Basic electronics
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Lecture- 21

Typical Characteristic of Operation Amplifier

Hello everybody! In our series of lectures on basic electronics learning by doing let us move on to the next lecture. Before we do as usual we will look at topics that we learnt during the previous lecture.

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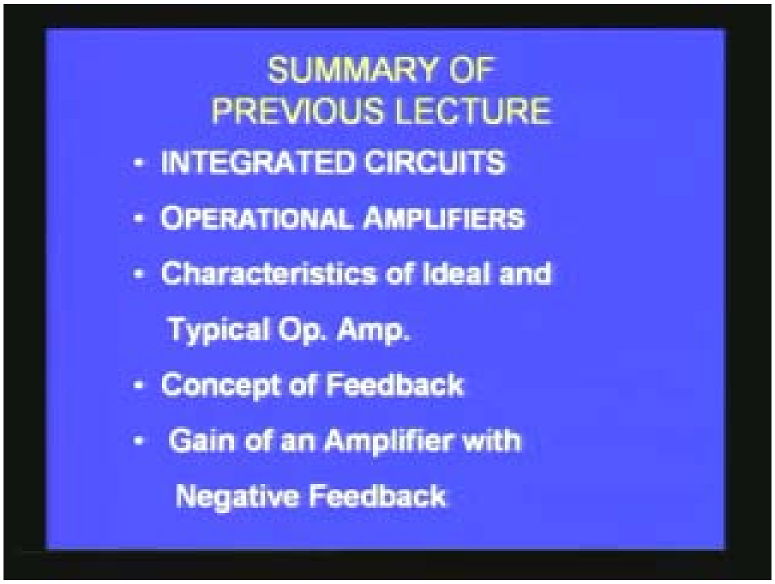

SUMMARY OF
PREVIOUS LECTURE

- INTEGRATED CIRCUITS
- OPERATIONAL AMPLIFIERS
- Characteristics of Ideal and Typical Op. Amp.
- Concept of Feedback
- Gain of an Amplifier with Negative Feedback

You might recall that we discussed the basic principle of integrated circuits. How integrated circuits are developed, formed and then operational amplifiers; some of the characteristics of an ideal and a typical operational amplifier and the concept of feed back and we also derived an expression for the gain of an amplifier with negative feedback which is one of the very important aspects of electronics. Before we move on to the next topic it will be good to recall the typical characteristics of the operation amplifier once more; both the ideal and a typical op amp which is a very popular one, 741. So if you look at the open loop gain which is called A_{OL} the symbol, the ideal op amp has got infinite gain, very large gain whereas typical 741 has got a gain of 100,000 which also is a very large number.

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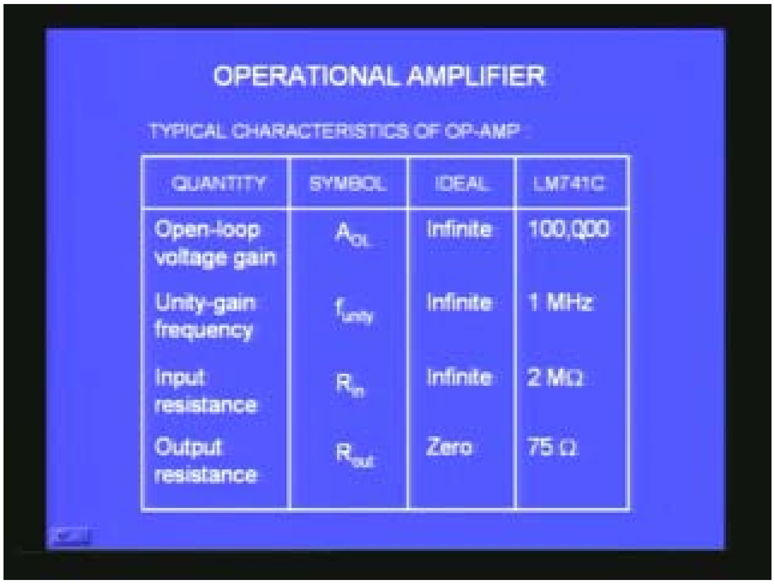

OPERATIONAL AMPLIFIER

TYPICAL CHARACTERISTICS OF OP-AMP :

QUANTITY	SYMBOL	IDEAL	LM741C
Open-loop voltage gain	A_{OL}	Infinite	100,000
Unity-gain frequency	f_{unity}	Infinite	1 MHz
Input resistance	R_{in}	Infinite	2 MΩ
Output resistance	R_{out}	Zero	75 Ω

If you look at the unity gain frequency that means it corresponds to the bandwidth with gain 1; for an ideal operation amplifier it is again infinite and for 741 it is 1 mega hertz, 10 to the power of 6 hertz. From 0 to 10 the power of 6 hertz the amplifier will have reasonably constant gain of about 1. The input resistance if I look at for an ideal op amp it is again infinite and for typical operation amplifier 741 it is about 2 meg ohms. Similarly output resistance is 0 for an ideal op amp and about 75 ohms or around that for a typical operation amplifier which you buy from the market. Most of the numbers are really very close between the ideal and the actual op amp. There are other characteristics that also we saw. We did not discuss in detail about them. We will perhaps do it in the course of next couple of lectures.

Input bias current that also should be zero and typically it is about 80 nano amperes. Input offset current that is also 0 ideally but it is about 20 nano amperes; a small value and input offset voltage is 0 but it is about 2 millivolt for a typical op amp. The common mode rejection ratio, we discussed this in some detail when we discussed about differential amplifiers and the common mode rejection ratio is an ability to distinguish between common signals and differential sequence at the input of any difference amplifier. The op amp input stage being a difference amplifier we have to worry about the common mode rejection ratio of that and ideally it should be very large CMRR, infinity and in actual case it should be 90 db and 90 db should be more than 10,000. More than 10,000 is the voltage gain for differential input to common mode input. Gain A_d by A_c is what is called a CMRR and that is nearly 10,000; 0 10 to the power 4, 10,000 and large.

We also saw in the previous lecture about negative feedback. How negative feedback is very important for control applications and in an amplifier when we say negative feedback what we mean by that. We take a portion of the output voltage and feed it back at the input and when we feed it back we try to feed it back at opposing phase not in phase with the input signal and therefore it is called a negative feedback.

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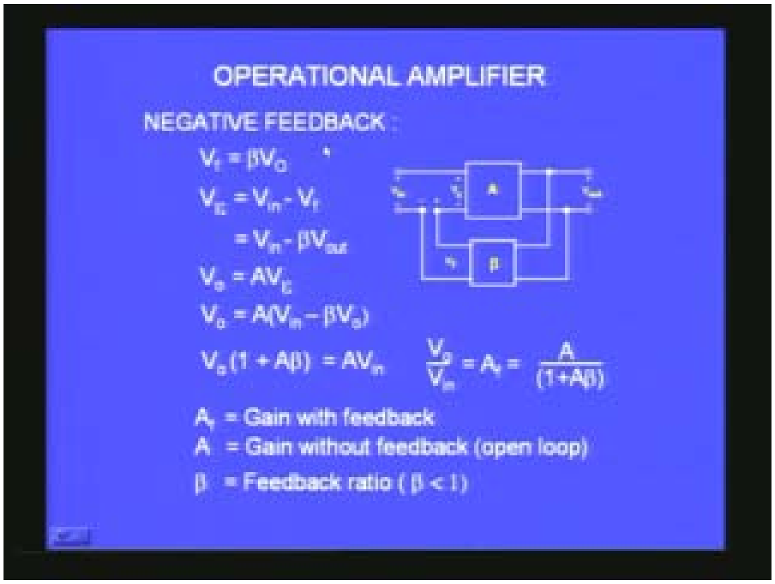

OPERATIONAL AMPLIFIER

NEGATIVE FEEDBACK :

$V_f = \beta V_O$

$V_E = V_{in} - V_f$

$= V_{in} - \beta V_{out}$

$V_o = AV_E$

$V_o = A(V_{in} - \beta V_o)$

$V_o(1 + A\beta) = AV_{in}$ $\quad \frac{V_o}{V_{in}} = A_f = \frac{A}{(1+A\beta)}$

A_f = Gain with feedback

A = Gain without feedback (open loop)

β = Feedback ratio ($\beta < 1$)

If you recall we derived an expression for the gain with negative feedback V output by V input. The negative feedback is inside the amplifier and that new gain I called A_f which is the gain with feedback. This is related to the intrinsic gain A of the amplifier by this expression which we derived last time also. I have shown here the mathematical steps. A_f the gain with feedback is equal to the gain without feedback A divided by 1 plus A beta where beta is called the feedback ratio. What is the proportion of the output voltage which is given at the input? This is called feedback ratio. It is usually less than 1 and so A beta will be a very large number. In an ideal case when you have A tending to infinity, limit A tending to infinity, this expression will become 1 by beta. That also I explained to you last time; limit A tending to infinity. This will reduce to 1 by beta and that means beta is in the hands of the user of the op amp. You can choose proper network for the feedback by which you will be able to completely decide the property or the behavior of the amplifier by using the external resistors, capacitors. That is why we want to have as high a gain as possible for the operational amplifier. That is why we want to have the gain of the amplifier to be around 100,000 or more. In the ideal case it is infinity because then it becomes very convenient. The characteristic of the op amp itself is not the deciding factor but the external resistors, components that I use for the feedback network I can control and thereby I can control the behavior of the amplifier.

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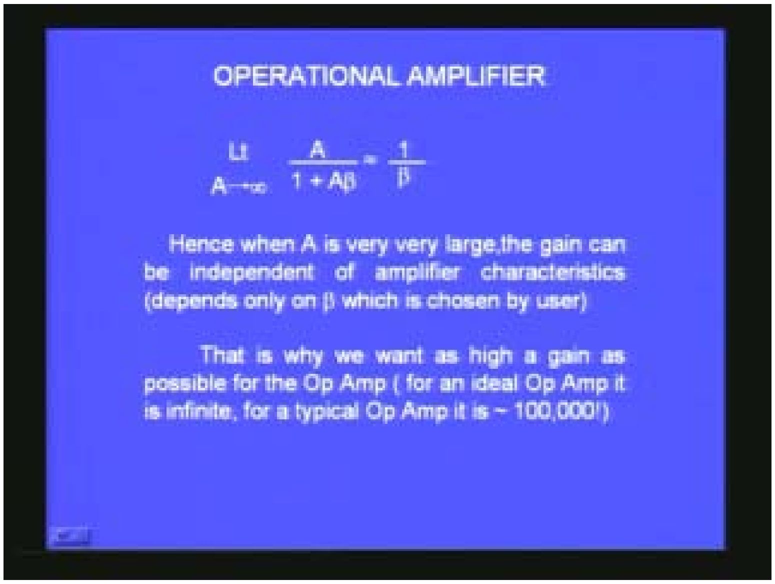

OPERATIONAL AMPLIFIER

$$\underset{A\to\infty}{Lt} \frac{A}{1+A\beta} = \frac{1}{\beta}$$

Hence when A is very very large,the gain can be independent of amplifier characteristics (depends only on β which is chosen by user)

That is why we want as high a gain as possible for the Op Amp (for an ideal Op Amp it is infinite, for a typical Op Amp it is ~ 100,000!)

