Integrated Circuits and Applications

Prof. Shaik Rafi Ahamed
Department of Electronics and Electrical Engineering Indian Institute of Technology, Guwahati

Introduction to Operational Amplifiers
Lecture – 02
Summing and Difference Amplifiers

In the last lecture I have given introduction to Operational Amplifier. Today we will discuss some of the applications of the operational amplifiers. Before going to the applications, I will discuss the different modes of the operational amplifier. So, you can operate this operational amplifier in either closed loop configuration or open loop configuration. So, as I have discussed in the last lecture, that the equivalent circuit of this operational amplifier is, We have the two input terminals, there will be some input resistance, there will be output voltage, output resistance, the output will be taken across these two terminals. Here the input is applied, this is the difference voltage, I call this one as v_1 v_2, $v_d = v_1 - v_2$.

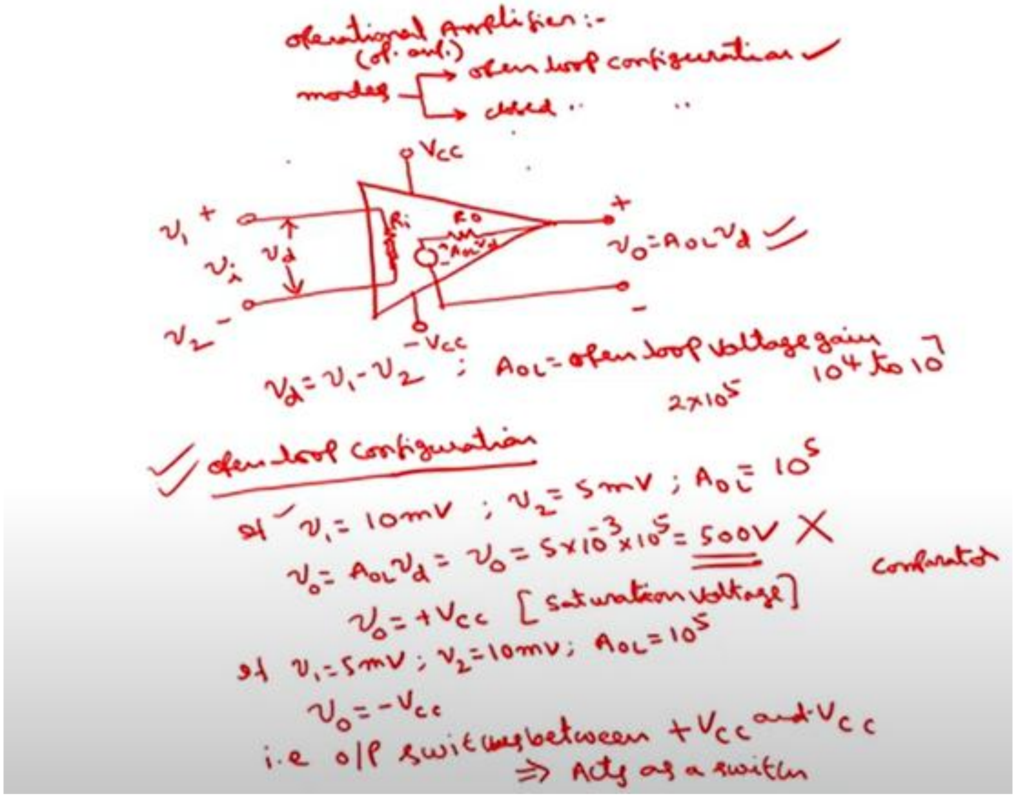
This is input resistance Ri, this is output resistance Ro, the output voltage is A_{OL} times V_d, where A_{OL} is called as open loop gain. As the name implies this is an open loop configuration, we will consider the open loop gain. Open loop voltage gain. There are some limited applications of this op-amp in open loop configuration.

So, I will discuss why the open loop configuration is rarely used for operational amplifiers. If I assume that the input voltage $v_1 = 10mV$ and $v_2 = 5mV$ and $A_{OL} = 2 \times 10^5$. As I have told in case of 741 op-amp this is 2×10^5. So, normally this open loop gain varies from 2×10^4 to 2×10^7. So, what will be the output voltage V_0? V_0 is A_{OL} times if I neglect the drop across this Ro,

$$v_o = A_{OL} \times v_d = v_o = 5 \times 10^{-3} \times 10^5 = 500V.$$

So, theoretically it will be 500V, but 500V is not possible. So, the maximum voltage that we will get at the output of the operational amplifier which is called as the saturation voltage, that is equivalent to the power supply voltage. This is $+V_{CC}$ and this is $-V_{CC}$ whatever the output voltage which is greater than V_{CC} output will saturate to V_{CC} only, this is what is called saturation voltage. So, on the other hand if I take reverse $v_1 = 5mV$ and $v_2 = 10mV$ and $A_{OL} = 2 \times 10^5$.Then what will be output voltage? Suppose to be -500V, but this will saturate to $-V_{CC}$.

