DESIGN OF MODERN TRANSISTOR CIRCUITS

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PREFACE

This book is intended to teach students to design actual electronic circuits in a practical, down to earth manner. It is designed as a first text in electronic circuits for both the university and technical school student. Its primary emphasis is on the design aspects of electronic circuits. Therefore, it should be valuable to practicing design engineers as well.

The text begins with a partial review of circuit theory which serves to emphasize the approximation aspects of circuit calculations. This material is not generally covered in most circuit theory texts. However, it is assumed that the student has a working knowledge of ac and dc circuits.

Design of simple circuits are presented as early as possible (Chapter 2) to provide motivation for the new student. Here a simple but accurate discription of biasing and amplifier operation is given. This is followed by a more detailed approach in chapters 3 through 6, using *h* and *r* parameters. Transistors are treated from a terminal behavior point of view with the exception of Chapter 5 where a descriptive treatment of the physics of solid state devices is presented. Chapter 5 begins with only those results from solid state physics which are of immediate interest to the circuit designer. The remainder of the chapter then employs these results to embellish the theory obtained from using the terminal point of view in the three previous chapters. The field effect transistor is introduced in Chapter 7. Chapters 8 through 13 deal with techniques of circuits such as; amplifiers, power supplies, regulators, oscillators, etc. The objective in these chapters is to develop, by means of circuit analysis, formulae which aid the student in designing practical circuits.

This book emphasizes the fundamentals of circuit theory and its application in the design of practical circuits. An attempt has been made to provide many additional comments for the student which would not normally be found in electronics books, in order to motivate the student toward the design aspect of electronics.

I am indebted to many colleagues for their help and, especially, to all the students who have helped with their questions, comments and criticisms throughout my teaching experience. I would like to mention especially my former teacher, Professor A. Simeon, and Professor J.P.C. McMath. The staff of Prentice-Hall has been most cooperative and have contributed greatly to the manuscript. Special thanks are extended to Mrs. Jean Heinamaki who typed most of the manuscript.

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ESSENTIAL POINTS OF CIRCUIT THEORY

To design electronic circuits successfully we must have, in addition to a knowledge of the basic tools of circuit theory, a knowledge of how and when to make reasonable approximations. Besides simplifying the designer's work, appropriate approximations usually lead to a better insight into the actual operation of circuits and provide the designer with an intuitive and often more direct approach to his design. Approximations enable him to adjust the more predominant variables.

In this process of making such approximations, however, the designer must never lose sight of the definitions and results of the very fundamental tools of circuit theory.

Thus our study begins with a review of some simple fundamental idealizations from circuit theory and the use of approximations to simplify the manipulative labor.

1.1 Ideal Sources

An *ideal voltage source* may be defined as a device that delivers a defined voltage across its terminals independently of what is connected to these terminals. The symbol for an ideal voltage source is shown in Fig. 1-1a.

An *ideal current source* is defined as a device that delivers a defined current from its terminals regardless of the nature of the circuit connected to it. The symbol for an ideal current source is shown in Fig. 1-1b.

Let us now observe some of the implications of these ideal devices. The

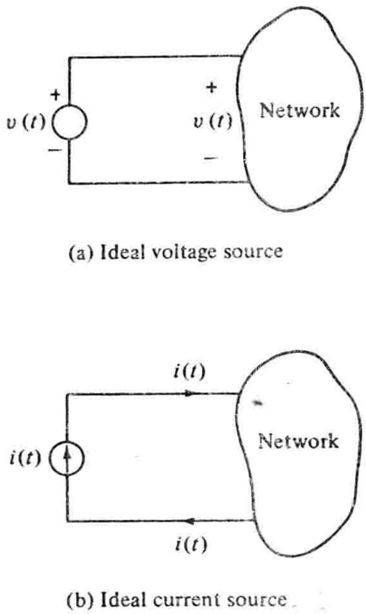


FIGURE 1-1 Symbols showing ideal voltage and current sources.

