

ELECTRICAL MEASUREMENT, SIGNAL PROCESSING, and DISPLAYS

ELECTRICAL MEASUREMENT, SIGNAL PROCESSING, and DISPLAYS

Edited by
JOHN G. WEBSTER



CRC PRESS

Boca Raton London New York Washington, D.C.

Library of Congress Cataloging-in-Publication Data

Electrical measurements, signal processing, and displays / John G. Webster, editor-in-chief.

p. cm. -- (Principles and applications in engineering)

Includes bibliographical references and index.

ISBN 0-8493-1733-9 (alk. paper)

1. Electronic measurements. 2. Electric measurements. 3. Signal processing. I. Webster, John G., 1932- II. Series.

TK7878.E435 2003

621.3815'48—dc21

2003048530

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.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming, and recording, or by any information storage or retrieval system, without prior permission in writing from the publisher.

All rights reserved. Authorization to photocopy items for internal or personal use, or the personal or internal use of specific clients, may be granted by CRC Press LLC, provided that \$1.50 per page photocopied is paid directly to Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923 U.S. The fee code for users of the Transactional Reporting Service is ISBN 0-8493-1733-9/04/\$0.00+\$1.50. The fee is subject to change without notice. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

The consent of CRC Press LLC does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from CRC Press LLC for such copying.

Direct all inquiries to CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431.

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

Visit the CRC Press Web site at www.crcpress.com

© 2004 by CRC Press LLC

No claim to original U.S. Government works

International Standard Book Number 0-8493-1733-9

Library of Congress Card Number 2003048530

Printed in the United States of America 1 2 3 4 5 6 7 8 9 0

Printed on acid-free paper

Preface

Introduction

The purpose of *Electrical Measurement, Signal Processing, and Displays* is to provide a reference that is both concise and useful for engineers in industry, scientists, designers, managers, research personnel and students, as well as many others who have measurement problems. The book covers an extensive range of topics that comprise the subject of measurement, instrumentation, and sensors.

The book describes the use of instruments and techniques for practical measurements required in electrical measurements. It includes sensors, techniques, hardware, and software. It also includes information processing systems, automatic data acquisition, reduction and analysis and their incorporation for control purposes.

Chapters include descriptive information for professionals, students, and workers interested in measurement. Chapters include equations to assist engineers and scientists who seek to discover applications and solve problems that arise in fields not in their specialty. They include specialized information needed by informed specialists who seek to learn advanced applications of the subject, evaluative opinions, and possible areas for future study. Thus, *Electrical Measurement, Signal Processing, and Displays* serves the reference needs of the broadest group of users — from the advanced high school science student to industrial and university professionals.

Organization

The book is organized according to the measurement problem. [Section I](#) covers electromagnetic variables measurement such as voltage, current, and power. [Section II](#) covers signal processing such as amplifiers, filters, and compatibility. [Section III](#) covers displays such as cathode ray tubes, liquid crystals, and plasma displays.

John G. Webster
Editor-in-Chief

Editor-in-Chief

John G. Webster received the B.E.E. degree from Cornell University, Ithaca, NY, in 1953, and the M.S.E.E. and Ph.D. degrees from the University of Rochester, Rochester, NY, in 1965 and 1967, respectively.

He is Professor of Electrical and Computer Engineering at the University Wisconsin-Madison. In the field of medical instrumentation he teaches undergraduate and graduate courses, and does research on RF cardiac ablation and measurement of vigilance.

