Analog Electronic Circuits

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Lecture – 16
Differential circuits

Welcome to Analog Electronic Circuits this is the lecture number 16 and today we are going to continue with our discussion on Differential Circuits. We actually did not quite start in the last class; in the last class we were discussing the difference between interference and noise and what we discussed was that noise is something very intrinsic to the physics of the electronic system.

For example, when you have a resistor inside a resistor the electrons are pushing and shoving each other because of temperature, because of heat; the same as the gas dynamics the same mechanism as gas dynamics and as a result they create a potential this is called noise this is what we are going to call noise. So, noise in analog circuits is very specific it is related to the physics of the electronic system ok.

On the other hand interference is any unwanted signal which is part of the signal you know I am speaking to you at the same time somebody else is speaking to you right that is interference alright. Now, it turns out that I mean these systems where have been developed for several decades and we have a few pretty robust ways of canceling out interference and for example, if I have a cable right.

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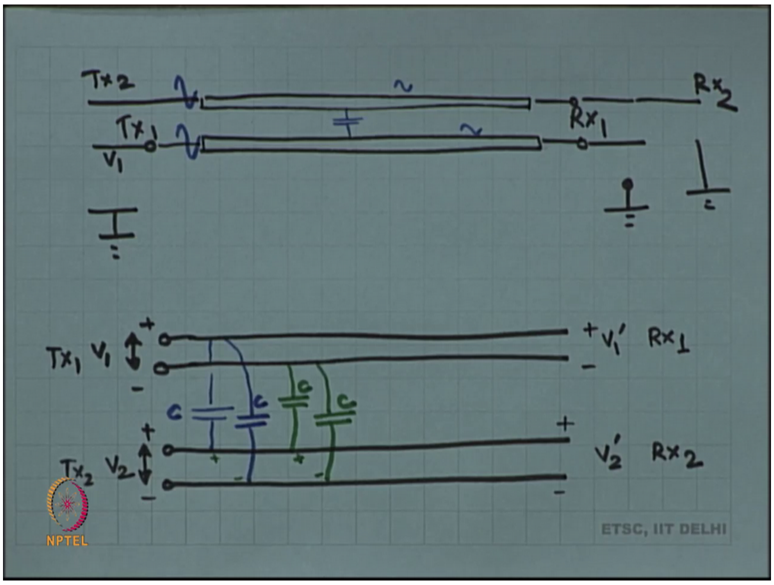

A long wire alright; so, this is the transmitter this is the receiver. So, I have a setup like this where I have a transmitter maybe in the US and then a long cable copper wire coming all the way to India and I have a receiver telephone sitting on this. So, transmitter telephone receiver telephone or between the exchange and so on and so forth alright in between there is a long wire.

Now, if this is the system then this is very susceptible to interference because if I have yet another party, yet another similar cable. So, this is R X 1 T X 1 this is T X 2 and R X 2 say there is a second telephone wire which is coming in the same you know under C sheet.

Now, these two have capacitance between them these two long wires have capacitance between them. So, any voltage signal on T X 1 will appear on T X 2 will get coupled onto T X 2 any voltage signal on T X 2 will get coupled onto T X R X 1 ok. So, this is the problem this is the basic problem

The popular way of getting rid of this interference is by using differential signaling. So, instead of an absolute signal with respect to ground; So, T X 1 right is transmitting a voltage V 1 with respect to ground right R X 1 is trying to receive that voltage instead of transmitting a voltage V 1 with respect to ground why do not we transmit a voltage between two wires.

So, now instead of transmitting having one copper cable let us have two copper wires and we say the transmitter sets up a voltage V 1 between these two. And the receiver has to measure the voltage V 1 prime between the two wires ok. So, this is the strategy that is used.

Now, what is going to happen is this is going to be a second pair of cables with T X 2 where V 2 is being set up and R X 2 is trying to measure V 2 prime alright and now let us look at the interaction between V 1 and V 2 between T X 1 and R X 2 and the interaction between T X 2 and R X 1. What is going to happen?

There is capacitance between each of these. So, between the positive wire of T X 1 and the positive wire of T X 2, there is capacitance likewise there is capacitance between positive wire of T X 1 and negative wire of T X 2. Again there is capacitance between negative wire of T X 1 and positive wire of T X 2 and there is capacitance between negative wire of T X 1 and negative wire of T X 2.

