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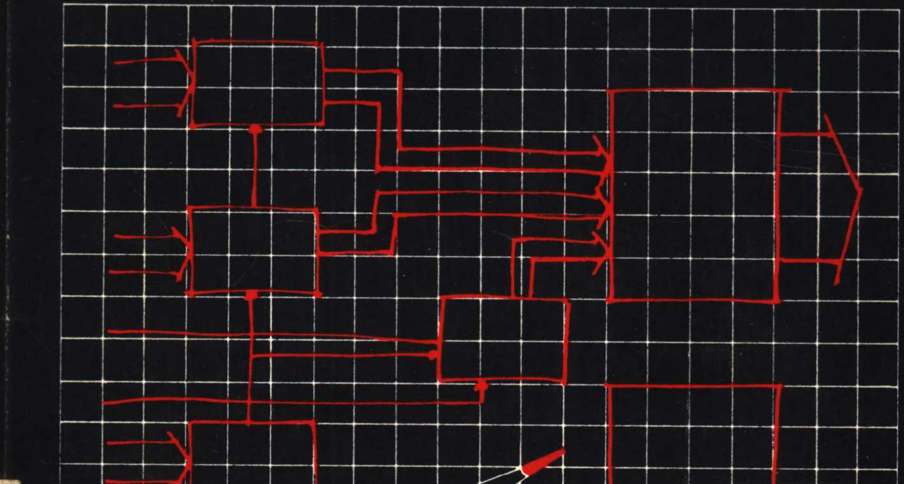
ELECTRONIC DESIGN WITH INTEGRATED CIRCUITS

David J. Comer



DAVID J. COMER
California State University, Chico

electronic design with integrated circuits

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preface

Every book written on the subject of integrated circuits focuses on one of two possible topics: fabrication of the integrated circuit or application of the finished device. Although there is overlap of the two areas that may introduce some ambiguity, most IC textbooks can immediately be classified into one of these two topical areas.

This book covers the application area. The IC manufacturers employ a number of electrical engineers, but a far larger number will apply those ICs in designing more complex circuits and systems. Ideally a course using this text would follow one or more courses on basic electronics that focus on discrete devices and perhaps cover IC fabrication processes. On the other hand, if this text were used for a first electronics course, the material in the appendixes, Integrated Circuit Building Blocks, should be covered initially. The instructor would then supplement this material with some of the basic concepts of electronic analysis before proceeding to Chapter 1 of the text.

This text presents the material actually needed by the system designer to do an effective job—nothing more, nothing less. It should not only prepare the undergraduate student to design systems based on ICs, but should also prepare the practicing engineer to move into the area of IC system design.

Traditionally electrical engineering students have been taught everything about each device they study. They are given some background in solid state physics, basic device operation, and application information before they are taught to design with the device. To be very blunt, the world of electronic circuit design has changed, and the designers of computer systems could care less about the holes or electrons that flow through the circuits. They are concerned with the signals that must be present to activate an IC output or with the interconnection of several ICs to produce a required output.

There is a major emphasis on digital systems in this book which is in line with a similar emphasis by industry. Digital systems simply outnumber analog systems by several factors. However, Chapters 1 and 2, along with 7 and 8, are primarily concerned with those analog circuits that are most popular.

I am grateful to those at Addison-Wesley for encouraging this project and to the reviewers and production editor for their many suggestions. Likewise my wife has my gratitude for typing the manuscript (even though she demanded ten percent of the royalties for her services!). I am grateful to be an instructor with industrial ties that allow me to participate in and observe the field of electronic system design.

March 1981 D. J. C.
Chico, California

introduction

THE INTEGRATED CIRCUIT

The development of the integrated circuit (IC) has changed the direction of the entire field of electronics. No other device, with the possible exception of the transistor, can be credited with the degree of advancement in capability that electronic systems have achieved in the last decade. Abrupt improvements in performance per volume and cost per function by factors of over one thousand have resulted in many new and exciting concepts. Hand-held calculators, personal computers, low-cost operational amplifiers, intelligent terminals, and microprocessors are a few examples of systems made possible only by the existence of the IC.

To see why the IC has had such a tremendous impact on the field of electronics, let's examine the physical makeup of this amazing device. A monolithic IC consists of a single chip of silicon containing hundreds or thousands of electrical components. Resistors, diodes, transistors, and capacitors are formed within the silicon material, allowing over 10,000 transistors and their associated circuitry to occupy a chip of one square centimeter in area and two millimeters thick. Very precise photolithographic work is required to form these microscopic devices in the silicon chip. Procedures have been developed that isolate these components from each other and make connections between them as required. Hybrid circuits, using films deposited on the monolithic chip to form components, extend the capabilities of the IC even further.

