

Battery Management Systems for Large Lithium-Ion Battery Packs

Battery Management Systems for Large Lithium-Ion Battery Packs

Davide Andrea



**ARTECH
HOUSE**

BOSTON | LONDON
artechhouse.com

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the U.S. Library of Congress.

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

ISBN-13 978-1-60807-104-3

Cover design by Vicki Kane

© 2010 ARTECH HOUSE
685 Canton Street
Norwood, MA 02062

All rights reserved. Printed and bound in the United States of America. No part of this book may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying, recording, or by any information storage and retrieval system, without permission in writing from the publisher.

All terms mentioned in this book that are known to be trademarks or service marks have been appropriately capitalized. Artech House cannot attest to the accuracy of this information. Use of a term in this book should not be regarded as affecting the validity of any trademark or service mark.

10 9 8 7 6 5 4 3 2

To Ann

Contents

Preface	<i>xi</i>
CHAPTER 1	
Introduction	1
1.1 Naming Conventions	1
1.1.1 Cells, Batteries, and Packs	1
1.1.2 Resistance	1
1.2 Li-Ion Cells	1
1.2.1 Formats	2
1.2.2 Chemistry	3
1.2.3 Safety	4
1.2.4 Safe Operating Area	6
1.2.5 Efficiency	6
1.2.6 Aging	9
1.2.7 Modeling	10
1.2.8 Unequal Voltages in Series Strings	12
1.3 Li-Ion BMSs	15
1.3.1 BMS Definition	16
1.3.2 Li-Ion BMS Functions	16
1.3.3 Custom Versus Off-the-Shelf	16
1.4 Li-Ion Batteries	18
1.4.1 SOC, DOD, and Capacity	18
1.4.2 Balance and Balancing	22
1.4.3 SOH	31
References	33
CHAPTER 2	
BMS Options	35
2.1 Functionality	35
2.1.1 CCCV Chargers	35
2.1.2 Regulators	37
2.1.3 Meters	38
2.1.4 Monitors	39
2.1.5 Balancers	40
2.1.6 Protectors	41
2.1.7 Functionality Comparison	41

2.2 Technology	41
2.2.1 Simple (Analog)	42
2.2.2 Sophisticated (Digital)	43
2.2.3 Technology Comparison	43
2.3 Topology	44
2.3.1 Centralized	44
2.3.2 Modular	45
2.3.3 Master-Slave	46
2.3.4 Distributed	47
2.3.5 Topology Comparison	49
CHAPTER 3	51
BMS Functions	51
3.1 Measurement	51
3.1.1 Voltage	52
3.1.2 Temperature	54
3.1.3 Current	54
3.2 Management	58
3.2.1 Protection	58
3.2.2 Thermal Management	63
3.2.3 Balancing	64
3.2.4 Redistribution	84
3.2.5 Distributed Charging	87
3.3 Evaluation	88
3.3.1 State of Charge and Depth of Discharge	89
3.3.2 Capacity	95
3.3.3 Resistance	96
3.3.4 State of Health (SOH)	97
3.4 External Communications	97
3.4.1 Dedicated Analog Wire	98
3.4.2 Dedicated Digital Wire	99
3.4.3 Data Link	102
3.5 Logging and Telemetry	105
References	105
CHAPTER 4	107
Off-the-Shelf BMSs	107
4.1 Introduction	107
4.1.1 Simple	107
4.1.2 Sophisticated	107
4.1.3 Cell Manufacturers' BMSs	111
4.1.4 Comparison	117
CHAPTER 5	118
Custom BMS Design	118
5.1 Using BMS ASICs	121
5.1.1 BMS ASIC Selection	121

