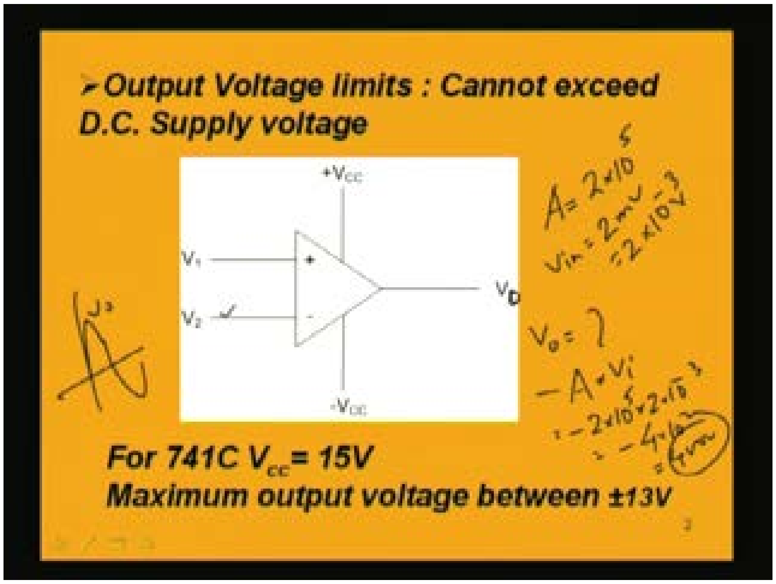
Basic Electronics
Prof. Chitralekha Mahanta
Department of Electrical Communication Engineering
Indian Institute of Technology, Guwahati

Module- 4
Operation Amplifier (Op-Amp)
Lecture - 6
The practical Op-Amp

When you connect an op-amp to a circuit you will have to consider these parameters of an op-amp and that is the topic we are going to discus today. The non-ideal effects of an op-amp have certain limitations on the characteristic of an op-amp. Because of these non-ideal effects, we have to look into the consequences. So far, all the analysis of our discussion was based on ideal op-amp. But practically when we connect it in a circuit we are not going to have those ideal effects. We will get non-ideal characteristics of the op-amp. We are going to discuss today those parameters that are there for a practical op-amp. When we had earlier considered an ideal op-amp, we did not consider any limitation on the input voltage which is applied to an op-amp. But practically for an op-amp to operate properly that means for proper transistor biasing and linear operation because in the op-amp what is there? Inside the circuit, an op-amp will have transistors and so the linear operation of the transistor is one important thing; only then you will have the distortion less output and also we have to take care of the biasing in transistor. That is why we have to consider this input voltage limitation in an op-amp also. When you apply the common mode operation of the op-amp that means suppose we are giving a DC voltage which is common to both the input terminals of an op-amp we cannot give any arbitrary value of input voltage.

The common mode operation will have a limit and that maximum limit is given. In all the op-amp data sheets it is available as to how much input voltage you can apply in the common mode. Suppose if we are applying 741 C that is an IC having op amp. The integrated circuit of the op-amp has this number 741 C. Then 741 C op-amp, which we use in the lab that will have a limitation of this maximum common mode input as plus minus 13 volt. That is we cannot exceed this limit and if we will exceed this limit plus 13 volt or minus 13 volt given in common mode operation to the op-amp then we will not get proper transistor operation of the circuit in the op-amp and that will not be linear. That is why the input voltage has a limit in op-amp.

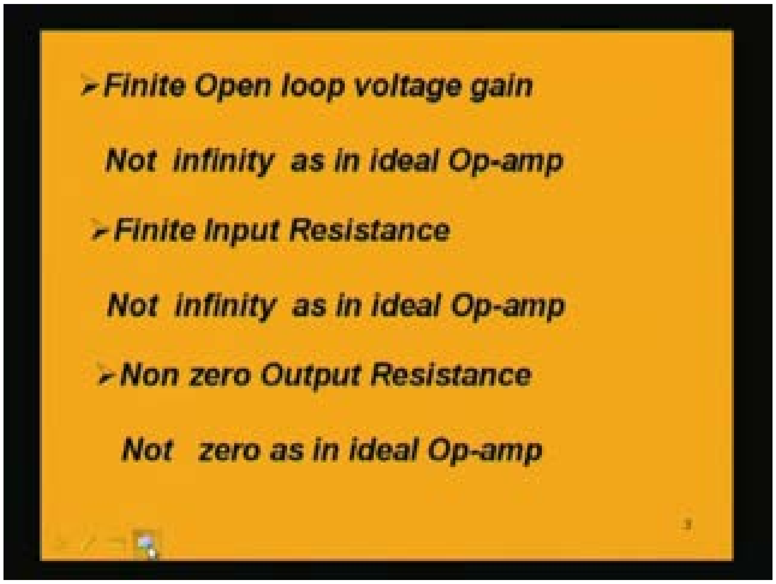
(Refer Slide Time: 4:56)



Another limitation on the op-amp is the output voltage. That is an output voltage of an op-amp cannot exceed the DC supply voltage. If we consider an op-amp IC, for example 741 C that is the integrated circuit having op-amp then, the voltage which is to be applied is plus 15 volt and minus 15 volt; V_{CC} and minus V_{CC}. These voltages are to be applied in an IC, there are pins for this. Generally in 741 it is up to 15 and minus 15; I mean it should be around plus 15 and minus 15. The output voltage V_O, which we will get for the op-amp, cannot exceed this supply voltage. For example we consider an op-amp having a voltage gain of say 2 into 10 to the power 5 and for example we are taking an open loop circuit. That is open loop gain is 2 into 10 to the power of 5. Suppose we want to amplify a signal which is say 2 millivolt. The signal which is given at the input is say 2 millivolt. That means 2 into 10 to the power -3 volt and suppose it is an inverting connection or inverting type of op-amp we are connecting.

If we consider these voltage given at this inverting terminal say which is 2 into 10 to the power -3 volt, what will be output voltage V_O? V_O is the output voltage what will be V_O? Theoretically we should get minus A into V_i. That means -2 into 10 to the power 5 into 2 into 10 to the power -3. That means -4 into 10 to the power 2, it is 400 volt. But this 400 volt at the output is not possible because we are having the supply voltage given by 15 volt. It will not reach that 400 volt. What will happen is that it will be saturated. The output will be saturated at 15 volt and it is not exactly actually 15. Every op-amp has the output voltage rating given and for 741 C which is having the op-amp, the maximum output voltage can be between plus 13 and minus 13 volt. That is it cannot go beyond plus 13 volt and it cannot go down below minus 13 volt. Suppose if we are applying two AC signals at V_1 and V_2 and the output we are going to find out. Then the swing at the output V_O will be having a maximum swing of 26 volt. This swing if we consider, V_O will be between this plus 13 and minus 13. That is 26 volt will be the swing possible in the output.

(Refer Slide Time: 8:30)

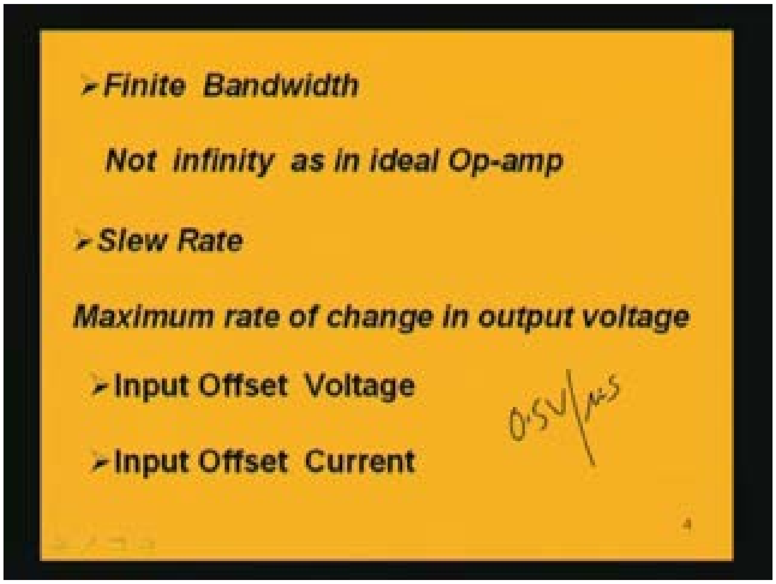


This limit is there coming from the consideration of the output voltage because it has a limitation given by its supply voltage. Other practical considerations are the open loop voltage gain that we were considering earlier in ideal case to be infinite. But that is practically not true. We will have a finite open loop voltage gain. We do not get infinite open loop voltage gain as we considered for the ideal op-amp. Similarly the input resistance and output resistance, we consider for an ideal op-amp as infinity and zero. But practically we do not get that infinite input impedance or resistance and we do not get zero output resistance. What is exactly obtained is that input resistance of an op-amp is not infinite; it will have a finite value. It is large but it is not infinite and also the output resistance is small but it is not zero. It may be in the order of ohms but it is not zero and input resistance may be in the order of mega ohms but it is not infinite.

