Power Electronics

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Lecture - 13

Design of the Converter controller & Ac to Dc converter

Last class, we designed the current loop of our closed loop control of our ac dc converter. Now, from the current control design, we have to go the voltage control design that controller design. So again, let me draw our close loop control schematic for clarity.

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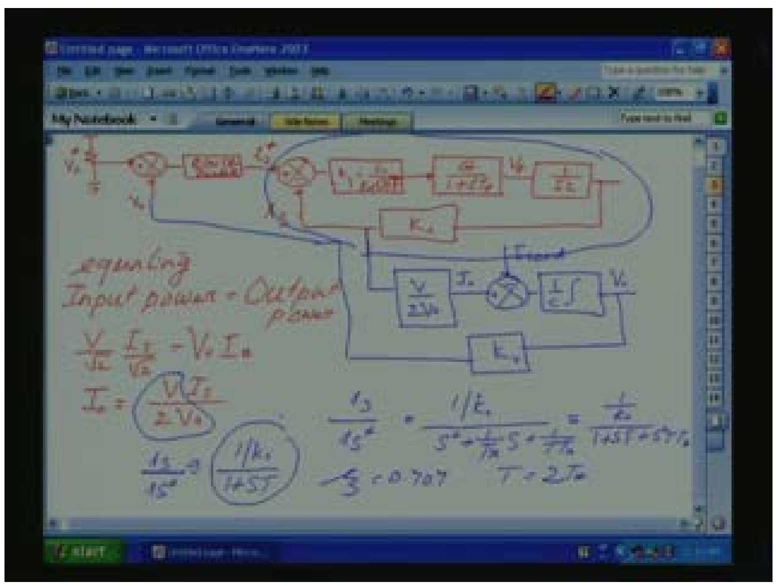

So, this is our V_0 reference that is the one we want. This, we will be giving it here, then we will be comparing with a feedback voltage that is V_0, then we will give to the current controller. So, this is our controller, this we have to design now, controller. This controller output, we will give our I_S reference, this is your feedback, then your current, current controller; current controller what we got, this is a proportional gain only you require.

So, what we got here? It is equal to K_1 is equal to L divide by K_i G into T, T is the first order lag. T, this will go to our converter, converter we have we have got it as G by 1 plus ST_r, r is the triangular period; so we are representing as a first order lag. Then here, you will get the actual fundamental component of the V_A V_{AB}. So, this is minus V_S. That V_S, we are not considering here for the controller design because controller design, it is based on our input I_S star. So, that we will remove as a disturbance input and then the close loop block diagram will be 1 by SL, then you have this one, current feedback, K_i comes here. This is our current loop.

Now, how we design the voltage loop? So, voltage loop, this current I_S is based on the output dc current, load current. So, we should have a relation between this I_S and the output dc. So, equating real, equating the real power, input power should be equal to the, equating input power to the output power, power, equal to the output power; we will find the relation that is V_S that is our V input rms if this is the maximum value, this V divide by root 2 into I_L peak value, these are peak value, I_{load}, our I_S peak divide by root 2 is equal to V_0 into I_0, our I_0 is the output Tc. From this one, I_0 is equal to V I_S, these are peak value into 2 into V_0. This is the I_0.

So, this I_0 if there is if there is no change in load, this I_0 will go to the load and the capacitor voltage will be stable. If any mismatch in the, if there is I mean change in the load happens, it has to be reflected. The controller should know that and based on that, you should adjust the I_S so that the capacitor voltage should not change in. So, the block diagram for our voltage loop is like this; maybe we will draw with a different color.

So, we will take it from here; this is our I_S, I_S, this a gain block, this gain is this much only 2V by V_0, V is our input voltage. So, V by $2V_0$, we get our I_0 here plus minus, this is our actual I_{load} current if there is any change in. If there is no change, this I_0 will be equal to I_{load}. This difference will be 0 and the capacitor voltage will be stable. If any change in I_{load} happens, this I_0, the flow I_0 will disturb the capacitor voltage. So, that difference will go to the capacitor and it will disturb the capacitor voltage. So, that will be 1 by C integral. That will give the V_0, change in, V_0 plus V_0, the change in V_0. Then you have the gain K_V. This is our, we will give it here as feedback.

Now, we have designed our control loop here yesterday and we got the transfer function. If you see here, I_S by I_S star, this I_S by I_S star is equal to star is equal to 1 by K_i divide by S square plus 1 by T_r into S plus 1 by T T_r and we also found out for a damping zeta is equal to 0.707 T should be equal to 2 Tr.

