CMOS Analog VLSI Design

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Lecture – 18
OPAMP Design Issues

I mean, in this class as well as evening class of five, I think we will be doing the actual design of an OPAMP. Those who feel that is not relevant need not come in the extra class, but today is the day when I will actually show you how to evaluate for given specifications, how do we make a choice of different W by Ls? So, coming back to the issue which again will be used in the OPAMP design is the stability issue. Please remember the as I keep saying by joke that when you are design in amplifier, you tend to find that it does not work an amplifier, it act like a going system instability grooves and vice versa occurs when you want oscillated to work, it does not oscillate at a frequency is dams down.

So, the issue of probably is related to something feedbacks, and we have been looking into the feedback was quite some time. I may quickly say the closed loop gain that is there is a feedback available which has a beta network; and in this case, the beta is also a function of frequency, like a capacitive will always be a function of frequency. So, beta is also a function of s in the amplifiers which we design earlier in our earlier second year classes, there we always show that you know series resistance, series feedback through the R source resistance or so you always took a very simpler situations. But in internal circuits like OPAMPs, the capacitance will play dominant role and therefore beta is not constant like R 2 by R 1 plus R 2 kind, but it will be something like a function of frequency.

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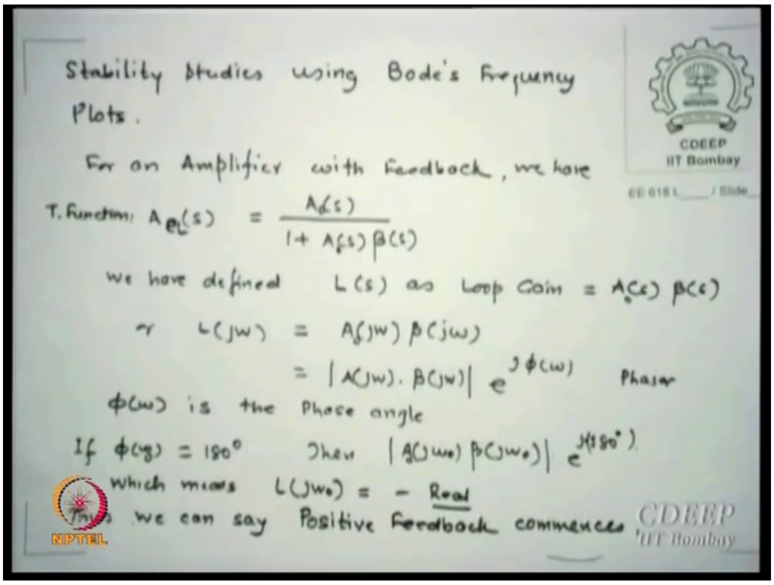

We also defined that the loop gain is called the A s into B s call it A 0 if you wish. I think that 0 stand for open loop gain not the dc gain, it is an open loop gain maybe you should write over well. Then at the any frequency the loop gain can be written as A 0 j omega into B j omega and in a phaser I suppose all of you know phasers that magnitude e to the power j phi omega is the phaser representation of this function, and where phi omega is the phase angle.

Now, if I really see clearly that at a given frequency omega 0, and I figure out this phase omega at that frequency is 180 degree, then we figure out that this loop gain at that frequency is essentially minus, but real because there is no cos 180 sine 180 cos 180, so it is minus 1. And therefore, this quantity is real and negative. Now, if you can see what is happening, if this quantity is negative and real which is what this phaser is telling me at a given frequency, I am just trying to recapitulate what we did or what we did not do correctly or otherwise or what you learned in second year.

The reason why I am interested in doing this kind because ultimately there are number base stability criteria as can be tested for any second or third order transfer functions control theory course. If you have any doing it or have done it, you are well aware of all other techniques root locus techniques or the request criteria or T methods. But we are interested to show only one method which is the Bode's plot method because it gives you some direct relationship with the components which we are going to use, no one to say that those techniques will not result into same, but this is only to take case that we are only looking for Bode’s plots. So, for the Bode’s plot, all these analysis is done only for the sake of finding out when stability has or when does not have is decided by looking at the Bode’s plots.

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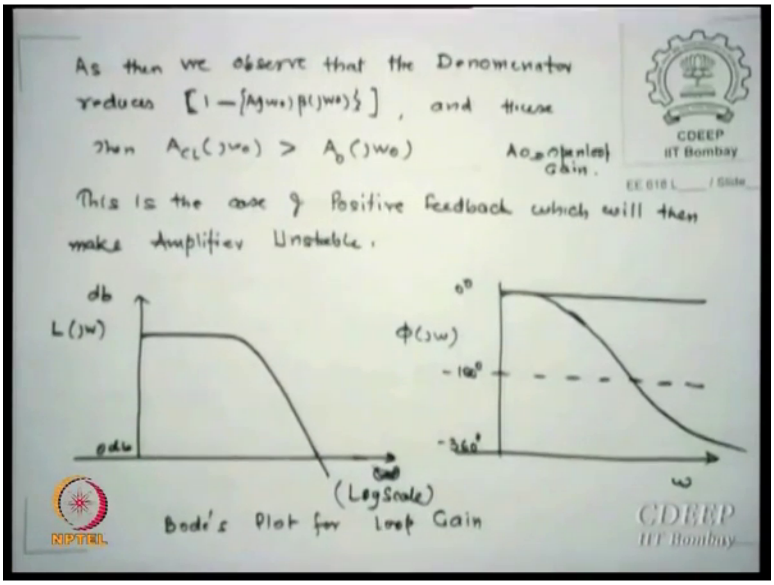

So, if you see this quantity is negative and real, obviously denominator is going down because that quantity is real. And if this quantity real, obviously closed loop gain is higher than open loop gain which essentially means that growth is starting. That means, closed loop gain normally it should be less than open loop gain but in this case if that happens at that degree 180 degree above, we will figure out that this quantity will then which closed loop gain higher. And we say instability certain simply because positive feedback has started.

So, obviously, if I do not want positive feedback to occur, so the loop gain maximum the degree up to which I should go is 180 degree of preferably lower, so that this positive feedback does not come into that is the stability issue. Typically, if you plot the loop gains for magnitude and fetch, one can show that this is the standard Bode’s plot for loop gain versus frequency in log scale; same way omega versus phi j omega goes from zero to 180 degree. And this 180 may come from the network, 180 come from the phase of the amplifier itself. So, in phase component may start increasing as feedback increases and therefore, more and more grows can be actually seeing instability occurs.

So, now how do I get rid of this or I how do I figure out that I am safe, so that is what the condition, which we are going to show. If the beta network is constant that is resistive that is much easier to see from the Bode's plot how much is that stability issues are, but if it is not then probably you should plot loop gains. I will show you the other figures also. Just note down I think these are very trivial. Just to show you typically there is a pole and right now I am assume only single pole system, you can have multiple poles and we can have two poles now, 20 db per decade may become minus 40 db and third make it minus 60 db. This is just to get a single pole and this is the wave phase appreciated with this.

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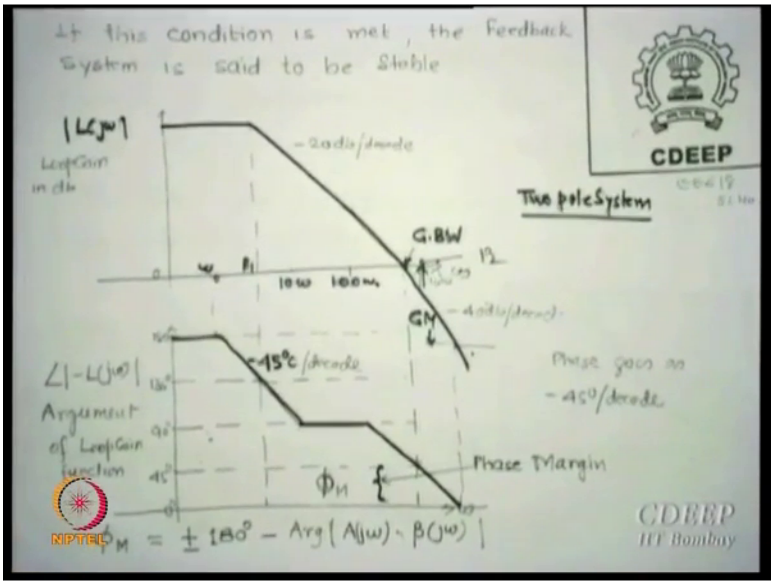

So, if I really plot for a given case for say two pole system, this is called second order system which has a feedback. And if I plot loop gain in db versus log in frequencies, the first pole occurs somewhere at P 1 and that is our bandwidth. And then the weight is chosen right now is this pole all the way single pole is occurring till the gain bandwidth point is reached that is 0 db gain is achieved. Beyond that there is a second pole occurs at GBW at it may occur earlier or it may occur later, but this is the mid case where the second pole starts at GBW itself. Then the fall will be minus 40 db per decade 20 from this, 20 from the other. And if you now see if you plot this into the in the case of phase values at every pole we know 45 degree it should show from zero to 45.

