Integrated Circuits, MOSFETs, OP-Amps and their Applications

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Lecture – 17
Operational Amplifier Characteristics Contd.

Welcome to this module and in this module, we will see some more characteristics of an operational amplifier. Until now, we have seen few characteristics of an operational amplifier including the block diagram of an op-amp. And we have also solved one problem related to the input bias current and input offset current.

So, here let us see few more characteristics of operational amplifier and that will be the end of this particular module. And then we will continue the circuits of op-amps in the next lecture.

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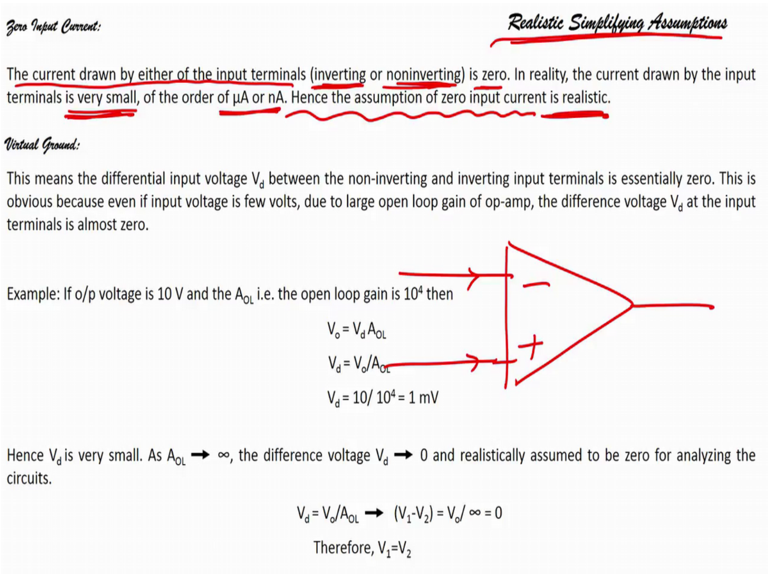

So, if you come to the screen; what we see here is realistic simplifying assumptions. There are few assumptions that is realistic and we will assume something; the first one is 0 input current. So, what is it? The current drawn; this is what we are assuming as far it is realistic and simplifying assumption.

The first assumption is the current drawn by either of the input terminals inverting or non inverting is 0; these are first assumption. That the current drawn by either of the input terminals, so when we say either of input terminals means we had two terminals inverting terminal. non inverting terminal and we have output terminal. What we are assuming is that the current drawn by inverting or non inverting terminal is 0.

In reality, the current drawn by the input terminal is very small that we have seen. While understanding input bias current; input offset current, we saw that there is a very small current that flows in the inverting and non inverting terminal; which is order of microamps to nanoamps, hence the assumption of 0 input current is realistic.

Second and the most important concept in op-amp is the virtual ground; what is virtual? Virtual means not real. So, what is it? This means that the difference in input voltage V d between the non inverting and inverting input terminal is essentially 0. This is obvious because even if input voltage is of few volts; due to large open loop gain the difference of voltage V d at the input terminal is almost 0.

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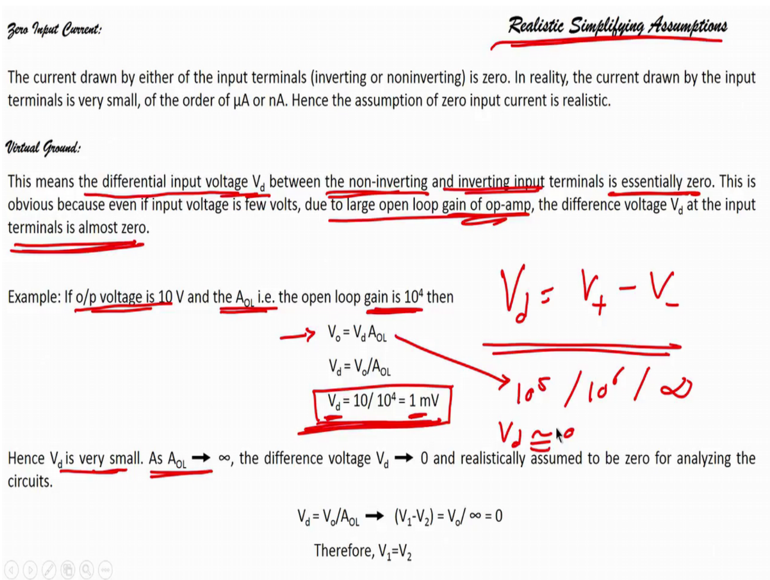

