CMOS Analog VLSI Design
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Lecture – 23
Fully Differential Amplifier & Noise

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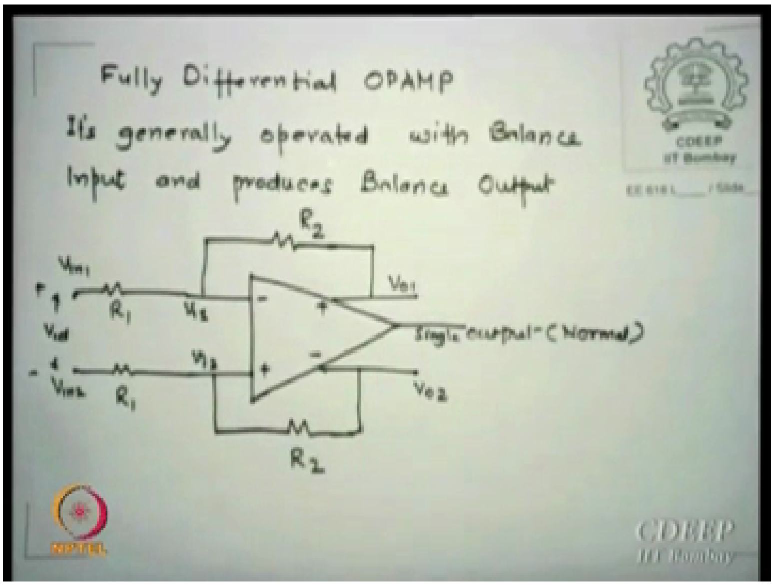

We are looking for fully deferential opamps or fully deferential systems. The typical differential opamp can be connected in this fashion. You can see from here these are two inputs of a differential opamp and you are receiving V in 1 and V in 2, and they are two outputs V o 1 and V o 2, which are feedback in a negative fashion negative feedback from both sides. And if I have only single ended, the output could have been in the center which is what we already done earlier. In this case, we have two outputs and we are feeding it back, please remember both are negative feedbacks. Right now for the sake of this stability in everything and performance I chose R 1, R 1, R 2, R 2, but they are different also can be solved a case in which there are some issues will come later.

Now, if why differential we already discuss it earlier last time one of the interesting point we said there was anything noise sitting on these can be canceled. Because if you take the difference of V o 1, V o 2, the noise which is super reading either be inputs can also get cancelled and subtractions this is what we said.

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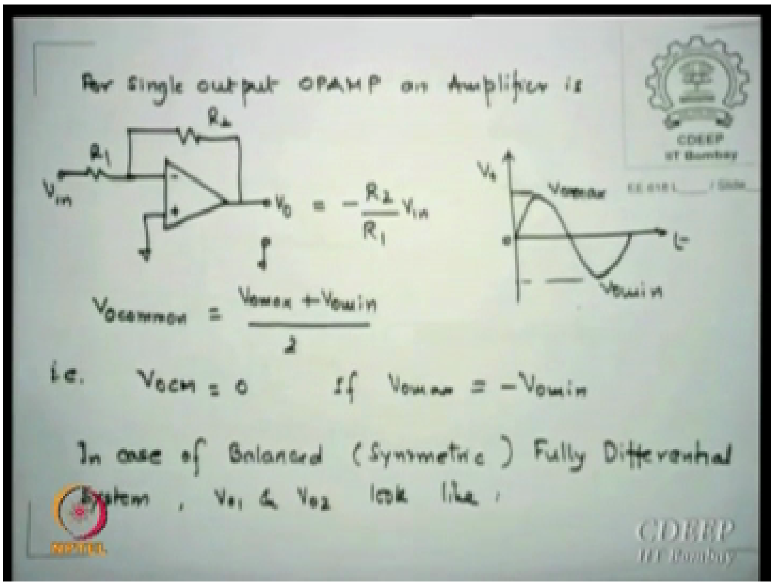

But that few more interesting thing which is of relevance and I think that should go first before we start noise. Where single output opamp a typical amplifier shown here which is a in inverting mode amplifier, and the output looks something like sinusoid let say if input is sinusoid. And you receive V o max V o min if there is no distortion and V o max will be equal to V o min. And we define a output common value V o common or V o vcn as the common mode voltage at the output which is sum of V o max plus V o min by 2.

The maximum you can reach is V dd a lows you can get V ss and therefore, some could be zero or if V SS is zero it could be anything else. So, V cm is something which you can decide how much you want by deciding up to which these two will actually go. If they are equal as the shown here then their V cm is V oc is or may be V ocm I should say or V cm we shall say later f 0. Please locate the system, which I shown you earlier just a minute before this is symmetric, symmetric to this, this is symmetric structure is called balance structure. In case of balance fully differential system, we can also figure out what will be V o 1 and V o 2 independently. And if I subtract what can happen at the net output which I am going to get. So, I repeat you see the single stage opamp or sorry single ended opamp, now I am using with similar structure which I shown earlier.

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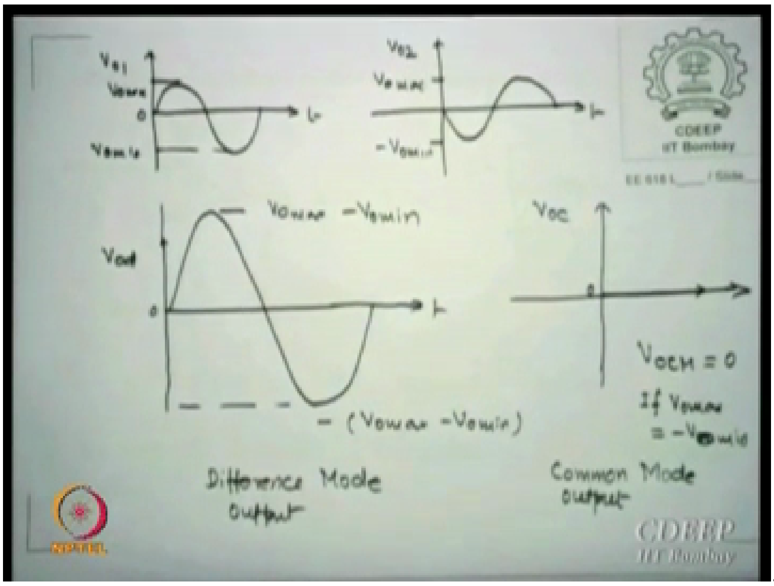

We have a differential mode opamp fully differential. So, you may have for V o 1 and V o 2, because they have opposite polarity they are they may look like this. And if I subtract take a differential of them, the peak value is V o max minus V min minus V o max minus V o min and they are equal and opposite then twice of the earlier values you can attain. However, the common mode, which is still subtraction with two is still zero because we are holding them equal this and this, this and this are same. So, the common mode is still average value which is still 0.

So, please remember that by making a differential I am still able to get V cm 0 which I wish if I can set any other value, but we can get the output which is V o 1 minus V o 2 differential output is double data of the single ended one's. So, one feature of the fully differential is you can get twice the value of output swings. So, what is this called the swings. The swings in the case of differential opamps is larger compared to single ended system. Many application required larger signal outputs, but you do not want to reach saturation mean in this non-linear zones in V o, V i, this may be one possibility in which you can get larger output swings is that point clear? Otherwise, for larger output if input increases you may reach into a non-linearity zone of V o, V i characteristic, and then you get distortion will see that little later.

Now, the problem which is why this kind of amplifiers are used valid of course, swing; the other is of course, for say most of the circuit which requires higher gains differential systems are very popular. But as you know there say higher gain we will see what kind of loads I should have compared to single ended opamp which we already discussed.

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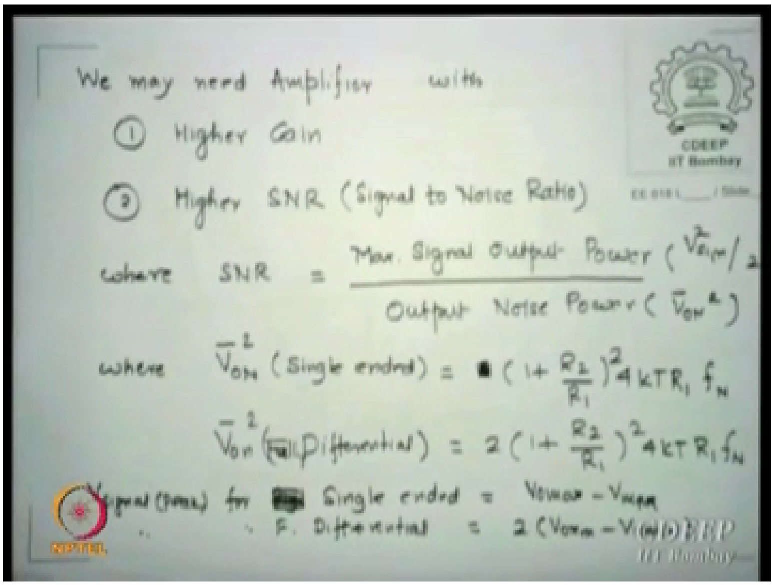

So, the issue let say we need an amplifier which as a higher gain and we also request we also desired that such an amplifier has large signal to noise ratio. For your set of those who are not done earlier this, the signal to noise ratio is maxim signal output power divided by output noise power is the ratio of this is called signal to noise ratio - SNR. If v square signal is the peak value of this is a peak value of this square by 2 is the maximum signal and output noise power is gone V ON bar square or V ON square bar average value.

