LINEAR AND NONLINEAR CIRCUITS

Leon O. Chua
Charles A. Desoer
Ernest S. Kuh

LINEAR AND NONLINEAR CIRCUITS

Leon O. Chua

Charles A. Desoer

Ernest S. Kuh

University of California—Berkeley

McGraw-Hill Book Company

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

This book was set in Times Roman
by Intercontinental Photocomposition Limited.
The editors were Sanjeev Rao and Alar E. Elken;
the cover was designed by Scott Chelius;
the production supervisor was Diane Renda.
Project supervision was done by The Total Book.
R. R. Donnelley & Sons Company was printer and binder.

LINEAR AND NONLINEAR CIRCUITS

1234567890DOCDOC89210987

ISBN 0-07-010898-6

Library of Congress Cataloging-in-Publication Data

Chua, Leon O. (date)
Linear and nonlinear circuits.

(McGraw-Hill series in electrical engineering. Circuits and systems)
Includes bibliographical references and index.
1. Electric circuits, Linear. 2. Electric circuits, Nonlinear. I. Desoer, Charles A. II. Kuh, Ernest S. III. Title. IV. Series.
TA454.C56 1987 621.319'21 86-12498
ISBN 0-07-010898-6
ISBN 0-07-010899-4 (solutions manual)

ABOUT THE AUTHORS

Leon O. Chua received the S.M. degree from Massachusetts Institute of Technology in 1961 and his Ph.D. from the University of Illinois, Urbana in 1964. He was awarded *Doctor Honoris Causa* from the Ecole Polytechnique Fédérale de Lausanne (Switzerland) in 1983 and an Honorary Doctorate from the University of Tokushima (Japan) in 1984. In 1971 he joined the faculty of the University of California, Berkeley, where he is currently Professor of Electrical Engineering and Computer Sciences. Dr. Chua is the author of *Introduction to Nonlinear Network Theory* and coauthor of *Computer-Aided Analysis of Electronic Circuits: Algorithms and Computational Techniques*. His research interests are in the areas of general nonlinear network and system theory. He has published numerous research papers and has been a consultant to various electronic industries.

Dr. Chua is a Fellow of the IEEE (1973), the Editor of the *IEEE Transactions on Circuits and Systems* (1973–75), and the President of the IEEE Circuits and Systems Society (1976). He has been awarded four patents and received several honors and awards, including the IEEE Browder J. Thompson Prize (1967), the IEEE W.R.G. Baker Prize (1973), the Frederick Emmons Terman Award (1974), the Miller Professor (1976), the Senior Visiting Fellow at Cambridge University (1982), the Alexander von Humboldt Senior U.S. Scientist award (1983) at the Technische Universität (München), the Japan Society for Promotion of Science Senior Visiting Fellowship (1983) at Waseda University (Tokyo), the IEEE Centennial Medal (1984), the Guillemin-Cauer Prize (1985), and the Professeur Invité award (Université de Paris-SUD) from the French National Ministry of Education (1986).

Charles A. Desoer received his Ph.D. from the Massachusetts Institute of Technology in 1953. He then worked for several years at Bell Telephone Laboratories on circuit and communication system problems. In 1958 he joined the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley, where he has taught and researched in the areas of circuits, systems, and control.

Dr. Desoer has received a number of awards for his research, including the Medal of the University of Liege (1970), the Guggenheim Fellowship (1970–1971), the Prix Montefiore (1975), and the 1986 IEEE Control Systems Science and Engineering Award. He received the 1971 Distinguished Teaching Award at the University of California, Berkeley and the 1975 IEEE Education Medal. Dr. Desoer's interests lie in system theory with emphasis on control systems and circuits. He has coauthored several books, including *Linear System Theory* with L. A. Zadeh, *Basic Circuit Theory* with E. S. Kuh, and *Multivariable Feedback Systems* with F. M. Callier. He is author of *Notes for a Second Course on Linear Systems*.

Ernest S. Kuh is author of over 80 technical papers in circuits, systems, electronics, and computer-aided design, and is a coauthor of three books, including *Basic Circuit Theory*, which he wrote with one of his present coauthors, Charles A. Desoer. He received the B.S. degree from the University of Michigan, Ann Arbor in 1949, the S.M. degree from the Massachusetts Institute of Technology in 1950, and the Ph.D from Stanford University in 1952.

Dr. Kuh was a member of the Technical Staff of Bell Telephone Laboratories from 1952 until 1956. He joined the faculty of the University of California, Berkeley in 1956, and there, he served as Chairman of the Department of Electrical Engineering and Computer Sciences from 1968 to 1972. From 1973 to 1980 he was Dean of the College of Engineering. Dr. Kuh is a Fellow of IEEE and AAAS and a member of the National Academy of Engineering and of the Academia Sinica. He has been the recipient of a number of awards and honors, including the Lamme Medal of the American Society of Engineering Education, the IEEE Education Medal, and the IEEE Centennial Medal. He has served on several committees of the National Academy of Engineering and the National Academy of Sciences.

PREFACE

Electrical engineering is a discipline driven by inventions and technological breakthroughs. To mention one: 20 years ago, engineers barely knew how to produce an IC chip: now some chips have one million devices; it is expected that with foreseeable developments in silicon technology during the next decade chips will have 10^8 devices. Also the ubiquitous presence of the computer terminal reminds us of the enormous impact of computers on engineering design. Clearly such tremendous changes would have considerable influence on engineering education.