So, the differential voltage V d; V d will be what? V d would be V at non inverting minus V at inverting; it is a differential voltage. We assume that the differential voltage is essentially 0; if this is essentially the 0, then this is obvious because the input voltage even if it is few volts; due to large op-amp the difference of voltage V d will always be 0.

Let us see an example if a output voltage is 10 volts and A OL; that is open loop gain is 10 raised to 4, then what we can write? V o equals to V d into A OL; V o is an output voltage, V d is a difference voltage. So, is from here V d will be V o upon A OL or V d will be very small which is 1 millivolt. Now hence V d is very small as A OL is infinite see for 10 raised to 4, you can get V d of 1 millivolt. But if I increase to 10 raised to 5; if I increase to 10 raised to 6, if I go on increasing 10 raised to infinite, then what will happen? or infinite tension for infinite; infinite.

What is this value? These are the values of open loop gain; if I keep on increasing the open loop gain, my V d will come near to 0, my V d will come approximately equal to 0. So, the point that we are making here is that the difference voltage V d is 0 and realistic assumed to be 0 for analyzing the circuits.

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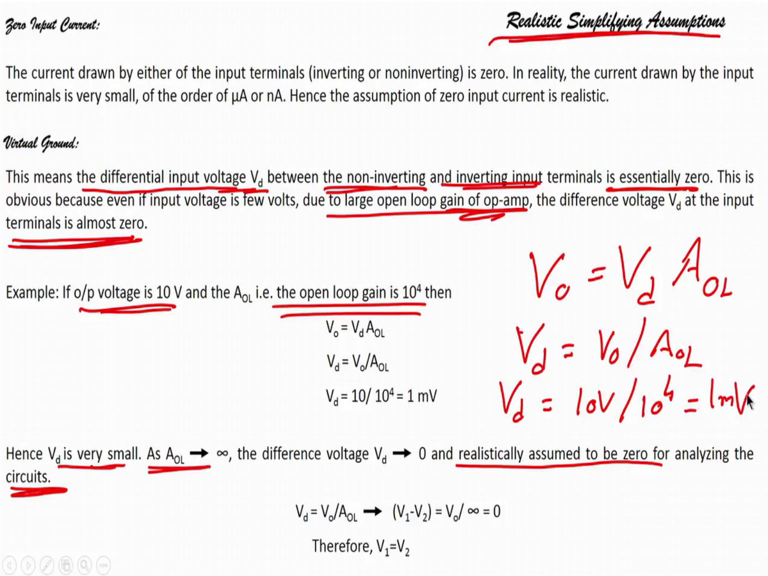

So, if I have this particular equation which is very easy to understand that the output voltage is nothing, but difference of the input voltage; V d into open loop gain A OL. So, if I want to have V d, then V d is nothing, but V o divided by A OL. Now in this particular case our output voltage is given, our open loop gain is given; that means, we can have V d equals to output voltage is 10 volts divided by open loop gain is 10 raised 4; which gives us answer of 1 millivolts.

Now, V d is very small and as A OL goes towards infinity; the difference voltage V d will become 0 and the realistically assume 0, for analyzing the circuits that so; that means, that this is also realistic simplifying assumption saying about the virtual ground let us further see.

