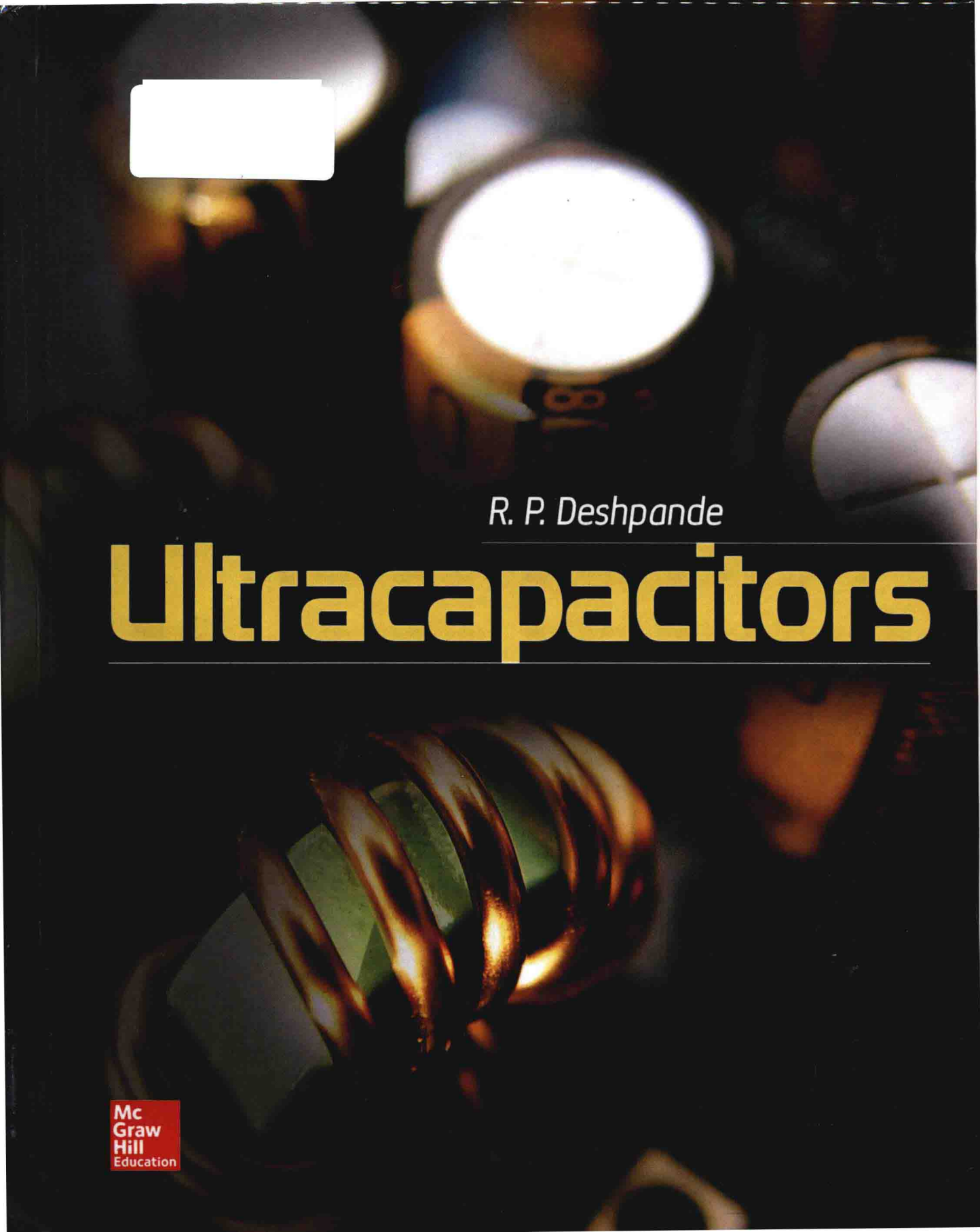
R. P. Deshpande
Ultracapacitors
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Education

ULTRACAPACITORS

R. P. DESHPANDE

B. Tech. Hon. Elect. (IIT, Bombay)
Fellow, The Institution of Engineers (India)

New York Chicago San Francisco
Athens London Madrid
Mexico City Milan New Delhi
Singapore Sydney Toronto

1 2 3 4 5 6 7 8 9 0 QVS/QVS 1 2 1 0 9 8 7 6 5

ISBN 978-0-07-184167-2
MHID 0-07-184167-9

The sponsoring editor for this book was Michael McCabe and the production supervisor was Pamela A. Pelton. The art director for the cover was Jeff Weeks.

