NIHAL KULARATNA

ENERGY STORAGE DEVICES FOR ELECTRONIC SYSTEMS

Rechargeable Batteries and Supercapacitors

Energy Storage Devices for Electronic Systems

Rechargeable Batteries and Supercapacitors

Nihal Kularatna
School of Engineering, The University of Waikato
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Dedication

This book is dedicated to Professor W. P Jayasekara,
who honourably dedicated his long academic career in Sri Lanka
to teach fundamentals of electrical
engineering to many engineering students,
supported by his capable team of academic staff at the Faculty of
Engineering,
and giving me,
the wisdom of applying simple fundamentals to practical circuits.

Preface

Electronic engineering advances at a rapid rate where designers and researchers are expected to maintain their *knowledge half-life* at 3-5 year levels. New subjects enter the field of electronics, and we have to keep up-to-date by learning these new subjects and still maintain our historic and practical experience-based know-how in the background to mix with the new subject areas. In this process one simple thing has never changed—that is the simple fundamentals we apply in circuits on a daily basis.

During my last 13 years of the full-time academic career, I have learned something important. If the simple fundamentals can be practically and effectively applied to new circuit topologies and state-of-the-art devices, we can come up with novel techniques, and develop them into very useful industrial applications, provided we also learn from our globally distributed subject experts and mix those knowledge elements with our own work. In this exercise, attributes such as perseverance, creativity, and life-long learning help us immensely.

This book is my eighth major work, and this is mostly based on my last 10 years of the academic and industrial experience in working with energy storage devices (ESDs), particularly in the subject of nontraditional supercapacitor applications. In this subject area, I was once again convincing myself of the most important aspect of learning—how to apply simple circuit fundamentals with new (energy storage or other) devices, with persevering efforts to understand the underlying physics and electrochemistry. Particularly in developing the Chapters 2, 3, and 5 of the work, I practically learnt that there is a massive ongoing concerted effort by the electrochemists, physicists, and technologists to enhance the performance specifications of ESDs. I sincerely thank all of them for their concerted efforts to give the electronic circuit and system designers new packaged devices where we could start with simplified equivalent circuits, and industrial device data sheets to develop new applications.

This work reflects a summary of the applications knowledge gained by a team of researchers lead by me in New Zealand, directly and indirectly supported by the concerted efforts of the global team. In this work, most of research projects we work on could help the nature and the environment too, with an effort to understand that the energy resources are limited and renewable energy area should be well supported by new research efforts on ESDs and applications.

Thank you,

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8th September 2014

Acknowledgments

From my university graduation with a degree in electrical engineering, I have spent over 38 years in the industry and academia, and completing almost 13 years in a full-time academic career in New Zealand. All my subject learning mixed with life experience tells me one thing... learning a subject is a life-long exercise, and it is a moving target. In this journey, all my school teachers, university teachers, senior industry engineers, and the mentors/advisors have helped me immensely. I thank all of them who helped me come a long-way in an electronic-engineering career.

For my engineering expertise I thank Professor W.P. Jaysekara and his team at University of Peradeniya, Sri Lanka who gave me the courage and the perseverance to think of fundamentals first in any EE project. My previous work places such as the Area Control Centre of Department of Civil Aviation, Sri Lanka; Saudi Telephone; Arthur C Clarke Institute for Modern Technologies (ACCIMT), Sri Lanka provided me all the opportunities to gain real-world on-the-job engineering experience, for which I am very grateful. At ACCIMT I was inspired by Sir Arthur C Clarke, and also he introduced me top US engineers such as John Robinson Pierce who named the transistor. I strongly believe that my mid-career was well supported by the opportunities, facilities, and the team at the ACCIMT and I am very thankful to Sir Arthur and the ACCIMT team with whom I worked for 16 years. I am very grateful to a mentor such as Prof Pierce, who guided me in 1992 on how to complete a book project successfully.

I am very thankful to Prof. John T. Boys of University of Auckland, who invited me to come into the academia in 2002. After 25 years in the industry, this move made me develop a new research area with an academic inclination into the depth of a selected subject utilizing my breadth of the subject area and a strong team work.

I thank all my colleagues and the senior management at the University of Waikato who continually encourage me to contribute. During the last 7 years with various commercial type grants from the university's commercial arm, WaikatoLink Limited (WLL), we were very much encouraged to develop new commercially useful supercapacitor-based techniques, and I am very thankful to the whole team at WLL. I am very thankful to Professors Janis Swan, Ilanko Sinniah, Brian Gabbitas who were my line managers who encouraged me to develop my academic research programs with a strong industrial flavor. In my post graduate research work, for cosupervision, I am very grateful to my colleagues such as Alistair Steyn-Ross, Rainer Kunnemeyer, Howell Round, and Sadhana Talele. I am also very thankful to my school administrators Janine Williams and Mary Dalbeth for assisting me on a daily basis to perform my teaching and research tasks effectively.

