Introduction to Electronic Circuits.
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Lecture-7.
Periodic Waveforms and Elements of Amplifiers.

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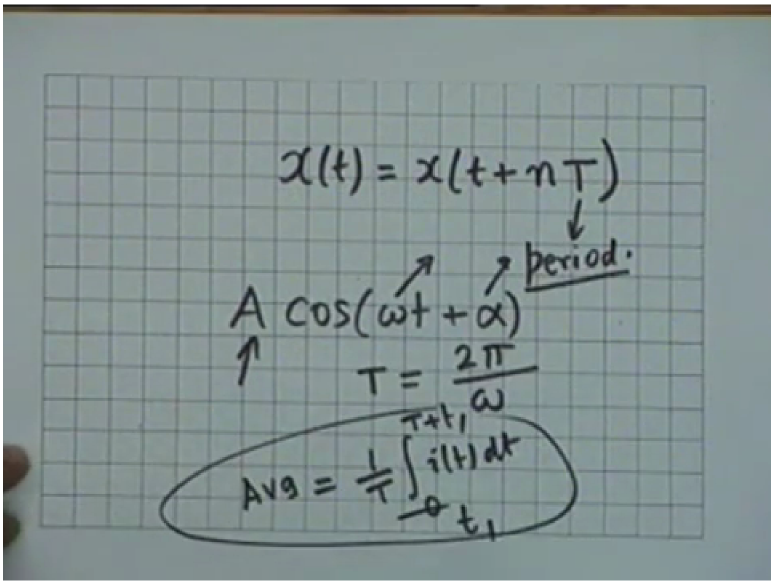

Professor: This is the 7th lecture on, we will complete the characterisation of periodic waveform and we will also discuss elements of amplifiers. You recall that a periodic waveforms x of t is such, it is periodic if and only if x of t is x of t plus n times capital T, where capital T is a constant and n is an integer and capital T is called the period of the periodic waveform. A periodic waveform, sinusoid is a very common example of a periodic waveform, sinusoid of the form a cosine or sin omega t plus alpha is a simple and a very frequently encountered example of a periodic waveform of which the capital T, the time period is given by twice pie divided by omega. All right.

To get a measure of the periodic waveform, will you can display it on an oscilloscope. If you do that, then you then you get the complete picture. But another way of doing characterising a periodic waveform which is sinusoid is to satisfy capital a the amplitude, the frequency omega and the initial phase alpha. But if the periodic waveform is not a sinusoid, then you either have to display the complete waveform and on a cro or take some characteristic parameters of the waveform. In one of the parameters that we have discussed last time was the average value.

That is the average of the waveform is, let us say if this is current, if it is the current waveform, then it dt integrated over 1 complete period, it could be 0 to capital T or it could be any arbitrary time small t1 to capital T plus t1, that is the area under the curve for one, that is averaged over the period t, this is the average value. This is one of the parameters of a periodic wave. And as i have commented, if it is a sinusoid, then over a complete period, the sinusoid, the total area under the curve is 0 and therefore the average value strictly is 0.

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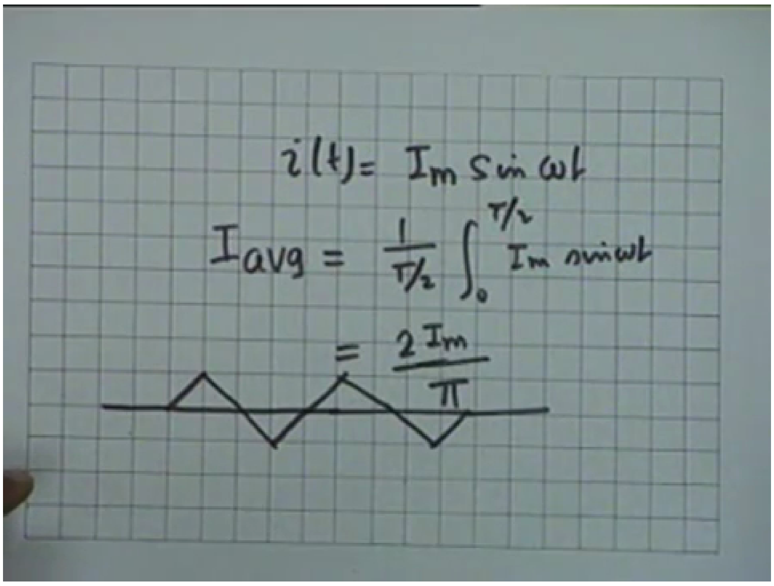

And therefore for a sinusoidal waveform like i of t equal to im sin of omega t, we may add alpha, we may not add, it does not make sense to talk about its average value is the average is considered over a one-time basis. And therefore for a sinusoid the average value i average is considered over half the time period. Therefore it is 1 by t by 2 integral 0 to t by 2 im sin omega t and as you saw last time, the value is simply im divided by pie. Is that correct?

Student: (())(4:34).

Professor: So twice im by pie, this is the value, okay. So the average is over half the time period, all right, for a sinusoid. But for all other waveforms, all other periodic waveforms, for which the average over a time period is not equal to 0, one usually speaks of average over one time period. For example if i have a triangular wave like this, absolutely symmetrical and so on, all right. Then what is the average value in the conventional sense, it is again 0. And therefore we talk of the average value over one half period, all right. It is a matter of convenience, average value over what period should be clear in the context of the problem, all right.

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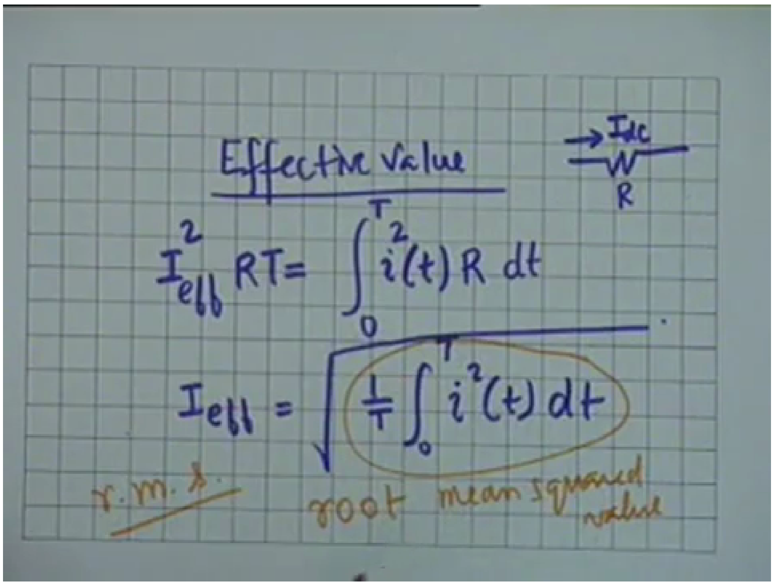

Another parameter for a sinusoid is the so-called effective value. And effective value is defined like this, suppose we have a current, a current waveform i of t which is periodic and suppose this current passes through a resistance capital r, then the power instantaneous power dissipated in a resistor will be i square times r. And over a small interval dt, the energy studies dissipated will be i square r dt, the energy dissipated over 1 complete time period 0 to capital T is this integral.