This is a very important concept and you would see in this lecture and the next one also I will keep stressing about this point and I will show you how this comes about. Let us look at some of the important things. I generally mentioned about feedback, negative feedback. That means a portion of the output is connected in phase opposition to the input. That does not tell you what is it that I sense at the output and what is it that I give at the input. I send something from the output and the portion of it I give at the input.

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OPERATIONAL AMPLIFIER

BASIC IDEAS :

The input to a negative-feedback amplifier can be either a voltage or a current. Also, the output signal can be either a voltage or a current. This implies that four types of negative feedback configuration exist.

You have several choices. For example the output; I can sense the voltage, the output voltage and feed it back also as a portion of a voltage at the input. So I can sense a voltage and give a voltage at the input; a fraction of the voltage in phase opposition. The other way I can sense the voltage and give it as a current at the input or I can sense the current at the output and give it as a voltage or vice versa. So you can see there are 4 different ways in which I can take a portion of the output and give it at the input. These 4 different configurations of feedback is very important for us to learn about in this case and I have shown you in the picture on the screen the 4 different configurations.

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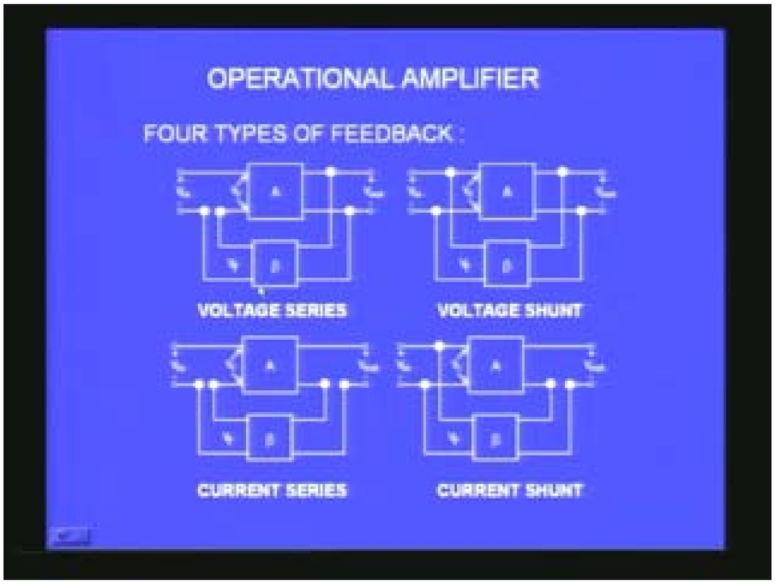

OPERATIONAL AMPLIFIER

FOUR TYPES OF FEEDBACK :

VOLTAGE SERIES

VOLTAGE SHUNT

CURRENT SERIES

CURRENT SHUNT

For example the first one you would sense the voltage because you are connecting them. The beta, the feedback network you connect in parallel to the output points and you are actually sensing the voltage at the output point. So you sense the voltage and you give also a voltage here in series with the input terminals of the amplifier. Voltage series is what some people call this type of a feedback; voltage sensed and given in series. If you look at the second picture the voltage is again taken here because it is taken in parallel at the output and it is also given in parallel at the input terminals. The input voltage at the terminals of the amplifier and the feedback voltage are actually connected in parallel. The two networks are in parallel. This is a shunt. Voltage is given as a shunt at the input. So this is the second configuration.

Similarly you can sense the current in series. If I put something in series the same output current will have to flow through the beta network also and this is a series connection whereas in the other case it is a parallel connection. You connect in parallel to the output impedance of the amplifier the network also in parallel and this is a series connection. If I connect the series then the current is a constant in a series circuit. Voltage is constant in a parallel circuit. We have seen that also. This series current generates a voltage and that voltage is fed back at the input. This is called current connected as a voltage in series and the other one you sense again the current and give it in parallel; therefore in shunt so current shunt feedback. So you have 4 different types of feedback configurations possible for a given amplifier, voltage amplifier like an op amp. In an op amp we can implement these 4 different types of feedback circuits. All of them correspond to negative feedback and all of them will correspond to a very good, nice circuit which is very useful for several applications. We will see it.

What I am now going to do is take one by one each of these feedback configurations and try to explain to you the consequence of this feedback configuration on the output; effective output resistance of the amplifier and the effective input resistance of the amplifier.

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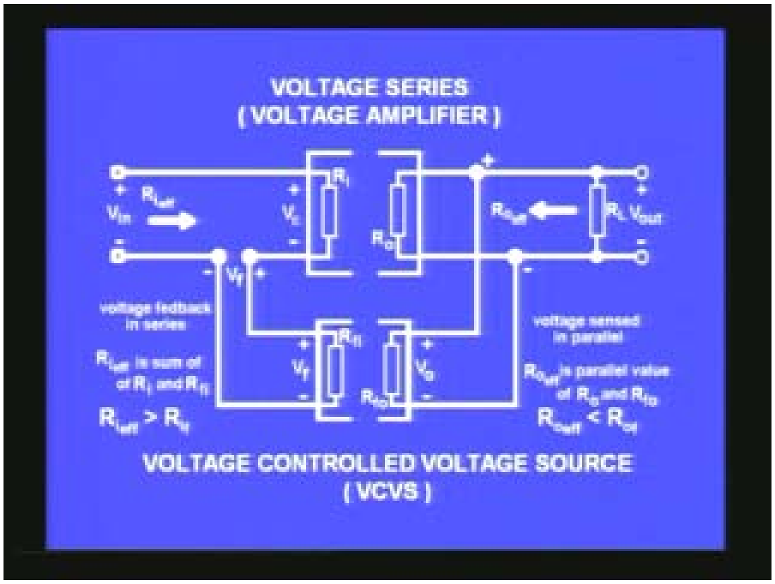

VOLTAGE SERIES
(VOLTAGE AMPLIFIER)

voltage fedback in series

R_{ieff} is sum of of R_i and R_{fi}

$R_{ieff} > R_{il}$

voltage sensed in parallel

R_{oeff} is parallel value of R_o and R_{fo}

$R_{oeff} < R_{ol}$

VOLTAGE CONTROLLED VOLTAGE SOURCE
(VCVS)

You have to remember that every amplifier can be drawn as an equivalent circuit with an input resistance R_i and the output resistance R_o in series with a voltage source which is actually A_{OL} times V epsilon. This is a voltage source which is taking care of the gain factor of the amplifier which is in this case the open loop gain. I have not show this because I am trying to look at in the terms of the Thevenin's equivalent circuit and the voltage source is short here and what you see here is only the output impedance R_o. Now I take an equivalent network of resistance here at the feedback network. I can always look it as some resistance R_{fo} which is the feedback network resistance of the feedback network and I am sensing the voltage in parallel. The same voltage V_o is also applied across this R_{fo} and by some potential divider I take an effective voltage at the output and that output I give in this configuration with a phase inversion. You can see this is plus minus this is plus minus.

So whatever is the input voltage the entire voltage will not be applied here because they are connected in series. This is like connecting two batteries in series. V_E epsilon plus V_f is what is equal to V_{in}. What is V epsilon which is the voltage exactly connected at the input? This is going to be V_{in} minus this V_f. Because of the feedback the input voltage is decreased. V_{in} is larger than V epsilon. That means all the input voltage that you connect is not applied at the input terminals of amplifier op amp because some has been neutralized by the feedback voltage V_f that I have taken. So voltage is sensed in parallel at the output. This is R_L which is the load resistance at the end of the amplifier. This load can be anything. It can be a loud speaker or something which we want to drive after amplification. Now if I look from that end the output resistance end and look into the amplifier what you would observe? You would observe two different resistors coming in parallel one is the output resistance of the amplifier and the other one is the output resistance as seen as the Thevenin's resistance of the beta; the network that we have connected for the feedback.

These two resistors when you connect in parallel what is going to happen? The effective resistance is going to be the parallel value of these two resistances. The parallel combination of two resistors is always less than the smallest in that group. So you can never get R_o. You will always get a value which is less than R_o effective resistance. So the effect of connecting in parallel a feedback network is to reduce the output impedance. That is what I want you to understand. When I connect any network in parallel to the input you will always get an effective resistance of the output reduced. Let us see what happens? R_o effective is a parallel value of R_o and R_{fo} where R_{fo} is the feedback network. Then R_o effective is always less than R_o the output resistance of the amplifier. Similarly if we look at the input, voltage is connected in series with the input signal and what I get will be less than the actual applied input because some feedback voltage will reduce some of the magnitude. R_i effective the input resistance is the sum of this plus this. They are coming in series. The total resistance will be the sum of the input resistance of the amplifier and the input resistance of the network together.

What is going to happen? The effective resistance because of the feedback will always be larger than R_i alone without feedback. So the effect of feedback network at the output resistance when I sense voltage in parallel at the output is to reduce the output resistance. The effect of connecting the voltage in series at the input is to increase the input resistance. If an amplifier has got increased input resistance and decreased output resistance what will be the type of an amplifier? For an ideal voltage amplifier the input impendence should be very large. We have seen it number of times. The input impedance of an ideal voltage source should be very large so that the entire signal is applied across the amplifier; very small fraction is dropped inside the source resistance. If I have a very large input resistance due to this configuration the input will have to be a voltage and I connect a voltage here and what I get at the output is a decrease in the resistance due to the feedback, output resistance. Whenever there is decrease that means it becomes much closer to an ideal voltage source and the output will be able to drive any kind of load, any magnitude of the load. That means this has to be a voltage source. Only a voltage source will have a least internal resistance and the reduction in resistance due to this configuration makes the output more and more closer to a voltage source and the feedback that is given at the input makes the input higher resistance, input resistance higher and that makes it much more useful as a voltage amplifier. The input is a voltage output is also voltage. The output voltage is controlled by the input. This configuration is called voltage controlled voltage source. The output is a voltage source because the output impedance is decreased due to the feedback and it is controlled by the input voltage. This configuration is called voltage controlled voltage source by some people.

In the same way we can argue for each of the configurations that I showed you; 4 different configurations. For example here again sensing is done in parallel.

