PRACTICAL TECHNIQUES OF ELECTRONIC CIRCUIT DESIGN

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1807 175 YEARS OF PUBLISHING 1982

A WILEY-INTERSCIENCE PUBLICATION

JOHN WILEY & SONS
New York • Chichester • Brisbane • Toronto • Singapore

Library of Congress Cataloging in Publication Data:

Bonebreak, Robert L., 1921–
Practical techniques of electronic circuit design.

"A Wiley-Interscience publication."
Includes index.
1. Electronic circuit design. I. Title.

TK7867.B63 621.3815'3 81-11394
ISBN 0-471-09612-1 AACR2

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Preface

This book is written to serve those who are faced with practical electronic circuit design problems in their work.

Some familiarity and experience with electronic circuits is assumed, so that the book is not a beginner's text. It is, however, directed toward the straightforward design of electronic circuits, by those who lack a strong background in electronic circuit design. This book is more concerned with facts and correct procedures than with proofs or derivations.

The electronic design techniques presented are based on the most effective use of present day components. This is a constantly shifting pattern because integrated circuits continue to replace discrete transistor circuits. For example, the design of the flip-flop, which has been a classic schoolroom project for years, has now been made virtually obsolete by the available monolithic circuits.

There are, however, many areas in which discrete design is and will continue to be needed.

Chapter 8 on laboratory procedures should be read first and then reread from time to time to make certain that good working techniques are followed. Chapter 1 on the basic transistor is written in engineering terms as contrasted to the usual physics approach and should be read before Chapter 2. Aside from this the chapters are largely independent and can be referred to as required.

Where practical, tables or nomographs are provided to speed the design process. This is particularly true of both passive and active filters, where the previous use of computers has greatly reduced the design effort for the majority of requirements.

The subjects were selected for their widespread application and also because they contain information that is commonly misunderstood by designers with limited experience. Definitions and symbols are carefully indexed to allow the reader to study the chapters in preferred order.

The design procedure and techniques of electronic circuits vary substantially with the application. For example, consider the following classifications:

1 High-reliability and wide-temperature equipment such as military, space, and some industrial applications.

2 Very-low-cost high-production consumer-oriented products.

3 One-of-a-kind designs for obtaining data, testing other types of equipment, prototype design concepts, and providing assistance in areas not covered by available commercial products.

Although the information in this book is useful in all areas, it is specifically directed toward the last category. Here it tends to be important to keep the design costs to a minimum by substituting some "after the fabrication" adjustment in place of a more rigorous initial design. This is especially evident when it is realized that most important parameters have a tolerance range of 2 or 3, and often as high as 10 to 1. Indeed, many parameters that are important in a particular design may not be specified at all. Accordingly, explanation of the procedures are presented largely on an intuitive basis, with some occasional simple algebra.

Devices are generally described as ideal components so that the fundamental concepts can be emphasized. This is then followed by a detailed list and description of the deviations from the ideal case and of the circumstances under which they are important. In all cases parameters from present-day devices are used to illustrate when variations from the ideal case must be considered. To aid in this effort some data sheets are included in the text. However, for proper design it is necessary to obtain a good selection of current data sheets and publications directly from the manufacturer.

Finally, completed designs (many with test data) are shown with step-by-step explanations of how and why the parts used were selected.

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October 1981

Contents

1

Transistors

This chapter is different than the rest of the book in that it provides specific background material for the succeeding chapter. The emphasis is on describing, rather than proving, the transistor properties so that useful design equations can be developed.

1-1 FUNDAMENTALS

The ideal transistor is a simple device. It is shown in Fig. 1-1 connected as collector-loaded amplifier or, as it is generally called, a common emitter circuit.

Transistor action, which results in its ability to amplify, occurs because a small change in base current results in a larger change in collector current. This is represented as

$$\beta = \frac{\Delta i_c}{\Delta i_b} \tag{1-1}$$

The base current flows into the emitter so that

$$i_e = i_b(1 + \beta) \tag{1-2}$$

The ideal transistor has these properties:

The current transfer ratio, $\beta = \infty$.
The transistor output resistance, $r_o = \infty$.
The transistor base resistance, $r_b = 0$.
The transistor emitter resistance, $r_e = 0$.
The transistor reverse gain, $h_{re} = 0$.
The transistor collector-to-base leakage current, $I_{CBO} = 0$.
The transistor base-to-emitter voltage drop, $e_{be} = 0$.
The transistor collector-to-base capacitance, $C_{cb} = 0$.
The transistor emitter-to-base capacitance, $C_{eb} = 0$.
The transistor current gain-bandwidth product, $f_t = \infty$.

