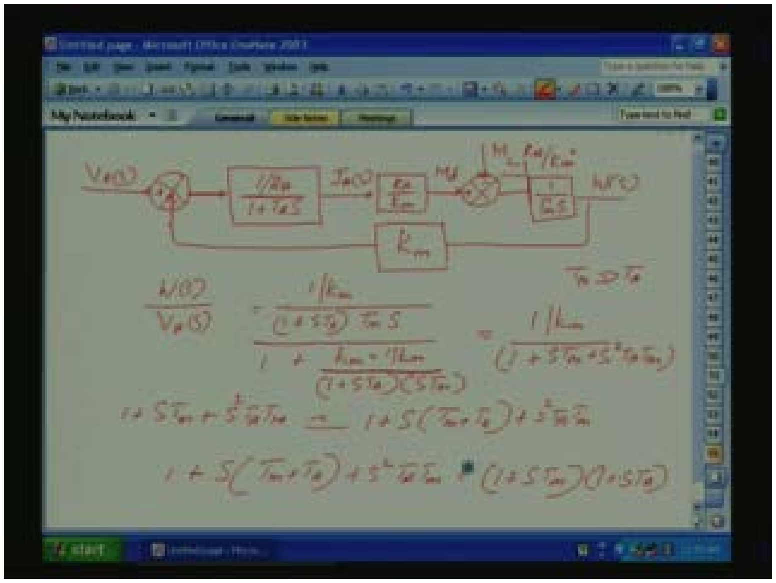

Let us say, this is our V_A (s), V_A (s) here, 1 by R_A divided by 1 plus V_A (s), this is our I_A (s). So, from the previous equation, I_A (s) into R_A by K_m is equal to M_d, R_A by K_m; this is our M_d, driving torque plus minus M_L into R_A by K_m square into sorry here, 1 by T_m S, this is our omega S speed. That K phi, we have taken as K_m now, this back emf.

So, this is a back emf, so we will get the transfer function same as like pervious. We have derived it omega (s) by V_A (s) is equal to G(S) by 1 plus 1 plus G(S) H(S) 1 by K_m divided by G(S) is 1 plus S T_A armature time constant into electromechanical time constant 1 plus T_m (s) G(S) by 1 plus G(S) H(S) that is 1 plus K_m into 1 by K_m, this will get cancelled divided by 1 plus S T_A into S T_A.

See, for all these exercise is to represent this transfer function in time constant form that is one plus S T_A into 1 plus S T_V into S T, so time constant form we have to do it. So, why it is required? If you know the time constant form, if you put it, we know it which time constant is the largest time constant. So, that will delay the system. So, we can use a controller to if I use a PI controller, the 0 of the PI controller can be chosen such that these large delay can be cancelled. So, delay means there is a lag, it will introduce a lag.

So, the moment will give a zero means it give the lead. So, this lead and lag will try to compensate the total system of the delay, we can try to compensate that is the purpose. So, this

will be finally of the form, this will be equal to 1 by K_m divided by 1 plus S T_m plus S square T A T_m. See, this is not the time constant form; this is not in the time constant form.
So, here we will, we know that the T_m, T_m is much greater. Let us take the condition where electromechanical time constant is much greater then T_A. For example, if T_A is in millisecond, T_m can be in seconds; so T_m we can assume we can assume T_m is much greater than T_A. So, this 1 plus this one, 1 plus denominator S T_m plus S square T_A T_m, we can approximately write as 1 plus S into T_m plus T_A plus S square T_A T_L.

See, we are not disturbing this T_m, we are only say small, to the second, we are having only millisecond. So, this model has T_m only. But when you do this one, the final transfer function, we can write it like this; this is a symbol, approximation to get to get the transfer in a proper form. So, 1 plus S into T_m plus T_A plus S square T_A T_m will be equal to 1 plus S T_m into 1 plus S T_A.

So, we got the time constant form 1 plus S T_m, the standard form, the pole zero form, 1 plus S T_m. So, if you do this way, the final motor transfer function, input output. That means we are giving V_A, see all these blocks, we do not require now. We are only looking at the output V (s) with respect to omega S. So, omega (s) by V (s) will be final transfer function will be, let us go to the next page.