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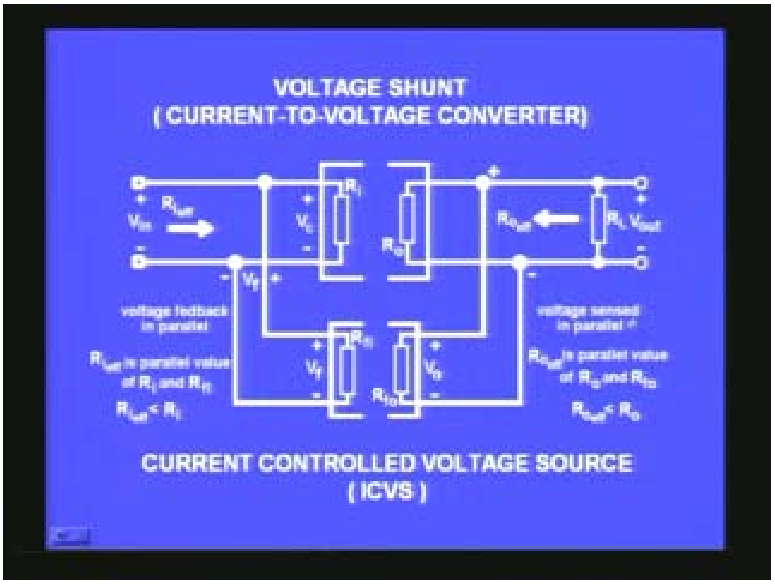

VOLTAGE SHUNT
(CURRENT-TO-VOLTAGE CONVERTER)

voltage feedback in parallel

R_{ieff} is parallel value of R_i and R_{fi}

$R_{ieff} < R_i$

voltage sensed in parallel

R_{oeff} is parallel value of R_o and R_{fo}

$R_{oeff} < R_o$

CURRENT CONTROLLED VOLTAGE SOURCE
(ICVS)

Voltage is sensed in parallel and the effective resistance is the parallel value of R_o and R_{fo} which in principle is effectively to reduce the output impedance of this combination and the output resistance is reduced here and if you look at the input it is different from the previous thing. Here I am giving it in shunt. I am actually connecting the voltage in parallel to the input voltage of the terminals of the amplifier. When I have two resistors in parallel the effective resistance is going to be small. It is no more a voltage input. Because if it is a voltage input I must have large input resistance. Then only it can be a voltage input. The effect of this feedback is to reduce the input resistance and the input will have to be a current. It is no more V_{in}; it has to be I_{in}. The input is going to be a current. The output resistance is decreased. Therefore the output is going to be still a voltage source and it is a current controlled voltage source. That is what we get when I give a feedback of this nature and this is also called incidentally current to voltage converter. We can get a very nice current voltage converter by making this type of a feedback configuration using of an op amp at a later stage.

Let us move on to the next circuit. Here you see the voltage is actually not sensed. You will sense the voltage when you take the output in parallel. But you are taking the output in series. You are actually sensing the I_o. The output current is being sensed here and if you sense the output current you are connecting it in series to the output and the effective output impedance is increased as you can see here. This R_o and R_{fo} will come in series. The effective resistance is larger than R_o alone. So due to feedback the output impedance is increased. If output impedance is increased then the output should be a current source because only for a current source the internal resistance is very high.

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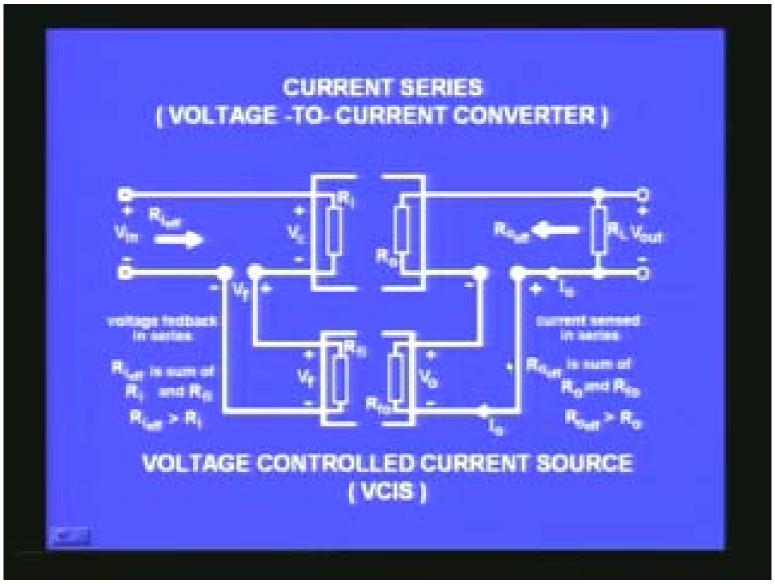
CURRENT SERIES
(VOLTAGE -TO- CURRENT CONVERTER)



voltage fedback in series

R_{ieff} is sum of R_i and R_{fi}

$R_{ieff} > R_i$

current sensed in series

R_{oeff} is sum of R_o and R_{fo}

$R_{oeff} > R_o$

VOLTAGE CONTROLLED CURRENT SOURCE
(VCIS)

If the internal resistance of the amplifier at the output is having a higher resistance that means it is becoming more a current source. If you look at the input it is very similar to the first configuration we saw. We are giving the feedback voltage in series with the terminals and the effect is to reduce the effective input voltage connected to the amplifier and it will increase the effective input resistance because here also it is coming in series and when I connect two resistors in series the effective resistance should be larger and so the resistance is increased at the input; resistance is also increased at the output. The increase in resistance makes sure that what we apply will be a voltage. The increase in resistance at the output shows that it has to be a current which is being given at the output through the load and this is a voltage to current converter. Basically the circuit becomes the voltage to current converter or in another way you can call it as a voltage controlled current source. The current source will be controlled by whatever voltage that we connect here. So this becomes a voltage controlled current source which is the third configuration.

Now we will come to the last configuration, the 4th configuration where the feedback voltage is to be obtained by sensing the output in series and again it is going to be increased resistance of the output stage and it has to be a current source at the output. At the input I again connect it in parallel to the input terminals and the effective resistance is the parallel value of R_i and R_{fi} which is always small. The effective input resistance is decreased. When the effective input resistance is decreased then it has to be the current which is driving the input rather than the voltage. This is a current input here and you also get a current output here because the output impedance is also increased. This is a current amplifier. You give some current here you can get a higher current at the output. So it becomes a current amplifier and it is also called current controlled current source.

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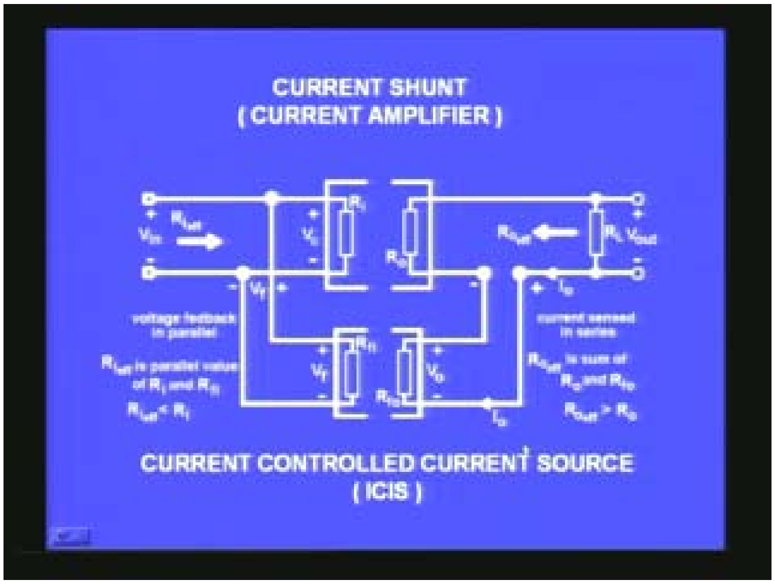

CURRENT SHUNT
(CURRENT AMPLIFIER)

CURRENT CONTROLLED CURRENT SOURCE
(ICIS)

The output current source is controlled by the input current that you drive through the input terminals and this feedback leads to a circuit which is current controlled current source.

Having seen all the four different configurations I have put it in the form of the table to show you in a nut shell.

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OPERATIONAL AMPLIFIER

IDEAL NEGATIVE FEEDBACK :

INPUT	OUTPUT	CIRCUIT	Z_{in}	Z_{out}	CONVERTS
V	V	VCVS	∞	0	V to V
I	V	ICVS	0	0	I to V
V	I	VCIS	∞	∞	V to I
I	I	ICIS	0	∞	I to I

For example in the first configuration it was the voltage at the input. You also got a voltage at the output because it was closer to the voltage source due to the feedback and it is called the voltage controlled voltage source. Ideally the voltage controlled voltage source should have infinite resistance at the input. It should have zero resistance at the output. In our case the input resistance was increased because of the series connection of the feedback and the output voltage is decreased because we are taking that in parallel to the feedback network. So this is a V to V converter. In the second circuit you have the parallel connection and therefore the input resistance is reduced and therefore it becomes a current drive and at the output is again the voltage because you are sensing it in parallel and it is a current controlled voltage source and an ideal current controlled voltage source should have zero input resistance and zero output resistance and it becomes a I to V converter.

The third circuit is the V at the input I at the output. It becomes a voltage controlled input source and it will have infinite resistance at the input corresponding to voltage and it will have the infinite resistance have the output corresponding to a current source and it becomes a voltage to current converter or V to I circuit. The last one is basically current controlled current source, an ICIS and it will have zero input impedance and very high output impedance and it becomes a current controlled current source. In an actual case when we discuss with the normal op amp, these four configurations I would like to discuss, each one of them will turn out to be a very nice amplifier almost an ideal circuit.

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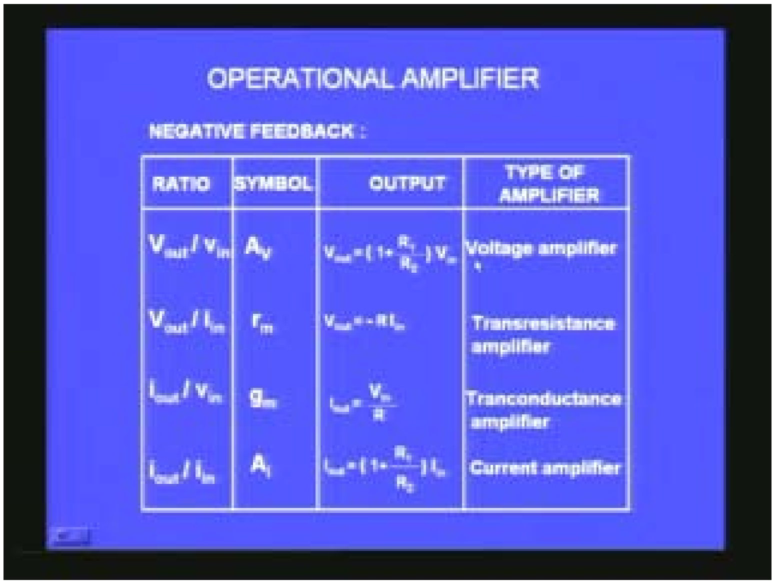

OPERATIONAL AMPLIFIER

NEGATIVE FEEDBACK :

RATIO	SYMBOL	OUTPUT	TYPE OF AMPLIFIER
V_{out} / V_{in}	A_v	$V_{out} = (1 + \frac{R_1}{R_2}) V_{in}$	Voltage amplifier
V_{out} / I_{in}	r_m	$V_{out} = - R I_{in}$	Transresistance amplifier
I_{out} / V_{in}	g_m	$I_{out} = \frac{V_{in}}{R}$	Tranconductance amplifier
I_{out} / I_{in}	A_i	$I_{out} = (1 + \frac{R_1}{R_2}) I_{in}$	Current amplifier

First one will be a voltage amplifier; second one will be a transresistance amplifier because the transfer function has got dimensions of resistance; output voltage by input current gives me resistance. This is a transresistance amplifier and the third circuit is going to be a conductance I output divided by V_{in}; voltage by current is resistance current by voltage is conductance. 1 by R value I will get for I out for V_{in} which I call 'G_m' and this a transconductance amplifier which is also very, very useful in different applications and the last one is a current amplifier and the ratio appears to be the same as what you get in the first case for the voltage amplifier 1 plus R_1 by R_2. We will take different configurations. I will explain to you what is R_1 and R_2. Where from it comes? But this is in general the four different circuits that you get from a single op amp by simply connecting one or two resistors in the feedback network. That is the greatest advantage and you can see these voltage amplifier, transconductance amplifier, transresistance amplifier, current amplifier are almost very close to an ideal current source, current voltage, current amplifier, voltage amplifier, voltage current source, etc because of the very good characteristics of the op amp in the integrated circuit form. That is why we discuss about that in detail.