This textbook will discuss many important applications of the IC from the viewpoint of its users, rather than that of its designers.

*In 1960 an *npn* silicon transistor with modest capabilities by today's standards could cost as much as $30 per unit. In 1965 as the diffusion process was improved, the price for an even higher performance *npn* silicon device had dropped to 30¢. This represents a cost improvement of 100. By the middle of the 1970s, certain IC chips with 10,000 transistors apiece were being produced with a market value of around $30 each. This represented another factor of 100 cost improvement. Now very large-scale integration (VLSI) techniques promise to improve the cost per unit by another factor of ten, these devices averaging less than a hundredth of a cent apiece.

THE OPERATIONAL AMPLIFIER

Many electronic circuits require an amplifier to boost an input signal to a usable level. Little more than a decade ago these amplifiers had to be designed from the ground up. Quiescent points of all transistors were established, appropriate interstage coupling circuits were selected, and gain and impedance levels were often determined with great difficulty. An engineer who could efficiently design amplifiers possessed one of the most important tools in analog circuit design. Those who were poor in amplifier design were often not very effective designers.

This situation has been changed considerably by the development of the operational amplifier or op amp. The op amp is now made as a single chip device with a very high voltage gain (perhaps 100,000 or 1,000,000) and a 3 dB bandwidth extending from dc to a few hertz. Generally, gain and bandwidth can be exchanged directly by proper connection of external resistors. Thus, an op amp with a gain of 100,000 and a bandwidth of 10 Hz can be used in a configuration resulting in a gain of 100 and a bandwidth of 10,000 Hz. The bandwidth is extended by a factor of 1,000 while the gain drops by this same factor. The ease with which the gain and bandwidth can be controlled by external resistors makes the op amp an unusually versatile circuit element.

Another important feature of the op amp is its differential input capability. The output can be made proportional to the positive value of one input or the negative value of another (phase inversion), *or* to the difference between two input signals.

Since the first IC op amp was introduced, many improvements have been made. Op amps using either bipolar transistors or field-effect transistors have been developed along with circuits that combine these two devices to optimize important parameters of performance.

For many applications, the op amp is so simple to use that a person with only minimal experience in electronics can design workable circuits. Designers, however, must have a much greater understanding of the device to use it effectively in the more complex configurations they manipulate.

The simplicity and flexibility of the op amp warrants a thorough study of this very important circuit element.

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* These shaded sections throughout the book deal with speculative material, more detailed derivations, or interesting background relating to the topic under discussion.

DIGITAL CIRCUITS

There are several possible methods of using electronic systems to perform mathematical operations. One method represents numeric values by voltage level. For example, 0 V might represent the number 0; 0.4 V might represent the number 1; 0.8 V would then represent the number 2; and 3.2 V would represent the number 8. If the number is represented by a voltage level, an analog system is being used. A typical representation would find the numeric value varying proportionally to voltage level, though proportionality is not required for all analog systems.

Unfortunately, it is difficult and expensive to control precisely a voltage level. Changes in temperature and age can cause resistor and capacitor values to drift and can drastically affect transistor parameters. Analog computers use this approach to effectively solve differential equations; however, the cost is relatively high, and the accuracy of the results is relatively low.

Digital systems can represent numeric values very accurately even though the circuits used may not include precision elements. The output voltage of a digital circuit is not proportional to a numeric value; it represents a state. Most digital circuits are based on the binary number system, which requires only two states. If the output voltage falls in the 1.5-V–5-V range, for example, the state represented may be the ONE state. A voltage from 0 V to 1.5 V may represent the ZERO state. A drift in output voltage from 0.2 V to 0.4 V does not change the numeric value of ZERO assigned to this output. The disadvantage of digital systems is that only two numeric values can be assigned each circuit; thus the binary system must be used rather than the familiar decimal system. Binary numbers require many more positions than decimal. To represent the number 999 requires three decimal positions, while the binary representation is 1111100111, which has ten positions. Since one circuit is required for each position, many circuits must be used when larger numbers must be treated.

Although digital circuits were popular before integrated circuits were developed, the IC ideally augments them. Many circuits can be packed into a very small volume and precision is not a major requirement. In fact, digital circuit design was the first area to which ICs were applied in high volumes: Logic gates, adders, subtractors, encoders, decoders, registers, and other digital circuits all have the characteristics that they have two possible output states, need not be highly accurate, and are easy to integrate in large volumes. These circuits form the basis for digital computers and other binary systems and will be treated in some detail in later chapters.

contents

the op amp

1

One of the important fields of study in electronics is that of amplifier design. Before moving directly into the study of the integrated circuit amplifier, we will clarify why this element is so useful.

