Power Electronics

Prof. K. Gopakumar

Centre for Electronics Design and Technology

Indian Institute of Science, Bangalore

Lecture - 21

DC Motor Speed Control Controller Design # 3

Last class we were trying to design the speed loop using the symmetric optimisation using graphical technique; there, we considered the loop gain. So finally, we got the transfer function of loop gain.

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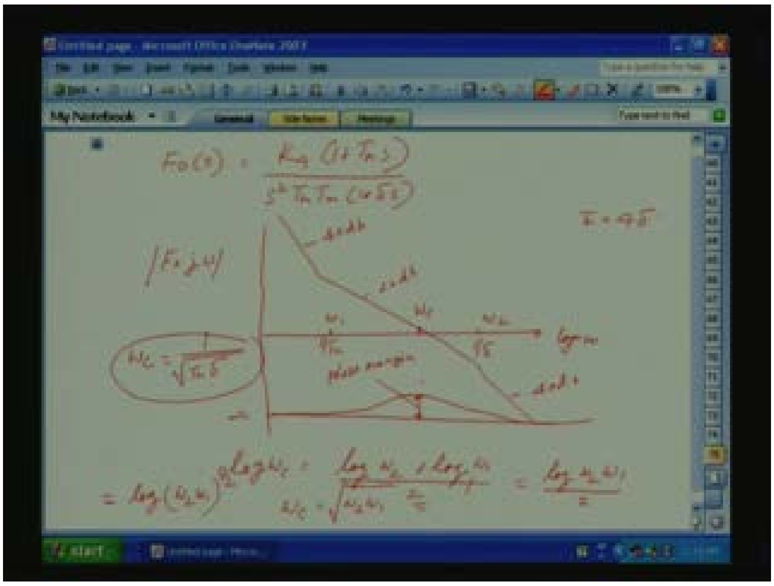

$$F_0(s) = \frac{K_4(1+T_n s)}{s^2 T_n T_m (1+\delta s)}$$

We got K_4 into 1 plus T_n S by S square T_n T_m into 1 plus delta s. Now, from the control system theory, we know that one condition for stability is that the loop gain of the system should cross the unity gain with minus 20 dB per decade. So, let us draw the frequency gain of this one. If you do it, F_0 omega, this is our log omega, this here it is our gain and one, this pole at delta that is 1 by delta this we know it. Choose T_n from the last example; we know it, T_n is equal to 4 delta. So, 1 by T_n will somewhere here it will happen.

Now, till this corner frequency is approached, this S square is the dominating factor. So, it will come minus 40 dB per decade. Then, the 0 will come; 0 will make it minus 40 dB, it will give a lead and then finally it will lead into minus 20 dB per decade. So, we choose T_n such sufficiently away from delta; once it comes to one delta, again minus, minus 20 it will introduce. So, minus 20, again minus 20, it is parallel to this one, minus 40 dB per decade.

So, if you see, this is minus 40, this is minus 20 dB, this also minus 40 dB. So, this will be approximately at the centre of this one it is happening. Now, if you do the phase plot; this is minus phi and minus 40, here also minus phi. So, in between, it will go like this; at the gain cross over, it will become maximum and then length here. So, we are interested this phase margin.

If this, from the basic control system theory; this phase margin, if we can adjust and away from minus 180 degree, then we can ensure the stability. So, let us find out, this is our omega C; at omega C, it will be here. So, let us find, usually this omega C will be placed at the centre of these two. Log omega C is equal to C log of omega $_2$ plus log of omega $_1$ by 2 which is omega $_2$, omega $_2$ is 1 by delta. This is omega $_2$, this is omega $_2$ and this is omega $_1$.

Now, this will be equal to log of omega $_2$ omega $_1$ by 2. That is equal to log of omega $_2$ omega $_1$ raise to 1 by 2. So, omega C is equal to, from this one, omega C is equal to root of omega $_2$ omega $_1$. We know omega $_2$ is 1 by del, omega $_1$ is one by n. So, omega C will be equal to 1 by, we can write it here, omega C is equal to 1 by root of T_n del. Now, T_n we have to find out, we have to find out K_n and we know that omega C, the gain is 1.

Let us go to the next page now and find out the values and then find out the phase margin. So, we have chosen omega C 1 by T_n away from 1 by delta and we found omega C at the middle of these two and we choose T_n is equal to omega del. So here, T_n is equal to 4 delta. That is we got the T_n from the previous, through equations, from the previous example. So, we will apply that one also here.