Now, if you measure these capacitances what you are going to find is that the capacitance between plus of T X 1 and plus of T X 2, if that is some C then the capacitance between plus of T X 1 and minus of T X 2 is also going to be approximately C or you can make sure that that is also C you can set up the wires in such a fashion that they are equidistant ok. And therefore, you will get see in that case too likewise if this is C, this is also going to be C approximately.

Now, what is going to happen? A voltage on T X 1 with respect to ground a voltage on T X 1 is going to affect T X 2 with the positive of T X 2 with respect to ground a voltage on the positive of T X 1 will also affect the negative of T X 2 with respect to ground and the difference is going to be nothing ok. You will find that the affective difference between these two because of perturbation and the positive of T X 1 is 0.

Likewise you are going to find that the if I make a perturbation in T X 1; in the negative of T X 1 then the positive of T X 2 and the negative of T X 2 are going to be affected equally. And the net result is going to be that any perturbation in T X 1 is not going to change anything in the difference V 2 alright. So, this is basically the idea of differential signaling.

So, when it comes to telephony these long cables are no longer used right, but do not think about telephony, think about you know a set of wires coming out of a processor which are moving up and down at high speed. So, all of these typically modern communications these happen in terms of differential signaling and this is the reason why ok.

So, you have been able to successfully cancel out interference in this case right. Noise; let us not bother about noise let us not worry about it noise is outside really outside the scope of this course right, we are not going to talk about it any further. Is this understood? This differential signaling.

So, invariably what is going to happen is that when you when you have an input voltage to your amplifier; it is going to be a differential input voltage and this has to be amplified as opposed to an absolute voltage with respect to ground ok.

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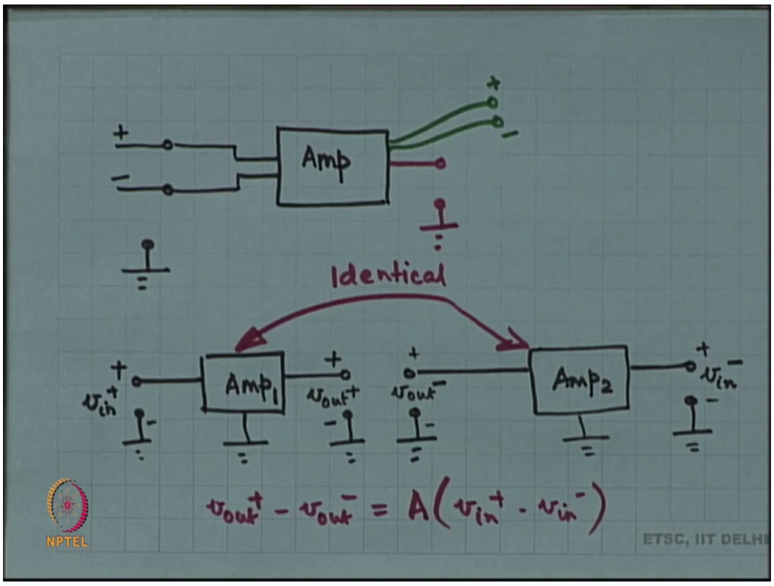

So, invariably your input signal to your electronic system is the difference of 2 potentials as opposed to an absolute potential with respect to ground alright; this is basically what is going to happen in future.

Now, how do we make an amplifier? That is going to take 2 inputs and amplify the difference between the 2 inputs and ideally so, there are two ways to produce the output. One way to produce the output would be to produce one output with respect to ground this is one possibility, a second possibility would be to make a difference of 2 outputs right; these two possibilities exist alright.

So, this is our job right our job is to make an amplifier now that amplifies the difference between 2 inputs. How do you propose to do it? One way to do it would be to take this plus wires with respect to ground put an amplifier generate the plus output. And take the minus wire with respect to ground use an amplifier and generate the minus output is this good?

So, I make 2 amplifiers I take v in plus amplify make v out plus; so, I am doing the green strategy. I take v in plus amplify generate v out plus I take v in minus amplify generate v out minus is this or not ok? Is there any constraint there is a constraint right the constraint is that these 2 amplifiers have to amplify by the same amount or in other words; these 2 amplifiers have to be identical.