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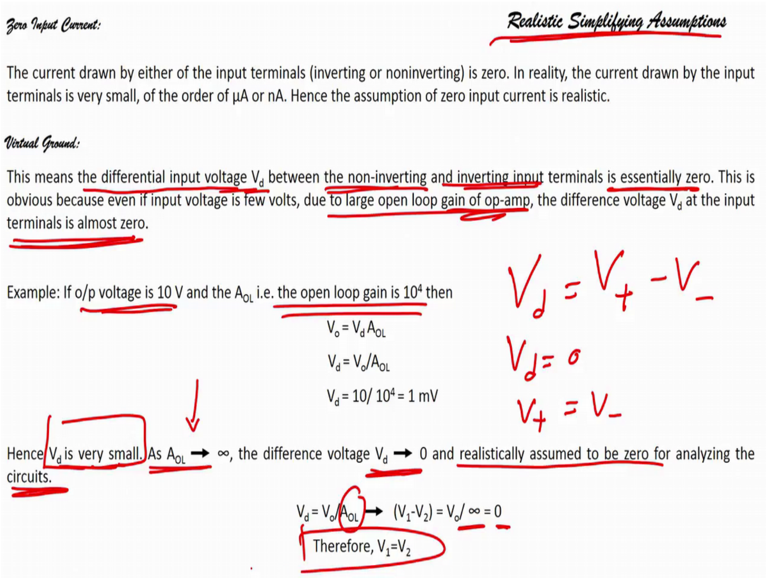

So, if I put infinite as A OL value my V d will become 0; therefore, if V d is 0; if V d is what? V d is V 1 minus V 2 or in another way I can also write V d is nothing, but a voltage in non inverting terminal minus voltage inverting terminal. If I have V d equals to 0; that means, my voltage at inverting terminal should be equal to voltage at non inverting terminal; this much is easy.

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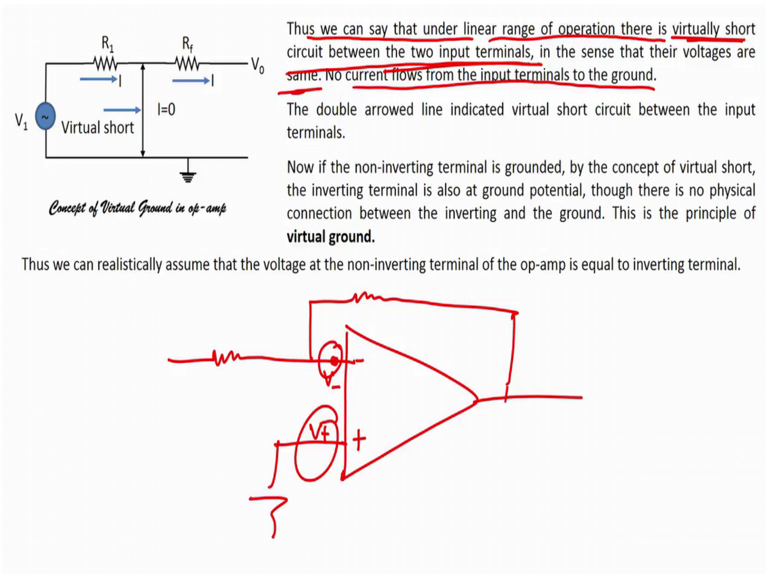

So, if that is the case what we can say that? Thus we can say that under the linear range of operation, there is a virtual short circuit between two input terminals. In the sense that the voltages are same and no current flows from input terminals to the ground.

So, if I draw a circuit and if I have ground here then this terminal minus and plus; let us say this is V minus, this is V plus then this is at virtual ground because this is ground; that is what we have understood until now. Because if my gain is different; then I will have different value of input voltage, but difference voltage V d.

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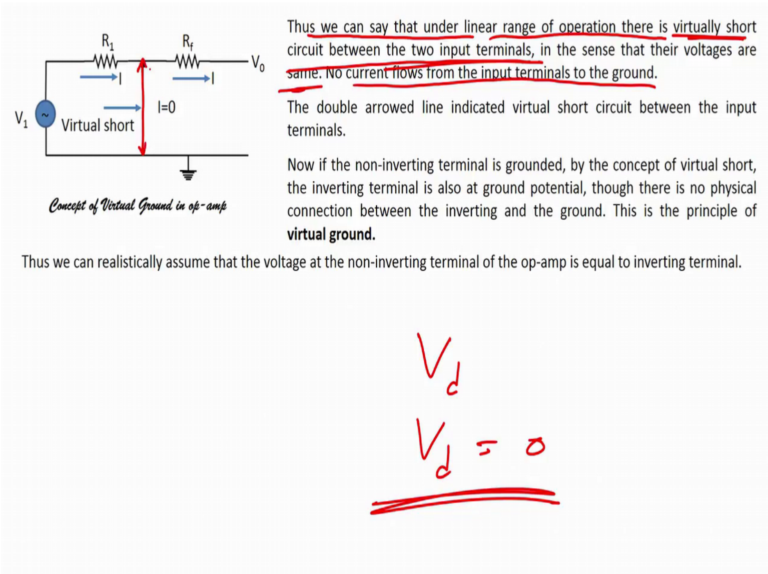