We are considering another important parameter that comes from actually the bandwidth. In ideal op-amp, we consider that the bandwidth is infinite. That means over the whole range of frequency we will get the same characteristic of the op-amp. They do not drift or they do not change over frequency ranges, whole frequency ranges. But practically that is not the case and we have a finite bandwidth. If we consider the frequency response of an op-amp, we will find that the gain will vary because of capacitances, etc existing in the actual op-amp circuit. That is why the gain will not be constant which should be the case if we have an infinite bandwidth. But practically in the high frequency range we will find that the gain will drop. So the bandwidth is not infinite; it is a finite bandwidth in the practical op-amp.

Similarly one another important parameter which we have to consider while practically dealing the circuit or using it in a practical application is, the slew rate. What is a slew rate?

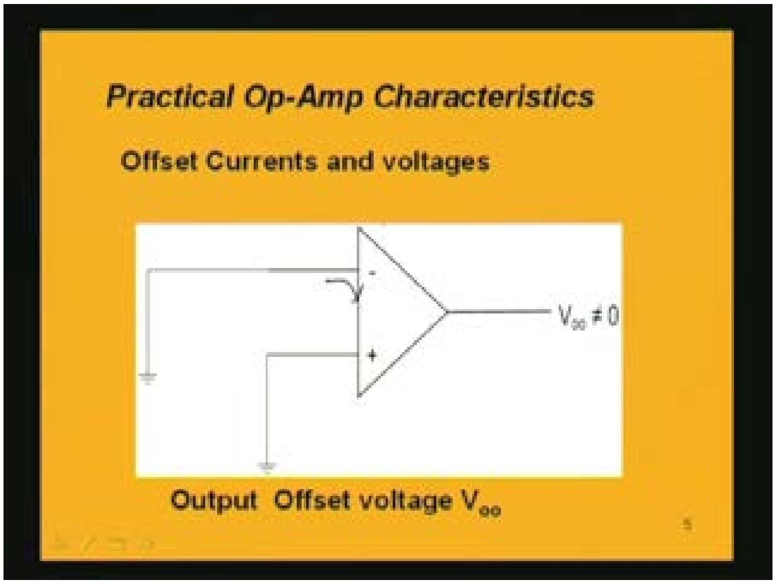
(Refer Slide Time: 11:17)



The slew rate is the maximum rate of change of output voltage per unit time. Actually that determines how fast the output voltage can change. Suppose an input voltage is given to the input of the op-amp whose frequency is very high. At the output side also we expect that the voltage should change at the same rate. But practically this is not the case. There is a limitation on how fast the change can occur. That means the maximum rate of change in the output voltage is limited. Even if we have a very high frequency input, voltage at the output we will not be able to get that at the same frequency and that is why if we have a very high frequency signal at the output you may get a distorted signal because it will not be able to follow the frequency of the input signal because of this slew rate. Generally if we consider a 741 IC, it has a slew rate given by 0.5 volt per micro second. That means 0.5 voltage per micro second is the maximum voltage change per unit time that can happen in an op-amp given by 741 IC. That means that in 1 micro second, the change can be maximum of 0.5 volt. If we have more than that, we will have a distorted output. That has to be kept in mind.

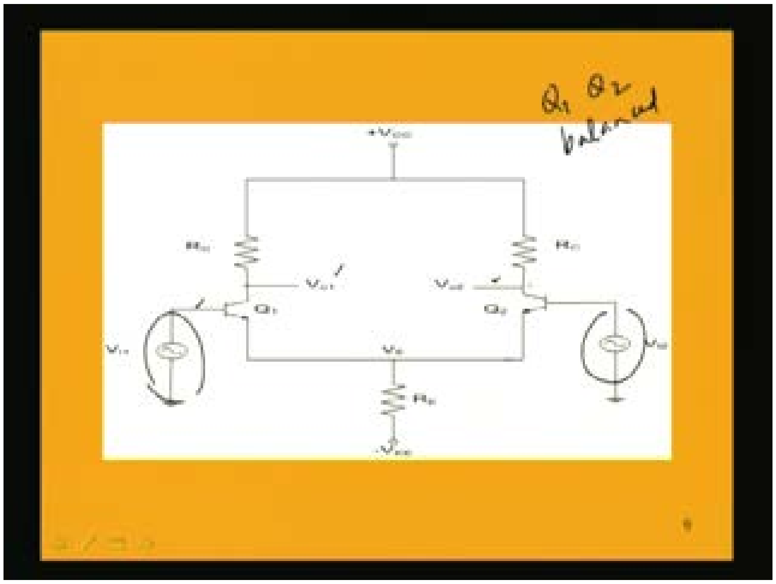
Similarly some other important parameters that we have to know about is the input offset voltage and the input offset current. What is an offset voltage or an offset current? Basically these come if we consider the circuit of an op-amp. It is nothing but differential amplifier what we have initially discussed about. We have transistors, which are perfectly matching; that is the requirement. If the transistors in the differential amplifier are perfectly matching that means the same collector current, same base current and the resistances which are connected are also exactly same then, the offset voltage and current will not appear. This is the DC condition. Mind it this is coming from the DC condition of the differential op-amp.

(Refer Slide Time: 14:02)



Let us again see an op-amp circuit. Here in this op-amp we are connecting the inverting or non-inverting terminal to ground. Expected output voltage should be zero because both are zero; so differential voltage is zero. So what should we get at the output? We should get zero voltage, but practically this is not so. If we ground both the input terminals of an op-amp and see measured output voltage, you will get a very small voltage but it is not zero and why is this happening? This is happening because of non matching of the transistor in the differential amplifier.

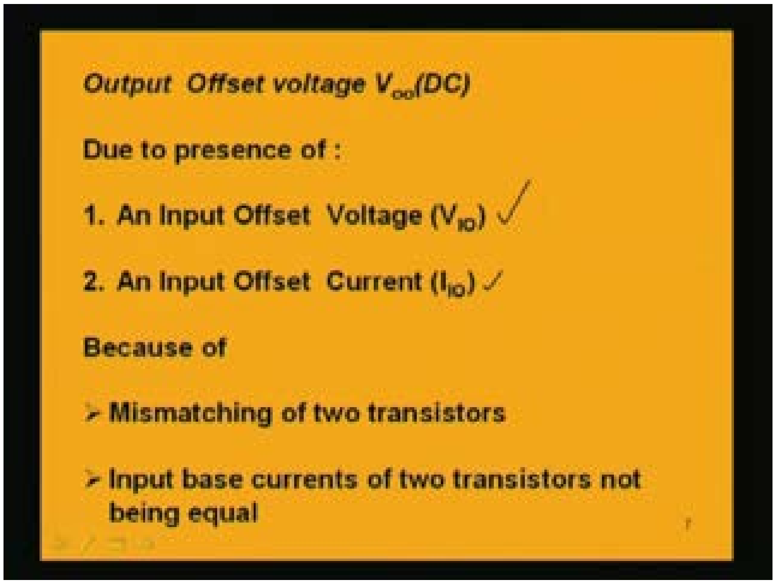
(Refer Slide Time: 14:44)



If we consider the differential amplifier circuit again, we see here that the two transistors Q_1 and Q_2, these two transistors, are connected to same resistance R_C. If Q_1 and Q_2 are exactly balanced or they are matched that means their collector currents are same, base currents are same. Then there will not be any voltage appearing at the output under DC condition. If the voltage across this R_C and the voltage across this R_C are same, V_{O1} and V_{O2} are same, without any signal; you are not applying any signal, they are grounded. Then V_{O1} and V_{O2} should be same and that output voltage should be zero. If you use the same IC, we expect that these transistors should match. But that practically does not happen. Because of this imbalance between the collector currents, the voltages across these two resistances will not be exactly equal and that is why we will be getting a non-zero voltage at the output. Because V_{O1} and V_{O2} are not exactly equal, V_{O1} minus V_{O2} is the output available, V_O and that will not be equal to zero. Due to this input offset voltage, we will not be getting the output voltage zero when you simply ground the input terminals. That means there is an offset output voltage.