Now, see this, let us write down in a different way. This can also be written as 1 by K_i divided by there is time constant from (… 9:00) 1 plus ST plus S square T T_r, S square T T T_r. So, if you see here, this also in a different way, we can write it. This S square T T_r, these are frequencies, these are the square of frequencies. So, this current loop is, in this close loop, the current should loop should act as, act very fast compared to our voltage loop. So, that means the frequency response of this one is much higher compared to this voltage loop for fast action.

So, if when you consider the voltage loop; now we have to design the voltage loop, see this higher frequencies which we will be much beyond the response range of this current voltage loop, so this current loop we can approximate it. That is I_S divide by I_S star, we can approximate to design our voltage loop. This is 1 by K_i divide by 1 plus ST. We know T is equal to $2T_r$; so, general term. So, we can use this one. So, from this one that means all this block, here circled by the green line, we can represent by 1 by k by 1 plus ST_r. So, from this one, let us draw the voltage loop, the block diagram of our voltage loop. Let us go to the next page.

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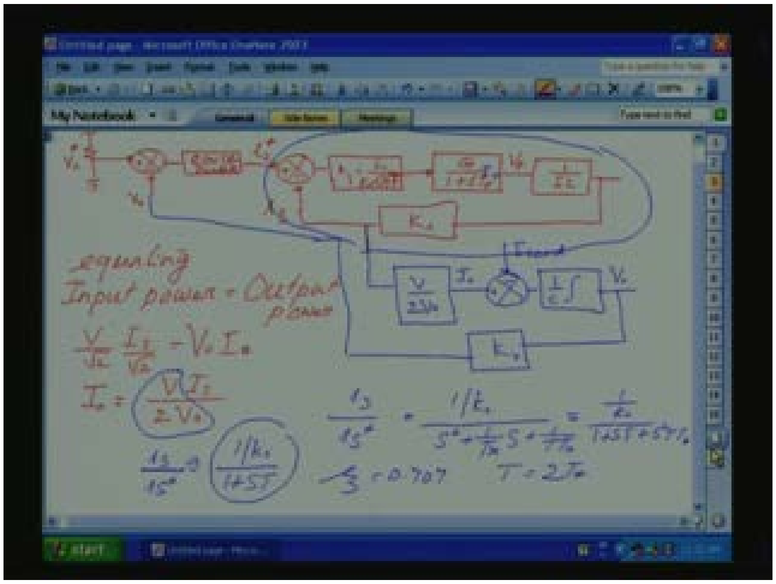

You have V_0 star, our reference again, plus minus; then our controller. So, let us again take for controller with for good dynamic response. Let us take the PI controller. See here, we get the I_0 that is this, this point sorry this, this point, we will get the I_0. This I_0 minus I_{load} if there is a disturbance in load, that difference will go to the capacitor. So, let us take a worst case design, your full I_0 is going to this capacitor so that we can assume I_{load} is 0. Then we will try to design our controller.

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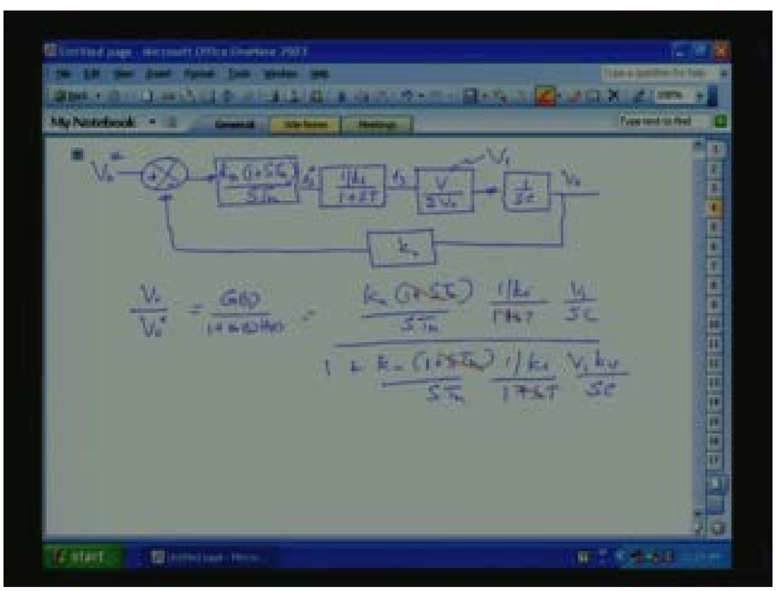

So, if you go back to our controller; we will assume worst case condition, I_0 is equal to 0. So, the full I_0 will go to the capacitor. So, it will be 1 by SC. This is our actual V_0. This V_0, we will put with a gain to bring to the controller gain that is KV and feed it here. This is our close loop controller. Now again, let us see what do the purpose of this lead? There is a lead here, 1 by, 1 plus ST_r. So, if you write down the transfer function that is V_0 by V_0 star is equal to G (s) G (s) by that is forward gain divided by 1 plus forward plus closed loop. This will be K_n into 1 plus ST_n divide by ST_n into 1 by K_i divide by 1 plus ST.