If they are not identical then funny things are going to happen ideally you want v out plus minus v out minus should be some gain times v in plus minus v in minus. Now if this one has voltage gain of A 1 and this has A 2 and A 1 and A 2 are not equal then you know you have a problem; in which case you can rewrite it probably.

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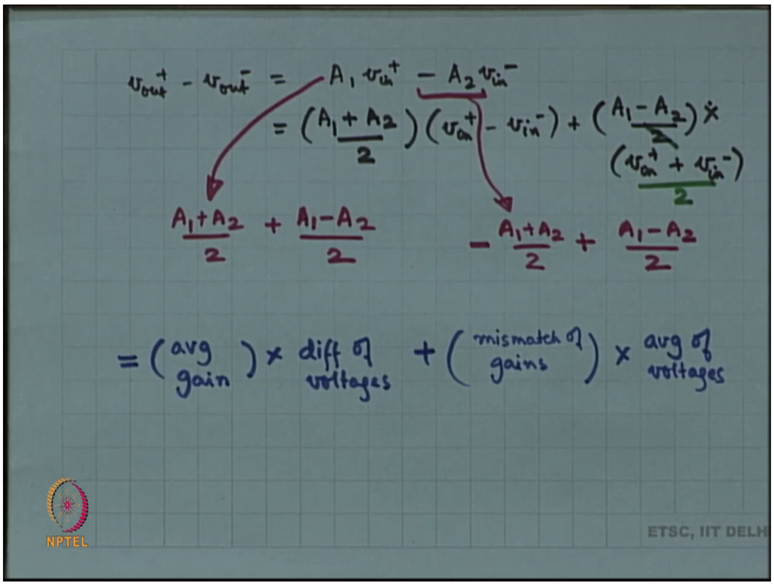

So, suppose this is the case then it is possible to rewrite it as something times v in plus minus v in minus plus something else times v in plus plus v in minus ok. So, this would be something of this fashion the average of A 1 and A 2; yes and what would this be? This would be the extra portions.

A 1 plus A 2 by 2 plus A 1 minus A 2 by 2 is A 1 and A 1 minus A 2 by 2 minus A 1 plus A 2 by 2 is minus A 2 check that this is correct; this is correct according to me v in plus has a coefficient. So, I am rewriting A 1 as A 1 plus A 2 by 2 plus A 1 minus A 2 by 2 that is what I did.

So, A 1 plus A 2 by 2 times v in plus A 1 minus A 2 by 2 times v in plus. So, that is A 1 and likewise I can write A 2 as A 1 plus A 2 by 2 plus A 2 minus A 1 by 2 that is A 2, but minus A 2 is minus of this fine and therefore, you get over here you get minus v in minus times A 1 plus A 2 by 2 and then plus v in minus times A 1 minus A 2 by 2 this is fine this is just a rewriting of the same thing.

Now, this portion is the difference between the 2 voltages, this portion is the sum of the 2 voltages alright. So, for example, if A 1 is equal to A 2 then it is not proportional to the sum of the 2 voltages alright at all; if A 1 is equal to A 2 then v out plus minus v out minus works out to be A times v in plus minus v in minus if A 1 is equal to A 2 right if the 2 amplifiers are identical right.

Then this portion becomes equal to 0 otherwise you have a portion that is proportional to the difference between the 2 voltages. And you have a portion that is proportional to the sum of the 2 voltages or in other words the average of the 2 voltages. So, you can bring in this 2 inside also alright.

So, let me rephrase what I am trying to say is that any v out plus minus v out minus, where you have done a job like this right you have taken v in plus gained it up, you have taken v in minus gained it up. And these 2 should ideally be identical, but let us say they are not in which case you have a function that looks like this. This could also be thought of as sum gain the average gain of the 2; A 1 plus A 2 by 2 into difference of voltages plus A 1 minus A 2 which is the difference of the 2 gains times v in plus plus v minus by 2 ok.

So, this is how I am trying to rephrase it. So, this mismatch of gains should ideally be equal to 0 and if you do it this way then it is probably not a very good way of doing it because it is very hard to get amplifier 1 and amplifier 2 to have exactly the same gain. Is there any other way? For example, think of just think of what we did last time ok.