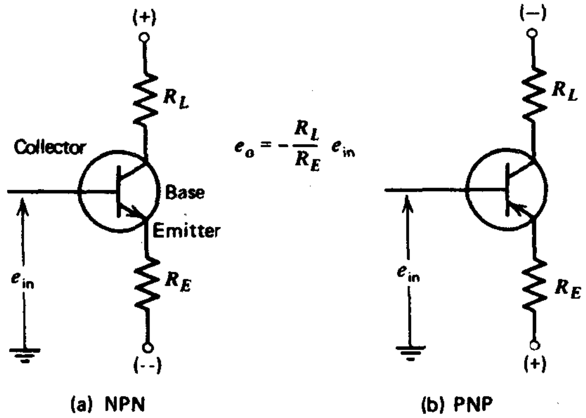

Figure 1-1 The ideal transistor. (*a*) *NPN*. (*b*) *PNP*.

1-1-1 Common Emitter Connection

To evaluate the ideal transistor, let us further consider the common emitter connection that is shown in Fig. 1-1.

Because $\beta = \infty$, the signal current induced in the collector flows in the emitter. Also, since r_b and r_e are zero, any signal change applied from base to ground occurs across R_E. Accordingly, the signal at the collector must be R_L/R_E as great as the input signal. From this

$$\text{gain} = -\frac{R_L}{R_E} \tag{1-3}$$

This is a strange equation because it states that the voltage gain of the ideal transistor is independent of the transistor. R_L/R_E is the theoretical limit of the voltage gain of a transistor without positive feedback. Positive feedback, generally undesirable, promotes instability or oscillation and is caused by poor layout and decoupling techniques. In practice R_L and R_E are limited by design considerations and the gain equation will be modified by considering real transistor parameters, as illustrated in Fig. 1-2*a*.

At this time it would be well to point out that for a transistor to function properly it must have a defined DC current flowing in the collector and emitter which is developed because of a properly applied voltage and a DC base current input. These DC currents are designated as I_C, I_E, and I_B respectively and are discussed in the section on transistor biasing. The development of the signal relations is based on the superposition of the signal currents, respectively i_c, i_e, and i_b, on the defined bias condition.

As previously stated, when an input current is directed to the base it flows through the base-emitter junction to the emitter. This allows a larger current, β_{ib}, to flow from the collector to the emitter. Accord-

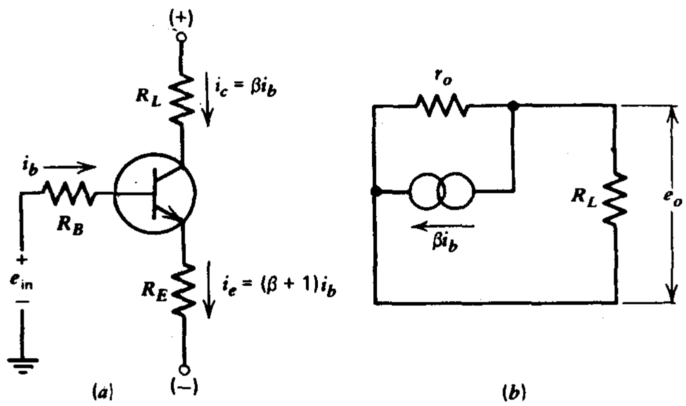

Figure 1-2 Common emitter amplifier.

ingly, the emitter current is equal to $(\beta + 1) i_b$. From this it is apparent that R_E is $(\beta + 1)$ times as effective as R_B in limiting the base current. From this we have

$$\text{base input resistance} = R_B + R_E(\beta + 1) \tag{1-4}$$

Likewise, when a current is inserted in the emitter $1/(1 + \beta)$ of it flows out the base. Thus a value of R_B in the base is equivalent to a value of $R_B/(\beta + 1)$ in the emitter, as far as controlling the gain and impedance of the transistor is concerned. This is not the case in controlling other conditions such as bias stability and frequency response, which are discussed in later sections. It remains true, however, that

$$\text{emitter input resistance} = R_E + R_B/(\beta + 1) \tag{1-5}$$

Now in addition to the exterior resistors R_E and R_B the transistor has resistance expressed as r_e and r_b. r_e must be added to R_E and r_b must be added to R_B. As a very reasonable approximation we use β in place of $(\beta + 1)$ so that our gain equation now becomes

$$A_v = \frac{e_o}{e_{\text{in}}} = \frac{-R_L}{[(R_E + r_e) + (R_B + r_b)/\beta]} \tag{1-6}$$

When the collector resistance, r_o, departs from the ideal and becomes finite, the gain will be lowered. Referring to Fig. 1-2*b*, it is seen that the output of the transistor is represented by a current generator in parallel with the transistor output resistance r_o. If the load resistor R_L is connected as shown, it is seen that R_L and r_o are in parallel.

