CIRCUITS
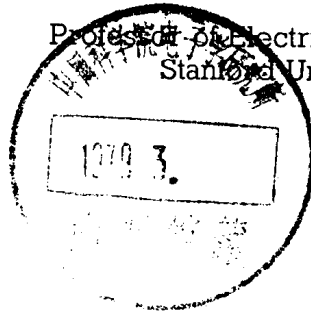
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1979 3.

McGraw-Hill Book Company

New York   St. Louis   San Francisco   Auckland   Bogotá
Düsseldorf   Johannesburg   London   Madrid   Mexico
Montreal   New Delhi   Panama   Paris   São Paulo
Singapore   Sydney   Tokyo   Toronto

McGRAW-HILL SERIES ON THE
FUNDAMENTALS OF ELECTRONIC SCIENCE

Consulting Editor
James F. Gibbons, Stanford University

CIRCUITS

PREFACE

Books on electric circuits and circuit analysis are legion. Another such textbook must therefore begin with an apologia. That this book has novelties, that it uses simple, relevant, very informative, easily reproduced physical demonstrations of the soundness of circuit models as accurate representations of reality; that it makes good use of the digital computer; that it is based on the perspective that comes only from experience (of both teacher and student)—these make up an apologia of sorts. But only in the text itself can the justification for such a book be found. (Chapter 1 sketches out its rationale, describes what the book tries to do, its method of attack, and the demands it places on the reader.) In particular, the approach to generality is *gradual*: from simple, easily understood (special, perhaps, but useful and informative) cases, cases that require only a *minimum* of background, through more elaborate examples eventually to fulldress discussions, but only when the student is ready. Students who work their way through it will have built a sound foundation in a basic practical discipline of electrical engineering.

The whole derives from the teaching opportunities offered me at Stanford University over many years, including the wholesome benefits of sabbatical years spent at other institutions with different viewpoints. Innumerable discussions with colleagues and students have contributed; in particular, certain ideas stem from Professor L. A. Manning. Especially does the book depend on my students (see Sec. 1.01).

Finally to those who helped perhaps not so much in technical matters but infinitely much with patience and encouragement and support, the other members of my family, Becky, Jacqueline, and Robert, are due thanks immeasurable.

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David F. Tuttle, Jr.

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Chapter 1

INTRODUCTION

B egin at the beginning
  and go on till you come to the end:
Then stop.

                              —The King of Hearts

At the start of a voyage one needs some sort of chart, the proposed course being plotted thereon. This first chapter plots *what* it is we are to study in this book, *why* it is interesting and important to engineers and engineering students, and *how* we are going to study it. Moreover, it will reveal some of the most important results to be obtained later. These will of course be unsubstantiated, without proof, mere "say so" (though often with some physical or intuitive justification). The intent is to help readers by giving them a clear idea of what lies ahead, hopefully without robbing them of the joy of discovery, study, and even of making proofs. And browsers will surely know, in a few pages, whether or not this book is what they want to invest many of their hours in.

1.01 BACKGROUND

There can be no better advice than "begin at the beginning." But the real beginning was long ago, when we first learned to put numbers together, and even before that, when we first touched something and felt a response. Now as we start this study of electric circuits we have already come a long way from the beginning, and already have an impressive background.

As to numbers (mathematics) we suppose a reasonable knowledge of the calculus; as to experimentation we suppose a reasonable background in general physics and particularly in electricity, and that not purely empirical but developed with the aid of the calculus. We start, that is, with a year or two of college work behind us—and that is long after the beginning. But it is a convenient place to start, and a suitable one for most engineering students, and so a good one for this book. Ability to program and use a digital computer and access to one

is important: the computer need not be large, nor does the language matter. But beginning in Chap. 4 its use is important. Finally, contemporary (or previous) study of electronics is important for understanding many of the hypotheses taken as starting points and whence come some of the models used.

The book has evolved from teaching a "circuits" course over a number of years, for students at Stanford University. They have generally been third-year electrical engineering students; but there have been students, undergraduate and graduate, from other disciplines, whose dissimilar reactions and questions have been very valuable. The debt I owe these students is incalculable and unstatable, for they are responsible for many of the questions asked and answered in the book, the manner and detail thereof. It is they who have really written most of it.

