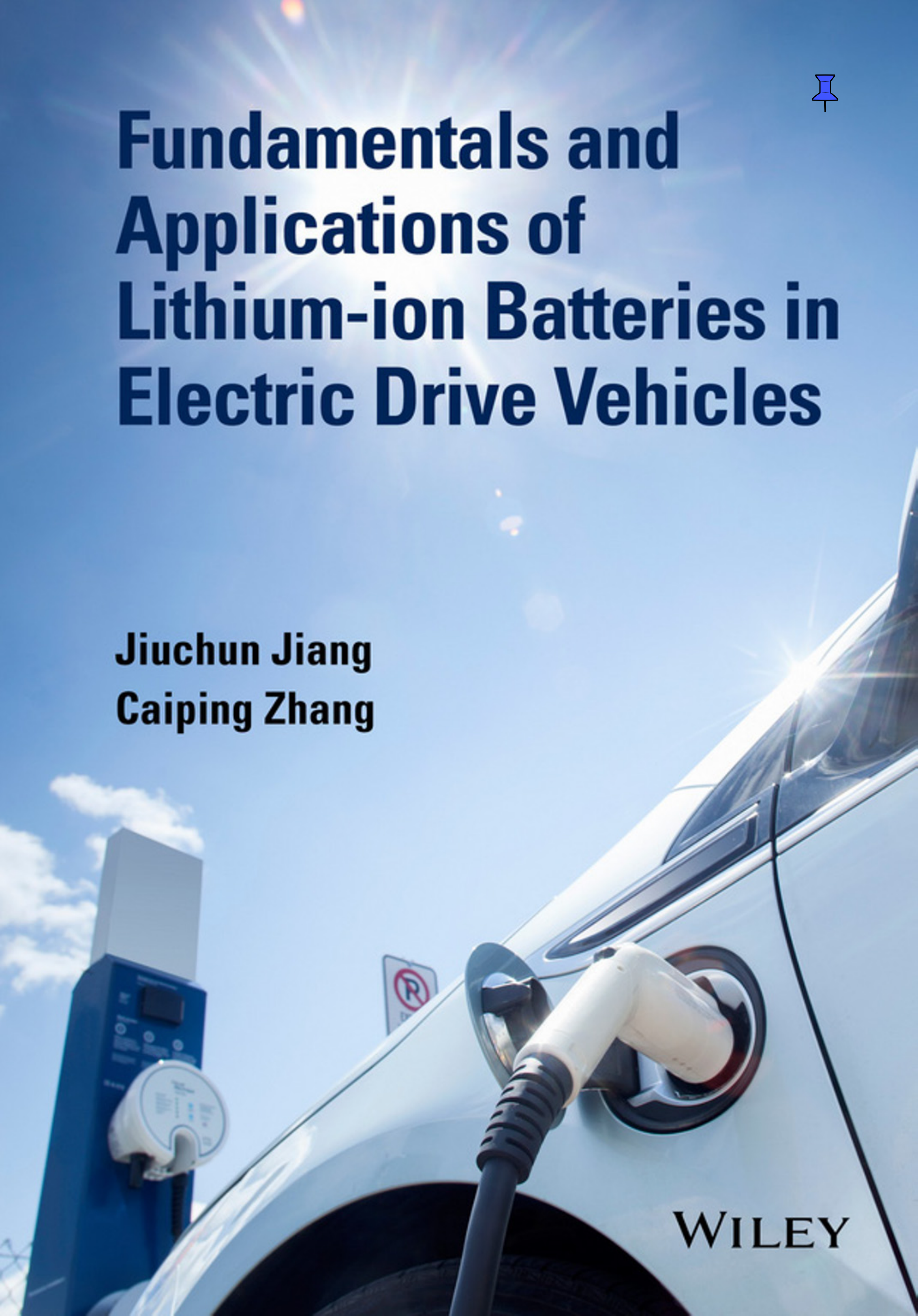
Fundamentals and Applications of Lithium-ion Batteries in Electric Drive Vehicles

Jiuchun Jiang
Caiping Zhang



WILEY

FUNDAMENTALS AND APPLICATIONS OF LITHIUM-ION BATTERIES IN ELECTRIC DRIVE VEHICLES

FUNDAMENTALS AND APPLICATIONS OF LITHIUM-ION BATTERIES IN ELECTRIC DRIVE VEHICLES

Jiuchun Jiang
and
Caiping Zhang
Beijing Jiaotong University, China

WILEY

This edition first published 2015

Registered Office
John Wiley & Sons Singapore Pte. Ltd., 1 Fusionopolis Walk, #07-01 Solaris South Tower, Singapore 138628.

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

Jiang, Jiuchun.
Fundamentals and applications of lithium-ion batteries in electric drive vehicles / Jiuchun Jiang, Caiping Zhang.
pages cm
Includes bibliographical references and index.
ISBN 978-1-118-41478-1 (cloth)
1. Electric vehicles–Batteries. 2. Lithium ion batteries. I. Zhang, Caiping (Chemist) II. Title.
TL220.J53 2015
629.25′02–dc23

2014040218

Set in 10/12pt Times by SPi Publisher Services, Pondicherry, India

1 2015

Contents

About the Authors

Professor **Jiuchun Jiang** is the Dean of the School of Electrical Engineering at the Beijing Jiaotong University, China. He has more than 17 years research experiences in renewable energy technology, management of advanced batteries and EV infrastructural facilities. He has more than 50 publications and holds 8 patents. His research has contributed to the commercial battery management system (BMS) products. The developed BMS products ranked first in the domestic market in the last three years. He has also designed a number of large scale battery charging stations, such as for the Beijing Olympic Games, the Shanghai World Expo, and the Guangzhou Asian Games. He was the winner of China National Science and Technology Progress Award and Ministry of Education Science and Technology Progress Award.

