Power Electronics

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Lecture - 14

Front-End Ac to Dc Converter-Design

So, we will start designing the front end ac to dc converter for a particular specification. Let us take, let us write, front end ac to dc converter specifications.

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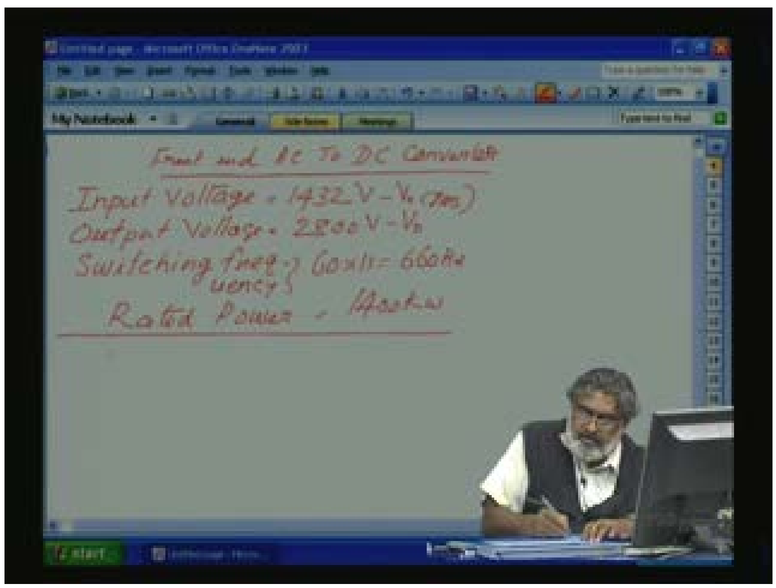

Let the input voltage is equal to 1432 V and the output dc we require; input voltage is our V_S source voltage, source voltage peak value. Then output voltage, output dc is equal to 2800 V, this is our V_0. Then the switching frequency, switching frequency that is let us say the mains frequency is 60 hertz, 60 into or 50 means 50 into 11, 60 into 11 is equal to 660 hertz. So, our triangle period is 11 times the input frequency, 60 hertz. Rated power, rated power is equal to 1400 kilowatt.

Now, let us find out, these are the input specifications; let us find out the other parameters. This input voltage 1432 is equal to the V RMS voltage, V_S rms. So, input peak voltage, you will just note it down, input peak voltage is equal to root 2 into 1432 is equal to 2025 V.

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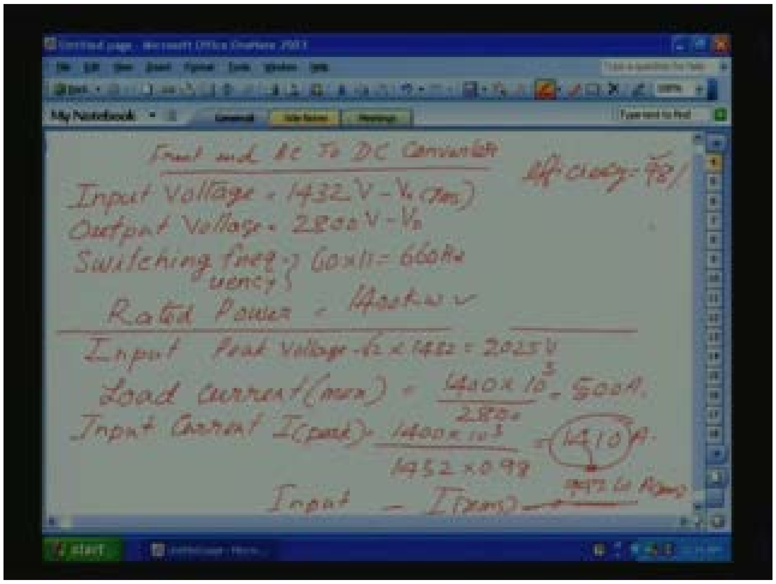

See, rated power is given; from the rated power, what is the rated load current, output maximum load current? Load current maximum that is a maximum value, peak load current, peak load current is equal to output power 1400 kilowatt divide by is equal to 500 arms. This is the output maximum load current.

Now, let us assume an efficiency of 98%. This also, we will get efficiency; efficiency of the system, 98%. So, if the efficiency is 98%, how to find out the in rms input current, maximum input that is input current? There is a peak value rms, I_S rms. See, we can equate the output power to the input power, so output power divide by the input voltage. So here, if you say, this will be is equal to output power, we know it. That is 1400 into 10 power 3 divided by input power is equal to output power if the efficiency is 100%. So, input voltage is equal to rms is equal to 1432. Now, this efficiency factor comes.

So, efficiency is not 100%, 98%. So, input current will also increase accordingly. So, 0.98 is equal to 1410 Ampere. So this, this current is the peak value. So, the rms will be 9.9761 ampere, this is the rms. So, this into root 2 is this value peak value no sorry this is not rms, this is the peak. So, I will change this one; this is the peak value. So I rms, input rms, this is the input is this value.

Now, we know the output voltage is equal to 2800 volts. Now, with our converter, then what is the converter input that is V_{AB}, rms value with a modulation index of 0.8? So, that means when the converter AB line to line in the converter voltage, the Pole V_{AB} when rms, that fundamental, when fundamental is equal to with a modulation index of 0.8. So, what should be that voltage so that we can get a maximum, with that condition also, we can get a maximum output dc of 2800. So, let us go to the next page now.

