MALVINO

ELECTRONIC PRINCIPLES

THIRD EDITION

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Third Edition

Albert Paul Malvino, Ph.D.

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Preface

This third edition is not a skin-deep revision. Almost every chapter has been rewritten to reflect the changes that have taken place in industry. Some of the earlier chapters on discrete devices have been combined to make room for new material. Although the discussion of discrete devices has been streamlined, you will still find a complete treatment of diodes and transistors because an understanding of what these components are and how they function is the foundation needed to understand ICs.

In revising the book, I discovered several areas that needed expansion. Now, you will find new discussions of troubleshooting, optoelectronic devices, power-supply filtering, load lines, graphical analysis, cascaded stages, *h* parameters, classes D through S, JFET switches, JFET voltage-variable resistances, dual-gate MOSFETs, VMOS interface circuits, diff-amp analysis, negative-feedback circuits, foldback current limiting, parasitic oscillations, and phase-locked loops.

Besides the foregoing changes, I wrote many new chapters to cover topics such as voltage and current feedback, JFET-controlled op-amp circuits, voltage-controlled current sources, current boosters, active Butterworth filters, comparators with hysteresis, window comparators, Schmitt triggers, integrators, differentiators, waveshaping circuits, dc-to-dc converters, switching regulators, 555 timers, and thyristors.

In addition to the changes in material, this new edition contains two major changes in format. First, I have rewritten the book to allow you to use either conventional or electron flow. Since either approach is valid, there is no reason why I should saddle you with one type of flow when you prefer the other. Chapter 1 discusses both types of flow and indicates how either can be used in subsequent chapters.

The second major change is in the homework problems. Because of many requests, I have expanded the problems at the end of each chapter to include five categories: straightforward, troubleshooting, design, challenging, and computer. The straightforward section is similar to the problems of earlier editions. The troubleshooting, design, challenging, and computer sections are new with this edition. Consider these new problems optional. If they fit your program, fine. If not, ignore them. For example, most schools will want to include the straightforward and troubleshooting problems because they are basic to any technician program. Other schools may use the design and challenging problems as well. And finally, schools where computers are available for students may want to include the computer problems to round out their programs. Chapter 1 describes the new homework problems in more detail. In my opinion, the problems in this book will enhance any program and bring a new dimension to electronics education.

As before, this book is for a student taking a first course in linear electronics. The prerequisites are a dc-ac course, algebra, and some trigonometry (at least enough to work with sine waves). In many schools it will be possible to take the ac and trigonometry courses concurrently.

A final point. In addition to this textbook, a correlated laboratory manual *Experiments for Electronic Principles* is available. It contains over 50 experiments including optional exercises in troubleshooting and design. An extensive instructor's guide is also available.

Albert Paul Malvino

SOFTWARE FOR ELECTRONIC PRINCIPLES, Third Edition

Software, on floppy disk, is available from the author. It allows an Apple II or IBM PC personal computer to be used to practice troubleshooting electronic circuits from the textbook. Write to Dr. Malvino at

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229 Polaris Ave., Suite 14
Mountain View, CA 94043

Acknowledgments

First, I would like to thank everyone who returned a questionnaire for *Electronic Principles* in the Spring of 1982. I know it took a lot of time to answer the questions and to add comments on what to delete, expand, and include. I want you to know I read each questionnaire carefully. Without them to guide me and the many excellent suggestions given, I could not have attained the perspective and quality found in this third edition.

Second, I want to thank each instructor who allowed me to interview him. My visit to your school and talking to you gave me great insight into what had to be done. Our exchange of ideas led to excellent new ideas that I could never have come up with alone. I found the interviews an invaluable asset during the months of rewrite and revision.

Third, I want to thank all the reviewers who read some or all of the revised manuscript. Several times, you caught me wandering off the true path. Furthermore, you were constantly suggesting better ways to discuss ideas, word passages, and draw figures. Your help has raised the quality of the final product to a level that would have been impossible working alone.

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CHAPTER 1

Introduction

One of the prerequisites for reading this book is a course in dc circuit theory in which topics like Ohm's law, Kirchhoff's laws, and other circuit theorems have been discussed. This first chapter reviews a few basic ideas and introduces some viewpoints that you might have missed the first time through basic dc theory.

1-1 CONVENTIONAL AND ELECTRON FLOW

Which way do electric charges flow? Murphy's law says that the number of deeply held beliefs is equal to the number of possibilities, no matter how ridiculous. Fortunately, there are only two possible directions for current: plus to minus, or minus to plus.