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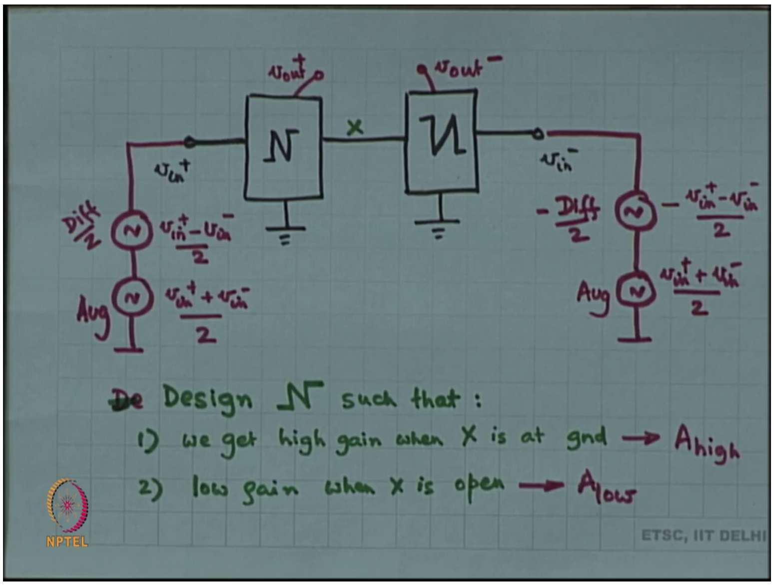

So, I am going to apply v in plus over here and v in minus over here right and I can always think of v in plus and v in minus as the superposition of 2 voltages; One being the difference of the 2 and the other being the average of the 2 right. Likewise v in minus is equal to minus v in plus minus v in minus by 2 plus v in plus plus v in minus by 2.

So, this is the average and this voltage is the difference by 2; this is minus diff by 2 ok. For example, if v in plus and v in minus are perfectly anti symmetric then their average is 0 right if v in plus is equal to minus v in minus suppose in that case the average becomes equal to 0 and the difference by 2 is pretty much equal to the amplitude of v in plus because v in plus minus minus v in plus. So, that is 2 v in plus by 2 which is v in plus alright. Is this is this ok? So, I can always look at v in plus and v in minus as the superposition of 2 signals.

Now, think of the following in one case in one experiment when I had v in plus minus v in minus by 2 and minus v in plus minus v in by 2; the node in between was at ground. And in the second case the node in between had no current flowing through it this was the theorem that we had studied last like in the last class. So, I am going to think of superposition and by thinking of superposition in one case, I will have 0 volts over here in the second case I will have no current through this wire alright. These are the two things that we are going to do in one case 0 volts in between in the other case no current in between.

Now, let us take an output v out plus and v out minus ok; let us take an output from these 2 networks which are mirror copies of each other. And let us try to do it this way let us try to have low gain when this wire is open and high gain when this wire is short to ground.

So, let us make N such that we get high gain let us call this wire X let us design n network n such that we get high gain when X is at ground and low gain when X is open ok. Can we do such a thing? If we do this then what is going to happen? Then v out plus minus v out minus; So, v out plus will be some high gain times you are going to do superposition. Suppose we do this suppose we do this suppose this high gain is A high and this low gain is A low; suppose. Then what is going to happen? Then what is v out plus and we are what are these voltages how do we do the analysis?

So, we are going to do the analysis of this circuit in two ways using superposition. First we are going to apply diff by 2 and minus diff by 2 we are not going to do superposition one voltage source at a time right. So, there are only 2 voltage sources v in plus and v in minus traditional superposition is by first applying v in plus, you ground v in minus then you apply v in minus ground v in plus alright; this is traditional superposition. Then what did I do? I broke up v in plus into 2 voltage sources diff by 2 and average v in minus I have broken it up into minus difference by 2 and average alright.

Now, what I am going to do is I am going to do superposition and I am going to do two at a time as opposed to one at a time. So, first I am going to kill the average. So, now, let us make sure that the average is 0 ok; I am going to apply diff by 2 minus diff by 2 on both sides. And in the next experiment I am going to kill the difference, I am only going to have average in which case I will apply average and average on both sides. So, these are the two experiments we are going to do alright.