To read this book with profit, one must of course have some interest in the subject. And one must be willing to work: the problems, of various sorts, are numerous (see Sec. 1.12), and a reasonable number thereof *must* be "done"; the "demonstrations" have to be seen and felt, and that requires some work too, which can profitably be shared by professor and student. An engineering "bent" is at least desirable. The book really deals with applied mathematics but the emphasis is on the adjective there, and a certain liking for the physical approach will be very helpful. In any event the book aims to develop a physical feel for "what goes," the perspective of a good engineer.

1.02 METHOD

Electric circuits are fundamental to electrical engineering—that we here postulate. We leave demonstration of this fact to experience, to come in later years, and other studies; we cannot do it here. Exactly what "electric circuits" are we shall define in due course. Definitions of terms, after all, are often profitably postponed until one knows what one is talking about; as long as one has a rough idea of the meaning to work with, one may better wait until more ideas and vocabulary come. The impatient reader need only consult the index to locate any precise definition.

Electric circuits are therefore deserving of careful study. Such a study must cover a number of ideas that are sufficiently different one from another that the study can easily become very disjointed. But they are closely related, too, so the study ought to be a smooth, continuous, and fascinating story, and we shall try to make it so.

Circuit theory depends heavily on mathematics. It has sufficiently precise premises (the models with which it deals) to permit lengthy and complicated mathematical developments. And such developments are often of great engineering value. But they also have a Lorelei character of which we must beware. It is engineering that we are to study here, and we must resist temptations (they will come) to develop theory for elegance's sake alone when it has no immediate engineering application. That it may some day have some important application

is of course possible; only a fool will say categorically that some particular abstract mathematical derivation can never have engineering relevance. But our concern here is not with tomorrow's research developments; it is with today's circuit theory and its applications. We shall therefore concentrate on those aspects of circuit analysis that have demonstrated their permanent utility and are in wide use. Certain more advanced viewpoints and techniques we shall briefly mention, for the sake of perspective, but then leave (usually with regret) for detailed study elsewhere (a phrase we'll often use). Their detailed development here would be confusing indeed and completely obscure the forest with their trees.

Because its history is a long one, and because it builds on models (of physical systems) that are mathematically tractable, circuit theory is today a very imposing edifice. It is logically strong, and we need not fear climbing to the upper levels. But we must not forget that our principal concern is with *engineering*. Because the foundations are *models*, and not actual engineering devices or systems, there may be discrepancies between a prediction made by circuit theory from the twenty-third floor, and actual performance of the engineering artifact on the ground. Such discrepancies are extremely important to the engineer. It will not do to ignore them or to postpone or delegate consideration of them. Nor is it difficult to monitor the distance between our circuit-theoretical devices, as we make them, and "reality," the actual performance of corresponding physical, engineering circuits. Simple concrete realizations for most of our work are not hard to build. The cathode-ray oscilloscope will display their performance simply and lucidly. Moreover, the displays can be photographed and some are presented here, so that even in the pages of this book one can continually evaluate the discrepancies. This we shall do, and so estimate the physical validity of our results.

Looking at the still photographs of cathode-ray-tube faces in this book is of course no substitute for three-dimensional viewing of actual apparatus. Especially does it *not* replace watching the screen as controls on the apparatus are moved to vary parameter values. Readers of this book, especially instructors of classes, should make every effort to assemble the demonstrations and see for themselves. It is even better to arrange things so that each member of the class can handle the apparatus, "twiddle the knobs," and really see for himself. Most of the "hardware" is simple and readily available. The instruments necessary are conventional, with few exceptions. And the descriptions given will minimize the time needed to set up and adjust the demonstrations. The important thing is to *do* them! And in doing them, modifications for improvements, variations to give better insight, and additional demonstrations will tumble head over heels to suggest themselves. To *see* along with the mathematical development the physical development of a waveshape as a circuit actually operates on a signal is an experience of tremendous educational value. The value comes from the *feeling* of the effect; "tremendous," trite though it be, is accurate. The photographs here do what they can; keeping your feet on the ground by using actual instruments and seeing for yourself is up to you.

