GTE LENKURT

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Operational Amplifiers

parts 1 and 2

The operational amplifier is one of the most versatile tools available to analog circuit designers. A list of its applications would easily fill a page, and the list is still growing. A large number of today's non-digital integrated circuit packages contain operational amplifiers. These packages are frequently used in telecommunications equipment. Our discussion is presented in two parts. Part 1 describes an ideal operational amplifier and tells how it is used to make the design of practical circuits easier. Part 2 describes operational amplifier applications to telecommunications equipment.

Operational amplifiers originated in the vacuum tube era. The name, "Operational Amplifier", was first coined in 1947, sometime after the first designs were put to use. The name was soon shortened to today's familiar term, "Op Amp".

One of the earliest applications of op amps was in analog computers. Vacuum tube op amps were the basic building blocks for these devices.

The first solid-state, modular, operational amplifiers were introduced in the early 1960's. At that time, engineers began to use op amps in many linear and non-linear circuits. These modules are almost as common as transistors, in today's analog systems.

Ideal Op Amp

Figure 1-A is a symbol for an operational amplifier. These are usually three terminal devices, although a few two terminal one are available, for specialized applications.

Note that one input terminal is marked with a plus (+) sign and the other input terminal is marked with a minus (–) sign. The input marked + is called the non-inverting or direct input; the input marked – is called the inverting input.

Figure 1-B depicts the op amp's internal circuits. Most operational amplifiers contain three direct-coupled amplifier stages. The input stage is a high gain differential amplifier. The intermediate stage is a high gain buffer amplifier between the input and output stages. The output stage provides some gain and isolates the high gain stages from the output load.

Three series connected, high-gain amplifiers provide a voltage amplifica-

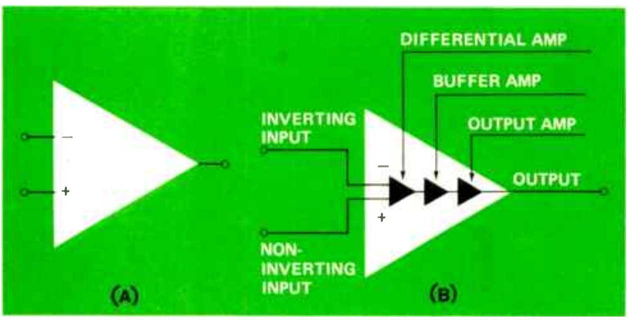


Figure 1. The schematic symbol generally used to represent an operational amplifier is a triangle with dual inputs and a single output (A). Most op amps consist of three direct-coupled amplifier stages (B).

tion (gain) factor of 100,000 or more. *Extremely high gain, approaching infinity, is one characteristic of an ideal operational amplifier.*

Another characteristic of an ideal op amp is infinite input impedance. An infinite input impedance does not present any load to the input source. The ideal op amp should also have zero output impedance, so that the output signal will not be affected by the output load. *Infinite input impedance and zero output impedance are the second and third characteristics of an ideal operational amplifier.*

A fourth characteristic of an ideal op amp is infinite bandwidth and therefore zero delay response. This characteristic is a corollary of the other three. Each of the first four characteristics implies, and is dependent upon, the existence of the others. Infinite gain cannot be realized without infinite input and zero output impedance. These impedances can exist only if they are independent of frequency. This implies infinite bandwidth. The ideal op amp provides infinite gain and immediate response to all signals, from DC to the highest frequency in the spectrum. *This statement defines infinite bandwidth, which is the fourth characteristic of an ideal operational amplifier.*

The fifth characteristic of the ideal op amp is perfect common mode rejection. This means that when the voltages at the two inputs are equal, the output will be zero. Since the input stage is a differential amplifier, only the difference between two input voltages will be amplified. The amplifier does not respond to any signal which the two inputs have in common, i.e. common mode signals. This explains the term *common mode rejection; the fifth characteristic of an ideal operational amplifier.* All five characteristics are listed in figure 2.