But if my gain is infinite, my V d will be 0 and if V d is 0; that means, my non inventing terminal is same at inverting terminal. If inverting terminal is grounded non inverting also grounded; that means, it looks like we are virtually shorting the two ends of the op-amp; two input terminals of the op-amp.

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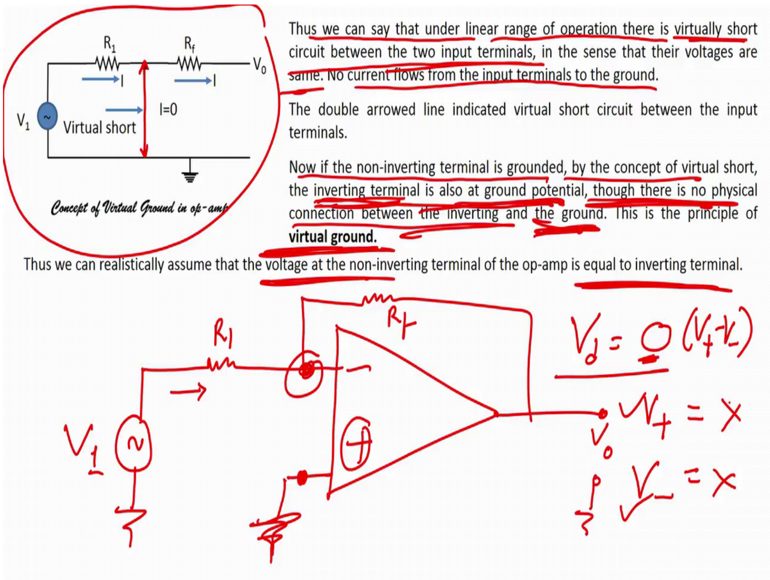

So, this circuit what you can see here; inverting, non inverting; this is R f, this is R 1, this is current, ground.

Now, what we are saying is; this particular terminal will be similar to this terminal because of the concept of virtual ground; this is what circuit is. So, there is a virtual short; now if the non inverting terminal is grounded, by the concept of virtual short; inverting terminal also is at ground potential. Though there is no physical connection between inverting and the ground; you see, is there any physical connection like this? Like this? No right? There is no physical connection or wire there connecting inverting and non inverting terminal.

So, now if the non inverting terminal is grounded; if this terminal is grounded then by the concept of virtual short the inverting terminal is also ground potential; though there is no physical connection between the inverting and the ground. As there is no physical connection between inverting terminal and ground; this is also called virtual ground.

Thus we can realistically assume that voltage at the non inverting terminal of the op-amp is equal to the voltage at the inverting terminal. Why? Because my V d would be 0 because my V non inverting and V inverting voltage are same. Suppose this is X; this is also X and V d is nothing, but V plus minus V plus minus; V minus X minus X; same value; so this will be 0. So, my answer is 0; if this is a 0; that means, I am assuming that

V plus and V minus are connected. If V plus is grounded, then V minus is also called virtual ground this is the concept of virtual ground.

That means, that we can realistically assume that the voltage at the non inverting terminal of the operation amplifier is equal to the inverting terminal. So, this is what is your virtual ground; now I hope that you guys can understand what we mean by virtual ground.