And if i take the energy dissipated, well if this energy, if the energy dissipated in the resistor for one time period is equated to the same resistor through which passes a dc, dc, let us say idc and it creates the same amount of energy dissipation, then the effective dc, then the dc value is called the effective value. So if you wish to define effective value is that direct current which when passing through a given resistor produces the same energy dissipation as the periodic wave in 1 time period, all right. Has it has it become too complicated? What we want is that we want to come to compute due to the periodic waveform, due to the periodic current the energy dissipated in the resistor, given resistor over 1 time period.

And then this energy is equated to an effective value square and which is a constant multiplied by r. This is the definition of the effective value. And you can see that i effective, they must be multiplied by capital T, agreed. Alright, the total energy dissipated in the resistor due to a dc which is equal to i effective over a time capital T is i effective squared rt and therefore i effective is equal to 1 over t integral 0 to t i square t dt, capital r cancels, square root of this. And you can see that under the square root sign, this quantity is, this quantity is the mean squared value, mean squared value of the current i.

What you do is you take the area under the squared value, then you divide by the interval, therefore this is the mean squared value and then we take the square root and therefore this is the, i effective is therefore the root mean squared value. And this is simply abbreviated as rms value, rms, root mean squared, you understand the interpretation of the root mean squared value. This is the effective value or that value of direct current which when passing through a given resistor produces the same dissipation as the periodic current in one time period, all right.

Student: The concept of this i effective then that even (())(9:15).

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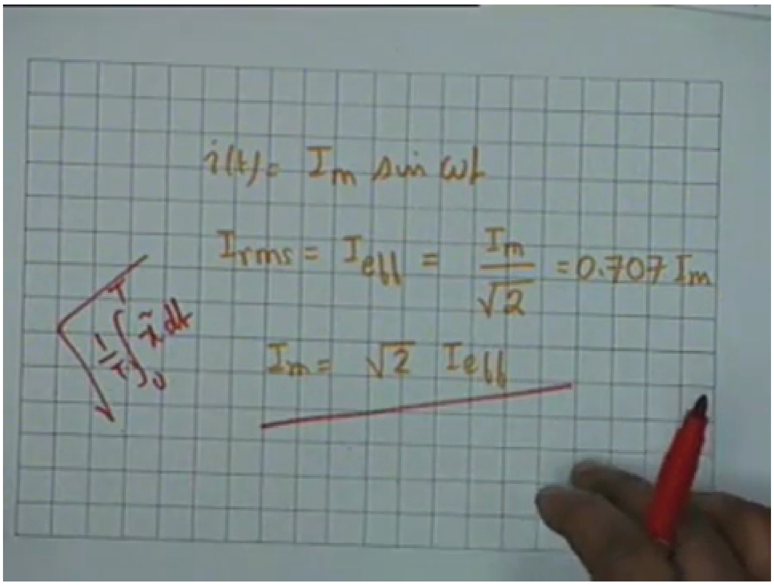

Professor: It is a linear resistor, yes. Your question is quite justified, when you talk of a resistor, it is implied that it is a linear resistor, the resistor is not dependent on current, it is a linear resistor, all right. Usually you specify this is 1 ohms but you see the value of the resistance is not important. But yes it must be linear resistor, all right. For a sinusoid if i of t is equal to i sub m sin omega t, let us drop that initial phase alpha, it is hardly hardly important. For a sinusoid i rms or i effective, i effective can be shown by carrying out this integration over one time period and then dividing by capital T taking the square root, this algebra you can do yourself, it is given by im divided by root 2.

Which is 0.707 im, that is the 70.7 percent of the maximum value or peak value, all right. In other words effective value is given i effective, then the peak value is given as square root 2 i effective. And when you say 230v ac, we mean the rms value of the ac. So the peak value if you take, if you take a cro and connect it to the mains power supply, then the maximum value you can measure will be 230 times root 2. This is true i warn you only for sinusoid, it is not true for other periodic waveforms. For other periodic waveforms you shall have to calculate by substituting in 1 by t integral 0 to capital T x square dt, then taking the square root, you shall have to calculate for each case.

It is only for a sinusoid that this shall be valid, that is the peak value is root 2 times i effective. Now according to, according to these 3 measures, we have so far discussed 3 measures, that is the complete waveform for a periodic wave, the average value, the root mean squared value, all right. As i have told you the total waveform can be displayed on a cro, the average value you connect any dc meter, any dc meter in the circuit, it shall read the average value, all right. The root mean squared value can be measured by any ac meter in which the torque developed, the torque developed which causes a reflection of the meter is proportional to square of the current or the square of the voltage, all right.

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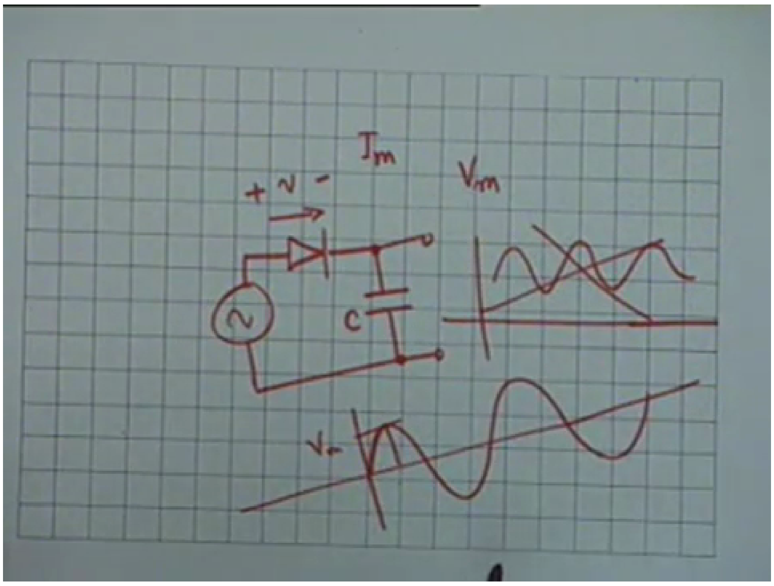

And therefore the, so what we can display is the square, not the root, the square of the quantities. In actual meters however, the meter is calibrated in terms of the square root of the values. That means it is calibrated to read rms value, root mean square value. So dc meter measure the square value, ac meters measure the, measure the root mean square value and if you wish to measure, a 4th measure is the peak value i sub m or that of a voltage v sub m. And the peak value is measured by a very simple, very simple device. What we do is, the periodic waveform, it could be ac or dc, it could be ac or non-alternating let us say.