Please remember if I use I will solve this in the noise case this value, but these are trivial one can solve that von square for a single ended case is one plus R 2 by R 1 square 4 K T R 1 into f N and f N is called the noise bandwidths. This 4 K T R is something value will see soon in few minutes, which is essentially the thermal noise of a resistor. So, output noise voltage square express always-explicit square terms, why square anyone, essentially represents power, so V square by R is 1, we represent power by V squares. Where in the case of fully differential it happens to be twice that of this square however, you also see the swing in the case of single ended is just V o max minus V o min. Where in the case of full differential it is twice that of V o max minus V o min Swing is also larger. So, if I square this I will get 4, this is half. So, still SNR will be how much larger or smaller twice that of single ended opamps is that clear? This will give you a 4, this is half, so 4 by 2 which means at least signal to noise ratio will double when I use fully differential systems.

Then another term which we will see in the case of analog designs which is called noise figure. Noise figure is expend SNR at the output divided by SNR SNR at the input divided by SNR at the output. Some other time when we come to actual noise figure calculations these are the specification for a given amplifier. They wish specify (Refer Time: 07:55) typically what is the SNR needed. So, the kind of through which I was trying to talk to you that for higher gain, one and the second is higher SNR.

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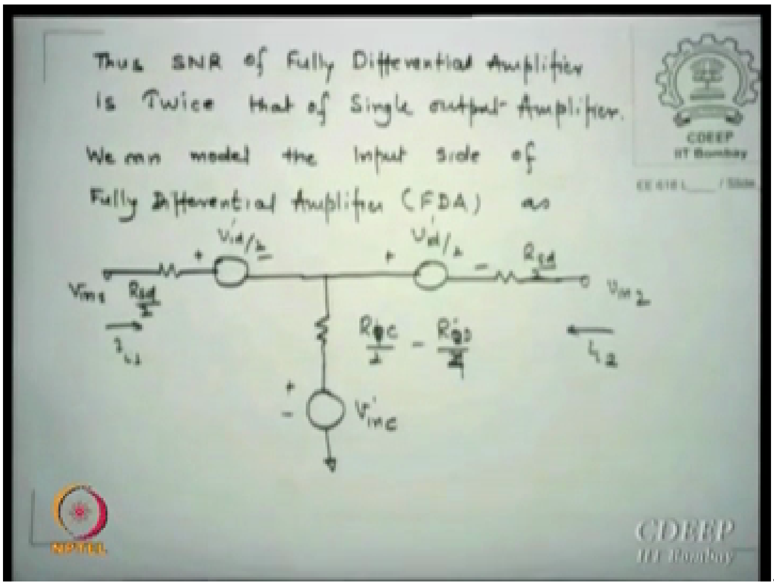

So, if you are fully differential one can say is twice that of single ended amplifiers and larger the SNR grater is the amplifier is that clear, signal to noise ratio larger means lower noise higher signal in a ratio. So, it is better to use differential amplifiers fully differential amplifiers instead of single ended opamps, if you are looking for higher SNR.

Student: Sir, if single ended there are ac current is (Refer Time: 08:38) at that point.

Where?

Student: single ended.

In single ended, the problem is slightly different; in this case, single ended since the one end of the circuit we are only putting direct connected load. So, the load at the one and only R o 3 parallel R o 4 in a single ended opamp. Whether, in this case, now I show you I can have larger R os on the both side and that why increasing the gain as well as increasing the SNRs. This the equivalent circuit of a differential amplifier both at the input and output, I will post it on the website, you can check it. It takes little time one can express inputs for the differential stage.

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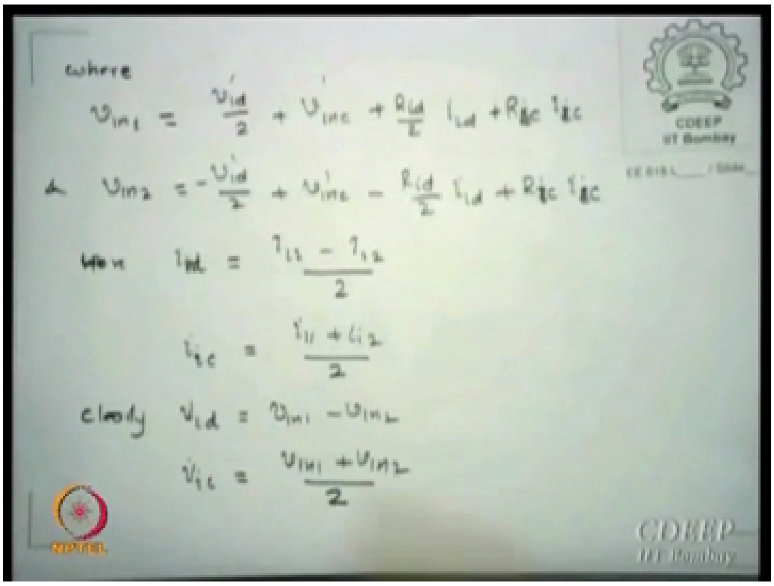

I will show please relate in case you do not I will come sometime then I can get some relationship between V id, R ic, V ics.

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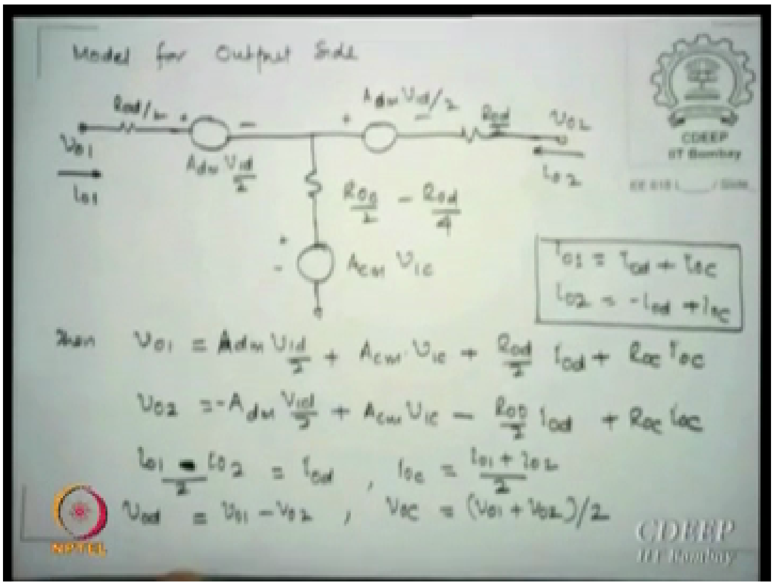

By similar argument I can put an equivalent T network or the output of a different fully differential system. And again I can get V o 1, V o 2, V o d and V o c accordingly, this is what has been done. And using this we will be able to calculate A cm and A dm for a fully differential amplifiers. Please remember I am sorry I am not able to spend time on this because they are lot many things to be done, but I am going to posted, so you can look all of it.

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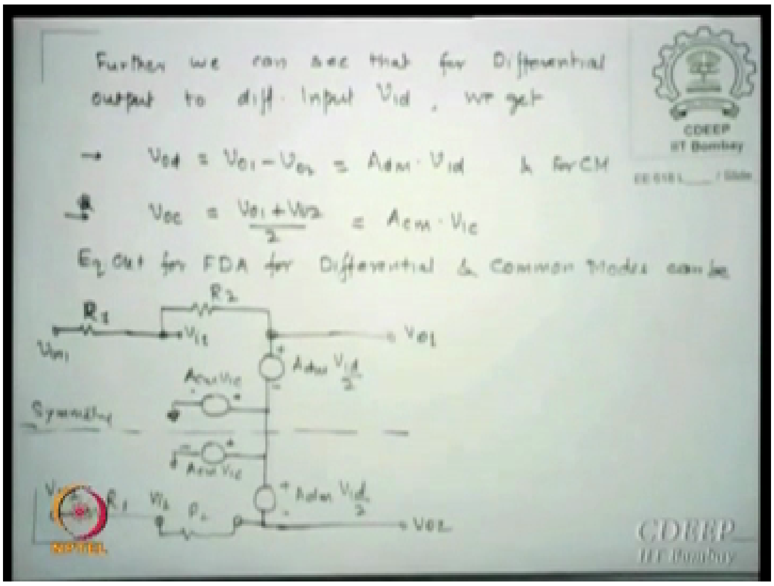

For example if I before we go ahead this is V od is V o 1 minus V o 2, which is called A dm times V id; and for common mode voc is V o 1 plus V o by 2, which is A cm times V ic. So, we can evaluate both V od and V oc and what is important for us in this particular this common mode voltage stood be fix and less. Why I am so much worried about fixing the common mode voltage, the theory about this, please read it and my website. In case there is an issue there may be some other day, I will again explain to you. This figure do not right now, because it will be available to you.

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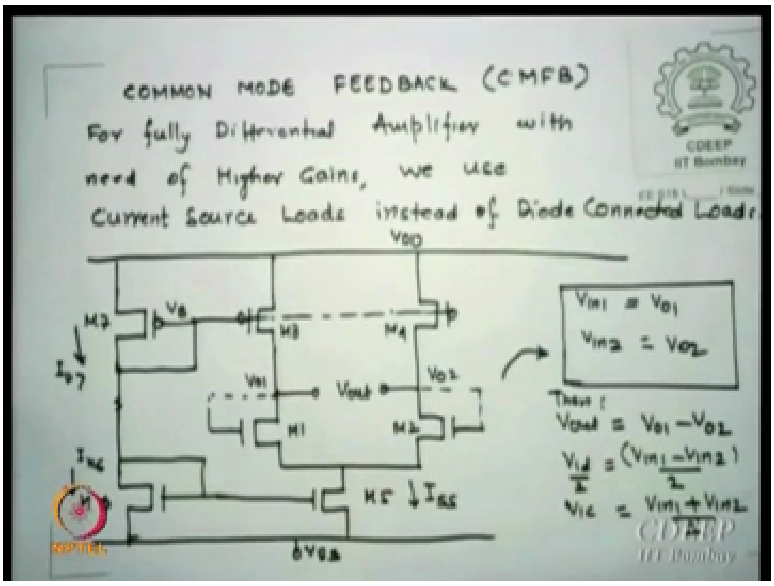

We keep saying to maintain at good common mode voltage, we are said that normally fully differential systems are use where higher gains. Now, if you see this is your standard double ended opamp one at V o 1 and other is V o 2. And to make it common mode or rather to make it simpler to first understand, I have connected output of this to the input of this. In normal case what will be here, the resistance output to input R, but right now I chose R to be even feedback can be near a feedback differential feedback. So, this is a differential feedback which I kept. This is your bias circuit. These devices receives a potential V B which decides the R os of M 3 and M 4, is that point clear, M 3 and M 4. This is a potential V b which decides the r o 3 and r o 4 of this, this is not direct connected load, this fact has to be appreciated.