My former PhD student Kosala Gunawardane and the current student Jayathu Fernando are gratefully acknowledged for coauthoring three chapters of the work. Many other postgraduate students helped me developed lot of details in various research projects and I am thankful to all of them for their efforts, which are directly or indirectly used in chapter contents. Jayathu Fernando, Tanya Jayasuriya, and Dhanya Herath were helping me immensely to generate a significant number of figures required for the book and I am very thankful to him for that work.

From establishing the initial contract into the final production of the printed work I gratefully acknowledge the editorial and the production team of Elsevier with special thank you notes to Joe Hayton, Tiffany Gasbarriny, Kattie Washington, Preethy Mampally, and Chelsea Johnston. I also thank IEEE, PET Magazine, EDN, CRC Press, and Elsevier Publications for me to reuse various figures required in developing the manuscript. Natalie Guest, Nicoloy Gurusinghe, and Jayathu Fernando are gratefully acknowledged for the cover page image of the book.

In my home environment, I am fully supported and always encouraged by my loving wife Priyani, daughters Dulsha and Malsha, son-in-laws Rajith and Kasun to do my technical writing. I am most grateful to them for this continuous encouragement. Two little grand-daughters Nethuli and Mineli are keeping me and Priyani entertained and it provides me a reason to think of future and the environment.

I thank all my friends and extended families who have always appreciated my technical work and the authorship of technical books.

I trust that my current work on ESD applications will help the environment in the longer run, and provides us creative means apply these devices in unique ways.

Last, I thank all my past and future students who will use this new book and encourage them to point any errors, and suggestive improvements.

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9th September 2014

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Contents

Preface **xi**
Acknowledgments **xiii**

1 Energy storage devices—a general overview **1**

1.1 Introduction **1**
1.2 Simple fundamentals **2**
1.3 Energy storage in electrical systems **9**
1.4 Compressed air energy storage **20**
1.5 Superconductive magnetic energy storage **21**
1.6 Rapid energy transfer requirements and fundamental circuit issues **21**
1.7 Technical specifications of ESDs **25**
1.8 Ragone plot **26**
References **27**
Bibliography **28**

2 Rechargeable battery technologies: an electronic engineer's view point **29**

2.1 Introduction **29**
2.2 Battery terminology and fundamentals **30**
2.3 Battery technologies: an overview **36**
2.4 Lead-acid batteries **39**
2.5 Nickel-cadmium batteries **45**
2.6 Nickel metal hydride batteries **49**
2.7 Lithium-based rechargeable batteries **51**
2.8 Reusable alkaline batteries **55**
2.9 Zn-air batteries **56**
References **59**

3 Dynamics, models, and management of rechargeable batteries **63**

3.1 Introduction **63**
3.2 Simplest concept of a battery **63**
3.3 Battery dynamics **64**
3.4 Electrochemical impedance spectroscopy for batteries **72**
3.5 Battery equivalent circuit models and modeling techniques **76**
3.6 Battery management in practical applications **97**
3.7 Prognostics in battery health management **107**
3.8 Fast charging of batteries **111**

3.9 Battery communication and related standards 122
3.10 Battery safety 123
References 130
Bibliography 135

4 Capacitors as energy storage devices—simple basics to current commercial families 137
Kosala Gunawardane
4.1 Capacitor fundamentals 137
4.2 Capacitor types and their properties 142
4.3 Ragone plot 147
References 148

5 Electrical double-layer capacitors: fundamentals, characteristics, and equivalent circuits 149
Co-Author - Jayathu Fernando
5.1 Introduction 149
5.2 Historical background 149
5.3 Electrical double-layer effect and device construction 151
5.4 Pseudocapacitance and pseudocapacitors 164
5.5 Hybridization of electrochemical capacitors and rechargeable batteries 165
5.6 Modeling and equivalent circuits 168
5.7 Testing of devices and characterization 172
5.8 Modules and voltage balancing 178
References 182

6 Supercapacitor as a lossless dropper in DC-DC converters 187
Kosala Gunawardane
6.1 Introduction 187
6.2 DC-DC converters and DC power management 188
6.3 Supercapacitor assisted low dropout regulator (SCALDO) technique 196
6.4 Generalized SCALDO concept 199
6.5 Practical examples 202
6.6 SCALDO implementation examples 204
6.7 Wider applications of SCALDO technique 219
6.8 Comparison between SCALDO regulators and charge pumps 221
References 223

7 Supercapacitors for surge absorption 227
7.1 Introduction 227
7.2 Lightning and inductive energy dumps in electric circuits and typical surge absorber techniques 227
7.3 Supercapacitor as a surge absorption device: summarized results of a preliminary investigation 231

7.4 Design approaches to a supercapacitor-based surge protector **237**
7.5 Conclusion **243**
References **243**

8 Supercapacitors in a rapid heat transfer application **245**

8.1 Introduction **245**
8.2 Problem of wasted water in day-to-day situations at home **245**
8.3 Problem of traditional heating from direct AC mains supply and heating system specifications **246**
8.4 Commercial solutions for eliminating water wastage due to storage in buried plumbing **246**
8.5 Practical requirements for a localized solution **247**
8.6 SC-based solution with prestored energy **248**
8.7 Results from an ongoing prototype development exercise **251**
8.8 Specific advantages of SC energy storage **253**
8.9 Implementation challenges **254**
References **254**

