Power Electronics

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Lecture-12

Ac to DC Converter Close loop Control Block Diagram

This is the control block diagram for the Ac to DC converter, we have completed last class. Here we have put V_r, there is a change here; this V_r has to be positive here, here it is to be minus.

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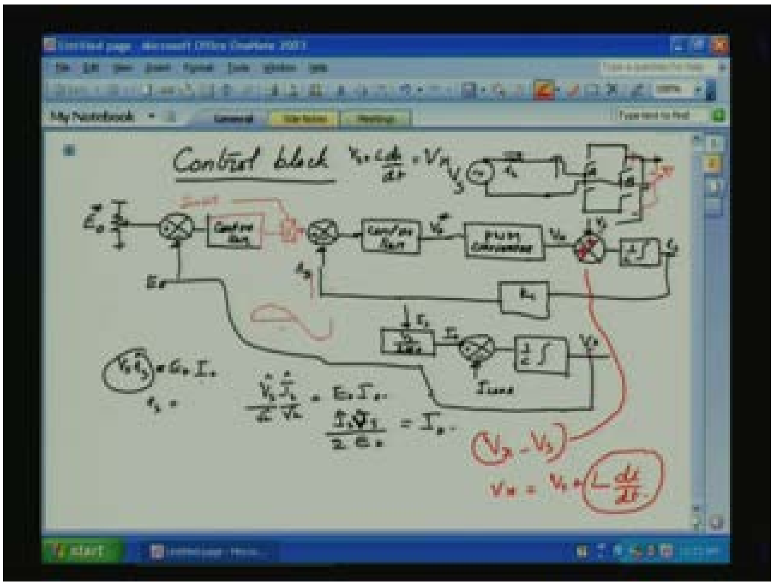

Why? From our front end converter, the V_r is the fundamental between A to B. So, if you see here, V_r is equal to V_S plus L di by dt. So, to find out L di by dt, it should be V_r minus V_S; so this is the one, it is represented here. So, it has to be plus here and minus here. How to find out the controller? We have to find out the controller. Then PWM converter, how to represent so that we can choose a controller such a way, we get a very good response? That means for any change in the input, the feedback current will follow it as quickly as possible. So, converter what we told, it is a sine triangle converter. So, let us go to the next page.

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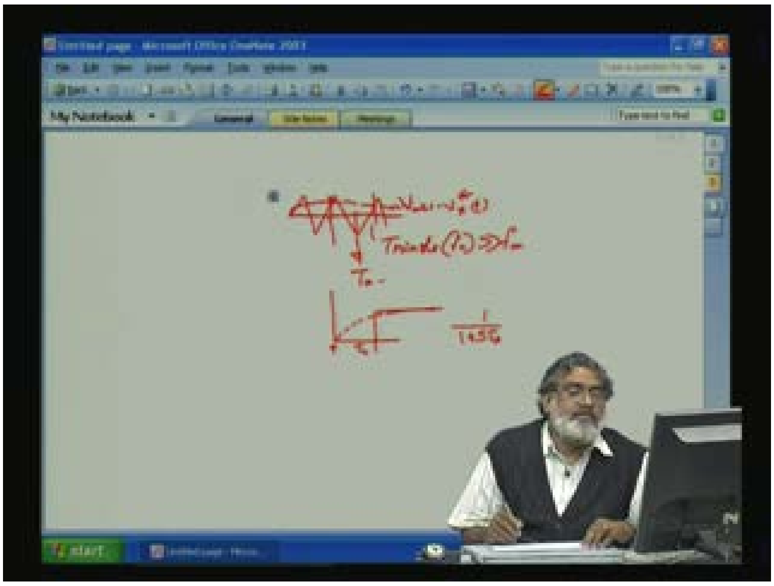

This is the triangle signal and we are comparing this one with sine wave. So, the comparison, the comparison is based that is this V_m. Triangle wave is fixed and V_m is coming from the V_m is our present V_r (t), V_r (t) reference. So, this V_r (t) is coming from our control signal; so, that will that will control our converter. So far, instantaneous control, the control should be as fast as possible, triangle wave form should be triangle frequency that is the frequency of the triangle wave form, fr should be very high compared to f_m that is one thing.

But here, this not true; there is always a delay in control. That means once a comparison happened here, the next comparison is happening here. So, we have a delay of tr, we have a delay of Tr in control. So, this in control, we can approximately model as a first order lag that means a delay. We are initiating a control action here but the action happens somewhere here with a delay of tr. So, this we approximately can be modelled as a first order lag. so, first order lag means the time constant, the representation input output representation is 1 by 1 plus S tr. So, tr is this period, one triangle period tr.

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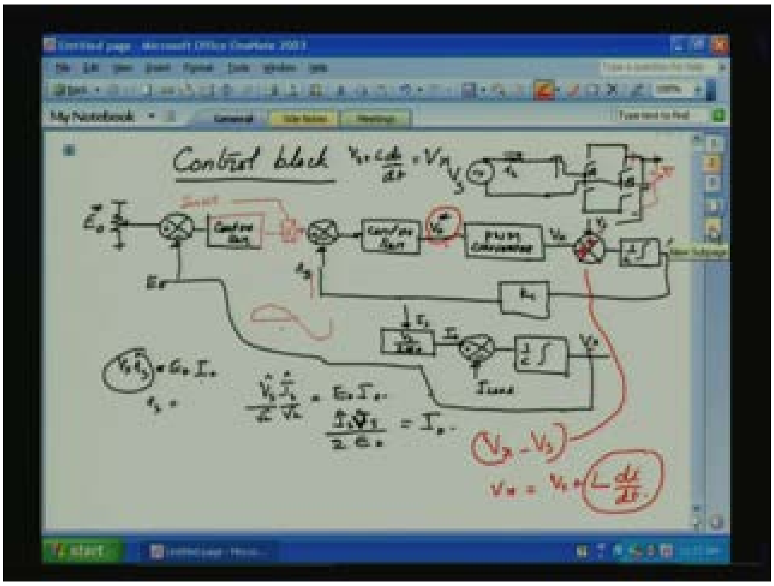

Now, converter if you see if you see, go to the previous slide; see, there is a V_r reference and V_r, V_r is the actual V_r and V_r is the reference value from the control signal that is this one. So, there is a gain. When you make the model here, PWM, when you sine triangle comparison, this sine triangles are done in our analog control signal level or digital DSP signal level. So, V_r will not go more than 0 to 5 volt or 0 to 10 volts and the V_r depends on the actual output. So, there is a gain. So, the converter has to be represented as like this; you have to include this gain also into this one.