Caiping Zhang is an associate professor with the National Active Distribution Network Technology Research Center, School of Electrical Engineering, Beijing Jiaotong University. She has more than 10 years research experience in the field of battery modeling and simulation, states estimation, battery charging, and battery control and optimization in electric vehicles. She also does research on the reuse technology of EV used batteries and battery energy storage systems. She has had more than 20 publications in the last five years.

Foreword

Battery management is not a new concept—monitoring and control concepts were proposed as early as the 1960s to improve battery safety. After years of intensive study, it remains a field needing more research. This is not because we did not learn much during the past 50 years, we did. But the subject of study is rapidly changing. The materials and structure of the battery anode, cathode and electrolytes continue to evolve and improve, and the electrochemistry and aging mechanisms also continue to change. The performance and capacity of batteries degrade due to the disordering and deforming of electrode structure, decomposition of the electrolyte, dissolution of metal, dendrite formation, and so on. The relative importance of these mechanisms is battery-chemistry dependent, and the rate of degradation changes significantly with many factors, including operating temperature, charge and discharge rate, and depth of discharge. Finally, these aging mechanisms happen at different timescales, posing challenges to data collection and analysis. The safety incidents of the Boeing Dreamliner battery systems in 2012 remind us that much remains to be done before advanced high energy density battery systems can be used safely and reliably in challenging applications such as aircraft and electric vehicles.

While the interaction among many chemical and physical reactions makes it a challenging task to fully understand battery safety and reliability, model-based battery managing algorithms start to appear, showing excellent potential in engineering applications. This book by Professor Jiuchun Jiang reports his research outcome and contribution made over the last 17 years. Most notable contents included in this book are his work on the lithium-ion battery performance model, methods to estimate lithium-ion battery state of charge, state of energy, and peak power, charging technique, and battery equalization techniques. These functions are critical in the pursuit of safer and more reliable battery systems. After we gain better understanding and confidence, the cost of battery systems will reduce through reduced over-design. All of these are existing barriers for wider adoption of advanced batteries in transportation applications.

I recommend this book not only because of its solid technical content, but also because of the unique role Professor Jiang plays in the development of battery management systems in China. The results reported in this book are based on his extensive experience in designing commercial battery management systems and charging stations used in large demonstration projects held during the Beijing Olympic Games, Shanghai World Exposition, and Guangzhou Asian Games. I think this book is a must-read for anyone who wants to learn more about vehicle lithium-ion battery management technologies developed and used in China.

Huei Peng
Professor, University of Michigan
Director, US-China Clean Energy
Research Center-Clean Vehicle Consortium

Preface

The power battery is the main power source for electric vehicles; its performance has vital influence on the safety, efficiency and economy of electric vehicle operations. Currently power batteries for electric vehicles mainly include lead-acid, nickel cadmium, nickel metal hydride and lithium-ion batteries. For a long time, the lead-acid battery was widely used because of its mature technology, stable performance and low price. However, its disadvantages of low energy density, long charging time, short life, and lead contamination limit its usefulness in electric vehicles. The nickel cadmium battery has been used for its large charge-discharge rate; however, its disadvantages of memory effect and heavy metal contamination cannot be solved. Nickel-metal hydride batteries have been widely applied in hybrid cars for their large charge-discharge rate and they are environmentally friendly. However, their single cell voltage is low and they should not be connected in parallel, restricting their application in electric vehicles. The lithium-ion batteries are widely accepted because of their high voltage platform, high energy density, good cycle performance, and low self-discharge, and are regarded as a good choice for the new generation of power batteries. The lithium-ion battery cathode material can be lithium cobalt oxide, manganese oxide, lithium iron phosphate, nickel manganese cobalt oxide, lithium nickel cobalt aluminum oxide, and so on.

Currently, one of the key factors restricting the development of electric vehicles is that the battery power is not satisfactory; the battery specific energy, specific power, consistency, longevity, and price are not as good as expected. A battery acts as a power system which converts electrical energy and chemical energy. Its operation is very complex because the reactions are related to temperature, accumulated charge-discharge, charge-discharge rate and other factors. The battery management system (BMS) protection mainly ensures that the battery works within reasonable parameters. It detects voltage, current,and temperature of the battery pack and relays this information. It carries out thermal management, balancing control, charge and discharge control, fault diagnosis, and CAN communication. It also estimates the SOC and SOH at the same time.

The BMS needs people who are familiar with both the electrochemical properties of the battery and its electrical applications. It is necessary to write an instruction book since there are not many people with this compound knowledge. This book provides basic theoretical knowledge and practical resource materials to researchers engaged in electric vehicles and lithium-ion battery development and design, and people who work on the battery management system.

In this book we discuss key technologies and research methods for the lithium-ion power battery management system, and the difficulties encountered with it in electric vehicles. The contents include lithium-ion battery performance modeling and simulation; the theory and methods of estimation of the lithium-ion battery state of charge, state of energy and peak power; lithium-ion battery charge and discharge control technology; consistent evaluation and equalization techniques of the battery pack; and battery management system design and application in electric vehicles.