(Refer to the slide at 05:54)



Means the output of the operational amplifier in case of open loop configuration varies between or switches between two states, plus V_{CC} and minus V_{CC} means this will acts as a switch. So, in order to operate this operational amplifier for amplification applications, we cannot use this operational amplifier in open loop configuration. But open loop configuration is having some applications, such as the comparator. We are not implement the comparator using op-amp we have to operate this op-amp in open loop configuration. Op-amp is actually short form of operational amplifier.

And second application is waveform generator. In waveform generator also we can use this operational amplifier in open loop configuration. Except for that in most of the applications we will use this op-amp in closed loop configuration. So, coming for this closed loop configuration. In closed loop configuration we are going to use feedback.

The drawback of open loop configuration is it will be having very high gain. So, of the order of $10^4$to 10^7. So, the drawback of this open loop configuration is still be having high gain. So, which is of the order of 10^7. So, in order to reduce that gain normally we will use feedback.

So, in that feedback also we have two types of the feedbacks, negative feedback and positive feedback. So, normally negative feedback decreases the gain. This you might have studied in your feedback amplifiers whereas, positive feedback increases the gain. So, this positive feedback will be used in applications such as oscillators, whereas negative feedback will be used in applications such as amplifiers. So, if you take this operational amplifier with negative feedback, there are two important circuits or the amplifiers in negative feedback configuration.

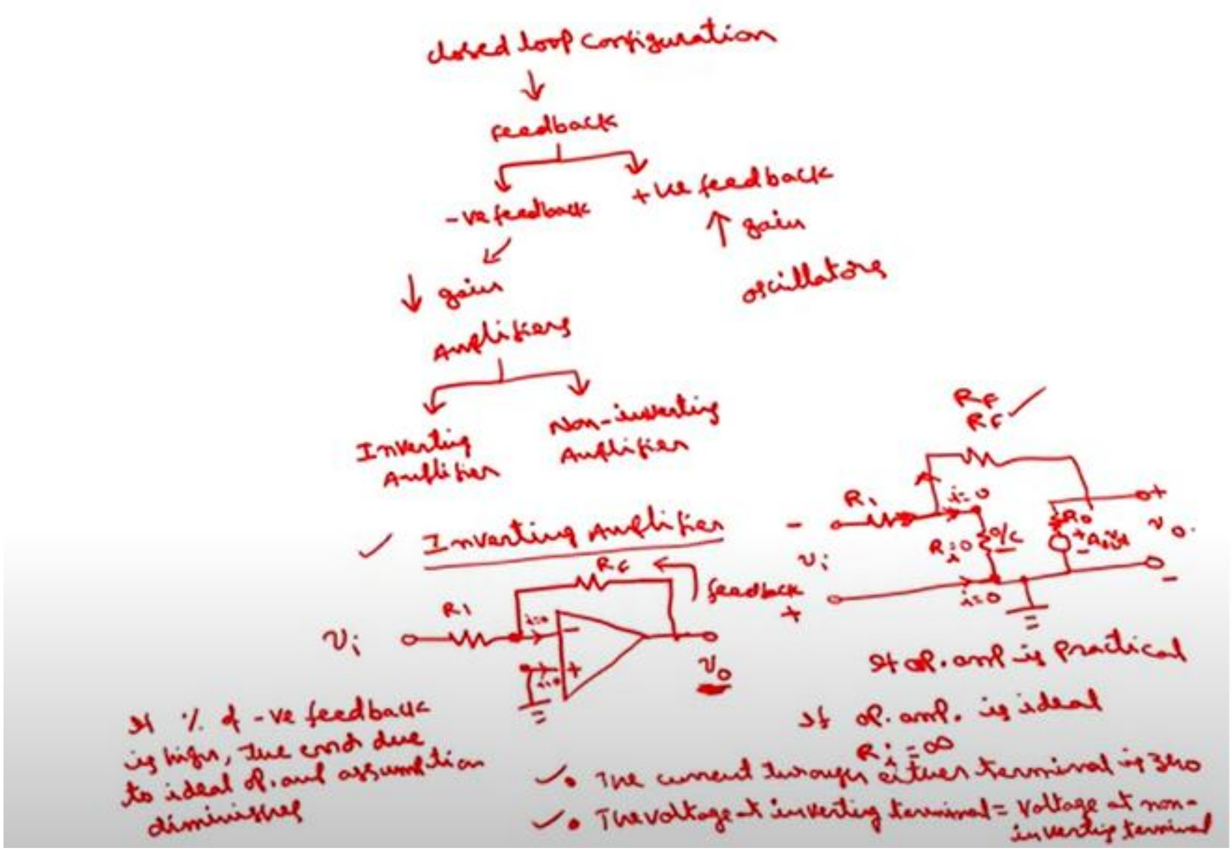
So, this amplifiers in negative feedback using op-amp are called as inverting amplifier and non-inverting amplifier. So, if I consider this inverting amplifier circuit diagram, this is the operational amplifier, which is minus plus the input is applied at inverting terminal output is taken from here. This is the output voltage v_o this you called as a R_F R_1. This is the circuit diagram of simple inverting amplifier. Now, here if I assume that operational amplifier is operating in a practical mode then the analysis will be somewhat difficult.