Let us take V plus V_0 or some constant V_1, so this we will take it as some constant V_1. V_1 by SC divide by 1 plus k_n into 1 plus ST_n divide by ST_n into 1 by K_i 1 plus ST V_1 KV by SC. Now, if you use the pole zero cancellation so that this zero which will be a lead, we can choose T_n such that we can remove this lag due to 1 plus ST so that response can be faster. So, if you cancel this one, again if you write down the transfer function in the denominator if you see here, escort time will be there, S time, damping will be missing. So, if you use the Pole zero cancellation here, this system will become unstable. So, we want this, we want to keep this controller so that study state error should be 0 and we should have a good bandwidth.

Now, how do you choose our T_n and K_n in this case? Now, let us say, here you will use some sort of optimization technique. What is the technique? We will make that definitely, what is meant by optimization?

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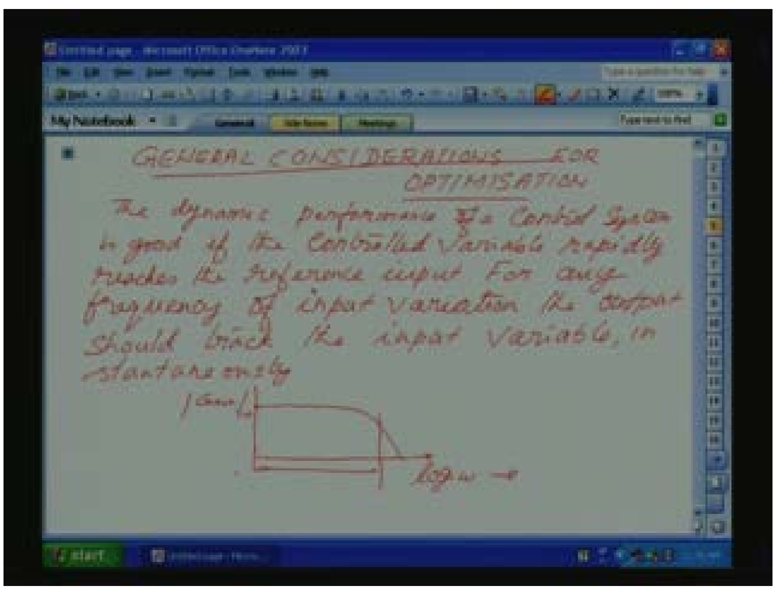

See, general consideration for optimization, for optimization: see here, what we want in a closed loop control? The input should follow the output for any variation in the input as fast as possible. That is any variation; any variation means any frequency of response. See, for in a system, input cannot change with any frequency of area. So, system may not be, system dynamics, system time constant will not allow.

So, with a system time constant, there is a frequency limit upto which input can vary. That shows the bandwidth such that the output should vary as close as possible to the input. That means the input output gain should be, for wide frequency range, it should be unity. That shows the bandwidth. So, this optimization aims at choosing K_n and T_n such that the bandwidth can be extended as for as possible.

So, let us have what do the definition says? The dynamic performance of a control system is good if the controlled variable rapidly reaches the reference input. This means for any frequency, any frequency within the bandwidth; any frequency of input variation input variation, the output should track the input variable or in other terms, the output should track the input variable instantaneously.

So, for a practical system in terms of frequency range, the modulus of the output or the output gain should be closed to one. That means if you say that it should be if it is tracking the input, the input divide by the I_S that modulus should be as closest one over a wide frequency range that is the bandwidth.

So, if you draw the gain that closed loop gain; let us say this is in log omega sorry omega here and the gain modulus, input output gain should be, what? For a large frequency range, as the frequency increase, this will slowly change. So, this will show the bandwidth. So, bandwidth of the system that frequency range we want to optimize. By choosing T_n our controller gain such that we should have maximum bandwidth. That is another way of choosing our parameter, controller parameter. So, the optimization, what is this optimization is planning?