Another factor is due to the presence of the input offset current and that happens because the base currents in the two transistors are not exactly equal; If IV_1 and IV_2 are not exactly equal then, due to the unbalanced base currents, there will be a current at the input terminal of the op-amp. Here there will be a current in the input terminal of the op-amp, unbalanced base current will be there.

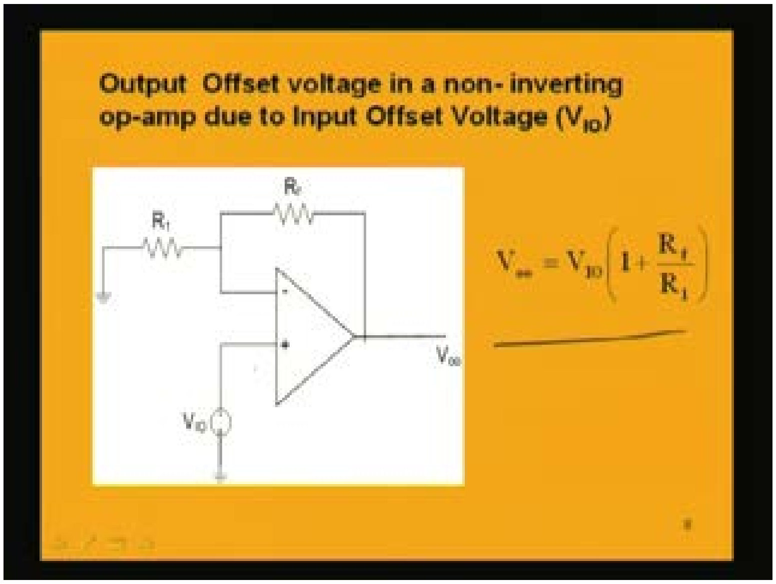
(Refer Slide Time: 17:01)



As the two base currents are not equal, due to the unbalance of these two input base currents we will get an output voltage. That means we have the output voltage available even if you make the input terminals grounded. This is because of the two reasons: one is due to the input offset voltage V_{iO}, suppose we are naming it, and the other is due to the input offset current I_{iO} and that happens because of mismatching of the two transistors as well as the input base currents of the two transistors not being equal. Because if the input base currents are not equal there is an unbalanced base current, which will create an output voltage.

If we consider only say the input offset voltage, we want to show what will be the output voltage?

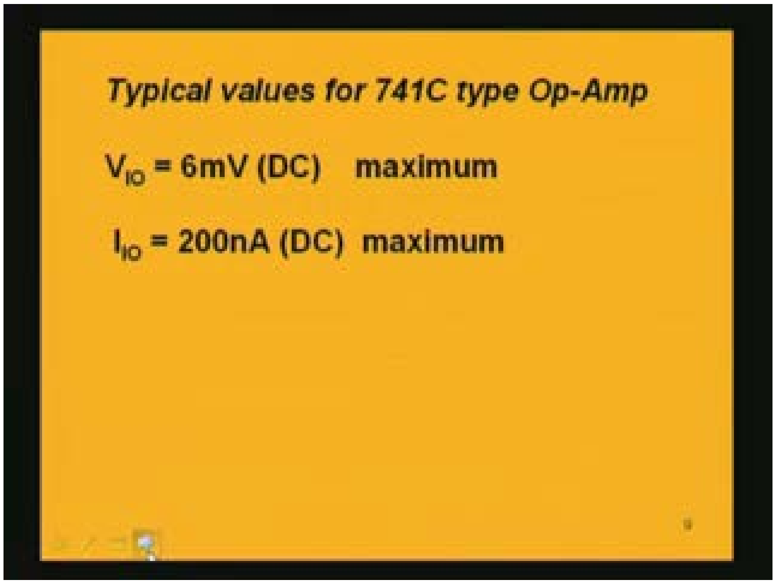
(Refer Slide Time: 18:02)



The input offset voltage is shown by a source here and the polarity of this input offset voltage is not fixed. That means depending upon which transistor has more unbalanced collector current that means which transistor has a higher collector current, the polarity of the offset voltage will also be accordingly; it may be positive, it may be negative. If we consider the output voltage due to this input offset voltage alone, then it is like a circuit where we are having already a source. Now we consider only the non- inverting circuit of an op-amp suppose, the non-inverting op-amp has a resistance, feedback resistance R_f and R_1; we are not applying any input signal but this input signal is available because of the input offset. So input offset voltage is there and if we consider a non-inverting op-amp, then the output offset voltage V_{OO} that will be simply V_{iO} into 1 plus R_f by R_1, as if it is having a source. Exactly this is coming from the input offset voltage because of which we are getting an output voltage even without a signal. We are having already a voltage at the output even though both the input signals you ground and that is why we have to compensate this output voltage.

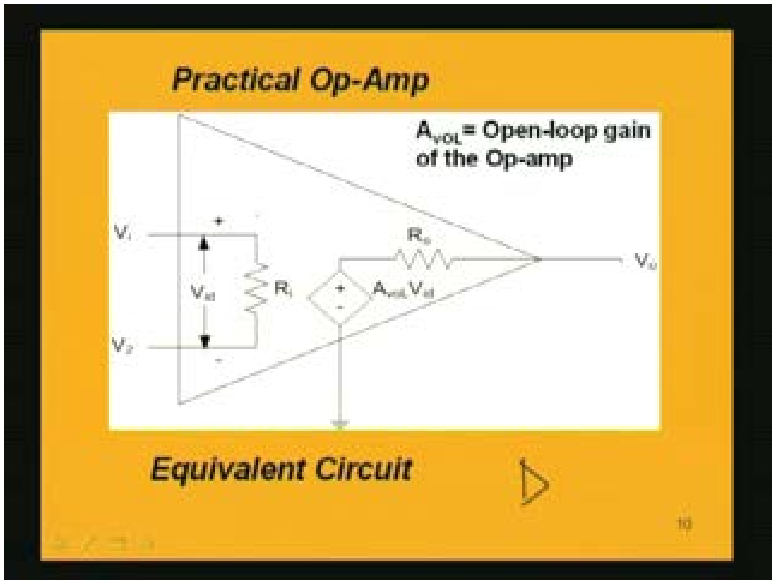
Whatever the output voltage is coming if we measure it then we have to compensate it by properly designing a compensating circuit so that this offset voltage can be balanced. Then the exact circuit analyses or proper behaviour of the circuit which we are using can be determined because we have to somehow get rid of this offset. Otherwise it will hamper or it will interfere in the actual output voltage which we are going to get when we use the op-amp in some practical consideration or in some practical circuit. There are ways to overcome this offset voltage but we will not discuss those details. We only want to emphasize that there is a DC condition already prevailing means we have a DC voltage already at the output that is called the offset voltage and that is to be first of all balanced.

(Refer Slide Time: 20:34)



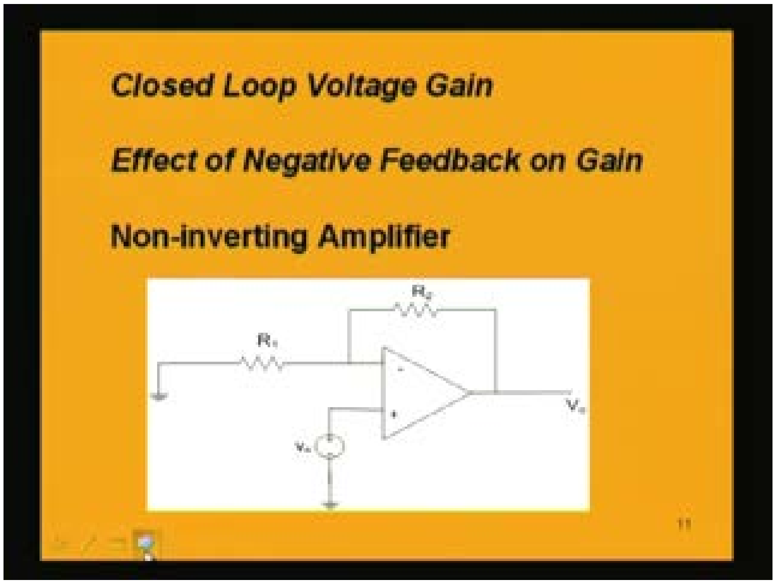
Typical values of this offset voltage and current at the input for a 741C if we consider, around 6 millivolt input offset voltage is existing and if we consider input offset current maximum can be 200 nanoampere. Both are DC voltage and DC current. These are coming from the unbalanced or imperfect transistor matching in the differential amplifier circuit. These are the typical values; maximum 6 millivolt can be the input offset voltage and maximum 200 nanoampere DC current may be there as input offset current in 741 IC.