So, it shown says it is shown from one a minus of this I am starting from 180. So, somewhere at the pole it is must go 45 degree down from this maximum value 180. So, at 135 this is the pole. Until the second pole occurs, there is no another fall should occurs. So, it should keep constant, but at this point you want another 45 degree from here; that means, at one 45 degree this point must get hit which means the slope will be then 90 degree like 45 degree per decade, so in two decades into reach phase of 0 degrees.

Now, this essentially is trying to itself that the when the gain bandwidth product point or GBW point that is the loop gain is 0 at that time the phase is not zero, phase is not zero, but it is some positive quantity shown here. What does this essentially means it is essentially trying to tell you that before this reaches 180 degree when the positive feedback starts, the gain has already become negative, so the numerators will start increasing because gain itself has become negative because phase has appeared already from there. In this case, gain was positive and if 180 point occurs then there is the issue of positive feedback to occur.

So, one can see from here, I can have the second pole start from here or I can have second pole start from somewhere down. Of course, it may still pass through this point the point is in the second pole occurs somewhere earlier to this that means 45 point will come somewhere here and then it is likely the GBD by that time it would have correspond it. Because if it is occurring earlier or 135 next 45 down it may reach 180 even before gain bandwidth point is reached which means you are guaranty length positive feedback system because gain is still positive.

So, this means the minimum, I should not say minimum, the safest point because 45 degree is from here that means, the safest possibility that phi M phase margin what we declared is this value should be at least 45. Somewhere here also it is safe I am not trying to safe, but you do not know how much pole is then away from this may decide whether you will come very close to GBW or you maybe even reaching 180 before GBW is attained. So, for the safety margins that you know is 45 per decade, so even if one decade shift is there you are just at 180 if the pole is for one decade ahead earlier then it you are actually adding 180 point.

And any problem starts in parasitic because in the circuits we believe that we have assume all the parasitic properly, but there are metal line in actual chip, there are metal lines, they are polylines, there are metal oxide metal lines. There are many lines at some nodes they may contribute to some parasitic and those each parasitic capacitance will give what another pole and let us say it happens to be earlier than this then your stability criteria is in hey wires.

So, at least 45 will say you up to 180 another pole will come, so ok 180 you will hit. So, you are still in the margin of safety. You may say 30 degrees also safe, 10 is also safe yeah I am not saying is not safe, but for the circuit performance to be guaranteed the minimum phase margin you should keep is 45 degree. Please take it zero above everything is safe; even if this point is reached just here it does not matter because its fair enough that still not positive feedback, but that may change because of the other parasitic. For example, even the gains which you thought on a single chip it may have some devices may have different W by R different parameters, and the adjoining transistor or adjoining other chip may had not the same values variability. Which may again push you do other value, which may actually have that means, some chips should be stable some may not be and that risk we cannot take. So, the minimum phase margins you should hold for any amplifier is 45 degree.

So, please do not think that zero is not safe zero is safe zero plus safe, but safer is 45. It is higher it is even safer. Now, to make it higher; obviously, you can see if this pole occurs even far not from here, but somewhere here that is even safer because the second pole 135 value will now reach even closer this. And by then gain bandwidth has already more than 135 degree it is showing that means, more than 45 it is showing. So, if the pole second pole occurs beyond gain bandwidth point, safer for you, always safer for you, but minimum it should occur is at the point itself because the pole should not start or second pole should not start earlier than gain bandwidth. Because otherwise that 45 degree in risk situation, I am not saying still it is safe if it is close to the still it is safe, but not very, very safe to be a 100 percent safe, I would prefer the second pole should be outside GBW point or at least at GBW point, is that clear.

So, why we always look for that GBW point is that this point we are looking for phase because phase margin in measured at that point is that correct. So, at that point we will like to see whether sufficient margin is provided for me so that the loop gain does not allow you positive feedbacks is that clear, so that is the way all stability people start looking into it, is that clear. Now, this case is shown only for two poles. If there are multiple poles, multiple problems, but in general there are techniques which you have learnt splitting poles or nulling the poles or nulling zeros. We can do tricks to actually get rid of some of these poles problems and strength still can attain what we call stable amplifier, is that clear. The two techniques which we will use later in my design one is using the pole splits, the other may be nulling the pole itself by 0.

So, this issue why this 135 or 45 should be very clear that why keep everyone says 45, 45, 45 is not sin cosine otherwise, but one pole another pole may give you another 45 degree per db decade that may create huge problem for you instability, and to avoid that always go beyond 45. So, the minimum phase margins which amplifier use is 50 degree minimum. Then you may say can I use 90, yes, you can, but then the what else it will happen will have to see if you keep increasing phase margins, does it affect something else. Can if that affects then you will have to go back is reduce the phase margin. So, it should preferably I may show you later somewhere that between 55 to 70 is typical phase margins are used in almost all analog amplifiers is that correct, 55 to 70, 72 some designs are, but around that value and not beyond 75 anytime, is that clear to you.

So, these are not figured out by just by we do some evaluations, we do some experiments actually on chip and by I am knowing parasitic now you figured out this is the range at least you should hold, so that stability is guaranty. Please remember we are always thinking of two-pole system. If there is a the third pole more values more problems may come to see to it that the third pole actually never occurs before GBW at any cost at any cost that should be moved away or removed moved away or removed, whichever you can that is the best for you.

The technique which I do not know my second year than second year students remember, but just to give that interesting figure, which we use you can always find from the open loop, need not plot loop gains. Of course, the assumption in all these decision is beta is independent of frequency easier to do it.

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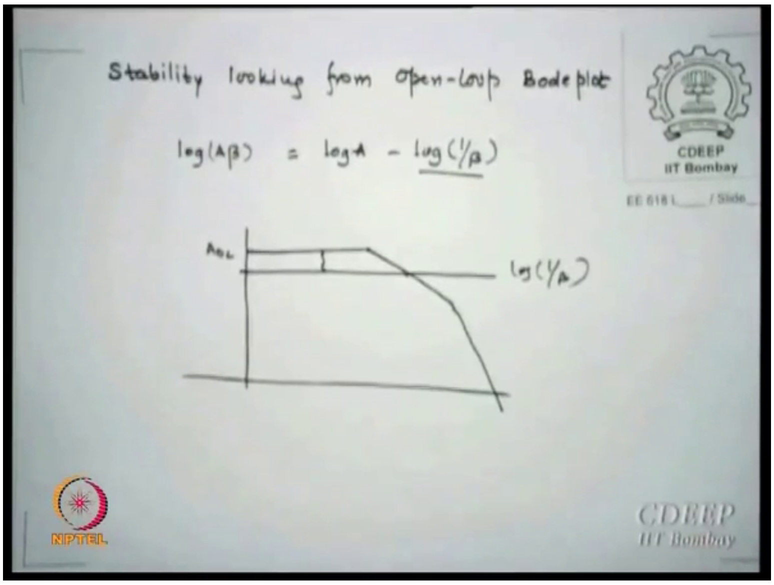

You can see from here log A beta essentially can be written as log A minus log of 1 upon beta match nothing great nothing simple. Now, if that happens now I have plot log A, I have plot A as the normal open loop gain. So, let us say quickly let us say right now two poles system, this is my A open loop, then I assuming beta is constant which in our last case is not, but in case it is resistive feedbacks, I can put log 1 beta is one value because beta is constant. So, I draw a line somewhere here which is log of 1 upon beta. So, what is this value, loop gain, this is the loop gain. So, what is this value therefore loop gain is 0, is that point clear? This is the point where loop gain is 0.

Now, if you take the phase for this it will reach 45 degree, this will reach 135 degree. And as long as you are within this range, your feedback 1 by beta point, you are always more than 45 degrees phase margin, you can create, is that clear to you. So, what is the thumb rule? If you have an open loop gain see to it that your feedback does not go beyond second pole, it should be within first pole and second pole. If you can fix your this value there, you are hundred percent stable, is that clear, so that is how actually from the bode plot by just looking you can say oh it stable. So, this is the technique which normally many books show, but I thought that you should know why they show, they inside of showing T or A beta they show simply this they say this is this at this point.

So, anyone between this if you have one beta one log one beta lies then you are always say because you are not going beyond 135 anyway. So, 45 below you will never reach and therefore, you will always be safe in this. So, a thumb rule is adjust your feedback such that you remain between first pole and second pole. As long as you maintain that, you will be safer. So, these are some tricks of the feedback networks those who have done if you have control theory that may it may looks trivial, but that is what we say there are different way of looking things, Bode's plot actually gives you some idea of numbers and that is why I follow Bode's plot.