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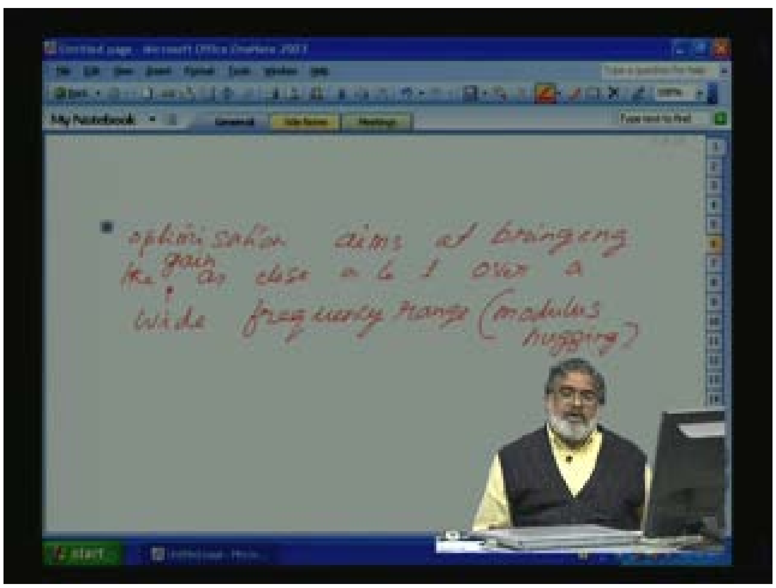

Now, we will talk about, the optimization aims at bringing the bringing the input output gain as close as to as to one over a wide, bringing the gain sorry, over a wide frequency range. This is also called modulus hugging. So, let us see, how we can do? That is let us take the closed loop transfer function for a general second order and general third order. So, we will restrict to these two and then how we can do the optimum bandwidth, maximum bandwidth that is a modulus input output gain is as close as to one for wide frequency range.

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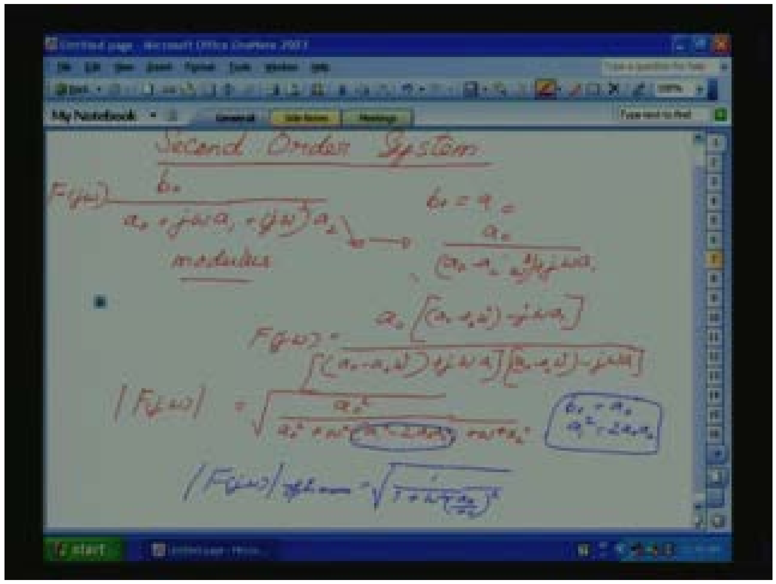

Let us take the second order system. Let us take the general transfer function b_0 divide by a_0 plus s, s will do as j omega a_1 plus S square - j omega square a_2. So, we want low frequency range, low frequency very close, starting. For that one condition is very clear b_0 should be equal to a_0. When frequencies are very small, this we can neglect. Still low, we can neglect this one, so very close to that is dc side, a_0 should be equal to b_0. Then let us take from this one, the modulus of this is the closed loop transfer function, this is our F j omega.

Now, let us take the modulus. This we can again, write this one, write as a_0 divide by a_0 minus a_2 into omega square plus j omega a_1. So, we can multiply the numerator and denominator by minus c omega. So, this again will be equal to F j omega equal to a_0 into a_0 minus a_2. So, sorry this here, if you see, a_0 minus a_2 omega square; so omega square is not coming with a_2, so this is we have to correct it. This is omega square. So, the square is coming here. So, a_0 minus a_2 omega square minus j omega a_1 divided by a_0 minus a_2 omega square plus j omega a_1 into again a_0 minus a_2 omega square, here minus j omega a_1.

So, from this one, we can find out the modulus. Modulus F j omega will be equal to root of, we can simplify this equation; finally it will come to a_0 square divided by a_0 square plus omega square into a_1 square minus 2 a_0a_2 plus omega square a_2 square. This is the modulus. Now, let us see, how we can control this one so that the bandwidth can be increased. So, low frequency, a_0 square a_{01}, we will have modulus 1.