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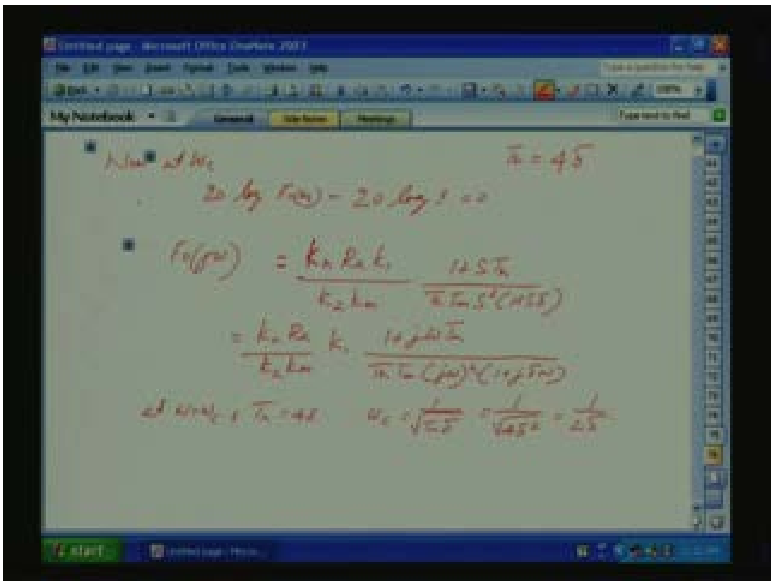

Now, at omega C, what is the gain of open loop gain? 20 log F_0 omega C is equal to 20 log 1 0 that is the gain cross over frequency at the unity gain, correct? See, why this unity gain we are taking? We want our feedback loop which is connected to the controller input where the reference and feedback is coming. We want in the all frequency variation, for all frequency variation of the input variation, input variations; the output, the feedback should follow the input. So, that is the thing.

Now, from this, the K_4 and the controller gain can be found out. Let us see, F_0 j omega is equal to K_n R_a K_1 by that is a previous equation, K_2 K_m into 1 plus ST_n, here K_4 we have actual constant we have put it there, then it will be T_n T_m S square into 1 plus S delta. Now, this is equal to K_n R_a by K_2 K_n K_1 into 1 plus j omega T_n by T_n T_m into S J omega square, S j omega square into 1 plus j delta omega. At omega is equal to omega C, we know it, now we know it, at omega is equal to omega C and also T_n is equal to 4 delta, omega C is equal to 1 by root of T_n delta is equal to, T_n is equal to 4 delta, substituting 1 by root of 4 delta square is equal to 1 by 2 delta. So, substitute this one here and let us find out what is the gain modulus? See now, so previous equation, we will copy it again here. For clarity, let us go to the next page.

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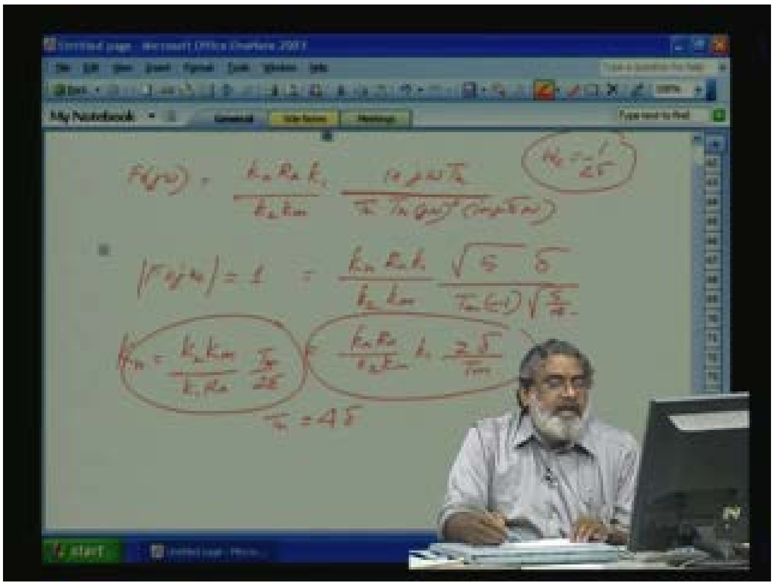

That is F_0 j omega is equal to K_n R_a K_1 by K_2 K_m 1 plus j omega T_n divide by T_n T_m j omega square into 1 plus j delta omega. Now, we know that at omega is equal to omega C, at omega C will be T_n is equal to 4 delta we know, omega C is equal to 1 by 2 delta, that we have derived last time.