You see this is also a periodic waveform, it is not an ac because the sign does not change but it is not a dc either, it is not a constant current, it is a pulsating current, it is a fluctuating current. So suppose i have a fluctuating, fluctuating voltage let say and we wish to measure its peak value, then what we do is we rectify this by means of a non-linear device diode which passes current easily in the forward direction and it does not pass current easily in the reverse direction. And then what we do is we take a capacitor. So what happens is if, if this is a periodic waveform, then during the positive, well, not this, let us take an ac.

Once again what we are going to say is applicable to an ac in which the average value is 0. All right, what happens is during the positive cycle this diode conducts, the diode conducts and the capacitor c charges, c charges tilde voltage which is this point. Then, then when this voltage goes down, the diode becomes reverse biased, that is this voltage becomes greater than this voltage, so that the diode does not come back. It comebacks only when the polarity of its drop is like this, that is the left side is positive with respect to the right side. If the right side becomes higher potential as compared to the left side, the diode refuses to conduct.

And therefore this capacitor then charges to the maximum value of the voltage v sub m. And if you put a meter here, dc meter, it will measure vm. This is one way, as you will see this is very much used in instruments to measure the peak value. To illustrate the concept of the root mean squared value, let us take an example.

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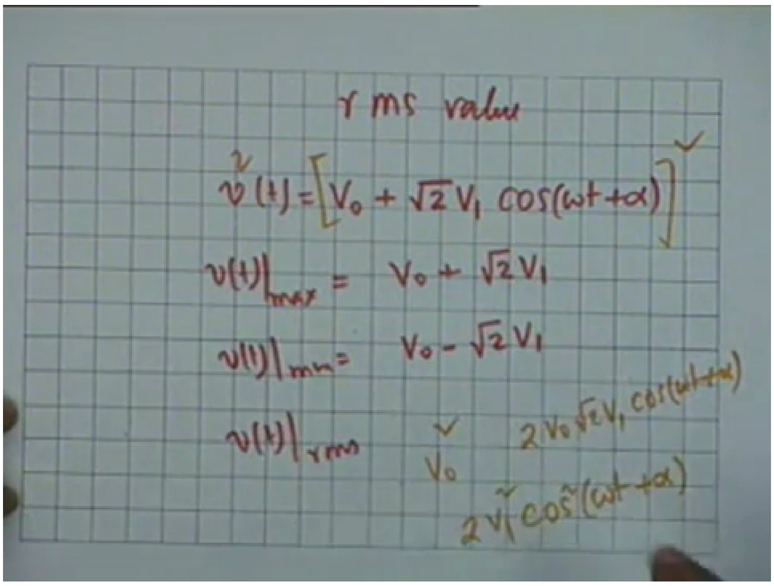

This is a very important measure of a periodic wave. Suppose we have a voltage vt which is some v0 plus root 2, it is a mixture as i had shown in the last page, it is mixture of dc, of a dc and an ac, all right, the 2 are combined, root 2 v1 cosine of omega t plus alpha, all right. So we have a dc voltage which is v0 and an ac voltage who speak value is root 2 v1 and therefore it is rms value is v1. Now what is the peak value of vt, what is the peak value of vt? Vt max, it is v0 plus root 2 v1 force what is the minimum value of vt? Okay, v0 - root 2 v1.

What is the rms value of vt? To find that out, to find that out, it is a very simple formula but let us derive this formula, okay. To find that out what with we square this, v squared will be this and it will have 3 terms a plus b the whole square, so it shall have a term v0 squared, it will have a term twice v0 times root to v1 cosine of omega t plus alpha and it shall have a 3rd term which is twice v1 square cosine square omega t plus alpha. And to find, is that okay? To find the root mean square value, each of these terms have to be integrated over one time period and then divide by the time period, capital T.

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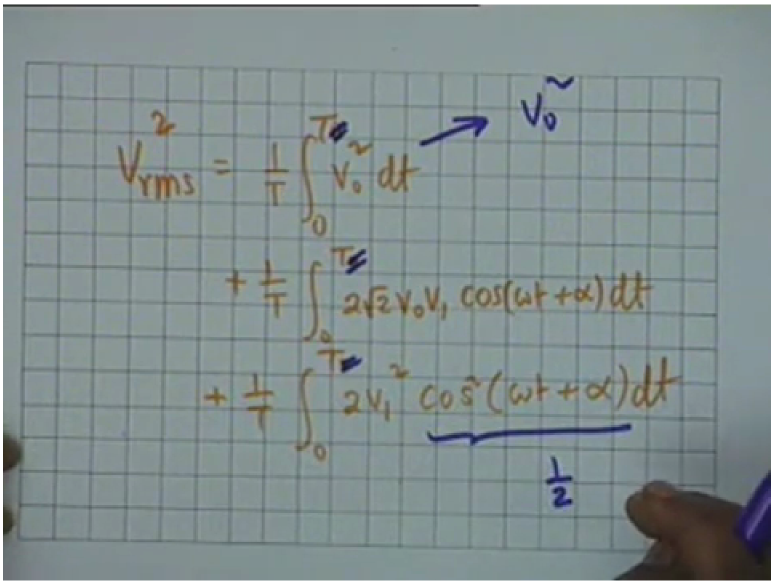

That is, and the whole thing is to be square rooted. So if i say v rms squared shall be equal to 1 by t, the 1st term is v0 dt, 0 to t0, 2nd term, v0 squared, thank you, 2nd term would be 1 by t, 0 to t0 twice root 2 v0 v1 cosine of omega t plus alpha plus the 3rd term, have i missed the square, no, 1 by t, 0 to t0 twice v1 squared cosine squared omega t plus alpha. This would be my v rms squared, there shall of course be a dt, yes.

Student: Where do we have (())(18:33).

Professor: This is capital T, thank you, this is inertia from v0, i rooted t0, this is capital T. Now you notice that the 1st term, 1st term we simply v0 square, integral dt is capital T and therefore capital T and capital T cancels and it is simply v0 square. Integral of the 2nd term is

0 because it is a sinusoidal waveform integrated over one time period. Integral of the 3rd term, this would be cosine squared omega t plus alpha dt integrated over one time period is equal to half, half, right. Is this is known to everybody? Is it known to everybody on have to prove it?