THE FLUID THEORY

Franklin (1750) made an outstanding contribution with his fluid theory of electricity. He visualized electricity as an invisible fluid. If a body had more than its normal share of this fluid, he said it had a positive charge; if the body had less than a normal share, its charge was considered negative. On the basis of this theory, Franklin concluded that electric fluid flowed from positive (excess) to negative (deficiency).

The fluid theory was easy to visualize and agreed with all experiments conducted in the eighteenth and nineteenth centuries. As a result, everybody accepted the notion that charges were flowing from positive to negative (now called *conventional* flow). Between 1750 and 1897, a large number of concepts and formulas based on the conventional flow came into existence. During this period, the scientific community became committed to conventional flow as a way of life.

Even today, the bulk of engineering literature continues to use conventional flow. Somebody (usually an engineer or scientist) who invents a new device tends to insert arrows on the device that point in the direction of conventional current.

THE ELECTRON

In 1897, Thomson discovered the electron and proved that it had a negative charge. Nowadays, the planetary concept of matter is well known. Matter is made up of atoms. Each atom is a positively charged nucleus surrounded by orbiting electrons. The outward push of centrifugal force on each electron is exactly balanced by the inward pull of the nucleus. Therefore, electrons travel in stable orbits, in a manner similar to the motion of the planets around the sun.

A copper atom has 29 protons and 29 electrons. Of the 29 electrons, 28 travel in tight orbits around the nucleus; because of their small orbits, these electrons are locked into the atom by the strong pull of the nucleus. But the 29th electron travels in a very large orbit. Since it is relatively far from the nucleus, this electron feels almost no nuclear attraction. As a result, it is called a *free electron* because it can easily wander from one copper atom to the next.

ELECTRON FLOW

In a piece of copper wire, the only charges that flow are the free electrons. Under the influence of an electric field, these free electrons flow out of the negative terminal of a battery through the wire to the positive terminal. This is exactly opposite to conventional flow, which creates a problem. Everybody now agrees that charges actually flow from negative to positive in a piece of copper wire, but not everyone is willing to discard the use of conventional flow.

Why the resistance to change? Because once you get above the atomic level, it makes no difference whether you visualize charges flowing from negative to positive or vice versa. Mathematically, you get the same answers either way. Therefore, even though electron flow is the truth, the whole truth, and nothing but the truth, conventional flow preserves the mathematical foundations of almost 200 years of circuit theory.

What it comes down to is this: It is convenient for engineers to use both conventional and electron flow, rather than choosing one or the other. At the atomic level, they use electron flow to explain what is actually happening. Above the atomic level, they pretend that a hypothetical positive charge flows, rather than an electron. Maybe someday the engineering community will change to electron flow when analyzing circuits mathematically, but at this time the consensus is that such a change is not worth the hassle.

EITHER FLOW VALID

When a device is discussed for the first time, both types of flow will be shown, with a solid arrow for conventional flow and a dashed arrow for electron flow. You can use either type of flow, so ignore the one you don't want. As an example, Fig. 1-1*a* shows a circuit with conventional current, and Fig. 1-1*b* shows the same circuit with electron flow. In using this book, you should settle on either conventional flow or electron flow; either is valid. Furthermore, occasionally seeing both types of current is probably good training because you will encounter both types in industry.

After we introduce a device, we will drop the use of current arrows. Again, this is good practice because industrial schematics show voltage polarities but not current

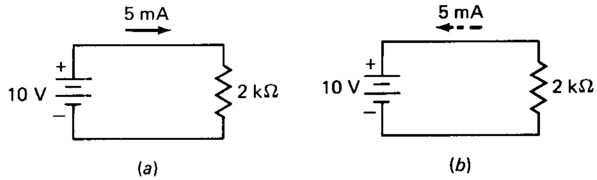


Fig. 1-1
(a) *Conventional flow.* (b) *Electron flow.*

directions. It's up to you to know that charges flow from positive to negative (if you use conventional flow) or from negative to positive (if you prefer electron flow).

1-2 VOLTAGE SOURCES

For any electronic circuit to work, there has to be a source of energy. An energy source is either a voltage source or a current source. This section discusses the voltage source, and the next section is about the current source.

IDEAL VOLTAGE SOURCE

An *ideal* or perfect voltage source produces an output voltage that does not depend on the value of load resistance. The simplest example of an ideal voltage source is a perfect battery, one whose *internal resistance* is zero. For instance, the battery of Fig. 1-2*a* produces an output voltage of 12 V across a load resistance of 10 kΩ; Ohm's law tells us that the load current is 1.2 mA. If we reduce the load resistance to 30 Ω, as shown in Fig. 1-2*b*, the load voltage is still 12 V; the load current, however, increases to 0.4 A. (Don't reach for your calculator; all calculations in this section should be done mentally.)