1.1 THE ELECTRONIC AMPLIFIER

A. Amplifier Applications

There are many signals in electronics that carry important information, but are too weak to be useful without amplification. A public address system is an example of this situation. A microphone converts the voice pressure waves or audio signals into corresponding voltage signal variations. The voltage signals may only be 20 mV in average amplitude. While the output of the microphone contains the complete speech information, it is so weak that it cannot begin to drive a loudspeaker. If the microphone output voltage and current are amplified by a factor of 100 or 1000, the resulting signal can be coupled to a loudspeaker that produces a very loud signal. In fact, several loudspeakers may be driven from this amplifier to distribute the sound to several points simultaneously.

Another application requiring signal amplification is wireless transmission of information—that is, radio or television transmission. A transmitting station emits great amounts of power from the antenna. This power emanates in all directions and is diminished or attenuated by the atmosphere. When a receiver located forty miles away is tuned to this station, the signal strength may be measured in microvolts and must be greatly magnified or amplified before the transmitted audio or video information can be recovered by the radio or TV receiver.

The telephone is yet another example of a device that could function only for short distance transmission were it not for the electronic amplifier. The mouthpiece of a phone is basically a microphone that converts audio pressure waves into voltage signals. These signals become smaller as they travel over lossy phone lines. In a typical phone system, amplifiers are spaced at intervals of several miles to retain a large signal. The signal reaching the earpiece of the receiving phone is larger than that transmitted and can be converted back into sound waves.

The bulk of electronic amplifier applications are designed to increase or magnify a voltage signal. In so doing, the power or current may also be amplified. There are other situations where a current amplification is the major requirement and the voltage may not change. A digital circuit might have a 4-V output signal, but can only supply 2 mA of current. If 100 mA of current is required, a current amplifier must be used.

Thus we conclude that an amplifier is a device used to magnify a voltage or a current or both simultaneously.

B. Important Parameters of the Amplifier

Obviously the gain of an amplifier is important. This indicates the magnification of the input signal. Gain is defined by

$$A = \frac{\text{Output}}{\text{Input}}.$$

If both output and input quantities are voltages, the gain A is voltage gain. If both are currents, A is a current gain. A third gain is power gain that expresses the ratio of output to input power.

While gain is an important quantity, so also are the input and output impedances of the amplifier. To demonstrate this point, suppose we have a microphone that puts out a typical signal of 20-mV peak and has an output impedance of 10 kΩ. If this microphone is coupled to a 16-Ω speaker with an amplifier of gain 200, we might expect an output signal of 200 × 20 mV = 4-V peak. However, the output signal depends not only on the gain, but also on the input and output impedances of the amplifier. If the input impedance to the amplifier is 20 kΩ and the output impedance is 16 Ω, the circuit will appear as shown in Fig. 1.1. The output signal is now given by

$$e_{\text{out}} = e_{\text{in}} \frac{20\ \text{k}\Omega}{20\ \text{k}\Omega + 10\ \text{k}\Omega} \times 200 \times \frac{16\,\Omega}{16\,\Omega + 16\,\Omega} = 66.7\,e_{\text{in}}.$$

The overall gain or in-circuit gain is 66.7 due to the loading effect of input and output impedances.

Another important parameter of the amplifier is bandwidth. The gain of any amplifier will decrease at higher frequencies. The frequency at which the gain has dropped to 70.7% of the low-frequency value is called the bandwidth of the

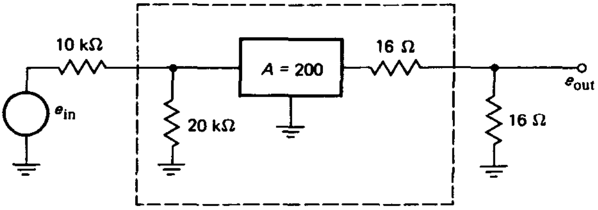

Fig. 1.1 The practical amplifier.

amplifier. This assumes the gain at lower frequencies does not decrease. If an amplifier has a bandwidth of 10 kHz it cannot be effectively used to amplify a signal with 200-kHz components.