He is author of *Transducers and Sensors*, an IEEE/EAB Individual Learning Program (Piscataway, NJ: IEEE, 1989). He is co-author, with B. Jacobson, of *Medicine and Clinical Engineering* (Englewood Cliffs, NJ: Prentice-Hall, 1977), with R. Pallás-Areny, of *Sensors and Signal Conditioning* (New York: Wiley, 1991), and with R. Pallás-Areny, of *Analog Signal Conditioning* (New York: Wiley, 1999). He is editor of *Encyclopedia of Medical Devices and Instrumentation* (New York: Wiley, 1988), *Tactile Sensors for Robotics and Medicine* (New York: Wiley, 1988), *Electrical Impedance Tomography* (Bristol, UK: Adam Hilger, 1990), *Teaching Design in Electrical Engineering* (Piscataway, NJ: Educational Activities Board, IEEE, 1990), *Prevention of Pressure Sores: Engineering and Clinical Aspects* (Bristol, UK: Adam Hilger, 1991), *Design of Cardiac Pacemakers* (Piscataway, NJ: IEEE Press, 1995), *Design of Pulse Oximeters* (Bristol, UK: IOP Publishing, 1997), *Medical Instrumentation: Application and Design, Third Edition* (New York: Wiley, 1998), and *Encyclopedia of Electrical and Electronics Engineering* (New York, Wiley, 1999). He is co-editor, with A.M. Cook, of *Clinical Engineering: Principles and Practices* (Englewood Cliffs, NJ: Prentice-Hall, 1979) and *Therapeutic Medical Devices: Applications and Design* (Englewood Cliffs, NJ: Prentice-Hall, 1982), with W.J. Tompkins, of *Design of Microcomputer-Based Medical Instrumentation* (Englewood Cliffs, NJ: Prentice-Hall, 1981) and *Interfacing Sensors to the IBM PC* (Englewood Cliffs, NJ: Prentice-Hall, 1988), and with A.M. Cook, W.J. Tompkins, and G.C. Vanderheiden, *Electronic Devices for Rehabilitation* (London: Chapman & Hall, 1985).

Dr. Webster has been a member of the IEEE-EMBS Administrative Committee and the NIH Surgery and Bioengineering Study Section. He is a fellow of the Institute of Electrical and Electronics Engineers, the Instrument Society of America, and the American Institute of Medical and Biological Engineering. He is the recipient of the AAMI Foundation Laufman-Greatbatch Prize and the ASEE/Biomedical Engineering Division, Theo C. Pilkington Outstanding Educator Award.

Advisory Board

Gene Fatton

Consultant
Loveland, Colorado

Jacob Fraden

Advanced Monitors Corporation
San Diego, California

James E. Lenz

Honeywell Technology Center
Minneapolis Minnesota

Ramón Pallás-Areny

Universitat Politècnica de Catalunya
Barcelona, Spain

Dennis Swyt

National Institute of Standards and Technology
Gaithersburg, Maryland

Peter H. Sydenham

University of South Australia
Mawsons Lakes
South Australia
and
University College
London, UK