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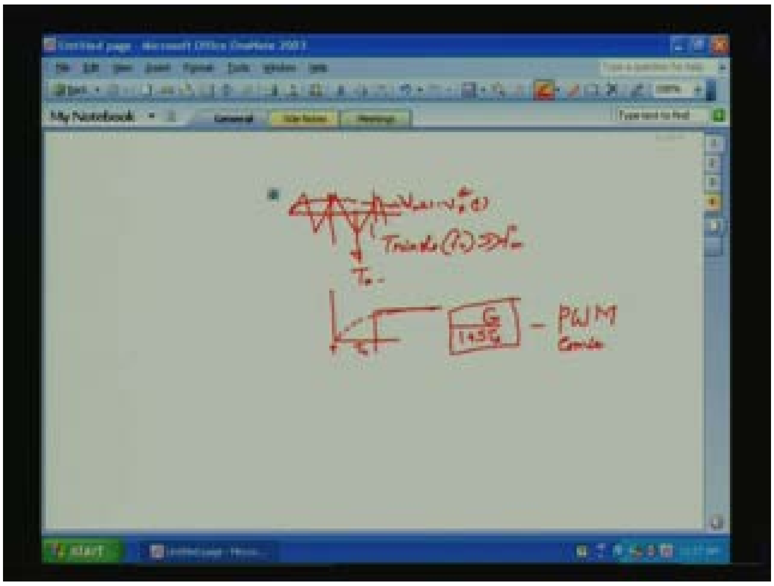

That is the gain G. May be when we come to the model, before the similar model we will try out; there, we will see what is that. So, the converter can be represented, this is the converter PWM converter, we are representing, PWM converter.

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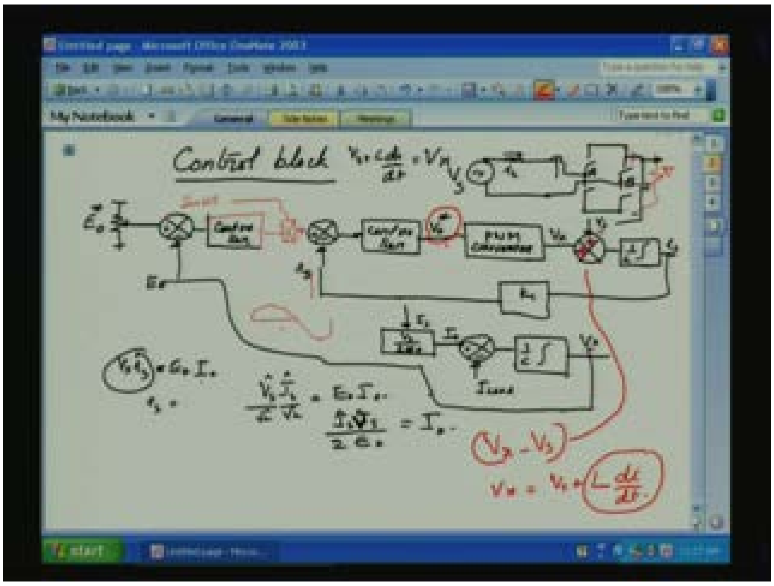

Now, let us first go back to the inner current loop that is we have the current reference, this is multiplied by sine omega t which is this sine omega t is which is in phase with V_S (t), this V_S (t), so here this one. Let us draw the current loop first. So, the current loop, we have the current reference multiple.

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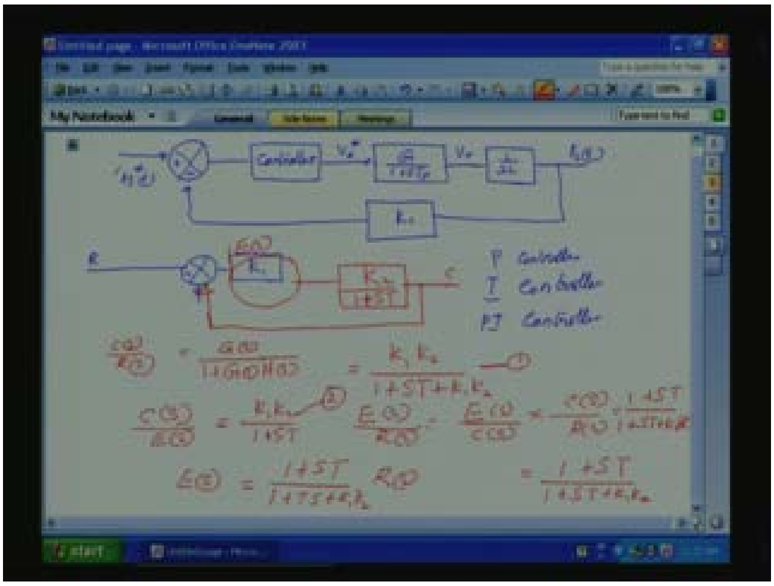

Multiplication is instantaneous, so we will not bring that one. That one, we will not bring it here, only the delay elements we will bring it here. Then you have the plus minus, this is the feedback. This is our controller. This controller output will be going to our converter. Converter, we are representing this as gain G and a first order lag that is one plus S tr. This is our V_r reference. Then here, this minus, this is the actual V_r minus the source, minus V_r integral the current, integral of this difference gives the current.

But this is the controller we are trying to control with input as I_S (t) star that is this one. So, this we will assume as a disturbance input and we will not take in this control loop here. Because our controller we are defining with, we are going to design with respect to any variation in our reference I_S (t). So, differentiation 1 by SL. Then this is the actual converter current, we tap this current through some current some current transformers or other current sensors and we will put a gain of Ki. So, we have to bring it to the controller level. So, gain will be there. So, this is the control loop. This is our actual I_S (t), source current. So, how to design our controller?