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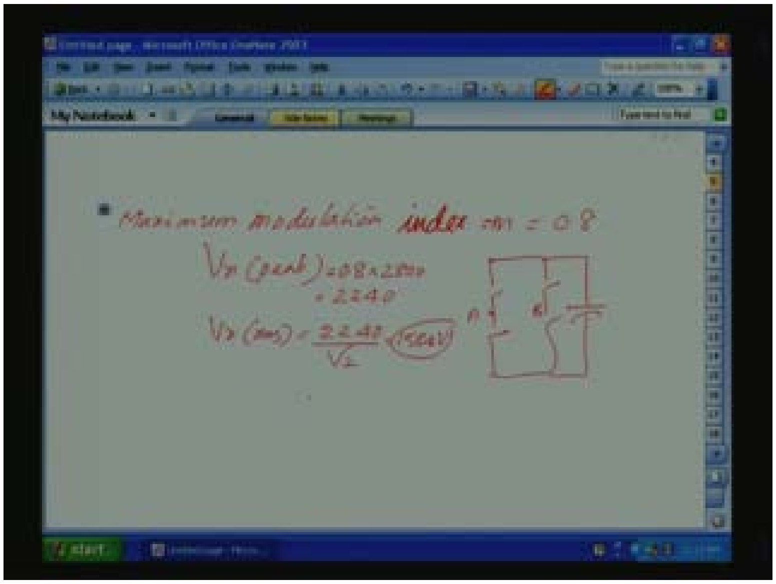

See, maximum modulation index, maximum modulation index is only 0.8. That means we are not, our sine wave reference is not going to touch the peak value of the triangle wave form to take care of the small notches or gate pulses which are which are produced when the sine amplitude is very close to the triangle. So, the switches may not be able to response. So, maximum modulation index here, we are only we are assigned 0.8.

So, our V_r (peak), V_r (peak) the V_r (peak) is our converter is like this; this is our output dc. So, this voltage V_{AB} fundamental of the V_{AB} that is a V_r (peak) is equal to 0.8 into 2800 is equal to 2240. So, rms value, rms value will be equal to 2240 divide by root 2 is equal to 1584 V. That is a fundamental rms value of this one, AB.

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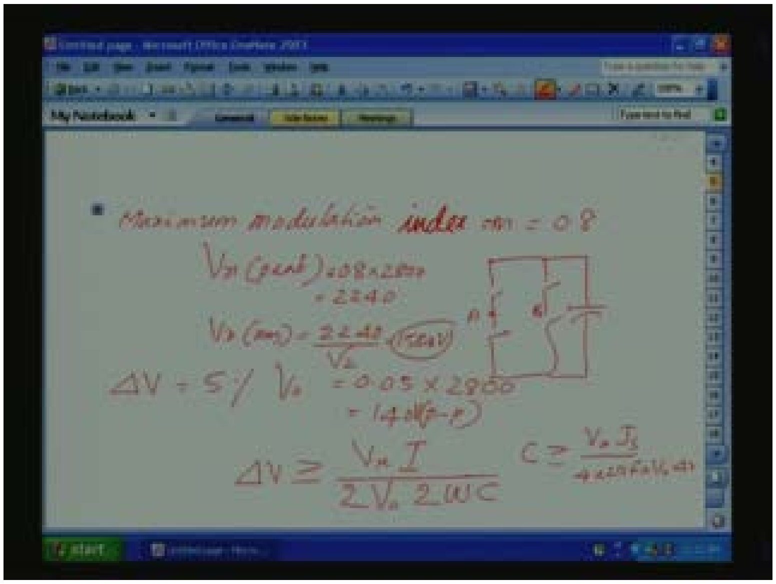

Now, let us design our capacitor and the inductor. See, we said, we want a delta V that is a capacitor voltage of delta V. Ripple only 5% of V_0, 5% of the zero means 0.05 into 2800. That means we want 140 volts peak to peak, 140 volts V only we want peak to peak capacitor ripple. So, from this one, we can design the capacitor C. See, we have the derived the equation before. This equation what we said, delta V should be greater than or equal to that V_r into our I divide by 2 V_0 into 2 omega into C. This is the equation; V_0 is the output voltage, V_r is the fundamental of this one and I_0 is the source current that is the rms current, no sorry the peak current, we are taking here, I is the peak current.

So, from this one, we can we can see C is will be greater than or equal to V_r I_S divide by 4 into 2 pi F into V_0 into delta V. We know V_r by V_S, V_r by V_S is equal to modulation index.

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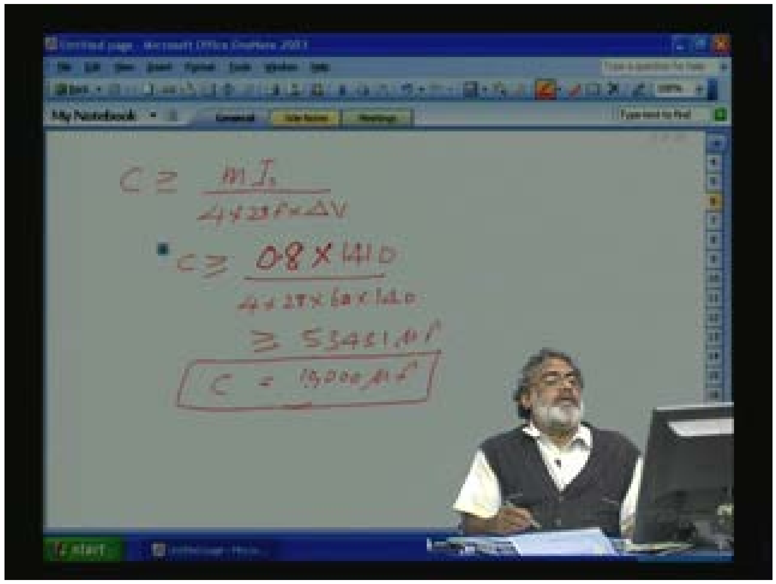