This book focuses on systematically expounding the theoretical connotation and practical application of the lithium-ion battery management systems. Part of the content of the book is directly derived from real vehicle tests. Through comparative analysis of the different system structures the related concepts are made clear and understanding of the battery management system is deepened.

In order to strengthen the understanding, the book makes deep analysis of some important concepts. Using simulation technology combined with schematic diagrams, it gives a vivid description and detailed analysis of the basic concepts, the estimation methods and the battery charge and discharge control principles, therefore the descriptions are intuitive and vivid, readers can have a clear understanding of the principle of battery management system technology and, combined with case analysis, the readers' perceptual knowledge is enhanced.

The contents are summarized as follows:

Chapter 1 is an introduction, which presents the terms, types and characteristics of the power battery, and the functions and key technologies of the battery management system.

Chapter 2 introduces the operating principle, charge and discharge characteristics, model classification and characteristics of the lithium-ion battery, and performance simulation of the equivalent circuit model.

Chapter 3 introduces the definition and estimation methods for battery SOC and SOE.

Chapter 4 introduces the definition and test methods of battery peak power, and the determination of available power for a battery pack.

Chapter 5 introduces lithium-ion battery optimization charging methods, taking charge life and charge time together into account, and expounds battery discharge control technology combined with vehicle operational states, battery SOE and SOC.

Chapter 6 introduces the reasons for inconsistency of a battery pack and battery consistency evaluation parameter indexes, and describes the battery equalization method and strategy.

Chapter 7 introduces the structure of the BMS, the battery parameter collection scheme, logical control and security alarm theory of BMS, and BMS application analysis in electric vehicles.

This book is a group achievement of the faculties and PhD students of the National Active Distribution Network Technology Research Center (NANTEC), Beijing Jiaotong University (BJTU). The book benefits from their hard work in the field of electric vehicle battery management, and tireless efforts to provide the most advanced knowledge and technology over decades. The faculties involved in the preparation are Weige Zhang, Zhanguo Wang, Minming Gong, Bingxiang Sun, Wei Shi, Feng Wen, Jiapeng Wen, Hongyu Guo, and so on. The students involved are Zeyu Ma, Dafen Chen, Xue Li, Fangdan Zheng, Yanru Zhang, and so on. We would like to express our sincere thanks to them all!

Jiuchun Jiang and Caiping Zhang
NANTEC, BJTU
Beijing, China

1

Introduction

1.1 The Development of Batteries in Electric Drive Vehicles

1.1.1 The Goals

Energy and environmental issues have long been challenges facing the world's automotive industry. In recent years, the grim energy and environmental situation around the world has accelerated the strategic transformation of transportation and energy technology, and thus set off a worldwide upsurge of new energy vehicle development. Under the various scenarios depicted in the technology roadmaps of new energy vehicles, hybrid electric vehicles (HEV), battery electric vehicles (BEV), and fuel cell vehicles (FCEV) are generally considered as important development directions for future automotive energy power systems, and have become a high strategic priority of major automobile manufacturers worldwide.

The power battery is an important component of an electric vehicle (EV), directly providing its source of energy. In general, the goals for a powertrain system in EVs are: excellent safety, high specific energy, high specific power, good temperature characteristics, long cycle life, low cost, no maintenance, low self-discharge, good consistency, no environmental pollution, good recoverability, and recyclability. In BEV, the specific energy determines the total driving distance in the pure electric drive mode; the specific power determines the vehicle dynamics, such as the maximum gradeability and the maximum vehicle speed; and the cycle life and the cost of the powertrain system have direct effect on EV manufacture and running costs. For a long time, battery technology has been a bottleneck in the development of EVs; some existing battery technologies have achieved some of these goals, but it is far more challenging to meet all the goals simultaneously [1].

1.1.2 Trends in Development of the Batteries

Power batteries used in EVs basically include nickel-metal hydride and lithium-ion batteries (LIBs). The nickel-metal hydride batteries are widely used in HEVs owing to their high charge-and-discharge rate and environmentally friendly features. However, the application

Fundamentals and Applications of Lithium-ion Batteries in Electric Drive Vehicles, First Edition.
Jiuchun Jiang and Caiping Zhang.

of nickel-metal hydride batteries in EVs remains limited because they have low voltage and are unsuitable for parallel connection. The LIBs, with the advantages of a high voltage performance platform, such as high energy density (theoretical specific capacity reaches 3860 mAh g^{-1}), environmentally benign features, wide operating temperature range, low self-discharge rate, no memory effect, high efficiency, and long cycle life, have become widely accepted in recent years, and have become one of the most important components for the new generation of EVs.

LIBs can be classified into lithium cobalt oxide, lithium manganate (LMO), lithium iron phosphate (LFP), lithium-polymer, and lithium nickel-manganese-cobalt (NMC) batteries, which are based on positive active materials. The comparisons of various materials are shown in Table 1.1 [2]. Lithium cobalt oxide and nickel acid lithium batteries, developed earlier, have encountered a bottleneck owing to the use of cobalt and nickel, which have high costs and poor consistency. The LMO and LFP batteries have more application opportunities in EVs in recent years, with the progress in technology and enhancement of safety performance; safety no longer being a concern due to the improvement of consistency and elimination of explosion risk. At the Beijing Olympic Games, 50 pure electric buses used LMO batteries as the power system, the Shanghai World Expo and Guangzhou Asian Games, used 60 and 35 units, respectively. A type of 8-ton sanitation truck produced by Foton Motor and a large number of trolleybuses in Beijing also use LMO and LFP batteries as a power source. Furthermore, EVs developed by most automobile manufacturers in China use LFP batteries as the power system, such as the E6 pure electric taxi by BYD, 2008EV, and 5008EV by Hangzhou Zhongtai, "Tongyue" pure electric cars by JAC, Bonbon MINI pure electric cars by Chang-an Automobile, S18 pure electric cars by Chery, and so on. So far, the E6 pure electric taxi by BYD, 2008EV, and 5008EV by Hangzhou Zhongtai, and "Tongyue" pure electric cars by JAC have achieved small-scale mass production and have been put into demonstration operation.