See, if you controller, we have studied about many controllers like P controller, I controller, PI controller. So, which one to use here to start with? We will start from the basic; we will start some of the idea from the basics of control system. So, let us take we know the PI controller, the steady state error is equal to 0. So, what you mean by PI controller, steady state error is 0?

Let us take a let us study little bit more P, I and PI even though you know about in your, studied about in your control course, just for continuity. Let us take, there is a reference input R. This reference input, there is a feedback. Let us take a P controller, P controller with a gain of K_1. Controller part, we are using K_1 that is this one, K_1.

Now, this converter, again let us make some system with the first order lag, first order lag, I will put as with a gain K_2 by 1 plus ST some time constant with a unity feedback, this is our output. Output I will represent as c, c. We will make our controller, our system very simple. So, this comes here. Now, let us find out how to design our K_1 for a system like this? Let us take c as output, all in Laplace domain, C (s) by R (s). See, this is we know it; for a system, open loop gain by 1 plus, open loop plus 1 plus open loop gain plus feedback loop gain. So, that is we know it; G (s) by open loop gain by 1 plus G (s) H (s). So, H (s) is unity here. G (s) is equal to, so this we can write as K_1 K_2 divide by if you do this one, this whole thing will come to 1 plus ST plus K_1 K_2. That is if you find out the transfer function, output by input.

Now, what is C (s) by E (s)? That is error here. See, for ideal control, input should be always tracking or output should be always tracking the input and this, here the signal here, E of s should be 0. So, let us take E (s) plus C (s) by E (s). That is let us take, C (s) by C (s) by E (s), this will be equal to K_1 K_2 by 1 plus ST. Now, what is E (s) by R (s)? E (s) by R (s) is equal to E (s) by C (s) into C (s) by R (s). So, E (s) by C (s) we know it, this one by this one.

So finally, this will be equal to, using this one, this equation and this equation, we can find out this part. This will be equal to 1 plus ST by 1 plus ST plus K_1 K_2. I will rewrite here, this will be equal to 1 plus ST divided by 1 plus ST plus K_1 K_2. So, for an input of R (s), the steady state error, steady state error that is E (s) is equal to 1 plus ST divided by 1 plus TS or ST plus K_1 K_2 into R (s). This one we can again simplify in a better way, we can write it like this; E (s) is equal to 1 plus ST divide by 1 plus ST plus K_1 K_2 into R (s).

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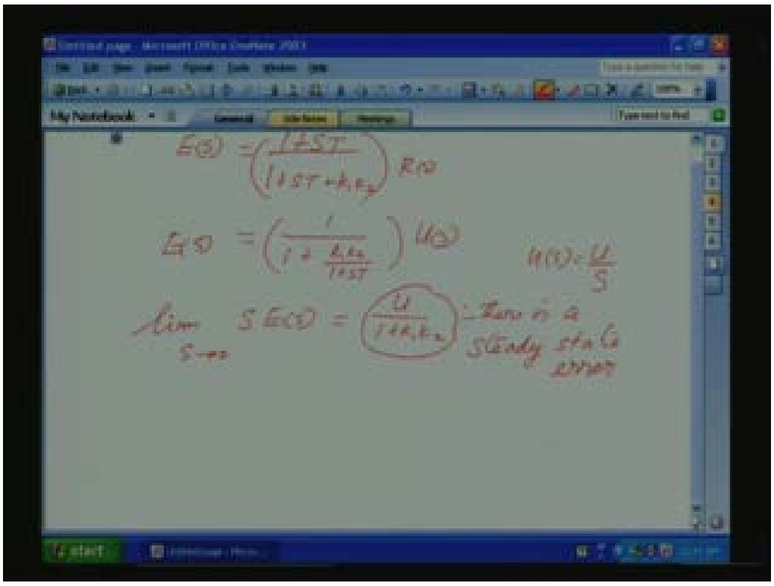

This again, we can simplify as in a simpler form is equal to 1 by 1 plus K_1 K_2 by 1 plus ST into R (s). Suppose, R (s) is a unit step input, unit step input, it is like this, this is E (s). Now, we know that the steady state error should be 0. If you have chosen the right controller, steady state; here we use a proportional controller and let us see whether the steady state error is equal to.

Again from the basics of control system, the steady state, how do you find out? Limit S tending to 0, SE (S), what it will be? Limit S tending to 0, SE (S) for a unit step input? Unit step input u by u(s) is equal to some value u by S. So, again multiplied by S, these two will get cancelled. Finally, the output will be u by 1 plus K_1 K_2. Now, if you here, for steady state error to be 0; there the steady state error is not 0, there is a there is a steady state error when we use this one with a first order plant. Steady state error is equal to there is a steady state error. Now, to make this steady state error 0, let us go back to the previous one.

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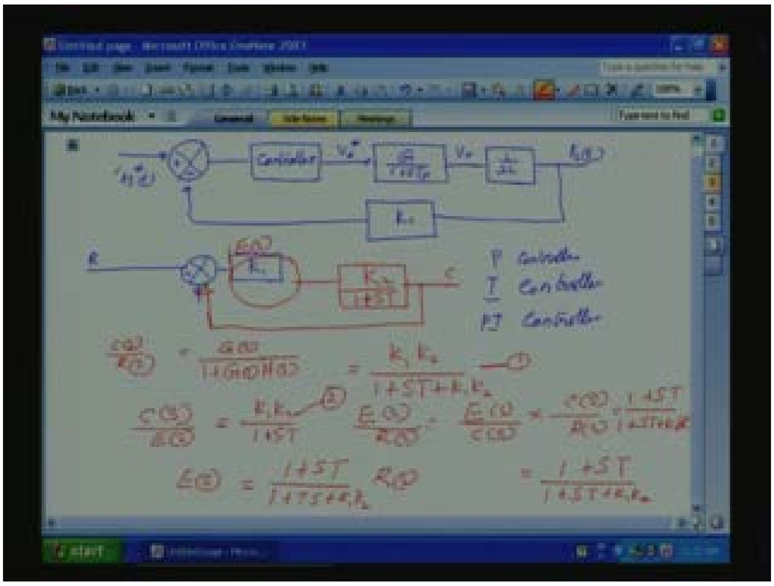

The steady state error if you want to make it 0, see only K_1 is in our control, this K_1, this the planned gain, that is not in our control.