So, this can be further simplified as C greater than or equal to modulation index m into I_S that I is the input current, I_S into 4 into 2 phi f into delta V. So, from our data's given, C should be greater than or equal to 0.8 into 1410 divide by 4 into 2 phi into f is equal to 60 hertz into delta V is 140. So, this will give greater than or equal to 5343.1 micro Fahrenheit.

So, approximately we can choose it, next higher value, C will be used with 10,000 micro Fahrenheit. This the one we have used for simulation. The converter system, this one and this one, we will know how much effect. So, as close as 10,000 we will. So, that will reduce the ripple much less.

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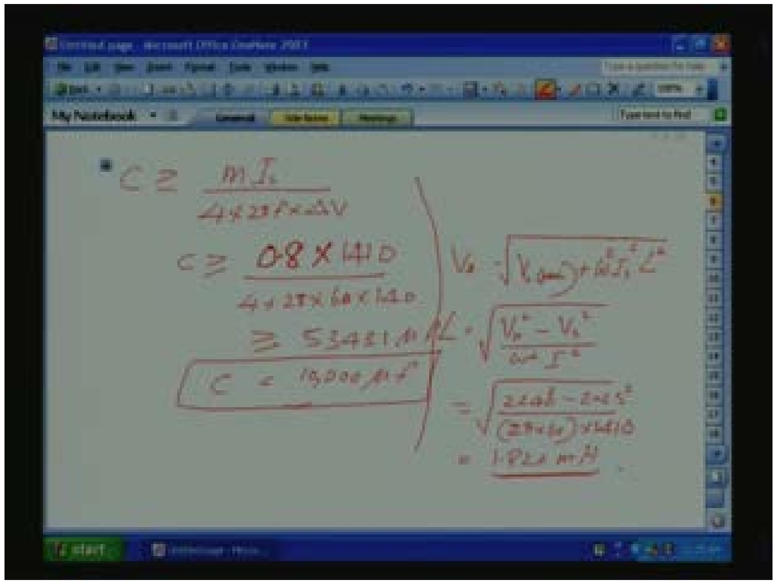

Inductance, from the converter input fundamental V_r peak, there is a peak value is equal to our V_S source voltage peak value plus omega square I_S square into L square. So, from this one, L is equal to root of V_r square minus V_S square, these are all peak values, divide by omega square I square. Here also, peak value. So, this will be root of 2240 square minus 2025 square divide by 2 pi into 60 into 1410. This gives approximately 1.20 milli Henry. This way we can find out.

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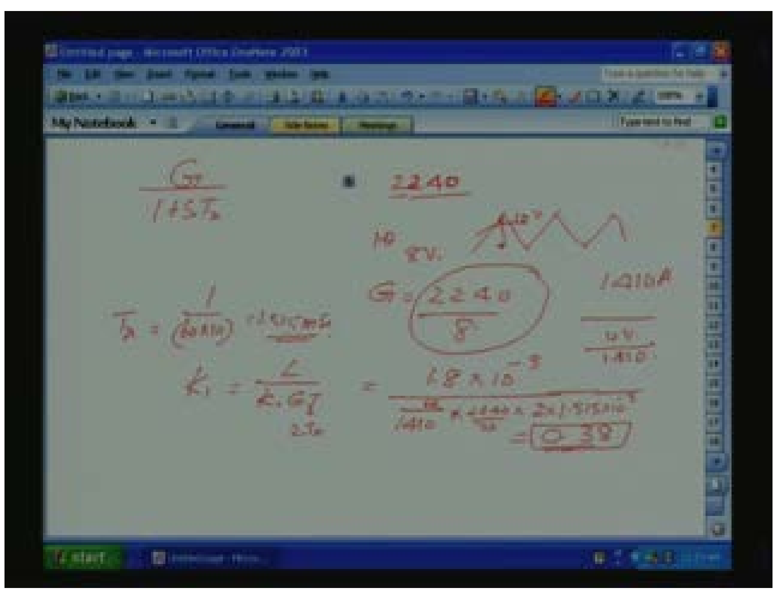

Now, what are the other parameters? Converter, we have this, the front end converter, the transformation is G by 1 plus ST_r, G. So, with a modulation index of 0.8, the maximum converter gain, fundamental amplitude we are getting 2240. So, our sine triangle comparison if the reference amplitude is 10 volt, suppose our triangle amplitude, we are generating with 10 volt amplitude, 10 volt and with 0.8, m is equal to 0.8. So, the maximum triangle amplitude is only 8 volt.