(Refer Slide Time: 21:22)



If we consider a practical op-amp and draw the equivalent circuit then, we get such a type of circuit. We are considering this op-amp by this symbol. This is the op-amp but inside this op-amp we are having an input resistance R_i which is not infinity. We are having a finite value of R_i and we are getting at the output side, the output voltage which is given by A_{vOL} into V_{id}, V_{id} being the differential voltage at the input and multiplied by this open loop gain of the op amp, A_{vOL} which is very high. But it is not infinite; may be it is 2 into 10 to the power of 5, typical value, multiplied by this difference in voltage at the input terminals we get the output which is shown here by a dependent voltage source. Apart from this output voltage there will be a resistance R_O, which is the output resistance of the op-amp and that is not zero. That is having a small value may be in the order of ohm and typical value is 75 ohm. But this is not zero and this R_i is not infinity. So the practical op-amp circuit will be something like this. We will consider this circuit for our analyses because we are considering a practical op-amp. If we now consider this circuit and we want to use this op-amp say for example in non-inverting amplifier then we will have to consider these parameters. It is not an ideal op-amp, mind it; now we are not having an ideal op-amp but we are having all those parameters.

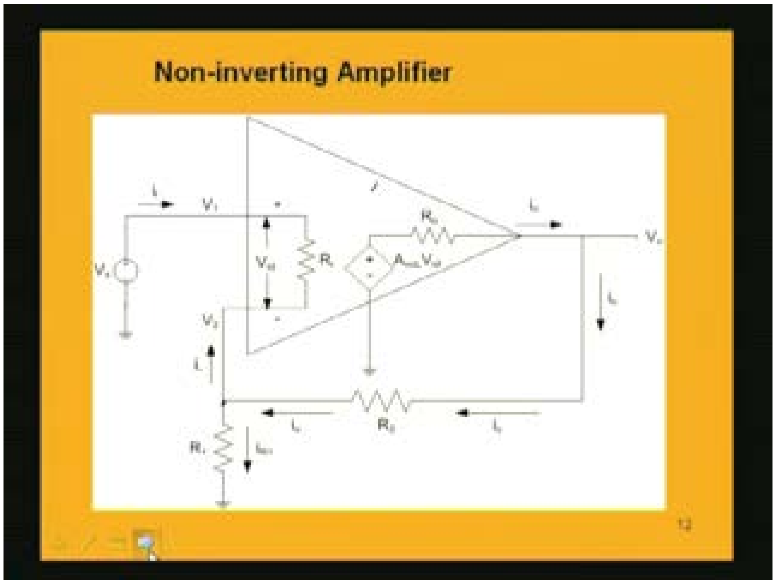
(Refer Slide Time: 23:16)



Let us now take this and we are going to see what effect we are having in the circuit which we are going to use because of these non-ideal parameters. We are revisiting the non-inverting amplifier and we will find the closed loop voltage gain. Why we are calling it a closed loop is because we are having at the output, a resistance which is say R_2. That is the feedback resistance means it is having a path from output to input. That output to input path is called feedback path and that is why this circuit is a closed loop. It is in the form of a loop, it is not open loop. If we do not have this resistance R_2 then, it will be not closed loop. But because of this resistance in the feedback loop, another resistance is there, R_1; so there is a path from output to input which is known as closed loop.

This type of circuit when we have at inverting terminal or the negative terminal, a feedback path or a feedback resistance loop given by R_2 and R_1, we will get a negative feedback effect on the gain and we will see, how we are getting a negative feedback and how the output voltage is negatively coupled with the input? We will also discuss the effect of this negative feedback gain on the gain of the op-amp. If we look into this circuit this is a non-inverting amplifier circuit we are taking as an example. In all the applications which we discussed earlier like non-inverting, inverting, differential, integral, op-amps, etc, everywhere you will get this effect. If we have a negative feedback, there will be an effect on the gain also, but we are considering as an example the non-inverting amplifier and see the effect of this negative feedback on the gain of the op-amp. In this circuit now we are having two resistances R_2 and R_1 apart from this op-amp and we are connecting a signal V_S at this non-inverting terminal. So we will redraw the op-amp circuit by using the equivalent circuit.

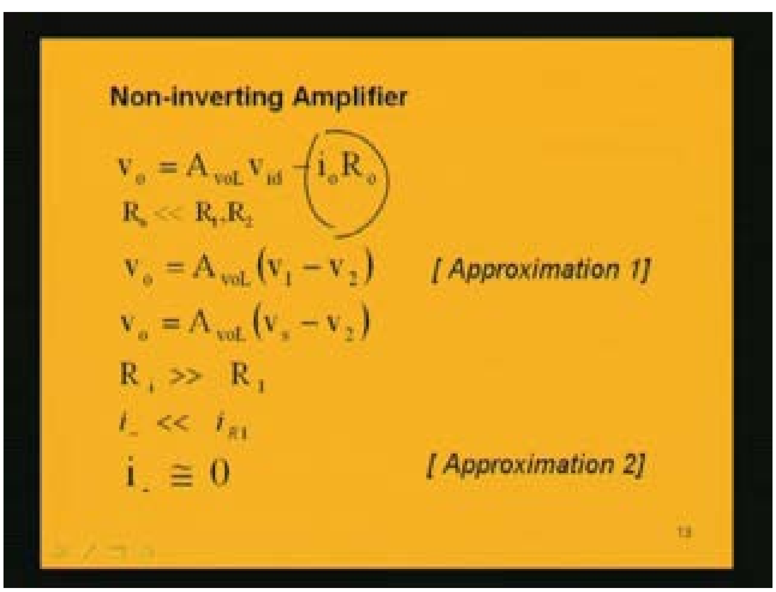
(Refer Slide Time: 25:41)



The whole circuit will be like this. We are having the op-amp circuit given by the input resistance R_i, the dependent voltage A_{vOL} into V_{id} where V_{id} is the difference in the voltage between the two terminals positive and negative. The voltage here is V_1 minus V_2. If V_1 is the voltage at this positive terminal, V_2 is the voltage at this terminal then, V_{id} is V_1 minus V_2 which is the difference in voltage and that difference voltage is amplified by this open loop gain of the op-amp which is A_{vOL}. So we are having this dependent voltage source. Apart from this the resistance R_O which is having a small value, but it is existing. It is there and R_2 and R_1, the feedback resistances are there because we are having a non-inverting amplifier. This R_1, R_2 will be there, connected to the inverting terminal. Now if we look into this part from the output to the input, this is the feedback resistance R_2. Here it is connected to another resistance which is grounded and both of them are connected to the negative terminal. Output voltage is V_O. We have named the voltages at this inverting and non-inverting terminal as V_1 and V_2 and this signal which is applied at the non- inverting terminal is V_S; that is the applied signal. We want to get an amplified non- inverted output at V_O that is the non-inverting amplifier. If we denote the currents flowing in the circuit, let us name the input current coming from the source as i_i and output current is i_O, it is going out of the op-amp.