Cosine squared theta is cosine 2 theta plus1 divided by 2. And it is that 1 divided by 2 which brings in half because the periodic waveform once again integrated over one time period is equal to 0. And therefore my final result becomes v rms square becomes equal to be 0 squared plus v1 squared, that is it, as simple as that. And therefore v rms is equal to square root of v0 square plus v1 squared. And this can be extended to more than one sinusoid, all right, more than one sinusoid. That is if we had another sinusoid of the same frequency or a harmonic frequency, then i could add other terms square, v3 square and so on and so forth, all right.

So the root mean squared value of a mixture can be very easily found out, with restrictions that the frequencies must be multiples of each other or the same. You either have the same frequency because otherwise this averaging over capital T, capital T relates to one of the sinusoid. So the other sinusoids must be related to capital T, only then this formula shall give value.

Student: We have different (())(20:51).

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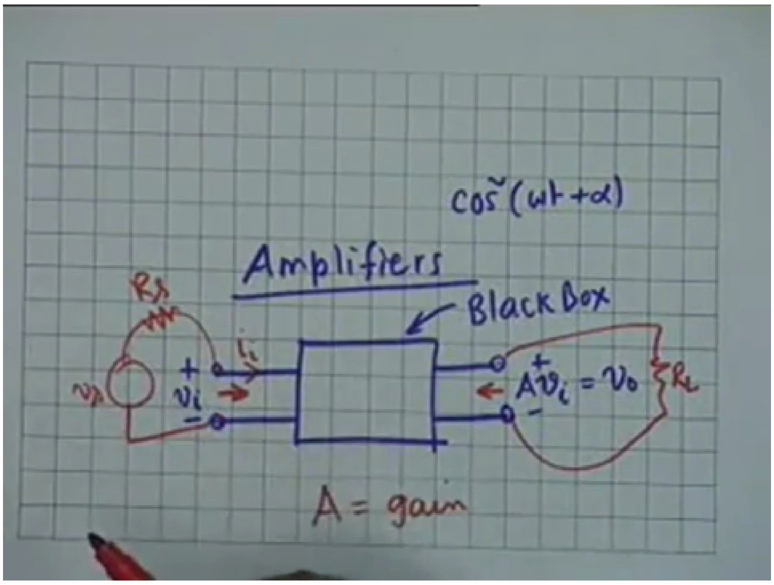

Professor: If you have a different alpha it does not matter because cosine squared omega t plus alpha over one, where would you start if it does not matter, one complete period. Alpha can be different, it does not matter. We then consider elements of amplifiers. By definition, by definition an amplifier is a box and any electronic circuit of which we are reluctant to look inside, what goes inside, we are only interested in the terminal characteristics that is if this is a 2 terminal network, if this is a 2 terminal network, then we are only interested in the vi relationship. That is if i plug in a voltage source, what current flows or if i plug in a current source, what voltage is developed?

If it is a 4 terminal network or a 2 port, then we are interested in, what we are interested in is if we plug-in source here, what is the response here, right. We do not want to look into what goes on inside when such a box in electronics is known as a black box. A black box is the one whose terminal characteristics are important, not the, not what is inside. Of course there has to be something inside and the purpose of this course, one of the purposes is to find out what should go inside to be able to achieve a certain terminal performance. Or the terminal characteristics, to realise a certain terminal characteristics, what should go inside.

And an amplifier can be defined in terms of a black box, such that if i if i feed if i connect a voltage source vi at one of the ports, then had other port the voltage developed is avi, a times vi, all right. This is the definition of an ideal amplifier. That irrespective of what happens to the outside world, if we connect a voltage source vi, an output of avi shall be developed irrespective of what is connected to these terminals, irrespective of what is connected to these terminals. For example we could connect a resistance rl, irrespective of what else is connected here, we do not really care.

Student: A is greater than 1 (())(23:37).

Professor: Not necessarily. In general an amplifier, the term amplification refers to capital a greater than 1 but we have amplifiers with less than 1. In that case the amplification is negative, not negative, fractional amplification, all right. These are ways of saying the same thing, that actually an attenuator, one which attenuates reduces can also be called an amplifier with the gain of a fraction. Capital a is called the gain of the amplifier, gain. Now this irrespective of what goes on, what, what is connected here, this implies that the thevenin equivalent resistance looking here shall be equal to…

If the voltage developed here is avi irrespective of what is connected here, irrespective of the value of rl, what does it imply with regard to the thevenin equivalent resistance looking back from these 2 terminals? 0, that is correct. So this is one of the implications of an ideal amplifier. That the output resistance, this thevenin equivalent resistance is called the output resistance. So the output resistance shall be equal to 0. One of the other characteristics that is implied for an ideal amplifier is that the input current i i is equal to 0 for an ideal amplifier. Now what does that mean?

Input current is 0, this means that the equivalent resistance looking into the amplifier is infinite. So it is not thevenin, this is not thevenin, thevenin is this one, this is the input resistance. That is if you connect a source which let us say an internal resistance rs, if you connect a source let us say vs with an internal resistance rs, all right, the current taken here is 0, then what would be vi equal to? Vi should be equal to vs, is not that right? So an ideal amplifier disregards the internal resistance of the source, internal resistance of the input, okay, it does not respect, it has no respect for the internal resistance of the source.

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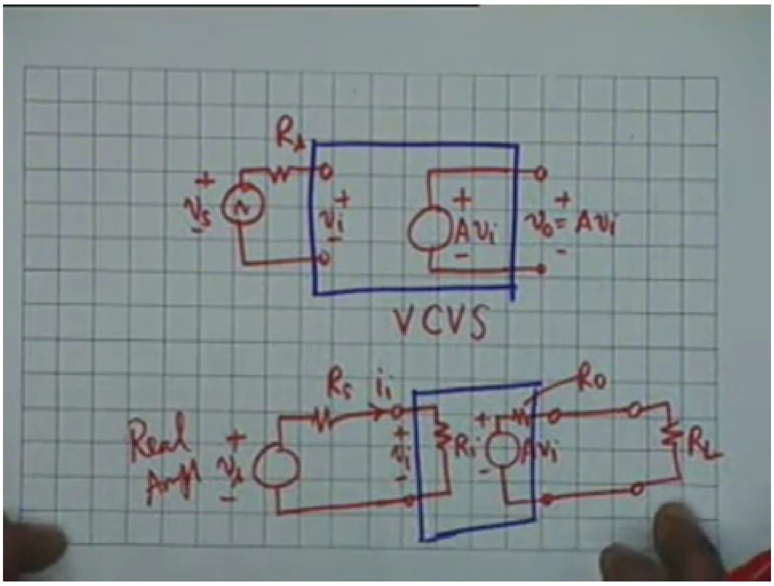

Whatever the internal resistance, it develops a voltage equal to the voltage that you wish to amplifier. And as i said the output thevenin resistance is equal to 0. And therefore an ideal amplifier can be modelled like this that you have a source vs and an internal resistance rs, this is connected to the ideal amplifier, all right and the ideal amplifier produces a voltage v0 is equal to avi, whatever be the resistance connected to this. Which means, which means that it behaves like a voltage source of value a times vi with this polarity, all right. The internal resistance or the thevenin resistance is equal to 0 and therefore it behaves like this.