So, when it comes to 8 volts, we will get an output from the converter fundamental of maximum 2240. So, the gain G will be 2240 by 8 or we are trying to have a gain with 1 volt. So, depending on 10 volts or 1 volt, we can have G like this, gain u can use it. Then T_r, T_r is the triangle period that will be 1 by 60 into 11, 1 by f that is 1.515 millisecond, this we can find out. Current controller gain K_1 is equal to L by K_i into G into T. L is equal to 1.8 milli Henry approximately. So, 1.8 into 10 raise to minus 3 milli Henry and K_i; so the maximum peak current is 1.41 amperes, so again here, K_i 1.410 amperes.

Now, if use a sensor and step down and bring it to the, so we will drop to a resistance and we get the voltage and step down to a smaller voltage level; then suppose 10 volt, 1.410 ampere comes you know the feedback gain, you said 10 volt maximum, then the gain is how much? 10 divide by 1.140 or if it is 1, 1 volt, it is 1 divided 1.410. So, here you can approximately you can, suppose here in the simulation, we have all made it plus or minus 1 volt; so 1 divide by 1410 into G sorry, here we made it, if it is 10 volt, 10 divide by 1.140 and the gain is equal to 2240 divide by 10 into T, T is equal to 2 T_r, this is equal to 2 Tr that is 2 into 1.515 into 10 raise to minus 3. So, this will get cancelled, this will approximately give gain of 0.38 that is the gain we get.

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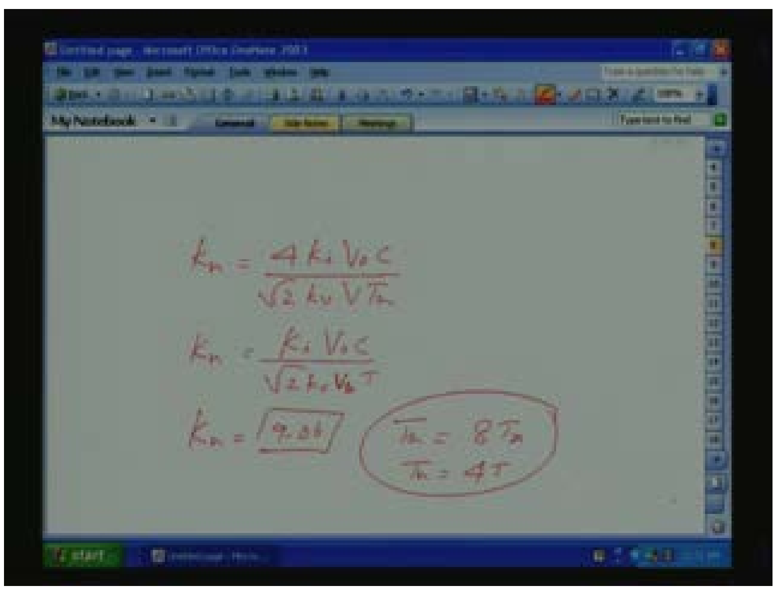

Similarly, we can find out the T_n and K_i values. We have derived the equations yesterday; so from that yesterdays equation, K_n is equal to 4 K_i V_0 C by root 2 K_V input voltage V_S into T_n, one equation, from one equation. Other equation, we got two equations by equating the a_0 a_1 a_2 a_3 from the third order system, K_n is equal to K_i V_0 C by root 2 K_V V_S into T. V_S, all this subscript with Cs is referring to the source. So, from this one, with appropriate gains we can, K_n what we got is 9.06 and T_n, we got T_n is equal to 8 T_r or T_n is equal to 4T. So, these are the values, we get it. Now, with these values, we can attempt a simulation; before simulation, then we can do the fine tuning. So, let us get the final block diagram before simulation.

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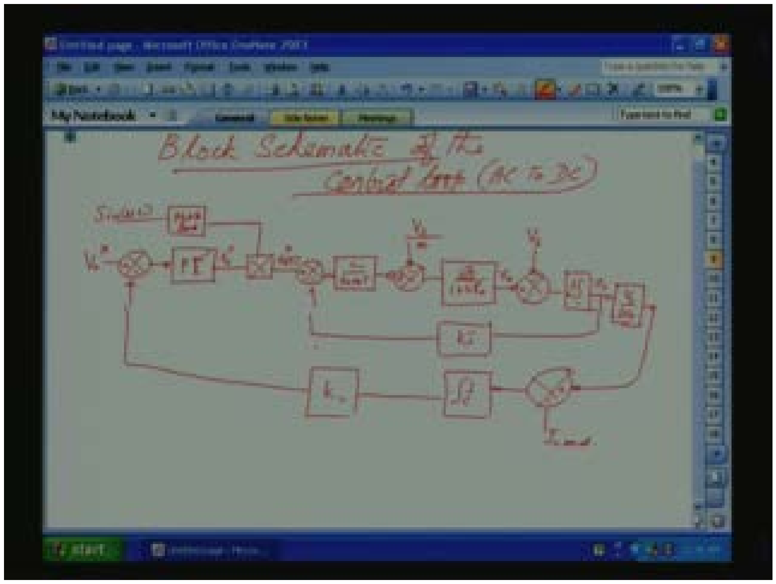

So here, the block schematic of the current controller of the control loop, control loops ac to dc converter. So here, we have the V_0 reference. Here comes the feedback. This, we are giving to a PI controller. The parameters of PI controller we have. Then, this give our I_S reference. This we are multiplying with a sinusoidal reference sin omega T which is taken from our which is in phase with our mains. Then some phase lead, we have to give to take care of because sinusoidal we are controlling the sinusoidal input and sinusoidal currents and as I told before, assuming high frequency PWM.