Now, if you say I can have phase margin of 45 above, the issue is not still trivial. There is another problem seen because bode plot is what kind of response you are looking, frequency domain. You are always in frequency domain, but if you see much of the amplifier properties are actually found by what response, step response, that is how we actually evaluate how the outputs will properly go with the inputs.

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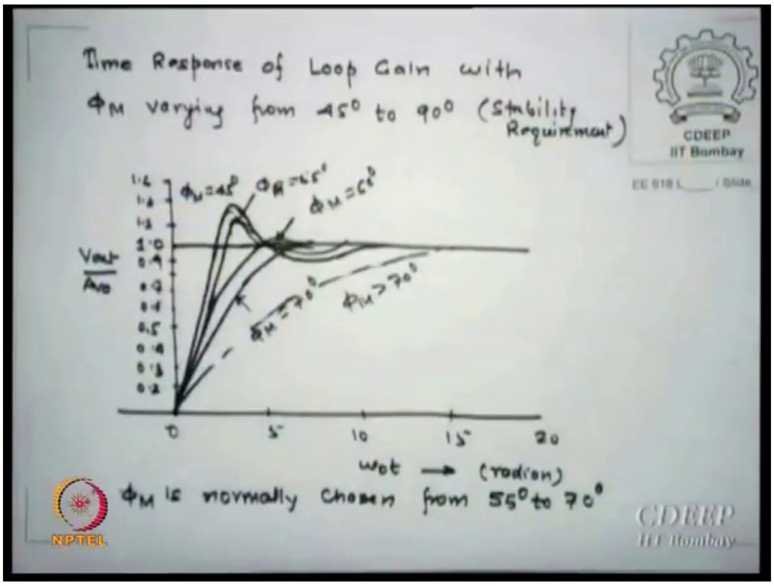

So, here is a time domain analysis if you do for the loop gain, you say you are sorry it is V out by A V 0. So, if you very phi M from 45 to 45 which is what you set by stability is the range up to which you should work. And if you plot the output, this is called what is it called normalize output versus normalized frequency or time. Now, if I plot this, I will figure out for different phi M, I have plotted V out normalize V out, 45 degree is this. So, at 45 I figured out there is a ringing going on.

You can see this risers and comes lower and it may take more than I had only showed in one, but it may take two three rings to finally a settle. So, this will be settling time, this will be a huge settling time. If I increase phase margin, which I did of course, this figures are not up to the scales, these are just represented to scale. If I go for 55, I figured out that the peak goes down; and it also reaches the constant point faster. I have increased to 60, I find very little overshoot and it dies down very fast, this dies on come from what is the damping factor which in the second order function, you have 1 upon 2 Q as we say is actually a damping coefficient.

So, we figure out that if phase margin is around 60, the damping is so that it reaches and almost settles to V 0. If you increase further 70, it takes even longer time now to it may not ring, but it may take longer time to settle. And if you go further it may not reach or it may take long enough to settle, is that clear. So, if you see this time response and you look your stability issue, where would you like to pay your phi M somewhere between 55 to 70 at best is that clear. So, in this range, phase margins are always chosen is that clear, because then I am assuring you that output will not ring; even if it does little bit it dies down very fast, this is our second order any non-linear system you study, any transform function and this can be proved otherwise is that clear.

So, why phi M as 55 to 70 because I have figured out that other than the other requirement which may occur even the time response may create a issue which at time please remember here I am only showing you say 1.4 times. Sometimes if you lower you can see this may become twice and then it will take hell of time to settle and within your time frame it will never set up, is that correct. So, lower phase margins are also risky for even settling times is that clear. And therefore, we always prefer from the 2.1 is of course, the stability issue 45 is of marker sorry say 10 degree above or at least 5 degree above, so 50 to 70 is all that I should look for in my designs is that clear.

So, you must be finding that every time I stick to 50 to 70 this is the reason why I am sticking to 50 to 70; not that I cannot design at above 70; not that I cannot design below 45 by the risk of stability and transient is very obvious. And I must look into both before I decide what margins I have, is that clear. So, this issue which is not some books do, some many books do not even consider that why so I thought from the second orders transfer function theory, you can see you can evaluate how much is the range really available to you, is that clear to you. So, please take it that these values which I choose yes.

Student: (Refer Time: 24:09) sir time response.

Yes, this is omega T is time response.

Student: (Refer Time: 24:14)

Omega is radian per second. So, omega T is radians. Do you regards correct that is theta, theta is in time frame. So, having decided that in all my designs I will keep phase margins between 55 or 50 to 70 and not go beyond is that correct or no not go below these two value. So, bound I have already fixed this is my range up to which. So, any design now I will do in amplifiers or op amps or anyone this factor will tell me whether I am or I am not is that clear. So, the first thing I will what is the design thing will be in design analysis, what we did we actually a given function and plotted and figured out what is phi M. In real life what will be this there is say this is the gain, this is this then I will have to make my choice, this phi M I am choose. And then I solve if I meet all my specs, I am still stable, thank you very much, otherwise change my phi M, do it again till I satisfy everyone that is what design is otherwise, is that clear. In phase margins are never specified that is your design spec that is what you will control.

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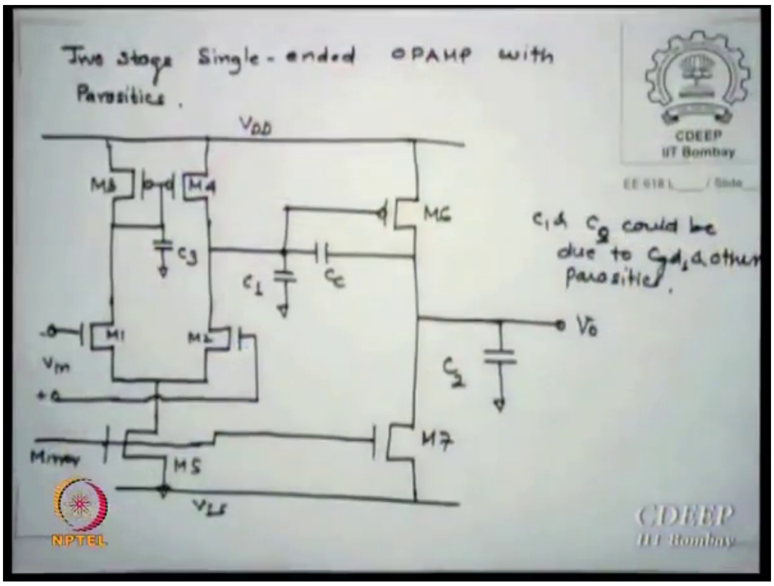

So, before going to that, today we are going to hopefully solve the OPAMP issue, but before OPAMP actual numbers we come let us see the analysis part as well. This is a typical twister single ended OPAMP with parasitic available. I think this C 1 C 2 everything last time I have already explained which values of capacitance as to C 1 and C 2; only thing now I added is C 3. And we will see whether that has some influence if not being just forget about it, but will figure it out. We will not like to say C 3 has no influence. When it will not have an influence, when the time constant associated with this becomes extremely small R c time constant is very, very small then what will say that the frequency at it will come it will a far away from GBW is a damn care. But if the does then we will have to actually figure out that this pole as well 99.99 this values because of the W by L s parasitic available to you always shape enough to thing that C 3 does not effect, but will solve that also.

So, this is M please remember this is the diff amp you have been input here and the current in M 5 which is your I SS current for this is decided from the mirror side, we will actually show final circuit for OPAMP there will put the bias circuit here itself. So, what M 5 decides, the mirror current coming from the mirror, because there will be a whatever I parallel it will come here and that is which value, I will choose here, I will choose the I SS or what we call I 5 current is the major current making all decisions for us. Why it is making most decisions because you will see later this will not only decide the g ms this will also decide the slew rates therefore, and also power dissipation. So, everything is going with what current I choose at M 5s.

So, another parameter for my design is I 5 or I s that decides my everything. So, I like to see what sizing M 5 I should have to create as much current I may have mirror any size, but I should have to mirror here with that much current which is my design parameters is that clear. So, the issues are now getting clear that I must look very carefully what M 5 size comes, I also should see that C 3 R or C 3 is not very important and then as no head. Now, I say this is a diff amp the output of diff amp which is single ended, because this is diet connected loads is fed to the p channel driver which is M 6. And right now you may forget C c or you may write now maybe you can put dotted lines on that if you wish. This is been which is what is the purpose of C c it is the feedback capacitor which we are putting between output and the input, is that correct.