This is through p channel, and the lower current I SS is governed by this n channel never shown here. Now, the problem which is worrying me right now is this. If anything goes well, what is that output resistance at this arm, r o 3 parallel r o 1, what is the output resistance of this arm r o 4 parallel r o 2. So, gm times that is the voltage which I can get gain I can get individually. My problem is now something more, my assumption is this current is I SS is governed by this device, and this potential is governed by this p channel device which is also current source. Let us say for reasons variety of reasons, sizes abilities, other reasons, these two currents are not equal. In a Kirchoff's law one forces the current should be equal, but let us say it starts with to equivalent saying I am a say to put it non-equivalency say I have put a small resistor in between which probably can then control the current and then drops here I am not drops here.

Now, this issue which look to be very odd, it is very interesting for to understand. If this current, which is essentially flowing in this current in I DS 3 or I DS 4 is not same as I SS by 2 and I SS by 2. We want them to happen, but let us say for variation purpose, it does not occur. Now, what can happen, there are two possibilities can happen. This current is larger than I SS by 2 or this current either way this or this, this current is less than I SS by 2 because of the p source current is not same as n source current is that clear to you. Now, if that happens let us say what are the problems which we can get.

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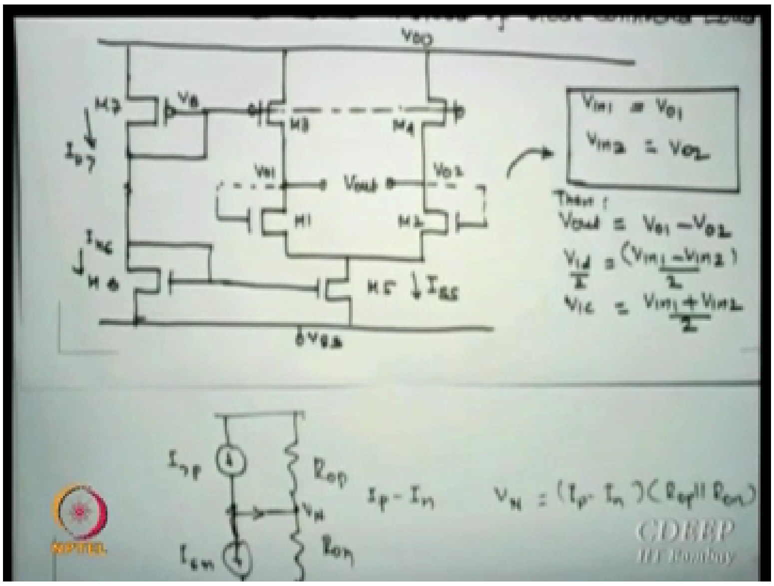

I repeat this is essentially please just see the figure, why I am saying equivalently saying this is given in (Refer Time: 14:10) book. This is I 7 p may be right now I can say this is I 6 n, and across them they may output resistance R op and R o for this sources R on. If these are not equal in this I am there will be I p minus I n, which is whichever is higher minus plus sign will appear and since the at this node these are parallel resistors. So, there is this at this mode I have I p minus in times R op parallel R on.

Normally, what should have been there zero drop across, they are two currents sources no drops there should have they have balanced it out, but it may happen that p channel current may not be exactly same as n channel current. And because of that this node voltage is not at 0 is that clear. Now, this is a very which in real life occurs, it is not something which I am thinking about as a new thing.

Now, that happens as I said the other thing that I explain normal opamp businesses. So, there is nothing more to right. What is relative feedback purpose to stabilize a system. I am stabilizing. So, I believe that with this any change should have actually been managed, but to my surprise I find this negative feedback which is actually a differential feedback does not solve the problem, which I am going to face. Normally, what is the negative feedback purpose is to stabilize a system, should pull down or pull up to get to a normal mode. Here I am now trying to show you it does not even if there is a differential negative feedback, this does not return to equivalence. So, where is the issue which we should look into, you can here write down if you wish.

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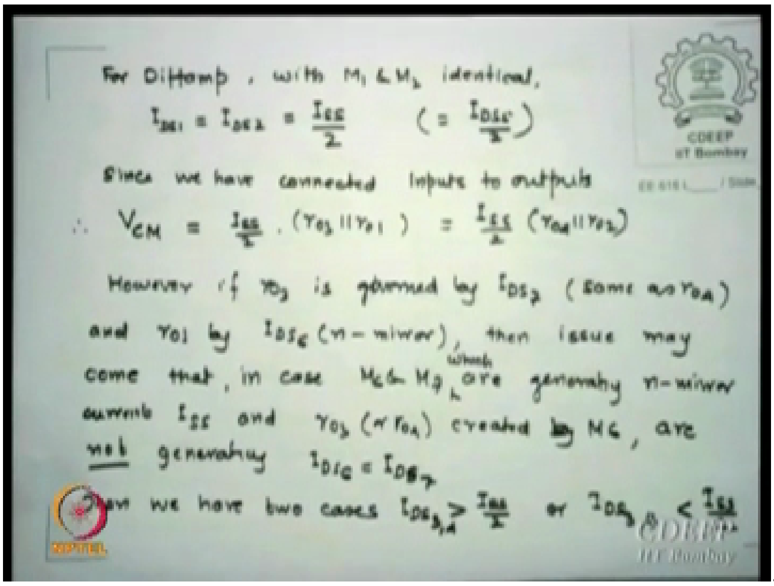

The last line is what is bothering me that the current in M 3 or M 4 may be larger than I SS by 2 or less than I SS by 2. A p channel currents are not same as n channel currents.

Now, if this happens what can happen to us? Please remember I SS is controlled by whom, M 5, I DS 3 and I DS 4 as current controlled by M 3 and M 4 is that which I will governed from six and seven mirrors M 6 and 7 mirrors. We first write down and you will take the two cases and you will happen what is going to a problem if this happens is an we says large work could I happen if say it is larger I DS 3 is larger than I SS by 2 what could happen you cannot hold this situation. So, if you want to make it equal then what should happen to something some transistor must change its status, otherwise to currents cannot be equal is that correct? The change its status is worrying me the most because change as status means the resistance of that device will change, and if resistance changes my gain changes.

So, though my common mode I am in differential mode feedback was there, but I still feel change in outputs, but let us see you finish this, then I will discuss this. The two issues of interest is let us say the current drain current of M 3 or M 4 is larger than I SS by 2 or less than I SS by 2. These are not issues which are trivial, this is real designs, these issues keep coming at least in fully different state, this is what we are elevating and that is why that they become very popular opamp systems for many of the applications fully differentiate. But what is the problem, cost extra [FL] pay for that. And I already shown you fully differential can always be used as single ended look at the single end only and do not worry about the other one.

So, there is no issue if you really use this are there single ended amplifier I DS 3, 4 is the current drain current of M 3 and M 4 is that correct, I SS by 2 is the current is M 1 and M 2, half-half. As I said this is been given from (Refer Time: 18:52) book, though my nomenclature are slightly different from them and the way I have written they might not have written so that is only difference, but the content is same as the (Refer Time: 19:04) book. This is under the section in opamp called common mode feedback CMFB [FL] is it.

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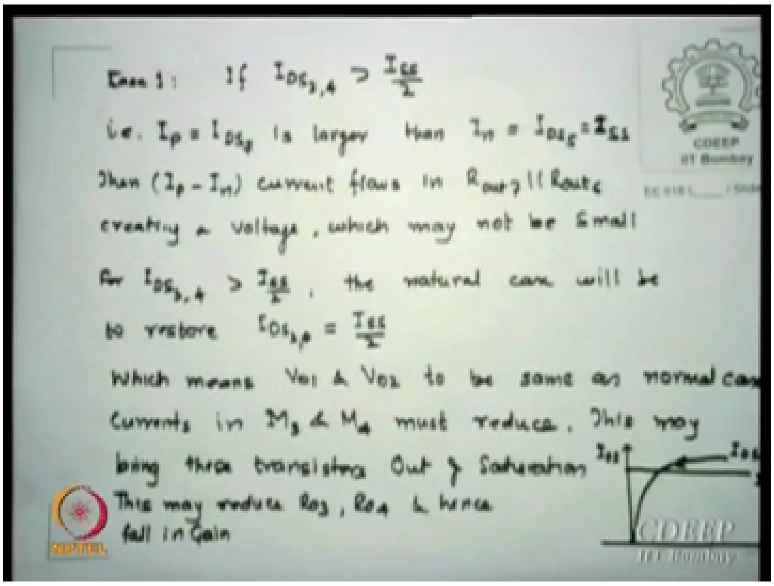

So, take the first case I DS 3, 4 is larger than I SS by 2. Please remember our I DS I SS is controlled by five for five transistor current which is coming from n channel mirror; whereas, I DS 3, 4 is coming from M 7 mirrored p channel. Now, these are greater we will like to restored I DS 3, 4 equal to I SS by 2 that is the natural in a Kirchhoff's law in a one arm positive to negative and one current only can flow, but in reality right now it was instant in read did not. Which means V o 2 or V o 1 to be same in normal cases; however, currents in M 3, M 4 than must reduced I must say what is there.