We shall devise models of engineering systems, models simple enough to analyze. After each mathematical analysis we shall observe the actual behavior of simple realizations of the models. We can then decide on the value of the analysis. If it seems valid, we add it to our repertoire, and may use it in *synthesis*, in the design of engineering systems. When we come to the end of this book we shall have a reasonably large repertoire. This is not the real end, of course; but we shall then have added to the background with which we started a solid foundation in electrical circuits on which to build the next stages of our educational and engineering work.

Had the book 10 times its pages, it could not be complete; it could not discuss "circuits" in all detail, for too much is known about them. So we shall compromise, distill, select; the best of yesterday's work, organized and compressed, constitutes most of the book. But there is an attempt to show where circuits seem to be going tomorrow. It is incumbent on us to prepare ourselves for reading other books, to fill lacunae here that may some day become very interesting, and to scan and to study the flood of journals of today and tomorrow. In short, one objective of the book is to teach you "how to read."

We shall try to maintain standards of literary quality. The jargon of technology proliferates without restraint; much of it is nonsense, inaccurate, of little value. But some technical slang is colorful, descriptive, precise, and concise, and a valuable addition to our language. This we accept and use.

1.03 SUBJECT

We have some idea already of what electric circuits are. But some clarification is necessary here.

Communication (the transmission of information) and control (of energy) constitute most of what electrical engineering is about. And from a few moderately complicated systems, of either type, we could easily obtain examples enough to develop all the circuit theory we may need. These could be the backbone of our story, the skeleton of this book. To provide this, and to keep us close to engineering reality, we begin by looking at three such systems.

The first is a long-distance telephone connection, say between California and France, some 10,000 km apart. To connect a telephone in San Francisco with one in Marseille is today a routine matter; it takes only seconds to establish the connection (by machine switching almost entirely), and the quality thereof is excellent. But the complexity of the system involved is great enough to defy description here. Any analysis thereof is beyond us—and in fact probably never was nor ever will be made. The design and construction work had to be limited to subsystems, so made that when connected together (in unpredictable ways, according to demand), they would operate well as a large system. The elementary diagrams of Fig. 1.03-A suggest this structure. The blocks represent local apparatus; the connecting lines represent the transmission media between them.
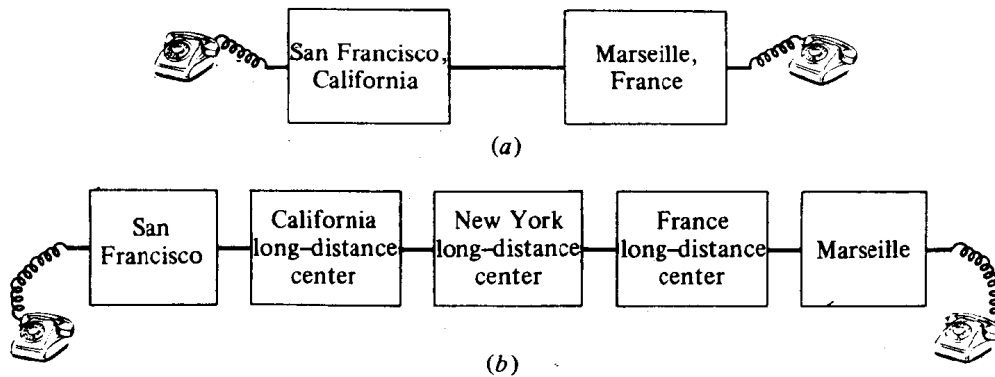
FIG. 1.03-A

We need not be expert communication engineers to know that switching centers of some sort must be provided, as in Fig. 1.03-A*b*, and that the transmission systems that connect them may be quite different one from another. From the telephone subscriber's instrument to the local central office the connection is probably a pair of insulated wires tightly packed with many others into a cable. From the local central office to the nearest long-distance switching center the connection is probably made by a "short-haul" multiplex system that uses wires in another type of cable and handles a large number of different conversations simultaneously. The transcontinental link will be a more complicated multiplex system that uses coaxial cable or microwave radio links. The transatlantic link may be either a submarine cable system or a radio system that uses an earth satellite as a relay station. Similar systems will complete the connection in France.