Now, this is the input, this is the output. So, we are actually giving a feedback for that gain stage. This C 1 we already said is the bunch of all capacitances such which last time I had write, same way I has set C 2 also have all the capacitor plus any external capacitor this. There is the issue. We will see that if this C 2 is that function of external load you have a problem. What is the problem; that means, something else I have connect or I will have to redesign and check nothing can we design as of now we will think yeah C 2 is known and does not query how do we get rid of this will see whether there is a possibility is that point clear. My worries are chip is once designed there is no something add on there that is it.

So, you do not know ok, then we have to design over design for something and over design means over sizing, over power dissipations which means you have paid lot of penalty for doing nothing, which may never actually come into picture, but it comes then you should be ready. So, you actually thought and put it. So, if you know it, it is independent, it does not influence so much then you say [FL]. So, let us see how we do that that is also another problem which OPAMP designers have to look for this C 2 influence, they looks very strong should be actually not as strong. How much I can do is our gain because I remember C 2 will contain capacitance external to which keep itself, which it will drive next.

So, this is typically another thing you should other day some on ask. So, I am clarify for those for others, 99 probably new and therefore, did not ask or did not know and did not want to ask either. Someone was saying is this current and this current is same it will not be it need not be the current is decided by M 6 is that correct because gm of this is going to decide the gains outputs. So, what current this is going to pass has to pass through this. So, if whatever current is passing here, if they are same, jolly, well good you put one to one ratio otherwise adjust ratio of here to here to get this current. M 7 is not deciding the current here M 6 is deciding the current, M 7 gets it and then it figures out if I get connection in mirror what sizes I should keep, so that this current translates into this current.

So, please remember though biasing looks we from this side current source side, it is not decided from this it is decided from the gm of this M 6 is that point clear, gm of M 6 is going to decide the gains bandwidth. So, whatever you should what wish to pass here will pass here, and that must be adjusted by W by L to suit mirror requirements is that clear. So, never think [FL], which will be decided by M 6, is that clear issue. So, this last time after the class some two gentleman came and they were asking. So, I thought maybe clear today that M 7 is not mirrored biasing though it, it is mirrored it is decided by M 6 current requirements, is that clear to you.

So, it may happen in some cases they may be equal, but in some cases they may not be equal for g ms you are requiring different here. So, what can you do, is that clear. So, please remember these are design issues, we should keep in mind because the designers should be the best analysis people because they know, what hurts when that is why designers show also be able to solve problem correctly because otherwise they do not know which is hurting us most.

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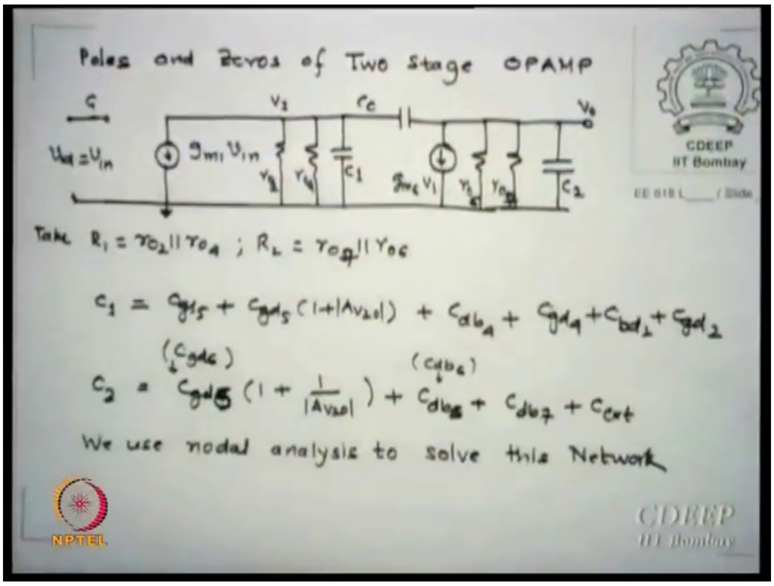

We have done this. Again, I repeat for you this the equivalent circuit of two stage opamp. This is my g m 1 V n this is r o 2 parallel r o 3, C 1, C c g m will also C 2 cases C c removed and C c put. g m 6 v 1 r o 6 r o 7 C 2. This is the ac equivalent circuit of two stage amplifier and I think this last time if I am not written please write down these are the C 1, C 2 values which means in real life once you decide the W by Ls you will have to verify whether this is reaching C 1 and C 2 values. So, there is an issue. So, this gain function is going to decide C 1, C 2 values. So, there is a feed loop kind here is well adjust your C 1, C 2s.

Please note down because these are but of course, these are given in books. So, it is not that I have invented or something. Just see the transistor and at that node which you are looking which parasitic capacitance for each transistor comes there. Please remember one more thing circuit wise you must know unless the second terminal of the capacitor is ac grounded that node does not receive any contribution from that capacitor. Is that point clear? At this node a capacitor is sitting here and if this is not grounded this does not play any role ac or dc, dc means ac, for ac its ground is that correct. So, unless there is other end is going to be grounded, at that node they do not add to. So, only those capacitance like if they substrate is not grounded let us say floating then the c ds, this will not be there because substrate is not actually grounded. So, those capacitance does not exist is that clear?

So, please verify that all those nodes at all the capacitor that node the other end of then should be ac grounded even if it is dc means ac grounded down. And this is a compulsory requirement to add any node, any capacitances. Everyone as written done C 1, C 2 , but what are C 1 C 2 I thought maybe I will explain normally books do not give C 1, C 2 you I only thought that you should know what C 1, C 2 actually are coming into our picture. Of course, some books maybe giving I say [FL], this is C g d 6 [FL], this is 6, 7. What V 1 is across C 1 that is the input to the gain stage that is the input. These are ac [FL], it may look capital, non capital all are ac's, may have confusion I have once told you now onwards unless said otherwise there is no dc we are only solving equivalent circuit all our ac components is that ok, [FL].

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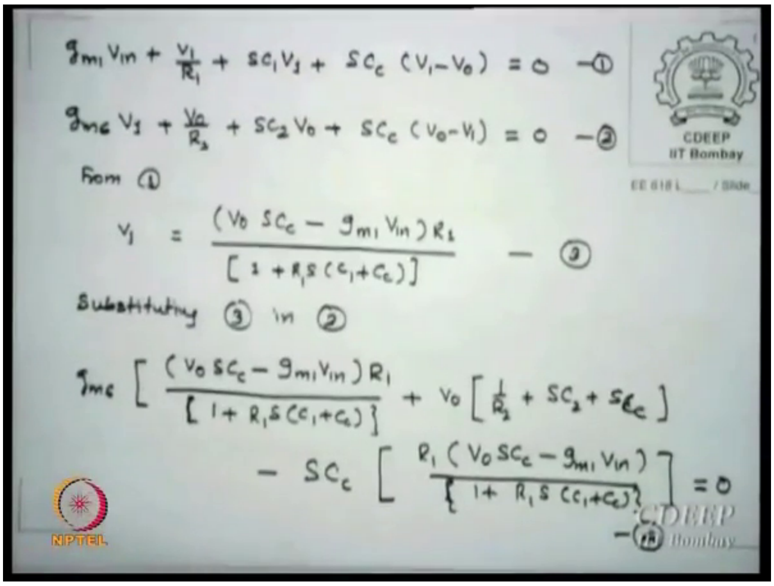

Using the Kirchhoff's law nodal analysis, g V plus I plus I plus g whatever it is, I wrote the equations for the two nodes at V out and V 1 you have only two nodes V out and V 1. So, I wrote this equation. From the equation one I evaluated the value of V 1, because I am interested in V n and V 0 relationship is that correct. So, I replace V 1 from this relation from here then V 1 is essentially equal to V 0 S C c g m 1 V n bracket R 1 upon 1 plus R 1 S C 1 plus C c. You get the one these are just corrected the terms and figure out what is V 1, V 1 occurs here, V 1 occurs here, V 1 occurs here this does not have and this does not have. So, only V 0 S C c minus g 1 V 1 this R 1 is multiplied everywhere and then you get this expression.

If I substitute this into second equation, why, I want a live in at V one I only get relationship between V 0 in V 0 and V n. So, remove V 1 we just someone askness of where is V 1 is the output stage for stage gain I am first stage output that we figure out. Now, substitute into second and then strike this same g m 6 into V 1 plus V 0 by 1 upon R 2 plus S C 2 plus S C c minus S C c. Again V 1 is appearing here, so minus S C c R 0 V 0 S C c minus gm and V one upon these this. Now, again there is an issue because there are V 0 terms here, there are V 0 terms here. So, collect V 0 terms and then on the right get being terms divide V 0 by V n to get your gain, is that clear? [FL] V 0 zero term may V 0 term [FL]. If I do that is it ok, I want to write, why are you doing all this? I want to design an opamp, so I am trying to correlate the gain function, the slew rate function, power everything with what (Refer Time: 38:50) I have.