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Praise for *Ultracapacitors*

'This book brings together the component technology with system level application information, allowing the technology to be further adopted. Any power engineer should include this book as a must-have reference.'

—**Chad Hall,** Co-Founder and Vice President of Marketing & Product Management, Ioxus, Inc., New York

'The book deals with basic principles, manufacturing techniques of ultracapacitors and their applications in variety of fields. This book is the outcome of vast experience and in-depth knowledge of the author in the field of this new type of capacitor. Energy storage is becoming increasingly important for a host of demanding applications. Ultracapacitors are ideal for a variety of new and exciting fields such as electronics, automobiles, and lighting, transmission and distribution systems. The book fills up the need for students, industries and researchers as reference to understand various aspects of ultracapacitors. I strongly recommend the book to practicing engineers, students and researchers. I also hope and wish that the usage of ultracapacitors will spread rapidly in all sectors of industry.'

—**Professor (Retired) M. L. Kothari,** Department of Electrical Engineering, IIT Delhi

'Advances in nanotechnology are enabling capacitor manufacturers to push the envelope in the area of energy storage. Ultracapacitors are beginning to energize all sorts of equipment—from toys and mobile phones to cars and buses. This significant development is aptly captured in R.P. Deshpande's book. He holistically deals with the subject in his remarkably simple to understand, insightful way.'

—**Vinod Sharma,** MD, Deki Electronics Limited; Chairman, ESC; Chairman, CII National ICTE Committee

'With this book, R.P. Deshpande has written about a critical and pivotal technology. Ultracapacitors will figure prominently in the complex future of energy storage and the author provides a strong, complete foundation for understanding the technology and its commercial considerations along with a snapshot of the competitive/manufacturing landscape in a dynamic and evolving industry.'

—**Michael A. Everett,** Chief Technical Officer, Maxwell Technologies, Inc., USA

'The topic chosen by R.P. Deshpande, whose authority in the world of Capacitors today is unchallenged, is virgin, unexplored and unknown to many experienced engineers. The name "Ultracapacitor" itself is prudently selected to describe the extra benefit this industrial equipment offers in bridging the gaps in smooth availability of the vital power for industrialization of emerging economies and developing nations. The beauty of the contents of this book is that it carries reader from the depth of constructional details without any clutter of complex words. After the successful launching of the first book on Industrial Capacitors which was well-appreciated and consumed by industry owners and users, I strongly believe this is another "jewel in capacitors" that R.P. Deshpande has come up with. The book is a compelling must-have in every industry's reference for driving energy efficiency and harnessing ecological benefits without any noise and environmental pollution in the industrial domain.'

—**Himanshu Dalvi,** President and CEO, Lighting Business Group & High Mast, Surya Roshni Ltd., New Delhi

Author's Profile

With over 45 years in the industry, Mr. R. P. Deshpande is among the most experienced and respected specialists in the Indian capacitor sector. He has helped various capacitor manufacturing organizations, both growth-oriented start-ups and established companies, to achieve enviable positions in the industry. Some of the capacitor brands nurtured by him continue to retain their market-pole position. Throughout his career, he has pioneered the development of many capacitor products, technologies, processes, and related applications.

Mr. Deshpande's interest in ultracapacitors first manifested as a paper at an international seminar (CAPACIT, Mumbai, Jan 2010), and his work on the use of capacitors for energy storage keeps appearing as articles, papers, and lectures on several platforms. This book is a result of continuing research over many years. His first book, *Capacitors*, filled up a crucial knowledge gap and has received wide appreciation and response in the industrial and academic fields.

Mr. Deshpande, a Fellow of the Institution of Engineers (India) and an electrical engineering graduate from the Indian Institute of Technology, Mumbai, continues to work as an independent advisor to capacitor manufacturing enterprises. He is often invited as an expert speaker to various forums and in a visiting faculty role; he loves to share his experience with students at the universities.

Foreword

Electrical energy storage has become a much talked about subject with regard to power supply utilities, hybrid and battery electric vehicles and several other applications by professionals and also certainly by governments, legislators and policy makers. Even professionals have to re-look into the various options and the distinctions provided between physical and chemical forms of electric energy storage that aptly fits them into the required environment. This book takes a critical look at physical storage of electricity in electrochemical capacitors, ultracapacitors.