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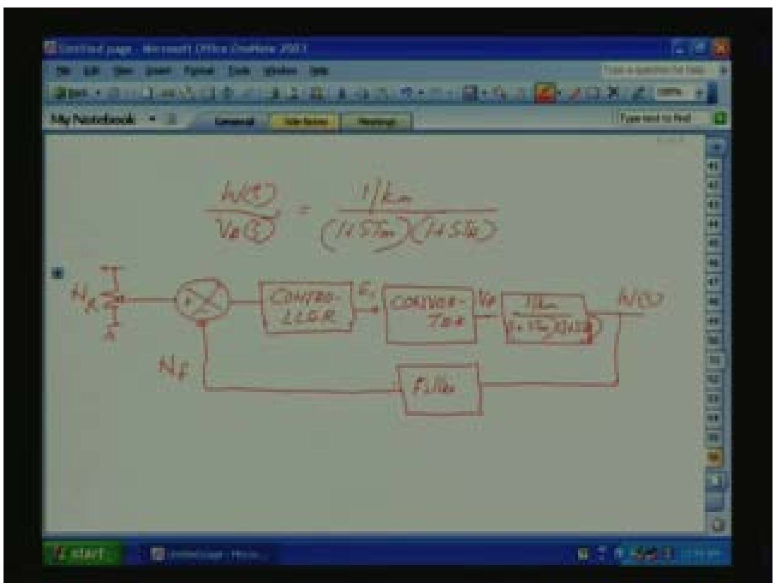

Final transfer function V_A (s) sorry omega (s) divided by V_A (s)S is equal to 1 by K_m divided by 1 plus S T_m into 1 plus S T_A. So, we are controlling the speed omega with V_A. The response of the machine depends on two times constant; one is armature time constant T_A, one is the electromechanical time constant T_M. So, these two T_M and T_A will determine the response of the system. These are the time constant of the system.

Now, let us go back to our original diagram that is we have applied the speed control that is N_R reference speed. We are getting speed feedback. See, these are all voltage levels for controller, we are bringing it down. So, this will go to a controller, this controller output will control firing angle. Let us say the firing angle cosine comparison E_c, this we have to give to your converter. This converter output give the required V_A armature voltage and this we are giving to motor. So, motor transfer function, how do we get? That is 1 by K_m divided by 1 plus S T_m into 1 plus S T_A, this is our omega S.

Now, this omega S will process it to bring back to the controller level filter. These are our speed control system but let us say the machine is at stand still, it has not started and operator gives us speed command. Operator does not know all those things; he will give a high speed command. Let us see motor has to go to the full speed; so full speed is represented by plus 10 volt. So, let us say its 10 volt is given and machine will take because mechanical time constant, it will take its own time to speed up. But the controllers are very fast speed, speed for feedback is 0 initially. So, what will happen?

This will loss for the full control output E_c so that we want full controlled output means if for a three phase control rectifier, it is proportional to cos alpha. So, cos alpha is equal alpha is equal to 0, cos alpha is equal to 1. So, E_c will go to the required controller so that the convertor should give the maximum voltage. So, we will be applying the maximum voltage here. So, let us take a case in induction machine.

We know the speed is proportional to armature voltage. So, we want a full speed machine is at stand still and we are giving full voltage. So, what will happen? There is no back emf if you go back to our pervious equation, the armature voltage and armature current, back emf is not there. So, the full applied voltage has to be dropped across the resistance and the leakage inductor. So, what happens? Full voltage is applied to the machine, so heavy current will flow initially.

So, sometimes depending on the applied voltage, the current can be beyond the rating of the machine. So, till it speed picks up, the current will be going and the winding will get up, sometime heat up, get heated up and the machine can get damaged. So, here the problem is current is not controlled, we are only looking at the speed and the voltage. But what is the machine, current requirement?

For a machine, there is not only the voltage rating, there is a current rating also there, maximum current rating or short time over load. We cannot exceed that one. So, any speed change, any speed control also has to have a current control to take care of the motor. So, that part we have not put here. So, from the convertor and controller, inside the machine, from V_A before going to the machine, there should be a current control loop is there.

What means, the V_A applied voltage to the machine, now is not depend on the speed around. Applied voltage also has to be dependent, it has to be dependent on the present current available to the motor or we should always see to it that V_A is applied in such way a machine during acceleration and deceleration, during giving positive torque and negative torque machines should not be drawing more than the maximum current.

So, there is an inner current loop is required same like our phase control convertor, outer voltage loop and inner current loop. So, there an inner current loop, fast acting current loop because that has to be very fast because any change in the omega s depend on the mechanical time constant. So, V_A has to be controlled depending on the current requirement of the machine. So, we have to modify, alternate this block diagram and we have to introduce the inner current control loop and then we have to find out the controller.