So, I am trying to get the relations. And what is the measure relation I will get from this, the poles and the zeros, because they are going to decide some they my g m s because pole is essentially a g m by c. Now that may g m is now decided not just by a factor, but also decided by the poles available to you and that is why we are interested to get those expressions is that correct, is that ok?

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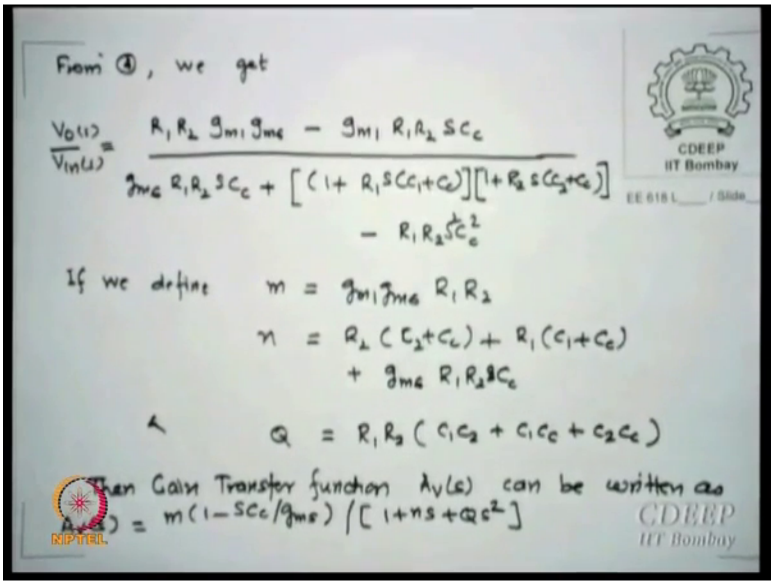

So, we get the transfer function of gain V 0 by V n of course, to be precise you should write it is A v s. So, it is the transfer function and as most books this has taken just to convert it to what books give. So, I figure I made same constant as they have given in the expression, so that it looks identical to second order system which many books actually tell. So, we wrote m is equal to g m 1 g m 6 r 1 r 2 n is equal to r 2 C 2 plus C c r 1 C 1 plus g M 6 this. Now, there is no s here Q is R 1 R 2 C 1 C 2 C 1 cc C 2 C c [FL]. So, I have taken g m 1 g m 6 R 1 R 2 outside, so I get 1 minus g m 1 this 8 g m 6 sorry this. So, then we have 1 minus S C c by g m 6. So, how the transfer function looks now, it is very familiar transfer function something on the top is trying to give you zero and something on the denominator since is a second order term I am going to get two poles. Please remember each capacitor contributes a poles, so there are two capacitance C 1 C 2 use, so there should be two poles second order system.

So, A v s is m times in the bracket 1 minus S C c by g m 6 totally divided by 1 plus n s plus Q s square here g m g R 1 R 2 [FL] is that ok. This transfer function is very familiar. So, I thought I should represent a second order stand. If you see this Q is essentially the term which you will get there the only difference is Q is used with n and 1 upon 2 Q, they write which is the 2 zeta or zeta is the damping factor. So, I did not want to correlate there, but I just made some second order system. Please remember whatever goes with S is one upon 2 Q and that is the zeta. Zeta is damping it you see ringing is essentially for the zeta factor that phi M can be therefore, represented in terms of zeta that is exactly what we are saying. So, that choice of phi M is related to your zeta's is that ok, everyone has the firmly we are still not done design we are still working on analysis, but some issues which we will want to clear.

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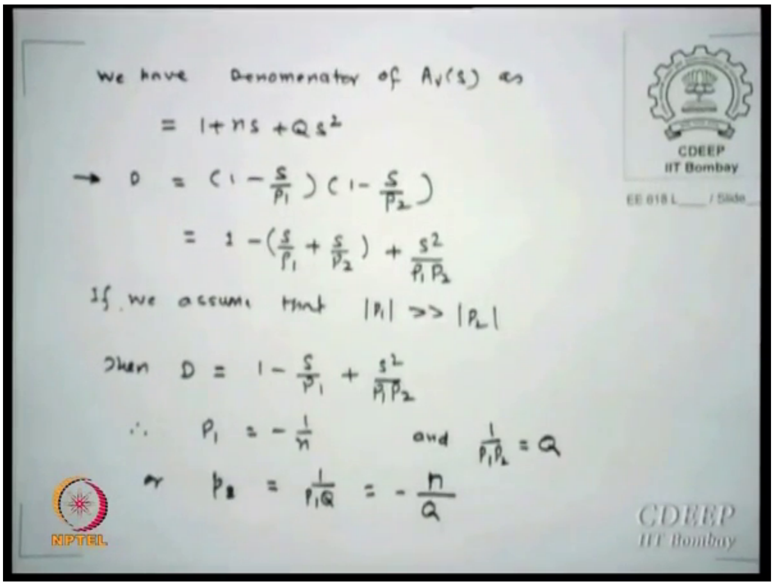

So, if you see the denominator A v s, it is 1 plus n s Q s square which can be written as one minus s by P 1 into 1 minus s bar P 2 partial fractions. I expand it 1 minus s by P 1 s by P 2 plus it is a technique [FL] every controls books [FL], but I just thought I will do it for my own sake my [FL]. So, if I expand this, I get the only thing I made only [FL] analog people know this. I said in general the first pole which is my dominant pole is much higher how much away from if I take such decisions then it is easier because the second term then I can do it. So, I said it is 2 minus by P 1 is a square P 1 P 2 then P 1 is because this is n, so it is minus 2 upon n. So, and then that is 2 upon P 1 P 2 is Q. So, P 2 is minus n by Q or 1 upon P 1 Q.

So, now, I have both poles available to me P 1 and P 2. Since, I know n and Q, I can now substitute n and Q in terms of P 1 for P 1 and P 2; n and Q in what terms R 1 R 2 g m c all. So, now, my actual circuit components will actually appear and in not have done this I could not, if you are smart enough you know which term at from where you can see those terms from zero time as constant value can actually know which terms are coming alternatively solve Kirchhoff's law and get the same relations.

What are the problem why I said I do not want to do the 0 value time constant value this because I will miss the zero. In the zero time constant situation, you always miss the zero; in other case you know have the very dominant influence, therefore, I did not show you the other technique, but pole still can be figured out by using zero time constant value both dominant by open circuit and short time short circuit you can evaluate it.

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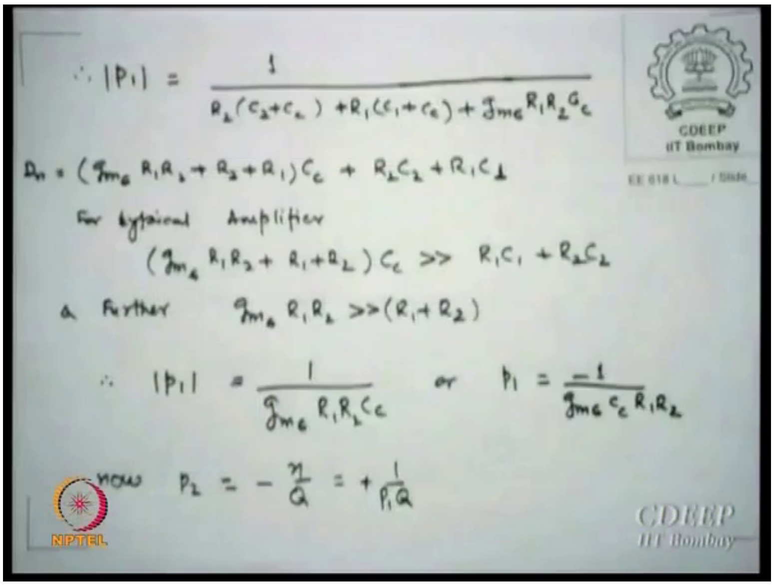

So, using this I have the pole one upon R 2 C 2 c plus R 1 C 1 C c plus g m 6 R 1 R 2 which is my denominator now for this P 1. For typical amplifiers g m 6 is quite large. So, therefore, g m 6 R 1 R 2 is larger than R 1 plus R 2, so it is only this, and this is always larger than R 1 C 1 into R 2 C 2. So, one may say g m R 1 R 2 is greater than R 1 plus R 2, or to say P 1 can be that just written as g m 6 R 1 R 2 C 3. You can verify this is what the value will get from zero time constant method, so that you can you have directly figured out, but this is what it is.

And therefore, the please remember pole has to be negative is that magnitude wise. Now, magnitude we say positive, but actually it is the negative value, which you are getting. We what does that negative value means on sigma g omega x is pole lie on the left half plane that is one the criteria will loop request criteria says as long as your minus 1 0 you circle and there pole is then, you are stable otherwise not stable, so that is exactly what we are achieving. By now figure it out P 2, I also should say cc is normally larger than C 1 and C 2, C 2 is larger than everything, but this is larger. So, we say the dominant pole will come from g m 6 R 1 R 2 C c, so this is the dominant pole. The second pole which is minus n by Q or plus 1 by P 1 Q the first pole.