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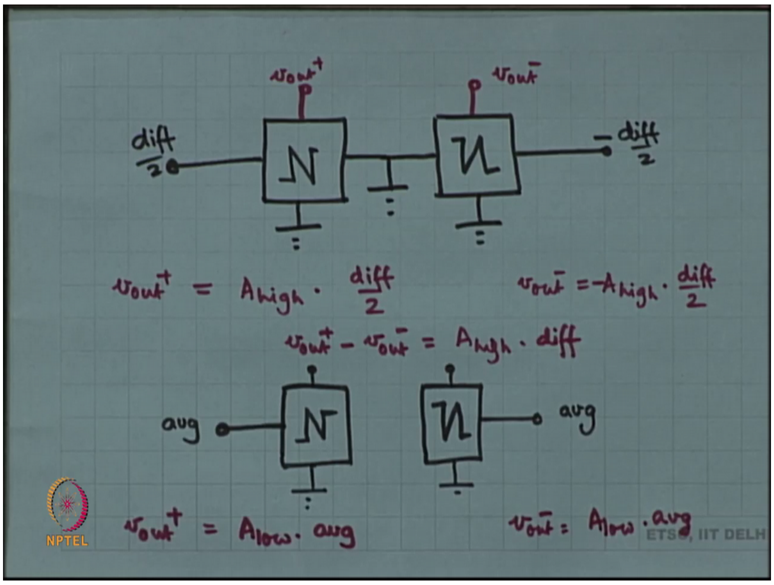

Now, let us do them; so, my first experiment is going to be diff by 2 and diff minus diff by 2. And when I do this node is at ground we know that that node is a ground which means that v out plus. So, now these two networks are decoupled from each other because the middle is at ground. So, they are really not coupled to each other anymore, but they are identical otherwise.

So, now v out plus what is it going to be? Some high gain A high times diff by 2 and v out minus is minus diff by 2 times the same A high alright or in other words v out plus minus v out minus is A high times diff by 2 minus minus diff by 2 times the difference of 2 voltages; so, this is my experiment 1.

So, I have called it A high, but we are yet to design it we need to design network n such that from v in plus 2 v out plus the gain is high when X is at 0 volts; we are going to do it just now, but before that I need to do the second experiment. The second experiment of the superposition is with the wire open and there is no wire in between anymore because it is to cut the wire remember yeah.

So, on both sides you have applied the voltage average you have applied the average voltage on both sides ok. So, they are basically the same thing; you have got average network N output average network N output and the relationship we know between output and average is some gain which is V low a low.

In which case v out plus is equal to A low times average v out minus is some A low times average in which case v out plus minus v out minus is 0 right it is automatically 0 v out plus plus v out minus is A low times 2 times average over here v out plus plus v out minus was 0 ok. So, in one case the sum of the outputs is 0 in this case; in one case the difference of the outputs is 0 in the second experiment.

Net what is going to happen when you apply when you do both of the experiments at the same time what is going to happen? The output voltage v out plus is going to be A high times diff by 2 plus A low times average v out minus is going to be minus A high times diff by 2 v out minus is going to be plus A low times average ok. So, one when you do superposition and what are these diff by 2 an average; diff is v out v in plus minus v in minus average is v in plus minus v in minus by 2 fine.

So, far so good; so, this is the plan is this helpful? Do you think this is something nice? This is something nice because even when there is mismatch between N and mirror copy of N; even when there is mismatch the gain is still A low. So, even if a low is a small number A low is a small number right even if they are different from each other even if they are different from each other the net difference from each other as far as the average is concerned is going to be low ok. So, that is why this kind of a setup is very nice and this is the way we are going to make the differential amplifier ok.

Now, all that we have to do is figure out network N and the answer to that lies in your common source amplifier.

