

CIRCUIT ANALYSIS and FEEDBACK AMPLIFIER THEORY

CIRCUIT ANALYSIS and FEEDBACK AMPLIFIER THEORY

Edited by
Wai-Kai Chen
University of Illinois
Chicago, U.S.A.



Taylor & Francis

Taylor & Francis Group

Boca Raton London New York

A CRC title, part of the Taylor & Francis imprint, a member of the Taylor & Francis Group, the academic division of T&F Informa plc.

The material was previously published in *The Circuit and Filters Handbook, Second Edition*. © CRC Press LLC 2002.

Published in 2006 by
CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2006 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group

No claim to original U.S. Government works
Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8493-5699-7 (Hardcover)
International Standard Book Number-13: 978-0-8493-5699-5 (Hardcover)

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. A wide variety of references are listed. Reasonable efforts have been made to publish reliable data and information, but the author and the publisher cannot assume responsibility for the validity of all materials or for the consequences of their use.

No part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC) 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

Catalog record is available from the Library of Congress



Taylor & Francis Group
is the Academic Division of T&F Informa plc.

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>
and the CRC Press Web site at
<http://www.crcpress.com>

Preface

The purpose of *Circuit Analysis and Feedback Amplifier Theory* is to provide in a single volume a comprehensive reference work covering the broad spectrum of linear circuit analysis and feedback amplifier design. It also includes the design of multiple-loop feedback amplifiers. The book is written and developed for the practicing electrical engineers in industry, government, and academia. The goal is to provide the most up-to-date information in the field.

Over the years, the fundamentals of the field have evolved to include a wide range of topics and a broad range of practice. To encompass such a wide range of knowledge, the book focuses on the key concepts, models, and equations that enable the design engineer to analyze, design and predict the behavior of large-scale circuits and feedback amplifiers. While design formulas and tables are listed, emphasis is placed on the key concepts and theories underlying the processes.

The book stresses fundamental theory behind professional applications. In order to do so, it is reinforced with frequent examples. Extensive development of theory and details of proofs have been omitted. The reader is assumed to have a certain degree of sophistication and experience. However, brief reviews of theories, principles and mathematics of some subject areas are given. These reviews have been done concisely with perception.

The compilation of this book would not have been possible without the dedication and efforts of Professor Larry P. Huelsman, and most of all the contributing authors. I wish to thank them all.

Wai-Kai Chen
Editor-in-Chief

Editor-in-Chief



Wai-Kai Chen, Professor and Head Emeritus of the Department of Electrical Engineering and Computer Science at the University of Illinois at Chicago, is now serving as Academic Vice President at International Technological University. He received his B.S. and M.S. degrees in electrical engineering at Ohio University, where he was later recognized as a Distinguished Professor. He earned his Ph.D. in electrical engineering at the University of Illinois at Urbana/Champaign.

Professor Chen has extensive experience in education and industry and is very active professionally in the fields of circuits and systems. He has served as visiting professor at Purdue University, University of Hawaii at Manoa, and Chuo University in Tokyo, Japan. He was Editor of the *IEEE Transactions on Circuits and Systems, Series I and II*, President of the IEEE Circuits and Systems Society, and is the Founding Editor and Editor-in-Chief of the *Journal of Circuits, Systems and Computers*. He received the Lester R. Ford Award from the Mathematical Association of America, the Alexander von Humboldt Award from Germany, the JSPS Fellowship Award from Japan Society for the Promotion of Science, the Ohio University Alumni Medal of Merit for Distinguished Achievement in Engineering Education, the Senior University Scholar Award and the 2000 Faculty Research Award from the University of Illinois at Chicago, and the Distinguished Alumnus Award from the University of Illinois at Urbana/Champaign. He is the recipient of the Golden Jubilee Medal, the Education Award, the Meritorious Service Award from IEEE Circuits and Systems Society, and the Third Millennium Medal from the IEEE. He has also received more than a dozen honorary professorship awards from major institutions in China.