So, substituting this one, F_0 j omega C should be 1. That will be equal to K_n into R_a K_1 by K_2 K_m into root 5 that is mod we are taking, T_n is equal to 4 delta. So, this will be root 5 into delta by T_m j omega square, S square that is the one, minus one combines S square into root 5 by 4. So, if you substitute this one in this 1 by 2 delta, from there we get this one. This finally will be equal to K_n R_a K_2 K_n K_1 into 2 delta by T. From this one, what is K_n? K_n is equal to K_2 K_m by K_1 R_a into T_m by 2 delta. T_n we got, we know T_n, T_n is equal to 4 delta. So, we got it.

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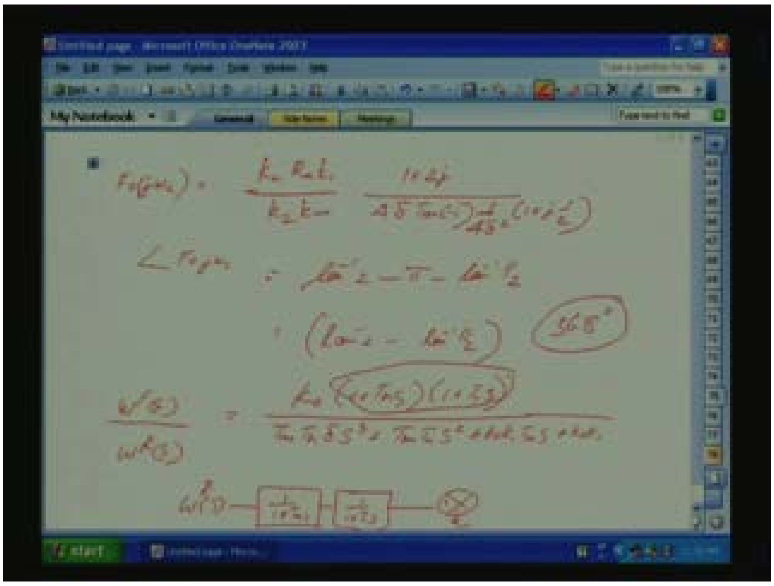

Now, from this equation, let us find out the phase margin that is F_0 at j omega C will be this will be equal to K_n R_a K_1 by K_2 K_n into 1 plus 2 j by 4 delta T_m into minus 1, 1 by 4 delta square into 1 plus j into 1 by 2. So, let us take angle F_0 j omega. This is numerator, numerator will be tan inverse two because of the minus one we have minus pi and minus tan inverse 1 by 2. So, the phase margin that is away from pi, it will be equal to tan inverse 2 minus tan inverse 1 by 2. This will be approximately around 36.8 degree. So, we got a very good phase margin.

Now, from this one, let us go back to again our design. If you see here, our pervious transfer, we have found out our K_n and T_n. Our pervious transfer function omega F (s) divide by omega R (s) is equal to K_0 into 1 plus T_n s into 1 plus T_1 S divide by T_mT_n del S cube plus T_mT_n S square plus K_0 K_1 T_n s plus K_0 K_1.

The effect of zero, we can we know from the current loop, how to cancel it. See, when you have the speed reference happens that is our omega R (s), you pass through another filter that is 1 by 1 plus T_n s, then again 1 by 1 plus T_1 S or you can combine this one into one filter, 1 plus T_n plus T_1 S. Then, the feedback should come here, then this part will go, the final transfer function will be like this and here the K_n and T_n is already 4 del, K_n is we are designed according to our symmetrical, symmetric optimisation using graphical method.

Let us design a controller. We have designed pervious front end AC to DC convertor also, we have designed it. Let us design a controller now.

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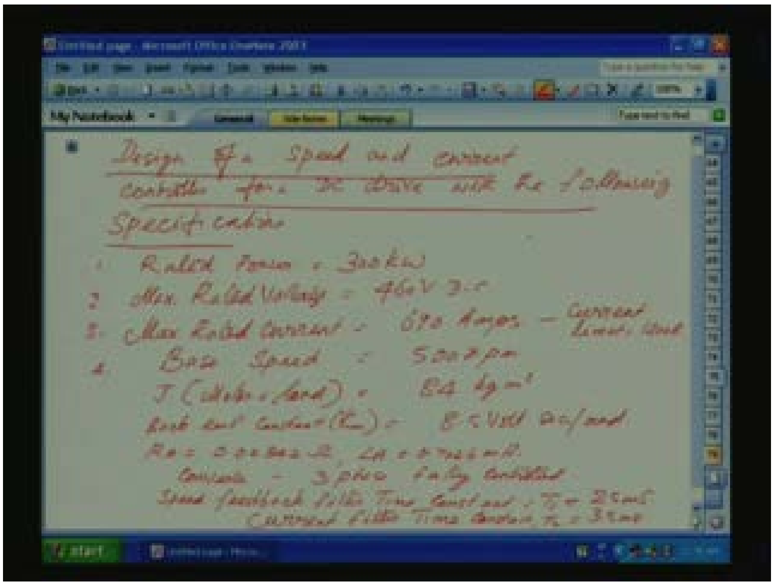