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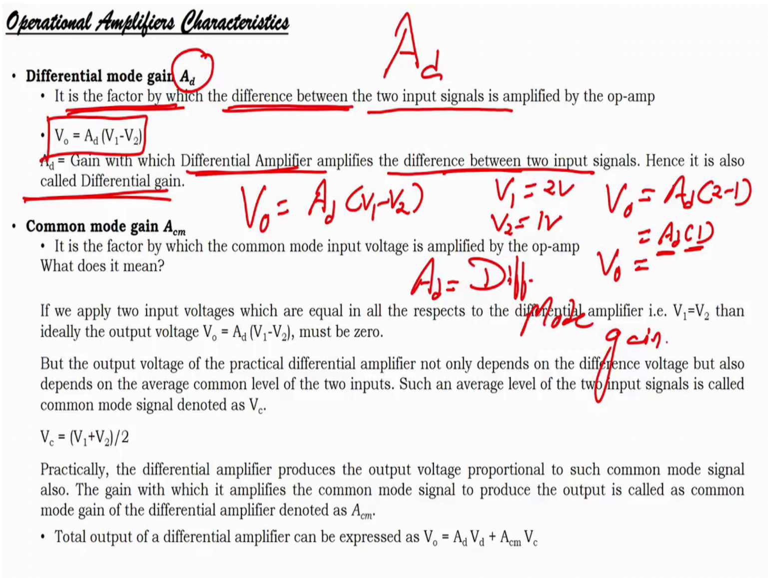

So, let us see some other characteristics; let us see other characteristics of operational amplifier. Let us see some more characteristics of an operational amplifier; starting with differential mode gain. So, what is differential mode gain?

Differential mode gain is given by A d; gain is a differential mode that is why d; then we have a symbol A d for differential mode gain. What is it? It is a factor by which the difference between two input signal is amplified by the op-amp. So, if my V o equals to A d into V 1 minus V 2; A d is gain with which differential; amplifies the difference between two input signals and it is also called differential gain.

That is if I have V o; I am writing the same equation A d into V 1 minus V 2. In this case my V 1 is 2 volts, V 2 is 1 volt; then my V o would be nothing, but A d into 2 minus 1, that is A d into 1 and what is my A d? Whatever my gain of A d would be there; my difference voltage would be amplified by that particular gain and that is why A d is called differential mode gain.

Easy? So, now, we know what do you mean by differential mode gain? Concepts are really easy. If you really think what we are looking at; is we are just at some equations which are so, simple to understand. So, when you talk about differential mode gain; you can easily see, it is a difference of voltage and we are amplifying the differential and that is why it is a differential mode gain. So, now let us see the another concept which is the common mode gain. So, when we see common mode gain; you will see a little bit different than compared to differential mode gain.

So, if you see common mode gain on the slide; what we see? That it is a factor by which the common mode input voltage is amplified by the Op-amp; it is a factor by which the common mode; this word very important, input voltage common mode input voltage is amplified by the operation amplifier. So, what does it mean? If we apply two input voltages, which are all in equal respects to the differential amplifier; which are equal in all respects, then V 1 equals to V 2 So, that will give us; we have this one V o equals to A d into V 1 minus V 2.

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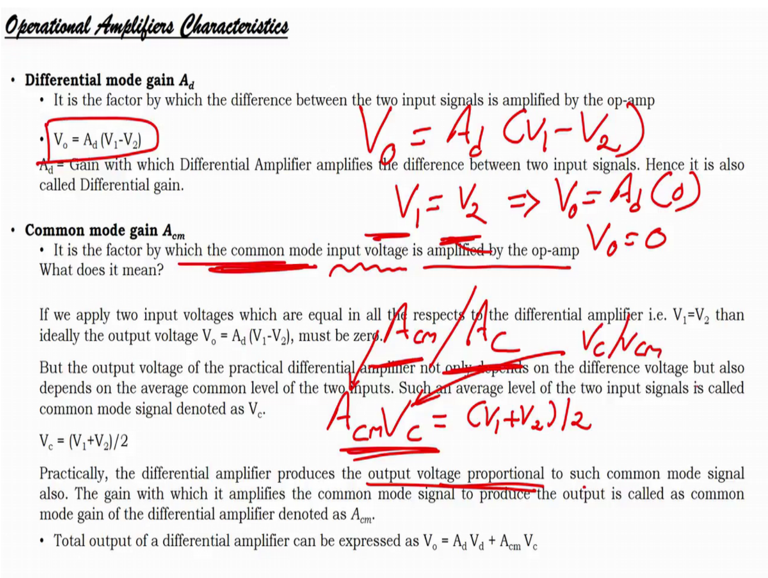

If I say I am applying V 1 equals to V 2 that is why voltage is area same at the input of terminal that implies that my V o is nothing, but A d into 0 or V o is nothing, but 0 because V 1 is equal to V 2; correct? Because V 1 equals to V 2; my output voltage will be 0; this is what we are saying that if we apply two input voltages, which are equal in all respects to the differential amplifier then my output voltage must be 0.