This book covers various aspects of ultracapacitors and is a genuine effort in itself, useful to both the people from industry as well as academicians, and is a wonderful extended effort following the first book on Capacitors by Shri Deshpande. The book covers all aspects relating to ultracapacitor technology, its materials and applications in various fields. Right from the basics of ultracapacitor and its historical background, the book covers in detail different types of ultracapacitors, their classification based on energy storage mechanism and electrode combinations. Special characteristics of ultracapacitors, their reliability, cycle life, properties and other applications are also discussed in detail.

Large scale research and product developments are unfolding in the subject of ultracapacitors and many papers are also being presented at various platforms covering new designs, principles and applications. Stored energy has become a matter of prime importance in power grids, vehicular applications, electronics as well as defence, and the future is galore with changes in technology and associated applications. This book takes you systematically through present technology trends, manufacturing processes and present known applications. Also, it attempts to elaborate on developments taking place, emerging applications and market scenarios in the exciting world of ultracapacitors.

I am confident that this book will be a useful guide in the usage of ultracapacitors for students, researchers, electrical and electronic industries dealing in energy storage devices, as ultracapacitors are one of the most significant among the new emerging energy storage devices with huge benefits with a bigger role to play in this ever increasing quest for betterment of technologies.

J.S.S. Rao
Principal Director
National Power Training Institute
Ministry of Power, Government of India

Foreword

In the context of the variability of the temporal need—the available electrical energy is not sufficient for many applications and the conventional solutions generally have adverse cost benefit ratios. The prospect of a new, viable, and practical short-term energy storage alternative is bound to attract the attention of application designers and energy professionals all over the world.

Storage of energy in capacitors for use when and where needed has been a well-known solution practiced in such mundane and diverse devices as photoflash, automobile ignitions, explosive detonators, life-saving defibrillators, etc. In these and many other applications, the energy quantum was limited by the voltage to which the conventional capacitors had to be charged. The new technology of ultracapacitors, however, increases this quantum by several orders of magnitude at lower voltages in view of the large capacitance value possible because of the breakthrough in new dielectric materials as well as in a radically new energy transfer and storage mechanism. These features make it a game changing technology.

This book outlines the essentials of the technology of ultracapacitors in a lucid, easy-to-grasp yet comprehensive manner that should satisfy the curiosity of lay readers and energy enthusiasts, as well as meeting the requirements of application design engineers from a wide and diverse range of industries.

Certainly, the subject is complex and requires a thorough comprehension of the many nuances and facets of the nature, structure, and mechanisms of capacitors. This includes the concepts of ionic adsorption, charge transfer dynamics without the attendant chemical mass transfer (as in batteries) and issues of voltage limitations, energy densities, specific energy, etc. All radically new technologies require for their acceptance a convincing regime of life-cycle testing, reliability evaluation, and how to withstand wear and tear in the hands of end users.

The author of this book has an enviable record of life time involvement in industry and has a successful track record of designing commercially successful applications. His treatment of the topics reflects his mastery of the intricacies involved regarding the principles, processes, and products.

I welcome the pioneering effort of the author and congratulate the publishers for bringing out this timely, topical, and interesting book, which will contribute substantially in the vital arena of efficient energy storage applications in some of the vitally important sectors of our technological support system.

M.U. Deshpande
Former Professor, IIT Bombay
Former Director, VNIT, Nagpur

Preface

Electrochemical capacitor (EC), invented in the 60s, brought a revolution in capacitor technology. A third type of capacitor came into existence—along with static and electrolytic capacitors commonly known till then. This new capacitor makes extensive use of nanotechnology, a science developed over the past few decades, and has changed the way we perceive and use capacitors. The basic function of electrochemical capacitors is energy storage, and it stores much higher energy than hitherto possible, reaching to levels comparable to battery. Farad was all along considered too large a unit for practical application, and microfarad has been the common unit used for most capacitors. All capacitance meters measure values in microfarads, or a few millifarads. Thanks to EC, Farad is no longer too large, and capacitors of several thousand farads are now available.

Although capacitors have been known for energy storage, their energy storage capabilities were extremely limited, and batteries dominated the energy storage function. Though the basic principles were known for a long time, EC had to await the advent and progress of nanotechnology for its proper development. Its economic and commercial usage major development has taken place in the past two decades and new technologies are rapidly evolving. Applications of ECs are today found all over, many times without the knowledge of equipment user.