PROPERTY	IDEAL VALUE
GAIN	INFINITE
INPUT IMPEDANCE	INFINITE
OUTPUT IMPEDANCE	ZERO
BANDWIDTH	INFINITE (RESPONSE DELAY IS ZERO)
COMMON MODE REJECTION	INFINITE (OUTPUT VOLTAGE IS ZERO WHEN INPUT VOLTAGES ARE EQUAL)

Figure 2. To simplify the equations required for circuit analysis, certain properties of the op amp are assigned ideal values.

Although an ideal op amp cannot be physically realized, the concept has great value to the circuit designer. By selecting the right op amp, he can assume ideal characteristics for his particular application. This will simplify his calculations and allow him to concentrate on determining the best arrangements and values for the other circuit components required to realize his design objective. The degree to which the selected op amp approaches the ideal determines how well a circuit built to his design meets its predicted performance specifications. Of course, his calculations can only be close approximations because an ideal op amp does not exist in reality.

Feedback Loops

A feedback loop is used to feed a portion of an amplifier's output back to its input. The type, arrangement and electrical values of the components in the feedback loop of an operational amplifier largely determine its performance in a circuit. The feedback loop establishes the circuit gain and input and output impedances. The following discussions of four basic op amp circuits illustrate the importance of the feedback loop.

Inverting Amplifier

Figure 3 is a schematic of an op amp arranged as an inverting amplifier (voltage inverter). The signal voltage V_{in}, is connected through input resistor, R_{in}, to the inverting terminal of the op amp. The output signal, V_{out}, appears across the load, Z_L, but a portion of the output is fed back to the input through resistor R_f. The non-inverting input is shown directly connected to ground but the connection is often through a resistor.

The figure does not show a power supply because it is not important to our discussion of circuit operation. However, one is required in an actual circuit. Normally the power source is a split supply, with equal positive and negative voltages connected to the op amp. Manufacturer's data sheets specify maximum and minimum supply voltage requirements. A ±15 volt supply is quite common.

The output voltage of a voltage inverter is a replica of the input but is of the opposite polarity. The output voltage may also be an amplified inversion of the input, depending on the ratio of R_f to R_{in}. If the resistors are equal, the ratio is unity and $V_{out} = -V_{in}$. The proof of these statements shows how the assumption of an ideal amplifier simplifies the circuit analysis. An additional, necessary assumption is that the inverting input is a virtual ground, zero potential point.

Since the input impedance of an ideal op amp is infinite, the input appears as an open circuit to the input signal. Current cannot flow through the input circuit of the op amp even though the signal voltage is applied. Also, since the inverting input of the op amp is a virtual ground, the input signal must be across R_{in}. This voltage causes a current, I_{in} to flow. Since the inverting input and therefore the junction of R_{in} and R_f is also a zero potential point, the same amount of current must flow from the junction as flows into it but this can only occur if a potential difference exists across R_f. This potential must have a polarity opposite to V_{in} and have the right magnitude to cause a current, I_f to flow at a value equal to I_{in}. This potential is V_{out}. From the foregoing it can be seen that:

$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}};$$

solving for V_{out};

$$V_{out} = -V_{in}\left(\frac{R_f}{R_{in}}\right).$$

The usefulness of this equation is apparent. To achieve a desired gain, values are selected for R_f and R_{in} which provide a ratio equal to the

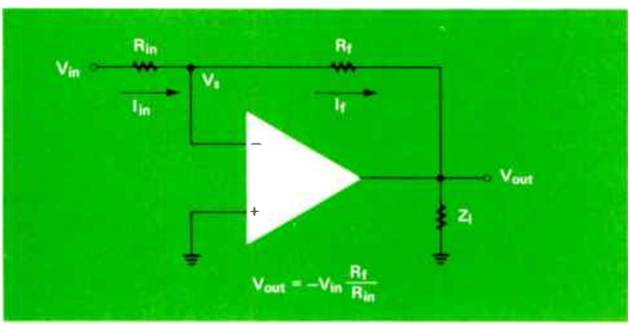


Figure 3. The voltage gain of the voltage inverter is determined by the ratio of feedback resistance to input resistance.

required amplification factor. The accuracy of the results depends upon the validity of the ideal op-amp assumption.