So, if I take this the equivalent circuit if I consider this operational amplifier in practical mode. So, this will be the input circuit. So, inside this will be having Ri, this will be output resistance, this is the output voltage, this is the way you are going to take output, this is the feedback resistance R_F. This is Ri, this is R_o, this is plus minus A_{OL} times v_d, this is $\pm v_o$. This is equivalent circuit if op-amp is practical.

So, here the analysis will become difficult. So, what we will assume is we will assume that operational amplifier is ideal. Then for ideal operational amplifier $R_i = \infty$. So, this $R_i = \infty$, means this will acts as open circuit. So, that whatever the current flowing through this terminal is 0, this terminal is 0.

Suppose the current that is flowing through this will pass through this one whereas, the current through this one is 0. Here i is equal to 0 because there is a open circuit here and here also i is 0. So, by assuming that the operational amplifier is ideal there are two assumptions which are very important in the analysis of any operational amplifier circuit. The first assumption is because this Ri is infinity, the current through this inverting terminal as well as non-inverting terminal from here to here this is 0, this i is equal to 0, this i is equal to 0. So, the current through, either terminal is 0.

(Refer to the slide at 14:46)



This is one of the important assumption. And second assumption is because this will acts as open circuit, the voltage at this point and voltage at this point are same that is voltage at inverting terminal and voltage at non-inverting terminal is same. Second assumption is the voltage at inverting terminal is equal to voltage at non-inverting terminal. And because of this negative feedback if I properly choose this negative feedback, if this percentage of negative feedback is high, a large amount of this output is feedback to the input this is feedback, this is feedback. A large amount of this v_o is fed back to the input then in that case.

So, whatever the output that we are going to get. So, that will be almost equivalent to that of the practical circuit. If the percentage of feedback is high, the error due to ideal assumption, ideal op-amp assumption, diminishes means it is decreases. Means even though if you assume this op-amp as ideal, the amount of the error that we are going to get from the practical op-amp and ideal op-amp is very very less that is negligible. So, that is why so, normally we will assume that op-amp is ideal in most of the practical applications in especially for the analysis of the operational amplifier circuits.

So, these are the two important assumptions that we have to assume to analyze any operational amplifier assuming that op-amp is ideal. So, now, with these assumptions I will derive the expression for the voltage gain of this inverting amplifier. So, the voltage gain of inverting amplifier. This is input v_i, this is R_1, this is R_F, this is output v_0. So, two basic assumptions are the current through this one is 0, current through this terminal is 0 and the voltage at this point is equal to voltage at this point.

So, voltage at this point is 0 volts because this is grounded 0 volts means this is also 0 volts. So, if I assume that this is current I, the entire current will flows through the feedback distance because the current through this terminal is 0. So, the voltage gain can be defined as A_V output voltage by input voltage $A_V = \frac{v_o}{v_i}$. So, in the previous slide we have used A_{OL} which is open loop gain whereas, here this is feedback gain, A_V is the gain with feedback. A_{OL} is as the name implies open loop voltage gain whereas, this is voltage gain with feedback.

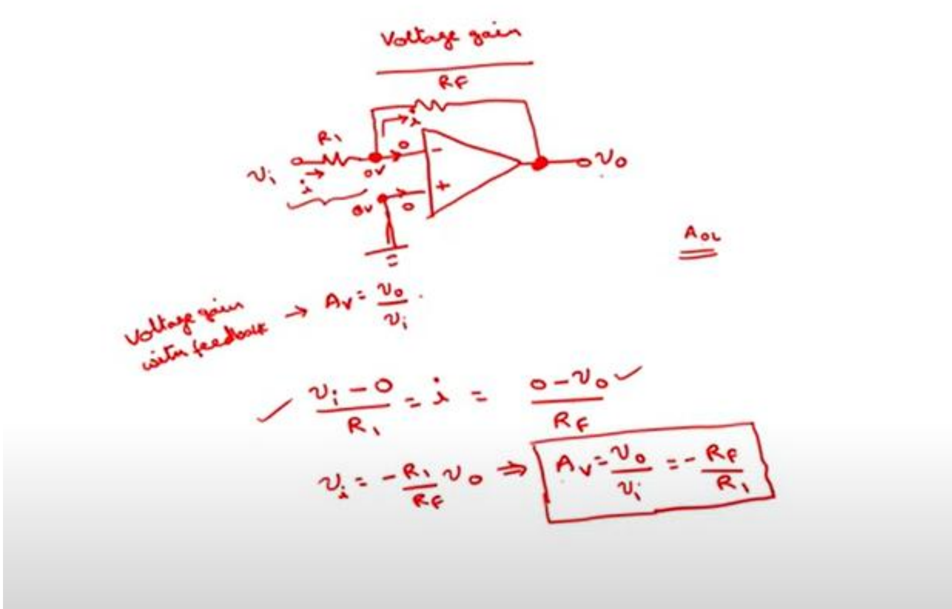
So, what is the expression for the current?