Now, as the frequency increases, this time to disappear, still we want slightly higher frequency, it should be 1. The condition is b_0 is equal to a_0. The second condition from here, we want this to disappear. So, that means a_1 square should be equal to 2 a_0 a_2. This we cannot do it when the frequencies, for the frequencies where omega, when this term come into picture. So, it would slowly drop.

So, the final transfer function, final modulus F j omega, the modulus of this one if you substitute this one for this second order will be there is an optimum, we have optimize this second order; so F j omega optimum is equal to root of 1 by 1 plus omega raise to 4 a_2 by a_0 square. So, by choosing these parameters, see this second order system; we can optimize so that for wide frequency range that is a maximum, we can get a modulus of one that is input will for any frequency variation, frequency variation, input output will closely track the input. So, this is one way.

So, now let us take a third order system because all our purpose is to optimize and choose the controller, PI controller parameter for our voltage loop. So, let us take the third order system.

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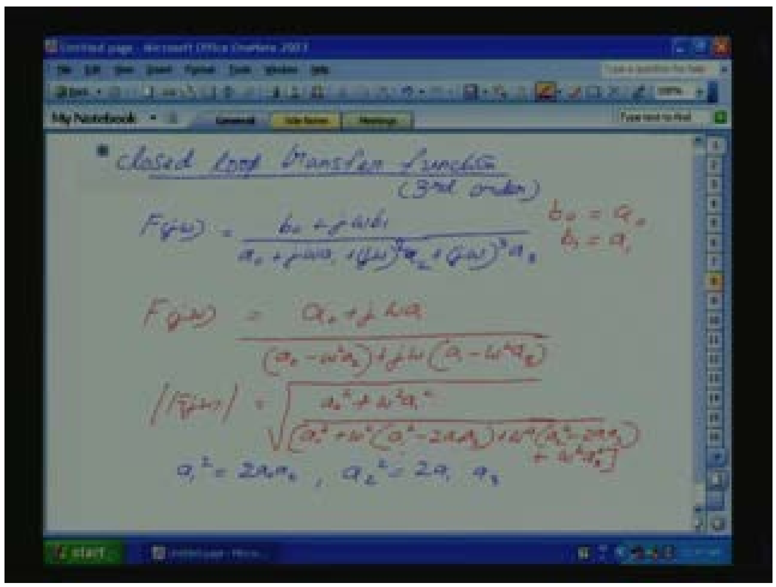

Now, we are talking about third order, a general third order system; omega is equal to b_0 plus j omega b_1 by a_0 plus j omega a_1 plus s square term j omega square a_2, this is 2 plus j omega cube a_3. So, seeing the numerator, one condition for low frequency range; the condition is b_0 should be a_0, also b_1 should be equal to a_1. Now, let us rearrange this one. F j omega that is equal to substituting this a_0 plus j omega a_1 divided by a_0 minus omega square a_2 because minus comes because of this j square, plus j omega into a_1 minus omega square a_2.

Now, multiplying the numerator and denominator, the complex conjugate of the denominator and finding out the modulus; so here if you do it, F j omega modulus will be equal to root of a_0 square plus omega square a_1 square divided by this modulus we have found out, a_0 square plus omega square into a_1 square minus 2 a_0 a_2 plus omega raised to 4 into a_2 square minus 2 a_1 a_3. Then one more term is there; plus omega raise to 6 a_3 square. So, this is the overall denominator.

Now, how do you do the modulus again? Bandwidth, we want as close as possible. One condition here, a_1 square should be equal to 2 a_0 a_2; so, one condition. From this, one condition is, already we said a_0 is equal to b_1 is equal to a_1. Now, the next condition is equal to a_1 square is equal to 2 a_0 a_2 and a_2 square is equal to 2 a_1 a_3. With this one, what is the final output transfer function? So, based on this condition, the final modulus will be, let us go to a new page, will be F j omega is equal to root of 1 plus omega square into $a_1$by a_0 square divide by 1 plus omega raise to 6 a_3 by a_0 square; this way, we will get it.