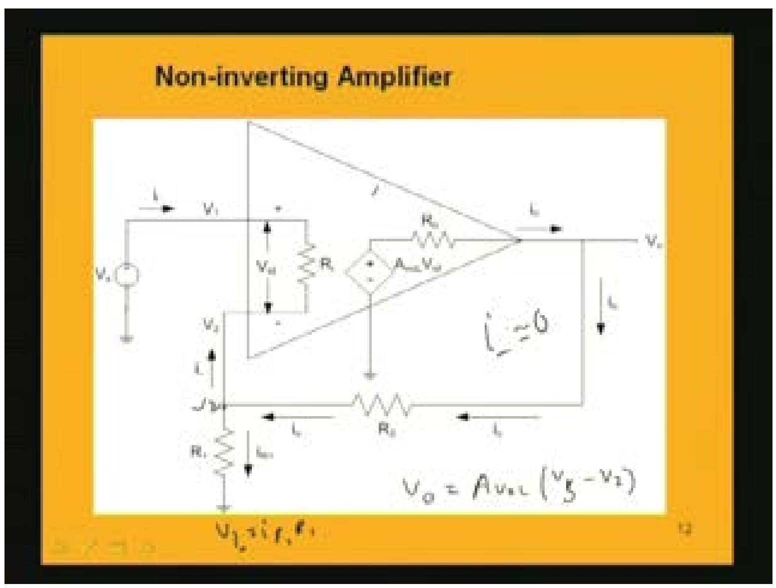
At this point the current will flow down because we are having an open loop here and there is no other resistance to ground. We are considering the open loop case; open loop means there is a no load here, no load resistance. There can be a load resistance at the output but for the time being here we are not considering that. This current will have to follow a closed path, so it will be flowing in this direction. This is i_O. At this point, there will be two branches; one will be going this way which is say i negative. I am denoting it by i negative because it is entering the negative terminal and the other part is iR_1 which is flowing through R_1. The current which is flowing through R_2 is i_O. The current which is flowing through R_1 is iR_1. This is the whole current flow direction in the op-amp. Here we will find out the output voltage. What is the output voltage for this non-inverting amplifier?

(Refer Slide Time: 28:25)



If we look into this circuit, V_O this voltage is nothing but A_{vOL} V_{id} minus the drop in the resistance R_O. Because the output resistance R_O is there, it is not zero. The voltage which is available at this source is A_{vOL} V_{id}, V_{id} being the difference in the voltage. We are following the op-amp principle that the difference voltage is amplified by the open loop gain A_{vOL} V_{id} minus this drop is i_O R_O that is V_O. V_O is equal to this. Here we will make one approximation which is a valid approximation. We can cross verify also. Approximation is that this R_O resistance is very small as compared to R_1 and R_2; R_1 and R_2 are generally in the order of kilo ohms and R_O is only in the order of ohms. So effectively this R_O is very small than R_1 and R_2. So the drop i_O R_O, this drop, we will neglect here. Then we will get V_O equal to A_{vOL} V_{id} and V_{id} is nothing but the difference between these two voltages V_1 and V_2. A_{vOL} into V_1 V_2 is equal to the output voltage.

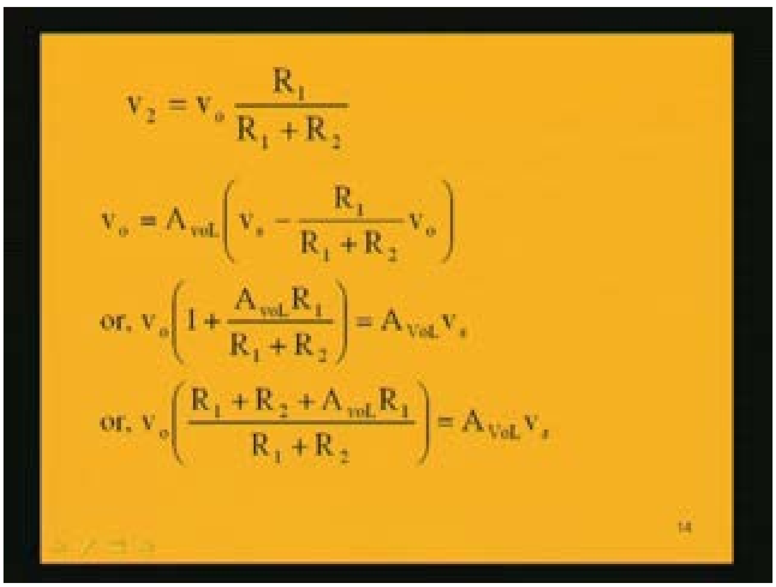
(Refer Slide Time: 29:49)



V_1 if we look into, this V_1 is nothing but V_S. So replacing V_1 by V_S we get the output voltage V_O equal to A_{vOL} into V_{id}, which is V_1 minus V_2 and V_1 is equal to V_S. So it is V_S minus V_2. Now you look into what is V_2? The voltage here is V_2. This voltage we have to find out. Again if we look into this part, the current part, the current is divided into two components here and here. So the voltage at this point V_2 is exactly equal to iR_1 into R_1. iR_1 into R_1 is V_2. But again we will make one valid approximation, the approximation being that this current which is flowing i minus or i negative, this current is very small because if we consider this resistance R_i, this is very high, this R_i is very high. If we consider these two resistances R_i and R_1, here the current has two parts. One is this through R_i and other is through R_1. But this resistance is very high, so we can practically assume that all the current that is flowing is through R_1. That means the same current i_O is flowing through R_1 also. i negative is almost equal to zero; that approximation we will use and then our task is easy because if we want to find this voltage, the voltage division is taking place, the same current flows. So V_O into R_1 by R_1 plus R_2 becomes V_2.

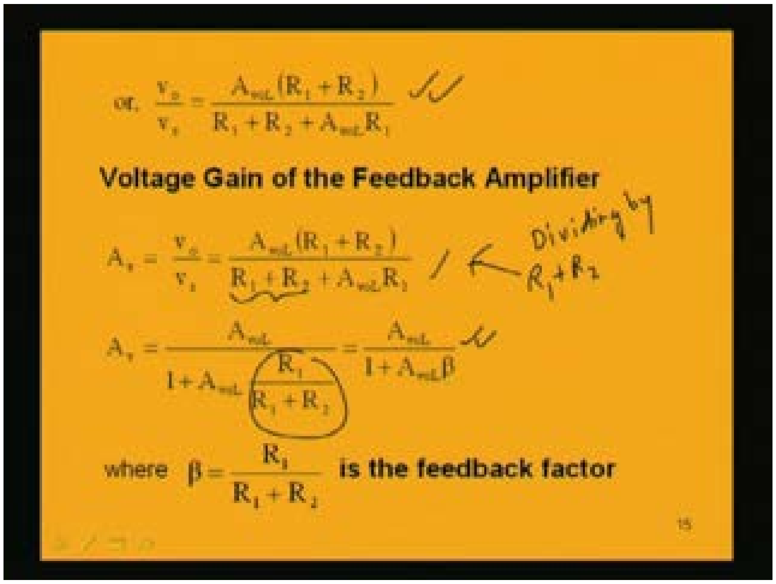
Here we are using that approximation and that approximation is exactly valid because R_i has a very high value. It is in the order of mega ohms compared to R_1 or R_2. Then i dash is very less than iR_1 and make it equal to zero and then we get V_2 which is equal to V_O into R_1 by R_1 plus R_2.

(Refer Slide Time: 32:19)



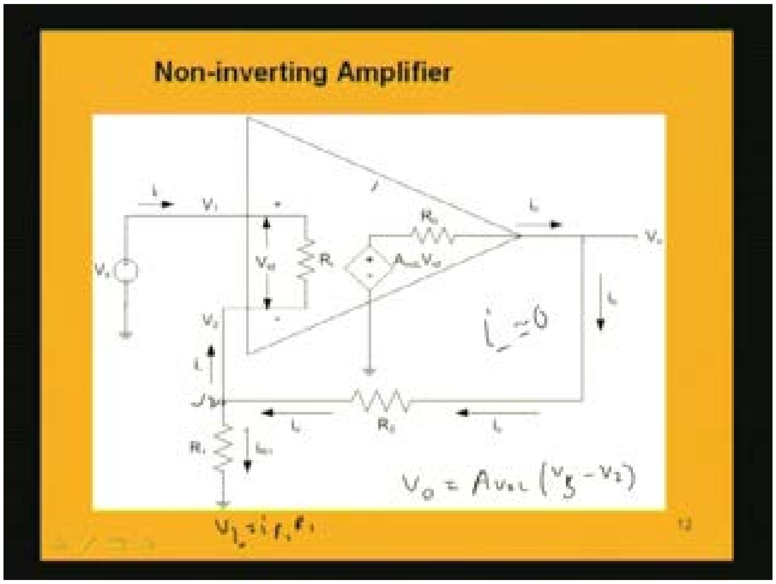
If we write down V_O from this expression, A_{vOL} into V_{id} that is equal to V_O, V_{id} is nothing but V_S minus V_2. V_S minus V_2 is replaced by this quantity V_O into R_1 by R_1 plus R_2 or if we transfer this part having V_O to the left side, take common V_O it will be 1 plus A_{vOL} into R_1 by R_1 plus R_2 that is equal to A_{vOL} into V_S and so our interest is V_O; that quantity we want to find out. Simplifying this a little bit what you get is V_O into R_1 plus R_2 in the denominator. In the numerator it is R_1 plus R_2 plus A_{vOL} R_1 that is equal to A_{vOL} into V_S. Now what will be V_O by V_S? That gives us the overall gain A_v.