$$\frac{v_i - 0}{R_1} = i = \frac{0 - v_o}{R_F}$$

$$v_i = -\frac{R_1}{R_F} v_o \Rightarrow A_V = \frac{v_o}{v_i} = -\frac{R_F}{R_1}$$

So, this is the expression for the voltage gain of operational amplifier with negative feedback assuming that operational amplifier is ideal. If it is a practical op-amp then we will get a different expression for this voltage gain which is A_{VL}.

(Refer to the slide at 17:46)



Now, the second important circuit is non-inverting amplifier. As the name implies gain is positive, in case of inverting amplifier the gain was negative now the gain is positive. Now, the signal is applied to the positive terminal this is v_i, this will be grounded, this is R_1, this is R_f, this is v_0 output voltage.

So, what is the expression for the voltage gain with feedback? Here also if I assume that this current is i, here the current is 0, here the current is 0. So, the entire current will flows through the feedback resistance. Now, here what is the voltage here now, this is short circuit this is v_i means voltage here is also v_i only the second assumption. First assumption is the current through either input terminal is 0 and the second assumption is the voltage at inverting terminal is equal to voltage at non-inverting terminal. So, voltage at non-inverting terminal is v_i.

So, inverting terminal also the voltage is v_i. Then what is the expression from the input side for the current?

$$i = \frac{0 - v_i}{R_1}$$

$$i = \frac{v_i - v_o}{R_F}$$

$$-\frac{v_i}{R_1} = \frac{v_i - v_o}{R_F} \Longrightarrow v_i - v_o = -\frac{R_F}{R_1} v_i$$

$$v_i + \frac{R_F}{R_1} v_i = v_o$$

$$v_i[1 + \frac{R_F}{R_1}] = v_o$$

Therefore, voltage gain

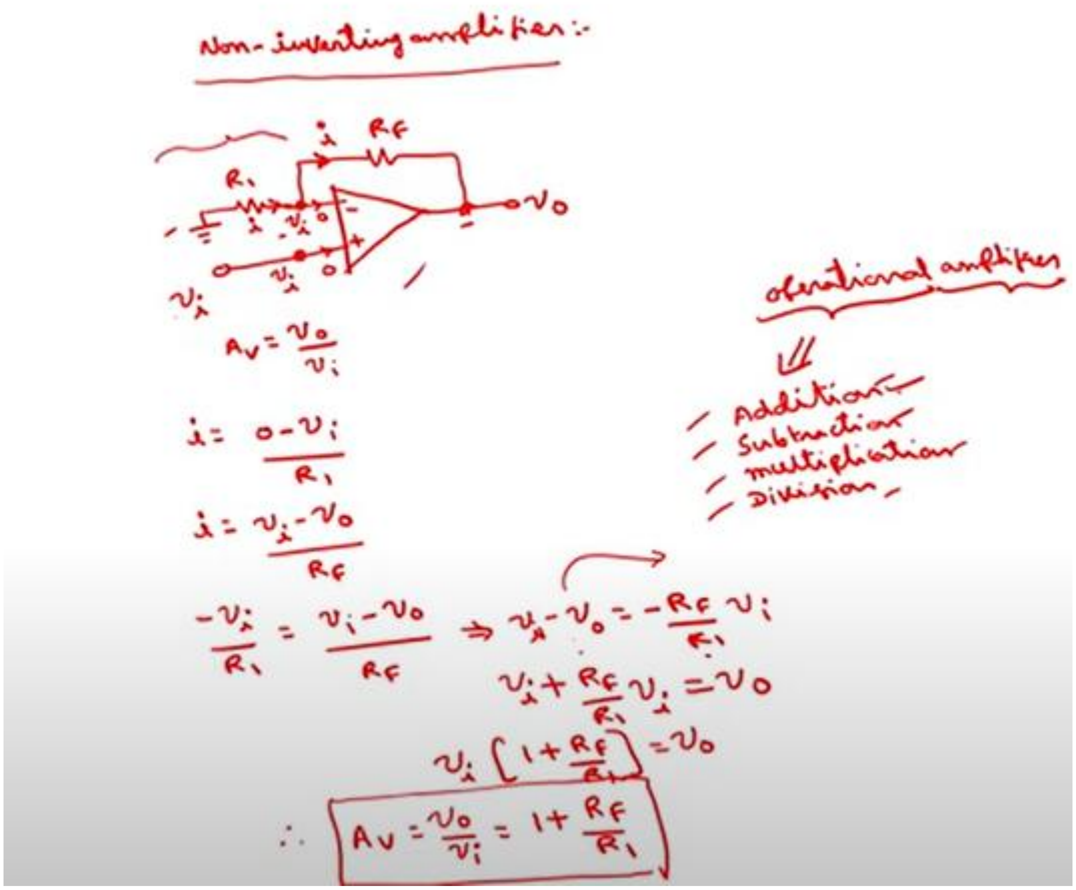
$$A_V = \frac{v_o}{v_i} = 1 + \frac{R_F}{R_1}$$