Having done that back ground on the negative feedback and how different configurations can be connected let us focus on one of the op amp which is very popular, which is very easy and not very expensive. It is very cheap. You can buy in the market for about 10 rupees or so and this is the 741 operational amplifier.

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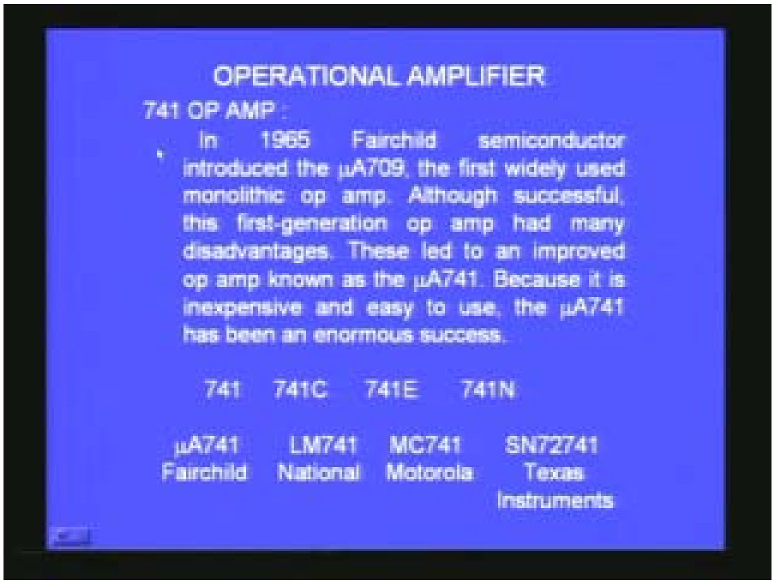

OPERATIONAL AMPLIFIER

741 OP AMP :

- In 1965 Fairchild semiconductor introduced the μA709, the first widely used monolithic op amp. Although successful, this first-generation op amp had many disadvantages. These led to an improved op amp known as the μA741. Because it is inexpensive and easy to use, the μA741 has been an enormous success.

741 741C 741E 741N

μA741	LM741	MC741	SN72741
Fairchild	National	Motorola	Texas Instruments

In fact in 1965 a company called Fairchild semiconductor introduced MuA709 as their first operational amplifier which was very widely used but it had several disadvantages in terms of frequency compensation and got out a more improved design of the same which they called MuA741 and it is very easy and inexpensive to use and this has become a great success many people use this for different …?…. You have hundreds of different types of operational amplifiers to be used at different situations. We will have a look at that at some stage. If you look at the 741 itself it has got different specifications. For example you can buy a 741; you can also buy a 741C. You would find 741C will be cheaper than 741; 741E, 741N, etc. This C, E, N have got some meaning with reference to the temperature ranges for which the operation amplifier can be conveniently operated or on the basis of the noise level.

741C is a commercial operation amplifier and they will be suitable for only small range of temperatures from 0 to 75 degree centigrade. If you go for a military specification for example then the same op amp will have to be manufactured for much stringent variations. That means much larger range of temperature variation from -50 degrees to +120 degree and that becomes a military specification and so it will automatically be more expensive because more care has to be put in the design of such op amps. So they become more expensive. But most of the time we will be discussing only the 741C which is cheap, inexpensive operational amplifier, easily available in the local market.

You also have the same 741 manufactured by different manufacturers. Even though it was the Fairchild who started the first manufacturing of 741 many other people also started manufacturing the same operational amplifier almost with identical characteristics. For example LM741 is actually op amp manufactured and commercialized by National semiconductors. MC741 is an operational amplifier manufactured by Motorola company and SN72741 is again an operational amplifier, with the 741 again coming here, manufacture by Texas instruments. Like that there are different types of manufacturers, device manufacturers but all of them have almost typical similar characteristics. So people normally leave out this specification of the manufacturer LM or MuA or MC and they only specify 741. So when I say 741 it could be from any manufacturer. It should have very similar characteristics.

Having looked at the operation amplifier let us now take one simple configuration of the operation amplifier. You have this symbol of an operation amplifier.

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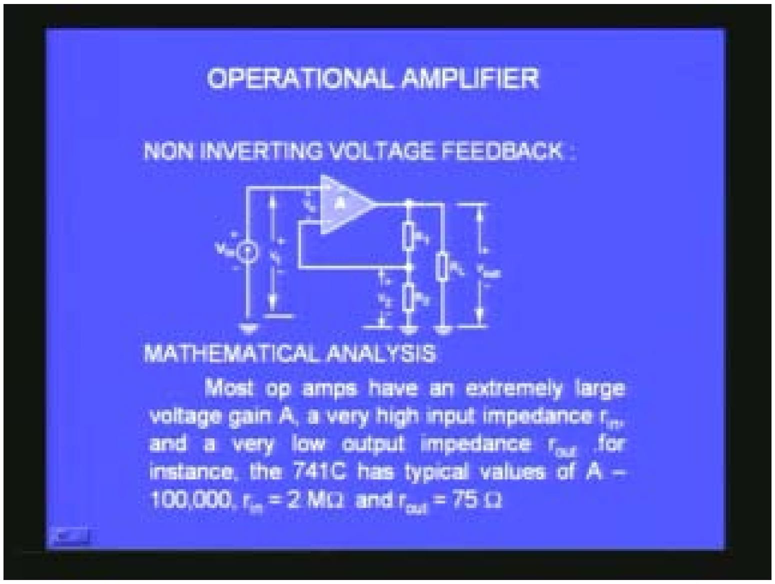

OPERATIONAL AMPLIFIER

NON INVERTING VOLTAGE FEEDBACK :

MATHEMATICAL ANALYSIS

Most op amps have an extremely large voltage gain A, a very high input impedance r_{in}, and a very low output impedance r_{out} .for instance, the 741C has typical values of A – 100,000, r_{in} = 2 MΩ and r_{out} = 75 Ω

We normally do not show the dual supply which I already explained to you in the previous lecture corresponding to V^+ and V^- and you have the input signal connected to the plus and there is a feedback that is given here. The feedback is a very simple configuration here. I just put a potential divider at the output R_1 R_2 and take the mid point and connect it to the input. So what I have effectively done is I have divided the output voltage into two parts one across R_1 and one across R_2 and the voltage developed across

R_2 is applied in series with the input voltage in phase opposition and what you can get here will be reduced voltage.

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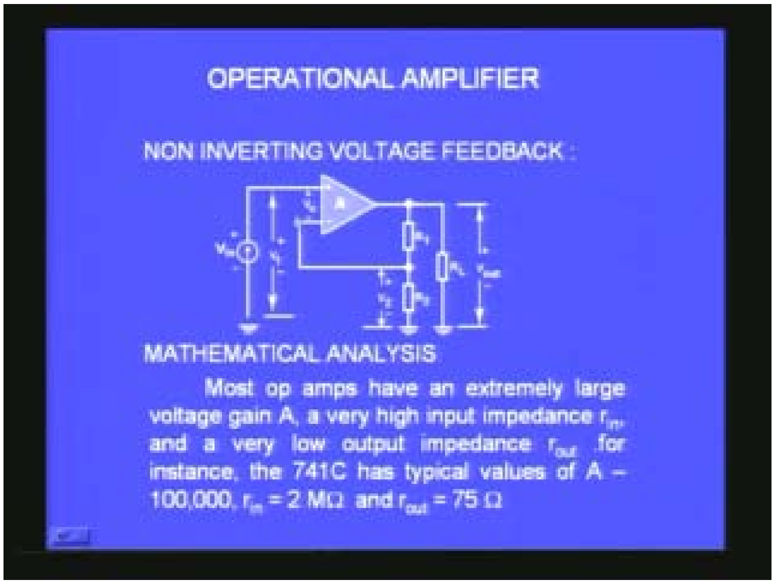

OPERATIONAL AMPLIFIER

NON INVERTING VOLTAGE FEEDBACK :

MATHEMATICAL ANALYSIS

Most op amps have an extremely large voltage gain A, a very high input impedance r_{in}, and a very low output impedance r_{out} .for instance, the 741C has typical values of A – 100,000, r_{in} = 2 MΩ and r_{out} = 75 Ω

That is the effect of feedback we have already discussed and what is this V_2 or V_f which we normally call. V_f is nothing but R_2 divided by R_1 plus R_2 times V output. This is the R_L. This is the V output. You have taken that by sensing the output voltage and this is the feedback that you are giving. Most of the op amps have very large gain, extremely large gain and very high input impedance r_{in} and very low output impedance even without any feedback. For example the 741C has A 100,000; I already gave you the typical table r input is 2 mega ohm and r output is 75 ohms.

What is going to happen with the feedback we will try to understand? What you have here is the feedback voltage V_f or V_2 in this case is R_2 divided by R_1 plus R_2 times V output and this R_2 divided by R_1 plus R_2 is effectively the beta that we represent in our other circuits. The feedback ratio here is beta which is always less than one.