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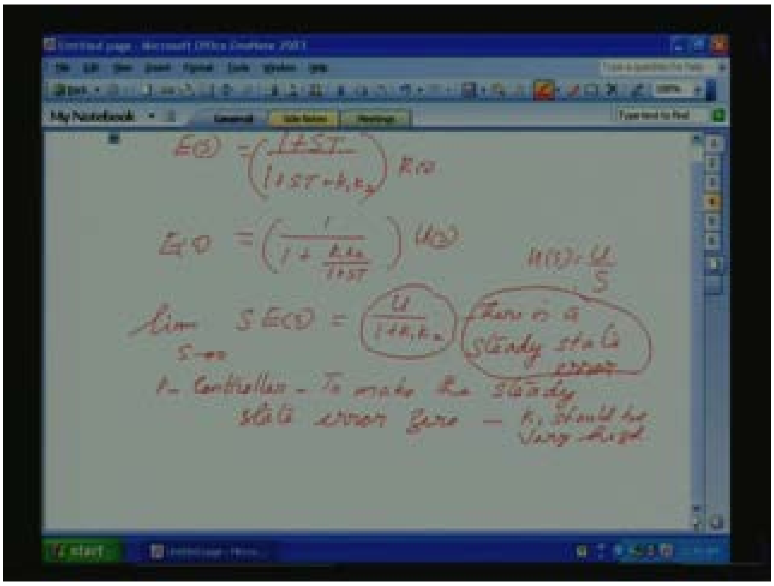

So, to make the steady state error 0 here, this value K_1 should be very high such that K_1 plus K_2 is u 1 plus K_1 1 plus K_1 K_2 should be equal to u by K_1 K_2 and if K_1 is very high, then u divide by K_1 will be approximately equal to it will be close to 0. So for this, so with a P controller, to make the steady state error 0; K_1 should be very high, very high. See, this may not be feasible in many applications, K_1. There is always a controller amplitude limit will be there, K_1 we cannot have any value. So, with proportional controller there will be always, there is always a steady state error.

So, we will not be using in this case; this is one case. And some case, proportional controller is sufficient to make the 0 for a system. Now, we are going to study P, PI, P, I, PI for control of a first order plant. So here, a steady state error can happen unless K_1 is very high. Now, let us take an integral controller.

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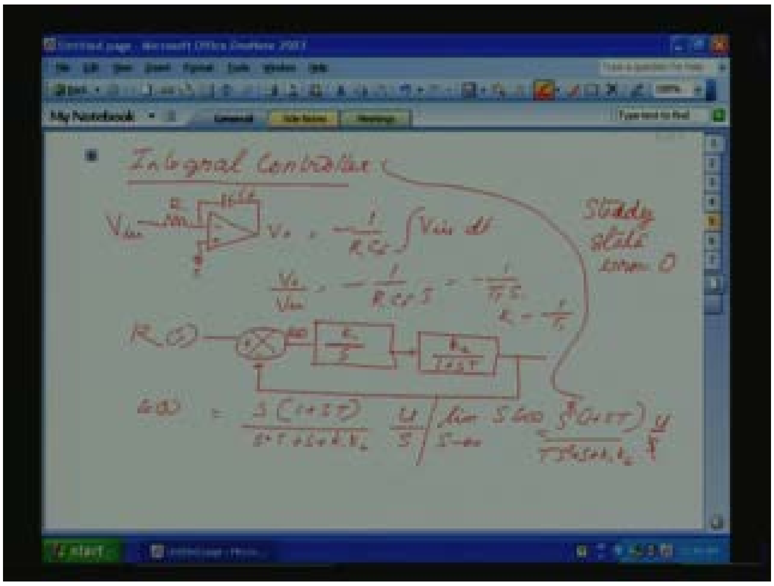

Integral controller is the transferred function. Let us take in analogue domain; integral controller will be something like this. This is our V_{in}, this is our vf, R_1. So, we know it, this is V_0 is equal to minus 1 by R_1 C_f integral V_{in} dt. So, the output, output by input in Laplace domain V_0 by V_{in} is equal to minus 1 by R_f C_f into S. This is equal to minus 1 by T, R_f I will take it T_1 into S.

So, if we use an integral controller, let us again take a first order plant. This is R (s), so integral with a gain we can put it. So, K_1 by, see this K_1 by s, this K_1 is equal to 1 by T_i here. So, this K_1 is equal to 1 by T_i. Forget about the negative side, that we can correct it with another inverting amplifier here. So, K_1 is equal to 1 by T_i. So, integral representation is K_1 by s.

Again, let us take a first order plant, K_2 by 1 plus ST. So, we are giving feedback here. Same like before, if we use the transfer function E (s) by R (s), this is E (s); same way if you do it, E (s) by R (s) or E (s) is equal to s into 1 plus ST divide by s square T plus s plus K_1 K_2 into R (s). R (s), let us see if it is a unit step, it will be u by s.

Now again, steady state error; limit S tending to 0, SE (s) will be equal to, here if you see, s square numerator s square into 1 plus ST happens, then denominator will be T into S square plus S plus K_1 K_2 and the u by S. So, this s goes; denominator, there is always a s. So, tending to 0, steady state error will be 0 here. So, for this controller, the steady state error that is always 0. But there is a disadvantage with this one. Sometimes, it can create problem. When?

See, we have only talked about the first order plant. So, first order plant if you see here, there is signal coming here signal and the feedback. So, it is going through first order lag. So, any sinusoidal signal, so if you consider R (s) contains various signals, it can be split into various frequency component. So, some frequency component, some variations, so

R (s) with some frequency variation, it can give a phase delay here also. So, if this is integrated, what is the phase delay of this integrated?