Design of a Speed and current controller for a DC drive with the following specification

1. Rated Power = 300 kW
2. Max. Rated Voltage = 460 V DC
3. Max Rated current = 690 Amps — Current Limit [illegible]
4. Base Speed = 500 rpm

J (Motor + Load) = 84 kg m^2

Back emf Constant (K_m) = 8.5 Volt sec/rad

$R_A = 0.02340\ \Omega$, $L_A = 0.7026$ mH

Converter – 3 phase fully controlled

Speed feedback filter Time Constant, $T_1 = 25$ ms

Current Filter Time Constant $T_2 = 3.5$ ms

So, let us start a design, design of a speed and current controller for a DC drive with the following specification, specifications. Rated power, let us take; one - rated power - 300 kilowatt, maximum rated voltage - 460 V DC that is our DC, maximum rated current - 690 amps, base speed - let us say 500 rpm and let us see the j also we have found out, when the beginning earlier classes we have said how to find out J, moment of inertia with motor plus load. So, moment of inertia J plus load is equal to 84 kilo gram meter square. Let us see, for the machine, the back emf constant that is C phi, back emf constant.

See, here we have that will be equal to let us represent this open as K_m that constant is equal to 8.5 volt second per radian. Then again, it is not sufficient, armature resistance R_A, R_A is equal to 0.02340 ohms and L_A is equal to 0.7026 milli Henry. Let us say our convertors we are using, three phase fully controlled, controlled thyristor bridge. Let us say our time constant T_1 for the tachometer, the filter, speed loop filter T_1 is equal to that is tachometer speed feedback filter time constant T_1 is equal to 25 milliseconds.

Similarly, the current filter time constant T_2 is equal to 3.5 milliseconds. Let us say our current, maximum current is 690 amperes and maximum current limit our maximum current limit that is let us say current limit is equal to 1200 amperes. So, this the maximum rated current. For momentary, we can have rated current of 1200 we can give it, that is the maximum current limit. So, let us design our first with this one, our current controller.

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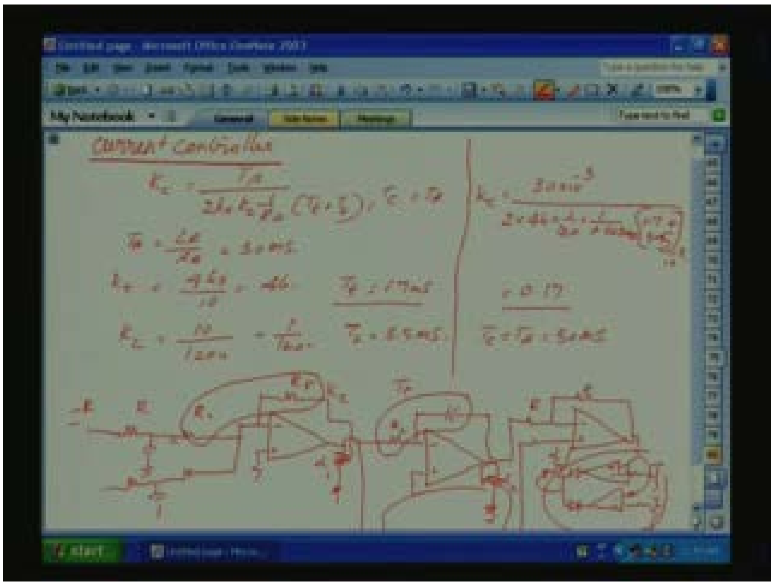

We know the current controller is equal to that is our K_c is equal to previous equation, T_A by 2 K_t K_2 1 by R_A into and we have product of the smaller time constant we have neglected and we have approximated as T_t plus T_2 this is the T_2, this is the converter lack and this is the current filter time and we know that T_c is equal to T_A, armature time constant. So, we are using a pole zero cancellation. Then we found out the transfer function 1 4 zeta is equal to 1 by root 2, we found out the T_c.