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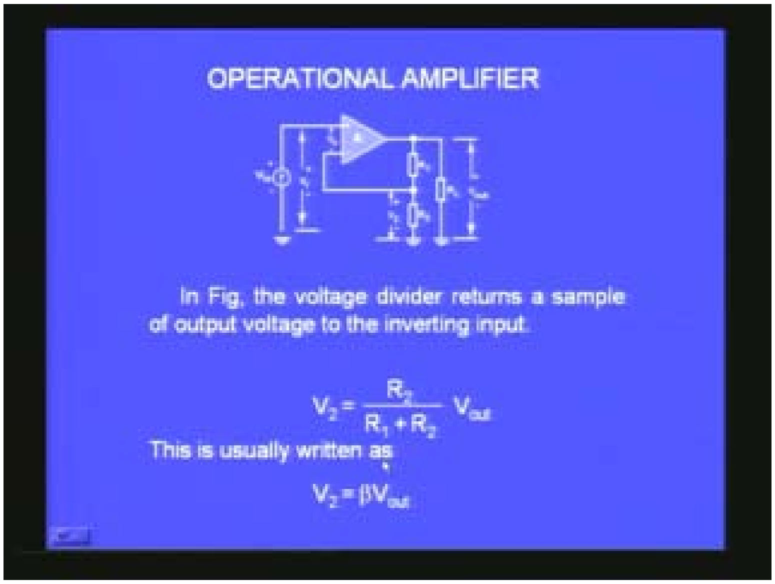

OPERATIONAL AMPLIFIER

In Fig, the voltage divider returns a sample of output voltage to the inverting input.

$$V_2 = \frac{R_2}{R_1 + R_2} V_{out}$$

This is usually written as

$$V_2 = \beta V_{out}$$

So V_2 is beta times Vout. We have assumed that R_2 and R_1 only are existing all the other things are not existing. You have input resistance here. There is an assumption here and the assumption is that R input of the amplifier is very much larger than R_2 and it is the R_2 which decides everything when they come in parallel.

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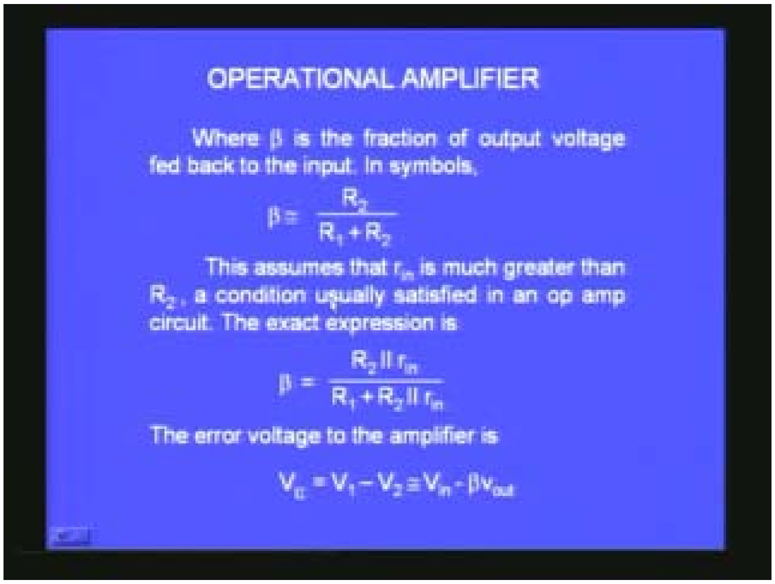

OPERATIONAL AMPLIFIER

Where β is the fraction of output voltage fed back to the input. In symbols,

$$\beta = \frac{R_2}{R_1 + R_2}$$

This assumes that r_{in} is much greater than R_2, a condition usually satisfied in an op amp circuit. The exact expression is

$$\beta = \frac{R_2 \parallel r_{in}}{R_1 + R_2 \parallel r_{in}}$$

The error voltage to the amplifier is

$$V_{\epsilon} = V_1 - V_2 \cong V_{in} - \beta v_{out}$$

This is also true most of the times. Otherwise you have to use very rigorous expression for beta which is R_2 parallel r_{in} divided by R_1 plus R_2 parallel r_{in} to take care of the parallel value of R_2 and r_{in}. The error voltage to the amplifier what I mean by error voltage is the actual voltage or the difference in voltage between the input voltage and the feedback voltage is what I call error voltage and which is the exact voltage which is applied across the input terminals of the operational amplifier circuit. So V epsilon, I call that V epsilon, is nothing but V_1-V_2. We will go back and look at that. V_1-V_2 is what I have here. Because it is negative feedback it is -V_2. So V_1-V_2 is V epsilon and that V_1 is V input itself. V_1 is basically the input voltage coming from the source. V_2 is beta times V output because it is a feedback voltage. If I now substitute that, V output is equal to A times V epsilon because A is the open loop gain without any feedback. That will only amplify the voltage applied across its input terminals which is V epsilon.

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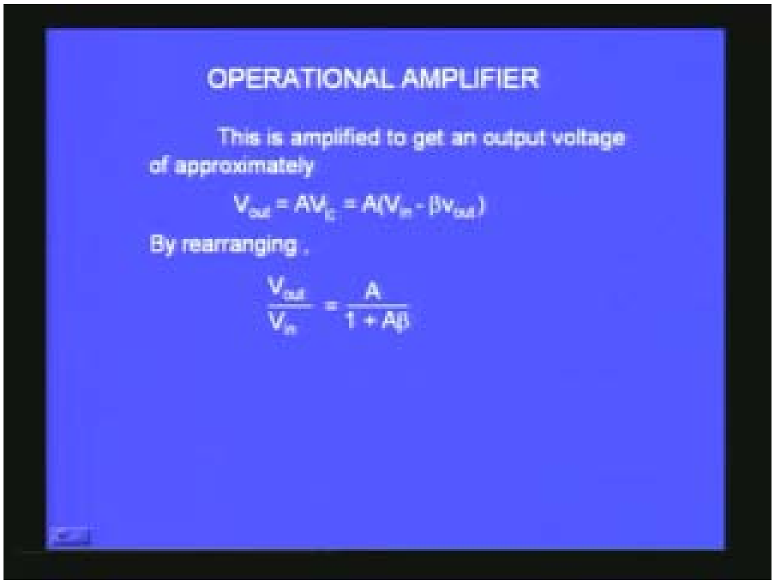

OPERATIONAL AMPLIFIER

This is amplified to get an output voltage of approximately

$$V_{out} = AV_{\varepsilon} = A(V_{in} - \beta v_{out})$$

By rearranging ,

$$\frac{V_{out}}{V_{in}} = \frac{A}{1 + A\beta}$$

So A times v epsilon is output voltage and instead of v epsilon we can write that IS nothing but V input minus beta times V output and when you rearrange we find V output by V in A by 1 plus A beta which is again the same equation we got previously for any negative feedback amplifier. The product A beta is actually called the loop gain for a non-inverting voltage feedback. This non-inverting voltage feedback to be effective the designer must deliberately make the loop gain very much larger than 1 which is also true in our case because A is going to be 100,000; beta is going to may be 0.5. Whatever it is the number becomes very large and A beta is very large compared to 1 and the V output by V_{in} then becomes almost 1 by beta and beta is in this case, because we have used a simple potential divider, beta is R_2 divided by R_1 plus R_2 and 1 by beta is the inverse of this which is R_1 plus R_2 by R_2 which can be rewritten as 1 plus R_1 by R_2. This is 1 by beta and this is the V output by V_{in} which we call the gain of the effective amplifier with feedback. The amplifier gain with feedback is 1 plus R_1 by R_2 and this is independent of A, the gain of the operation amplifier. This is the greatest advantage that we get and R_1 and R_2 are the two resistors that we select in the lab depending upon the convenience and we can very easily change this and change the gain of the amplifier.

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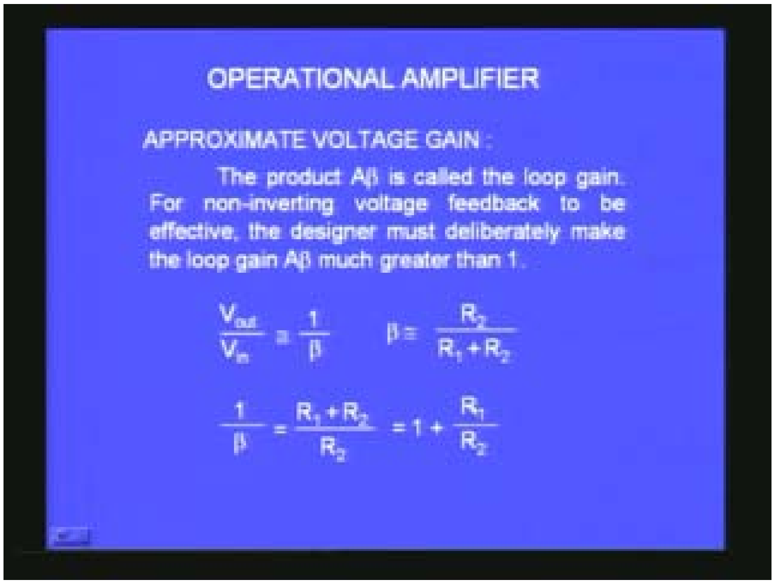

OPERATIONAL AMPLIFIER

APPROXIMATE VOLTAGE GAIN :

The product Aβ is called the loop gain. For non-inverting voltage feedback to be effective, the designer must deliberately make the loop gain Aβ much greater than 1.

$$\frac{V_{out}}{V_{in}} \cong \frac{1}{\beta} \qquad \beta \cong \frac{R_2}{R_1 + R_2}$$

$$\frac{1}{\beta} = \frac{R_1 + R_2}{R_2} = 1 + \frac{R_1}{R_2}$$

So it becomes very, very convenient to increase or decrease the gain by simply changing two resistors R_1 and R_2 by using a very effective negative feedback configuration that we discussed. That is the advantage of this. You also should recognize that people tend to write circuits in different ways; show in different ways. But you must be able to recognize that they are of the same configuration. For example these two circuits that I have shown on the screen appear as though they are two different circuits.

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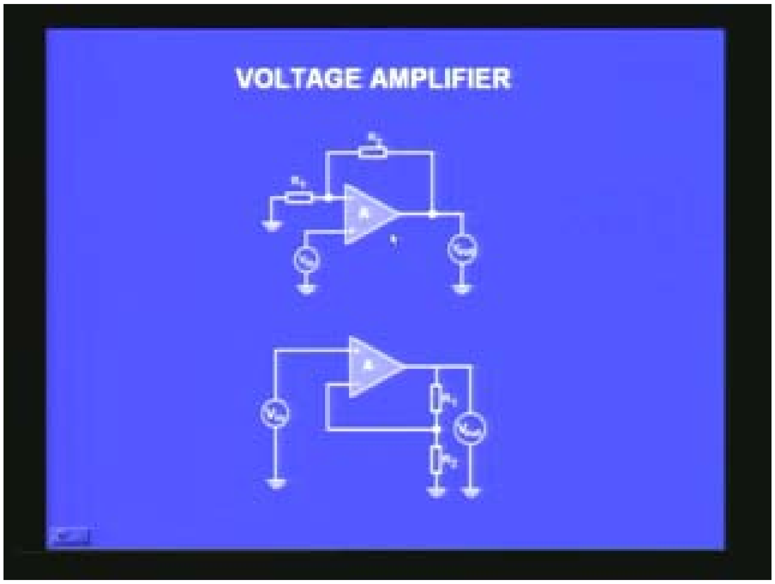
VOLTAGE AMPLIFIER



But if you carefully observe they are two identical circuits. You can see that the negative end is actually used for the feedback R_2 and the R_1 is connected to ground. This is R_2 plus

R_1 which is connected in the feedback loop and that is connected to the negative point. There is a negative feedback. The same thing the way we showed just now is R_1 R_2 put at the output as a potential divider and the middle point is connected to V^-. So this and this are exactly identical. We have only interchanged the amplifier; flipped the amplifier about an horizontal axis by 180 degrees. This is V_{in}. Here also the V_{in} is connected to the plus terminal; here also the plus terminal and output voltage is measured across the output terminal of the amplifier. So these two configurations are identical. In books some people show it like this; some people do it like this. It does not matter as long as they are given the negative feedback correctly and they are applying the input at the plus terminal and measuring the output corresponding to the output terminal.