A fellow of the Institute of Electrical and Electronics Engineers and the American Association for the Advancement of Science, Professor Chen is widely known in the profession for his *Applied Graph Theory* (North-Holland), *Theory and Design of Broadband Matching Networks* (Pergamon Press), *Active Network and Feedback Amplifier Theory* (McGraw-Hill), *Linear Networks and Systems* (Brooks/Cole), *Passive and Active Filters: Theory and Implements* (John Wiley), *Theory of Nets: Flows in Networks* (Wiley-Interscience), and *The VLSI Handbook* (CRC Press).

A fellow of the Institute of Electrical and Electronics Engineers and the American Association for the Advancement of Science, Professor Chen is widely known in the profession for his *Applied Graph Theory* (North-Holland), *Theory and Design of Broadband Matching Networks* (Pergamon Press), *Active Network and Feedback Amplifier Theory* (McGraw-Hill), *Linear Networks and Systems* (Brooks/Cole), *Passive and Active Filters: Theory and Implements* (John Wiley), *Theory of Nets: Flows in Networks* (Wiley-Interscience), and *The VLSI Handbook* (CRC Press).

Advisory Board

Leon O. Chua

University of California
Berkeley, California

John Choma, Jr.

University of Southern California
Los Angeles, California

Lawrence P. Huelsman

University of Arizona
Tucson, Arizona

Contributors

Peter Aronhime
University of Louisville
Louisville, Kentucky

K.S. Chao
Texas Tech University
Lubbock, Texas

Ray R. Chen
San Jose State University
San Jose, California

Wai-Kai Chen
University of Illinois
Chicago, Illinois

John Choma, Jr.
University of Southern California
Los Angeles, California

Artice M. Davis
San Jose State University
San Jose, California

Marwan M. Hassoun
Iowa State University
Ames, Iowa

Pen-Min Lin
Purdue University
West Lafayette, Indiana

Robert W. Newcomb
University of Maryland
College Park, Maryland

Benedykt S. Rodanski
University of Technology, Sydney
Broadway, New South Wales,
Australia

Marwan A. Simaan
University of Pittsburgh
Pittsburgh, Pennsylvania

James A. Svoboda
Clarkson University
Potsdam, New York

Jiri Vlach
University of Waterloo
Waterloo, Ontario, Canada

Table of Contents

1	Fundamental Circuit Concepts	<i>John Choma, Jr.</i>	1-1
2	Network Laws and Theorems		2-1
2.1	Kirchhoff's Voltage and Current Laws	<i>Ray R. Chen and Artice M. Davis</i>	2-1
2.2	Network Theorems	<i>Marwan A. Simaan</i>	2-39
3	Terminal and Port Representations	<i>James A. Svoboda</i>	3-1
4	Signal Flow Graphs in Filter Analysis and Synthesis	<i>Pen-Min Lin</i>	4-1
5	Analysis in the Frequency Domain		5-1
5.1	Network Functions	<i>Jiri Vlach</i>	5-1
5.2	Advanced Network Analysis Concepts	<i>John Chroma, Jr.</i>	5-10
6	Tableau and Modified Nodal Formulations	<i>Jiri Vlach</i>	6-1
7	Frequency Domain Methods	<i>Peter Aronhime</i>	7-1
8	Symbolic Analysis ¹	<i>Benedykt S. Rodanski and Marwan M. Hassoun</i>	8-1
9	Analysis in the Time Domain	<i>Robert W. Newcomb</i>	9-1
10	State-Variable Techniques	<i>K. S. Chao</i>	10-1
11	Feedback Amplifier Theory	<i>John Choma, Jr.</i>	11-1
12	Feedback Amplifier Configurations	<i>John Choma, Jr.</i>	12-1
13	General Feedback Theory	<i>Wai-Kai Chen</i>	13-1

14 The Network Functions and Feedback *Wai-Kai Chen* 14-1

15 Measurement of Return Difference *Wai-Kai Chen* 15-1

16 Multiple-Loop Feedback Amplifiers *Wai-Kai Chen* 16-1