You see this is an example, this is vi, this is an example of a voltage controlled voltage source. Here is a voltage source avi whose voltage depends on another voltage and therefore this is a voltage source voltage is controlled by another voltage v sub i. So it is called a voltage controlled voltage source, vcvs. Now in practice, in practice this is not the case, as i said ideal is ideal, a practical amplifier shall differ from this ideal characteristic by having an input resistance which is not infinity, input resistance which is finite. In other words a real amplifier takes in a certain amount of current, i sub i is not 0, it is nonzero.

Similarly the output resistance of a real amplifier is not 0, but it is a nonzero quantity. And therefore if i consider a real amplifier, the model of a real amplifier shall be like this. You have a source vs connects to the real amplifier, okay, in which the internal, the input impedance, input resistance is not infinity but let us say some value r i, then this voltage developed is vi. When you say vi, it is no longer equal to vs because there is a drop in rs, all right. And the current taken here is no longer equal to 0, it is given by v is divided by rs plus ri, all right.

And the output, it is a voltage controlled voltage source avi but it does not come with an internal resistance of 0, it comes with an internal resistance of r0 and these are my load terminals to which i can connect a load rl. This is the picture or the model of a real amplifier. And, is that being a bit fast? Okay, yes or no, it cannot be in between? Okay, all right we will go slow. You understand this model for real amplifier. In an ideal amplifier all that you have to do is to make this resistance infinite so that no current is taken by the amplifier. And you have to make this resistance equal to 0 so that the output voltage is equal to avi irrespective of what you connect here.

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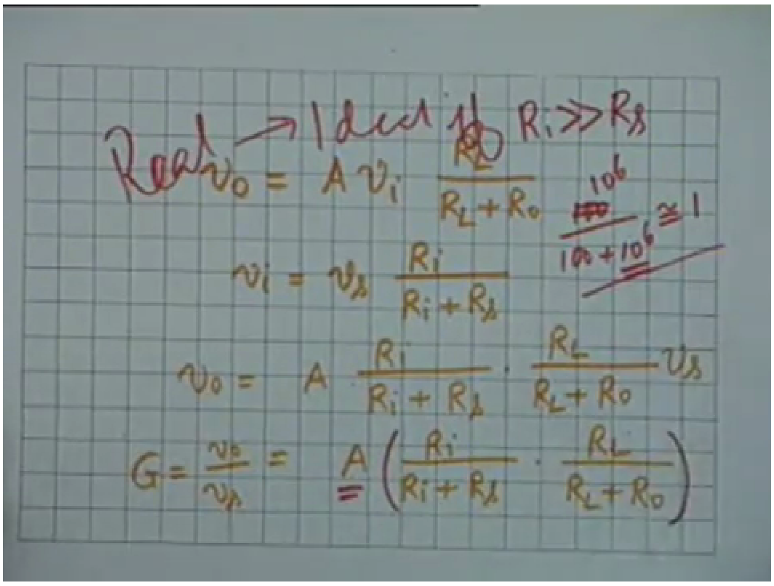

Now in a real amplifier if you want to find out v0, this voltage v0, then you notice, i cannot write here, you notice that vi, well, v0, the output voltage that is developed across the load rl, across the load rl is the voltage division between r0 and rl. And therefore this is equal to avi rl divided by rl plus r0, all right. And vi, vi is the voltage division of vs between rs and ri and therefore vi is equal to vs multiplied by ri divided by ri plus rs. And therefore v0 is equal to a ri divided by ri plus rs multiplied by rl divided by rl plus r0 and this multiplied by vs. Therefore the gain g of the real amplifier which is equal to v0 by vs is given by a times ri divided by ri plus rs times rl divided by rl plus r0. This is the expression for gain in a real amplifier.

How is this gain modified? If this amplifier was ideal, if the amplifier was ideal, then the gain would have been simply capital a. Alright. Ideal means what, r i goes to infinity, so infinity divided by infinity becomes 1 and r0 becomes equal to 0, so rl divided by rl, that also becomes equal to1. Alright, so in a real amplifier the gain shall always be produced as compared to the ideal case. And a real shall approach an ideal a real amplifier shall approach an ideal if r i is much greater than rs.

It does not have to be infinity but rs is so small, for example if rs 100 ohms and ri is 1meg, well, what does it mean, the ratio than becomes 100 divided by 100 + 10 to the 6, which is, which definitely to an electrical engineer or any other engineer, it is definitely very nearly equal to unity.

Student: (())(33:44), it should be 10 to the power 6 in the numerator.

Professor: Yes, that is what i said.

Student: No, in the numerator.

Professor: Oh, i beg your pardon, it is 10 to the 6 in the numerator and divided by 10 to the 6 + 100, what is 100 to 10 to the 6, it is nothing, all right, therefore this is approximately 1. Similarly what you need is that the load connected to the output, rl should be much larger compared to r0. Once again, 1 is to 100 is good enough, all right. So your amplifier design, your motivation, your objective should be to make as high input resistance as possible and as low output resistance as possible, this output resistance is obviously the thevenin equivalent resistance.