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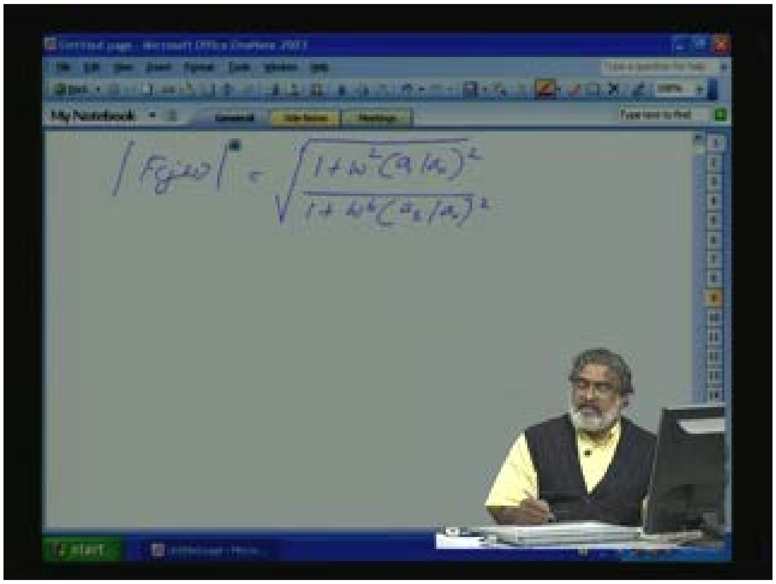

So, this is the way we can do for the third order system. Now, let us go back to our voltage control loop, this loop.

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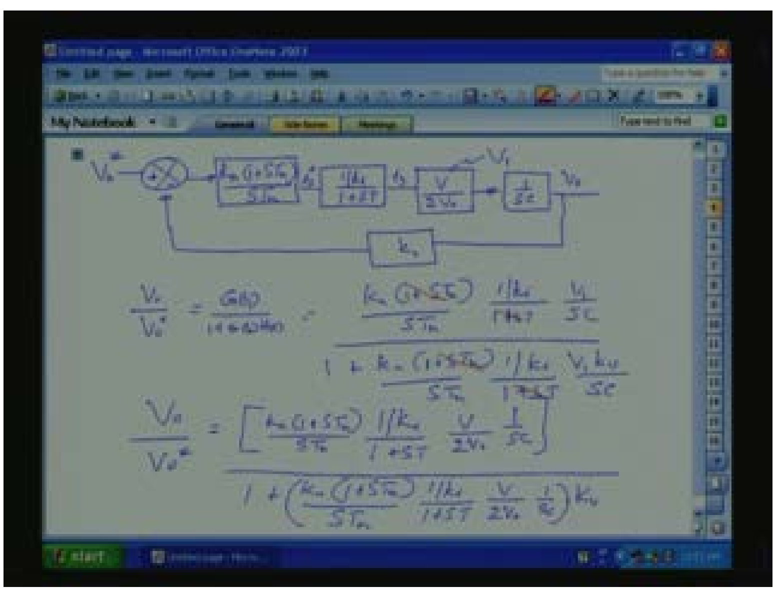

Let us draw the, let us write down the V_0 by V_0 star. So, if you write down the V_0 by V_0 star, it will be equal to K_n, I will slightly bring it down again, K_n into 1 plus ST_n divide by ST_n, then the current transfer function 1 by K_i by 1 plus ST when V by V by 2 V_0 1 by SC; this is G (s) part, divided by 1 plus G (S) H(S) that is again 1 plus K_n into 1 plus ST_n divide by ST_n 1 by K_i, this K_i is the current feedback gain, 1 by K_i by 1 plus ST again V_0 by V sorry V by 2 V_0, V by 2 V_0 1 by SC into KV, our H(S) voltage loop gain.

Now, let us expand this one. This is a simple mathematical manipulation but we will write down. Let us go to the next page now.

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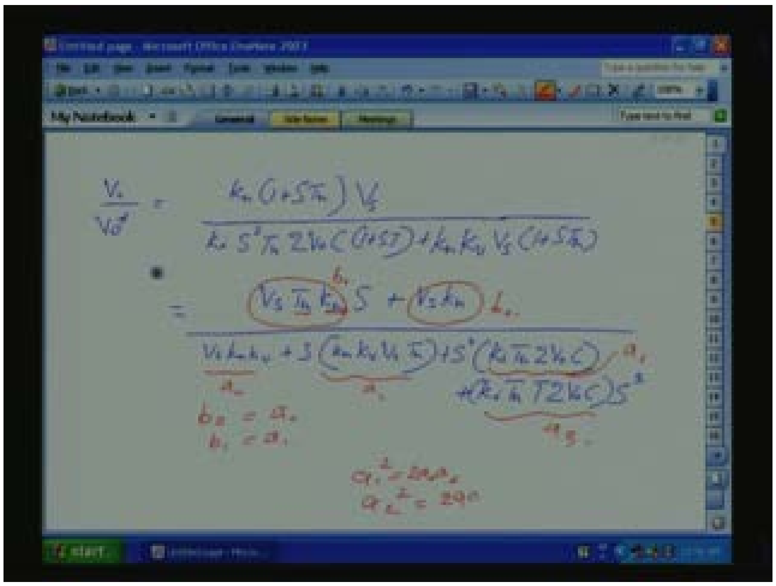