It is noticeable that the LIBs, which have lithium titanate (LTO) as a negative electrode, have attracted wide attention in recent years, because of their wide working temperature range, good ratio characteristics and long cycle life. However, they have been merely experimentally

Table 1.1 Comparisons of different types of LIB.

Category of lithium batteries	Lithium cobalt oxide	Lithium iron phosphate	Lithium manganate	Lithium titanate	Ternary materials	Lithium-polymer
Advantages	Good reversibility, high energy density	Long cycle life, high safety	Rich resources, high safety	Long cycle life, high safety, good rate characteristics	Good cycling performance and good thermal stability	Strong over-charge abilities
Disadvantages	Poor cobalt resource, bad anti-abuse capabilities	Low energy density, poorly conductive	Poor recycling performance in high temperature	Low density, high cost	High cost, complicated manufacturing process	Low density, long cycle life

demonstrated on EVs owing to their low energy density, higher cost, immature bulk production technology, and so on.

1.1.3 Application Issues of LIBs

Although LIBs, with their superior performance, have been widely used in portable devices, they have limited application in EVs, the main reasons being summarized below.

1.1.3.1 Poor Working Environment

1. A large number of large capacity batteries are used through series and parallel connection. In order to reach the corresponding level of voltage, power, and energy, a large number of large-capacity batteries need to be used in EVs through series and parallel connection, which requires high consistency among the battery pack. Additionally, different from an individual battery, grouping management in a battery pack also requires more advanced technology.
2. Large working current and extreme current fluctuation. Figure 1.1 [3] shows the working current, representative cell voltage and the speed of the Beijing Olympic Games EV bus during the acceleration process. It can be seen that the battery current is high (maximum value over 350 A) and changes quickly (the time to change from 300 to 0 A is <0.5 s), which may result in over-discharge and over-heating, as well as the problem of capacity and low energy utilization, and also may cause difficulty for the online estimation of the battery state.
3. Limited space. This may increase the difficulty of the assembly process, heat radiation and cooling ventilation design of battery systems (including batteries, battery management

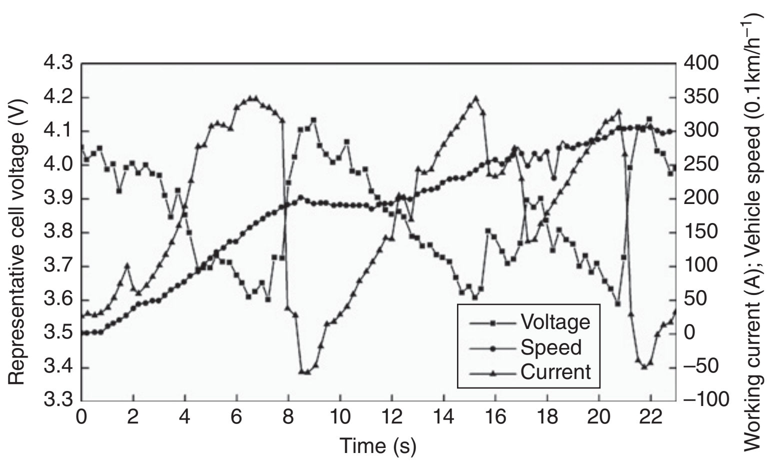


Figure 1.1 Acceleration curve of Olympic EV buses. (Reproduced with permission from Feng Wen, "Study on basic issues of the Li-ion battery pack management technology for Pure Electric Vehicles.", Beijing Jiaotong University ©2009.)

system (BMS), and protection modules). For example, if the battery works in a high temperature environment for a long time, the decrease in battery capacity will be accelerated, which may even result in thermal runaway and cause safety risks. Further, temperature fluctuation will cause differences between the degradation speed and the self-discharge coefficient, which may lead to accelerated inconsistency of the battery pack, capacity loss, and low energy utilization. Realizing efficient management of the battery pack poses a far more serious challenge in battery research and development.

4. Poor working conditions. Vehicle bumping and shaking requires higher anti-shock and anti-vibration performance; dusty, rainy, and line wear conditions may cause short circuit or other insulation problems.

1.1.3.2 Poor Anti-Abuse Capabilities

The anti-abuse capability of LIBs is insufficient. More specifically, irrational use (such as operation at high or low temperature regularly or for a long time, too high or low state of charge (SOC), over-current, etc.) will substantially shorten the battery life. Such battery abuse may cause battery failure, and even fire, explosion, or other safety problems.

1.1.4 Significance of Battery Management Technology

In order to improve the performance of future LIBs, researchers in the electrochemistry field have conducted further research on LIBs in terms of the electrochemical mechanism, including the effects of temperature [4, 5], voltage, current, and aging on the battery performance [6–8], the influence of over-charge, over-discharge [9], over-current and over-heating [10], and so on. By enhancing the anode and cathode materials, additives, binder, doping and coating, electrolyte formula and technology, the energy density, power density, and safety, the cycle life of individual LIBs has been improved significantly.