We need not remark further on the complexity of the complete system. But we can make a partial list of the principal kinds of subsystems that must make it up. There must be *amplifiers*, to compensate for the attenuation that signals experience as they travel over the transmission systems. There must be *modulators* and *demodulators*, samplers, coders and decoders, and devices for combining many signal channels at one end of a transmission system and separating them at the other. (The high cost of long-distance systems demands that they be efficiently and economically used, by serving many customers simultaneously.) Both cable and radio multiplex systems require transmitters and receivers at their terminals. Other subsystems provide the all-important power (energy) for transmission, to switch calls properly, and record enough information about calls made that toll charges can be calculated and collected. Sufficiently broken down into small blocks, every one of these subsystems can give us circuits (and devices) to study in wide variety.

For a second example, we consider the problem of precisely controlling the position of a massive load (a ship's rudder for example). Moving the load requires much power, but the command signal is weak. Not only must amplification be provided but some insurance that the load will actually obey the com-

(a)

"Ought to be" signal   Difference, or error signal
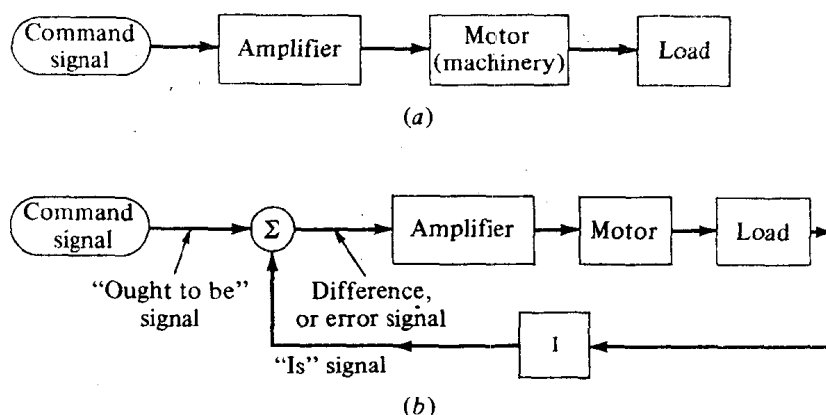
"Is" signal

(b)

FIG. 1.03-B

mands.   Directing a machine tool to cut and shape a steel block according to a previous pattern, steering a large ship, pointing a 60-ton antenna toward the satellite of the transatlantic radio link above (or making it follow a rapidly moving radar target to control air traffic, or a slowly moving stellar object if a telescope) —those illustrate such problems.   Figure 1.03-Ba shows elements of such a control system.   The arrows indicate an important difference from the telephone connection: the signal transmission here is in one direction only.   The command signal comes from a recorded pattern, from a prescribed course, from carefully selected spatial coordinates and observations, or from a hand-varied control—or perhaps it comes over a telephone line from elsewhere.   It is amplified and applied to machinery that is appropriate for moving the load in translation or in rotation about various axes.

Accurate motion is not likely to result.   The position of the (heavy) load is probably not going to be close enough to that commanded; error will exist.   But long ago someone brilliantly conceived that if this *error* could be measured, *it* could be used to make the motion accurate.   This is *feedback* control: to compare what *is* with what *ought to be*, and to use the difference for the actual command. We supply measuring apparatus (*I* in Fig. 1.03-B*b*) to convert the actual load position into an "is" signal that is consonant with the command signal.   It is now the comparing device Σ that produces, in the error, the command that actually drives the machinery.   If the system is properly designed and adjusted, the machinery will presumably operate to move the load until the error is reduced to negligible size.   For as long as there is error, there will be torque (or force) to act on the load to reduce the error.

Feedback, be it carefully noted, raises new problems.   For the closed loop is much like an Ozark hoopsnake once its tail is in its mouth: it can roll down a hill in a fashion quite different from its normal motion.   Improperly designed or adjusted, a closed-loop system can circulate and amplify some random noise or disturbance into large, annoying, and even dangerous (usually oscillatory) motion of the load.   So the design of the various blocks in the system is not
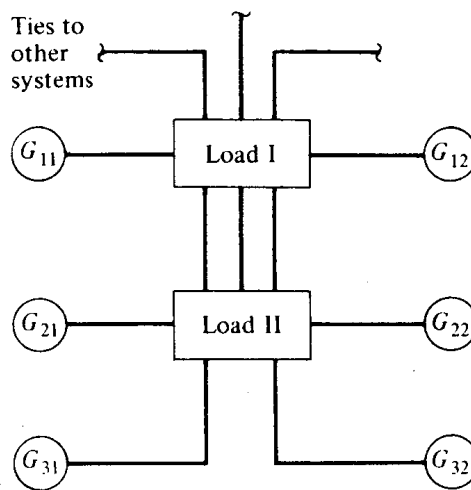
FIG. 1.03-C