Now, what is T_A from the previous equation? T_A is equal to L_A by R_A that is 30 millisecond now what is Kt our convertor K_t now let us say we are designing with unlock circuits so we want to limit the maximum controller variable output should not go beyond plus 10 or minus 10. So, for the converter when the input the control voltage is 10 volt, we want the required output voltage. Required output voltage if you see, what is the previous output voltage? We want maximum voltage of maximum rated voltage according to our rating 460 volts. So, the gain, K_t is equal to 460 divide by 10 that means the moment the 10 volts comes and the maximum rated voltage of 460, the firing angel should go into such a level such that three phase fully controlled converter output should give 460 volt. So, K_t is equal to 46.

Now again, speed controller output; see the pervious rating, we said the maximum rated current can go to 1200 amperes and here also K_2, current gain that feedback filter, K_2 is equal to the moment 1200 amperes current comes, you should get a output voltage or feedback voltage of 10. So, K_2 gain is equal to 10 by 1200. See, here 10 is in the numerator because from the controller output, we are getting 10 that is the filter when the input is 1200. So gain, we have to reduce it like this.

So, the gain K_2 gain is 1 by 120. The converter time constant is at the T_t, T_t is equal to and we are using three phase fully controlled converter, so a maximum lead delay of 60 degree or 0. So, we will approximate to 30 degree, 30 degree delay means one point we know 50 hertz what is the period, so 50 hertz 360 degree. So, for 30 degree it is 1.7 milliseconds, T_t be equated. Now, T_2 is already given, our filter time constant T_2; T_2 is equal to 3.5 millisecond.

Now, with this one, our K_c we can substitute these things in this equation and we can find out K_c. So, K_c is equal to T_A 30 milliseconds, so 30 into 10 raise to minus 3 divided by 2 into K_t, K_t is 46 that is 46 into K_2, K_2 is equal to 1 by 120 into 1 by R_A, R_A we know it R_A we said 0.02340 ohms. So, 1 by R_A is equal to 1 by 0.02342 into T_2, T_2 plus, T_t plus T_2. So, that means into here 1.7 plus 3.5; this is 3.5, 3.5 is T_2, this value into 10 raise to minus 3, here 10 raise to minus 3 is required because all are milliseconds. So, this will come to if you do it, it is 0.17. So, this gain we got, T_c is equal to T_A is equal to 30 milliseconds. So, how do you realise the current controller?

See, we know the PI controller, we will go back to our PI controller and we can design our values. See, this is our V_{in} that is our current reference is coming, we will draw it here, current reference is coming and we said, reference also we want to filter with the same time constant used for the current feedback. So, we will use a filter like this, simple filter we will use, then same resistance we will give. This is the I reference, I feedback after the gain, gain reduction we are putting the same filter here from the current transducer. After the gain reduction, same filter we will put it and feed it here.

So, we can choose this R_c and this R. This R_c is based on our current filter time constant that is 3.5 milliseconds and this also we can give 3.5 milliseconds. Now, this will go to our PI controller minus then our R_f, this is R_1. This R_f by R_1 that is our P, P controller that is our K_2 value not K_2, this K_c value; so how to control? We said we will put a resistance around 10 K port and will put it like this. So, by adjusting this one, we can have the gain of alpha gain, alpha. We can adjust, we have we have derived this one previously, so we can adjust the gain of 0.17.

Then this will go to the integral controller, again R_2 and see, integral time constant; we know T_n is equal to, T_c is equal to 30 milliseconds, so R_c we can choose it that way. Then how to adjust fine tuning? Fine tuning, we can do it again here like this with a potentiometer here and with a small resistance here so that we should not short it by controller. Alpha you can control, this will take care of our T_c, this is our, this will take care of our K_c and this is the adjustment.

Then here also, this controller we have to limit it. Now, P plus I, as I told before this is our controller - P plus I. This comes here, these are all same resistance R, R, then again from here, then our limiting circuit, this I told, this I explained in the previous class, then one more will be there that will be positive, these two shorts here and we will connect it with a small resistance, we will connect here.

So, this output, one is negative, we will put the references here, for limiting plus 10 and minus 10, potentiometer; this we have explained. So, this will go here and this will also go here, output for controlling. This I have explained when we we talked about the controller design. The same thing, we can put it also here so that capacitor should not go plus 10 minus 10 and by independently controlling this alpha $_1$ and this alpha $_2$, we can control, we can fine tune the PI controller. In the same way, we can use it for the PI controller for the speed loop.