5.1.2 BMS ASIC Comparison	124
5.2 Analog BMS Design	125
5.2.1 Analog Regulator	125
5.2.2 Analog Monitor	127
5.2.3 Analog Balancer	138
5.2.4 Analog Protector	144
5.3 Ready-Made, Digital BMS Designs	144
5.3.1 ATMEL's BMS Processor	145
5.3.2 Elithion's BMS Chip Set	146
5.3.3 National Semiconductors' Complete BMS	147
5.3.4 Peter Perkin's Open Source BMS	149
5.3.5 Texas Instruments' bq29330/bq20z90	151
5.3.6 Texas Instruments' bq78PL114/bq76PL102	152
5.4 Custom Digital BMS Design	152
5.4.1 Voltage and Temperature Measurement	175
5.4.2 Current Measurement	178
5.4.3 Evaluation	192
5.4.4 Communications	202
5.4.5 Optimization	215
5.4.6 Switching	218
5.4.7 Logging	219
5.5 Cell Interface	219
5.5.1 Nondistributed	220
5.5.2 Distributed	226
5.6 Distributed Charging	226
CHAPTER 6	229
Deploying a BMS	229
6.1 Installing	229
6.1.1 Battery Pack Design	243
6.1.2 BMS Connections to Pack	247
6.1.3 BMS Connections to System	252
6.2 Configuring	252
6.2.1 Cell Configuration	252
6.2.2 Pack Configuration	253
6.2.3 System Configuration	253
6.3 Testing	255
6.4 Troubleshooting	255
6.4.1 Grounding	255
6.4.2 Shielding	255
6.4.3 Filtering	256
6.4.4 Wire Routing	256
6.4.5 Nuisance Cutouts	256
6.5 Using Reference	256

List of Acronyms and Abbreviations	257
Glossary	261
About the Author	269
Index	271

Preface

As of this writing, lithium-ion (Li-Ion) cells have been the workhorse of small batteries for consumer products (such as cell phones and laptop computers) and are now starting to supplant lead-acid batteries and NiMH cells in large packs for applications such as vehicle traction packs and land-based distributed energy storage.

Compared to other chemistries, Li-Ion cells perform wonderfully, but only if treated well; hence, they require an effective battery management system (BMS).

This book is intended as an aid to the engineer or manager tasked with selecting, specifying, designing, deploying, or using a battery management system (BMS) for a large Li-Ion battery pack.

Over the past 6 years, while developing a few BMSs for large battery packs using Li-Ion cells, I have accumulated some understanding about their requirements, challenges, and solutions. I have shared some of that knowledge by giving talks, publishing white papers, and answering inquiries. With this book I hope to be able to share that knowledge in an organized and comprehensive way. I am fully aware of the fact that my understanding on this subject, while extensive, is by no means complete, making me dread the thought of committing to paper certain incorrect statements. For that I apologize, and ask you to please contact me at <http://book.LiIonBMS.com>, to correct me, so I may include clarifications and corrections in an online errata sheet, published on that same site.

This book is about control systems and electronics, and not about chemistry: cells are seen as black boxes and only in terms of their equivalent electrical circuit. In general, it is written for the reader with a basic understanding of physics and technology; Chapter 5 is intended for a reader with a good understanding of electronics and software algorithms.

This book is divided into six chapters, starting from general concepts, and then progressively getting into deeper, more practical details.

- Chapter 1 introduces Li-Ion cells, BMS concepts, and the need for a Li-Ion BMS.
- Chapter 2 discusses BMS options: functionality, technology, and topology.
- Chapter 3 explains the functions that may be found in a BMS.
- Chapter 4 explores commercially available BMS solutions.
- Chapters 5 delves deep into BMS electronics and algorithms (should you decide to design your own BMS).
- Chapter 6 guides you during the deployment of a Li-Ion BMS.

Once all the regulators in a pack are on, all the cells are close to the same voltage and, to a first degree, are all balanced. To a second degree, variations in individual cell resistance mean that the cells will not be exactly balanced, an issue that is discussed later (see Chapter 3).

A problem with regulators is that they can handle only so much current. If the charger can source more current than the regulator is designed for, two things can happen:

- If the regulator is current limited, the excess current goes into the cell, overcharging it.
- If the regulator is not current limited, the excess current goes through it, damaging it.

The solution is to match the charger and the regulators, in one of three ways:

1. Increase the regulators' current capacity to the charger's maximum current (larger, more expensive regulators).
2. Decrease the charger's maximum current to the capacity of the regulators (longer charging time).
3. Program the charger so that, by the time any regulator may be on [based on the pack voltage, but that cannot be relied on (see Section 1.2.8)], its output current is reduced.

By using a matched charger, regulators not only balance the pack, but also prevent overcharging, not by turning off the charger, but by bypassing charging current once all cells are fully charged.

In summary, all that regulators can do is balance a pack. Use of regulators alone is not sufficient as a BMS because:

1. It does not prevent overcharging of individual cells.
2. It does not prevent overdischarging of cells.

Even when used in combination with a matched charger, use of regulators is not sufficient as a BMS because it does not prevent overdischarging of cells.