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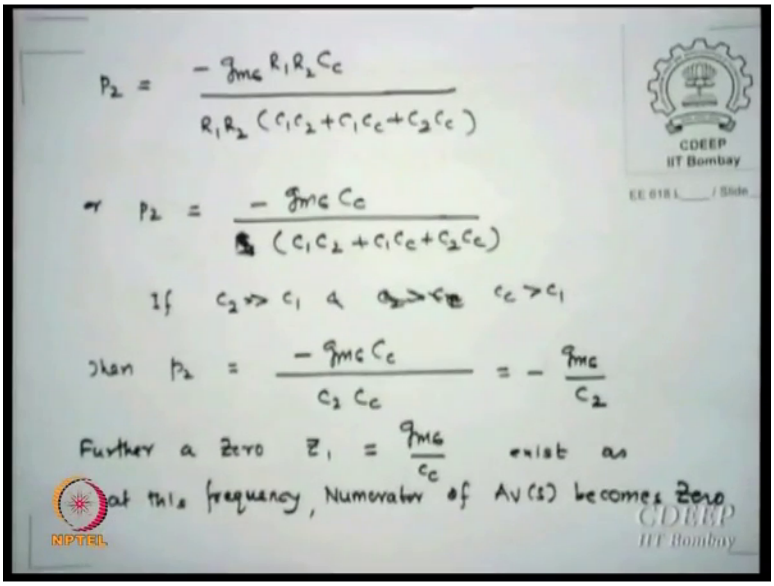

And therefore, substituting that I get the second pole. We assume that C 2 is larger than C 1 and C c is also larger than C 1, then P 2 pole can be roughly written as g m 6 C 2 C c or g m 6 by C 2 which also you will get from zero time constant technique. [FL] you need two poles from the second order function, so you got two poles. Could you now see this is an issue that output capacitance because P 2 is decided by g m 6 and C 2. If load is higher this pole shifts left sided here

Student: (Refer Time: 47:01)

Yes [FL] ok. And we also have said that the zero exist which is the zero part of the numerator which is g m 6 everywhere the gains, please remember where the feedback is going on at that gain stage a poles are hit by the gain stage. And the first one which you are saying should come from C 3, but that I show you that I am not looking into them.

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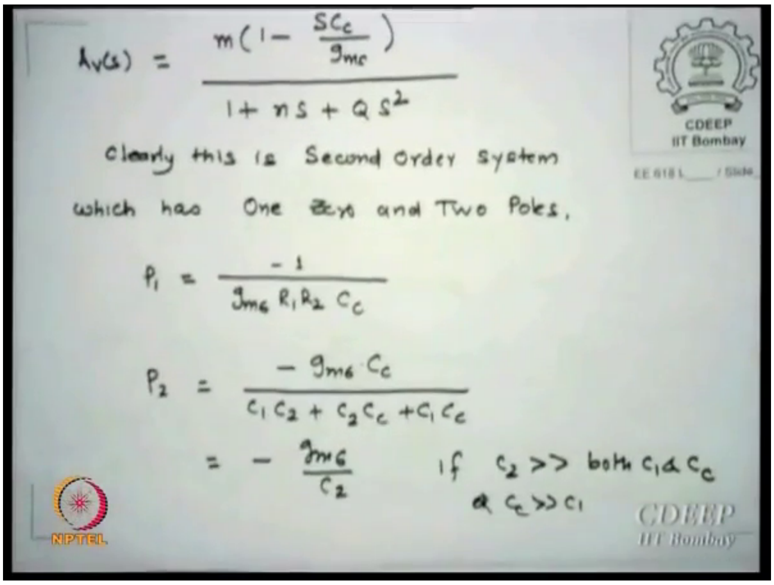

So, rewriting whatever I wrote here in nutshell is the following. Well if I will say final version may theorem. If you are not written, you can write down here the gain function is M 1 minus S C c by g m 6 1 plus n in have n n Q I already n Q I already defined. The first pole is minus 1 upon g m 6 R 1 R 2; the second pole is g m 6 cc upon this; and since C 2 is greater than C 1 and cc is also greater than C 1, this is g m 6 by C 2.

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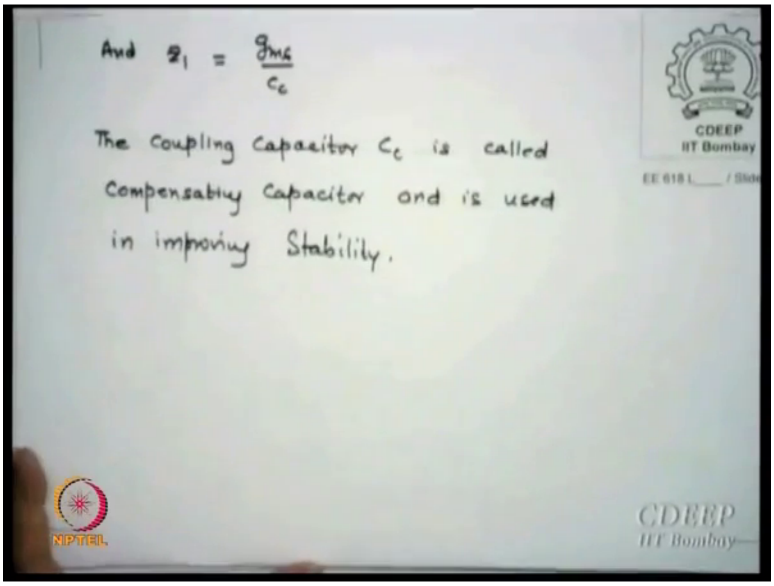

And finally, this way already derived, I am just trying to summarize it, and there is a zero which is g m 6 by cc is that correct. So, you have two poles and a zero. Yes, you want last sheet now they are just restatement in nutshell. So, how do you calculate phase margin for such this, I figure out phi M is equal to 180 minus phase up each of these P 1

P 2 and z, but what will be the phase of z plus 45 degree that is minus 45 degree. So, what we do is tan inverse minus is tan minus of tan inverse squared one [FL] w by z, if z by w [FL].

So, let us see now is that everyone has written now. I repeat this, this third last one is z 1 is g m 6 by C c, P 2 is g m 6 by C 2. This is the relation I am going to use please check it. The zero is at g m 6 by C c and pole second pole is that g m please remember five is decided not by P 1 so much, but that P 2 position where is it. So, this is C 2 and this is C c, and they are going to decide how much stable I will be is that is that, final [FL].

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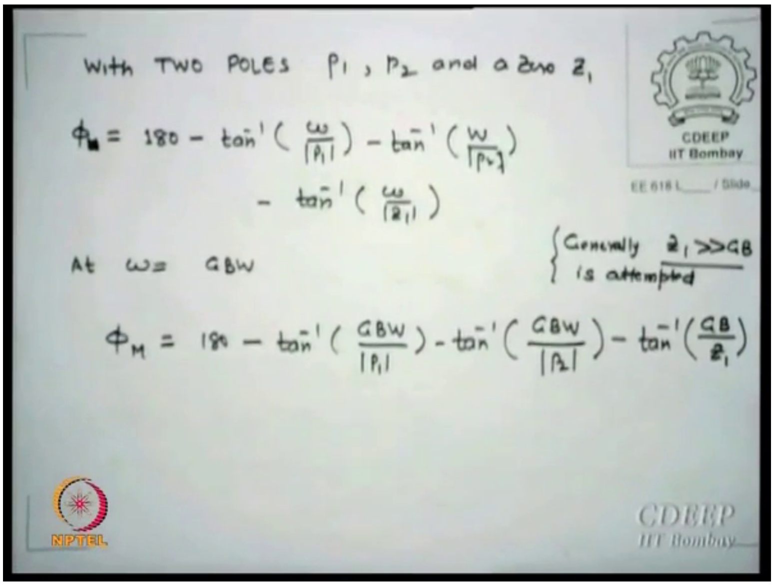

So, if I two poles and a zero last time I said the phase margin I wrote there is tan inverse omega by P 1 of course, it should not be call omega normal phase. Phase margin should be written at omega at what point where you neither it should not be m it should be only phi, but phase margin is chosen where and the frequencies are GBW is that correct. So, we write. So, this need not be called M. Phi M generally because of the g m and C c values z 1 will be far away from GB. So, by the time if the second pole has already gone to minus 80 db or minus 100 db, so another 20 db plus will make it minus 80 db, but it already you are well within your margin side.