This is the expression for the voltage gain of non-inverting amplifier. Now, we can extend this concept to realize the adder circuit. So, as the name implies as I have discussed in the last lecture this is operational amplifier. This is amplified in addition to that this will perform some operations also.

So, what are the different operation that will be performed if the first operation is addition? We can implement this operational amplifier to realize the addition operation. We can use for subtraction, for multiplication, division many other applications. Many other arithmetic operations can be performed by using this operational amplifier that is by name operational amplifier. So, in the earlier days when digital technology was not invented. So, these computers used to perform this addition, subtraction, multiplication, division by means of operational amplifier.

The olden days computers are based on the analog circuits. So, in those analog computers the addition, subtraction, multiplication, division will be performed by using operational amplifiers.

(Refer to the slide at 22:26)



So, now I will discuss how this addition operation will perform by using operational amplifier. This is called summing amplifier. It will perform some operation as well as will provide amplification also.

This also can be as adder. I just take a 3 input adder and I will first use this operational amplifier in non-inverting configuration. This is v_1, v_2, v_3 let this is R_1, R_2, R_3. This is the output voltage v_0 and this is the feedback resistance R_F. Now, what is the expression for output voltage v_0? So, this is a similar to inverting amplifier, but in inverting amplifier we have only this one input only now we have 3 inputs. So, there is one famous theorem called superposition theorem.

You might have shown in circuit theory or network analysis. So, this superposition theorem states that, the output correspond to several sources. Here I have 3 sources v_1, v_2, v_3. This will give some output let us call this output as v_{01} this will give some output say output voltage correspond to only v_2 is v_{02} correspond to v_3 the third input say output is v_{03}. v_{01} is contribution of v_1 only this is contribution of v_2 only this is contribution of v3 only.

Then the total voltage v_0 corresponding to all the 3 sources is equal to according to a superposition theorem v_{01} plus v_{02} plus v_{03}. Now, I will first find out v_{01} the output voltage due to v_1 only. So, what you have to do is you have to make the other two 0 according to superposition theorem $v_2 = v_3 = 0$. Then what will be the equivalent circuit? This is R_1 this R_2 R_3 how to make as 0 this is 0 this is 0 this is R_1 R2 R_3 these two you have to make as 0 you have to ground it. This is the equivalent circuit by considering $v_2 = v_3 = 0$.
And according to this second assumption that the voltage at this terminal is equal to voltage at this terminal this is grounded. So, this is 0 volts this is also 0 volts. So, this is also 0 volts. So, between 0 volts we have R2 and R_3 this is R_2 and R_3. So, means short circuited in the sense these two R_2 and R_3 can be removed.

So, this is again equivalent to only one single resistance R_1 R_2 is between the ground and ground means there is no R_2. Similarly, R_3 is also between the ground and ground. So, there will be a short circuit. So, there will be no resistance. Then what will be the equivalent circuit? This is only v_1 this is R_1 this is grounded this is R_F this output voltage I am calling as this is v_{01} v_{01} because this is due to only output voltage v_1 only v_1 we are calling as v_{01}.

So, now, this amplifier is this is exactly same as inverting amplifier whose gain is minus of this feedback resistance by this input resistance which you have derived in the previous slide. So, therefore, what is the expression for $v_{01} = -\frac{R_F}{R_1} v_1$. Similarly, you can find out the output due to v_2 only, $v_{02} = -\frac{R_F}{R_2} v_2$. Now, this R_1 and R_3 will be grounded if I take the equivalent circuit R_2 into v_2. Similarly, the output due to v_3 only, $v_{03} = -\frac{R_F}{R_3} v_3$.

Therefore, according to this superposition theorem what is v_0

$$v_o = v_{01} + v_{02} + v_{03}$$
$$v_o = -[\frac{R_F}{R_1} v_1 + \frac{R_F}{R_2} v_2 + \frac{R_F}{R_3} v_3]$$

If $R_1 = R_2 = R_3 = R_F$. If I make this assumption then what will be v_0, is $\frac{R_F}{R_1} = 1$, $\frac{R_F}{R_2} = 1$, $\frac{R_F}{R_3} = 1$.