So, during the control, we are we can assume nearly constant and also the frequency is phase, the loop can the feedback can have a phase lag, it can create a prior. To compensate that one reference, we will give a phase lead. That we can trial and though we can adjust minor phase lead because the phase lag is basically only due to the converter. So, this multiplied, this is our final I_S reference, I_S (t) reference. This is the function of time. This comes here, to this one we are giving the current gain that is L divided by K_i G (T). To this one, we are giving this minus, our source voltage we can sense it and in that also can be reduce by a gain of G so that converter gain will be G by 1 plus ST_r G by 1 plus ST_r.

This again, this is our V_r fundamental, actual value; this minus V_S, that source voltage V_S, integral 1 by a integral, we will get our actual I_S current that with a gain feedback. From the, from this one multiplied by the, from the power balance, input output power balance, we will get V_S peak divide by 2 V_0 that is our I_d plus minus our I_{load} 1 by C integral, capacitor voltage, then a voltage reduction, K_V. So here, all the parameters we are selected; G we know, 1 by C, C we know, L we know, K_i everything selected. These are all simple gain to bring it to the control loop. Now, we can design our controller.

How to design our PI controller? In software, it is very easy, lot of algorithms are available. But if you want to design with analog controller, PI; how you design it? So, we will before a simulation, simulation control blocks we can simply drag and do it but actual implement, how do you realize P, PI controllers, we will come to that one now.

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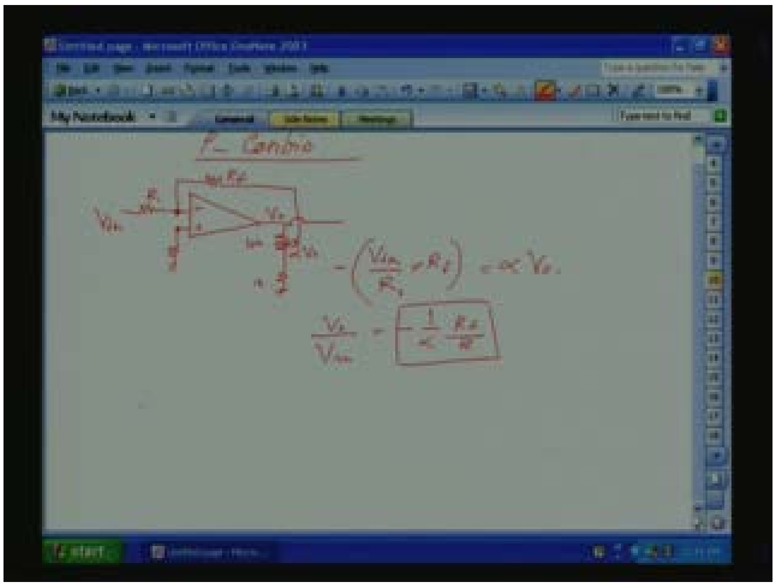

We will start from P, I and PI controller. How to take care of the saturation, how to design thing in analog domain using operation amplifier? Some simple technique, P controller using operation amplifier; see this is our R_1, here is our V_{input}, this is our R feedback. Now, many a times, we want to control the gain. So, either we can vary R_1 or R_f. But if you vary the R_1, operation amplifier, practical operation amplifier if you vary it, it can get into the offset minimum bias current problem here.

So, R_f by controlling by mistake we can short the input to output. So, we do not want to disturb the basic parameters of the operation amplifier to properly bios it. So, controller we will do it like this, we will put some 10 k resistance here and a small value here, may be 1 k so that and here you use support and give it here. So, this is actual V_0 and this is alpha V_0, alpha with potential with control, we will get the thing.

So here, 1 k we put by mistake we should know short the output quickly. It can in a real practical system if you do, suddenly we are shorting the output, it can create problem. So, what is the output? So here, this will have a negative gain; that we can again make it positive by another unity gain amplifier, another one more inversion.

So, let us see how do you do? Here, the input current we know because this point is grounded here because of the high gain of the operation amplifier, this output, this will also, this will follow this input. So this, since it is zero in steady state and the operation amplifier is biased, this point also at zero voltage. This is called virtual ground. This is because of the high gain of the operation amplifier, high gain with this feedback so that it will make this one, these input will the follow each other. So, the error will be very minimal.

Now, assuming this point is at zero potential that is here, what is the input current? Input current is equal to V_{in} divide by R. This current, because of the high input, it will not go to this one; it will go through R_f. So, the output voltage V_0 will be, what will be the output voltage? Here the output, this is connected to alpha V_0; so not V_0, so the output voltage V_{in} into R_f, there is a negative gain is there because the operation amplifier connection is equal to alpha V_0.

Now, but this may be the output we will be giving to the next stage. So, what we want exactly is not alpha V_0, V_0. V_0 by V_{in} that is a proportional gain is equal to minus 1 by alpha into R_f by R_1. So, by varying alpha, some varying potential potentiometer, we can control the gain p. This is one thing.

Now similarly, let us take the integral controller, same configuration we can use it, integral controller; let us take the integral controller.