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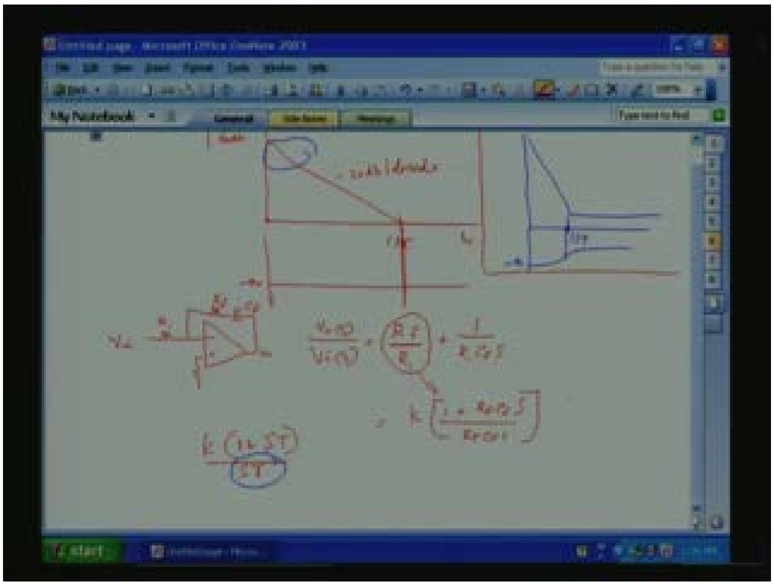

If you take, draw the plot of gain verses frequency, plot of integral controller, it will be gain verses omega will be something like this; this will be at 1 by T_1, the integral time time constant. So, here it will be 0. This will go with minus 20 db per decade. So, according to control system, this is good. But let us do the phase margin. This will always give a 90 degree phase shift, fixed 90 degree phase shift to the signal.

So, if the controller if the, if the plant has some, if the plant has some other frequency depend element and for signal, if we again you have minus 90 degree; so minus 90 plus minus 90, it will be minus 180. So, the negative feedback may sometimes become positive. So, it is not always preferred. That also depends on the controller, so the controller selection depends on the plant and is and its transfer function and again with the controller transfer function with the controller transfer close loop transfer function, how it behaves.

So, let us take PI controller. So, what we want? One controller where we should have large gain should be possible for steady state error. That means steady state error means for DC component, we should have very large gain. At the same time, we should be able to fix the margin at this zero across our period. Zero across our period where the gain will be one when the log scale.

So, let us take about the PI controller now. See, PI controller, see if you want to use it with an operational amplifier, it will be schematic representation will be like this; this is our V_{in}. So, let us this be R_1, R_f and C_f. So here, V_0 (s) divided by V_i (s) is equal to R_f by R_1 plus 1 by R_1 C_f s. So, the overall transfer function will be R_f by R_1 if you take as some K; overall transfer function will be K into 1 plus R_f C_f s divide by R_f C_f s. This is of the form, this is of the form K into (1 plus ST) by ST.

So, if you see here, it has the integrating part here. Then if in pole zero form, there is a 0 at here also. So, how is the frequency response for the PI controller here? Let me remove this one, PI controller. I can draw the PI controller here. The PI controller will be, I will draw with a different colour. So, gain will be if the gain verses frequency, you have the very high gain at the zero frequency side because zero frequency s equal to 0, it will be very high. s is equal to zero means the gain will be very high, infinity. So, the ideal concept of infinite gain or very high DC gain is possible, same like our PI controller.

So, steady state error is possible and at the same time, we can control the phase shift by choosing the T here. So here, if you see here, it will come here. Then when it comes to at 1 by, 1 by T, that frequency, the 1 by ST zero effect will come into picture and it will go like this. So, the p phase, phase margin if you see here, because of the integrating, it will start from minus 90 degree and slowly it will go to zero here.

So, by placing this one overall in an overall close loop control, the phase margin at the zero at the gain cross over, we can adjust it. So, both gain as well as the phase shift, we can control. So, this will also have the steady state error, zero steady state error because of the integrating element here. Now, because of the integrating element here that is this one; because of this one, zero steady state will be here.

Now, let us use a PI controller for our current loop transfer function and let us study, how it works.

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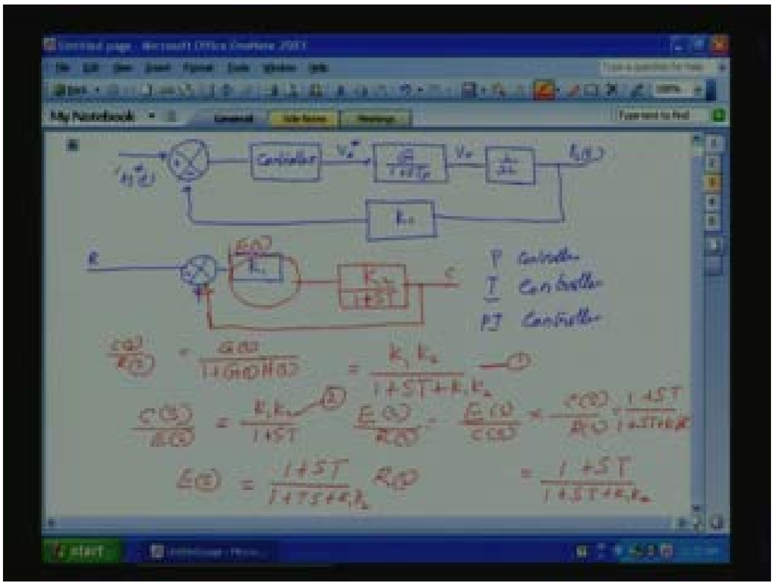

So, if you see here; this is this is our current loop. Now, in this controller part here, we will use a PI controller. Let us study the effect of PI controller.