Having seen that let us take a simple example of a 741C which has got a 100,000 gain. What is the close loop gain if V_{in} is equal to 1 millivolt? What does the output error voltage equal?

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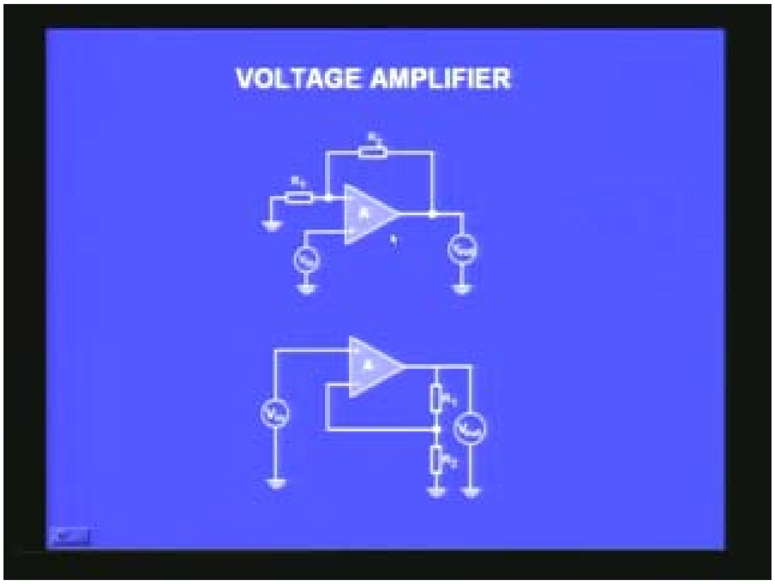

VOLTAGE AMPLIFIER

In this case the resistor values are given. It is 2 kilo ohm and 98 kilo ohm. R_1 is 2 kilo ohm; R_2 is 98 kilo ohm. So 2 kilo ohm by 100 kilo ohm that is equal to 0.02.

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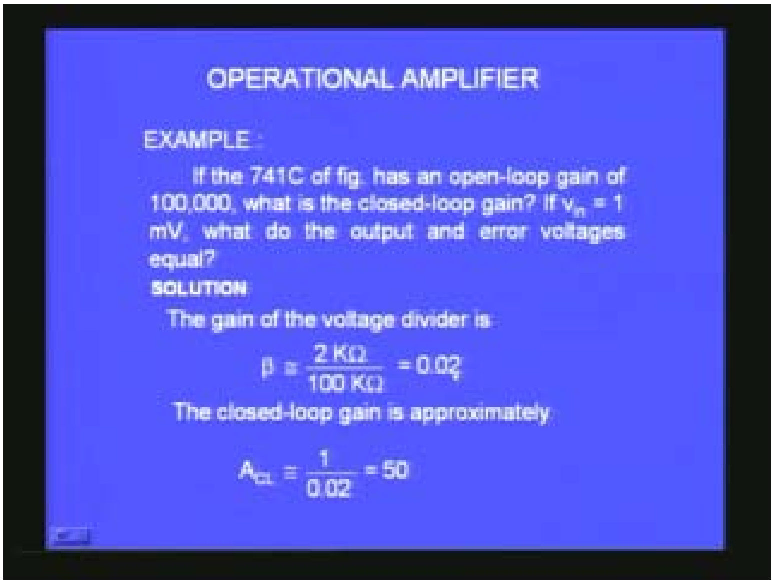

OPERATIONAL AMPLIFIER

EXAMPLE :

If the 741C of fig. has an open-loop gain of 100,000, what is the closed-loop gain? If v_{in} = 1 mV, what do the output and error voltages equal?

SOLUTION

The gain of the voltage divider is

$$\beta \cong \frac{2\,K\Omega}{100\,K\Omega} = 0.02$$

The closed-loop gain is approximately

$$A_{CL} \cong \frac{1}{0.02} = 50$$

That is the beta factor. The smaller the beta, 1 by beta will be much larger. It will be 50. The closed loop gain is 1 by beta and that is around 50 for this circuit. That means the closed loop gain is 100,000 A divided by 1 plus A beta which is also 49.975 very close to 50 and whatever way, whichever expression you use ultimately the correct number comes out.

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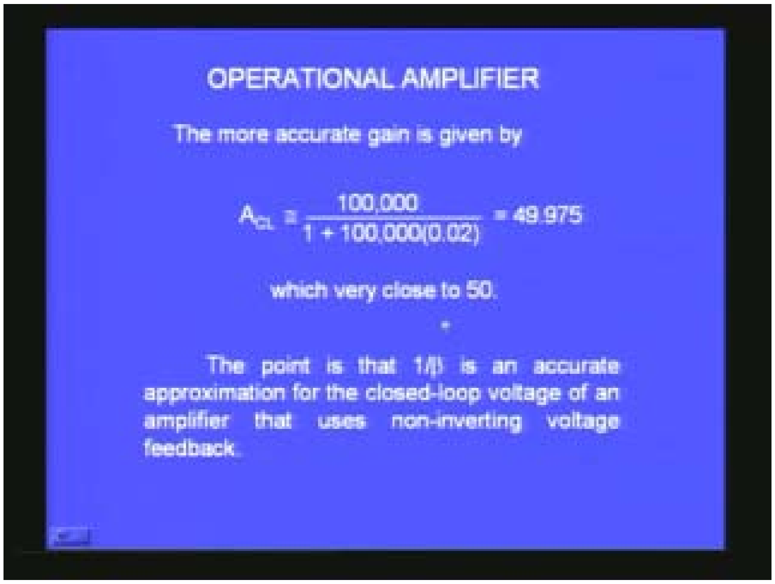

OPERATIONAL AMPLIFIER

The more accurate gain is given by

$$A_{CL} \cong \frac{100{,}000}{1 + 100{,}000(0.02)} = 49.975$$

which very close to 50.

The point is that 1/β is an accurate approximation for the closed-loop voltage of an amplifier that uses non-inverting voltage feedback.

Therefore we say 1 by beta is a good enough approximation for the closed loop voltage of an amplifier that uses non-inverting voltage feedback. This is called a non-inverting voltage amplifier because the input is given to plus terminal and between the output and input there is no phase difference. The output will be in phase with the input and it is called a non- inverting amplifier. If I have to give to the negative terminal of the input for the op amp there will be a phase difference between the input and output. In this case there is no phase difference. It is called non-inverting amplifier. A non-inverting amplifier is almost close to an ideal voltage amplifier. If V_{in} is equal to 1 millivolt the output voltage is closed loop gain multiplied by V_{in}; 50 multiplied by 1 millivolt you get 50 millivolt and what is the voltage that is exactly applied at the input? This 50 millivolt is the output voltage.

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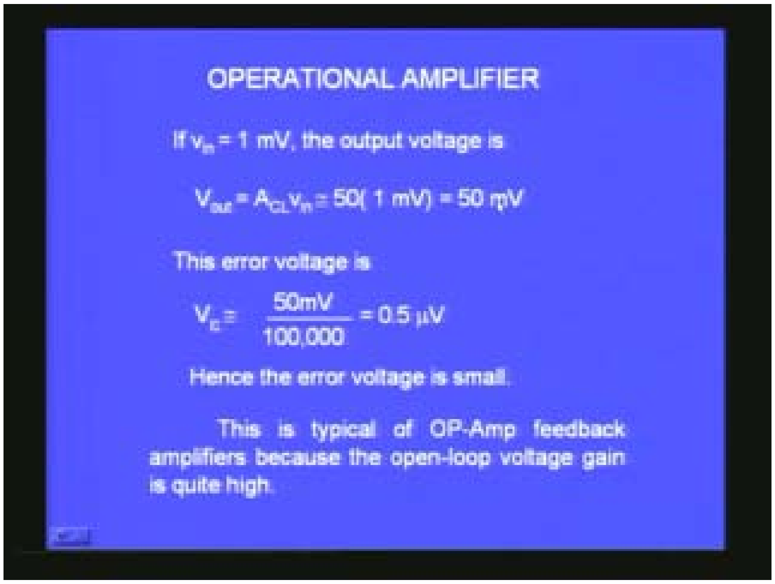

OPERATIONAL AMPLIFIER

If $v_{in} = 1$ mV, the output voltage is

$$V_{out} = A_{CL} v_{in} = 50(1\text{ mV}) = 50\text{ mV}$$

This error voltage is

$$V_{\varepsilon} = \frac{50\text{mV}}{100{,}000} = 0.5\ \mu\text{V}$$

Hence the error voltage is small.

This is typical of OP-Amp feedback amplifiers because the open-loop voltage gain is quite high.

If I divide that by 100,000 I will get the V epsilon the voltage which is exactly applied at the input terminals of the op amp. That is found to be 0.5 micro volt. It is a very, very small voltage that is only applied. Out of the 1 millivolt there is only 0.5 micro volt applied across the input terminals. So the same configuration is shown here to bring out a idea to you that even though the gain has decreased from 100,000 to 50 in the previous example you don’t have to worry.