While electrochemical capacitor is a generic term, the trade names "Ultracapacitor" and "Supercapacitor" have become synonymous for these capacitors. I have used the term "Ultracapacitor" (or UC) in most part of this book, while electrochemical capacitor (EC) is also used as a generic name. Several variant of this capacitor are made today, each with its own benefit and special characteristics. Of these, Li-ion capacitors, hybrid capacitors and pseudocapacitors find special place in industry.

One of the main uses of ultracapacitors is as battery backups. Batteries have been around for over two centuries, and are found everywhere to store energy. However, batteries have a limited life by nature, and have constraints imposed by virtue of the speed at which they can absorb or discharge energy. The ECs connected across batteries take care of sudden loads and deep discharges, and reduce surge loads on batteries, thereby increasing the battery life several fold.

In certain emergency equipment and remote locations, ultracapacitors serve as alternative to batteries from the point of reliability and accessibility. We may in near future find them in mobile phones in place of batteries, which may be charged in seconds instead of hours. Toys, medical equipment, screw drivers and other equipment which is only occasionally used, can do with ultracapacitors instead of batteries. These can be charged instantly when required, and the equipment is ready for use.

Vehicles are increasingly using ECs for various applications—start-stop, regenerative braking, jump start or cold weather starting, radio or auxiliary equipment, battery backup and so on. In fact, development of ultracapacitors was fast-tracked due to necessity of vehicle industry, mainly to take care of cold start in extreme weather. Today fork lifts, cranes, golf carts and even traction locomotives use them for the benefits they offer. Railways use them for energy recovery with huge savings in operational costs. Cranes in ports recover and reuse the gravitational energy while lifting and lowering of loads.

Manufacturers are even dreaming of cars powered solely by ultracapacitors. Already Capabus—a city bus powered solely by ultracapacitors is running on streets of Shanghai and more and more buses are being introduced in U.S. and Europe. Inter-city buses using a combination of Li-ion batteries and ultracapacitors are also making their appearance. Golf carts, cranes and campus transport vehicles are serving at many places in the world, powered by ECs. In addition, hybrid vehicles use them as auxiliary power for several functions, including starting of vehicles from rest.

Electric supply systems and utilities find ultracapacitor usage for power quality, grid stability, frequency and voltage regulation and as protection against surges due to sudden load changes. Alternative or renewable energies are being developed and used all over the world, but these need storage when the energy is being generated, to be available for use when needed. Ultracapacitors, along with batteries, make a very useful combination in this respect.

Electronic gadgets like computers, laptops, mobile phones, cameras and a host of electronic applications use ECs in large numbers today, and many functions of these devices as also miniaturization of mobiles, camera and some other equipment became possible after ECs appeared on the scene. We may soon have instant remote charging for mobiles, powered by ultracapacitors.

Military applications require absolute long term reliability, and ultracapacitor modules come in handy for jump start of vehicles, and also starting them even when the battery may be down. Lighting in remote areas may be provided by ultracapacitors charged by solar power. Submarine and underwater missiles may use ultracapacitors since these do not need replacements like batteries. Even spacecraft uses them for powering on-board equipment because of their long

term reliability and dependability. NASA is putting big stake in ultracapacitor research so as to improve its performance for rocketry and space missions. Space and military have been among main drivers of initial EC developments for mission critical applications despite prohibitive high cost, where benefits justified the investments.

Today the costs have come down by over ninety per cent, and they are now within the reach of most commercial applications. Improvements in production methods, scale of production, new materials and improved technologies will see ultracapacitor market go up by leaps and bounds in near future. Major investments are being made in research and production of these capacitors worldwide, and we may find an explosion of their applications, with costs still heading downwards. China, U.S., U.K., Europe, Russia, Korea and Japan have maximum concentration of ultracapacitor manufacturers as of now, and we will see major investments being made in near future.

The lifetime of these capacitors is invariably much more than the equipment they are used in. While batteries have a cycle life of a few hundred to a thousand charge-discharge cycle, ultracapacitors may last even a couple of million cycles. Response time in emergency situations is much faster, and even though ultracapacitors today are not used as independent energy sources, when used with batteries, they extend battery life several folds by avoiding deep discharges. Like most electronic products, even ultracapacitors are getting smaller and thinner, and with higher energy and power densities. These will in turn help miniaturization of electronic equipment.

I received requests for writing a book on ultracapacitors from my friends and academicians after the release of my earlier book on capacitors. I have tried to cover maximum aspects of ultracapacitor technology, its materials, as well as applications in various fields. The book starts with the basics of ultracapacitor and its historical background. It then goes to describe different types of ultracapacitors, their classification based on energy storage mechanism and electrode combinations. Special characteristics of ultracapacitors, their reliability and cycle life and other properties are discussed in detail.