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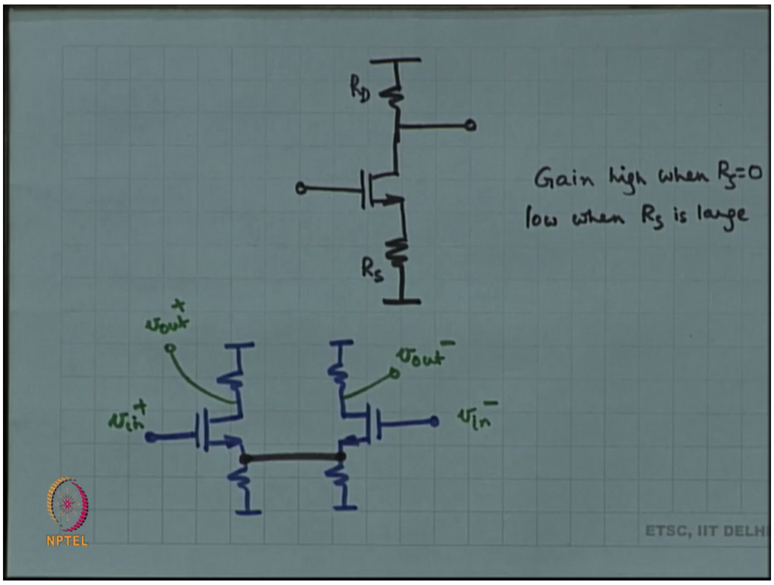

So, for example, the common source amplifier you remember right. So, ordinarily the common source amplifier the source is at ground, but let us have a resistor at the source in which case this becomes the source degenerated common source amplifier.

And if you recollect the analysis of the source degenerated common source amplifier the gain is minus R D by R S approximately actually it is less than that. But if R S is 0 then the gain is g m times the output impedance which is R D parallel RDS ok. So, the gain is high when R S is 0 the gain is low when R S is large ok.

And this is what we are going to do; what we are going to do is 2 such common source amplifiers. And we are going to connect them right here alright and look at the smartness of this is exactly what we want.

Because when I apply a differential signal this voltage that is when v in plus is exactly minus v in minus ok. Basically when I am doing this experiment the wire in the middle is at ground, if the wire in the middle is at ground this common source amplifier has high gain ok. On the other hand when this wire is open this is a source degenerated common source amplifier and it has significantly lower gain.

Or in other words, when you are doing the average experiment when your applied average on both sides then this wire is an open circuit in between this is open and then you have got your source degenerated amplifier. So, this is exactly what you want alright.

Now, the next thing is that this resistor does not even have to be a resistor you want this resistor to be very large right. Now, recollect what which object has a large resistance a current source right current source will ideally a current source has infinite resistance and infinity is very nice. Because then you will have no gain this low gain is going to become 0 gain right because it is minus R D by R S approximately and if R S is very very large then that gain is completely 0 alright.

So, what we are going to do is we are going to revise the circuit diagram.

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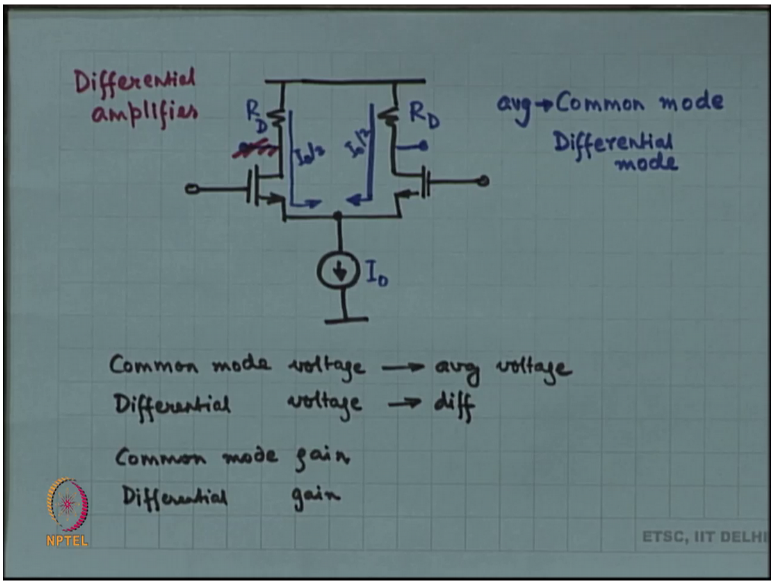

And draw it like this now when you have placed the current source over there automatically the DC operating point is also established for example, if this is I naught and these two are perfectly symmetric R D and R D. Then I naught by 2 is going to come through each MOSFET right and you have established the current through each MOSFET. So, all of these are falling into place.