Let us say this is my current in M 1, M 2, I SS by 2, this is coming from I DS 3, 4 which is following because of the current in the drain current of M 3 or M 4. If this current has to reach here, what should I do, it should traverse by to reach this point. And what this point then will make 3 and 4, enter into because that V x value if I to fix V o 1, V o 2, I have to same than M 3 M 4 must come out of saturation and try to enter lineal mode is that clear? You said that current is larger, but the current which n channel M 1, M 2 was received by I SS by 2 this was larger, so tries to reduce itself, so that the currents have same, so that Kirchhoff's law is valid. And if that happens M 3 M 4 comes out of saturation.

What is the advantage of the system we were discussing high gains. Did we now have the high gains because M 3, M 4 would be in a linear zone, which is the smaller R on therefore, gains will actually fall is that correct gains will actually fall. Now, this is an issue if I DS 3, 4 is greater than I SS bite the possibility exist m channel current may be larger than p channel, so opposite can also occur. So, to say I DS 3, 4 is less than I SS by 2. I SS by 2 is coming from, which device M 1 and M 2 or M 5 is that correct, M 1, M 2 is the same current form the tail current M 5, which is I SS which is coming from n channel M 6 transistor is that. So, let us as again thought over its.

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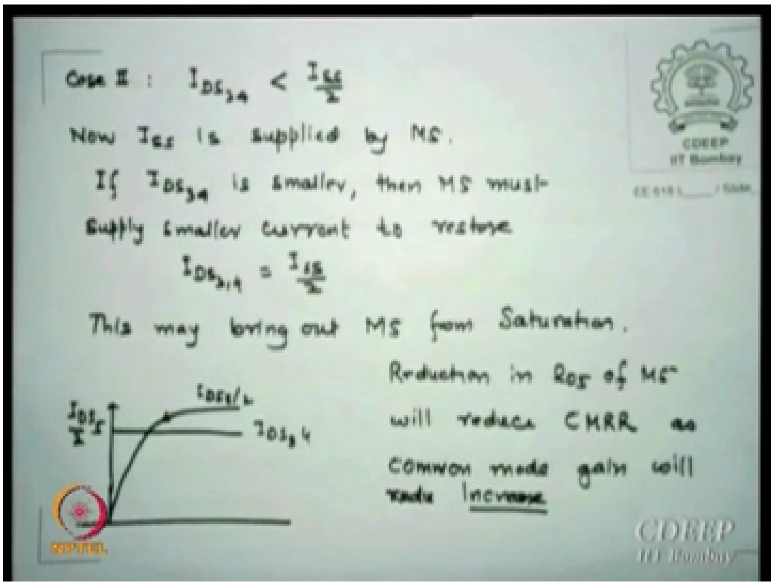

So, let us go to the next case if I DS 3, 4 is less than I SS 4 I SS which is supplied by M 5, now we say I DS 3, 4 is here and M 1 M 2 which is the same half the I SS current from I 5 is following this I-V law. Now, what will happen if this is to be made equal then M 5 will now come out of saturation, what will happen to M 5, it comes out to saturation then the R ee or these R o 5 it becomes very small. Do you recollect what will happen to other some other parameter of opamp? The common mode gain is proportional to one upon R ee, if that becomes common mode when will increase. So, what will decrease CMRR. So, by if it does happen that the other current is I DS 3 is smaller than this, the amplifier works may remain same V o 1, V o 2, but device will now show you much lower CMRR, is that clear?

So, case which look very trivial otherwise has actually though you have a differential feedback, we are connecting gave to the outputs. So, we have a feedback. And in spite of that such a situation is or it is not returning back, it is actually reaching one end this is something is not correct. So, if I can make something common mode constant then the my CMRR will not be dependent on this situation

So, let us see further, is that ok? All transistor current will reduce. So, that it becomes equal to I DS 3, 4 or I DS c whatever it is, which means M 5 will come out of saturation. And therefore, by doing this it will actually reduce the increase the common mode gain or reduce the common mode rejection ratio. Now, these issues are looks to be you know many people believe this never happens, but it is not so, it does happen and you need to put a circuit which is called common mode feedback, which retains the common mode. If something increases, it will reduce; if something goes down output, it will pull it up. So, that always CMRR remains constant source the gain the output resistant remain as high as they can be.

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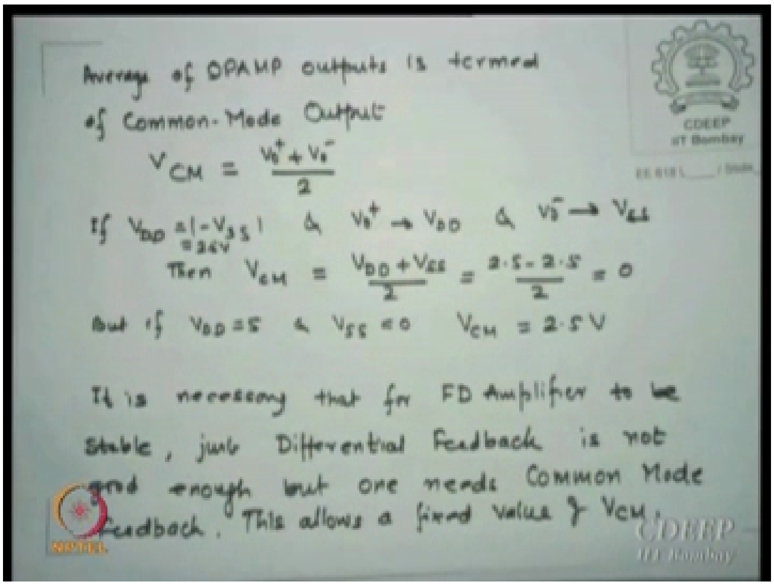

So, now we say average of opamp output is defined as common mode output CM CB CN and which is V o plus plus V o minus by 2. Let us say my full V DD get V o plus get V DD V o minus goes to V SS. And let us say V DD is 2.5, V SS is minus 2.5, then what is the CM 0 V CM is 0, but let us take as single supply opamps in this V DD is 5, 5 V SS is 0, in which case V CM is 2.5. I can actually decide to have any of the V CM values between V DD and V SS of my choice, which I can fix. So, it is necessary for a fully differential amplifier to be stable just differential feedback does not help you. And one needs what we called has common mode feedback or CMFB the word goes and this allies you to fix a value of V CM is that correct, because V o that coming out of the currents. So, if you can fix them then the outputs will be always V CM will be always adjusted to V o max plus V o min.

Please remember it need not be V DD it need not be it can be any value in between 0 to V DD minus V SS to V DD, you can fix anywhere. Choose any value average of does those two will be the V CM value which is dc value which you want decide on. Now, how do I decide normally I will preferred it is double ended, I should keep V CM 0. If it is single supply role then I should have to fix V CM value to a fixed choice of my choice. How do I then give a feedback, here is something has everyone noted down, these are something not necessarily useful directly in real spice also fails many a times in not having if you do not ask CMFB circuit the our amplify may not function properly. It starts actually ringing too much for a long time output never settles, these are one some issues which we will see in real life. So, you must put CMFB circuit to stabilize that output.

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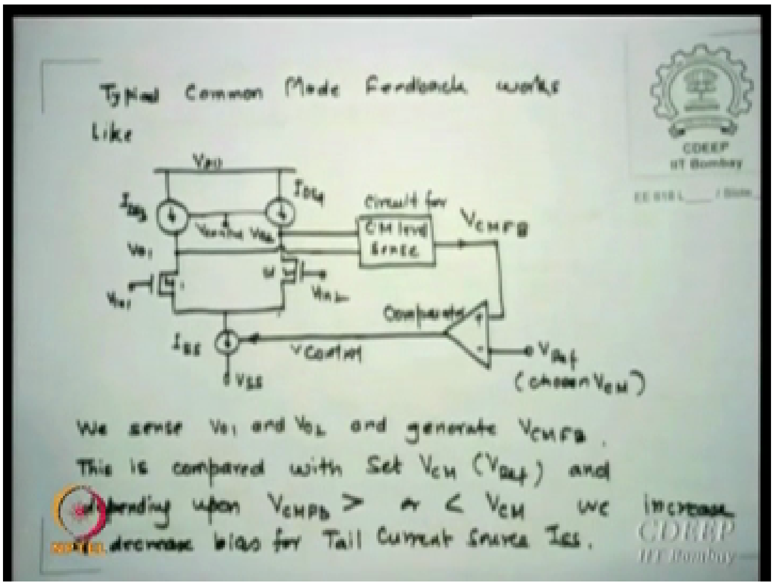

A typical CMFB this circuit is shown here this is your diff amp and this I DS 3, I DS 4 are coming from some BBN mirror as we did. I actually do one thing I figured out what is V o 1 and V o 2. So, I must first sense them. So, there is some circuit which is called common mode sense circuit. It figures out what is the V o 1 and V o 2 values, them some those to values it generates what we called as would CMFB voltage V CM. Then we compare it with the desired value, which is chosen V CM, which is called reference voltage in a comparator. Take if it is larger has smaller correspondingly the control voltage call it V control if we wish will be larger or smaller minus or plus or whichever values you fix. This value can control the voltages to either these two or these two I have shown you both ways, some people you actually control these currents, some people control this current. Any way we have to bring it down to equal now either on the top of in the bottom.