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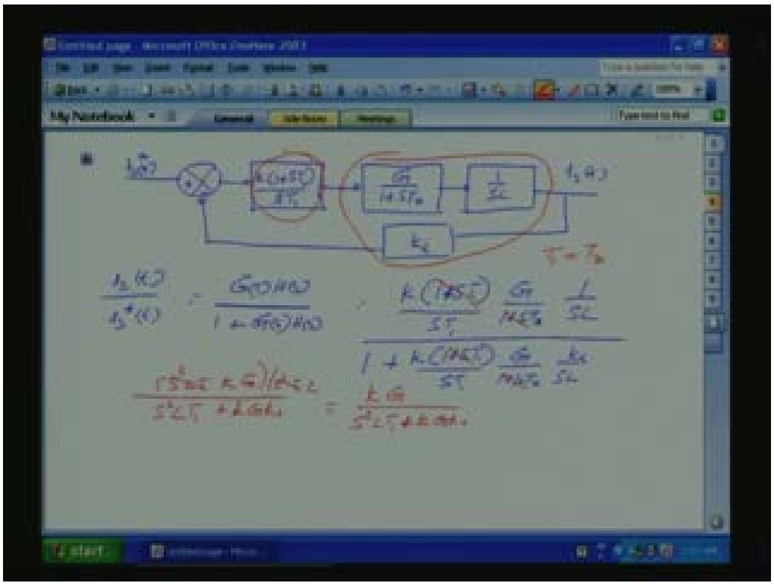

ST reference here, this PI controller, so transfer function we will represent as K into 1 plus ST_1 by ST_1 into G by 1 plus ST_r, this is our converter. Then 1 by SL, this gives our actual current which will sense at bring to the controller level, so it will be like this. Now, let us take the transfer function I_S (t) by output by input that is I_S (t) by I_S star t. G (s) H (s) by this open loop gain, then the close loop gain G (s) by 1 plus G (s) H (s). If you do, it will be equal to K into 1 plus ST_1 by ST_1 into G by 1 plus St_r into 1 by SL divided by 1 plus K into 1 plus ST_1divide by ST_1 into G by 1 plus ST_r and K by SL.

So, if you see, the moment PI controller is added, there is we are introducing a pole. So, here instead of K, we will make it K_i that is the current feedback gate. So, this is K_i. So, you are given a, we are giving a 0 here. So, the moment gives the zero means, it can give large over shoot. So, giving a 0 means you are giving a phase lead. So, it can give large over shoot and also the purpose of PI controller, this is introduced such that T_1 we can choose it such that we choose T_1 such that the dominant large element here.

So, the moment you have the converter, this type of 1 plus ST_r, it will give a delay. So, this delay can be cancelled by this one. So, the response can be faster. So, let us make t_1 is equal to T_r so that the large lag element, delay element due to this converter 1 plus ST_r can be cancelled by this lead element from our PI controller. So, let us take T_1 is equal to T_r. If we use it, we can cancel these two. So, the system becomes simpler.

But let us see, the final transfer function if you take it, it will be s square LT_1 KG divided by s square LT_1 plus KG K_i, this is the denominator. So, if you see here, see this, s square LI here, here also s square T_1L is there, s square T_1L, so this will get cancelled. So finally, the transfer function becomes KG by s square LT_1 plus KG K_i. If you see here, any response of the system for any unit step input here I_S, depends on the denominator. In the denominator, the moment you use PI controller and pole zero cancellation, the first order term is missing that is the damping factor is missing and the system become oscillatory.

So, what I want to say here; just like that we cannot use the PI controller, everything depends on the plant transfer function. Now, but this is the whole thing is coming from our converter model. This is only in our controller. So, how will be able to choose our controller now? PI controller is not possible. Let us take our, we have to choose a controller in such a way whenever there is a variation in the input, output should follow instantaneously.

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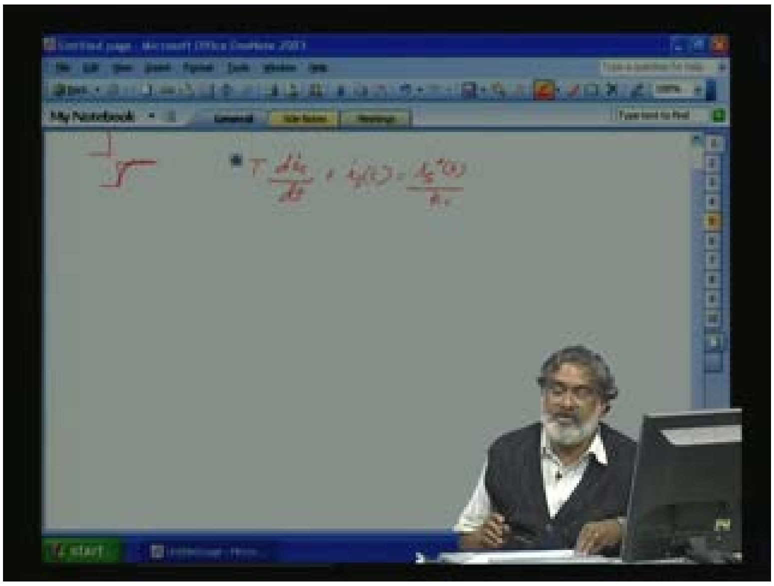

That means if have a variation like this, output cannot; see if you want to have a variation like this, sorry output cannot follow exactly like this. So, step input is not possible. As possible, it can have first order that is the mas fax first order way of changing it with time constant, with small time constant. So, we want the response to follow as a first order lag for any change in current. So, let us take the time constant for the first order lag. Let us see, how to find out that one.

So, let us take at the general nature; for any change in the reference, the feedback current should be varied as a first order lag. So, if you first order lag, if you write down the differential equation, it will be T rate of change our feedback current dt plus I_S (t) is equal to our I_S star t by K_i. What it shows?