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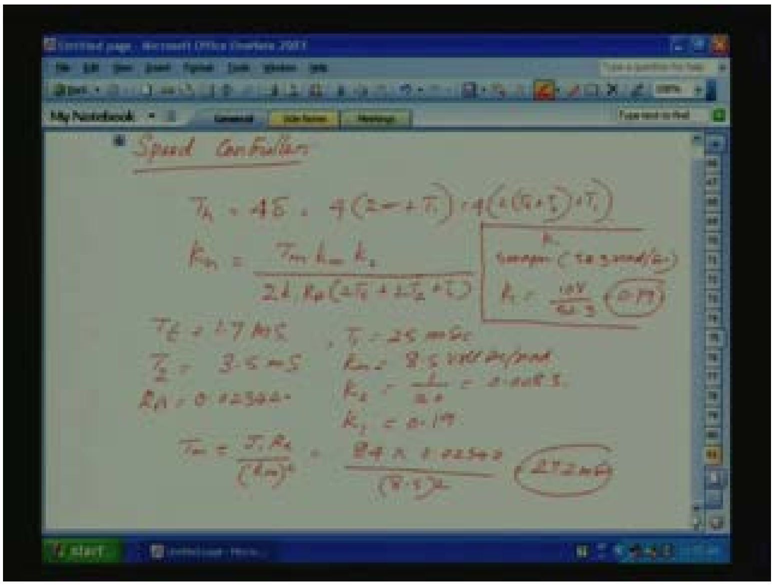

Speed Controller

$T_n = 4\delta = 4(2\sigma + T_1) = 4(2(T_t + T_2) + T_1)$

$K_n = \frac{T_m K_m K_2}{2 K_1 R_A (2T_t + 2T_2 + T_1)}$

500 rpm (52.3 rad/sec)

$K_1 = \frac{10V}{52.3}$ $\boxed{0.19}$

$T_t = 1.7$ ms, $T_1 = 25$ msec

$T_2 = 3.5$ ms, $K_m = 8.5$ volt sec/rad

$R_A = 0.02342$, $K_2 = \frac{1}{120} = 0.0083$

$K_1 = 0.19$

$T_m = \frac{J R_A}{(K_m)^2} = \frac{84 \times 0.02342}{(8.5)^2}$ $\boxed{27.2 \text{ ms}}$

Now, let us talk about the speed controller. Speed control also we can realise in the same way, we have realised the current controller. So, the reference voltage, speed reference we will always limit between plus 10 and minus 10. The T_n, T_n is equal to 4 delta that is equal to 4 into 2 sigma plus T_1; T_1 is our feedback time constant, sigma is our summation of the small time constant of the current loop.

So, this will be equal to 4 into 2 into T_t plus T_2 from the converter and the speed feedback filter time constant T_n and K_n is equal to, so we can use either symmetric optimisation through equations or graphical method. So, let us take this one. From the equation method, this will be equal to T_m K_m, this is the machine constant K_2 divide by 2 K_1 R_A into T_t plus 2 T_2 plus T_1. See, you have to substitute this equation and we have to find out only. So, T_t we know it, so we will drive T_t is equal to 1.7 milliseconds. Then T_2 is equal to 3.5 milliseconds and T_1 is equal to 25 milliseconds; this all we know, our filter smoothing time constant and K_n that is machine constant that is 8.5 volt second per radians. See, units you should match, very important and K_2 we know it, K_2 is equal to 1 by 120 is equal to 0.0083 and R_A we know R_A is equal to 0.02342.

Now, what do the filter gain K_1 and these we know that the maximum rpm, base speed rpm is 500 rpm, for 500 rpm. So 500 rpm, let us make it radians per second. That will be 52.3 radians per seconds. So, the moment 52.3 per radians per second comes, you are the maximum voltage of 10. So, our overall controller is plus and minus 10. So, the gain gain K_1 is equal to 523.10 volts, it will come to 52.3. So, it will be 0.19. K_1, we got. So, let us write K_1 is equal to 0.19.

Now, substituting all these values, we get easily we will get T_m. Now, what we have to find out is T_m also required here, correct? See, because T_m is there, T_m. Let us find out T_m. T_m is equal to J into R_a by K_m square that K_m is the C phi machine constant. So, that is equal j is equal to, we know from the previous specifications, j is equal to 84 kilogram meter square. So, 84 into resistance 0.02342 by K_m square 8.5 volt per Second Square. This is 27.2 millisecond and we found that this will have a unit of seconds and we call us the electromechanical time constant. Now, substituting this one what is K_n? K_n we can get it that is very easy.