The operational amplifier or op amp is perhaps the most popular single IC in the field of electronics today. In addition to amplifier applications, it can be used to construct a voltage comparator, a Schmitt trigger, a digital-to-analog converter, an integrator, and many other important digital and analog circuits. As many situations require only a basic understanding of the device, the almost ideal op amp will be discussed first. The nonideal effects that must be considered for more critical design will be treated in the last section of the chapter.

1.2 THE BASIC OP AMP

A near-ideal op amp has a very high gain, a low bandwidth, a high input impedance, and a low output impedance. The symbol for this device is shown in Fig. 1.2(a).

The op amp always has a differential input stage. The output voltage can be expressed as

$$e_{out} = A(e_2 - e_1) \tag{1.1}$$

where e_2 is the voltage applied to the noninverting input and e_1 is the voltage applied to the inverting input. The gain A might be 10,000 to 1,000,000 at dc or

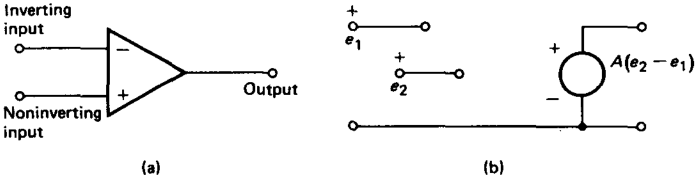

Fig. 1.2 (a) Symbol for the op amp. (b) Idealized equivalent circuit.

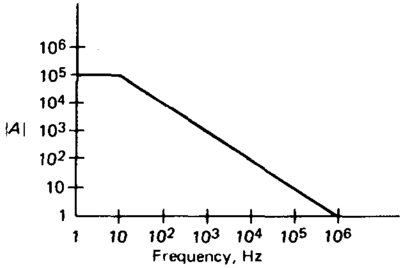

Fig. 1.3 Voltage gain as a function of frequency.

very low frequencies, but generally drops 6 dB per octave above a corner frequency that might be as low as 10 Hz. Figure 1.3 shows a typical variation of gain with frequency.

The equivalent circuit shown in Fig. 1.2(b) indicates that the op amp has zero output impedance and infinite input impedance. Although these conditions do not accurately describe the actual op amp, the simple model shown can be used in a surprisingly large number of practical applications.

A. The Noninverting Amplifier

A popular configuration for a noninverting amplifier is shown in Fig. 1.4. The resistors R_F and R_2 constitute a feedback network that determines the voltage gain of the amplifier. We can approximate the op amp gain dependence on frequency by

$$A = \frac{A_m}{1 + j(f/f_2)} \tag{1.2}$$

where A_m is the maximum gain (or dc gain) and f_2 is the upper corner frequency (the 3-dB point) of the op amp.

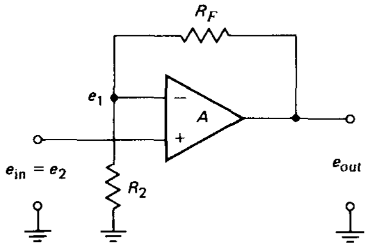

Fig. 1.4 A noninverting amplifier.

Assuming zero output impedance for the amplifier and high input impedance at the inverting terminal, we can calculate the voltage fed back from output to this point as

$$e_1 = \frac{R_2}{R_2 + R_F} \times e_{\text{out}} = Fe_{\text{out}}$$

where F is the feedback factor—or the transfer function of the feedback network. We can now determine the overall voltage gain by noting that

$$e_{\text{out}} = A(e_2 - e_1) = A(e_{\text{in}} - Fe_{\text{out}}).$$

Solving for $e_{\text{out}}/e_{\text{in}}$ gives

$$G = \frac{e_{\text{out}}}{e_{\text{in}}} = \frac{A}{1 + AF} \tag{1.3}$$

which is the well-known formula for closed-loop gain of a feedback amplifier.

If we now substitute the expression for A from Eq (1.2) into Eq. (1.3), we find that

$$G = \frac{A_m}{1 + A_m F} \frac{1}{1 + jf/(1 + A_m F)f_2}. \tag{1.4}$$

The overall dc or low-frequency gain of the amplifier is

$$G_m = \frac{A_m}{1 + A_m F} \tag{1.5}$$

whereas the upper 3 dB point is

$$f_{2f} = f_2(1 + A_m F). \tag{1.6}$$

In the typical case the product $A_m F$ will be much larger than one, and Eq. (1.5) can be reduced to

$$G_m = \frac{1}{F} = \frac{R_2 + R_F}{R_2} = 1 + \frac{R_F}{R_2}. \tag{1.7}$$

This equation is very useful in design work to set specified gain with minimal calculation.