following ideas may seen quite obvious, but they have very important consequences in the understanding of transistor circuits. First of all, let us connect a single variable resistor to an ideal voltage source, as shown in Fig. 1-2a, and vary it in some fashion from a very small value to a large value. Notice

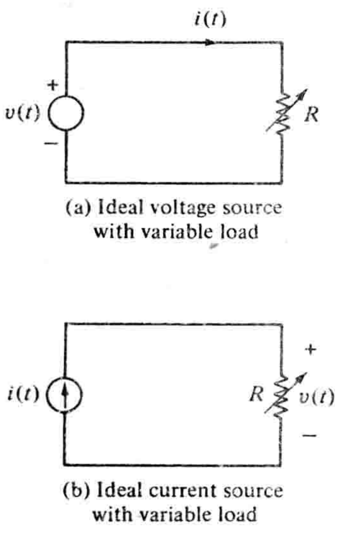


FIGURE 1-2 Action of ideal sources on variable resistor.

that the voltage (from our definition) remains the same and the current, $i(t)$, varies from a very large value to a very small value.

Next, let us connect this same resistor to a current source, as shown in Fig. 1-2b.* Here we see that the voltage becomes larger and larger as we increase the value of this resistor. It is this very property that makes a transistor operate in the fashion that it does, since the output of a transistor is almost like an ideal current source.

A current source is somewhat harder to visualize at first, since ideal voltage sources seem to be more common—such as a 110-volt (V) supply we use for electrical distribution. However, even this is not an ideal voltage source, since, if the load added to it is made large enough, the terminal voltage will drop. Thus, to bring us out of the idealized world, we should next consider some practical sources. Before doing so, however, let us first consider two very important theorems, which follow.

1.2 Network Theorems

Thévenin's theorem states the following: Any linear active network may be represented by an equivalent network consisting of a voltage source equal to the open-circuit voltage of the network in series with the original network, with all independent sources set to zero.

To set sources equal to zero we merely short-circuit all the *voltage* sources and open-circuit all the *current* sources. This process has an intuitive appeal, since a short circuit (a wire) has no voltage across it and hence a voltage source of zero volts. Similarly, an open circuit (a break) has a zero current flowing through it and may be thought of as current source of zero amperes. A pictorial representation of Thévenin's theorem is shown in Fig. 1-3. Here we obtain the Thévenin equivalent of network A, which is connected to network B by two leads. Notice that the active network A can be part of a larger network, as shown in Fig. 1-3a, and that v_θ, the open-circuit voltage, must be placed in the same direction as the one in which the measurement was done as shown in Fig. 1-3c.

To illustrate the use of this theorem let us consider a few examples, which will also incorporate reasonable approximations. In electronics it is reasonable to approximate within 5 per cent or sometimes as much as 10 per cent, since most components, as specified by manufacturers, have these types of tolerances. For example, the most common resistors are specified within 10 per cent of their given values.

*The sign convention adopted is a + sign for voltage at the tail of the current arrow for passive elements.