Figure 1-2*c* shows an adjustable load resistance (rheostat). The ideal voltage source will always produce 12 V across the load resistance, regardless of what value it is adjusted to. Therefore, the load voltage is constant; only the load current changes.

REAL VOLTAGE SOURCE

An ideal voltage source cannot exist in nature; it can exist only in our minds as a theoretical device. It is not hard to understand why. Suppose the load resistance of Fig. 1-2*c* approaches zero; then the load current approaches infinity. No real voltage source can produce infinite current because every real voltage source has some internal resistance. This resistance is typically less than 1 Ω. For instance, a flashlight battery has an internal resistance of less than 1 Ω, a car battery has an internal resistance of less than 0.1 Ω, and an electronic voltage source may have an internal resistance of less than 0.01 Ω.

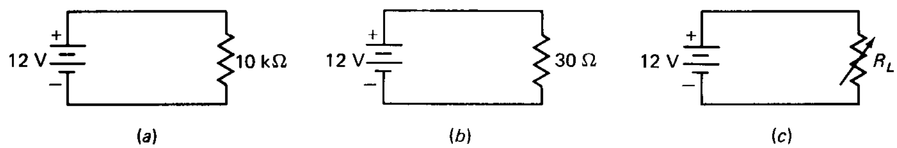
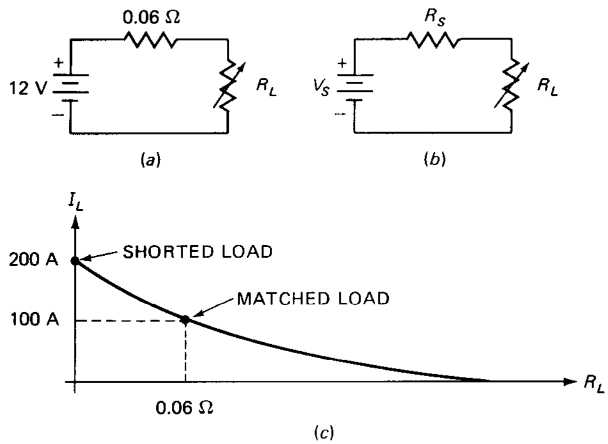


Fig. 1-2
Voltage source.

Fig. 1-3
Load current.



SHORTED-LOAD CURRENT

The internal resistance of a real voltage source appears in series with the load resistance. For instance, Fig. 1-3*a* shows a 12-V source with an internal resistance of 0.06 Ω. If we reduce the load resistance to zero, Ohm's law gives

$$I = \frac{12 \text{ V}}{0.06 \ \Omega} = 200 \text{ A}$$

This is the maximum load current that the real voltage source can deliver; this maximum load current is called the *shorted-load current.*

GRAPH OF LOAD CURRENT

You can visualize any real voltage source as shown in Fig. 1-3*b*: An ideal voltage source V_S is in series with an internal resistance R_S. With Ohm's law,

$$I_L = \frac{V_S}{R_S + R_L} \tag{1-1}$$

When the load resistance increases, the load current decreases. Plotting load current versus load resistance for Fig. 1-3*a*, we get the graph of Fig. 1-3*c*. There are no surprises here. The load current is 200 A for zero load resistance. Then, as load resistance increases toward infinity, the load current decreases toward zero. Note the intermediate point where the load resistance matches the internal resistance; at this point the load current is half the shorted-load current.

Figure 1-4 shows I_L versus R_L for any circuit. When R_L is zero, I_L is maximum and equal to V_S/R_S. When R_L equals R_S, I_L is half the maximum value and equal to $V_S/2R_S$. Further increases in R_L cause I_L to decrease toward zero.