Carsten Thomsen

National Instruments
Austin, Texas

Contributors

A. Roberto Ambrosini

Institute of Radioastronomy
Bologna, Italy

Jeff P. Anderson

LTV Steel Corporation
Independence, Ohio

Pasquale Arpaia

Università di Napoli Federico II
Naples, Italy

Francesco Avallone

Università di Napoli Federico II
Naples, Italy

Aldo Baccigalupi

Università di Napoli Federico II
Naples, Italy

William A. Barrow

Planar Systems
Beaverton, Oregon

Cipriano Bartoletti

Institute of Radioastronomy
Bologna, Italy

David M. Beams

University of Texas at Tyler
Tyler, Texas

K. Beilenhoff

Institut für
Hochfrequenztechnik,
Technische Universität
Darmstadt, Germany

Richard J. Blotzer

Cleveland, Ohio

C. Bortolotti

Institute of Radioastronomy
Bologna, Italy

Arnaldo Brandolini

Politecnico di Milano
Milan, Italy

Saps Buchman

Stanford University
Stanford, California

Barrett S. Caldwell

Purdue University
West Lafayette, Indiana

Robert B. Campbell

Sandia National Laboratories
Albuquerque, New Mexico

Robert M. Crovella

Plano, Texas

N. D'Amico

Institute of Radioastronomy
Bologna, Italy

Claudio de Capua

Università di Napoli Federico II
Naples, Italy

Alfons Dehé

Siemens AG
Munich, Germany

Achim Dreher

German Aerospace Center
Wessling, Germany

Halit Eren

Curtin University of Technology
Bentley, Australia

Alessandro Ferrero

Politecnico di Milano
Milan, Italy

K. Fricke

Institut für
Hochfrequenztechnik,
Technische Universität
Darmstadt, Germany

Alessandro Gandelli

Politecnico di Milano
Milan, Italy

Daryl Gerke

Kimmel Gerke Associates, Ltd.
Mesa, Arizona

W. A. Gillespie

University of Abertay
Dundee, Scotland

James Goh

Curtin University of Technology
Perth, Australia

G. Grueff

Institute of Radioastronomy
Bologna, Italy

H. L. Hartnagel

Institut für
Hochfrequenztechnik,
Technische Universität
Darmstadt, Germany

Michael B. Heaney

Palo Alto Research Center
Palo Alto, California

Albert D. Helfrick

Embry-Riddle Aeronautical
University
Daytona Beach, Florida

David A. Hill

National Institute of Standards
and Technology
Boulder, Colorado

Rahman Jamal

National Instruments Germany
Munich, Germany

Motohisa Kanda

National Institute of Standards
and Technology
Boulder, Colorado

Mohammad A. Karim

City College of New York
New York, New York

William Kimmel

Kimmel Gerke Associates, Ltd.
Mesa, Arizona

H. Klingbeil

Institut für
Hochfrequenztechnik,
Technische Universität
Darmstadt, Germany

V. Krozer

Institut für
Hochfrequenztechnik,
Technische Universität
Darmstadt, Germany

Carmine Landi

Università de L'Aquila
L'Aquila, Italy

W. Marshall Leach, Jr.

Georgia Institute of Technology
Atlanta, Georgia

Yufeng Li

Samsung Information Systems
San Jose, California

E. B. Loewenstein

National Instruments
Austin, Texas

Michael Z. Lowenstein

Harmonics Limited
Mequon, Wisconsin

Albert Lozano-Nieto

The Pennsylvania State
University
Lehman, Pennsylvania

Steven A. Macintyre

Macintyre Electronic Design
Herndon, Virginia

Allan M. MacLeod

University of Abertay
Dundee, Scotland

Sergio Mariotti

Institute of Radioastronomy
Bologna, Italy

P. F. Martin

University of Abertay
Dundee, Scotland

Edward McConnell

National Instruments
Austin, Texas

Robert T. McGrath

The Pennsylvania State
University
University Park, Pennsylvania

Douglas P. McNutt

The MacNaughtan Laboratory
Colorado Springs, Colorado

John Mester

Stanford University
Stanford, California

Jeffrey P. Mills

Illinois Institute of Technology
Chicago, Illinois

Devendra K. Misra

University of Wisconsin
Milwaukee, Wisconsin

William C. Moffatt

Sandia National Laboratories
Albuquerque, New Mexico

Stelio Montebugnoli

Institute of Radioastronomy
Fontano, Italy

Jerry Murphy

Hewlett Packard Company
Geneva, Switzerland

Steven A. Murray

California State University
Fullerton, California

A. Orfei

Institute of Radioastronomy
Bologna, Italy