So, please remember, we sense V o 1 and V o 2 outputs sense than generate this, compare with reference, create a control voltage which controls the current in either I DS 3, 4 or I DS 3, 4, I DS 3 and I DS 4 or I SS one of them can be controlled. So, the either we can change the tail current or we can change the load currents. Why an the circuits are shown this is the principle behind the CMFB circuit which we are going to show and in that case the way circuit which I have I am controlling the lode currents. The same can be use for I 5 current also I SS current. [FL] if I used CMFB circuit which is also to some extend and amplifies a kind of system, what can it create it can create stability issue you are increasing another R c time constant with it, is that clear to you? It now device [FL] system may become unstable soak.

In a normal case of op amp, how do you we stabilize that by actually putting a mirror capacitance in series to a resistance pole splitting or directly mirror poles, so that the phase margin is relatively 50 degree around. So, will have to do full analysis with two ended completely supported by R c network and figure it out whether even with this it stabilizes. So, there is a it is not so trivial, but typically if the loads are larger it happens to be stabilized. So, you do not have to do it, but I do not want to say a priori unless you see that let say I have put ten bob yes it will stabilize. This is natural phenomena, but some other time. Is that ok Siddanth?

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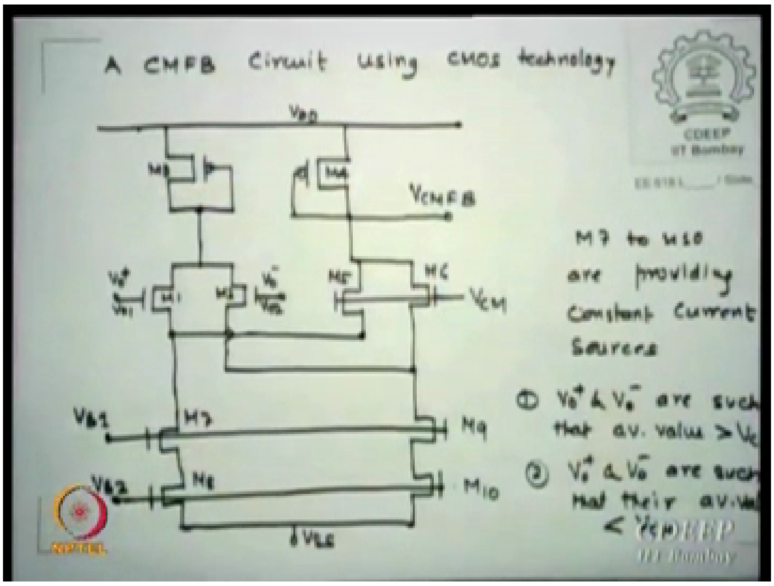

So, here is a circuit which is very simple and popular. Please remember I am only generating V CMFB, this is only generating common mode feedback voltage how to generate it, which includes the comparator. So, it is essentially controls itself I am generating. I have two transistor M 1 and M 2 which is my sense which is receiving signals V o 1 and V o 2 or V o plus V o minus, is that ok Santhosh? M 1 and M 2 are my sense devices, each receives V o plus V o minus or V o 1, V o 2 whichever names we have been following.

Then there are another two transistor M 5, M 6 which are so connected that the source of this are all over n channels. The source of this is connected to M 1, and source of this is connected to source of M 2 is that ok. M 1 source is connected to M 5 and M 6 source is connected to M 2. M 5 and M 6 receives the value of V CM which you want to set for that is the value you set there. Then this M 7, M 8, M 9 are essentially are current sources because they are given from a fixed supply V B 1, V B 2 may be banned from the band gap reference, so that these are constant.

So, please remember these are current sources. You can also ask me I could have done one single current source think of it why I do it in series, think of yourself, if not maybe, I will ask later. I could have done with one series transits one bigger transistor or the l length is larger which I had tried what is larger length helps, the lambda has a higher and therefore, you get a lambda has smaller therefore, get larger R os. So, this is some kind of pseudo cascades, it is not really cascodes which called pseudo cascodes. These are current sources and same currents are flowing here.

Now, let us say V o plus and V o minus are such that they average value of them is larger than the common mode voltage, this is first possibility. These are larger than average value of them is larger than the V CM. The other case kept be they are smaller, so that their value average value is smaller than V CM, s, two possibilities. If they are larger what will happen to currents of these, if V o plus and V o minus are larger, M 1 and M 2 will draw larger currents V js will increase for them. But they are actually getting currents from the current sources, these are of course, direct connected loads. These are actually I am pushing fixed currents, please look at it and pushing fix currents is that ok, but these two start drawing larger currents. So, which will draw smaller current M 5 and M 6 will draw smaller currents that is what we are added actually they together gives me these two currents.

So, if V o plus and V o minus or V o 1 V o 2 average value is larger than V CM these will draw larger currents, but for that these two should draw smaller currents. Now, if these two draw smaller currents then a voltage I have draw across this will be smaller and V M voltage will increase. If I increase the voltage, I can correspondingly change the load resistance currents or I 5 currents, is that correct?

Now, take the next case. If these are smaller what will happen they will draw lower currents compared to this, they will start increasing the current. So, V CMFB will actually go below. So, it will increase or decrease as per requirements of increase or decrease of V o plus and V o minus and average value will be then retain to V CM. V o plus V o minus either way it will bring it back to its V CM value. Once the common mode feedback is fixed, I mean settles that means, your common mode rejection ratio is permanently fixed value you, this is something which CMFB allows. Few more things I do not want to say more. These two currents are actually fed to the diff amp stage what we have seen with other cascode stays down at the single stage cascodes.

So, it also divides the current in diff amp as well as the signal gain stage. I have not showing the circuit. These currents can be chosen such that they feed both to difference as well as the cascode stage or gain stage. Change in those currents will decides if the diff amp stage is going down, it will actually boost the cascode stage. If the cascode stage goes down, the diff amp stage gain will increase, so that the output gain remains constant with the CMFB which I have not shown here but that is why it retains higher gains and constant common mode value which fixes higher SNR higher gains and stability. Of course, for stability I repeat you may have to do a RC network or your both ended opamps is that clear, that you cannot avoid because this additional this network is going to create additional poles and zeroes.

So, the system has to be stabilized. So, you must actually do more RC network analysis to get whether your system is still stable. But remember if the double ended outputs have larger load to drive which is the one of the major purpose of this, then compared to all others that they will be the dominant poles, and they will actually govern all the bandwidths and no others instability issue will come. But this is something guess work which I am telling unless you do one does not know.

So, do you get the point why I did common mode feedback? Because this is one of the major circuit which you will use in all over actual designs; whenever there is a issue at stability or ringing starts, look at it somewhere your gains I mean the currents are not matching. This matching problems can easily be handled by one common mode circuit prices additional power, lower bandwidths and extra area. Of course, all this is at the cost of getting perfectly good highest highly stable and high SNR amplifiers is that clear. This fact has to be understood in actual designs because these are not is normally used by everyone we can do a many a times your circuit may function without that, but if it does not, the solution.

Please remember, every circuit I show does not mean you have to put it. If you design and it works god saved you, but if your god is not ready to save, you can save yourself that is the trick behind all of it. This finishes everything related to opamps of course, there are few more things unending [FL]. Few more thing you must remember whenever I want gain stage to higher must cascode, this is something which we learnt day one cascode it. If I want to improve their bandwidths see to it that the first dominant pole is at least far away, so that the other pole shift further. So, the shifting of poles is one of them best is null; if we null it, your dominant pole is in your hand.

So, try to use null technique, but nulls are not very easy to attain, but as much as you can. These are tricks as much as possible if you know higher SNR or higher gains, we use always double ended fully differential system. The biggest advantage they gives the noises eliminated even what is the else is eliminated the offsets are also eliminated what is an offset voltage the output is 0, but in differential is still there. So, which means you have to offset input to get output 0, this value also automatically gets cancelled without differential this output also equally so both cancels since the differentials. So, these are very ideal amplifiers. So, this finishes essentially the opamp base systems. Please read (Refer Time: 40:13) whatever books you have [FL].

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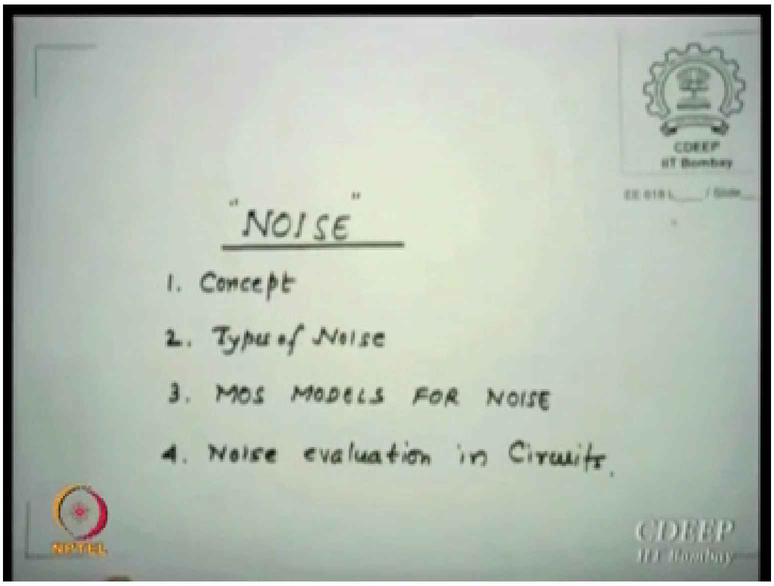

So, we start now a another area of interest which is actually not necessarily to analog, but in a analog it becomes very worry some problem. Though the word which all of you are so familiar noise. Why I brought it before other few things left because I thought that this is an issue which is also needs to be taken care during the design itself. Just now, I have talked about SNRs. So, this that preceded this, but actually it should follow after this. So, you will look into noise with following points first. What is a noise and what types of noise and then the MOS model for the noise because we are interested not on all other devices, we are more interested in MOS circuits. So, we will look more MOS models. And finally, for a given MOS circuits, how do I evaluate the noise.