Next thing of course, we like biasing with the current source because then I can accurately control the gm of the individual MOSFET right I can control the gm. So, all of these techniques are suddenly falling into place right first we did all of these theorems; the network theorem then we said that we will make sure that if for the average signal.

So, by the way this average signal is not really called average it is called the common mode; so, the technical term is common mode ok. So, we are henceforth going to call it the common mode signal and the difference between the 2 voltages is called the differential mode.

So, you have got the common mode, you have got the differential mode right. So, the common mode signal goes through a low gain whereas, the differential mode signal goes through a very high gain; why? Because the common mode signal when I have applied equal voltages on both sides right. Then this wire in between does not carry any current right you can think of I naught by 2 and I naught by 2 2 current sources in shunt; the wire in between does not carry any current right. Because you have applied equal voltages on both sides and therefore, it can be cut now if you cut it off then this entire half circuit.

So, that is called the common mode half circuit. So, this entire common mode half circuit starts looking like a source degenerated common source amplifier where R S is the output impedance of I naught by 2 and that output impedance of I naught by 2 is going to be hopefully fairly large.

In which case, the gain that you obtained from the circuit is going to be fairly low. So, the common mode signal even when you apply a common mode signal. So, the average if it changes on both sides; nothing comes out at the output. On the other hand, when you have a differential mode signal right one going up, the other going down at the input then the node in between that is the fulcrum it is static right one goes up the other goes down the node in between is the fulcrum it is static. So, it is effectively ground as far as signal is concerned this is ground.

Now, if this is ground then this entire circuit looks like a common source amplifier which has reasonably high gain you know gain of 100 minus 1 100 ok. So, this is the strategy this is your first differential amplifier alright do we understand the entire strategy that we talked about? So, the language alright let us define the terms; so, common mode voltage refers to the average voltage of 2 symmetric nodes. So, the common mode of the 2 outputs for example, is the average of the 2 outputs common mode of the 2 inputs is the average of the 2 inputs.

Then you have got the differential voltage or differential mode voltage is the difference between the voltages of 2 symmetric nodes ok. This could be the inputs these could be the outputs; so, the differential input is v in plus minus v in minus the differential output is v out plus minus v out minus the common mode output is the average of the 2 outputs, the common mode input is the average of the 2 inputs. Then you have got the common mode gain what is the gain from the input to output of the common mode signal? So, if I apply an average signal over here on both sides then what do I see? What is the what is the effect on the output right?

So, ideally you will not see any difference between the 2 outputs maybe you will see some difference and maybe you will see some average at the 2 outputs. So, what is the response in terms of difference what is the response in terms of the average. So, that is the common mode gain and then the differential mode gain ok. Differential mode gain is I apply a differential input and I observe what is the differential output right and find a workout difference between the 2 inputs and I observe the difference between the 2 outputs and what is the gain provided by the circuit.

Now, some of these circuits have 2 outputs 2 symmetric outputs and some other circuits we will say let us forget the second output; we can only we only require one output. So, some circuits will throw out one of the 2 outputs and give you just one. In which case the common mode gain is what is the voltage here? When I apply a difference a common mode signal that is average and average on both sides; What is the voltage here what is the gain? And the second is differential mode gain what is the signal when I apply a differential input a differential input is when the 2 inputs are anti symmetric.

So, plus 1 volt minus 1 volt a common mode input is when both signals move around together. So, common mode always refers to the average, differential mode always refers to the difference between 2 symmetric points alright. So, these are terms that we use then there is the common mode half circuit which is the half circuit with this wire cut in between right if I cut the wire I have 2 parallel I naught by 2 circuits and I cut the wire in between what remains on each half is the common mode half circuit.

Then I have the differential mode half circuit and that is when I apply a differential voltage the in; the node in between is the fulcrum it is static. So, in terms of signal it is not changing; so, it is ground. And then if this is ground then the circuit splits up into 2 halves each half is called the differential mode half circuit alright. So, these are terms that are commonly used and I will be using these terms in the classes that are coming right in the future classes, I will always be referring to these.