Peter O'Shea

Royal Melbourne Institute of
Technology
Melbourne, Australia

Ramón Pallás-Areny

Universitat Politècnica de
Catalunya
Barcelona, Spain

Ronney B. Panerai

University of Leicester
Leicester, England

Luca Podestà

University of Rome La Sapienza
Rome, Italy

Rodney Pratt

University of South Australia
Adelaide, Australia

Gordon W. Roberts

McGill University
Montreal, Canada

Giancarlo Sacerdoti

University of Rome La Sapienza
Rome, Italy

Kalluri R. Sarma

Honeywell, Inc.
Phoenix, Arizona

Christopher J. Sherman

Merrimack, New Hampshire

Robert Steer

Frequency Devices
Haverhill, Massachusetts

Timothy J. Sumner

Imperial College
London, England

Peter H. Sydenham

University of South Australia
Adelaide, Australia

Michał Szyper

University of Mining and
Metallurgy
Cracow, Poland

G. Tomassetti

University of L'Aquila
L'Aquila, Italy

Michael F. Toner

Northern Telecom Ltd.
Nepean, Ontario, Canada

**Ramanapathy
Veerasingam**

The Pennsylvania State
University
University Park, Pennsylvania

Herman Vermariën

Vrije Universiteit Brussel
Brussels, Belgium

Contents

SECTION I Electromagnetic Variables Measurement

1	Voltage Measurement <i>Alessandro Ferrero, Jerry Murphy, Cipriano Bartoletti, Luca Podestà, and Giancarlo Sacerdoti</i>	1-1
2	Current Measurement <i>Douglas P. McNutt</i>	2-1
3	Power Measurement <i>Pasquale Arpaia, Francesco Avallone, Aldo Baccigalupi, Claudio De Capua, and Carmine Landi</i>	3-1
4	Power Factor Measurement <i>Michael Z. Lowenstein</i>	4-1
5	Phase Measurement <i>Peter O'Shea</i>	5-1
6	Energy Measurement <i>Arnaldo Brandolini and Alessandro Gandelli</i>	6-1
7	Electrical Conductivity and Resistivity <i>Michael B. Heaney</i>	7-1
8	Charge Measurement <i>Saps Buchman, John Mester, and Timothy J. Sumner</i>	8-1
9	Capacitance and Capacitance Measurements <i>Halit Eren and James Goh</i>	9-1
10	Permittivity Measurement <i>Devendra K. Misra</i>	10-1
11	Electric Field Strength <i>David A. Hill and Motohisa Kanda</i>	11-1
12	Magnetic Field Measurement <i>Steven A. Macintyre</i>	12-1
13	Permeability and Hysteresis Measurement <i>Jeff P. Anderson and Richard J. Blotzer</i>	13-1
14	Inductance Measurement <i>Michał Szyper</i>	14-1

15 Immittance Measurement *Achim Dreher*..... 15-1

16 Q Factor Measurement *Albert D. Helfrick* 16-1

17 Distortion Measurement *Michael F. Toner and Gordon W. Roberts* 17-1

18 Noise Measurement *W. Marshall Leach, Jr.* 18-1

19 Microwave Measurement *A. Dehé, K. Beilenhoff, K. Fricke, H. Klingbeil, V. Krozer, and H. L. Hartnagel* 19-1

SECTION II Signal Processing

20 Amplifiers and Signal Conditioners *Ramón Pallás-Areny*..... 20-1

21 Modulation *David M. Beams*..... 21-1

22 Filters *Rahman Jamal and Robert Steer*..... 22-1

23 Spectrum Analysis and Correlation *Ronney B. Panerai, A. Ambrosini, C. Bortolotti, N. D’Amico, G. Grueff, S. Mariotti, S. Montebugnoli, A. Orfei, and G. Tomassetti* 23-1

24 Applied Intelligence Processing *Peter H. Sydenham and Rodney Pratt* 24-1

25 Analog-to-Digital Converters *E.B. Loewenstein*..... 25-1

26 Computers *A.M. MacLeod, P.F. Martin, and W.A. Gillespie* 26-1

27 Telemetry *Albert Lozano-Nieto*..... 27-1

28 Sensor Networks and Communication *Robert M. Crovella* 28-1

29 Electromagnetic Compatibility *Daryl Gerke, William Kimmel, and Jeffrey P. Mills*..... 29-1

SECTION III Displays

30 Human Factors in Displays *Steven A. Murray and Barrett S. Caldwell* 30-1

31 Cathode Ray Tube Displays *Christopher J. Sherman*..... 31-1

32 Liquid Crystal Displays *Kalluri R. Sarma* 32-1

33 Plasma-Driven Flat Panel Displays *Robert T. McGrath, Ramanapathy
Veerasingham, William C. Moffatt, and Robert B. Campbell* 33-1

34 Electroluminescent Displays *William A. Barrow*..... 34-1

35 Light-Emitting Diode Displays *Mohammad A. Karim* 35-1

36 Reading/Recording Devices *Herman Vermariën, Edward McConnell, and
Yufeng Li*..... 36-1