(Refer Slide Time: 33:26)



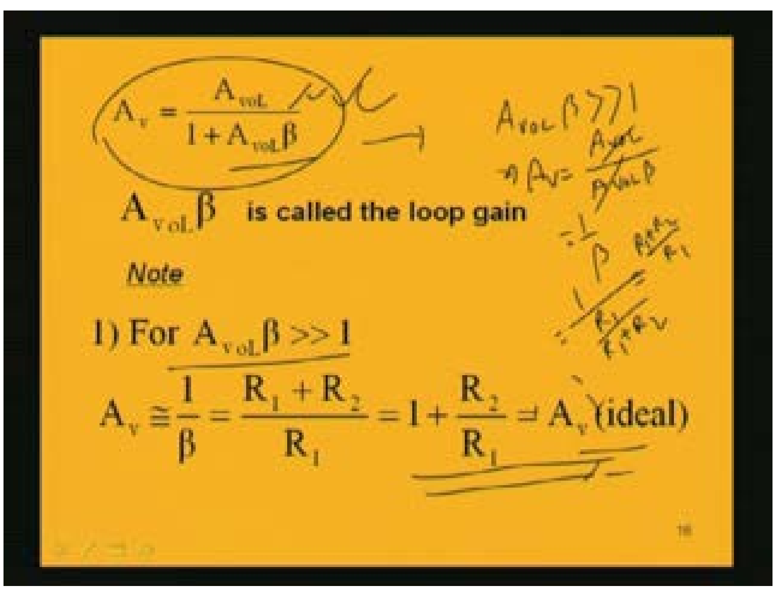
V_O by V_S if we find out taking the ratio between V_O by V_S, it will be A_{vOL} divided by this whole quantity. That is equal to A_{vOL} into R_1 plus R_2 by R_1 plus R_2 plus A_{vOL} into R_1. We get the voltage gain of the feedback amplifier or this is the non-inverting amplifier as V_O by V_S which is denoted by A_v and that is equal to A_{vOL} into R_1 plus R_2 by R_1 plus R_2 plus A_{vOL} into R_1. Doing a little further simplification, we can write down this gain A_v as A_{vOL} divided by 1 plus A_{vOL} into R_1 by R_1 plus R_2. Because here what we are doing is we are dividing both the numerator and denominator by the term R_1 plus R_2. Dividing this term by R_1 plus R_2, we get in the numerator free of R_1 plus R_2 and in the denominator, this part will be 1 plus A_{vOL} into R_1 by R_1 plus R_2. This R_1 by R_1 plus R_2 is given a name beta and this is known as feedback factor. The feedback factor means this is the resistive network from the output to input.

(Refer Slide Time: 35:18)



If we consider the output to input network that is this part of the circuit, we see that the output and input are connected by this network of R_1 and R_2 resistance. That is why this is known as the feedback factor, R_1 by R_1 plus R_2. Then we have another expression for this gain A_v which is given by A_{vOL} by 1 plus A_{vOL} into beta; R_1 by R_1 plus R_2 is beta.

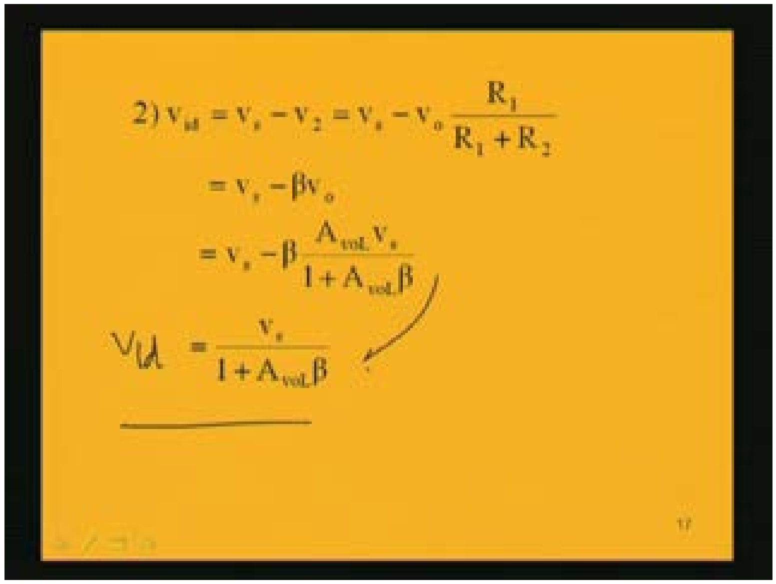
(Refer Slide Time: 35:49)



The gain has an expression given in this form where A_{vOL} beta is known as the loop gain. It is having a name loop gain because it is coming from the loop. In this expression of A_v, the difference between what we earlier got using ideal op-amp is coming from the denominator term 1 plus A_{vOL} beta. If we have A_{vOL} beta very large as compared to 1 then, what we will get is that the gain will be given by A_{vOL} by 1. Because if this A_{vOL} beta is very large as compared to 1 then, I can write A_v equal to A_{vOL} by A_{vOL} beta. These two cancel. That means I get 1 by beta. 1 by beta is what? 1 by beta is 1 by R_1 by R_1 plus R_2. 1 by R_1 by R_1 plus R_2 that is 1 by beta; that means it is equal to R_1 plus R_2 by R_1 which is nothing but 1 plus R_2 by R_1. If we now recall, the gain of a non-inverting op-amp, which you earlier got using ideal op-amp consideration, was 1 plus R_2 by R_1, where R_2 is the feedback resistance. If you look into this circuit R_2 is the feedback resistance from output to negative and R_1 is the resistance from negative terminal to ground.

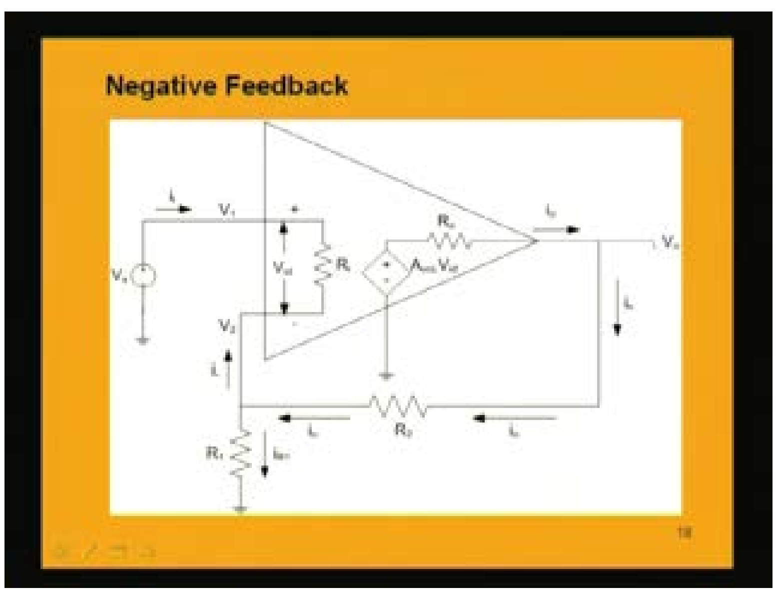
We have the ideal op-amp consideration given that value which is ideal A_v will be ideal op-amp consideration gain A_v and this is obtained if this condition of A_{vOL} beta is very much greater than 1 that is satisfied. Otherwise we will have a gain which is not given by the ideal op-amp gain 1 plus R_2 by R_1; but it is given by this factor. If we consider exactly the practical case of a non-inverting op-amp, we have the gain given by this term. The closed loop gain or the closed loop effect is coming here and another factor to be noticed here is the difference voltage.