Here it will be, V_0 by V_0 star will be K_n into 1 plus ST_n into V_{input} V, V is our input mains voltage, V peak value divided by K_i S square T_n into 2 V_0 into C into 1 plus ST plus K_n, PI controller again K_n feedback K, this we have to find out K_n K_V. So, the parameter which we have to find out, we will K_n K_V into V input voltage V. So, input voltage makes the input voltage, source voltage, I will make a subscript here V_S, this is V_S, V_S into 1 plus ST_n.

So again, so if you expand this one, we know this is a third order system. So, this will be finally if you do the thing, it will come V_S T_n K_n into S that is a Laplace plus V_S into K_n divided by a_0. a_0 is equal to V_S K_n K_V plus S into K_n K_V V_S T_n plus S square into K_i T_n 2 V_0 C plus the S cube plus K_i T_n T, this our current loop time constant - T, we know it is 2 T_r into 2 V_0 into C into S cube. This is of the form, third order form, transferable third order form where this is equal to b_0; This is the b_0 and this is equal to, b_0 if you see the transfer function, this is of the form b_0 b_1, then numerator, this is the a_0 a_1, this is a_2, this is a_3. So, we can one condition as previously; the first condition is b_0 is equal to we have to equate a_0 and b_1 is equal to a_1.

Now, if you equate the previous conditions, what we have to find out? We have to find out the value of T_n and K_n, all other things are known. So, let us use the previous condition. What was the previous condition? a_1 square is equal to 2 a_0 a_2 and then the next one is a_2 square is equal to 2 a_1 a_3. We can equate the condition.

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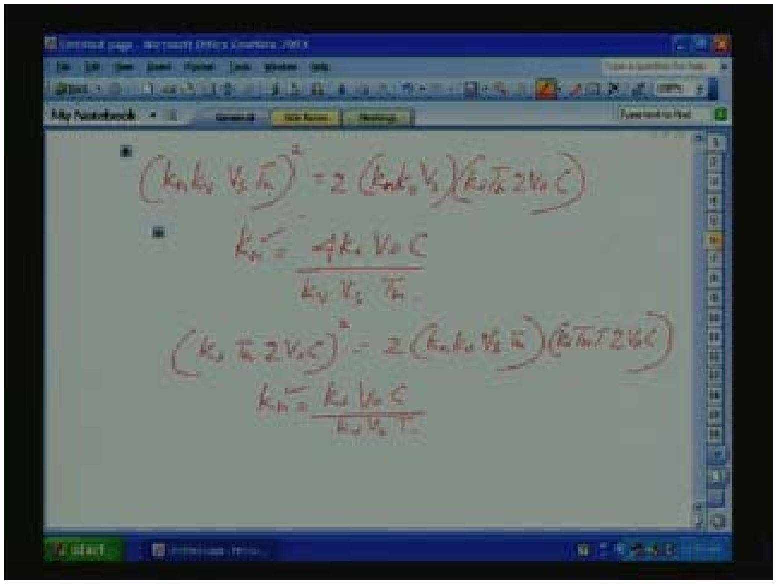

Here, K_n K_V V_S T_n square is equal to 2 into K_n K_V V_S into K_i T_n 2 V_0 into C. Two unknowns, we require two equations. So, from this one, we can get equation K_n is equal to 4 K_i V_0 into C divided by K_V V_S into T_n and the from the second equation, K_i T_n 2 V_0 C square is equal to 2 into K_n K_V V_S T_n into K_i T_n T_2 V_0 into C.

From this one, so from this equation, also we can find out K_n is equal to K_i V_0 C divide by K_V V_S into T. So, from this equation we can find out K_n; substituting here, we can find out T_n. So, this way, we can find out the close loop transfer function for the voltage control also.