The cycle life of a battery pack, serially connected LIBs used in EVs, is shorter than that of an individual cell. The manufacturer's technical specification only determines the initial performance of the batteries but. during the operation process, the battery parameters are always changed by the operating environment, working conditions, and aging status. Therefore, to avoid abuse and irrational use, the control strategy of the batteries needs to be in accordance with the change in the battery parameters.

Battery management technology aims to optimize usage. First, this technology could avoid abuse and irrational use to ensure safety and to extend the life of batteries. Secondly, it may timely detect and estimate the state of the batteries (including external voltage, temperature, current, DC resistance, polarization voltage, SOC, the maximum available capacity, consistency, etc.). Thirdly, it should maximize the performance of batteries to ensure that the vehicles can be run efficiently and driven comfortably. Ultimately, researchers should realize high efficiency of battery capacity and energy utilization with battery management technology. The importance of battery (group) management techniques has gradually been widely recognized by researchers in battery technology. In this book, from the application perspective, basic issues of LIB management technology are discussed in order to provide a theoretical basis and technical support for a secure, efficient and long-life application in EVs.

1.2 Development of Battery Management Technologies

The battery management technologies have developed from no management and simple management to comprehensive management.

1.2.1 No Management

For a long time, lead-acid batteries dominated the market because of their mature process, good anti-abuse capabilities and low price. However, development of the technology of battery management has lagged behind owing to the lack of connection with the market. In single cell applications, SOC estimation and charge–discharge control were based on the cell external voltage (the cell terminal voltage is called the external voltage in order to distinguish it from the terminal voltage of the battery pack). After series connection, a simple expansion was produced on the basis of single cell management technology. Based on the battery pack terminal voltage, SOC estimation and charge–discharge control were realized by researchers.

Practical application results demonstrated that the life of the battery pack in series connection was significantly shorter than that of a cell. By testing the limitation of the life of the battery, it was found that the management pattern was based on the battery terminal voltage which neglects the differences among cells. This situation resulted in some of the batteries in the pack being over-charged or over-discharged, which was the main reason for the reduction in the lifespan of the battery pack. Therefore, battery consistency was examined on a regular basis (such as once a month). In addition, the batteries with lower voltage were separately charged to ensure the battery's consistency, which thereby decreased the probability of over-charge and over-discharge. By periodically (e.g., once every 6 months) fully charging and discharging all cells, the battery pack capacity and states could be determined, which could prevent batteries from working in a fault status for a long time, and, to some extent, could expand the life of the battery pack. This was a rudiment of the BMS, whose functions included fault diagnosis, SOC and capacity estimation, as well as the evaluation of battery pack consistency.

1.2.2 Simple Management

With wide applications of the batteries, the problems of the traditional management approach became apparent, such as non-online detection, low automation, time-consuming periodical maintenance, and serious energy loss. The equipment used to monitor and manage batteries is called the BMS. The basic functions of the BMS are:

1. Online monitoring of battery external parameters, such as voltage, temperature, current, and so on.
2. Battery fault analysis and alarm.
3. Starting the cooling fan when the battery temperature is high.
4. Battery pack SOC estimation.

The BMS effectively reduces manual detection work, and improves automation and security of batteries utilization. However, it has some disadvantages. The BMS replaces the traditional manual operation with automated detection. The traditional manual operation could only discover the problems and raise the alarm, but could neither ensure the consistency of the battery pack, nor provide a guide to battery maintenance. Therefore, the workload and complexity of battery maintenance are not reduced.

Most BMS designers are electrical engineers, so their study focuses on the optimal design of the battery circuit detection, to improve the accuracy, anti-interference and reliability. They regard the batteries as a “black box” due to their insufficient knowledge of the electrochemistry of batteries, and analyze battery status and usage in terms of external characteristics. They consider the battery pack as a “big battery”, even though the batteries are serially connected into a group. They have made achievement in management research through a simple expansion based on single cell management technology, and therefore realized state estimate and charge–discharge control on the basis of the terminal voltage of the battery pack.

However, this method cannot ensure the accuracy of the estimation of the battery SOC. The issue that the battery pack has a shorter lifespan than a single cell still exists. This is because the BMS cannot play an effective role in the management and control function, only provide automatic detection of the external characteristics of the batteries and give a fault alarm. Hence, it is just a monitoring system and does not achieve optimal usage and effective management of the batteries.

1.2.3 Comprehensive Management

LIBs, with their excellent performance, have been widely used in portable devices and EVs. The anti-abuse capabilities of LIBs are inefficient. When the simple BMS is applied to LIBs, especially a battery pack in series, safety incidents repeatedly occur, showing that the states estimation and charge–discharge control method, based on the battery external characters, could not ensure the safety and life of the battery pack.

More attention has been paid to battery management technology in recent years, and, with the endeavor of researchers over time, its function can now be defined explicitly:

1. Real-time monitoring of battery states. By measuring external characteristic parameters (such as the external voltage, current, cell temperature, etc.), with the appropriate algorithm, BMS could realize estimation and monitoring of battery internal parameters and states (such as the DC resistance, polarization voltage, maximum available capacity, SOC, etc.)
2. Efficient battery energy utilization. Provide a theoretical basis and data support to battery usage, maintenance and equalization.
3. Prevent over-charge or over-discharge of the battery.
4. Ensure user safety and extend battery life.