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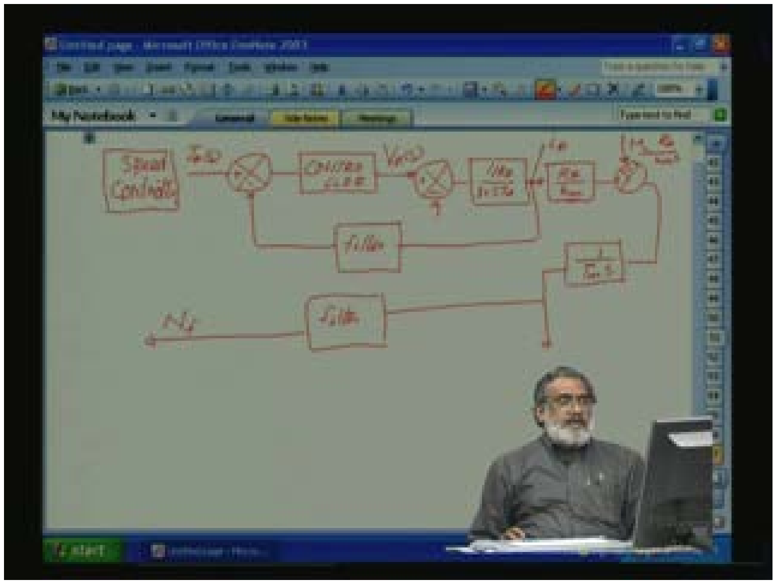

So, what should be our current control loop? That means our V_A, armature voltage should be controlled according to the current in the machine. So, let us take our I_A (s) is coming, I_A (s), I_A (s) reference is there. So, from where this I_A (s) reference comes? We will come to that one. So, I_A (s) reference that is a reference current; so, this reference current, we are putting so that this maximum and maximum and minimum positive and negative limit of this current for positive torque and negative torque depending on the machine rating.

So, there should be a current feedback from the machine. So, here also we require a controller so that if the current exceeds the rated current, this controller should act and bring back our armature voltage. So, this armature voltage depends on the current reference. So, we have to control the armature voltage in such a way as I told before, for fast dynamics, machine should be always drawing a maximum current, maximum torque, maximum positive torque and maximum negative torque depending on the current rating of the machine. So, V_A (s) applied armature voltage should be based on the current controller.

So again, if you write down the machine model; this is our E_b, so this transfer function is equal to 1 by R_A by 1 plus S T_A, then this is our here is our actual I_A, this we have to feedback here. So, this current from the machine, it will have we have, you to step down and because of the switching, there will be repel will be there. So, here we are dealing about DC current. So, there should be a filter also required here. So, this will go. So, what is the transfer function for the filter will come? Simple first water filter we will use.

So, I_A is required, so this inner current loop is required. Now, this I_A divided by K_m is our, we know our driving torque. So, minus M_L into R_A by K_m square, we have brought the electromechanical time constant into picture here. Then this is our 1 by T_m S, this is our speed omega (s); this is the output what we want. Next, this output again, we will put filter and give it to the speed reference. This is our N feedback.

So previously, this controller output was coming from our speed reference and speed controller. Now, this controller V_A is controlled by our I_A (s) reference, I_A (s) feedback. So, where the I_A (s) will come? This I_A (s) should be the output of our speed controller pervious speed controller. Now, the speed control output, speed control output is not directly connected to V_A (s). Previously, the speed control output was trying to control the V_A (s). Now, the speed control output is controlling I_A (s) that is true also if you see here. Why there is a speed in change reference speed and set speed when the driving torque is not matching with the load torque?

So, we have to give the correct torque where the applied voltage armature voltage V_A, we are controlling to get the correct current. So, this is an intermediate variable. The direct variable what we want is the current. Any speed, any change in the speed that should be reflected on the drive driving torque. So, that is driving torque means its K phi into I_A. K phi is constant, so it should the system should give the correct I_A and before that I_A, we have to control the V_A. So, based on this one, we will formulate the complete closed loop diagram in the next class and we will try to design our controller.

Now, we have to design our current controller and the speed controller. Once that is designed, then we can go for the actual implementation, we can stimulate also, then see the response and go for the actual implementation. This we will study in subsequent classes.