So, you are not worried because the gain has fallen down sufficiently below and then zero, please remember zero will push the gain plus 20 db per decade, but if it is already minus 100, so 80 dbs also fair enough, so that is something you have to understand that this zero should be away from this. We will check this for different value of z, how much phase margin we can evaluate; this is one problem, we will solve. So, please remember this I changed tan inverse GB by z 1 because I said its all are minus because otherwise should have been plus z by w. So, I inverted it. So, I had to now calculate what do I calculate from here.

Student: (Refer Time: 51:32)

No, no I will assume phase margin. I will check it what is this, I will assume this and then what I will get,

Student: P 2

P 2. So, I am only interested in P 2. I will say this always known this I will make it known, then I will say all that I need a relationship between gain bandwidth and P 2 because that is the one, which is deciding major this for me stable or non-stable is that clear. So, the tricks of the trade is fix this somewhere better this will come nice really you know how if you know this for this given value, I get a relationship between P 2 and GBW, that is what essentially.

Now, P 2 has g m 6 by C 2 is that correct, gain bandwidth gain is known to you, P 1 is known to you so the bandwidth is known to you. So, you know GBW. So, from this I can, no, it is I can get C 2 or relationship between C 2 and others and therefore, I can say w by g m 6 [FL] that is all that design is about is that yes. I told in a madam it should be read by W tan inverse minus of minus of tan inverse is same so [FL]. Now, before we quit this area, before we start OPAMP design there is an issue this was all done with C c available, I should have done the other reason at without C c [FL].

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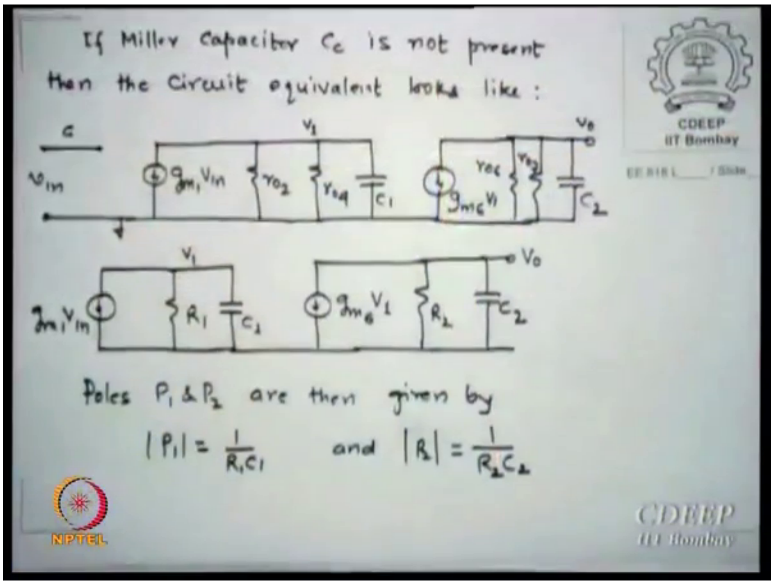

So, let us do without C c. If I remove C c I can see my input poles and output. So, without any calculate zero time constant technique I know the first pole is 1 upon R 1 C 1, the second pole is 1 upon R 2 C 2 is that correct. Since C 2 is larger than C 1 what will happen R 2, R 1 may be same is that correct, C 2 is larger than C 1, we do not know right now, why because that feedback was adding to C 1 now. This may be something different than that C 2, is that correct 1 1 plus av zero [FL], we will have to check really by the values. Now if I have this new poles which cc removed is that clear low feedback that is open loop system AOL, same equivalent circuit the C c here has been taken away [FL]. What is C c is also called

Student: (Refer Time: 54:25)

Miller capacitor, no, composition is doing, but it is essentially miller capacitance. So, the compensation is also called miller compensations, because say I because say miller capacitance which is doing the job is called miller compensations.

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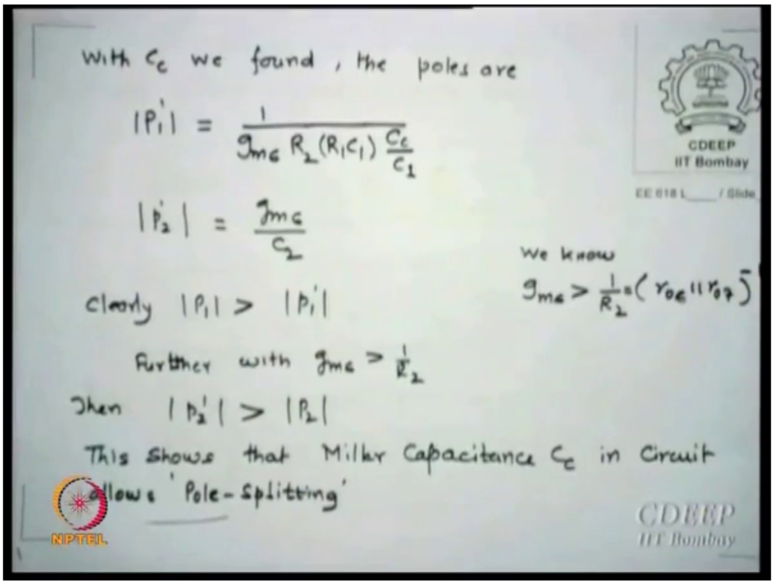

So, if we have a C c, the two poles are P 1 dash is g m 6 R 2, and just to make equivalence correct I put R 1 C 1 upon C 2 C c by C 1; and P 2 dash is g m 6 by C 2 . So, you can see from here, in the earlier case it is P 1 is 1 upon R 1 C 1 is that correct without C c; g m 6 R 2 is gain, so obviously, and this C c is larger than C 1. So, obviously, these quantities P 1 dash is reducing. So, P 1 is larger than P 1 dash is that correct. However, if you look at P 2, P 2 dash which is 1 upon R 2 C 2, but we know R 2 is R o 1 R o 6 parallel R o 7. g m 6 is always larger than 1 upon R o, because they are in mega ohms this is in 10s of kilo ohms 1 upon g m.

So, what does that mean. So, I can always say P 2 dash magnitude wise is much larger than P 2 is that correct. So, what has happened P 1 has reduced P 1 dash by C c, but P 2 dash has magnitude wise enhanced, is that point clear to you? P 1 let us say it was somewhere here it moved to ok, I will show the figure and then it will be much more easier to figure just this, this word which you often used in miller compensations or miller capacitances says split the poles is called splitting poles.

Student: (Refer Time: 56:33)

Yeah, but that is what I said you also C 2 is normally higher simply because the load is sitting there. If unloaded case may [FL], but normal [FL] that is the reason, but I do not want that so strong dependence which is I will remove that I do not want I should know a priori what is the load. So, I will try to see what you are asking [FL] let us see how do I do it is that ok.

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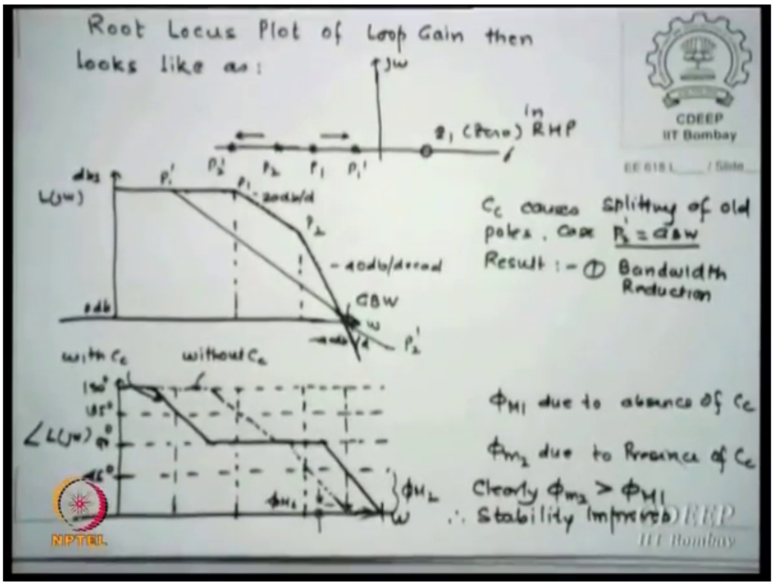

So, if I show you on the figures very now this gives you everything in nutshell. If I see now loop gain sigma j omega on the scale complex scale or complex graph, my 0 is positive so sitting here. My dominant pole was P 1 R 1 C 1 which was here, and my next pole is on to C 2 which is here. Now, these are like this as before C c applied. When I applied cc I figured out P 1 reduced or rather p is the other side. So, P 1 dash reached here, but P 2 actually enhanced the other side. So, P 2 dash reached here P 1 dash came closer to 0.