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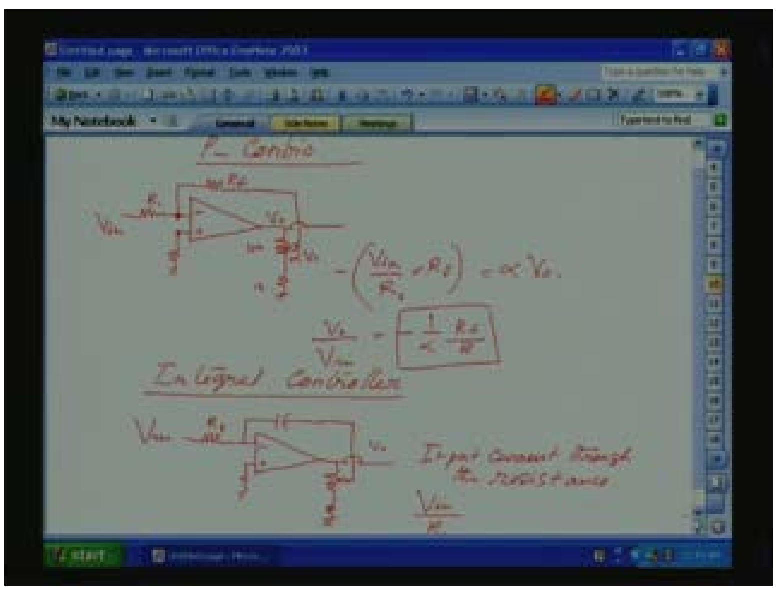

Again V_{in}, R_1, this will be connected here, this is the capacitance. Here also, the time constant, integral time constant we want to vary. See, capacitor variation, online tuning; it is very difficult. Then again, we can vary R_1 here. As I told, any R_1variation, practical operation amplifier, we will we will not we will be disturbing the bias current. So, we do not want to do that one. Again, we will use a high value potentiometer and small resistance to take care of shorting part. So here, this we will do, this is the V_0 we want.

So, here also what is the input current input current through the resistance? The input current is equal to V_{in} by R_1. This current will go through this capacitor and integrate it. So, the capacitor voltage will be, so the output voltage; so this capacitor voltage, it will increase and it will be equal to alpha V_0. So integral, so let us go to the next page; so the capacitor voltage will be integral I_{in} dt by C is equal to minus alpha V_0.

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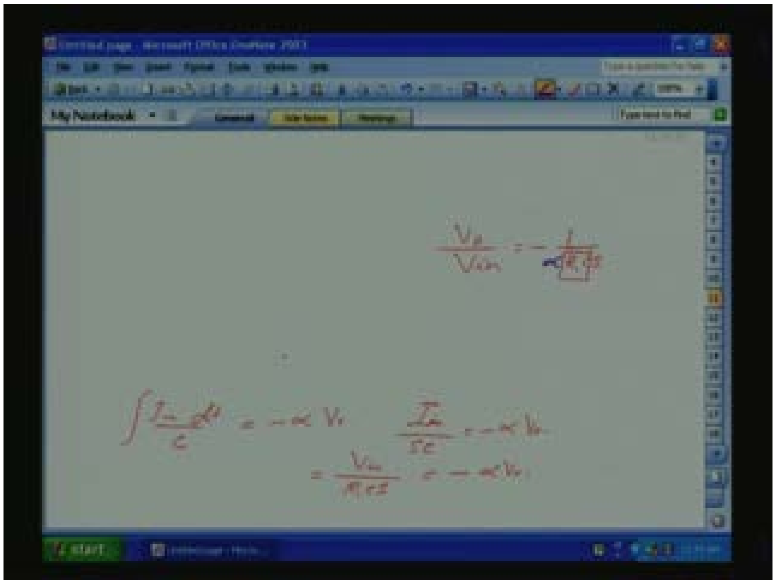

So, let us take the Laplace domain that will be equal to I_{in} divide by SC is equal to minus alpha V_0; I_{in} is equal to V_{in} by RCS. So, this will be equal to V_{in} divide by R_1 CS is equal to minus alpha V_0. So again, V_0 by here if you say, V_0 by V_{in} is equal to minus 1 by alpha R_1 CS. So here, what we are changing? This time constant RC by varying alpha. So, by varying alpha, varying this alpha, we are varying the R_1 C time constant. This way, we can vary the time constant.

Now, let us with P and I using this type of, this type of; using this technique of controlling the gain as well as time constant, let us realize a practical PI controller.

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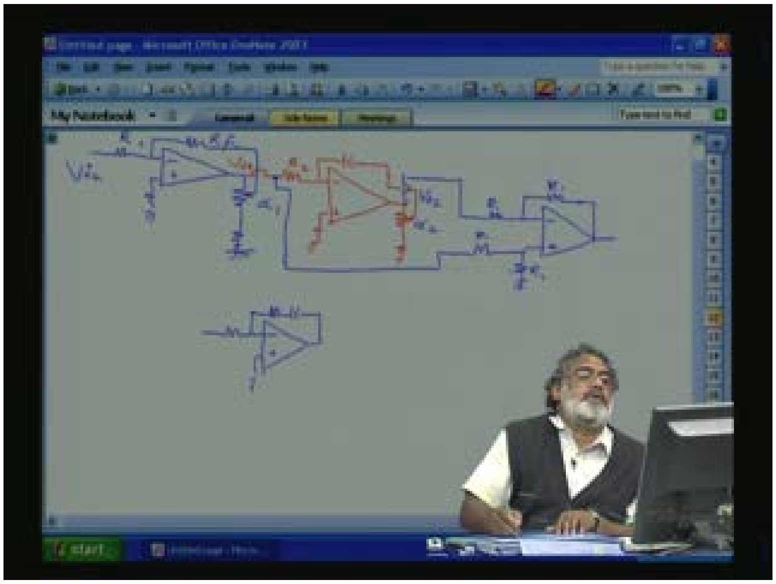

Let us take, this is R_1, this is V_{in} minus plus, this is our R_f, this is our resistance. Actually, we have to give one more; this is the potentiometer, here we have to give a one more small resistance and then ground it. So, potentiometer can be varied. Now, this one will be, this is the P part. Now, let us take the I part. I part will be, see from here, this is our R_2 grounded; again here, for time constant adjustment. This is our, this we will mark as V_{01}, this output will mark as V_{02}, this is V_{02}, so this is alpha V_{02}. This is alpha, this is alpha $_1$, this alpha $_2$; $alpha_2$ V_{02}, this is gain.