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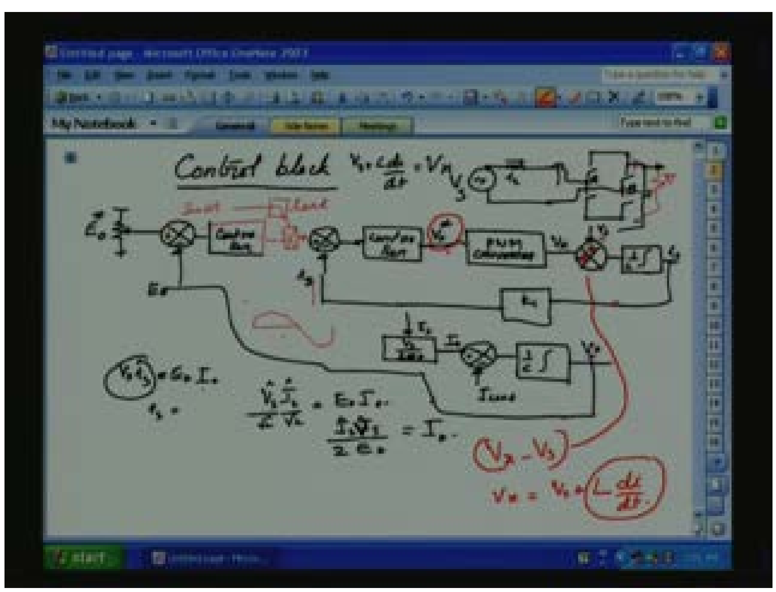

Now, if you go back to your old close loop control scheme; see here we said, I_S is given. Is is if you see the close loop controller schematic, old one, this I_S is multiplied by a sine wave. But all our controller we are assumed with the sine frequency is very high so that during that sine triangle period where the control is initiated; the input current, output current that amplitude during that period is nearly constant. But if you see, these are sinusoidal wave form sinusoidal feedback and sine throughout the operating condition, this frequency of this is constant. But it is going through a controller and converter. So, it will, it can create a lag.

So finally to control, to fine tune it, we can give a small lead network here so that sine can be seeing the waveform, so you can give a sine lead so that the feedback lag can be compensated here so that the I_S so that the I_S and our V_S will be in phase. So, this we can run, this is this we can do it.

Now, what I want to know, I want to take a typical example and find out the parameter and I want to model it through MATLAB and Simulink and I want to show it you, how it works. So, let us take a typical specification for a front end converter for traction applications and from then, let us design our parameters. These parameters we can use it for controller design. So, let us go to the next page.

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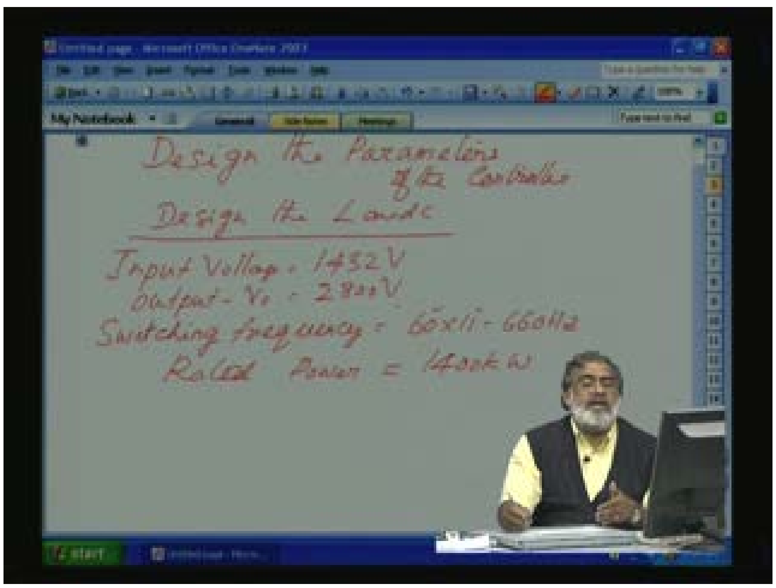

See design, design the parameters and the component value, parameters of the controller and also the, design the, first design the components L and C. Let us take an input voltage because this is what I simulated, input voltage peak value 1432 V and one output V_0 equal to 2800 V_{dc}. Let us take our switching frequency that is a triangle frequency 60 into 11, 11 times; 60 is the fundamental and our triangle frequencies 11 times the fundamental frequency, this equal to 660 H. Rated power, 1400 kilo watt and de-ceiling capacitor assuming a 5% ripple, de-ceiling capacitor can be designed. How to design the de-ceiling capacitor?

De-ceiling capacitor, we can design from the 5% ripple, the total dc that 5% of 2800 volts only and the ripple is due to the second harmonics of the mains, 2 times of second harmonics frequency. So, that is the one we have to use it. So, we already derived the equation. From that equation, we can find out L and C and once the L and C found out, using the standard technique use for the modulus again, we can find out the control parameter for the PI controller. And, already we know that control parameter for the current is a simple gain based on the L and the gain, converter gain E, G and the triangle frequency. So, this we will take up in the next class.