In order to achieve the above objectives, researchers focus on battery modeling, SOC estimation, consistency evaluation and equalization. Although battery management technology has developed rapidly, there are some difficulties in the following aspects.

1. Interdisciplinary. Battery management technology involves electrochemistry, electricity, thermology, and so on.

2. Multi-variable coupling. The performances of the battery are affected by mutual coupling components, such as temperature, voltage, current, SOC, working conditions, aging and other factors.
3. Nonlinearity. The battery temperature and degradation are nonlinearly related to battery internal resistance, polarization voltage, discharge capacity and rate characteristics.
4. Universality. The battery performances of various manufacturers differ with regard to self-discharge, temperature performance, capacity, internal resistance, and so on. Therefore, it is important to seek out a refined management method generally applicable to a state estimate algorithm and charge–discharge management.
5. Battery pack consistency. Difficulty remains in accurate states estimation and efficient management resulting from the differences between cells.

1.3 BMS Key Technologies

The development history of the BMS is from an initial independent monitoring system to data interaction and management with the vehicle and charging devices. Eventually, BMS realizes an optimal match with the vehicle system and its normative development procedure. The role of the BMS is thus substantially expanded, its key technologies are:

1. Battery state estimation. Battery state estimation is expanded from just SOC to state of energy (SOE), state of function (SOF), and state of health (SOH). Battery performance is evaluated from the energy, the maximum available charge and discharge power/current, the battery SOH, and other indicators, thus realizing an accurate estimate of the battery state.
2. Battery equalization. With the increase in the number of EVs demonstrations, heavy regular maintenance workload and other issues are becoming increasingly prominent. Battery equalization is becoming the obstacle for the development of EVs. BMS equipped with an equalization function is becoming the standard configuration of a power battery system. The balancing current is designed from tens of milliamperes to several amperes. The equalization pattern includes passive balancing or active balancing or both. The equalization objective is good voltage consistency, and maximum capacity and energy utilization. After the design of thermal management, a consistency evaluation method and systematic resolution of the actual demands of the equalization current, a rational and effective battery equalization system could become a reality.
3. Battery safety management. Battery safety is the basic requirement in the battery systems. A BMS can not only prevent a battery from over-charge, over-discharge, over-heating, and over-current by power control and diagnostic alarm, but also has the functions of high voltage interlock and insulation detection. In addition, from preliminary exploration, humidity sensors and collision sensors are suitable for automotive application.

In this book we will describe and discuss the key technologies and research methods of the lithium-ion power BMS. There are five main parts: LIB performance modeling and simulation; the theory and methods of estimation of the LIB SOC, SOE, SOH, and peak power; LIB charge and discharge control technology; techniques for the consistent evaluation and equalization of the battery pack: and finally BMS design and application in electric drive vehicles. In this book, part of the contents and graphics are taken directly from real vehicle tests. In general, this book describes the relevant concepts and fundamentals in detail through comparative analysis of various systems structures and scenarios.

References

[1] Chen, Q. and Sun, F. (2002) *Modern Electric Vehicles*, Beijing Institute of Technology, Beijing.
[2] Huang, K., Wang, Z., and Liu, S. (2008) *Fundamentals and Key Technologies of Lithium-Ion Batteries*, Chemical Industry Press, Beijing.
[3] Wen, F. (2009) *Study on basic issues of the Li-ion battery pack management technology for pure electric vehicles*. PhD thesis. Beijing Jiaotong University.
[4] Zhang, S.S., Xu, K., and Jow, T.R. (2006) Charge and discharge characteristics of a commercial $LiCoO_2$ based 18650 battery. *Journal of Power Sources*, **160**, 1403–1409.
[5] Xiao, L. (2003) *Studies of the problems related to the development of high performance lithium-ion patteries*. PhD thesis. Wuhan University.
[6] Ramadass, P. (2003) *Capacity fade analysis of commercial Li-ion batteries*. PhD thesis. University of South Carolina.
[7] Zhang, Q. and White, R.E. (2008) Calendar life study of Li-ion pouch cells: Part 2: Simulation. *Journal of Power Sources*, **179**(2), 785–792.
[8] Kwak, G., Park, J., Lee, J. *et al.* (2007) Effects of anode active materials to the storage-capacity fading on commercial lithium-ion batteries. *Journal of Power Sources*, **174**(2), 484–492.
[9] Zhang, S.S., Xu, K., and Jow, T.R. (2006) Study of the charging process of a $LiCoO_2$-based Li-ion battery. *Journal of Power Sources*, **160**, 1349–1354.
[10] Kima, G.-H., Pesaran, A., and Spotnitz, R. (2007) A three-dimensional thermal abuse model for lithium-ion cells. *Journal of Power Sources*, **170**, 476–489.

2

Performance Modeling of Lithium-ion Batteries

The battery model describes the mathematical relationship between voltage, power, current, state of charge (SOC), temperature, and other factors which impact performance during working. It not only shows the basis of state estimation, performance analysis, scientific evaluation and use, but also works as a bridge from external characteristics to the internal state. So the battery model has been of wide interest to researchers.