Figure 4 is a graph of electrical events in a voltage inverter represented by figure 3. Both figures show the points where the events could be measured. The graph shows how current (line slope) and output voltage vary with input voltage. The graph also shows that the voltage, V_S, at the inverting input is always zero.

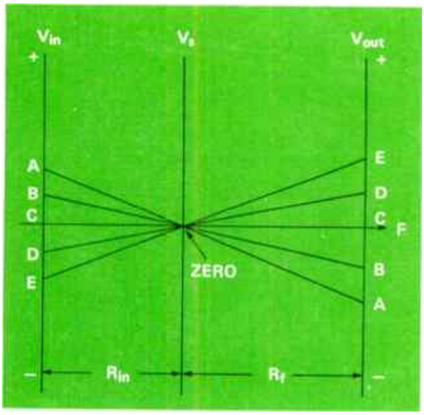


Figure 4. A graph of the electrical properties of the voltage inverter measured at certain points in the circuit at various instants demonstrates how current (slope of line) and output voltage vary with input voltage.

Summing Amplifier

From the discussion of the voltage inverter, it can be determined that the operation of the circuit is dependent upon the value of the elements external to the op amp and that the current is determined by the input resistor independently of the feedback resistor. Because of these facts, the inverting amplifier can be modified to work as a summing amplifier.

Summing amplifiers provide a simple, electronic method for performing addition and subtraction. Figure 5 shows how this is accomplished.

The input voltages, V_1, V_2, V_3 cause currents I_1, I_2, I_3 to flow through their associated input resistors R_1, R_2, R_3 to the "summing point" where the currents are algebraically summed to form the total current, I_t. The input currents are independent of the feedback resistor and are also independent of each other.

A few moments reflection on the operation of the circuits in figures 3 and 5 will help to understand why operational amplifiers are suitable for analog computers. The output voltage of either circuit can be viewed as the instantaneous resultant of a mathematical operation on the input voltage or voltages. The output may be a sum, difference, product or quotient de-

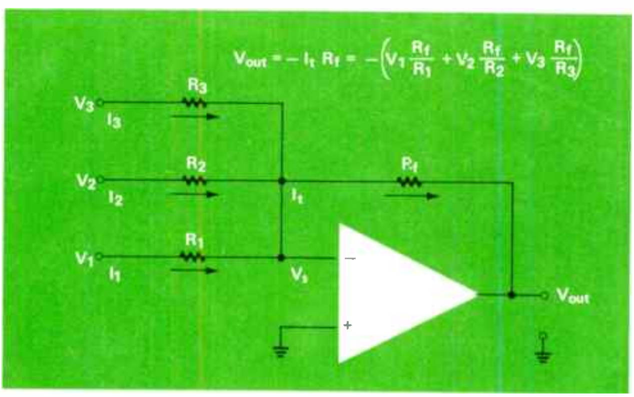


Figure 5. The summing amplifier circuit offers an electronic method for performing the mathematical operations of addition and subtraction.

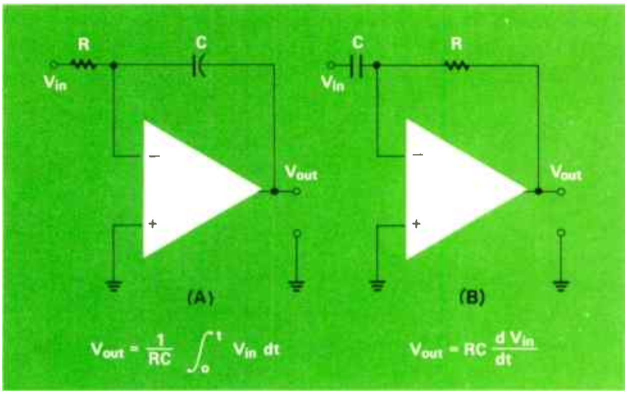


Figure 6. Inserting a capacitor into the feedback network in place of a resistor converts the inverting amplifier into an operational integrator (A) or operational differentiator (B).

pending upon the values and arrangements of the resistive elements in the circuit.