If you are being introduced to the op amp for the first time, you might well ask why feedback is used—that is, why not eliminate R_F and R_2, ground the inverting terminal, and apply the input to the noninverting terminal? The answer is that, in general, the exceptionally high value of gain would cause the output signal to clip as the voltage reaches the limit of the active region. With a gain of 2×10^5, an input signal of only 0.16 mV would lead to a 32-V output signal, and clipping would occur in several op amps for this value of input. Although there are occasional applications that require amplification of such a small signal, the bandwidth limitation also virtually eliminates the usefulness of the op amp as an amplifier when there is no feedback. A 5- or 10-Hz bandwidth is rarely acceptable; thus feedback is generally used to extend the bandwidth while reducing the gain of the amplifier.

Let's compare the gain and bandwidth of the op amp to those of the noninverting amplifier of Fig. 1.4. Equation (1.2) shows that the op amp itself has a low-frequency gain of A_m and a bandwidth of f_2. For the 741, a very popular op amp, $A_m = 2 \times 10^5$ and $f_2 = 5$ Hz. Suppose we add the feedback resistors with values $R_F = 99\ \text{k}\Omega$ and $R_2 = 1\ \text{k}\Omega$. This results in a feedback factor $F = 0.01$. The overall low-frequency gain given by Eq. (1.5) is

$$G_m = \frac{2 \times 10^5}{1 + 2 \times 10^5 \times 10^{-2}} = 100,$$

and the corner frequency is

$$f_{2f} = 5(1 + 2 \times 10^5 \times 10^{-2}) = 10{,}005\ \text{Hz}.$$

The gain after feedback has been reduced by a factor of 2,000 from 200,000 to 100, while the bandwidth is increased by this same factor from 5 Hz to approximately 10,000 Hz.

Using the noninverting configuration results in a nearly constant gain-bandwidth product (GBW). That is, gain can be decreased by controlling the resistors R_F and R_2, but the bandwidth increases by the same factor of gain decrease. This is demonstrated from Eqs. (1.5) and (1.6). The GBW is

$$GBW = G_m \times f_{2f} = \frac{A_m}{1 + A_m F} \times f_2(1 + A_m F) = A_m f_2.$$

Note that the amplifier with feedback has the same GBW as the op amp with no feedback. Gain and bandwidth are varied with F, but the GBW does not change with feedback factor. Thus, an important figure of merit for the op amp is the gain-bandwidth product. This figure can be used to compare the bandwidth of one op amp to another for a fixed gain.

There is an important configuration derived from the noninverting amplifier. For the circuit of Fig. 1.4, when R_F approaches zero (a short circuit) and R_2 approaches infinity (an open circuit), the feedback factor becomes

$$F = \frac{R_2}{R_2 + R_F} \rightarrow 1.$$

From Eq. (1.5) the low-frequency gain becomes

$$G_m = \frac{A_m}{1 + A_m} \rightarrow 1.$$

Figure 1.5 shows this unity gain amplifier or buffer stage. Although the voltage gain is unity, the current gain is quite high. This means that the input impedance is high and the output impedance low.

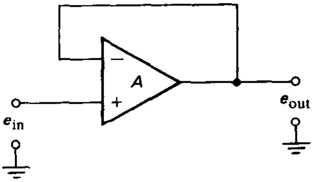

Fig. 1.5 Buffer stage.

The adjustment of R_F and R_2 affects both gain and bandwidth as shown in Fig. 1.6.

It will be shown later that the noninverting stage has higher input and lower output impedances than the op amp with no feedback.

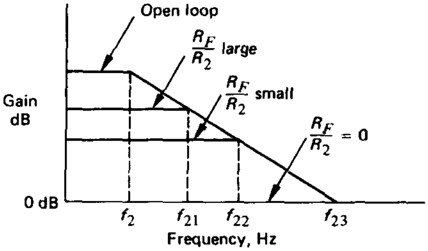

Fig. 1.6 Effect of R_F / R_2 on gain and bandwidth.

B. The Inverting Amplifier

If phase inversion is needed or if a smaller value of input impedance is important, the stage of Fig. 1.7 can be used.

Because the input impedance to the op amp is generally very high, little current flows into the inverting terminal. Thus, all input current flowing through R_1 can be assumed to travel toward the output terminal through R_F. With this

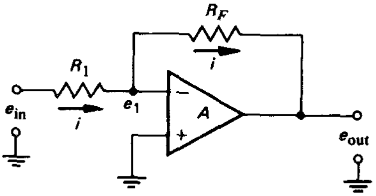

Fig. 1.7 An inverting amplifier.