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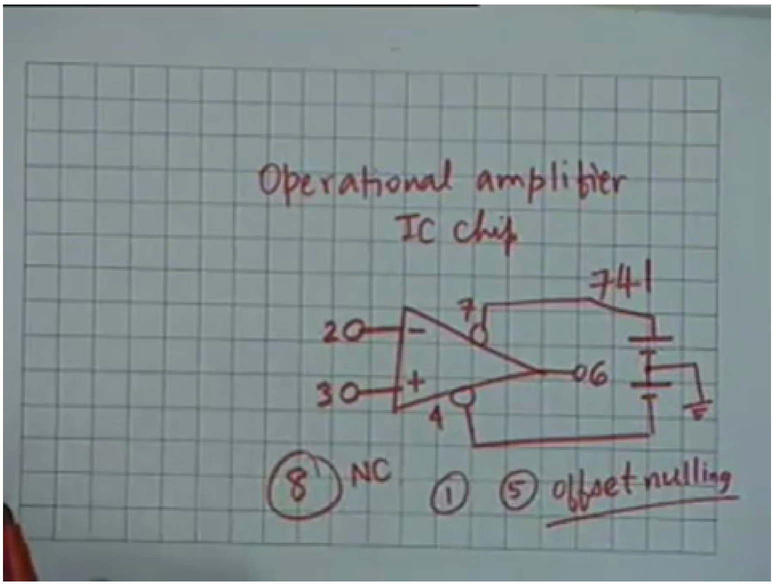

An amplifier which comes very nearly, very nearly equal to an ideal amplifier is the so-called operational amplifier, which is available as an integrated circuit chip, ic chip, a small multi terminal component. Actually there are 8 such components, let me 1st give you some familiarity with the actual chips. The actual chips is a, is an 8 terminal, 8 terminals are provided and the symbol for an operational amplifier, i will explain why it is called operational a little later. But the one, the one chip that is most popular is the so-called 741 chips, 741, something that this mu a or li, this indicates the company which manufactures.

But the generic name for the op-amp which is most popular is 741. And 741 as i said comes with 8 pins and these pins are numbered like this up in number 2 is an input connection, pin number 3 is also an input connection, pin number 2 is called inverting input terminal and a - sign is included here. Pin number 3 is called non-inverting input terminal and the significance is that if you provide an input at the number 2, the output shall be phase reversed. That is if you put a 1 millivolt signal here, the output shall be - let us say 100 millivolts if the gain is 100. Is that clear?

There is a phase reversal, if you put sin omega t here, the output shall be proportional to - sin omega t. On the other hand noninverting terminal is one which preserve the polarity or the phase of the input. That is if you put a +10 millivolts here, the output shall also be a positive voltage, right. The output terminal is the terminal number 6, output terminal is the terminal number 6. There are 2 inputs, one output, you require other terminal for power supply connection. And the power supply, an electronic circuit requires a power supply, a dc battery to be connected as the power supply terminals are 4 and 7.

And a typical 741 requires a power supply of 2 kinds of polarities, that is a positive one as well as a negative one. Typically this could be 12 volts, +12 and -12 and the middle point of the power supply, you understand what this is, this is a series of, since this is a series of batteries, this is actually a rectified ac which is available in the laboratory in the form of a box and it is called power supply, all that it supplies is dc. Typically it could be +12 and -12, the middle point of the supply is a reference potential and it is connected to ground, right. As far as amplifier characterisation is concerned, 4 and 7 do not come into the picture, all right.

4 and 7 have to be connected to the batteries, otherwise the circuit does not work. The other terminals which are 1 and 5, we shall learn later what the purpose is but for the present, we let it suffice to say that 1 and 5 pins, pins numbered 1 and 5 are for offset nulling, we will explain these terms later in great details, you just, you just hear the term now so that when i mention it again you will remember that yes this was spoken up. And of the 8 pins, there is another pin, that is 8 which is marked nc, that is no connection. If you want to connect another resistance for example, this provides a port or a terminal to which you can connect, all right. So 8 is nc and this is a typical…

Student: (())(39:33).

Professor: Pardon me?

Student: Does it provides a port or a terminal?

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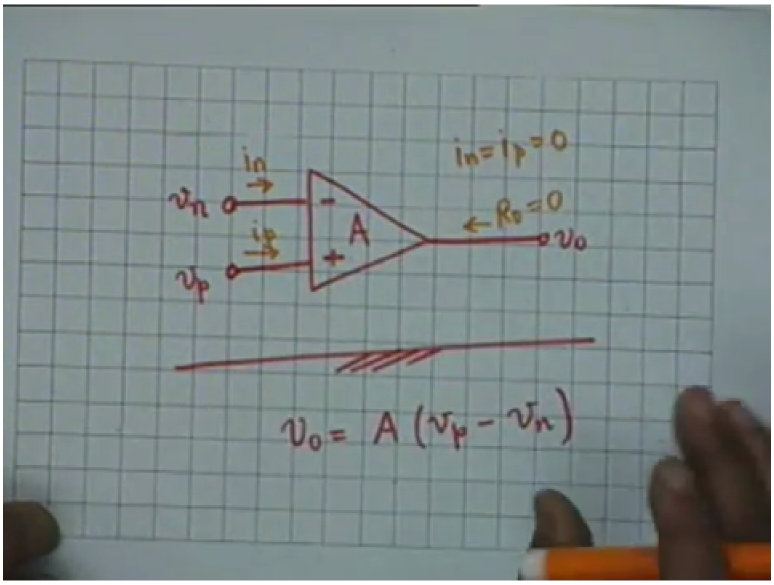

Professor: It provides a terminal but between 8 and the power supply ground it provides a port. This is obviously external, the 741 chip provides no ground, the ground has to be provided externally by means of the power supply, so the reference is set outside the chip, all right. So this is 741 and represent this now in a simple form, all that we are concerned with is the input and the output because we refuse to look at what goes inside access to the terminal connections are, we also forget about the pin number and all that, we have 2 terminals and a non-, and inverting input terminal to which let us say we apply a potential vn, voltage vn and a noninverting input terminal to which we apply a potential vp.

And all this is measured, these potentials are measured with respect to some ground, all right, these potentials are measured with respect to some ground and the output voltage is v0, then the op-amp, operational amplifier is characterised by again a, capital a, such that the definition of a is v0, the output voltage is a times the effective input voltage, that is the input voltage between these 2 terminals which will be vp - vn, all right. This is the definition of an op-amp gain. As you see capital a is a positive quantity, capital a is a positive quantity for that if there is no vn, if vn is 0 and this is only vp, the output v0 is equal to a times vp which preserves the polarity.

On the other hand if vp is 0 and we apply a voltage at the inverting terminal, then the output becomes - a vn which changes the phase, so if we apply sin omega t, it will be - sin omega t, there will be change of phase by 180 degrees, is that clear? The purpose of these 2 terminals is to make additions as well as subtractions, to have inverting gain, for example if you have one millivolts and you want a + 1 volt out of it, then you can apply to the noninverting terminal. On the other hand you might require a negative, a -1 volt, then you apply the input to the inverting terminal, all right.