But the output voltage of the practical differential amplifier not only depends on a difference voltage, but also depends on the average common mode level of two inputs you see. So, it does not only depends on differential voltage, but also depends on the average common mode level of input; such as average low level of two input signal is called common mode signal, denoted by V c. So, if I want to know the common mode signal this is nothing, but average of V 1 plus V 2 by 2.

Practically the differential amplifier produces the output voltage proportional to such common mode signal also. The gain with which, it amplifies the common mode signal to produce the output is called the common mode gain of the differential amplifier denoted by A cm. So, what does it mean?

That when we take amplifier and we insert the amplifier in the circuit; then what we see is that the output voltage is proportional to such common mode signal. So, it is also proportional to V c and the gain with which it amplifies this V c is called my common mode gain. Either I say A cm; I can also say A c; common mode gain; this is common mode voltage; V c or V c m.

So, now let us read once again the sentence and we will understand what does that mean? Practically, the differential amplifier produces the output voltage proportional to such common mode signal; the gain with which it amplifies the common mode signal to produce the output is called the common mode gain A cm.

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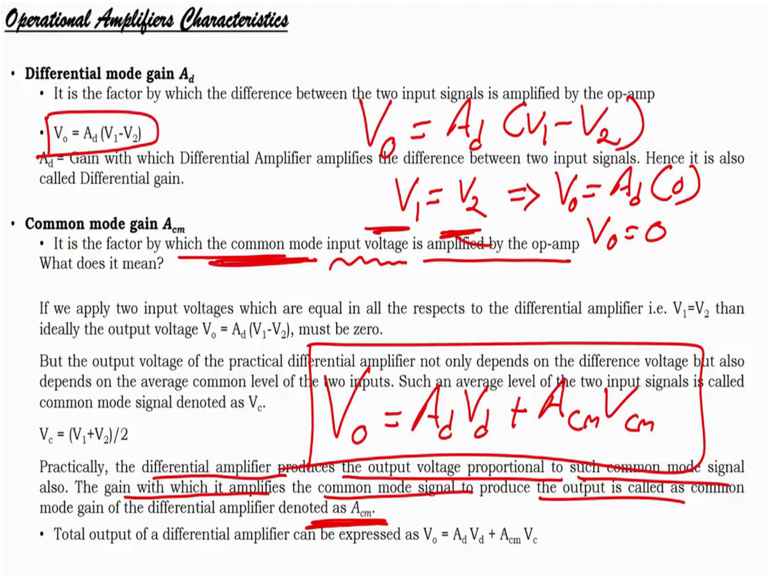

So, now my V o will not only depends on A d; V 1 minus V 2 is what? V d plus it will also depend on A cm and V cm. Now it will depend on the common mode gain and the common mode voltage. So, my new formula for output voltage will be A d, V d plus A cm, V c m.

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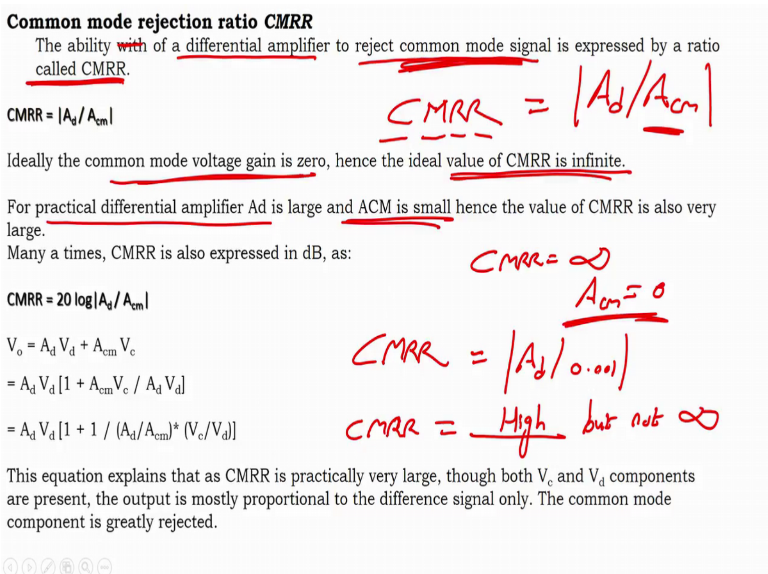