(Refer Slide Time: 38:57)



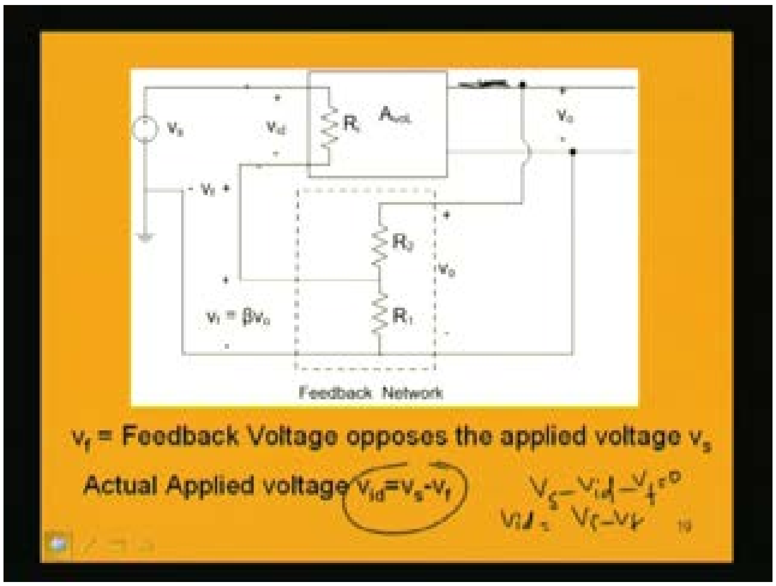
What is V_{id}? V_{id} if we consider in the circuit, this V_{id} equal to V_S minus V_2. Replacing V_2, we get it is equal to V_S minus V_O into R_1 by R_1 plus R_2 and that can be written as V_S minus R_1 by R_1 plus R_2 is beta; so beta V_O and V_S minus beta into V_O can be written as A_{vOL} V_S by 1 plus A_{vOL} beta and this simplifies to V_S by 1 plus A_{vOL} beta. The difference voltage V_{id}, if we see it is equal to V_S by 1 plus A_{vOL} beta.

(Refer Slide Time: 39:59)



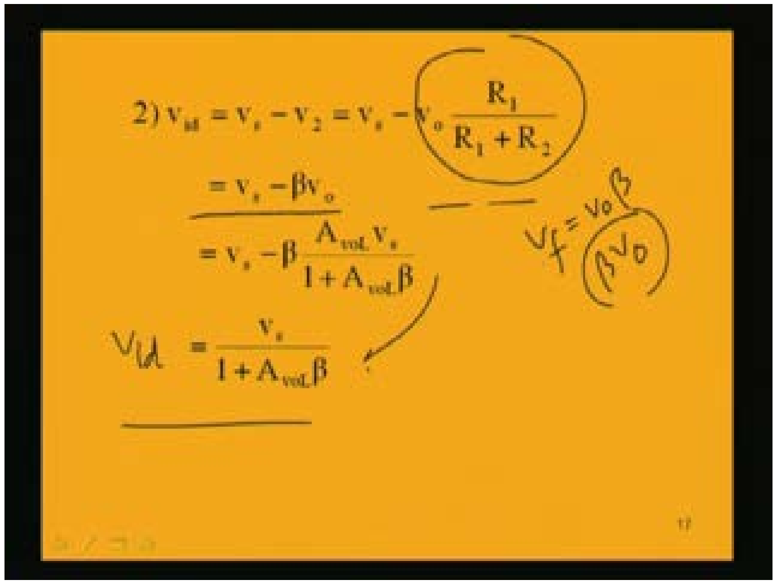
Now in this exact circuit using the practical op-amp consideration, one thing to be noted here is that the feedback which is there is a negative feedback; means to the voltage applied voltage V_S, the feedback voltage is adding up in a negative way. Feedback voltage means that voltage which is available due to the feedback loop. If we consider feed back voltage, this voltage is V_2 that is the feedback voltage available because of this loop.

(Refer Slide Time: 40:45)



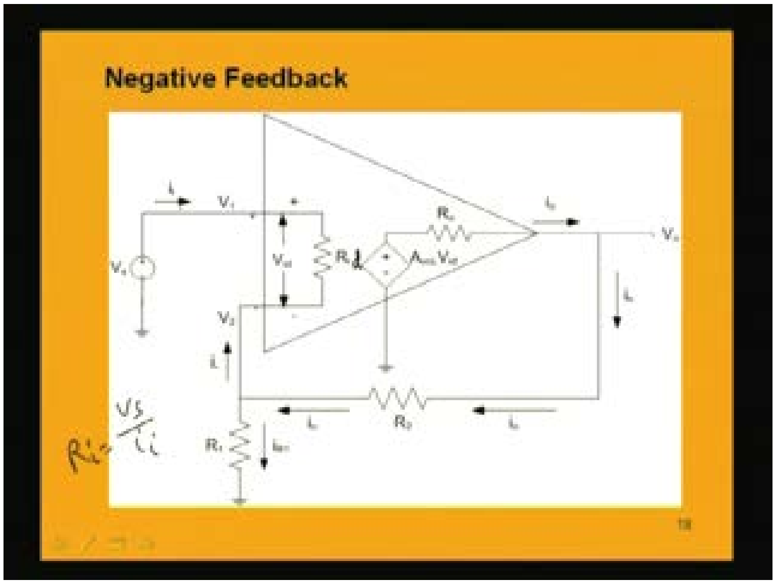
If we consider the whole circuit again and see from the point where this feedback voltage is being added up and what is the polarity of this feedback, then we will understand how negative feedback is happening here. Here if you look into the circuit, you are applying a voltage V_S. This block is the op-amp block, which is having this R_i resistance and the gain is A_{vOL} and this resistance R_O is very small. Basically that is why we are using that approximation that this is zero; that is why it is zero, output voltage is V_O. We are having a network of resistance coming from this output and it is having R_2 and R_1. The voltage across R_1 that is being added up to the input at a negative terminal and what is this voltage across R_1? Let us name it as the V_f or feedback voltage and that voltage is equal to beta times of V_O; that we have seen here.

(Refer Slide Time: 42:05)



What is this voltage? V_O into R_1 by R_1 plus R_2 is the feedback voltage and that can be written as V_O into beta. Beta V_O this much of voltage is the feedback voltage available here at this point. This voltage is applied and it is connected at this point which is negative of the op-amp. If we consider the input side we are having a voltage V_S and we are having another voltage V_f but the polarities are such that this point is positive, this point is negative because this point is positive and this point is actually ground. Here the voltage V_f and V_S if we look into the polarities, these two polarities are in such a way that V_f opposes V_S. If we consider this voltage at this point, it is V_S minus V_f is the voltage at the input of the op-amp V_{id}; that is very clear from here, if we consider this loop. This loop uses Kirchhoff's voltage law V_S minus V_{id}. This point is positive and this point is negative. So it is minus V_f that is equal to zero. What is V_{id}? V_{id} is equal to V_S minus V_f. That means the voltage at this point that is V_f, which is the feedback voltage available because of this feedback resistance R_1 and R_2 loop it is negatively adding to the input or supply voltage V_S. The voltage available at the input terminals of the op-amp is now V_S minus V_f. This is the reason why this feedback is called a negative feedback; negative feedback meaning is that the feedback voltage is negatively added up to the input. The actual applied voltage is V_S minus V_f, where V_f is coming from the feedback part. So due to this negative feedback, we are having the gain of the op-amp which is ideal gain should be A_{vOL} but this is not A_{vOL} now, it is A_{vOL} by 1 plus A_{vOL} beta (Refer Slide Time: 35:49). But if this quantity A_{vOL} beta is very high in comparison to 1 then, we will get that ideal non-inverting op-amp gain 1 plus R_2 by R_1. We again look into the circuit and find out one another important parameter which is the input resistance. In this circuit, the input resistance which is shown as R_i that is modified now in the actual circuit.