So it is a load versatile chip or amplifier chip, then the convention amplifier, where there is one input and one output, there are 2 inputs here which can change the sign of the given input voltage, implied in this definition. Now let us look at slightly further, implied in this definition is that the resistance, the current taken by the amplifier at both the inverting and noninverting terminals ideally are 0. That is in is equal to ip equal to 0. What does that mean? It means that whichever input terminal, from whichever input terminal you look into the amplifier, you face infinite resistance.

Ideally this should be the case and a real op-amp chip is not far from this idealness. Typically the input resistance is of the order of a meg, 10 to the 6 homes and ordinary sources like if you want to amplify let us say public address or the signal picked up from the microphone. Well microphone will not have an impedance more than let us say 1k, so compared to 1k it is 1000 times larger, all right. And therefore the input impedance is infinite, ideally in and ip are equal to 0, what would be the impedance looking between vn and vp?

Once again that shall also be now infinity, infinity, all right. And v0, the output terminal, the effective resistance looking into the amplifier ideally is equal to 0. In other words what does that mean, it means that the output of an op-amp can supply infinite amount of current, is not that right? If the output resistance is 0, then you can draw almost any current from this, which obviously, there is a fallacy. Is not that right? What is your source of energy, these 2 batteries. You know that batteries, they have a limitation, they cannot supply more than a certain value of current and therefore an ideal is ideal but for the limited purposes of instrumentation and control, the ideal characteristics are almost always valid.

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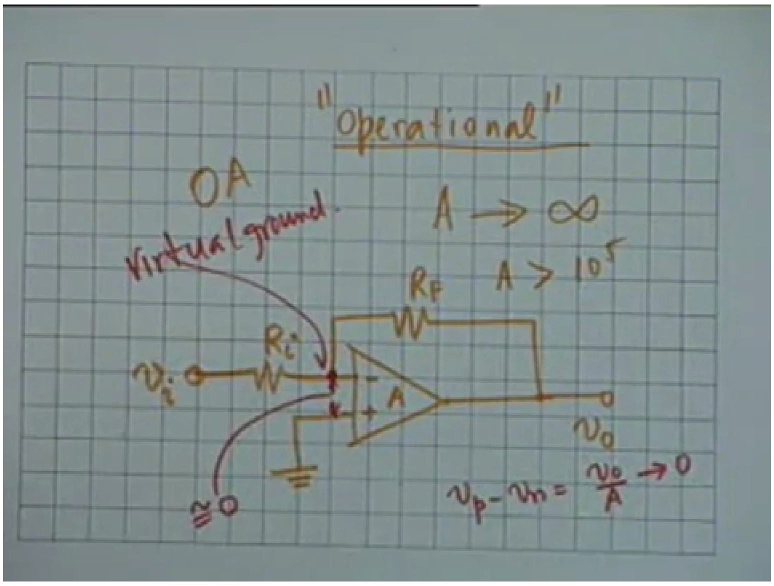

And therefore we usually treat an op-amp chip as ideal, unless it is a critical application where we shall have to look into the sources of non-idealness. Let me give you certain practical applications of an op-amp to give you a feel of what an op-amp can do and what an op-amp cannot do. Before that i must explain the term operational, why it is called an operational amplifier. Well the choice of this term is for historical reasons. It is a bit unfortunate because the modern 741 can be used in many operations rather than what it was meant to be with the adjective of operational.

Operational amplifier in old days when transistors were not invented, the integrated circuits were not available in the market, they used to be made for analog computers, digital computers were not known or were in a very rudimentary form, analog computers were very much invoke, they were very popular. Then what people used to do is to take vacuum tubes and configure them in an amplifier configuration such that it could perform operations like differentiation, like integration, like limiting, like amplification, like non-linear, even non-linear characteristics and so on. So this is why the term operational, the adjective operational was given to such amplifiers.

One of the characteristics that i have failed to mention is that capital a, the gain of the op-amp chip is very large, it tends ideally it tends to infinity. And very large the context means a gain of the order of 10 to the 5 or higher. So if capital a is greater than 10 to the 5 and in very good op-amp, in very good op-amp it could be as large as 10 to the 6 or even higher, all right, so it is a very large gain. So with the advent of transistors and integrated circuits, the amplifier that is, that replaced the vacuum tube operational amplifier was 741 but it was still called an operational amplifier. And history cannot be forgotten and therefore the operational, the term operational has continued and it is simply called op-amp.

The term operational is in a sense more valid now because this 741 chip can perform many more operations than they were, their poor cousins the vacuum tube operational amplifier which existed in the 40s for example. So in any case we shall call it simply operational amplifier or op-amp or sometimes we shall call amply and oa. Suppose you have an oa, just to get a feel of what an oa can do, you have an oa with the inverting, noninverting terminal grounded and the inverting terminal is connected to a resistance let us say r i and there is a voltage vi connected here. In addition there is a resistance rf connected between input and output and this voltage is v0, okay.

Suppose an operational amplifier is connected in this configuration. Now because capital a tends to infinity, this voltage, this voltage, the voltage that appears between the 2 input terminals, you know v0 is equal to capital a times vp - vn. If capital a tends to infinity, then what is vp - vn, that must be equal to 0, very nearly equal to 0. Which means that the potential of this point must be approximately the same as the potential of this point which is 0 and therefore this point also not connected to ground, behaves like a ground.

And therefore this point is known as a virtual ground. Okay, capital a in practical op-amps is extremely large of the order of 10 to the 6 and therefore vp - vn is equal to v0 - a, this tends to

0 because capital a is very large. Therefore vp is approximately equal to vn, that is the 2 potentials, the potentials of the 2 input terminals are approximately equal. Now one of them is connected to ground, so its potential is 0, therefore the other must also be 0. Now you see this as 0 potential point but not connected to ground, so it is not a real ground, it is a virtual ground.