LOAD VOLTAGE

When the load resistance increases to infinity in Fig. 1-3*b*, the load voltage approaches the ideal source voltage. We can prove this as follows. The load voltage

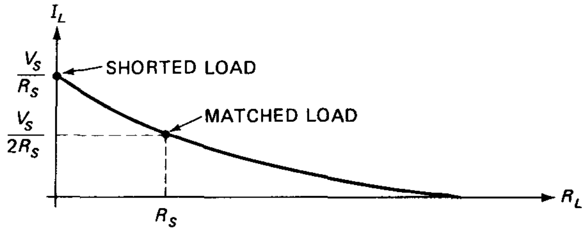


Fig. 1-4
Load current versus load resistance.

equals

$$V_L = I_L R_L$$

Since $I_L = V_S/(R_S + R_L)$, we can write

$$V_L = \frac{V_S}{R_S + R_L} R_L$$

or

$$V_L = \frac{R_L}{R_S + R_L} V_S \qquad (1\text{-}2)$$

Look at the denominator. When R_L approaches infinity, it *swamps out* (overpowers or makes negligible) the internal resistance. For instance, when R_L is 100 times greater than R_S, the load voltage is approximately 99 percent of the source voltage. When R_L equals infinity (open load), the load voltage equals the ideal voltage.

Figure 1-5*a* illustrates the swamping effect of large load resistance. This is a graph of Eq. (1-2) for a source voltage of 12 V and an internal resistance of 0.06 Ω. When the load resistance is zero (shorted), the load voltage is zero. When the load resistance equals the internal resistance (0.06 Ω), V_L equals 6 V because half the source voltage is dropped across R_S.

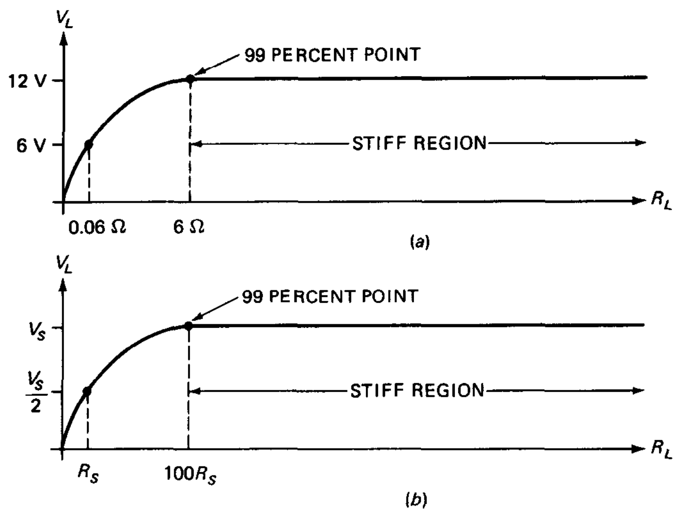


Fig. 1-5
Load voltage versus load resistance.

As the load resistance continues to increase, the load voltage begins to plateau at 12 V. The load voltage asymptotically approaches 12 V, the value of the ideal or open-load voltage. Notice the 99 percent point. At this point, the load resistance is 100 times greater than the internal resistance and the load voltage is approximately 99 percent of the source voltage.

Figure 1-5*b* shows V_L versus R_L for any circuit. When R_L is zero, V_L is zero. When R_L equals R_S, V_L is half of V_S. For larger load resistances, the load voltage approaches the ideal source voltage. When R_L is greater than $100R_S$, V_L is more than 99 percent of V_S.

STIFF VOLTAGE SOURCE

Often, the load resistance is much larger than the internal resistance of a voltage source. This is equivalent to saying that the internal resistance is much smaller than the load resistance. In this book, a *stiff voltage source* is one whose internal resistance is at least 100 times smaller than the load resistance:

$$R_S \leq 0.01 R_L$$

This is equivalent to saying that R_L is at least 100 times greater than R_S. The important thing about a stiff voltage source is this: It produces a load voltage that is between 99 and 100 percent of the ideal source voltage.

With a stiff voltage source the difference between the load voltage and the ideal or open-load voltage is less than 1 percent, small enough to ignore for most troubleshooting, analysis, and design. The word "stiff" reminds us that the source is delivering an almost ideal voltage to the load resistance.

1-3 CURRENT SOURCES

A voltage source has a very small internal resistance. A *current source* is different; it has a very large internal resistance. Furthermore, a current source produces an output current that does not depend on the value of load resistance.

HYPOTHETICAL EXAMPLE

The simplest example of a current source is the combination of a battery and a large source resistance, as shown in Fig. 1-6*a*. In this circuit, the load current is

$$I_L = \frac{V_S}{R_S + R_L}$$

When R_L is zero, the current is

$$I_L = \frac{12\ \text{V}}{10\ \text{M}\Omega} = 1.2\ \mu\text{A}$$

Because R_S is so large, the load current is approximately 1.2 μA for a large range of R_L. For instance, when R_L is 10 kΩ,

$$I_L = \frac{12\ \text{V}}{10.01\ \text{M}\Omega} = 1.1988\ \mu\text{A}$$