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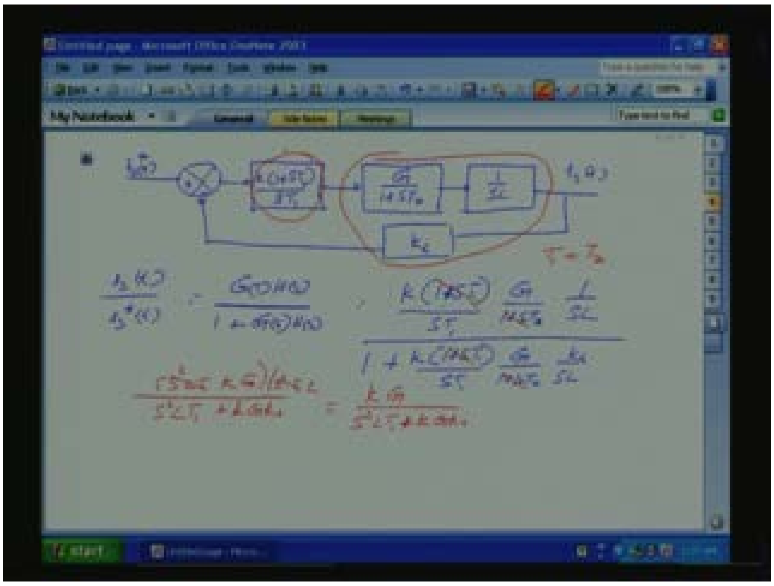

In our previous current control loop, the whole transfer function by putting the controller here, the whole thing with feedback should behave like a first order lag. That means output by input; if you go back to here, the transfer function will be I_S (t) into 1 plus ST is equal to I_S star t divide by K_i.

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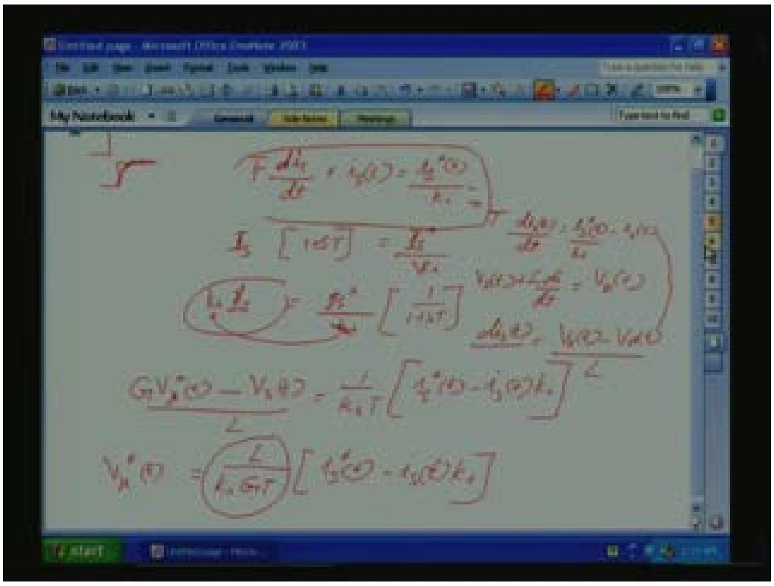

That means the output with respect to input will be I_S star t divide by K_i into 1 by 1 plus ST. That means for any change in $I_S{}^r$ (t), I_S (t) will be I_S (t) that is the feedback current, so that means feedback current means that gain factor is K_i into I_S (t) will, the change variation be I_S (t) will be in the form a first order lag. So, we want the current reference or current feedback to follow the reference with a first order lag and the time constant, let the time constant be T. The step changing may not be possible. The next optimum way of changing is the first order lag. So, T into di s by dt.

So, if you see here, in Laplace domain, it will be I_S into 1 plus ST into I_S star divide by K_i. That means K_i into I_S, it is a kind of, it is the Laplace function is equal to I_S star into 1 by 1 plus ST. K_i we take it and bring it here. So, this will give the first order lag.

Now, let us take from the first equation here, what is the rate of change? For this type of response, what is the rate of change we want? Rate of change we want is equal to d I_S (t) with respect to time by dt is equal to I_S star t minus I_S (t), I_S star t divide by K_i, the gain function. This is the change we want. From the converter, if you see here; see, the source voltage V_S (t) plus L di by dt is equal to Vr (t). So, d I_S (t) by dt is equal to V_S (t) minus V_r (t) divide by L. This is what is happening in the converter and this is the response we want, d I_S (t) by dt.

So from this, here one t is missing. We want to take T into d I_S (t) by dt. So, equating these two equations that is this one with respect to this one, this equation is what is actually happening in the converter. So, V_r (t) is the actual V_r (t). But what we want is the V_r (t) star for a first order response. So, let us introduce this, equate these two equation introducing V_r (t) star.

So, V_r (t) star is equal according to a converter with a gain G; so G into V_r (t) star minus V_S (t) divided by L is equal to 1 by K_i into T I_S star that is the reference minus the feedback with a gain reduction from the converter loop, this is the one. From this one, we can find out what is V_r star t? t is equal to L by K_i GT into I_S^r (t) minus I_S (t) into K_i. So, to get the V_r (t) star, we have to put this gain element L K_i GT in the close loop controller.

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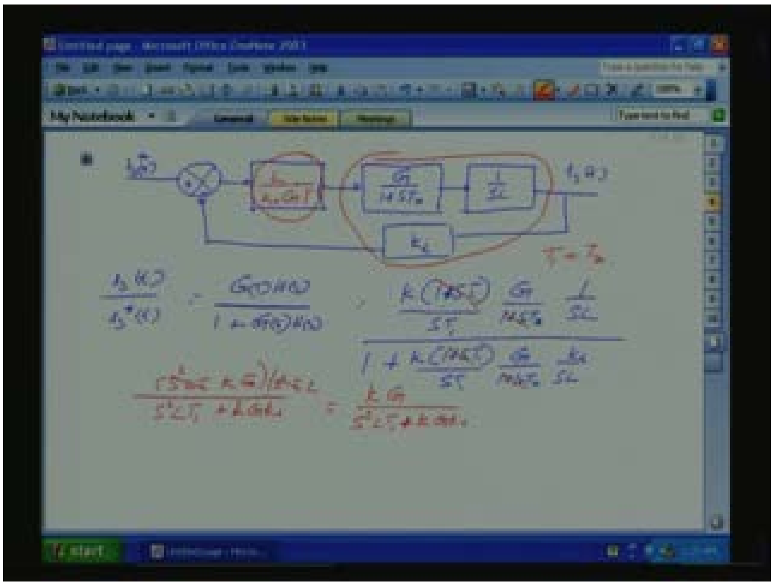

That means if you go back the controller here; instead of PI controller, instead of PI controller here, we have to put the proportional controller here. That is equal to, that proportional controller is equal to L by K_i. That is the current gain in this K, then the converter gain G into T, T is the time constant, first order time constant what we want.