Appendix A: capacitors and AC line filtering **257**
Index **263**

Energy storage devices—a general overview

1

1.1 Introduction

From the invention of the transistor in late 1940s, electronic products and systems have become an essential part of the modern world with interconnected global communication systems, intelligent white goods, electronic subsystem dominated automotive and a plethora of portable devices. With the world population growing beyond 7 billion in 2012, and with the portable electronic devices getting popular even in the poorest parts of the world, worldwide energy consumption keeps growing at a steady rate. In 2008, world's energy consumption was estimated to be around 144,000 TWh. Energy supply usually comes from several dominant sources, namely, fossil fuel and nuclear (as nondominant major sources), and from many renewable sources such as hydroelectric, solar, wind, geothermal, biomass, and biofuels.

In the world of energy usage, energy storage requirement comes in different forms. In our home and work environments, sometimes we need to store energy in systems such as the uninterruptible power supplies (UPSs) used for information systems and other critical facilities such as hospitals, airports, and factories in order to safeguard against power outages. In these situations, different types of energy storage systems (ESS) such as batteries, supercapacitor (SC) banks, flywheels, and compressed air are used together with suitable electromechanical energy conversion systems. In these systems, we usually deal with few 100 W to few megawatts order requirements with the outages expected in the range of fractional seconds to few hours.

In our modern hybrid electric vehicles (HEV) and electric vehicles (EV), battery banks and fuel cells are used to deal with kilowatt order requirements lasting for few minutes to few hours of driving, where the ESS comes into play. With the inefficiencies of internal combustion engine together with mechanical drive systems in the cars, overall energy efficiency is in the range of 15% to over 20%, encouraging the development of more energy efficient HEVs and EVs. In these applications, where tens of kilowatts of power is required, the capacity of the battery banks in terms of energy storage should be in the range of kilowatt-hours.

Compared to the above scenario, if we consider our portable electronic devices such as cell phones, PDAs, and laptops where battery packs are used, we commonly come across the capacity in terms of milliampere-hours (mAh) or ampere-hours (Ah), with battery packs with nominal voltage values varying from about 2.5 to about 16 V. Given these nominal voltage values, assumed to be constant over the operational range, will give us the energy storage capacity in mWh to Wh. Compared to the two above application areas, if we take much smaller power and energy requirements such as wrist watches, hearing aids and implants, the battery pack capacity may be specified in microwatt-hours to few milliwatt-hours only. Terminal voltages of these

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battery packs, mostly coming in the form of one or few single cells, may be in the range of 0.5 V to few Volts per cell.

Given a few common day-to-day examples of battery-based systems, we could practically appreciate that a few commonly identified electrical parameters such as terminal voltage, and the energy storage capacity in terms of Watt-hours or milliwatt-hours allow us to compare the capabilities of the battery packs. If a load consumes power at a steady rate of 1 W for 1 h, the device has consumed a total energy of 1 Wh during that period. In standard SI units, this translates to a value of 3600 J, since 1 W dissipated during 1 s is equal to 1 J.

So far we have considered only batteries as an energy storage device (ESD) family, but in general many different methods and devices can be used for energy storage suitable for electrical and electronic systems. This chapter provides an overview of energy storage and delivery devices, methods, and the essential fundamentals applicable to energy transfer into electronic systems and devices. With some quantification approach, the contents will assist comparing the details of energy storage capabilities, and energy delivery capabilities and limitations of ESDs in electronic environments in a practically useful way. The contents of this and the overall work are aimed as a practical guideline to engineers, designers, and researchers working in these areas. Reader is expected to have some essential prior knowledge on circuit theory applicable to simple circuits.

1.2 Simple fundamentals

Let us start with the simple analogy of a water tank at a certain height above the ground level. If we have a hose connected from the bottom of the tank, with a tap connected at the end of the hose, water flow starts when the tap is opened. We can measure the rate of water flow in terms of liters/second. If you consider the tank as the storage device, at this rate we can estimate the time to release the total quantity of water. If we make the tank bigger, we get more quantity of water stored in the tank. If the bottom of the tank is at the same level as before, we will have the same rate of flow at the end of the pipe. We will take a longer time to release that water at that same rate. Now we can raise the bottom level of the tank which will increase the rate of flow. This means the tank will empty faster. We can also increase the diameter of the water hose connected to achieve a higher flow rate of water. This happens since the resistance to water flow will reduce due to higher diameter of the hose. If you increase the length of the hose, the flow rate will be slower.

The above simple analogy helps us understand ESDs. The level of the water tank (above the reference level of ground) is analogous to the (positive) terminal voltage of the device of the with respect to the negative terminal (which is the reference voltage level). Volume of the tank is analogous to the amount of total charge (or energy) available for release into the external circuit. Water flow in the hose is analogous to the current (in Amperes or coulombs/second) in the external circuit. By changing length or diameter of the hose, we create the analogy of a resistance of a conductor (which

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