necessarily easy; it poses problems relevant to circuit theory, fascinating problems that we shall eventually touch on (Sec. 6.25). Sometimes, incidentally, one may design a closed-loop system deliberately to oscillate or vibrate "on its own," without any command signal. Then the system is a *generator* of motion, or of electrical signals (an oscillator) if the machinery and load are replaced by appropriate apparatus.

Both examples assume the existence of adequate supplies of power, probably electrical, and are usually taken for granted. In a third example we shall sketch a system for providing such power. It starts with the burning of coal or fuel oil or gas, or in a nuclear reaction, or from the potential energy of falling water. The energy is used to drive turbines to turn electrical generators. It remains to transmit the electrical power to the user and to convert it to a form (voltage) appropriate for use: 6 kV alternating at 25 Hz, 115 V alternating at 60 Hz, or 24 V direct (constant). Figure 1.03-C shows the rudiments of part of a large power system, but gives no idea of its true complexity. Each generating plant G has energy sources, prime movers, and electrical generators. But these require auxiliary apparatus in profusion: fuel-oil pumps, lubricating-oil pumps, compressors for air to operate switches and protective devices, auxiliary power sources, measuring apparatus, relaying apparatus, communications apparatus, etc. Transmission lines connect distant generating plants to loads, to sections of cities for example, with customers whose demands range from a few lamps and home appliances to the elevator motors and air-conditioning apparatus in large buildings, to the machinery of industry, and to the many large motors of electrical railways. Other transmission lines connect (tie) geographically distant systems together so that power may be generated and distributed efficiently and reliably. The problems of designing and operating such a system: determining what distribution of power production between generators is most efficient, switching generators in and out to obtain such efficient operation, handling changing

demands, guarding against instabilities, and the service interruptions they may cause (for it is a feedback system, and a very complicated one); these problems are tremendous.

But that is enough of examples. These three alone have in them, in the details of their blocks once opened up and subdivided into other blocks small enough for us to comprehend, electric circuits galore. They also give one at least a general idea of the rôle engineering plays in society, of the importance of systems built on circuits in the day-to-day "operation" of the world.

Circuit theory concerns itself not only with the purely electrical parts of such systems, but with the electromechanical and mechanical and other parts also; by analogy, the models by which they are described often have precisely the same mathematical forms. So simply to choose where to start is itself a bewildering problem.

1.04 A START

We have to go down to some simple block, simple enough for us to begin with. But it should not be so simple that it has no engineering significance. Somewhat arbitrarily we shall choose an *amplifier* box. Amplifiers are obviously prolific and important in the first two examples above, and are surely used in the communication and control apparatus necessary in the third. Ubiquitous, they must be important; some at least must be simple. An amplifier block (Fig. 1.04-A) receives signals and power; its output signals are stronger, amplified, and more useful. It need not be entirely electrical; hydraulic, pneumatic, and rotating electric machine amplifiers are useful in control systems. But we are interested here in amplifiers that are based on electronic devices. These are, broadly speaking, half electronic devices dependent on phenomena that occur in semiconductors (or in a vacuum) and half *circuits*. The circuits are ideal for us to study. They are necessary for utilizing the devices, they are vital to system operation, and they are prolific in engineering. Some simple and some complicated, they are exactly what we seek. Later we may look into other blocks. But the amplifier, in its circuit parts, is a good place to start.
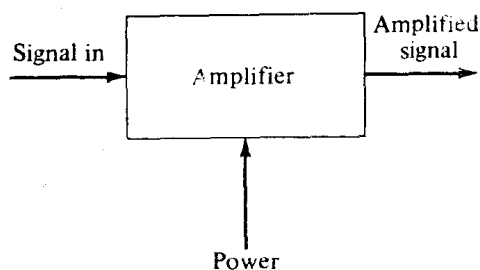

FIG. 1.04-A