2.1.3 Meters

Meters simply monitor parameters but do not actively control charging or discharging. They may meet the needs of a hobbyist or a researcher, who may be satisfied with simply knowing the individual cells voltages and doing something manually if anything is amiss. Such a device:

- Measures each cell voltage;
- May also measure other parameters such as pack current and temperature;
- Compiles this data;
- May also compute or estimate pack status, such as SOC;
- Reports them in a display;

- May also include a way to warn the user of abnormal conditions (with a light or a buzzer).

For lack of a better term, we will call these devices "meters" (Figure 2.4).

Users of such meters may think that they have a true BMS, but what they may not realize is that they themselves are an integral part of the system in the BMS. Without the user, the system is broken. If the user leaves and lets the pack keep on charging, the control loop in the system is broken, and the pack is likely to be damaged from overcharging (a CCCV charger is of no help, as explained in Section 2.1.1).

In summary, a meter is not sufficient as a BMS because:

1. It does not prevent overcharging of individual cells.
2. It does not prevent overdischarging of cells.
3. It does not balance the pack.

Even if constantly attended by a human, a meter is not sufficient as a BMS because it does not balance the pack.

2.1.4 Monitors

Monitors (Figure 2.5) are like meters in the sense that they measure each cell voltage, but they do close the control loop. Should anything be amiss, they don't rely on a user being nearby and taking corrective action, but take action themselves, by controlling indirectly the charger and the load. A monitor may not optimize a pack's performance (it cannot balance it), but will protect it from operating outside its safe area, and do so autonomously. Monitors are often chosen by researchers to test their Li-Ion packs.

A monitor does not include internally the means of interrupting the pack current. All it can do is to send a request to other devices (charger, load) to reduce or interrupt the pack current. If those other devices are not designed to receive and abide to such requests, a high-power switch (typically a contactor—a high power

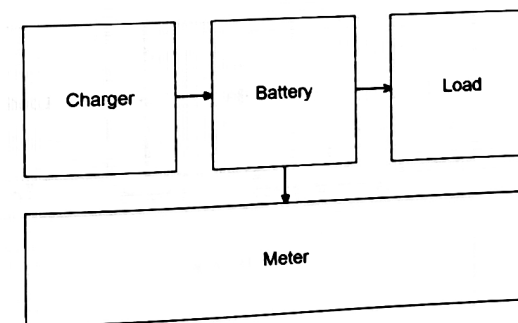


Figure 2.4 System block diagram using a meter.

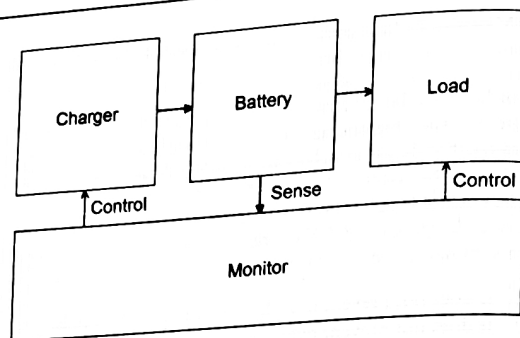


Figure 2.5 System block diagram using a monitor.

relay) must be included in the system, and the balancer must be able to activate it to interrupt the pack current.

A monitor may be standalone (with only a few wires to control the shutting down of the charger and the load), or it may have a display and/or a communications link to report pack data to the rest of the system.

In summary, a monitor provides full protection to the pack, but it does not balance it.

2.1.5 Balancers

A balancer (Figure 2.6) is like a monitor, but it is also able to maximize the pack's performance by balancing the cells. Also, it rarely is a standalone device, as it almost invariably includes a communications link to report pack data to the rest of the system. Balancers are by far the preferred choice by professionals for large Li-Ion packs.

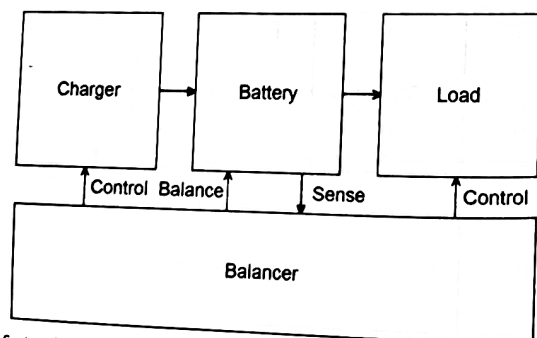


Figure 2.6 System block diagram using a balancer.