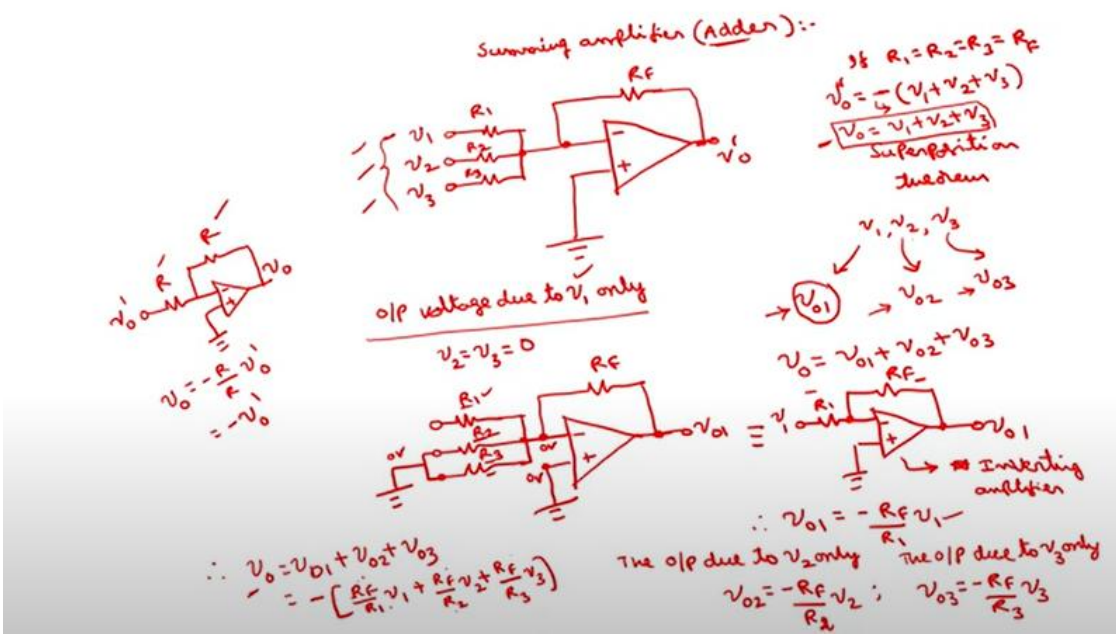
So, simply

$$v_o = -[v_1 + v_2 + v_3]$$

You see adding, but with minus sign extra. So, in order to remove this minus sign I want say $v_o = v_1 + v_2 + v_3$, which is addition of these three voltages that will acts as a adder. Then what I have to do? If I connect this output this is v_o' say. So, to get v_0 this is v_o' to get $v_o = -v_o'$.

So, this we are calling as v_o'. So, v_o' if I apply this is v_o' if you apply to a circuit whose output if I call as v_0 minus plus this is of R and R this is v_o'. So, what is relation between v_0 and v_o' minus feedback resistance by input resistance both are the same. So, this is simply $-v_o'$. So, $v_o = -v_o'$ So, this minus minus get cancel we will get $v_o = v_1 + v_2 + v_3$.

(Refer to the slide at 30:46)



So see you can implement a summing amplifier. Similarly, you can have a differential amplifier or difference amplifier or you can also call as this is a subtractor. Now, discuss will how to implement the addition using operational amplifier. I will discuss how to implement the subtraction using operational amplifier. Let us take simply subtraction of two signals. This is say v_2 this is v_1 and first consider the different resistors this is say R_1, R_2 this is R, R' this is output voltage v_0.

So, what is the expression for the output voltage v_0 of the circuit. So, this you can obtain by using the previous two results which is the gain of inverting amplifier and gain of non-inverting amplifier. So, as I have told if let v_{01} is the contribution is the output voltage caused by v_1 only means we have to keep v_2 is equal to 0 and v_{02} is the output voltage by v_2 only means we have to make v_1 is equal to 0. Then what is v_0? According to superposition theorem v_{01} plus v_{02} first derivation of v_{01}. So, what you have to do for derivation of this you have to keep this v_2 is equal to 0 set v_2 is equal to 0.