2.1 Reaction Mechanism of Lithium-ion Batteries

A lithium-ion battery is a high-energy battery in which Li^+ embeds into and escapes from positive and negative materials when charging and discharging. As illustrated in Figure 2.1, from left to right, a battery consists of a cathode current collector, negative electrode active materials, electrolyte, a separator, positive electrode active materials, and an anode current collector. Positive electrode materials of lithium-ion batteries are intercalation compounds of lithium-ion, commonly $LiCoO_2$, $LiNiO_2$, $LiMn_2O_4$, $LiFePO_4$ and $LiNixCo_{1-2x}Mn_xO_2$, and so on. Negative electrode materials are commonly Li_xC_6, TiS_2, V_2O_5, and so on. The electrolyte is an organic solvent in which the lithium salts, such as $LiPF_6$, $LiBF_4$, $LiClO_4$, $LiAsF_6$, and so on, are soluble. The solvents are mainly ethylene carbonate (EC), propylene carbonate (PC), dimethyl carbonate (DMC), chlorine methyl carbonate (ClMC), and so on. The main role of the separator in a battery is to isolate the positive and negative electrodes, while allowing the transport of ions. Recently, a microporous membrane of polyethylene (PE) or polypropylene (PP) has been used commercially as a separator.

Li ions deintercalate from the cathode compound and intercalate into the lattice of the anode during the charging process. The cathode has high potential and poor lithium state, while the anode has low potential and rich lithium state. When discharging, the Li^+ escapes from the anode and embeds into the cathode, producing a rich lithium state at the cathode. So the charging and the discharging process of batteries is also a deintercalation and intercalation process of lithium back and forth between the two electrodes, hence the name "rocking chair batteries". To keep the charging balance, during the charging and discharging process, the same number of

Fundamentals and Applications of Lithium-ion Batteries in Electric Drive Vehicles, First Edition.
Jiuchun Jiang and Caiping Zhang.

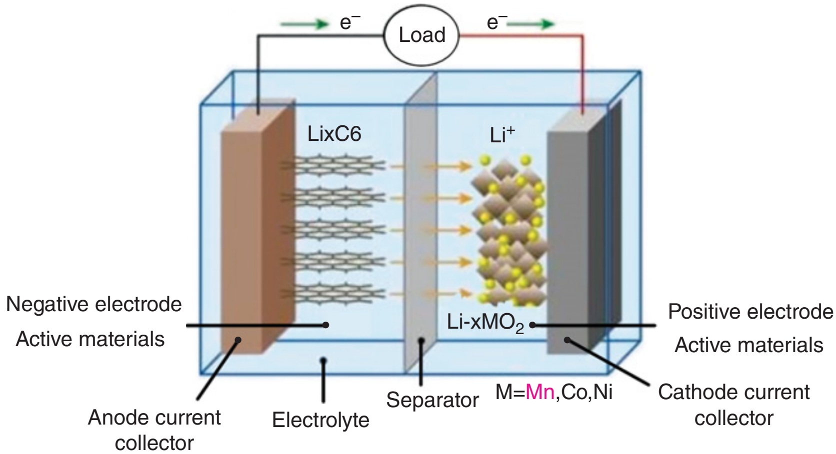


Figure 2.1 Schematic of the discharging process of lithium-ion batteries.

electrons move with the Li^+ between the cathode and anode through the external circuit. Thus a redox reaction occurs between the cathode and the anode.

Considering lithium manganese oxide (LMO) batteries as an example, during charging the Li^+ escapes from the $LiMn_2O_4$ at the cathode, under the electromotive force, the Li^+ passes through the electrolyte and embeds into the carbon interlayer of the graphite. Thus the lithium and carbon interlayer are combined internally. When discharging, the Li^+ escapes from the carbon interlayer of the anode, through an opposite process under the electromotive force, and embeds into the anode $LiMn_2O_4$. The reactions of the batteries are: Reaction in the anode:

$$LiMn_2O_4 \underset{\text{discharge}}{\overset{\text{charge}}{\Leftrightarrow}} Li_{1-x}Mn_2O_4 + xLi^+ + xe^- \tag{2.1}$$

Reaction in the cathode:

$$C + xLi^+ + xe^- \underset{\text{discharge}}{\overset{\text{charge}}{\Leftrightarrow}} Li_xC \tag{2.2}$$

Overall reaction:

$$LiMn_2O_4 + C \underset{\text{discharge}}{\overset{\text{charge}}{\Leftrightarrow}} Li_{1-x}Mn_2O_4 + Li_xC \tag{2.3}$$

120 pure electric buses were demonstrated in the Shanghai World Expo, using two types of LIBs, LMO and lithium iron phosphate batteries as their power sources. Their basic performance parameters are shown in Table 2.1.

Table 2.1 Comparison of the performance parameters of lithium manganese oxide and lithium iron phosphate batteries.

Indicators	Lithium manganese oxide battery	Lithium iron phosphate battery
Nominal cell voltage (V)	3.7	3.2
Nominal capacity (Ah)	360	255
Battery pack voltage (V)	312–437	527–595
Maximum discharge current (A)	360	300
Weight (kg)	~1670	~2050
Working temperature (°C)	−10 to 40	−10 to 40
Safety	Reliable	Reliable

2.2 Testing the Characteristics of Lithium-ion Batteries

2.2.1 Rate Discharge Characteristics

A battery module of 16 lithium-ion cells with nominal capacity of 100 Ah is considered. The relationship between the voltage and the discharged capacity of the battery module under different discharging current at room temperature is shown in Figure 2.2.