The word which we use in the case of amplifier is noise at which level we connected input reflect noise is what we are interested, and not at the output, noise not at the output, but before of the output what input noise we will receive these are relevance and we will see why I look into that little latter.

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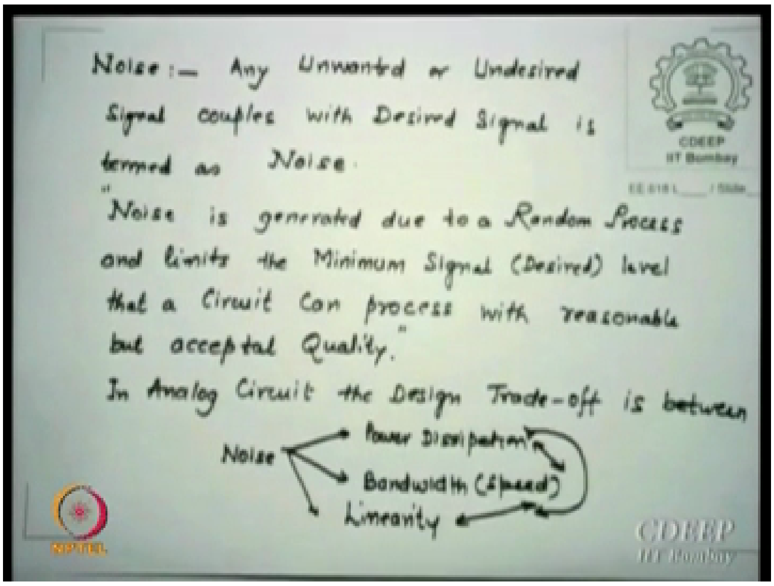

What is the noise, noise is a anything which is unwanted or undesired signal which couples with desired signal of this is termed noise. Noise is not something very odd or bad or something, you have none of you are from anyone from communication background here? All microwaves, ok. In communication you will learn later their noise is not all that bad there are algorithms, which use noise to improve the signal to noise ratio. You actually AGN noise you add and you actually get a greater figures greater images at least in image processing. So, do not go by my statement that noise is bad.

Noise is generated due to a random process and limits the minimum signal level that a circuit can process with reasonable, but acceptable quality. Noise is generated due to random process and limits the minimum signal level that a circuit can process with reasonable, but acceptable quality. The problem why I am interested before we do some V OCs or others is that in a normal analog design noise has something directly related to power dissipation it is related to bandwidth and it is also related to linearity. And then they also are connected to each other as, well they are also connected to we are seen hexa bonds. So, the problem is noise cannot be eliminated in design because they may affect any of the basic parameter design which you want to do. So, apply itself you should have an idea how much noise I have and how much I can tolerate that is the game in this. So, please remember noise is something unwanted and therefore, and also random. So, what is essentially random, some processes are called stochastic statistical behavior. So, we do not know noise is how it behaves.

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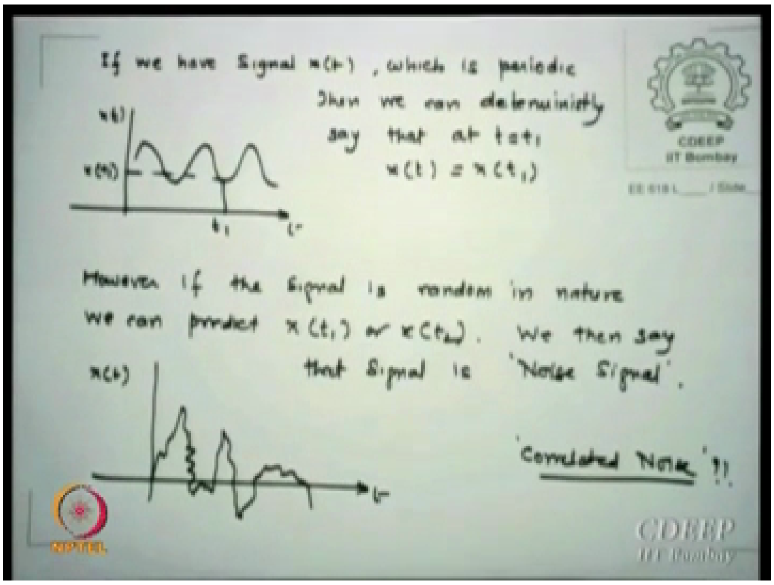

Let us take a xt function which is periodic and then we can deterministically say that if this is your function at any given time t 1, t 2, t 3, I can find the value of x which is x t 1 or x t 2 or x t 3 if this is periodic well behaved functions. However, if the signal is random in nature as shown here I cannot predictively say because I do not know the nature of the function that at any instant and time what is the value of x t I have, so that is my major worry that it is in deterministic. There are also other issues in noise and this is why I put it called correlated noise. And many of you primarily aware I do not know I do I forgot the name, but in a stadium when people come, they are in 40000 to a lakh people, but at noise in the background hardly it is heard by you. But what is that wave that they call it when all of them stand.

Student: (Refer Time: 44:41)

Ah

Student: (Refer Time: 44:43)

Huh maximum if that is so happens it makes a huge noise. So, if the noise is correlated, it can have a bombastic effects, uncorrelated noise normally distributes out and in average value is not those that strong. So, please remember that noise have many features to understand, but are we are only concentrating more from analog design side though issues of other noise are also equally important. Of course, basic idea of noise will remain same irrespective whether I do in a analog, digital, signal processing or whatever area noise is a noise. So, do not get too much worry. Is that ok Siddhanth?

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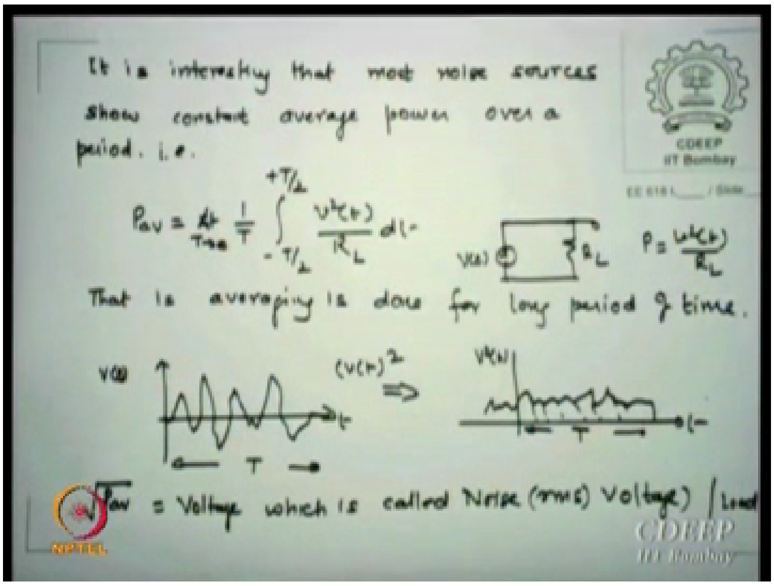

It is even though the noise is random, most noise waveforms if you see they at least show some average value, it is not zero, some average value. But of course, that decides if you do it averaging for a long period of time, very short period may becomes zero or it may be very large or very small. So, if you actually average it for a very large time, then the noise will have an average power. So, for example, I have a resister and I connect the V T source then the power delivered is V squared T by R L. So, if I use the average power for any random search V T then it is 1 upon T tends to infinity large infinity does not mean really infinity we use infinity because many of the integrals can be easily solidified put it infinity. So, minus T by 2 to plus T by 2 which is a period in which I am going to monitor V square by T by R L dt is the average power delivered for a resistor by noise of V T. Please remember this T has to be large to get reasonable averaging.

So, for example, if this is your function and you take a square of that this will be something like this. And you can see there is some average value I can get is that correct. As soon as I square it, I get some values which is reasonable enough and then I can get some average value which is V square as a averaging. In my normal all analysis R m is chosen 1 ohm. So, voltage square is defined as watts looks to be, but we say V square. So, it should have been in watts, power is in watts, but since R is always chosen 1, 1 ohm per say then the power average of a noise is essentially expressed in V square that is voltage square that is the method of expressing. If there is a addition load we may multiply it to get the actual noise value is that correct.

This is a RMS value yeah if you take away and root of this and it is called voltage per load if you wish or just voltage. But in normal case this is time domain analysis. If you look at that the if you take the frequency spectra with this, we find out that at different frequencies, the power is not same, this is called parallel resolution with it all also called PSD - power spectral density - PSD. So, if you look at the average power, we should look for spectral density for noise because at different frequencies noise have different values, so that is the definition of noise spectrum.