Operational/Integrators and Differentiators

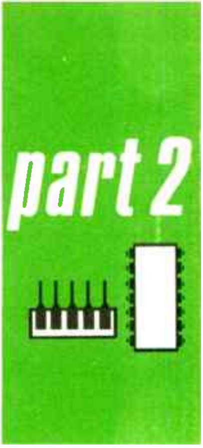
Replacing the feedback resistor with a capacitor changes the figure 3 inverter into the integrating circuit shown in figure 6-A. Replacing the input resistor with a capacitor changes the inverter into the differentiating circuit shown in figure 6-B. The voltage inverter, summing amplifier, integrator, differentiator and various combinations thereof, form the heart of an analog computer. The individual characteristics of each circuit are established by the configuration of their feedback loops.

The ideal operational amplifier concept has great value to the design engineer. However, he must exercise considerable engineering judgment in its application. A truly ideal amplifier cannot be realized. For example, infinite input impedance does not exist. There is always at least a few picoamps of input current. A dc return path must always be provided. Field Effect Transistors provide the highest input impedance but at the expense of bandwidth.

High gain amplifiers tend to oscillate at higher frequencies because it is difficult to maintain the correct phase relationships in the feedback loop. About 8 MHz is the upper frequency limit for general-purpose, operational amplifiers.

Sometimes, designers can take advantage of the less than ideal characteristics of a particular operational amplifier. For example, one popular integrated-circuit, op amp has a gain of 400,000 and is flat to about 10 kHz. At that frequency the response begins a sharp, smooth roll-off, descending to unity gain at about one Megahertz. This device is ideal for use as a 10 kHz, lowpass filter.

The trade-offs involved in selecting an operational amplifier almost always involve cost and performance. Selecting the exactly right unit can save many dollars in production costs, without adversely affecting performance.



Part one of this Operational Amplifiers article defined the characteristics of an ideal operational amplifier and described op amp applications in inverting amplifier, summing amplifier, integrating and differentiating circuits. This second part describes a few specific op amp circuits used in telecommunications equipment.

Non-Inverting Circuits

As stated in part 1, the input stage of an operational amplifier is usually a differential amplifier with an inverting and a non-inverting input. A signal may be applied to the non-inverting input and transferred to the output without a polarity reversal. In this application, the feedback loop is connected between the output and the inverting input in the same way it is connected in the voltage inverter circuit described in part 1. So, when a signal is applied to the non-inverting input, a signal is actually present at both inputs with the difference in potential held to zero by the feedback loop. This condition is identical to that in the inverting circuit where a virtual ground at the inverting input and an actual ground at the non-inverting input results in a zero difference of potential across the inputs. In both the inverting and non-inverting circuits, the input impedance appears to be infinite and no current flows into the input of the op amp.

Figure 1 is a schematic of a basic non-inverting circuit. It is called a voltage follower because the output voltage is an exact replica of the input. If the gain and input impedance is infinite and the output impedance is zero, the voltage follower gain is exactly unity.

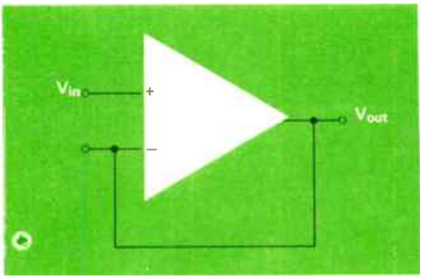


Figure 1. Voltage Follower. The name "Voltage Follower" is applied to this non-inverting operational amplifier because the output voltage is an exact replica of the input voltage.

The voltage follower is an excellent isolating device. It is often used as a buffer between a source and a load as in a PCM sample and hold circuit. Some of these are two-terminal devices with the feedback loop internally connected between the inverting input and the output. Voltage followers are also used extensively for filter isolation. Figure 2 is a circuit which might be used in a PCM transmitter.