So, even a P 1 P 2 are closer by putting them miller capacitor I separated them. So, one of the case we are all the time saying that there should be a dominant pole is guaranteed if I put a C c capacitance. In natural system C c exist why from there cgd is exist. So, partially [FL] because cgd is always sitting there, but that values is very small this C c may not be that small actually you may actually decide to put extra capacitance to suit your split requirements is that correct. So, do not believe that cgd is sufficient, in some cases maybe I am not saying it will never be, but generally it is not. If you use that cgd your phase margin will be closed to 45, and then you will have a problem. So, you want phase margin to be at least 55 or something and that is my worry.

So, let us look at the loop gain bode plots. This is my original pole P 1. This is my second pole. If I put the plots for phase, you can see at the first P 1, how much should be the phase 45 degree down. So, this is 180. So, I must reach 135 at P 1 is that correct, and second pole is away. So, it goes down and reach till 90 it remains till second pole it sees; and when it is see second pole at that time it should become another 45 degree which is 135 that is 45 here. Now, this 45 is that the second pole is that correct. And if I attend a down, you reach at this value at GBW you have a very marginal phase margin, still I would not say it is unstable, but very close to instability is that ok.

So, if I do not put miller I may have a situation of course, this still depends on C 1 C 2 values, but typically if you see it may have worst case may be that you may actually get zero phase margins kind of thing or close to that which is unsafe to a great extend is that clear? Now, I say since C c causes poles splitting. So, P 1 dash the [FL]. So, we first pole now we C c is reached here. The P 2, which is away now we can have a choice. We can initially at least say that this P 2 dash should be at the gain bandwidth, where at the gain bandwidth point. Why did I say so because at least at that point then 135 degrees what I am expecting so 45 degree at least I am getting them is that clear.

I repeat this P 2 at least should or a not before, it should cross GBW point at best at least, because at this point then if I plot the this, I at least have 45 degree phase margin, is that correct, because at that second pole I should get 45 degree. So, the minimum margin I now reached is 45. So, they every [FL]. So, what should I do here, this should continue to have minus 20 db further and then the second pole should start in which case this 135 point will be somewhere here. So, the margin will be larger than 45 and then you say sir we are safe. So, this pole how much to split is also now problem starts somewhere else. If you keep splitting too much this P 1 may actually is going to the right of them. So, you cannot put C c as much you like and you suddenly finite instability created because the P 1 itself, is that clear. So, [FL] we thought all this [FL] these does not exist, zero does not exist [FL], if we can play with z, then I have another parameter for phi m.

Now, this part is what we say controlling right half plane poles control right half plane zeroes in a such a way that this C c requirement is slightly reduced is that ok, otherwise what is the this you increase C c feedback increases, this will further go down ahead because you want this second pole should cross GBW. So, you will prefer what larger C c, but then this P 1 should not hit the imaginary axis. If hits imaginary it is still ok, very low bandwidths, but at least stable, but if we crosses than you have a problem, you have a zero equivalent zero on that.

Now, this is an issue, which makes something else you must think is that clear. So, it is not just see it must be something else there which may change the poles. So, I may add another equivalent pole are zero whatever I will call, so that C c is not increased very much because then I can I do not have to play too much with this, but still my cutting point is much away from it, so that I say I am safe now. So, this is what we will do the method I already explained; at the pole from the top value the slope 45 per db means 45 degree it should hit, it should continue till 90 because j vectors says 90 degree.

But if the poles come before that and even there itself another 45 should start because that much slope should change 90 db then and start decreasing right there, but normally they assume they are away. So, we are allowing this to settle at 90. And then the second poles appear at this point another 45 must show so that is how the graph. Without this we see that phase margin is close to zero or plus, but with C c you have shifted because of the splits we have shifted the P 2 points such that we are larger phase margins are possible infinite [FL]. So, infinity [FL] is that every one draw the figure [FL], because otherwise just drawing that becomes difficult.

So, you always draw lines so that you know way out draw things, but you are really calculating value from this do not because then you actually take a graph and then put on. Because this is not of course, these are called log scales, these are linear scales. So, log [FL]. So, phase margin improvement [FL], is that this issue is clear. Last slide and then we will stop, we will stop with this, is that clear to you has any one has a doubt now that. Why C c, C c is one, which is controlling, now next slide everyone?

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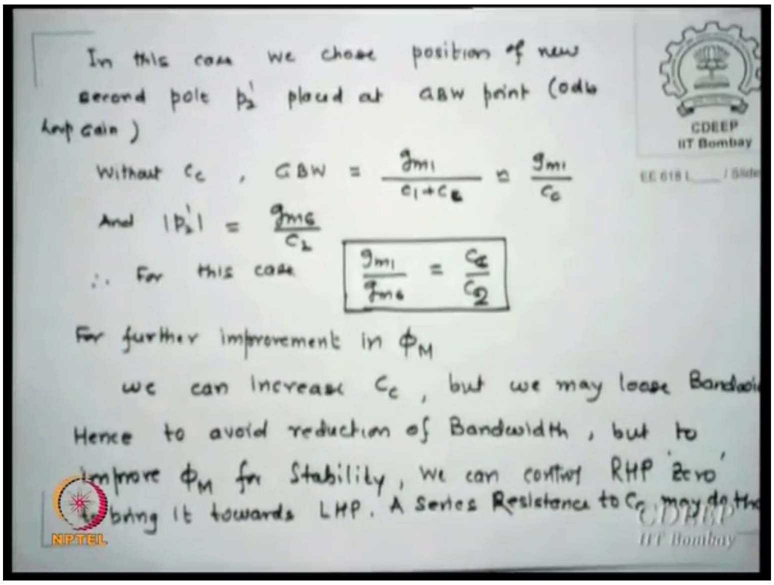

So, in nutshell what do we say the bandwidth gain bandwidth point g m 1 C 1 plus C g 1 plus C c and P 2 C n 6 from minimum phase margin 45 degree forces g m by g m C c C c by C 2 is that correct. This is equal that is at the point where phase margin is 45. So, at least you should not go beyond this; preferably what you should do g m 6 by C 2 should be greater than g m 1 by C c is that correct. And if that happens you have larger phase margin to play with is that correct.

Right now what is the minimum the corner case is g m 1 by C c must be equal to g m 6 by please remember the gain bandwidth is something to do with a diff amps drivers g m 1 or g m 2, they are equals. So, g m 1 by C c is the gain bandwidth to be actually it is C 1 plus C c, C c is larger than C 1, so gm by cc. So, the ratio of C c to C 2 is ratio of g m 1 to this is that clear to you. So, we must be now from the all that phi M value you choose, you probably get some ratio which will be able to get ratio of gms and gms have proportion to currents. So, you will get the ratio of currents that an current of proportion sizes, so get the ratio of sizes.

We can increase C c, but we lose bandwidth hence to avoid reduction in bandwidth, but improve phi M for stability we can control right half plane zero, which we are at right now thought [FL]. To bring it towards left half plane, if I somehow shift that to left half plane that can help a lot to nullify pole. And that if happens then we say C c requirement will minimum just sufficient for you and you have to do this we will see later, C c need not be alone it should be R series to C c. This will care another time constant R cc that will give you the zero shifts out. And if zero shift right half plane left half plane your much of the worries could be that is you sit that pole on something. So, null [FL] that is called nulling.

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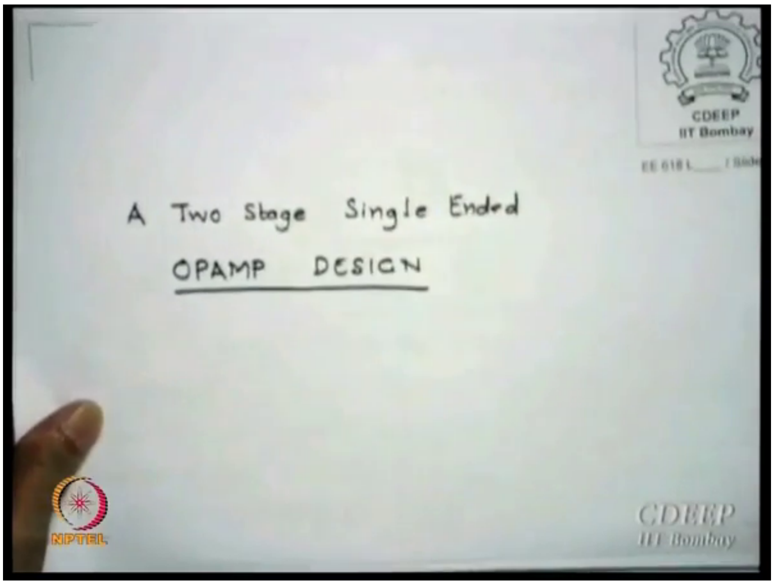

So, this is the thing which will do today evening it last line [FL]. So, [FL] is that ok? Theory has been discuss importance of every issue has been thought at least if not discus fully, and now actual values will see what do we gain that will give you some idea how one gets sizes.