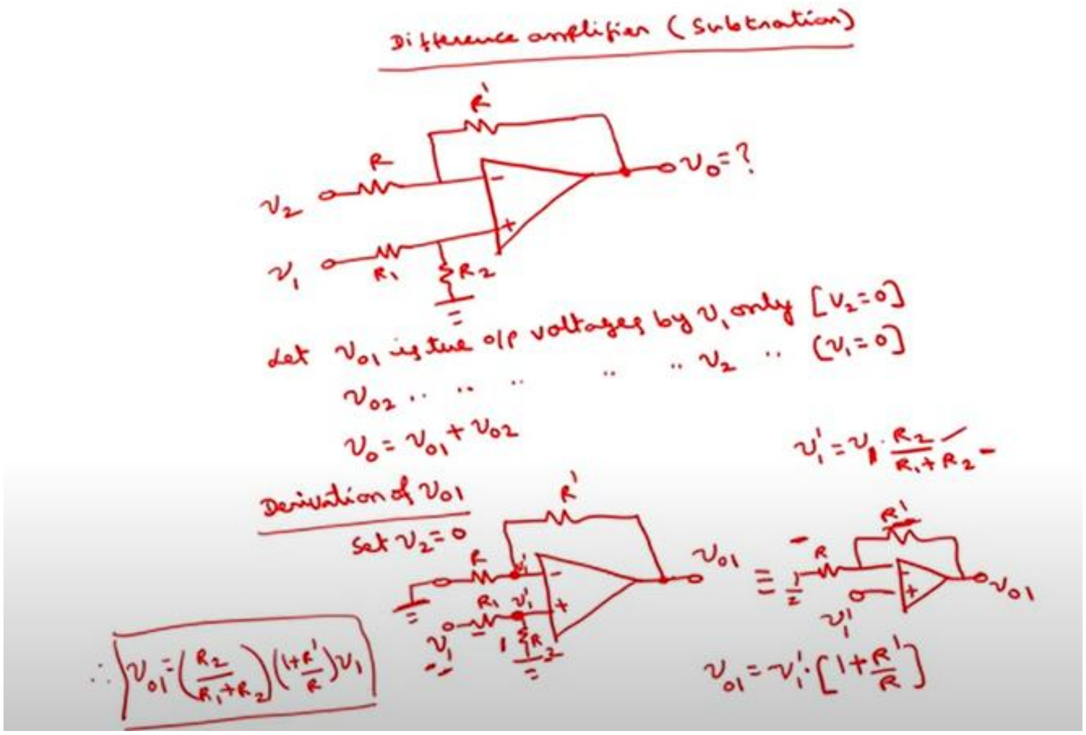
So, what will be the equivalent circuit? So, this equivalent circuit becomes this v_2 becomes 0 grounded. This is v_1 this is R_1 this is R_2 this is R, R' this point is grounded. Now, the whatever, the output voltage that will get this is nothing, but v_{01}. Now, how to get the v_{01} expression? So, what will be the voltage here? Let us call this voltage as v_1'.

So, what is v_1'? Voltage division. So, this v_1 is between R_1 and R_2 I am taking the voltage across R_2 this is voltage division this is equal to $v_1 \frac{R_2}{R_2+R_1}$. So, this v_1 is distributed across R_1 and R_2 to find out the voltage across R_2 you have to take v_1 into the same resistance divided by total resistance. Now, this is v_1' according to one of the assumptions this voltage at inverting and inverting is only the same. So, this is also v_1' this is also v_1'. So, this is v_1' now if I neglect this circuit this is also equivalent to now, this is grounded, this is minus plus now this is v_1', this is R this is R' and this is v_{01}.

So, what is this circuit now? You can see that this circuit is non-inverting amplifier whose gain is given by 1 plus the feedback resistance by the input resistance. So, what is the expression for v_{01} is equal to input voltage v_1' it is not v_1, v_1' times what is the gain 1 plus this feedback resistance is R' divided by the input resistance is R, this is expression for v_{01} in terms of v_1', but what is v_1' in terms of v_1 this v_1 is this. If you substitute this here what is v_{01}?

$$v_{01} = (\frac{R_2}{R_2 + R_1})(1 + \frac{R'}{R})v_1$$

(Refer to the slide at 36:25)



Now, what is the expression for v_{02} which is the output voltage due to v_2 only? You have to make v_1 is equal to 0 set v_1 is equal to 0. So, what will be the equivalent circuit? If v_1 is 0 you can refer the previous circuit.

So, this was v_1. So, this I am going to ground now. This is R_1 R_2 this was v_1 I have set to 0. So, means grounded and this circuit remains same. This output will be v_{02} this is v_2 this is R' this is R. Now, what will be the equivalent circuit of this? So, because this point is grounded this point is grounded. So, this current through this one is 0 this i is 0 and these two will be between this point and ground this R_1 R_2 will be in parallel.

So, what will be the voltage across this? So, the current through this line is 0 and this resistance is R_1 in parallel with R_2 because between this point and ground R_1 with this point and R_2 is ground means R_2. So, the parallel combination is R_1 in parallel with R_2 which is equal to $\frac{R_1 R_2}{R_1+R_2}$. So, what is the voltage drop across this? Because the current this is 0, 0 into $v = Ri$, v is equal to this resistance into 0. So, this is equal to 0.