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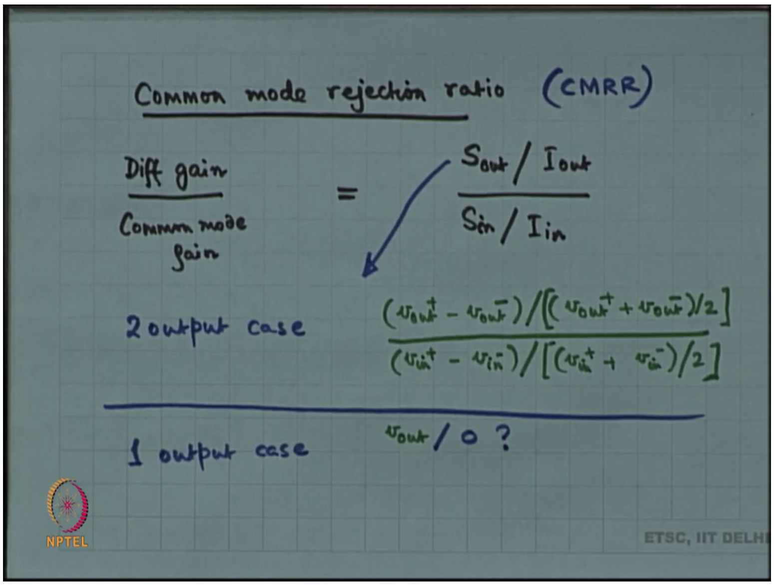

Then there is another term called; the common mode rejection ratio ok. So, the common mode rejection ratio is defined as the differential mode gain divided by the common mode gain ok. So, this is pretty much the definition of common mode rejection ratio; you could also think of it as the signal to interference ratio at the at the output signal output by interference output.

So, interference is the common mode divided by the signal input by the interference at the input and S out by S in is differential gain, I out by I in is common mode gain. So, these two are the same signal to interference ratio at the output divided by signal to interference ratio at the input.

So, I have got some signal some interference at the input and I have got some signal, some interference at the output what is the difference between these two ratios? Right and if you think about it this works out to differential gain by common mode gain. The common mode gain is A high, the differential mode gain is A low and therefore, A high by A low is a substantially large number right.

So, this is the common mode rejection ratio how much is the common mode rejected right it used to be there, but now it is no longer there at the output right even when it is there at the input it is not there at the output. So, that is called the common mode rejection ratio in short we call it CMRR alright. So, signal to interference at the output, differential mode by common mode at the output by differential mode by common mode at the input.

Now, this works in many ways for example, if you have a circuit which has 2 outputs v out plus and v out minus then the signal at the output. So, we will have to work this out; so, there are 2 different ways of making these differential circuits right one where we have symmetric 2 outputs in the other we just throw one of the outputs away and we just deal with one output.

So, let us think about it separately when you have the 2 output case what is S out? S out is v out plus minus v out minus the difference between the 2 outputs is S out. I out on the other hand is the average of the 2 outputs and likewise S in by I in; so, the difference between the 2 inputs fine.

Now, in the one output case you have got only one output. So, its v out alright now S out is always v out and what is I out in that case? You do not know right. So, let us work this out in the next class we will we are yet to work this out right. This is a little more intriguing this is a little more complicated.

Let us work this out in the next class for now I need to summarize and what we have done today is we have worked out circuits that can handle interference. First we worked out circuits that can handle interference, then we suggested that maybe we do amplifier one amplifier 2 and then we suggested that maybe not we should use our nice theorem to do a better design. And the better design is when I get for the differential signal I get high gain and for the average signal I get low gain. And this was my standard circuit right where as far as the high gain is concerned I get a common source amplifier, for the low gain I have a source be generated common source amplifier ok.

And then I said no the source degenerated common source amplifier is even better when I have a current source over there and therefore, this is the basic structure of my differential amplifier. So, we are going to study this, but before studying this I worked out a few terms common mode differential mode right; these are the two different terms that we are we popping we commonly use and common mode refers to the average differential mode refers to the difference.

So, common mode average at the output average at the input right so on and so forth. And then finally, we are discussing common mode rejection ratio which is the ratio of S out by I out and S in by I in or in other words differential gain by common mode gain. So, I have worked out the 2 output case if the out; if there is only one output there is a little bit of a question mark what is S out by I out going to be? So, we need to will work it out; hope to see you in the next class

Thank you.