The circuit is used to sample pulse amplitude modulated, PAM, pulses and remove any switching transients

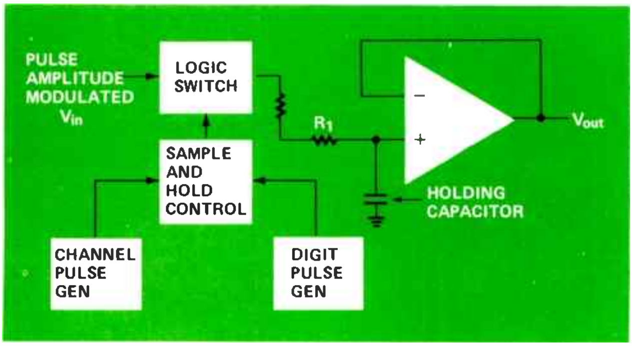


Figure 2. PCM sample and hold circuit. The holding capacitors must be quite small, so the amplifier input impedance must be very high to prevent capacitor discharge between pulses.

and voice amplitude variations that are present during each pulse period. The resultant output is a constant voltage which can be encoded. The holding period is generally long (125 μsec) so the high input impedance characteristic of the operational amplifier is important to minimize any holding capacitor leakage.

Resistor R_1 is a current limiting resistor. Its purpose is to limit the current to a value which will not damage the logic switch. The time constant of R_1 and the holding capacitor must be short (approximately 0.2 of the pulse period time) so that the capacitor will charge to the peak pulse voltage.

This circuit is similar to the integrator discussed in part 1 except that the output is not inverted. To avoid leakage through the load, the circuit in figure 2 connects the integrating capacitor to the non-inverting input instead of placing it in the feedback loop.

Balanced to Unbalanced Conversion

Figure 3 (a) shows an operational amplifier circuit which is used to convert a balanced circuit to an unbalanced circuit and to provide good common mode rejection at the input. The idea is to synthesize a differential output operational amplifier and then use the balanced feedback arrangement (see figure 3 (b)) to achieve the desired common mode rejection at the input and to achieve the desired gain.

Referring to figure 3 (a), the circuit accepts a balanced signal from a source that has an output impedance of R_1 (typically 600 ohms). The signal is amplified and the output at point e is unbalanced. In most cases the impedance of the unbalanced circuit is not specified because the output signal drives another amplifier with a high input impedance. However, the output impedance at point e is very low, so if the impedance of the unbalanced circuit is specified, it is easily realized by adding resistor R_{out}. Since the impedance at point e is assumed to be zero, R_{out} is set to the desired impedance of the unbalanced circuit.

As demonstrated in part 1, the amplifier gain is established by the ratio of R_2 to R_1: gain = V_e/V_{in} = R_2/R_1. The output in dB is V_e (dB) = V_{in} (dB) + Gain (dB).

If the output impedance is specified and R_{out} is added, the level V_{out} (across the termination R_{out}) is 6 dB lower than the level V_e; V_{out} (dB) = V_{in} (dB) + [Gain (dB) – 6 (dB)].

To understand the operation of the circuit assume that (c) and (d) are virtual grounds, and that