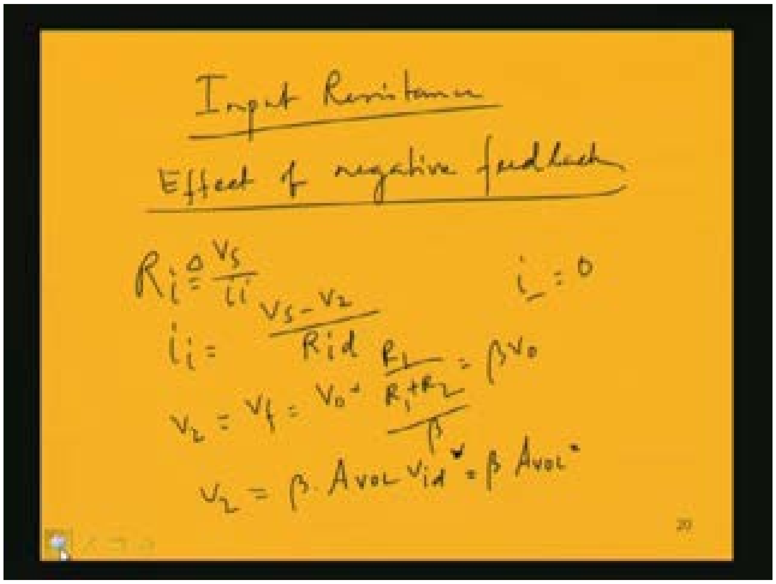
(Refer Slide Time: 45:25)



The op-amp input resistance which is R_i, now it will not have the same value of R_i; it will have a different value. To find that out, let us not name it as R_i, let us name it as R_{id}; that is the input resistance of the op-amp. If we want to find out the effect of this negative feedback on the input resistance, what will be that? Let us find the input resistance. Input resistance and the effect of negative feedback on the input resistance if we find out, again same circuit we are considering; only we have named it has R_{id}. Now what will be the input resistance? That can be found out if we again consider the circuit. What will be this input resistance R_i of the circuit? Suppose at these two points we are having the resistance R_i. We want find out this input resistance of this circuit. Then it will be simply V_S by i_i. V_S by i_i gives the input resistance of this whole circuit. The input voltage by input current, V_S by i_i that is actually R_i. V_S by i_i we have to find out; that is the input resistance. What is now i_i that we have to find out. If we look into the circuit what will be

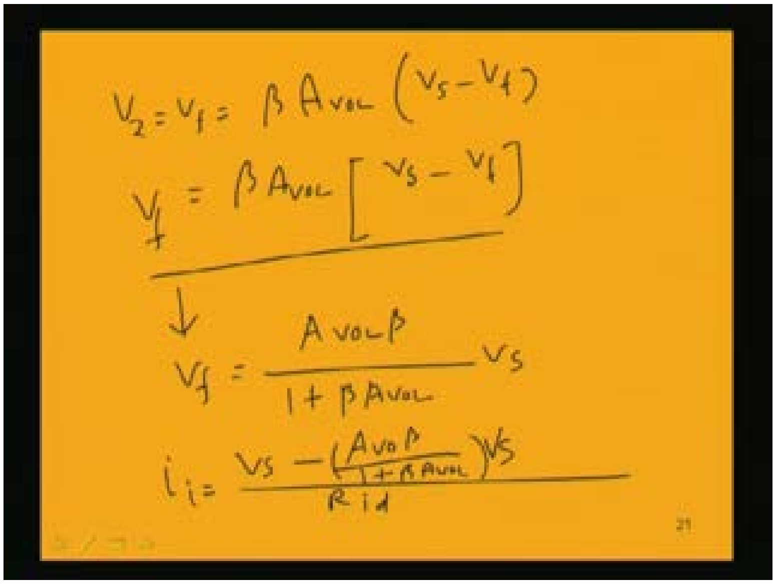
i_i? This i_i input current is nothing but equal to V_S minus V_2. This is the voltage here, this is the voltage here divided by R_{id}.

(Refer Slide Time: 48:24)



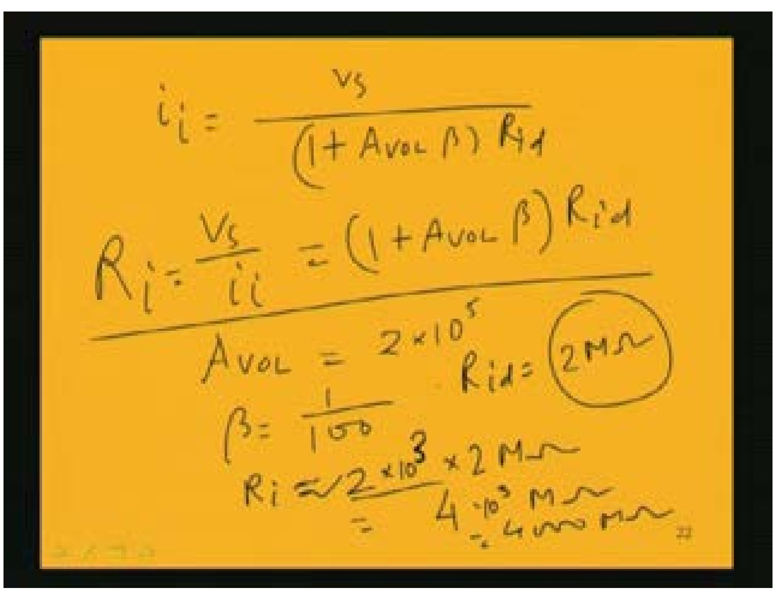
i_i equal to V_S minus V_2 by R_{id} because this is the current which is flowing and the current which is flowing between these two points, the voltages at these two points are V_1 and V_2. V_1 is nothing but V_S and what is V_2? V_2 is the feedback voltage basically here which is given by V_O into R_1 by R_1 plus R_2. Assuming the same approximations that the input resistance R_{id} is very large and neglecting this current i dash which is equal to zero, we get i_i equal to this and what is V_2? V_2 is equal to actually the feedback voltage V_O into R_1 by R_1 plus R_2 and that is nothing but beta times of V_O because this part is beta. Now we can write down that equal to again V_2 equal to beta times of V_O. What is V_O? If we look into this circuit what is V_O? V_O is equal to A_{vOL} V_{id} and what is V_{id}? We have already found out V_{id} to be equal to this value, V_S minus this term. Using those values we are writing V_O by A_{vOL} V_{id} and replacing this V_{id} by A_{vOL} V_{id} and that is equal to beta times A_{vOL} into what is V_{id}? That is again replaced by this term, V_S minus beta times of V_O. We write again what is V_f?

(Refer Slide Time: 50:46)



V_f is beta times of A_{vOL} V_S minus V_f. What is this? This beta A_{vOL} into V_S minus V_f is V_f. Finally V_f is obtained as A_{vOL} beta by 1 plus beta A_{vOL} into V_S. Now we can write down the current i_i equal to V_S minus A_{vOL} beta by 1 plus beta A_{vOL} into V_S by R_{id}. Simplifying this further we get finally what is Vs? If you simplify it further, in the denominator it will be 1 plus beta times A_{vOL} and in the numerator 1 plus beta times A_{vOL} minus beta times A_{vOL}. These two cancel. What will be remaining is simply V_S.

(Refer Slide Time: 52:41)



So i_i is V_S by 1 plus A_{vOL} beta into R_{id}. V_S by i_i that is our input resistance that is equal to 1 plus A_{vOL} beta into R_{id}. If we look into this term what we get is that the resistance of the op-amp, which was R_{id} that is multiplied by a term 1 plus A_{vOL} beta. For example suppose A_{vOL} for an open loop voltage gain of an op-amp we say 2 into 10 to the power of 5 and beta value is say 1 by 100 and beta means coming from that resistive network; so that resistive network has the beta value and that is equal to R_1 by R_1 plus R_2 and that is given as 1 by 100.

What is R_{id}? R_{id} is equal to 2 mega ohm, typical value of 741 IC. What will be this R_i? It is equal to 2 into 10 to the power 5. Almost A_{vOL} beta becomes 2 into 10 to the power of 5 into 10 to the power of minus 2 plus 1. Almost this is equal to 2 into 10 to the power 3; 2 into 10 to the power 3 into 2 mega ohm. One term I am just neglecting because it is very small. 1 is very small compared to A_{vOL} beta which is equal to 2 into 10 to the power of 3. What will be the R_i value? It is 4 into 10 to the power 3 mega ohm. That means 4000 mega ohm becomes the input resistance of the op-amp when the op-amp resistance was 2 mega ohm. But due to the negative feedback the input resistance of the whole network or whole circuit becomes 4000 mega ohm.

From this discussion we have seen that the input resistances become very high because of negative feedback and similarly we can also show that the output resistance becomes even smaller than the output resistance of the op-amp. Because of this negative feedback there is an effect on the voltage gain as well as the input resistance and output resistance of the whole amplifier and these are changed from the voltage gain which is open loop voltage gain of the op-amp or input resistance or output resistance of the op-amp. We have even higher value of the input resistance and we can show that the output resistance becomes lower than the output resistance of the op-amp only. Because of negative feedback, this effect is obtained. Because of practical considerations of the op-amp, because of the non-ideal effects or parameters which are present in the op-amp, when we use a practical op-amp in a circuit like we have seen in a non-inverting op-amp, similarly it can be shown in other applications also that the negative feedback effect is modifying the parameters of the circuit like voltage gain, input resistance, output resistance, etc.

This is negative feedback and there is another type of feedback, positive feedback which is giving you oscillators and that we will discuss later.