So, in this particular case; I will use this common mode signal, I will use the common mode gain, differential gain; to understand a very important property which is called common mode rejection ratio; a very important term for an operation amplifier. The ability of a differential amplifier to reject common mode signal is expressed by a ratio called common mode rejection ratio.

Because we do not require common mode signal, we only require the differential signals A d; V d, this is what we require. See in equation; what we have written? A d; V d plus A cm, V cm; V o equals to this one, but in reality common mode signals; we do not want common mode signals, we only want the differential signals.

So, if I know the ratio; there are differential amplifier can reject the common mode signal by a ratio called CMRR CMRR; Common Mode Rejection Ratio, it is given by mode of A d by A cm; differential gain divided by common mode gain. So, ideally common mode voltage is 0; ideally common mode voltage should not be there. So, ideally A cm should be 0; if A cm is 0, my CMRR would be nothing, but infinite; that is what then write ideally common mode voltage gain is 0; hence the ideal value of CMRR is infinite.

But for practical differential amplifier; A d is large, A cm is small; this c m should be in subscript, A d should be in subscript; A d should be large, A cm should be small hence the value of CMRR is also very large.

So, practically we cannot have A cm equal to 0; practically this is not possible, but A cm can be close to 0. Then if A cm is close to 0; let us say 0.001; then what will happen? My CMRR would be very high; but not; it will be very high, but not infinite.

So, CMRR is also many times expressed in decibels and CMRR is nothing, but 20 log A d by A cm. This is a value when we had to go express in decibels. So, now if V o equals to A d, V d plus A cm and V c m; if I keep common A d; V d, then finally, I will get equation which his similar to this. This equation explains that a CMRR is practically very large though both V c and V d components are present; you can see V d and V c are present, still this CMRR is very less; the output is mostly proportional to the different signal only and common mode component is greatly rejected.

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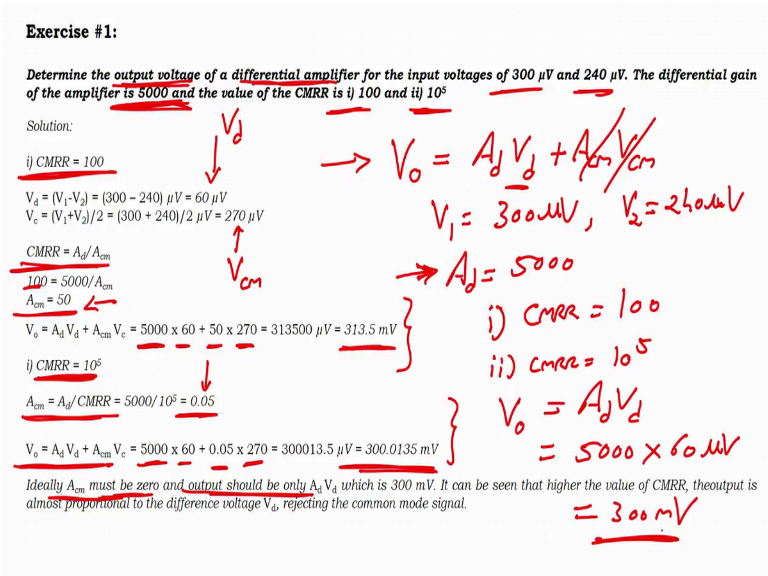

Now, to understand whatever we have told about CMRR; we have to solve some problem, then we will understand how CMRR is important? So, let us perform one exercise and that exercise is; we have to determine the output voltage of a differential amplifier.