In teaching a course on introductory electrical circuits, the traditional approach has been to teach exclusively linear time-invariant passive RLC circuits. Admittedly they constitute a good vehicle to learn the dynamics of such simple circuits. Clearly such an approach is obsolete.

It is clear that circuit theory is one of the basic disciplines of electrical engineering; a well designed circuit theory course should cover the basic concepts and the basic results used in circuit design. It should serve as a foundation course to be followed by courses in various fields of electrical engineering, e.g., communication and signal processing, electronic devices and circuits, control and power systems, microwaves and optoelectronics, etc. . . . The concept of device modeling and its applications to currently used devices are crucial in a course on linear and nonlinear circuits: many examples of device modeling are given in the text. Furthermore, the course should be designed so that the graduate from such a curriculum knows how to approach the devices and circuits yet to be invented but that he or she will encounter, say, 10 to 15 years from now. With these goals in mind, the present book presents material with sufficient breadth, depth, and rigor to give a solid foundation to the student's future professional life.

At the University of California, Berkeley, as in most American engineering schools, there is a sophomore 45-lecture-hour course called Introductory Electrical Engineering. Its purpose is to give a broad introduction to most of the aspects of electrical engineering.

This book is intended as a textbook for the junior course that follows.

Since it is a junior course, it takes advantage of the greater competence and maturity of the students: in particular, physics, linear algebra, and differential equations. This course is the electrical analog of the typical junior physics course in say, mechanics, electromagnetism, and so on.

This book differs from many other texts on circuit theory by the following features:

1. Due to the ubiquitous op amp and similar devices, it views a circuit as an interconnection of *multiterminal* elements rather than of *two-terminal* elements.
2. *Active* and *passive* circuits are given equal emphasis.
3. *Linear* and *nonlinear* elements are treated together. (Note that computers simulate nonlinear circuits almost as easily as linear ones.)
4. The concept of *operating point* and the topic of *small-signal analysis* are covered thoroughly.
5. Switching, triggering, and memory circuits as well as oscillators are illustrated with first-order and second-order examples.
6. Tableau analysis is used to greatly simplify the proof of many network theorems in linear and nonlinear circuits.
7. Modified node analysis is introduced in view of its complete generality and importance in the design of computer circuit simulators, such as SPICE.
8. Some numerical methods are introduced and implemented via equivalent circuits: in particular, solution of nonlinear algebraic equations (Newton-Raphson) and integration of the circuit differential equations (forward and backward Euler method).
9. Stability issues are met head on; in particular oscillators are analyzed and an elementary version of the Nyquist criterion (useful in the design of op amps circuits) is introduced.

CONTENTS OF THE BOOK

Chapter One treats Kirchhoff's Laws and Tellegen's theorem. The next four chapters introduce two-terminal and multiterminal *resistive* elements and *resistive* circuits; linear, nonlinear, passive, and active circuits; op amp circuits with linear and nonlinear models; operating points and small signal analysis; and network theorems and the Newton-Raphson procedure for solving nonlinear dc resistive circuits.

Chapters Six and Seven cover first- and second-order linear and nonlinear dynamic circuits: our goal is to exhibit their properties and illustrate them by numerous examples, including flip flops and oscillators. General dynamic circuits, analyzed by Tableau or modified node analysis, are covered in Chapter Eight.

The next three chapters build up the fundamentals of linear time-invariant circuits: sinusoidal steady-state analysis; very brief treatment of Laplace transforms; properties of natural frequencies and network functions such as poles, zeros, stability, and convolution; Nyquist criterion; and stability of terminated one-ports.

A brief Chapter Twelve broadens the background on network topology and treats the usual general circuit analysis methods.

Chapter Thirteen covers two-ports, n-ports, and their properties—reciprocity in particular.

The last chapter brings out design issues such as the approximation problem, design of active Butterworth filters, and sensitivity analysis.

We believe that the topics covered in this text constitute an excellent background for further education in electronic circuits, computer-aided design, communications, control, and power.

ACKNOWLEDGMENT

Even though this book is a systematic introduction to circuit theory, it uses many concepts and techniques which were developed by people doing research in circuits, communications and control. In fact, without our own deep involvement in research, this book could not have been written. It is a pleasure to publicly acknowledge the research support of the University of California, the National Science Foundation, the Department of Defense, the State of California, and the support of industry.

We are also indebted to many people who have taught the course while the preliminary notes were written and revised; they have given us valuable suggestions. It is a pleasure to mention in particular F. Ayrom, G. Bernstein, C. C. Chang, A. C. Deng, A. Dervisoglu, N. A. Gruñdes, H. Haneda, K. Inan, P. Kennedy, R. W. Liu, H. Narayanan, M. Odyniec, T. S. Parker, A. Sangiovanni-Vincentelli, E. W. Szeto-Lee, L. Yang, and Quing-jian Yu.

We also benefited greatly from the judicious comments of our teaching assistants and the penetrating questions of our students.

We wish to record our gratitude for the high professional skills and care that B. Fuller, I. Stanczyk-Ng, and T. Sticpewich gave to the preparation of the manuscript.

Leon O. Chua
Charles A. Desoer
Ernest S. Kuh

CONTENTS

7 Second-Order Circuits