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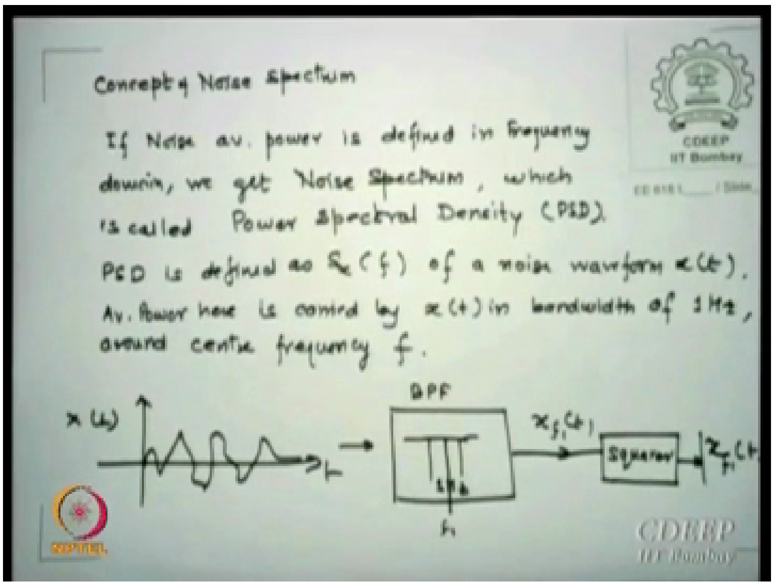

If noise average power you define in frequency domain, we get what we called as noise spectrum, which is called power spectral density or PSD. And it is defined as S x f, f is for frequency. Average power is carried by x t in a let us say I have a noise which I passed through a band pass filter its bandwidth is 1 hertz, band pass filter of one hertz bandwidth. If I pass through and square it I get x f 1 t square and then what is the range of frequency are used only 1 hertz. x f can be expressed in terms of volt square per hertz, volt square per hertz and voltage is expressed in under root of average, so we say it is volt per root hertz. So, noise is expressed as volt per root hertz is that ok.

At different frequency I actually calculate that I calculated f 1. Please remember this 1 hertz which I sorry I should have I made a mistake, the center frequency is f 1 around which the bandwidth is 1 hertz in a band pass you have to say where. So, I calculate similar thing at different frequencies f 2, f 3, f n and then plot this PSD all such frequency at different frequency, each will have a different value at this. So, and then I have plot essentially that is called the spectra is that clear? Please note down this then I will show the figure. So, what is my next stage, at different frequencies are evaluate except two square, except three square, every time I have band pass of one hertz around a frequency of my choice.

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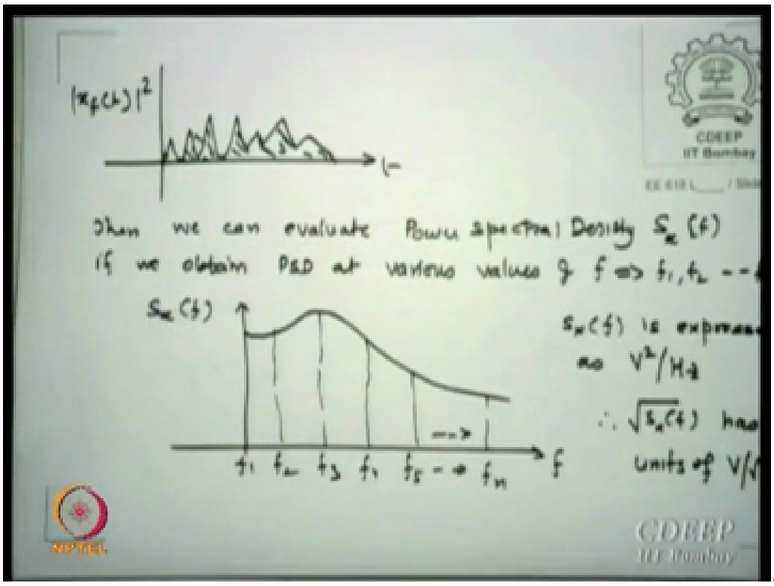

So, if I do this S x f at different frequencies average value at that, so I get a spectra. This is called noise spectrum or power spectral density S x f have with f is something the of course, this is random. This is not that for a given same curve will come. This some random figure which I have drawn, this is the kind of spectrum we get for noise. And since S x f has a unit of x square under root of that as a unit of volt square by under root is volt per hertz is per root hertz. So, now it is essentially expressed as volt per root hertz, assumption is or else are unit loads [FL], but normally it is not used. There will be very famous noise what is it call white noise. So, let us see what is the spectral density for that or spectrum for that. This is taken from Razavi's book any other figure is good enough ok. So, all that we did is fine x f 3, 4, 5, 6 n with one hertz bandwidth for every point and then plot is that ok?

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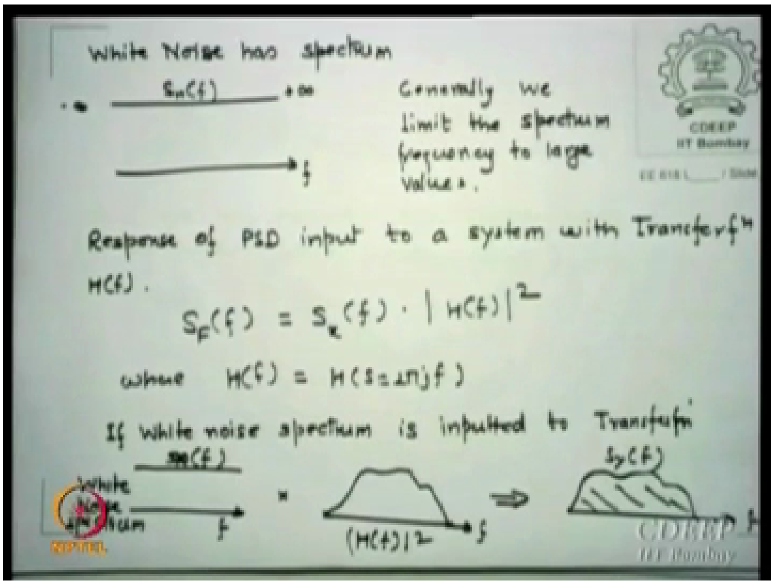

A white noise has a spectral density, which says that when minus infinity [FL] it is constant that is why it is called white noise. Of course, in a normal spectrum that minus infinity and plus infinity will have some larger bounds [FL] f 1 to f 2 is constant. Then definition it is minus infinity to plus infinite frequencies, the noise is constant spectral value is constant. Now, there is a interesting part there I can modify the content of white noise, if I pass through a transfer function H s which is H f is H s 2 pi j f.

So, if I have a white noise I pass through a transfer function of this nature which is the H f square. So, if I multiply this essentially I mean I am going to get a band limited S y f that means, this noise will get limited in the range of transfer function. So, choice of transfer function allow me the get spectral density of my choice. You use this function as you want and white noise will convert into a pattern of your choice is that clear, that is the fun part in designing these circuits.

Also normally this noise spectra is minus frequency to a minus two plus it is always shown spectra is somewhere here the transfer function may be a square [FL] it can take minus value and plus value square with the same. [FL] method [FL]. If the two, which is still band of this if it is S n x you want to see the last one please have it. One sided set to two sided say one side [FL], integral of minus infinity to plus infinite twice zero to infinity, same techniques is used. So, just double [FL] amplitude that is how noise spectra's are shown one sided. After we are doing averaging, averaging means integral.

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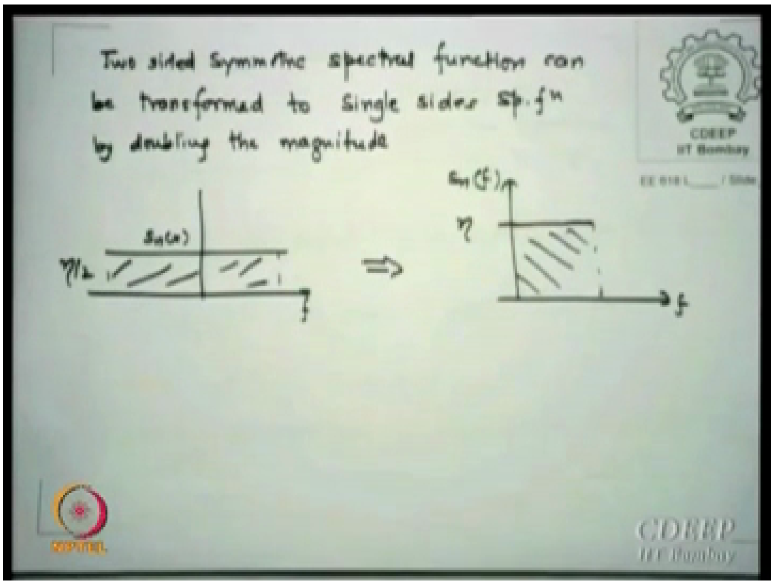

So, two sided spectrum can be converted to single sided it double the amplitude. So, this is the statistical behavior of noise. This was the first concept we wanted to give you that what is eventually noises all about and how it is you can actually get the pattern of your choice which device or which system, which is called a mix signal circuit, which is one of the most popular. I do not know whether it should be called a analog or digital which actually requires noise shaping what is it called AD, ADC, DAC. A to D converters and D to A converters requires noise shaping to the maximum you may have one loop two loop just to shape the noise, so that signal to noise ratio is very large. There are another term which is called signal to noise distortion which is SND are some make signal course some other time. So, noise in analog is very, very important parameter because if the please remember what will happen if noise is larger, we will require a larger power to actually dissipate. So, you have a first hit will be power dissipation is that ok figure, trivial.