So, basically this will be at 0 volts means you can remove this R_1 and R_2. This is simply whatever the ground potential will be available here because the current through this one is 0. So, this will be equivalent to now, this will be simply grounded. This is R', this is R, this is v_2 and the output is v_{02}. Now, this simply here this is a inverting amplifier whose gain is minus of feedback resistance by input resistance.

Therefore, $v_{02} = -\frac{R'}{R}v_2$. Therefore, total voltage $v_o = v_{01} + v_{02}$. v_{01} we have derived in the last slide this is nothing, but $(\frac{R_2}{R_2+R_1})(1+\frac{R'}{R})v_1$. v_{02} will be $-\frac{R'}{R}v_2$. Now, here to make this circuit simple I will assume that $R_1 = R$ and $R_2 = R'$.

Then what happens? R_1=R, R'= R_2= R'. Then what happens to v_0? This R_2 is nothing, but R', R_1 is nothing, but R, R_1 is R, R_2 is R' and this is anyhow if I take this R as LCM

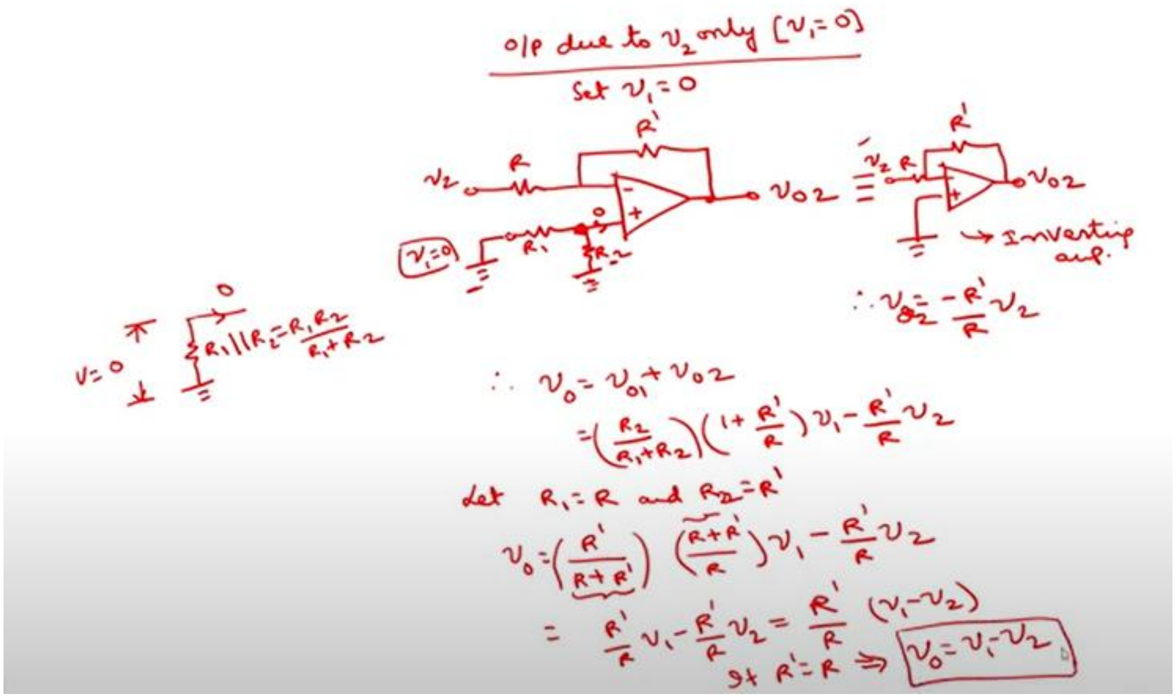
$$v_o = (\frac{R'}{R+R'})(\frac{R+R'}{R})v_1 - \frac{R'}{R}v_2$$
$$= \frac{R'}{R}v_1 - \frac{R'}{R}v_2.$$

What is equal to R' by R if you take as common?

$$= \frac{R'}{R}(v_1 - v_2)$$

Even if I set $R' = R$ implies output voltage $v_o = v_1 - v_2$, which is subtraction of v_1 and v_2.

(Refer to the slide at 41:05)



So, this circuit will acts as a subtractor. If I make this resistances $R' = R$ and $R = R_1$, $R' = R_2$. This v_0 becomes simply $v_1 - v_2$ which is subtractor. Under what condition? If $R = R_1$, $R' = R_2$ or simply 4 resistances are equal. The condition is basically all the 4 resistances are equal. $R = R' = R_1 = R_2$. So, under this condition this will acts as a subtractor. So, this is how we can implement the addition and subtraction using operational amplifier. There is one important parameter for this difference amplifier which is called as a common mode rejection ratio CMRR. This is one of the figure of merit of this operational amplifier and this is going to decide how efficiently your amplifier will reject the common mode signal such as noise which is undesired signals that I will discuss in the next lecture. Thank you.