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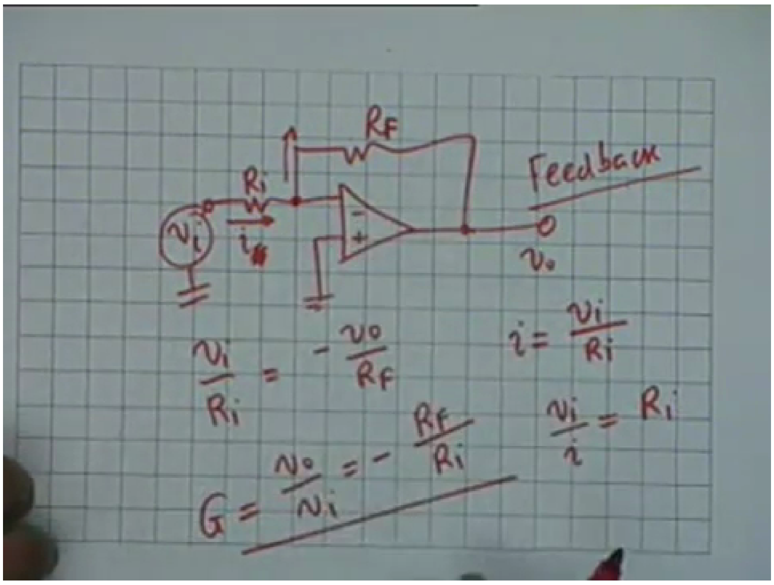

This virtual ground concept simplifies the analysis of such amplifier is tremendously. For example in this circuit if i draw it again, this is ground, ri and rf, this is vi, you see if this is virtual ground, if this is virtual ground, then what is the current here? Vi by r i, okay. Now the amplifier is ideal, so it does not take any current, this current mass flow like this, this current has no other way, by kcl it must flow like this and therefore this current shall be equal to the potential difference between this point and this point is - v0 because this is 0 potential and this is v0. So it is - v0 divided by rf, and therefore v0 by vi, which is the gain of the amplifier, the output voltage divided by the input voltage is simply equal to - rf divided by ri.

And you see the gain now is inverted, there is a negative sign here, that we expected because we are applying our potential to the inverting terminal. But what is surprising is that the op-amp parameter capital a does not enter into the picture at all, in fact the op-amp parameters do not, none of the parameters and. Why, because they have made that as shown that the op-amp is ideal. Now the gain is now determined by simply a ratio of 2 resistors, the significance of the subscript should now be obvious to you. F stands for feedback, that is feedback is a path provided from output to input, from input to output is feedforward and if something comes back, this is something comes back through this resistance, a current, it is called a feedback resistor. We shall understand the meaning of feedback in much greater details later on.

But as, well this is the feedback resistor and r i, the subscript i stands for input, input resistance. Alright, so it is a ratio of 2 resistors only. For example if rf is 10 k and ri is 1k, then the gain would be -10. And it will be determined by these 2 resistors only, nothing of the op-amp, op-amp only helps to stabilise the gain to -10. The other interesting feature is that if this current is denoted by i, then what is it, i is simply equal to vi divided by ri. And therefore what is vi divided by i? It is simply equal to ri. So the input resistance that this faced by the source is equal to r i, that is all.

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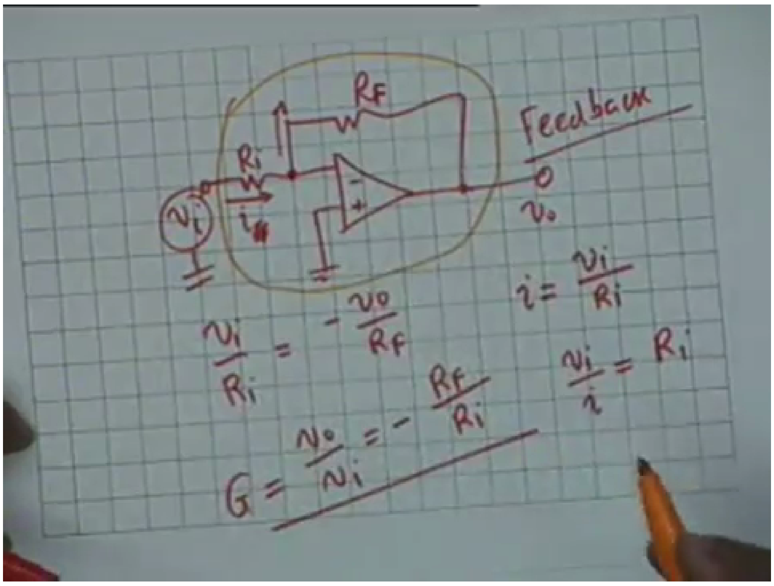

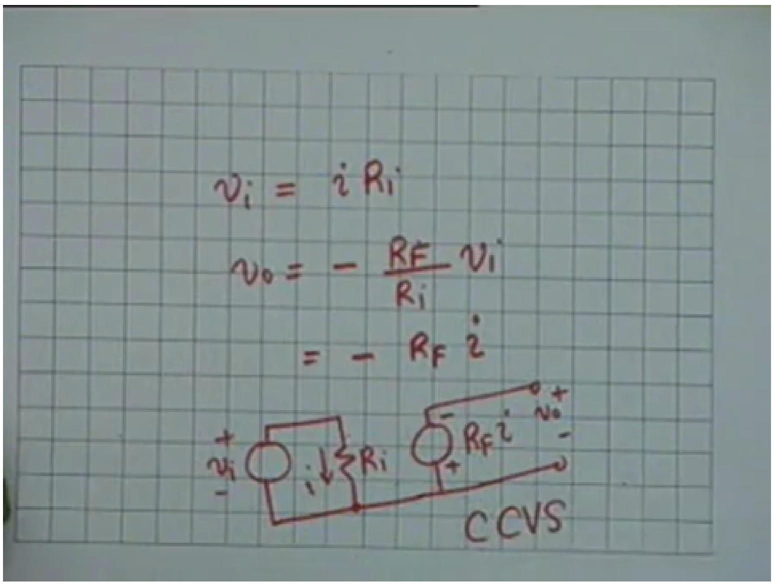

You see the source is here, the source is here, so the input resistance seen by the source is all right, which is also independent of the op-amp, okay. And if that is so, if that is so, then we can make a very useful analysis that is vi is equal to i times r i and v0 is equal to - rf divided by ri times vi, therefore this is equal to - rf times i, is that correct? The op-amp therefore between, between this point and this point, i include the input resistance that is r i can be modelled in a very simple manner, that is we have a vi, from vi we have created a current i, how, by connecting a resistance ri, this current is high and then the output voltage v0, it acts as a voltage generator equal to rf times i.

With what polarity, - here and plus here, so this is v0. Now what we can you say about the kind of model that we have here? It is a current controlled voltage source, is not that right? This is a voltage source rf i and it is controlled by current at another location and therefore this is a current controlled voltage source, ccvs, all right. This is a simple model, we shall continue this discussion…

Student: (())(56:34) v0 is plus - or - plus.

Professor: Plus - because this has been shown as - plus, if you write v0 in terms of rf i, it is v0 equal to - rf i.

Student: Sir is it not possible that v0 is also very large?

Professor: V0 can also be very large but the practical limitation is that v0, the output voltage cannot exceed the power supply. When it exceeds the power supply, the output gets saturated, that is a non-linear region of operation comes into play. All right, v0 cannot extend beyond 12 volts let us say typically, plus -12. Any other question? Thank you.