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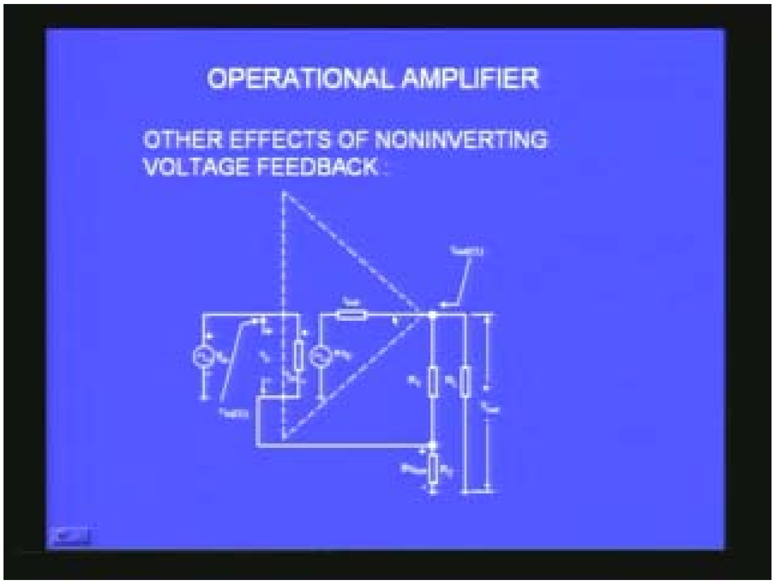

OPERATIONAL AMPLIFIER

OTHER EFFECTS OF NONINVERTING VOLTAGE FEEDBACK :

I already mentioned to you this decrease in gain comes out as an increase in features corresponding to a good amplifier like the input resistance, output resistance, bandwidth, distortion, etc. What it is amounting to is that the gain of the amplifier becomes something like a deposit in a bank with which you can take risks and buy different things in the market without any worry because you have lot of credit on your bank. You can go and do several things boldly; take bold steps financially. In the same way when you have a very large open loop gain then by sacrificing that large gain by some factors you will be increasing the other features outside. That is what I wanted to show you. For example the input resistance closed loop gain will be come much larger than the input resistance without feedback.

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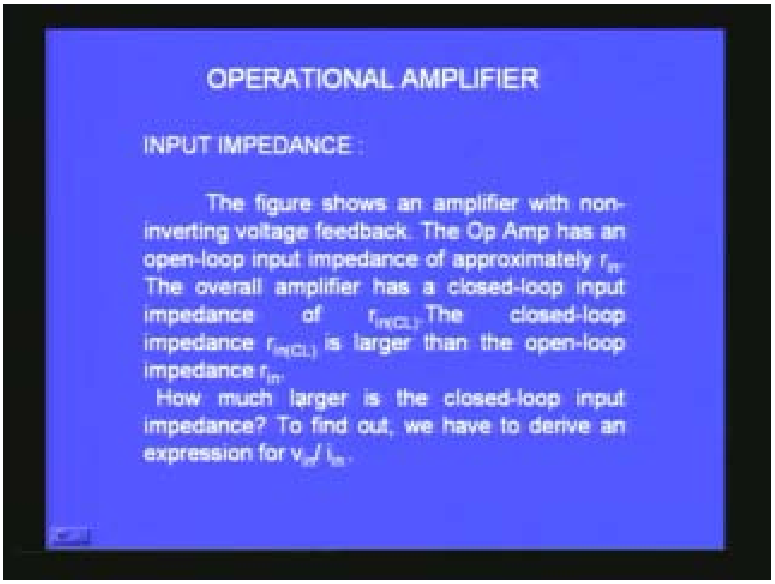

OPERATIONAL AMPLIFIER

INPUT IMPEDANCE :

The figure shows an amplifier with non-inverting voltage feedback. The Op Amp has an open-loop input impedance of approximately r_{in}. The overall amplifier has a closed-loop input impedance of $r_{in(CL)}$. The closed-loop impedance $r_{in(CL)}$ is larger than the open-loop impedance r_{in}.

How much larger is the closed-loop input impedance? To find out, we have to derive an expression for v_{in}/ i_{in}.

The output resistance will become much smaller than the output resistance without feedback. How do you show that? I hope you remember V input is V epsilon plus beta V output. V epsilon is V_{in} minus beta V output. That's what we already saw. So V_{in} is V epsilon plus A beta V epsilon. Because V output is A times V epsilon that is equal to 1 plus A beta V epsilon.

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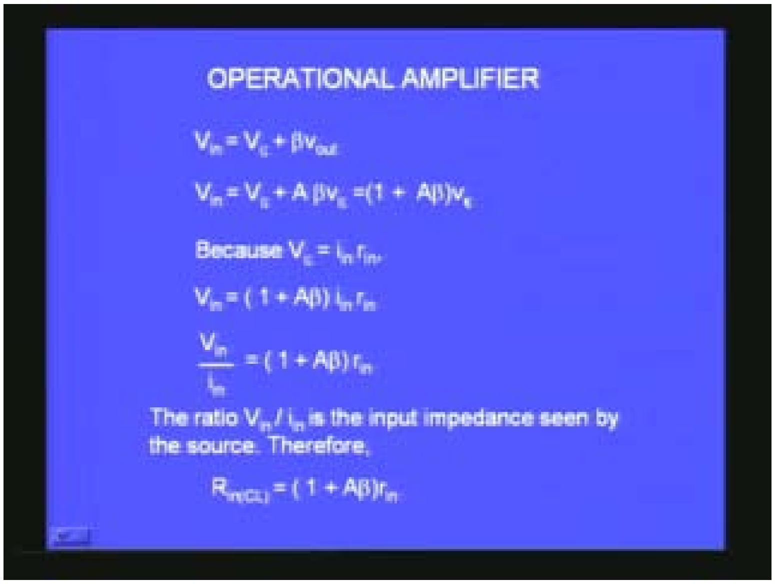

OPERATIONAL AMPLIFIER

$V_{in} = V_{\epsilon} + \beta v_{out}$

$V_{in} = V_{\epsilon} + A\,\beta v_{\epsilon} = (1 + A\beta)v_{\epsilon}$

Because $V_{\epsilon} = i_{in} r_{in}$,

$V_{in} = (1 + A\beta)\, i_{in} r_{in}$

$$\frac{V_{in}}{i_{in}} = (1 + A\beta)\, r_{in}$$

The ratio V_{in} / i_{in} is the input impedance seen by the source. Therefore,

$R_{in(CL)} = (1 + A\beta) r_{in}$

V epsilon is actually responsible for sending an i_{in} through the r_{in}, the input resistance. So V_{in} is 1 plus A beta times i_{in} into r_{in}. V epsilon I can write in that way where r_{in} is the input resistance and so V_{in} by i_{in} is equal to 1 plus A beta into r_{in} where r_{in} is the input resistance of the amplifier, op amp. So V_{in} by i_{in} is that new input resistance. I apply from my source V_{in} and it results in a current i_{in}. This current is now a reduced current because of the feedback voltage. Therefore V_{in} by i_{in} should be much larger than what it was without feedback. That is exactly what you are getting at the right side. The input resistance which was there before is multiplied by a very large factor which is 1 plus A beta, the loop gain. The A beta is a very large number compared to 1. It is multiplied by very large number and the effect of feedback is to increase the input resistance by several orders of magnitude; 1 or 2 orders of magnitude. The ratio output resistance R_{in} this I call $R_{in(CL)}$ CL means closed loop. Input resistance with closed loop is equal to 1 plus A beta R_{in}. The input resistance is increased by a factor which is 1 plus A beta. That is the factor by which the gain was decreased. The feedback gain is A by 1 plus A beta. It is decreased by 1 plus A beta times and here it is increased by 1 plus A beta times. That is why we still go for negative feedback. Even though it reduces the gain it improves the input resistance. Similarly it improves the output resistance also. It can be shown r output with closed loop will be r output by 1 plus A beta.

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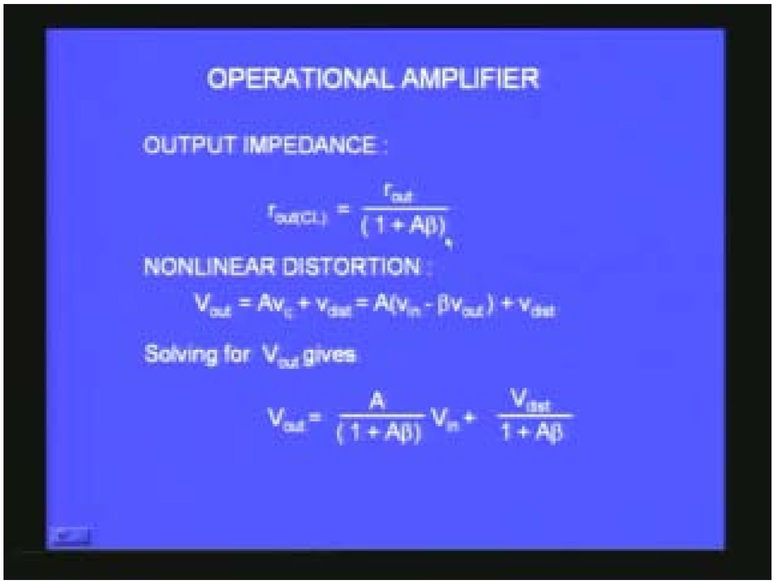

OPERATIONAL AMPLIFIER

OUTPUT IMPEDANCE :

$$r_{out(CL)} = \frac{r_{out}}{(1 + A\beta)}$$

NONLINEAR DISTORTION :

$$V_{out} = Av_{\epsilon} + v_{dist} = A(v_{in} - \beta v_{out}) + v_{dist}$$

Solving for V_{out} gives

$$V_{out} = \frac{A}{(1 + A\beta)} V_{in} + \frac{V_{dist}}{1 + A\beta}$$

That means the output resistance is still reduced by this factor 1 plus A beta. The non-linear distortion are there due to non-ideal conditions of the operation amplifier or any amplifier for that matter. So every amplifier will have some contribution to this. So V output is A times V epsilon which is the actual output gain plus some unwanted distortions that has come about due to the amplifier. If I give feedback part of the distortion also will be fed back. That distortion also will be reduced in effect and the output voltage will give a value which is A by 1 plus A beta times V_{in} which is due to the gain factor A_f plus V distortion divided by 1 plus A beta. That means it is reduced distortion now and the reduction factor is again 1 plus A beta which is the number which we already met. The effect of feedback is also to reduce the distortion.

Having seen that let us try to look at a simple simulation of the circuit. On the screen you see there is a bread board and you have a dual supply here. You have a voltage source which has got millivolts or volts input and you have a multimeter here. You have to connect them and the circuit is shown at the bottom; left corner. This is a circuit this is a non-inverting amplifier with a signal source shown here; voltage source shown here. If you want to try let us try a manual scheme. Then you take an op amp and build the circuit. So you put it in the corresponding gap. For example I take it and put it where the hand shows and now the other resistor is also taken and connected. We can connect the rest of the wiring. It will show you where the connection is done. I am connecting the V^- terminal, the ground terminal and completing the rest of the circuit. This is the way you will do it in the lab by wiring the circuit. Now we connect the multimedia output terminals to 6 and also the ground point to the ground of the multimedia. The multimedia is connected. Now I have to connect the voltage source and I will connect now voltage source and the ground point of the voltage source. The wiring has been completed.