A balancer may be physically separated from the batteries, or mounted directly on the cells, or some combination within that range (see Section 2.3), and may use various balancing technologies (see Section 3.2.3), some more effective than others. In summary, a balancer is sufficient as a BMS as long as it is wired in a way that allows it to control the charging source and the discharging load.

2.1.6 Protectors

A protector is like a balancer, except that it includes a switch to turn off the pack current.

A protector is usually an integral part of a battery, physically located inside the same enclosure, leaving only two power terminals coming out of its enclosure (Figure 2.7). A protector is the industry standard solution for small batteries for consumer products, but it is rarely used in professional, large Li-Ion packs, because its switch is not likely to be able to handle high-power loads. For large packs, a balancer is usually chosen instead (see Section 2.1.5).

The switch in a protector is usually a solid-state type (transistors), able to handle 5A to 50A, and on the order of 50V in both the charging and discharging directions (this requires two sets of transistors in series, one for each direction of the pack current). This power level is usually sufficient just for small batteries.

In summary, a protector is completely sufficient as a BMS for smaller batteries.

2.1.7 Functionality Comparison

As you can see from Table 2.1, full BMS functionality can only be provided by balancers (for large packs) and protectors (for small batteries).

2.2 Technology

There are basically two classes of technologies used to implement a BMS: analog and digital. The distinction between analog and digital is related to how the cell

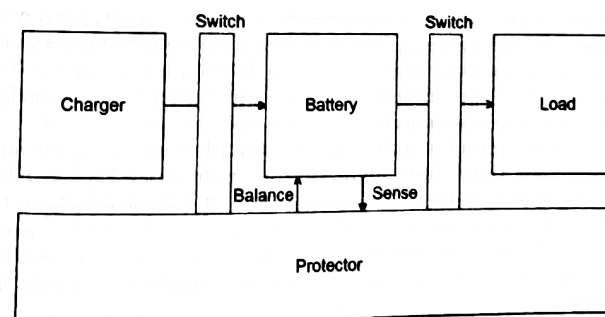


Figure 2.7 System block diagram using a protector.

Table 2.1 Comparison of the Features of the Various BMS Functionalities

	Measure	Compute	Report	Balance	Protect	
					Charge	Discharge
CCCV Chargers				✓		✓
Regulators		(✓)	✓		✓	✓
Meters	✓	(✓)	✓	✓	✓	✓
Monitors	✓	(✓)	(✓)	✓	✓	✓
Balancers	(✓)	(✓)	(✓)			
Protectors	(✓)	(✓)				

(✓) = Some may provide this feature
 ✓* = Requires additional measures.

voltage information is processed. While all systems require some form of analog front end, BMSs that then process the cell voltage with analog circuitry (an analog comparator, op-amp, differential circuit, or the like) is considered to be analog. BMSs that process the cell voltage digitally are considered to be digital.

Alternatively, one could say that there are two classes of complexity in BMS: simple and sophisticated.

Sophisticated BMSs are aware of each individual cell's voltage and can report it, while simple ones do not and cannot. These two sets of BMS classes tend to coincide: simple BMSs are typically analog, and sophisticated BMSs are typically digital. It is not inherent that analog solutions be simple, and digital ones be sophisticated. It is just that designers who are content with simple solutions are more comfortable with analog circuits, and those who have a full grasp of the challenges involved in managing Li-Ion batteries will opt to solve them with digital technology.

2.2.1 Simple (Analog)

The capabilities of analog BMSs are quite limited, and may be barely sufficient to perform the required BMS functions. For one thing, an analog BMS is not aware of individual cell voltages; it may know that one cell is too low, but it will not know which one, or how low. As long as the BMS can shut off the load in case of low cell voltage, not knowing which cell is low, or how low it is, is not a problem. It only becomes a problem if there is a need to analyze a battery without actually opening it up and start poking around with a voltmeter.

The example of an analog regulator may help (Figure 2.8). The regulator may use a power supply supervisor IC, powered by the cell's voltage, and driving a balancing shunt when the cell's voltage exceeds the IC's threshold voltage. Inside the IC there are two components: a voltage reference and an analog comparator, whose output changes state when the cell voltage (divided down) exceeds the reference's voltage. Because of that analog comparator, a regulator is considered an analog device.