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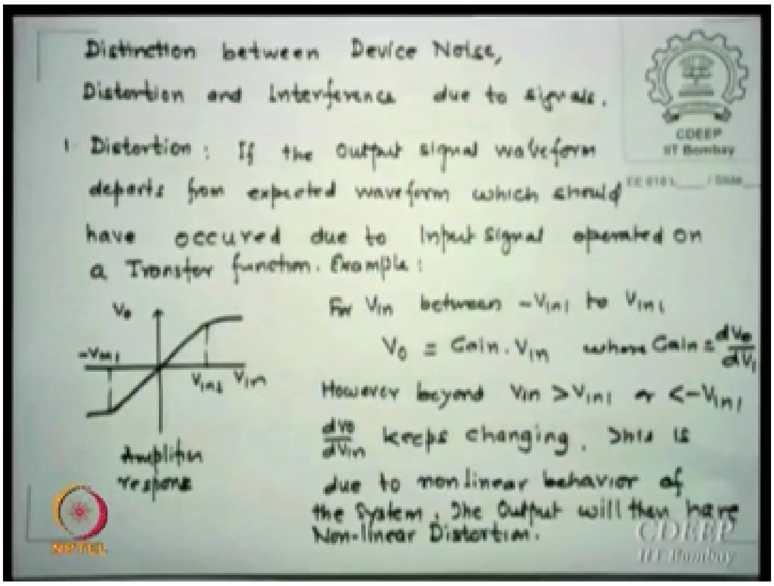

So, now let us see there are three terms many of us use very unknowingly that if they are same. There are three famous words, which we use in the case of systems, one is called the device or circuit related noise, second term is distortion and the third is interference all are word, but they are different. So, let us look the three differently, because we are more interested in the first part, but in systems you will require even though other two, its value. If the output waveform, which is a function of input time some transfer function and if that value which you now see in reality is not same as if it should have come then we say output is distortion, distorted from the ideal values you will thought you should have. Like, V o V in characteristics from these two inputs dV 0 by dV 1 is constant. So, to say any value here or here, I can predict the output by just multiply is equal to m x c zero here.

So, I know the slope that is the gain in this case. So, I know dV 0 by dV in. However, if I exceeds V in 1 or V in 1 either side then the V o vi characteristics does not seem to remain linear this essentially means you are entering a zone which is called non-linearity zone. And as soon as you enter non-linearity zone, you can see dV 0 by dv in is a function of V in. So, it is a non-linear term. So, if we expand it by Taylor series, you will get x cube in a x, b x square, c x higher order terms which means some power in the output is now deleted to one frequency, second frequency, third, fourth and highest power delivered generally is into the third harmonic and therefore it is called third harmonic distortions. Second harmonic in many circuits we will tune it that is we reflect it back, but third cannot be therefore, the distortions are normally strongly related to third harmonics.

We also feel as if it is due to only active device, no non-linearity come because of variety of other reasons one of course, is active device non-linearity, it is non-linear. So, this non-linear distortion is essentially because of the non-linearity in the transfer characteristics.

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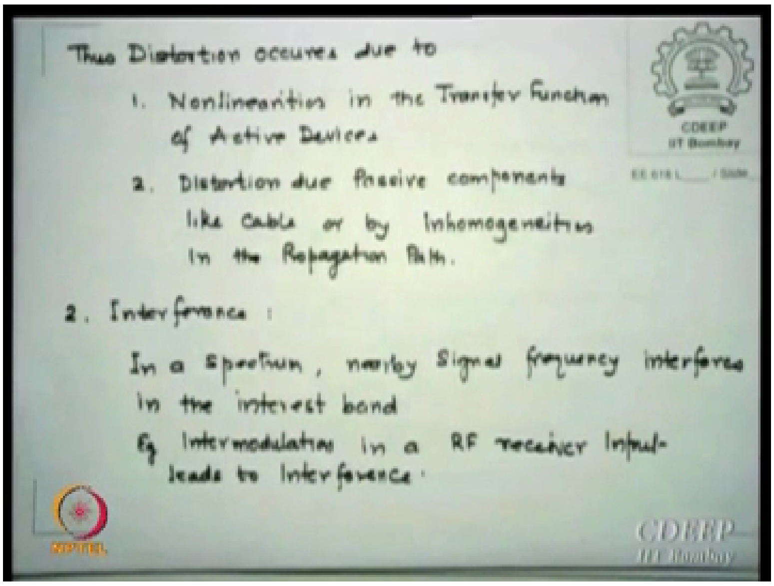

So, we say the distortion occurs due to non-linearity then transfer function of electric devices, but there is a possibility which is not just this though it is always there. Even in passive components, there is a non-linearity. For example cables, cable [FL], it is like a transmission line it is an RLC circuit, which also have different responses at different distances because the z 0 is changed there or z reflected would be different. So, even in a cable, you may get a distortion. So, you always say do not increased lengths so much put repeated somewhere even in fibers it are distortions. There is also in homogeneities in the path the cable RLC may be reading all three which may not be a constant or in a fiber the multimode fiber becomes someway only few not multi with smaller numbers. So, much of the area is lost and therefore, much it is radiates. So, any in homogeneity in the path also may lead to distortions so but we are more interested in devices because that is what we use often, but in systems anywhere noise can I mean distortion can occur.

The next worry for me is the interference. See, if you have a one spectra that is one signal spectrum, and we have another signal spectrum which is closed by then they may overlap. This essentially is called inter modulation. Simplest inter modulation thing can be understood without even a receiver, you have a two transmission lines or two signal lines, if they are closed by due to just mutual inductance coupling, signal in one may connect to the signal in the other, this is called crosstalk, this is called crosstalk. When is crosstalk highest, two lines are moving when the signals are in a opposite direction, the crosstalk is peak of both add like differential, so highest crosstalk's. So, but in RF receivers because of the entire input you received there is an image which actually interferes and creates higher harmonics and that needs to be further filtered. All filters lead disease, so that is major worry they have some other time.

So, the interference is a very common in most RF circuits or RF systems like an antenna you have two lines on any dielectric. As you have been closure the radiation pattern of one will interfere with radiation pattern of the other, so inter modulation will start and the pattern which we will see at the end at the antenna may not be single lobes may be a multiple lobe with deflectivity almost lost, it may those scatter out. So, everywhere the inter modulation is very common thing. We are not so much right now worried about these two both distortions we will probably, but we will always we will remain in linear that is the reason why we call analog circuit are linear circuit because it would remain in linear modes; otherwise it could have been non-linear circuits.

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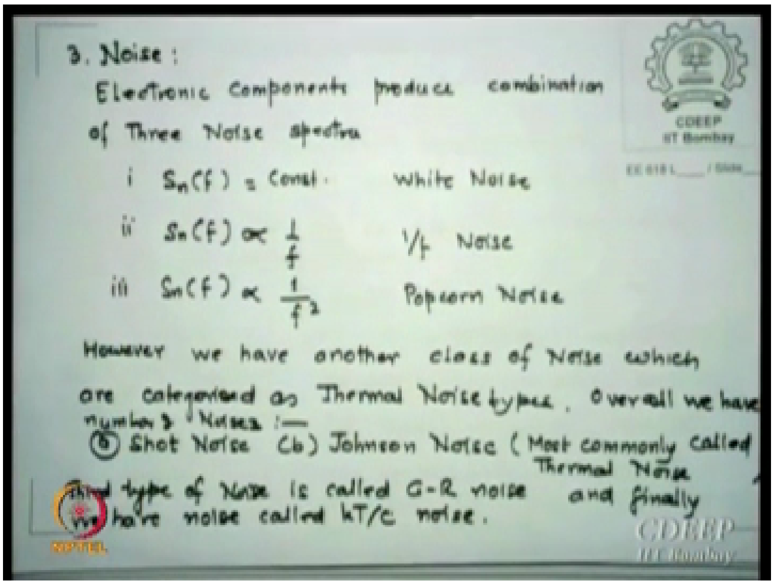

So, here is the third and the most important among them is the noise device noise. Electronic components produce combination of some noise with the spectra shown here. If it is constant and we say it is a white noise. And there are some noise which are inversely proportional to frequencies. They are called 1 upon f noise and there are certain noise, which are inversely proportional to 1 upon f square, this rarely you see in the books. So, I added this for you. It is called popcorn noise. The word popcorn noise use of course, use a another name if you are in communication area it is called burst noise. Since the burst occur when the data rate is much higher than the line can hold then the noise starts picking up which is called burst. And the burst is essentially like popcorns and on the pop up, so it is called burst. So, it is called burst noise or popcorn noise.

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Yes, larger the frequency smaller is the noise now, but some other noise must be taking over there. So, this is the one kind of noise which are the frequency dependent noise, no it is limited by lowered frequency that is what 1 upon f square is telling. However, there are another class of noise which are generally thermal noise as the word goes, however, other than thermal noise also there are other kinds of noises available. And these are named as short noise short, [FL] Mr. Johnson, a some noise [FL], but the most commonly known thermal noise is essentially named Johnson noise. The first research was done by Johnson on every noise which I thought is essentially Johnson's papers. And these are almost 100 year old papers still stands, they do a research hundred years [FL] that is the research, Newton [FL] apple [FL] Newton [FL]. There are hundred things which we think are there, but never bother, maybe I have a still time to do that [FL] research [FL] problem [FL], it is more money dependent, you need large equipments.

The third type of noise which is popular, it is called G-R noise. And the last and the foremost which is very, very troublesome in actual analog design it is called K T by c noise this is very, very tough to handle. So, you can see from here K T by I will come back to it K T by C noise is generated from the resistor, but there is no R here. So, that is the fun then I have a resistor which is creating noise, but my noise is essentially of independent at that resistor. So, [FL] noise [FL]. So, there is some issue which we will see in K T by C noise which is very, very troublesome in analog design.

We can see from here before I quit if I increase C, K T by C will go down assuming if T is constant see [FL] change [FL] if that is the worry C is capacitor. So, a C [FL] everything goes away. Now, that is the problem we will see this C, C is a output capacitance now any time you see you will see we have no problem. And we will see now. So, this evening we will start with the definitions of each of them and go up to device and to a circuit how to calculate noises.