Now, P and I but we want a PI controller. Finally, we have to sum these two so that output should be PI controller. Here we will do like this; this output we will connect it to a configuration like this. This is R_1, this is also R_1, so will go here, another R_1. We will take the difference of these two input; one is here, this input will go to V_{01}, V_{01} means here. So, this output will give a PI controller.

Here, independently, we can control the P as well as I part. See, suppose the previous representation if you take it this way, if you do in a PI controller, it is very difficult to independently control the P as well; anything varied, it will vary the time constant also. So, here also if you vary, it will change the P part also. So, this will not independently will not be able to adjust the P and I; so that is why. But this, we will be able to; with alpha $_1$ control, we can control P and alpha $_2$ control, as before we can write the integral time constant.

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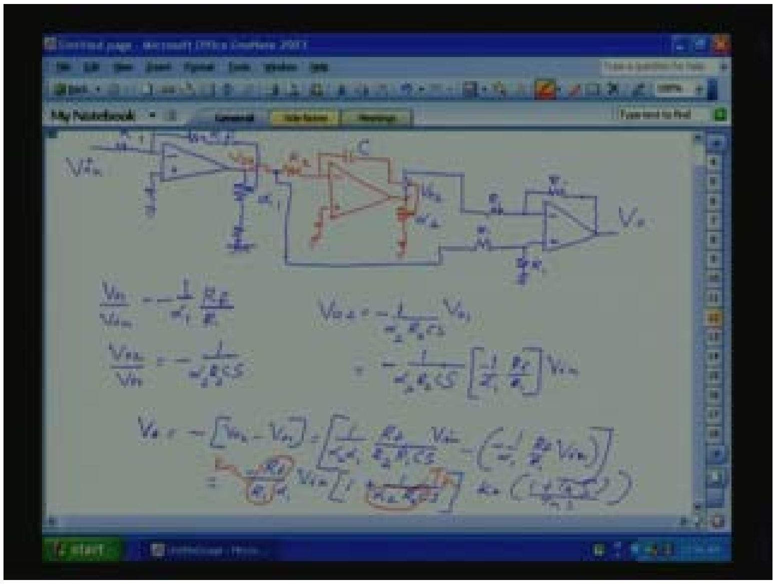

So, now let us find out whether this represent a PI controller, $V_{01}V_{02}$. So, let us say V_{01} by V_{in} is equal to from the previous is equal to 1 by alpha $_1$ into R_f by R_1. V_{02} by V_{01} is equal to minus by alpha $_2$ R_2 this C, R_2 C into S. So, from this one, V_0 so but V_{02} is depending on V_{01}. So, what is V_{02}? V_{02} is V_{02} is equal to minus 1 by alpha $_2$ R_2 CS into V_{01}. So, let us substitute for V_{01}. That is equal to minus by alpha $_2$ R_2 C into f into S sorry this f is not there, C, C into S, V_0 we are substituting that is minus 1 by alpha$_1$ into RS by R_1 into V_{in}.

Now, what is a final V_0 that is a final V_0? Final V_0 is equal to we are using R_1 R_1, so gain is same. That will be equal to minus of V_{02} minus V_0. So, V_0 will be sorry so final V_0, this V_0 is equal to minus of V_{02} minus V_{01}. That will be equal to V_{02} from this equation, 1 by alpha $_2$ alpha $_1$ R_f by R_2 R_1 CS into V_{in}, then minus of V_{01} that is minus 1 by alpha $_1$ into R_f by R_1 into V_{in}. So, this we can again simplify is equal to minus R_f by R_1 alpha $_1$ into V_{in} into 1 plus 1 by alpha $_2$ R_2 CS it will come.

This is of the form; this is of the form K_n into 1 plus T_n S divide by T_n S. So, T_n will be T_n is this value; this is the K_n value, R_f by R_1. So, K_n value we can control by varying alpha $_1$, then T_n value is alpha $_2$ R_2, R_2 C - this is the T_n; this is T_n, this is our K_n, PI controller K_n value. So, T_n can be varied with respect to this one.

See, in many applications, this output we want to control V_0. V_0, many applications output, we do not want we want from, we want to go from a minus negative to a positive negative, for control applications. Suppose, this is V_R, V_R reference we are giving V_R peak value; so V_R and if the control level is maximum plus 10 to minus 10 or plus 5 to minus 5 or 0 to 5, we have to limit the output. Similar way, we should because of large error, capacitor also should not saturate. Saturate, that means we should not go to the power supply level and operation amplifier should not saturate. Then this will affect the dynamics. So, capacitor voltage also we want to limit it, this output, plus or minus 10 value.