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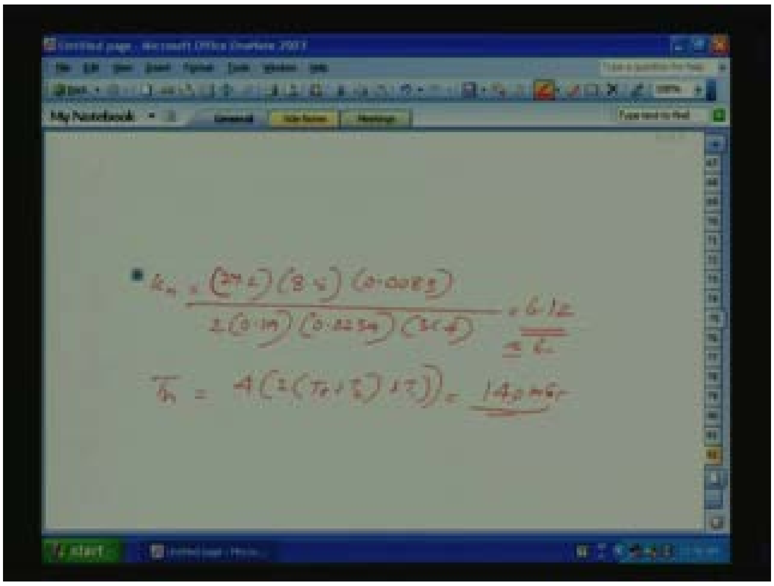

K_n is equal to 27.2, substituting all the values in the previous equation into 0.0083 divided by 2 into 0.19, 0.0234, 35.4 is equal to 6.12. We can take K_n is approximately equal to 6. Then we can do the fine tuning at the PI controller while running. Then T_n, T_n is equal to 4 into 2 into T_t plus T_2 plus T_1 is equal to 140 milliseconds. See, see the assumption; this time constant for the loop for the speed is much much higher than the current control loop. Now, with this one, we can again design our speed controller.

See, speed controller, again the same way; we want the speed loop to be filtered by we said that what we said, we have to design the whole thing by to avoid the overshoot at the numerator that is we found it is 1 plus T_n S plus 1 plus T_1 S. So, we can the transfer function if you see, the numerator you will have the 1 plus T_n S plus 1 plus T_1 S. See, we want the reference to the filtered through this 2 filter or we can approximately 1 plus T_n plus T_1 S. So, complete speed loop, we will write it. See, you have the speed reference.

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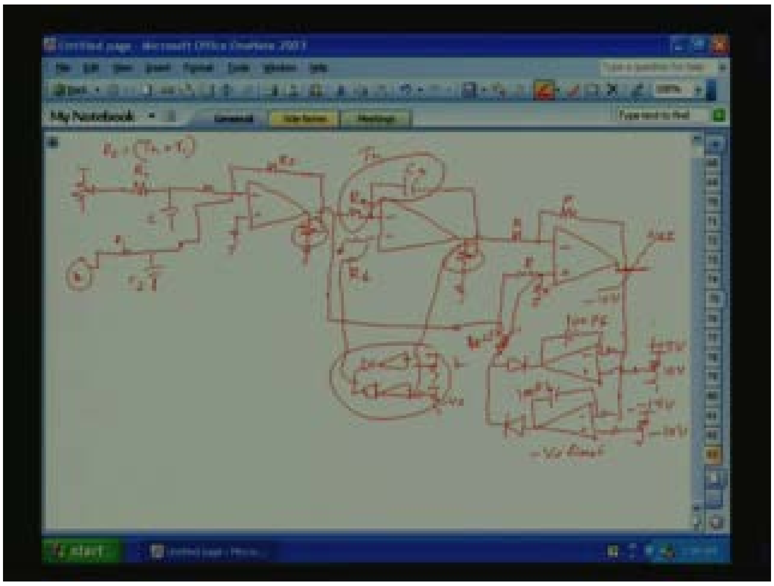

Then we will pass through a filter, simple filter that is R_1, C. So, R_c is equal to, time constant is equal to T_n plus T_1, we can use it. Then will give to the same way to operational amplifier minus this our R feedback, again we have to control the P part, fine tuning that we can do it with this way and the feedback, feedback after the gain reduction that means we are giving a K_1, again we are giving to this filter. Here the filter is R_1 C_2, R_1 C_2 should be equal to T_1 that we are giving it, feed it here, feedback.