Different types of ECs, like symmetrical and asymmetrical, Li-ion capacitors, pseudocapacitors, hybrids, etc. are discussed in detail. Applications of EC capacitors are then taken up one by one for different sectors like grid, electronics, vehicles, traction and public transport.

Ultracapacitor technology principles are now being applied to batteries called ultrabatteris, which are covered under a separate chapter. One chapter is devoted to water desalination with the help of ultracapacitors (Capacitive Deionization Technology, or CDI), which appears a promising field. Ultracapacitor modules, cell balancing, testing and measurements of ultracapacitors are adequately

covered. Since ultracapacitors have large stored energy, and a few may use corrosive materials, they need care in handling and usage in circuits. Notes on the use of ECs are therefore given to help users and engineers to apprise them on these matters. Appendices at the end give data on several aspects of ultracapacitors, the U.N. safety regulations and tables which will be found useful.

Ultracapacitors are subject matter of continued large scale research and developments. Many papers are being presented at various platforms and new designs, principles and applications are unfolding. Stored energy and power availability are on the rise, and we may expect sea changes in the technology associated with applications. This book introduces current technology status, manufacturing process along with applications as of today. An attempt is made to elaborate on developments taking place on new emerging applications and market scenario for this exciting world of ultracapacitors.

I trust the book will be helpful in understanding the product, and students of capacitor and energy storage, as well as researchers and electrical and electronic industries will find it useful. Ultracapacitors are one of the most important emerging energy storage devices with immense benefits, and they have much larger role to play in near future.

R.P. Deshpande

Acknowledgements

While writing this book on ultracapacitors, I received support and guidance from three internationally acclaimed experts. I am grateful to them for their encouraging response, whenever, I approached them for data and technical help. In fact, I was encouraged by each of them to write the book and make it comprehensive enough so that it may be useful to a large section of readers and researchers alike.

I would like to thank Maxwell Technologies Inc., San Diego, U.S., for readily accepting my request for assistance. Their Chief Technical Officer, Mr. Michael A. Everett, was an admirable guide and provided me all the data as well as technical guidance that I required. I have extensively drawn material from Maxwell catalogues, papers, and literature for this work. I owe a big debt of gratitude to Maxwell Technologies and Michael for their consistent involvement with this book.

Mr. Chad Hall, Co-Founder and VP, Ioxus Inc., N.Y., was also of great help in the shaping of this book. We shared a good rapport, he encouraged me and provided lots of information from the Ioxus literature and papers.

Mr. David Evans, Founder and President, Evans Capacitor Company, Rhode Island, U.S., who is among the pioneers of Tantalum-based hybrid capacitors and EDLC, responded to my request with full enthusiasm and provided all the information about his company, the development path of their capacitors, and many other aspects. I would like to acknowledge his words of encouragement and valuable inputs about button type and hybrid capacitors.

It would not have been possible to give the book a comprehensive coverage without the help and cooperation of these people. I cherish the relationships that we developed during the course of my work and the bonds of friendship over the time. In addition, I also received valuable support and data from various sources, including Mr. M.H. Lee of Nesscap, Korea, and Mr. John Kim of Vinatech, Korea.

Dr. M.L. Kothari, Ex-Professor, IIT Delhi, has vast lifetime academic and professional experience and is currently Emeritus Fellow with IIT Delhi. He critically examined this book and gave suggestions for improvement, just as he did for my earlier book *Capacitors*.

I am grateful to my distinguished friend Dr. M.U. Deshpande, Former Professor, IIT Bombay, Former Director, VNIT, Nagpur, and a well-known personality in engineering faculty, as well as a member of the E-learning Working Group of M. C. & IT, Govt. of India, and Director, Distance Education Council, IGNOU. I acknowledge his valuable suggestions and thank him for writing a foreword to this book.

Mr. J.S.S. Rao, Principal Director, National Power Training Institute, has been following my work and was available at every step. He has also contributed a foreword to the book.

I received unstinted support from my wife Aruna throughout. My son Abhijeet and daughter-in-law Navita have always stood by me, giving me the strength to write. Friends and well-wishers have helped me by giving their precious time, information, and personal views to improve the book. I am deeply obliged to them all.

I would like to thank the entire team of McGraw Hill Education (India), who have published my earlier book also and have worked meticulously towards publishing this book too.

R.P. Deshpande

Contents