$$R_2 = \frac{R_1}{2}.$$

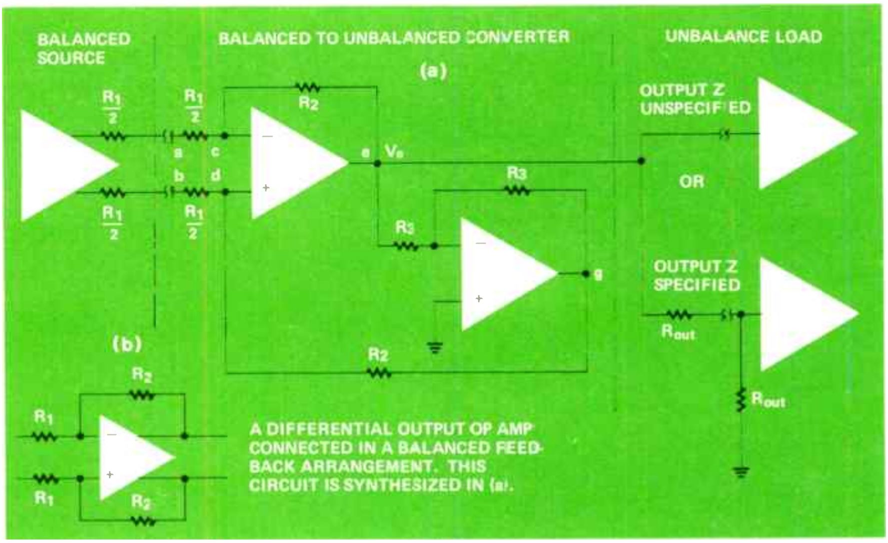


Figure 3. Balanced to Unbalanced Converter. The circuit accepts a balanced input signal at a specified input impedance (R_{in}) and converts it to an unbalanced signal with an unspecified output impedance or a specified impedance (R_{out}).

When a balanced signal is applied to the input, the voltage at (a) is $+V_{in}$ and the voltage at (b) is $-V_{in}$ (same amplitude but opposite phase). Since

$$R_2 = \frac{R_1}{2}$$

the amplifier has unity gain, and since (c) and (d) are assumed to be virtual grounds $V_e = -V_{in}$. Since the second stage is a unity gain inverting amplifier, $V_g = V_e$, so $V_g = V_{in}$. Using the assumption that the input impedance of an operational amplifier is infinite, it can be seen that the assumption that (c) and (d) are virtual grounds is correct, and the circuit does indeed work as a differential output operational amplifier connected in the balanced feedback arrangement.

To prevent loading of the output, R_3 is made very large relative to R_{out}. For example, if R_{out} is 600 ohms, R_3 is usually 10,000 or 20,000 ohms.

If the common mode rejection of the operational amplifier is good, the common mode rejection of the circuit is dependent upon the balance of the resistors. Very good common mode rejection can be achieved by careful resistor selection.

Unbalanced to Balanced Conversion

When op amps are used to convert from an unbalanced to a balanced circuit, the output impedance is generally specified. Figure 4 shows a circuit for use when gain is not required. The circuit uses a unity gain voltage follower buffer and an inverting amplifier. Since the gain is unity $V_{in} = V_{out}$ (with the output terminated). Two inverting amplifiers may be used if gain is required. The circuit is shown in figure 5. The gain is established by the ratio of R_2 to R_1:

$$\text{Gain} = \frac{V_{out}}{V_{in}} = \frac{R_2}{R_1}$$ (with the output terminated).

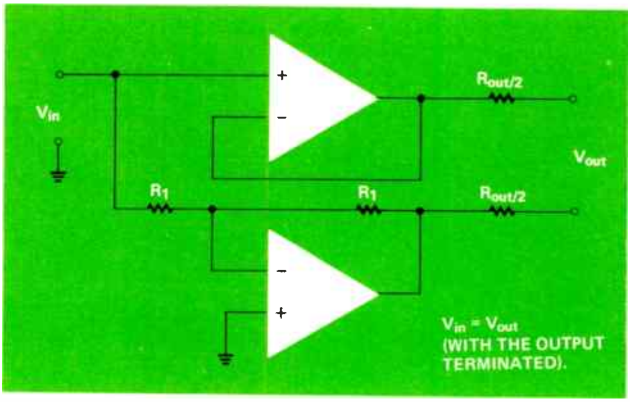


Figure 4. Unbalanced to Balanced Converter. This circuit is used where no gain is required. It uses a unity gain voltage follower buffer and an inverting amplifier.

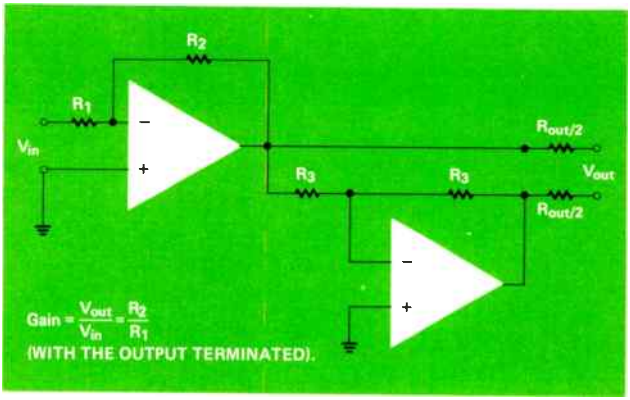


Figure 5. Unbalanced to Balanced Converter. This circuit is used when gain is required. It uses two inverting amplifiers.