So, you have to take care of the proper gain; this is plus or minus you have to do it, so gain. Through operational amplifier, you can make the negative proper gain and we can give it here. Then you have the integrator; we are not deserving this one, we will make it T_n, T_n is equal to we will say R_3 C_3, see this is our T_n and fine tuning we can do it here. So, this part again, P controller, this is for I controlling; independently we can control without disturbing the capacitor and R_3. So, we do not want disturb R_3 because it will affect the input bios current requirement of the operational amplifier and online changing C_3 is very difficult. So, we will use this one.

Now, from here, finally it will go to our fine summing amplifier. This is our same resistance, these are V_0. So, V_0 we want to limit, plus 10 and minus 10 depending on what is our variation we require here. So, here again, this we will take it from here R, R, then you had the limiting amplifier, output limiting. So, here also we will use two operational amplifiers in open loop gain sorry here it is the other way, so here we will have this way; this will be shorted and we will use a small resistor which much less than R_1 because this affect of this one should be faster than this one. So, one resistance we will put it here, some R_l less than R.

Now, this output we want to limit it, so we will use minus, minus here. So, this is our resist output. See, as I told before, see this output whenever this is the positive limit, this the negative limit that is lower limit; see negative limit or the over lower limit can be zero also. So here, we will again here plus 15 volt, here we will give to our negative limit, we will fix it minus 15 volt; if want 0 volt, we ground this one.

See here, any time as I told before, this output goes that let us see this is plus 10 and this is minus 10, whenever this output goes above this value that is this output is more than this value; what will happen? This operation amplifier is in open loop gain, so output goes negative and immediately this negative output will come here and reduce the gain. So, this open loop gain, gain is very high, so this error will slowly decrease and it will go to this error between these two are very minimal such that this output will have the correct output to limit the output as cursion to plus 10 only. So, it will be tracking the value here.

If you see here, this output, this reference point will be tracking this value so that output will come to the required value. So, if you see, here high frequency oscillation will be there. That you can avoid by using a 100 Pf here. So, this is our positive limit that is why we are given this to the plus 15 volt and this is our negative limit. Negative limit can be 0 also. In that case, I can ground this one. So, what happens?

Let us see, this output that is our this output, it goes more than 10 volts, more than 10 volts means this negative input is more than this value. So, because of the negative, this will go, because of the high gain, the output gone negative and this diode will conduct and this will appear here at the input positive terminal. So, output will be, negative output go to the positive terminal, so this output will come down. So, it will come down and it tracks 10 volt because of the high gain here. So, this is if you say, we are giving proportional gain, open loop gain very and we said for steady state error in this case proportional gain, we said it should be, the gain should be very high so that steady state error will be 0. So, we are using open loop here. So, open loop, it has very high gain, 10 raise to 6 power gain will be there. So, this output will exactly follow this one, 10 volt and it we would be slowly tracking the output. So, if you see here, there can be high frequency oscillations here.

So, to avoid this one, we can use a small resistance 100 Pf; this is for the positive case. Now, let us say, the output is going negative, minus 10 volt, so what happens? This is already minus, more than this minus 10; so minus to minus 10, it will come here. This 10 will immediately go here and output will be raise to minus 10 volt. So, if it goes below this one, it will raise this one.

So, as I told, here also, we are using a P controller here to control the output. These are all feedback controllers. But we are using P controller with very gain because operational amplifier is in the open loop gain. So, this error will, steady state error will be 0. That means this output will exactly follow this one whenever the output goes above this value and here also to avoid this one, the oscillation, we can use a 100 Pf here.

See, now here, this is this way output we are controlling. The same output, the same configuration, we can use it here also, PI controller. That is we have two operation amplifiers this way so that you have the resistance here. We can have a small resistance here, it will go here R_L. Again, we can have the same limits; positive limit and we have the negative limit and the output from here, we can give it to these negative sides.

So, we will ensure that whenever there is large error happen, this capacitor will never go to more than plus 10 or minus 10 and operational amplifier will never saturate. If it saturates, what happens? It would take longer time to come out of this one. And, while running, fine tuning we can use use it. We have already calculated our V controller, I controller based on our optimisation techniques with good damping, good stable for a stable output operation, see we can use it. But fine tuning we can do it, exact performers we can use it by fine tuning here so that it will not lead to very large oscillations while tuning; this way we can do it. So, with this, our DC motor speed control design, we will close it. Then we will study, further we will go from the next class onwards.