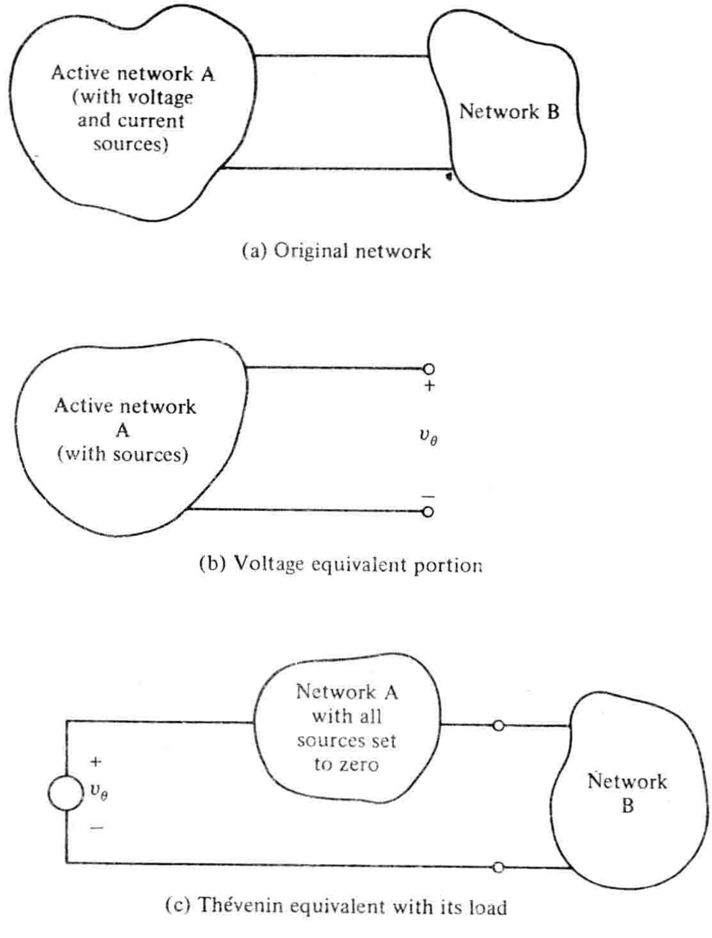


FIGURE 1-3 Decomposition of a network to its Thévenin equivalent.

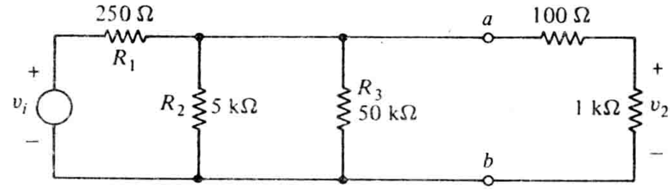
Example 1-1: For the circuit shown in Fig. 1-4a, (a) find the Thévenin equivalent to the left of terminals $a - b$, and (b) proceed to find v_2.

Solution:

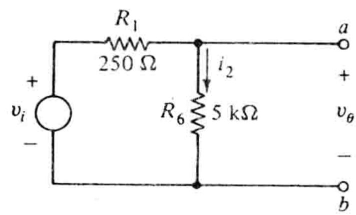
(a) The first step is to combine R_2 and R_3 to a single resistor and call it R_6. Then

$$R_6 = \frac{R_2 R_3}{R_2 + R_3} = \frac{5 \times 50}{5 + 50}\ \text{k}\Omega \cong 5\ \text{k}\Omega$$

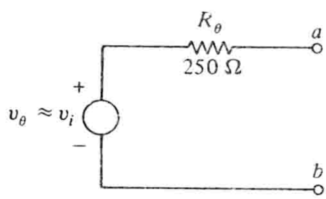
Notice that $R_6 = 5\ \text{k}\Omega$, since the effect of the 50-kΩ resistor in parallel with the 5-kΩ resistor is negligible.



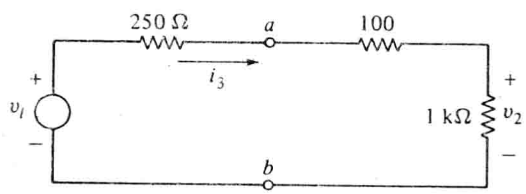
(a) Original circuit



(b) Equivalent Thévenin voltage



(c) Thévenin equivalent



(d) Thévenin equivalent with load

FIGURE 1-4 Solution of Ex. 1-1 using Thévenin's theorem and a series of reasonable approximations.

To find v_θ we open-circuit terminals $a - b$, as shown in Fig. 1-4b. Now

$$i_2 = \frac{v_i}{5\ \text{k}\Omega + 250\ \Omega} \cong \frac{v_i}{5\ \text{k}\Omega}$$

and

$$v_\theta = i_2\, 5\ \text{k}\Omega \cong v_i$$

In other words, the open-circuit voltage $v_\theta = v_i$, since the voltage drop across R_1 is negligible. These are reasonable approximations to make in electronics. Notice that a similar approximation is made to obtain R_θ in Fig. 1-4c. Placing R_θ in series with v_θ leads us finally to the Thévenin equivalent.