Now, let us from this converter, what we have to find out? Now, the system is stable and for the stable condition, what is the T required? So, let us write down the I_S by I_S (t) star here.

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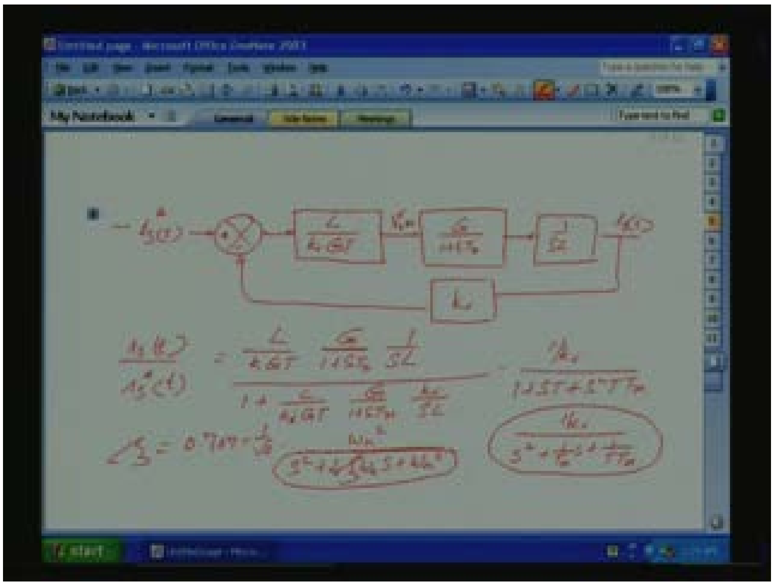

Our input I_S (t) star controller here; it is L by K_i G into T, here we will get the V_r (t) reference G by 1 plus ST_r, T_r is the triangular period T_r, then 1 by SL (s) sorry SL only we are using sorry, 1 by SL, this is our I_S (t), this our K_i, give it here. Now, let us find out what is the transfer function here; input, output? That is I_S (t) divide by I_S^r (t). This is equal to L by K_i GT. That is a gain into G by 1 plus ST_r that is the forward gain, forward gain divide by the close loop gain into 1 by SL divided by 1 plus L by K_i GT, G by 1 plus ST_r and K_i divide SL.

So, this we can simplify again taking this one to this side in a proper form. It will be 1 by K_i, this you can easily do it by 1 plus ST plus S square T T_r. So, if you see here, compared to the previous PI controller; here the second order and first order term is there. So, it has the damping factor here. So, system will be stable. Now, you have to choose T such that we should have an optimum respond. So, in control system, we know it for a transfer system of the form like this.

So, this also we can write in a different form like this that is 1 by K_i by divided by s square plus 1 by T_r s plus 1 by T T_r we can write it. This is of the form, omega n square by s square plus 2 zeta omega n s plus omega n square. So, it has been a second order; the response is like a second order.

Now, for a second order system, for a good response; we know the damping zeta should be equal to 0.707 is equal to 1 by root 2. So, let us substitute this one here and find out what is the T required so that we will get a good response based on the damping here that is 0.707.

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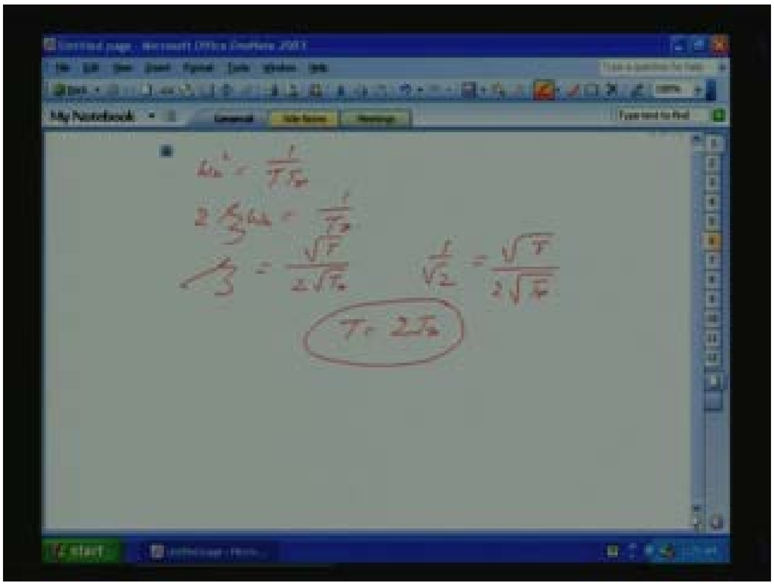

So, if you go there, the omega n square equating the previous value will be 1 T T_r, then 2 zero omega n is equal to 1 by Tr and zeta is equal to root T by 2 root Tr. That is now zeta is equal to 1 by root 2. That means 1 by root 2 is equal to root 2 divide by 2 into root T_r. This similar, T is equal to 2 is equal to 2 Tr. So, if you put T is equal to 2 Tr, we will get a good response according to the response, for a good response a class based on our control system point of view with zeta is equal to root 2. So, we can use that one.

Now see, this current loop, in the close loop control system, we have outside voltage loop, inside current loop and currents loop, inner current loop should be fast acting compared to the voltage control. Then only voltage current will be Pakka because of the mismatch in the load current and current control. So, current loop should act very fast. That means the response, frequency response of the current loop should be much much higher than the outside voltage loop. So, let us take put T into 2r, put this into the current loop and then find out what is the controller required for the output voltage loop in the next class.