So, what is said? That you determine the output voltage of differential amplifier; so, V o is nothing, but A d, V d plus A cm into V c m; we know this formula. Now, we are given input voltages; this is input voltage 1, input voltage 2. So, we are given V 1; 300 microvolts, we are given V 2; 240 microvolts; the differential gain of the amplifier is 5000; so, we know that A d is also given; 5000.

Now in the value of CMRR; so, for two values we have to calculate; first one, first value is given as CMRR equals to 100. Second value is given as CMRR equals to equal to 10 raised to 5. So, for the first one CMRR equals to 100 V d is what? V d is nothing, but V 1 minus V 2. So, we will substitute V 1 V 2; so, we get V d which is 60 microvolts.

What is V c? V c is V 1 plus V 2 by 2; we substitute 300 plus 200 by 2; we get 270 microvolts. What is CMRR? CMRR is A d by A cm; so, we have CMRR for 100; A d we have 5000, by A cm. From here what we will get? We will get A cm equals to 50; now what we know? We know V d, we know V c m, we know A cm.

So, let us substitute this value is in V o; so, V o will be A d; V d plus A cm, V c. So, what is A d? A d is 5000 here; given here 5000, then 60; 60 is what? My V d plus what is my A cm? 50; what is my V c? 270. When I solve this; what I get? 313.5 millivolts; this much is easy.

Now let us do the same calculation with CMRR equals to 10 raised to 5. When CMRR is equal to 10 raised to 5, what will be my answer?. So, for CMRR equal to 10 raised to 5 A cm equals to; you know that equation? CMRR equals to A d by a c m, so A cm would be nothing, but 0.05.

If I substitute this value; again in this equation rest of the things remain same; only my CMRR is 10 raised to 5. So, my A cm would change; in this case when I substitute the value; same value, same value, this is new value; 0.05, this is same value like previous example. So, what we have? Our value is 300.0135 millivolts. Here what was the value? 313.5 millivolts, here we have 300.0135 millivolts.

Now if I see; ideally A cm must be 0 and output should be equal to A d; V d only. So, if I just say; ideally my A cm, V c m should not be there and my V o should be nothing, but just A d into V d; this is ideal situation.

What is A d? Let us see A d; where is A d? 5000; 5000 into V d; what is V d? V d is 60 what is 60? 60 microvolts. So, my answer would be 300 millivolts. This is the ideal situation; when I have A cm, V c m is not there because common mode signal should be 0; this is the ideal situation my output should be 300 millivolts. Now you see, which value we obtained; which output voltage is close to 300 millivolts, whether it was a CMRR equals to 100 or it was CMRR equals to 10 raised to 5.

We will see that when you use CMRR equal to 100; my output voltage that we got was 313.5; my output voltage should be close to 300 millivolts, but when I use CMRR equal to 10 raised to 5; my output was 300.0135, which is close to 300 millivolts. That means, what I see is; if I keep on increasing CMRR, my output is close to my ideal value.

Guys, so for this particular module; we will stop here now you know how to use the CMRR? And what are the common mode gain? What are the differential gain? What are common mode voltage? What are differential mode voltage? We have seen an example; now if somebody ask you in a exam or in a viva; that if what should be the CMRR? It should be high? It should be low? Then you can you can answer very easily, the CMRR is a common mode rejection ration and it is given by differential gain by common mode gain. And CMRR is exploited to be extremely high because we do not require any common mode signal. You can also say that A as a common mode signal is low; my CMRR would be extremely high.

If my CMRR is high; my output voltage will be close to my realistic or ideal value, which is V o equals to A d; V d because in reality V o equals to A d; V d plus A cm; V c m, but ideally my V o would be A d into V d. So, if I do not want to consider A cm; V c m in practical situation I cannot just ignore A cm; V c m. So, in that case if my CMRR is extremely high, my output voltage would be close to my ideal voltage and thus the importance of CMRR comes into picture.

So, now you guys know how to use CMRR, you guys know how to use the; this is the parameter this is one of the parameter of a differential amplifier or our realistic parameter of operational amplifier. You have also seen what is virtual short; very important parameter virtual short.

Now, in the next module we will see few more parameters of the operational amplifier. Till then you just read once again, whatever I have taught and I will see you in the next class. Bye.