(b) To obtain v_2, we find i_3 and proceed:

$$i_3 = \frac{v_i}{1350\ \Omega}$$

$$v_2 \simeq \frac{1}{1.35\ \text{k}\Omega} v_i(1\ \text{k}\Omega) = \frac{1}{1.35} v_i$$

It is apparent that this theorem is a labor-saving device.

If we call the network in the Thévenin circuit with all sources set to zero Z_θ, then we can find Z_θ very easily by the method

$$Z_\theta = \frac{v_\theta}{i_{sc}} = \frac{\text{open-circuit voltage}}{\text{short-circuit current}} \tag{1-1}$$

This procedure may be justified by considering Fig. 1-5. Every network can be represented as shown here according to Thévenin's theorem, and it is obvious that Z_θ is given by the above expression.

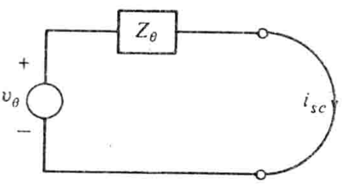


FIGURE 1-5 Method for determining the Norton equivalent from a Thévenin equivalent circuit.

Norton's theorem states that every linear network can be represented by a current source equal to the short-circuit current in parallel with the same network, with all the independent sources set to zero.

It is left as an exercise for the student to show that this is true (it follows from Thévenin's theorem) and to work out a suitable example to show the use of such a theorem. The Norton equivalent for the network in Fig. 1-5 is shown in Fig. 1-6. Hence we can find the Norton equivalent easily by first finding the Thévenin equivalent, although this may not always be the most convenient way.

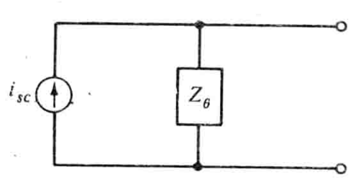


FIGURE 1-6 A Norton equivalent circuit.

1.3 Voltage and Current Division in Resistive Networks

Although the following equations do not warrant the name theorem, the author often refers to them in this manner. These "theorems" are actually labor-saving devices for quick calculations.

Consider the situation in Fig. 1-7, where a series connection of resistors is made. Then it follows that

$$i = \frac{v_i}{R_1 + R_2 + \ldots + R_n} \tag{1-2}$$

and

$$v_j = iR_j = \frac{R_j}{R_1 + R_2 + \ldots + R_n} v_i \tag{1-3}$$

Stating the results in words, we can say that the voltage drop across a resistor *R* in series with other resistors is equal to *R* divided by the total resistance in the circuit multiplied by the applied voltage.

Similarly, for a parallel setup, as shown in Fig. 1-8, it follows that i_j, the current in the *j*-branch, is given by

$$i_j = \frac{G_j}{G_1 + G_2 + \ldots + G_n} i \tag{1-4}$$

Where the *G*s are the conductances in the circuit in mhos.

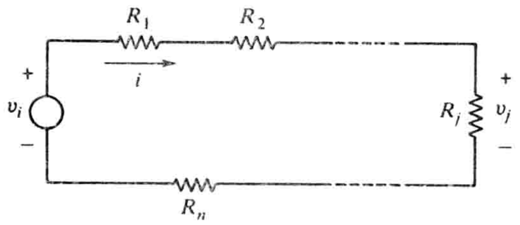


FIGURE 1-7 Network illustrating voltage division.

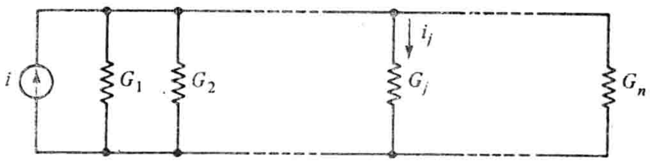


FIGURE 1-8 Network illustrating current division.

1.4 Practical Sources

Since few if any actual ideal voltage or current sources arise in practice, it is useful to define a *practical voltage* and a *practical current source*.