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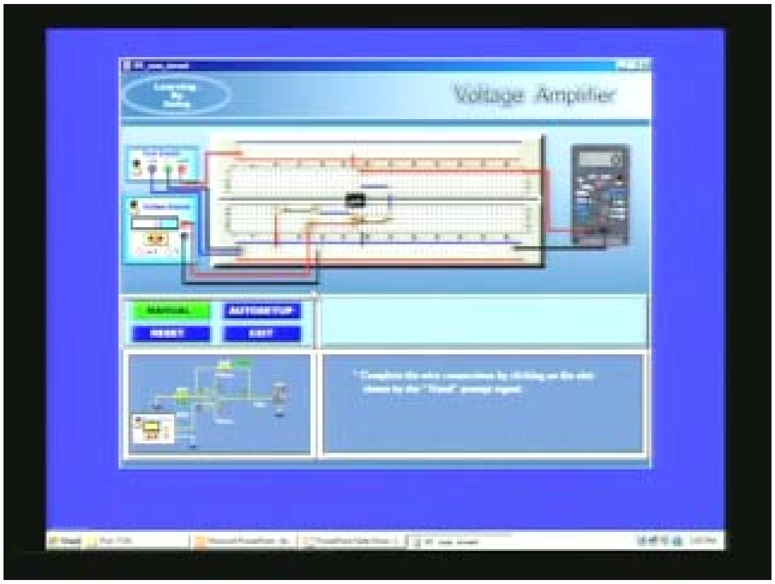

Now we will switch on the power supply, the voltage source and the multimeter. Everything is now ready and I will select millivolts. If I increase this I can increase the millivolt source at the input. I give about 100 millivolt and the output is 1.1 volt.

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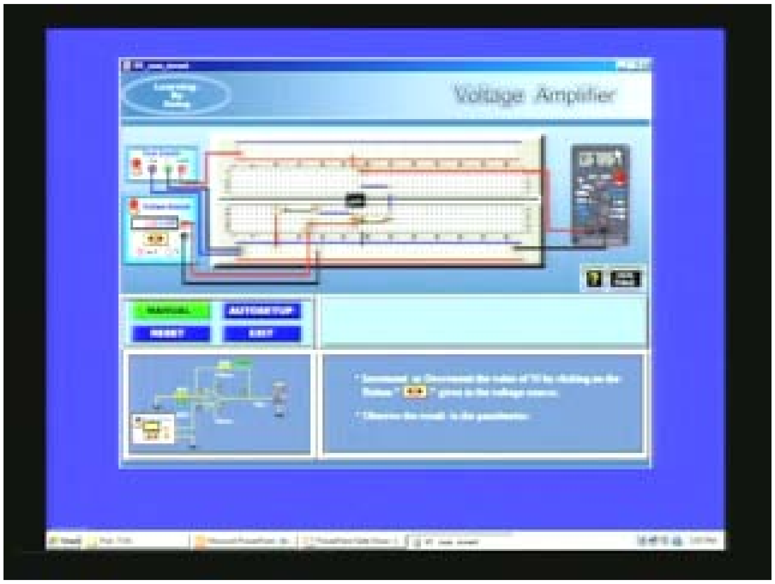

If I increase to 200 millivolt it becomes 2.2 volts. Why is it so? Because R_2 is 10 K, R_1 is 1K so 1 plus R_2 by R_1 is 1 plus 10 by 1 which is 11. So 11 times 200 is 2.2 volts, 200 millivolt. 11 times 300 millivolts is 3.3 volts etc. If I keep on increasing correspondingly the output voltage is also increasing proportionally by the gain factor. Having seen that let us now move on to the table and I have an actual circuit; the same circuit wired on a bread board and I will try to explain to you how this works.

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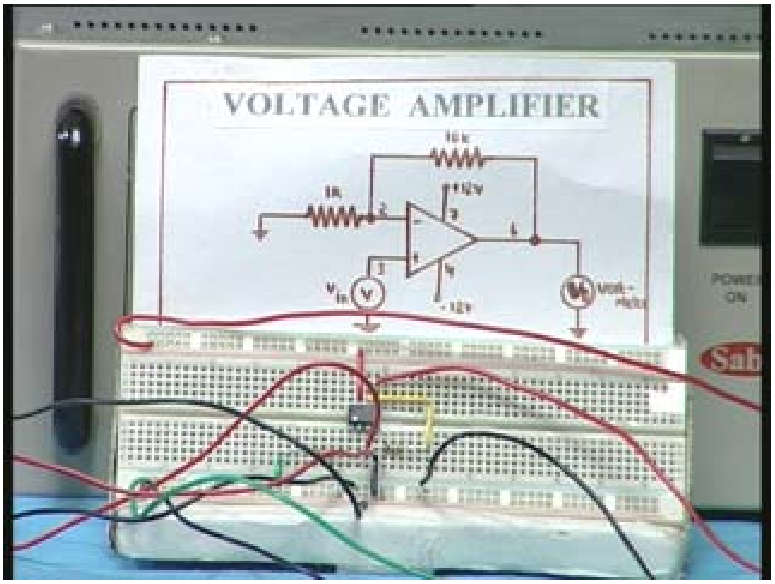

Here you can see a multimeter which is connected at the input terminal. It is connected to voltage and dc. This is a millivolt source. This is the voltage source. Here I can change the input voltage using the dials from 100 millivolt, 200 millivolt to several volts and that is connected to the input of the amplifier and I have a dual supply here and these are the three terminals for the plus, minus and the ground. The green one is the ground, red one is the $+V_{cc}$, black one is the $-V_{cc}$. This is the dual supply and you also have one more multimeter which is for measuring the output voltage. That is why it is called V output. You have the circuit here and to clarify I have given the circuit also here in the circuit diagram. You see here it is exactly the same non-inverting amplifier. The minus input is connected through R_1 to the ground and the R_2 is 10K here connected to the output and this is a voltmeter and you have the V_{cc} plus, minus and the ground connected. This is the voltage source V_{in} that is connected which is here.

If you carefully look at the op amp, there is an op amp 741 and you can see the seven terminal is for the V^+ that is connected to the red wire and the red wire goes to the plus of the dual supply and similarly the pin number four is connected by a small black wire to the negative terminal and this black wire goes to the negative V^- of the dual supply and the green wire is actually connected to the ground of the voltage source and this R_1 and R_2 are seen and it is very similar to what you saw on the simulation on the screen. If you look at the dial here I am sure you are able to see that it is about 100 millivolt.

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This is about 100 millivolt that is obtained from this voltage source. It is connected in parallel to the voltage source at the bread board and it reads 100 millivolt and after amplification you see some number here. It is 1.13.

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The gain is 1 plus R_2 by R_1. That is 11 and 11 times 100 millivolt is 1.1 volt. That is what you are getting here which is what also we got in the actual simulation. Let me change the 100 millivolt input by using this dial to 200 millivolt. Now the input voltage is changed to 201 and now let us see what is the output voltage you observe in the V output voltmeter? That shows 2.25. 11 times 200 millivolt.

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When I now increase the input voltage to 300 millivolt you can see on the dial it is reading 300 millivolt and correspondingly at the output voltage you see 3.37 volts.

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You may be wondering why I am getting not exactly 3.3; not exactly eleven times but slightly larger than 11 times. It is 2.25 or 3.37, etc and that can be very easily explained. Because this R_1 R_2 we have assumed to be 1K and 10K there is always a tolerance band. That means the resistance need not be very precisely 1K and 10K. It can be very close to 1K and 10K within plus or minus 10% and that tolerance variation is the reason for a slightly different voltage you get at the output. If I choose 1% or 0.1% resistors and put in the circuit it will be an exact multiplication of 11 and you would get that. Otherwise you can actually take these two resistors, measure the resistance value using the multimeter exactly and put that in the formula 1 plus R_2 by R_1 and then multiply the input voltage What you get is a exactly the same as what you should get with this multiplication factor. This is a very simple effective voltage amplifier; very small input voltage like 100 millivolt comes out to be 1.1 volt. It is amplified nearly 11 times.

If instead of 10K I have chosen 100K for the feedback resistor then the gain will be 101 times. So by choice of resistors R_1 and R_2 if I make it 100K it will be 101 times; if I make 50K then it will be 51 times the output. So the gain of the amplifier is very easily controlled by simply two resistors and if I have an input voltage from a thermocouple then I will be in a position to amplify that small voltage by using a very simple configuration which is not at all expensive and with that I will be able to get amplification. You can see what I have done is now with reference to dc because the operational amplifier can amplify starting from dc. The bandwidth of that starts from 0 frequency up to 1 mega hertz for example when we have unity gain. But when you have a gain of 11 automatically the bandwidth will be reduced because the product bandwidth into gain should be a constant. We will discuss this little later and we will perhaps take later on an example where instead of dc I will introduce the ac voltage and vary the frequency and try to measure as we increase the gain how the bandwidth gets decreased. We will also see that but for the present we are trying with a dc voltage source and you are measuring the input and the output using multimeter and you can see by just wiring the very simple circuit with two resistors, the feedback loop you are able to get a very good, almost ideal voltage amplifier and the sign of the input voltage and the sign of the output voltage are the same. This is also plus and this is also plus and that means it is a non-inverting amplifier. The output is in phase with the input. If I give plus voltage I also get plus voltage. If I give minus voltage I will get minus voltage and if I give the sinusoidal voltage I will also get another sinusoidal voltage at the output which is in phase, without any change in phase. It is called non-inverting amplifier and it is very close to an ideal voltage amplifier and it involves only two resistors in the circuit.

Having seen the demonstration I am sure you would have understood how in a very simple scheme by just having an operational amplifier which is not very expensive and just couple of resistors which are also very cheap you can form an amplifier which is a very, very powerful amplifier in the sense the gain can be very easily modified. You should compare it with the situation before where you had the transistors. You cannot get this high a gain 11 or 100 or 50 in a moments notice. By just switching some resistors you are able to get different values of the gain and the same circuit if I have do with transistors it is much more complicated because the transistor is more of a non-ideal device. Whereas an operational amplifier is very close to an ideal device and the design of the transistor amplifier is much more complicated and that is why you have to use a h parameter or r parameter or z parameter and you have to have lot of approximations and then analyze the circuit, design and then finally you may find that the design will not lead you to very high gains unless you have multiple stages. In the operational amplifier also there are multiple stages but everything is integrated into a very simple small area of silicon chip and the gain of the amplifier is 10,000 even when you buy as a one single device. By just using couple of resistors externally you can make any value of gain and the larger the gain you sacrifice for example from 100,000 we have come to 10 gain in the example. That means you have sacrificed nearly 10 to the power of 4. A gain of 4 orders of magnitude you have decreased in the gain. That will improve the input resistance by 4 orders of magnitude. Your 2 meg ohm will now become 20,000 meg ohm. Your output resistance 75 ohms will become 75 divided by 10,000. Every feature of the amplifier will be improved by 10 to the power 4 which is the value of the gain that you sacrificed. So a simple feedback amplifier, negative feedback amplifier, can lead to a very effective, good voltage amplifier by just simple connections with couple of resistors.

We will see in the next lecture about the rest of the feedback configurations and how they also lead to a very good, close to an ideal current voltage converter or voltage to current converter or current amplifier. Thank you!