From this several different expressions can be derived. First,

$$e_o = \beta i_b (R_L r_o/(R_L + r_o)) = \beta i_b R_L/(1 + R_L/r_o) \tag{1-7}$$

or when $r_o = \infty$,

$$e_o = \beta i_b R_L \tag{1-8}$$

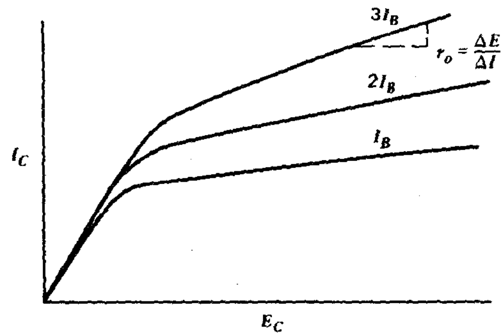

Figure 1-3 Transistor *E-I* curves.

A more general expression for the voltage gain is obtained from (1-6) by substituting r_o and R_L in parallel for R_L:

$$A_v = \frac{e_o}{e_{in}} = \frac{-R_L}{\left[(R_E + r_e) + \frac{(R_B + r_b)}{\beta}\right]\left(1 + \frac{R_L}{r_o}\right)} \tag{1-9}$$

Another way of looking at what a finite r_o does in an amplifier circuit is shown by Fig. 1-3. $1/r_o$ is the slope of the *E-I* curve. If a signal is put on the base in such a way as to make I_C increase, the drop across the load resistor causes the collector voltage to decrease. This in turn reduces the original current increase, which is a loss of gain.

Again, as in the case with r_e and r_b, the output resistance is seldom a known value. r_o, however, unlike r_e and r_b, is not a physical value of the transistor; it is instead a function of the transistor collector resistance, r_c, and the external resistors R_E and R_B. This is demonstrated as follows. Figure 1-4*a* shows an ideal grounded base configuration (See Section 1-1-2). If a signal is applied to the collector, a current flows through the collector to the base and to ground. The output resistance r_o is e/i. In the case of the ideal grounded emitter, the current created by the applied voltage, e, flows through the base across the base emitter junction. Because of the transistor action this causes the current to be multiplied, resulting in an output resistance for the ideal grounded emitter case that is $1/\beta$ times that of the ideal grounded base configura-

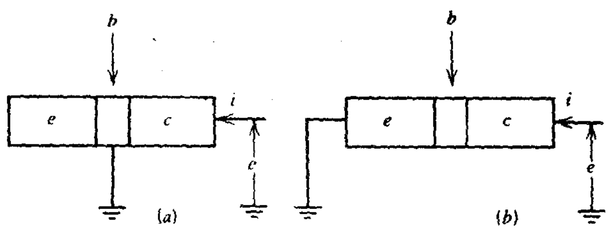

Figure 1-4 Transistor output resistance. (*a*) Grounded base. (*b*) Grounded emitter.

$$r_o = \frac{r_c}{\beta} + \frac{r_c}{1 + R_B/R_E}$$

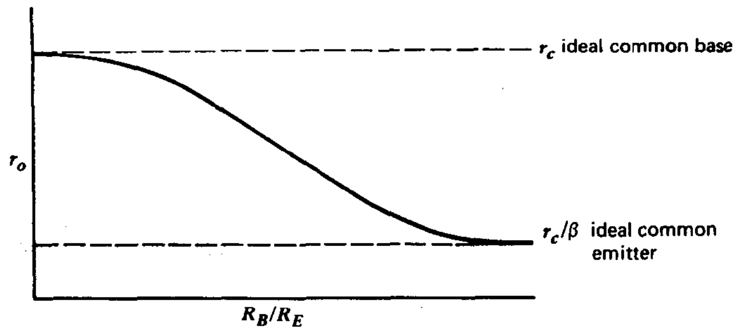

Figure 1-5 r_o versus R_B/R_E.

tion, a very considerable reduction. In a real circuit there are always finite resistance values associated with both the emitter and the base, so that neither is a pure ground.

Figure 1-5 is a plot of the equation for the common emitter output resistance and clearly shows the relationship to the base and emitter resistances. Fortunately, r_o is not generally a major factor in determining the gain of a transistor amplifier circuit. This is especially true in broadband amplifiers where R_L must be kept low to ensure the necessary high-frequency response.

There remains one more consideration in the low-frequency common emitter amplifier. This comes about from the fact that the output voltage has a feedback effect on the input base current. This is represented in the h parameters by h_{re}. However, h_{re} is also a function of R_E and R_B, and since the published values of h_{re} are generally for the intrinsic transistor, the information is not very useful. Happily, this effect is generally quite small and can usually be neglected.

1-1-2 Common Base Connection

In addition to the common emitter there remain two other ways in which the transistor can be connected. The common base is discussed first and is shown in Fig. 1-6, where

$$\begin{aligned} I_o &= \alpha I_{\text{in}} \quad \text{by definition} \\ &= I_{\text{in}} - I_B \\ &= I_{\text{in}} - \frac{I_{\text{in}}}{(1+\beta)} \qquad (1\text{-}10) \\ &= I_{\text{in}}\left(\frac{\beta}{1+\beta}\right) \end{aligned}$$

$$\therefore \alpha = \frac{\beta}{1+\beta}$$