Figure 2.2b is a partial enlarged drawing of Figure 2.2a. The discharging capacities are 93.43, 94.43, 94.55, 95.24, and 95.96 Ah, respectively, at the points M1, M2, M3, M4, and M5 with constant current regime 200 A(2 C), 150 A(1.5 C), 100 A(1 C), 50 A(0.5 C), and 33 A(1/3 C), respectively. The open-circuit voltages after keeping in the open-circuit state for 1 h are 54.85, 54.15, 53.44, 52.83, and 52.48 V, respectively. It is seen that the open-circuit voltages increase when the discharging current increases. The decrease in the capacity is not apparent as the discharging current increases. The discharging capacity with the current of 200 A only decreases by 2.6% compared to the discharging capacity with the current of 33 A. The above phenomenon, on the one hand, demonstrates that LMO batteries could keep a high discharge efficiency at the high discharging rate, showing good rate discharging performance. On the other hand, the battery temperature increases rapidly when discharging at high current. The viscosity of the electrolyte is then reduced so that diffusion of the active material to the reaction zone is speeded up, decreasing the concentration polarization and activation polarization of the battery. Hence, the discharge efficiency is improved and the discharge capacity increases due to sufficient active material reaction.

As shown in Figure 2.2a, the working voltage of the battery is relatively stable when the SOC ranges from 20 to 80% (denoted by area B). Homogeneous electrochemical reaction happens inside the battery in this region, which means that the various substances involved in the chemical reaction are in the same phase. The discharge efficiency is high, since most of the chemical energy can be converted into electricity. Because of severe cell polarization and internal resistance, the battery voltage changes rapidly and the discharge efficiency is remarkably decreased when the SOC of a battery increases from 0 to 20% (area A). As shown in Figures 2.3 and 2.4, the internal resistance and polarization resistance of the battery significantly increase when its SOC is within the ranges (0–20%) and (80–100%). The terminal voltage falls rapidly, especially at the end of the discharge. It is suggested that the polarization is serious at the end of the discharge and the discharge efficiency is low. Deep discharge would affect battery cycle life. Hence, deep discharging needs to be avoided to make the battery work in the high efficiency region and to extend the battery life [1].

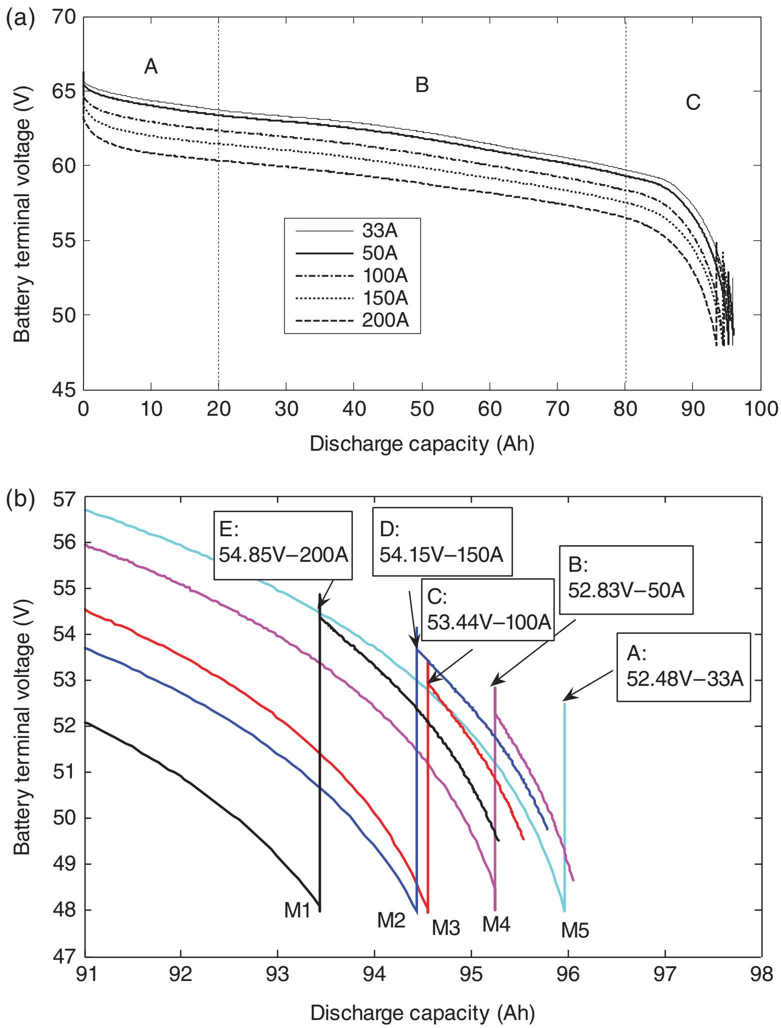


Figure 2.2 Relationship between battery voltage and discharging capacity at various currents of the lithium ion batteries, (b) is a partial enlarged drawing of (a). (Reproduced with permission from Caiping Zhang, "State of Charge Estimation and Peak Power Capability Predict of Lithium-Ion Batteries for Electric Transmission Vehicles", Beijing Institute of Technology, ©2010.)

2.2.2 Charge and Discharge Characteristics Under Operating Conditions

Batteries in hybrid electric vehicles are always in the frequent charging–discharging state, while pure electric vehicles have charging conditions under the regenerative braking system. Therefore, the capability of dynamic charging and discharging is an important indicator for the evaluation of battery performance, which lays the basis for the formulation of battery charging and discharging management strategies. The DST (dynamic stress test) cycle conditions test