Filter Circuits

The May/June, 1975 issue of the Demodulator contains a detailed discussion of operational amplifier applications in active filter circuits. The following paragraphs reprint a portion of that discussion.

Negative Impedance Converter

An impedance converter is a two-port network whose function is to change an impedance characteristic in some manner. Ideally, when the impedance converter is terminated at one port by an impedance, Z, the input impedance at the other port is directly proportional to Z for all frequencies; the proportionality in a network containing only an amplifier and resistors is determined by a conversion factor, or impedance transformation function, K. If an energy-storing device such as a capacitor is placed in the network, as is often the case, a complex frequency variable, s, appears in the relationship, making the conversion factor K(s). A capacitor serving as a terminating impedance does not introduce the frequency variable, so in this discussion, which deals with the simplest realizations, the (s) complex notation is not used.

Negative impedance is a characteristic of some circuits and components which causes a decrease in current for an increase in voltage, and vice versa; this property has been recognized for some time, and is exhibited by such

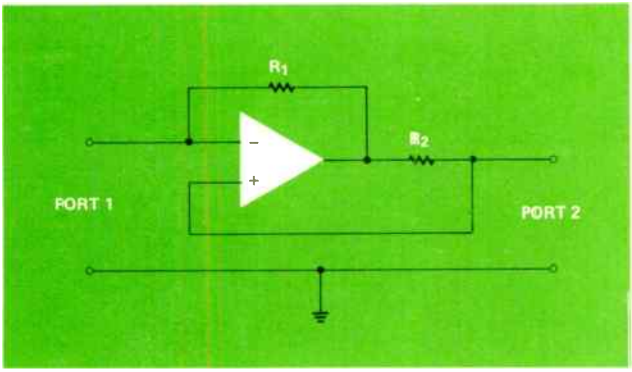


Figure 6. Realization of a current inverting negative impedance converter (INIC) using an operational amplifier.

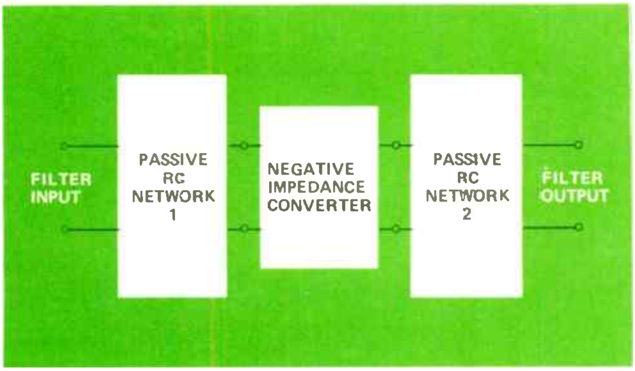


Figure 7. A negative impedance converter is typically placed between two passive RC networks to form a filter section.

devices as tunnel diodes and, under certain conditions, vacuum tubes. A negative impedance converter (NIC) is a two-port network which converts an impedance terminating one port into its negative at the other port. For example, if port 2 were terminated by impedance Z_L, the input impedance, Z_{in}, at port 1 would be related to it by

$$Z_{in} = -KZ_L$$

where K is the network conversion factor.

A realization of an NIC is typically composed of one operational amplifier and associated resistor (see Figure 6). The circuit is placed between two passive RC networks to form a filter section (see Figure 7), so that the negative impedance of network 2 created by the NIC can interact with the positive impedance of network 1. This interaction produces the desired filter response characteristic.

The op amp is generally preferred for active filter circuit realization because of its operating characteristics, its size reduction, the ease with which it can be incorporated into integrated circuits and its ready availability as an inexpensive component. Theoretically, an op amp has infinite input impedance, and infinite gain; these characteristics along with the ability to produce a single output proportional to two inputs make the op amp ideal for active filter applications.

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