So, how to limit this one? We will see for the output that is the same thing, we can use it for the I controller also. So, I will remove these parts and then see how we can limit it. So, now we want to limit the output. If you see here, in this equation, V_0 by V_{in} will be of the form, this PI controller value that is this PI controller. So, V_0 we want to limit it. How to limit it? So, let us take this another operation amplifier; not with feedback gain, negative. So this, here we will give it here, approximately around some 22 k.

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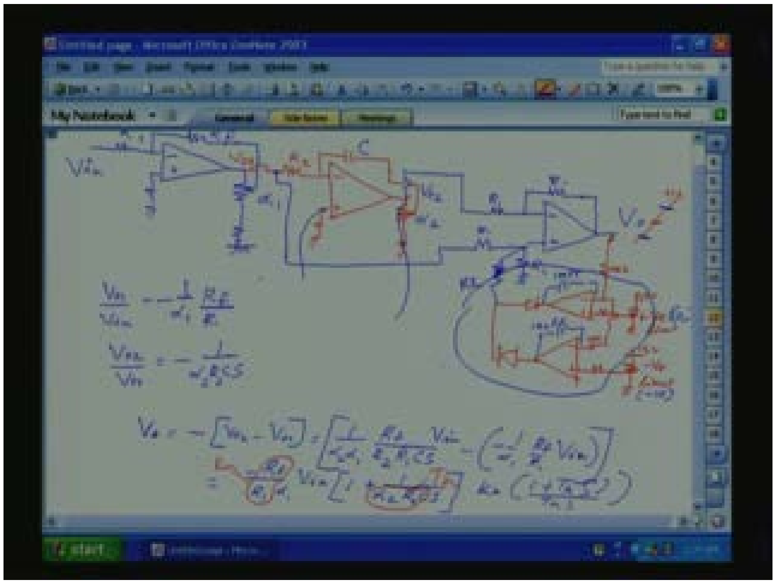

Then this part, we will give it to let us say plus 15 volt. So, this is the positive limit, positive limit that is upper limit. Then we will put a diode here. Now, one more operation amplifier we will put it for the negative limit. This is the negative terminal and this is the positive. Here also put around 22 k here, both are 22 k. Here, we will give to the negative limit, minus 15 volt that is negative limit that is or the lower limit of V_0.

Now, we have the, we will put a diode like this here. See, because there is no feedback, this operational amplifier output can positive or negative. So, normal operation, this should not come into picture. So, let us take the condition when the output goes, suppose this is output goes from 0 to this is 0, this is plus 12 volt; assuming this is limited, this limitation, we want to limit it for a 10 volt that is somewhere here, we want to limit it 10 volt, here also 10 volt, so this we will fix it to 10 volt, 10, this one minus 10.

So, let us say the output variation is within this period less than 10 volt. So here, this is, this point is less than 10 volt. But this is already 10 volt; so output is positive but it will not appear here because the diode is connected to the other way. Now, for the second one, this is less than 10 volt. So, this is already negative, so this output becomes negative and this will not come here.

Now, let us take output goes more than 10 volts; let us say this is limited to 10, it will go to 12 volt. So, what happens here? This is negative more than this value, so output become quickly go to a very high value because it is open loop, it can it can go to minus 10 and if this we connect here, from this point with a small resistance, some small resistance and connect it here so that this small resistance is much less than this one. Why? This wants to, effect of this one should have much more than these two.

So, when it becomes quickly positive here so sorry when this output goes more than 10 volt, this output become negative, immediately it will come here, it will try to bring the output. So, what happens? Because of the high open loop gain, this will make it this gain is sufficient so that even though this output goes, this output will be, output will stay here at 10 volt and again when the output goes more than this value, negative; so this side is more than negative, already negative, so this will become positive. This is positive, so output will try to push it here.

So, this output so that this output are very close and appropriate gain will come here, it will add to this one and bring the output to limit this output to these two value. So, if you absorb here, there may be because it is tracking the output, so it can be oscillations here. So, we can make a 100 pF here that will take care of the oscillation. Here also we can give a 100 pF, small capacitor. Why? See, it is trying to track this voltage here and there is high, this is high gain operation amplifier is quickly tracked. So output, there can be fluctuate, small oscillation can be that towered that one put 100 pF. So, this way this output can be limited.

Suppose, we want the output go from 0 to positive only, then this point, instead on negative you ground it; now suppose the output want to go to 0 to negative, so 0 means this output you ground it and this you minus 10, this way we can do. Same way, the same configuration we can use it here also across the capacitor and here the same configuration we can use it here so that we can ensure that this capacitor voltage will not saturate. That means it will not go to 15 volt plus or 10 volt within so that any error comes, capacitor will not saturate. If you saturate and if you go to power supply, then again to bring back the operation amplifier into the dynamic region, it will it can introduce the stability problem.

So, this can be incorporated here also, what we talk about the antivaintom, capacitor saturation, we can avoid here so that capacitor also will not keep on integrate and saturate, maximum is limited positive and negative. So, that will improve the dynamic response. So, this is the unlogged domain but in DSP we can use it with a standard algorithm, lots of algorithms are there which I will not be talking now, it is all DSP manuals it will give. But simulation we have standard blocks, we will bring it and write to put it and try to see our front end ac to dc converter.

So, what I want you to know that one; independently P and I can be controlled here and this stain output can be limited, whatever the value we want. Also, exactly using the same block here, the capacitor saturation also we can control. So, we will study the simulation part in the next class.