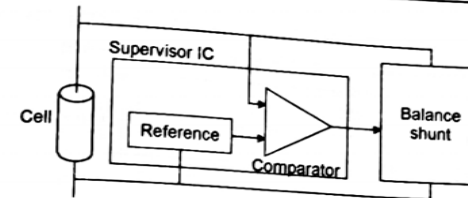


Figure 2.8 Example of an analog BMS: a regulator.

2.2.2 Sophisticated (Digital)

A digital BMS is fully aware of each cell voltage (and possibly more, such as its temperature and its conditions). Therefore, it is able to report this data, which is invaluable in allowing an analysis of the state of the pack. This is normally a requirement for a large, professional Li-Ion pack.

An example of a digital meter may help (Figure 2.9). This device includes an analog multiplexer, able to select and sample the voltage at one of the taps between adjacent cells in series, and send it to an analog-to-digital (A/D) converter. From that point on, the BMS performs all its functions digitally, such as subtracting the reading from two adjacent taps to calculate the voltage of the cell between those two taps.

2.2.3 Technology Comparison

Table 2.2 compares the difference between analog and digital BMS technology.

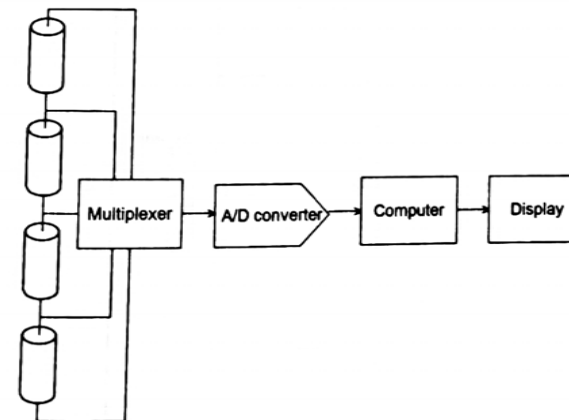


Figure 2.9 Example of a digital BMS: a meter.

CHAPTER 3 BMS Functions

In this chapter we will explore the various functions of a BMS (Figure 3.1). They may be grouped as:

- Measurement;
- Management;
- Evaluation;
- Communications;
- Logging.

A given BMS may implement any of these functions (Figure 3.1).

3.1 Measurement

The first function of a sophisticated, digital BMS is to gather data about a BMS (a simple, analog BMS does not include this function). These measurements are:

- Cell voltage (and possibly pack voltage);
- Typically, cell temperature, or at least battery temperature;
- Most often, pack current.

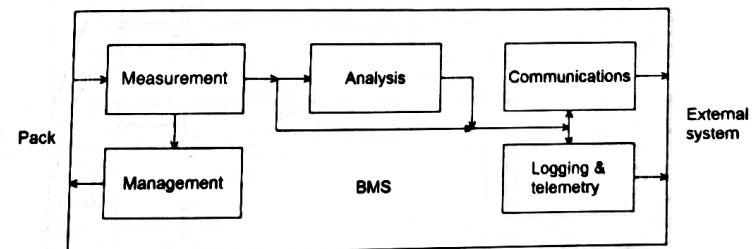


Figure 3.1 BMS functions.

3.1.1 Voltage

A sophisticated, digital BMS measures the voltage of each and every cell in series. It may also measure the total pack voltage, though that is not necessary, as that value can be calculated by adding the individual cell voltages.

3.1.1.1 Methods

A distributed BMS may measure directly the voltage across a cell. (Normally the cell board is powered by the cell itself, as it measures its voltage.) Otherwise, the BMS board is powered by the cell itself, as it measures its voltage. The BMS may measure the voltage of various taps in a battery, and calculates a cell's voltage as the voltage difference between two taps. Or, the BMS may take two measurements simultaneously of the two taps on either side of a cell, and calculate the difference as the cell's voltage. The voltage is sampled by an analog multiplexer, and the reading is taken by an analog to digital (A/D) converter (which may be on the same IC), which then passes the value to a processor (Figure 3.2).

3.1.1.2 Rate

The rate of the readings depends on the application.

- For a backup power application, one reading per minute or per 10 seconds is acceptable.
- For applications where the current varies rapidly (such as vehicles) one reading per second is acceptable.

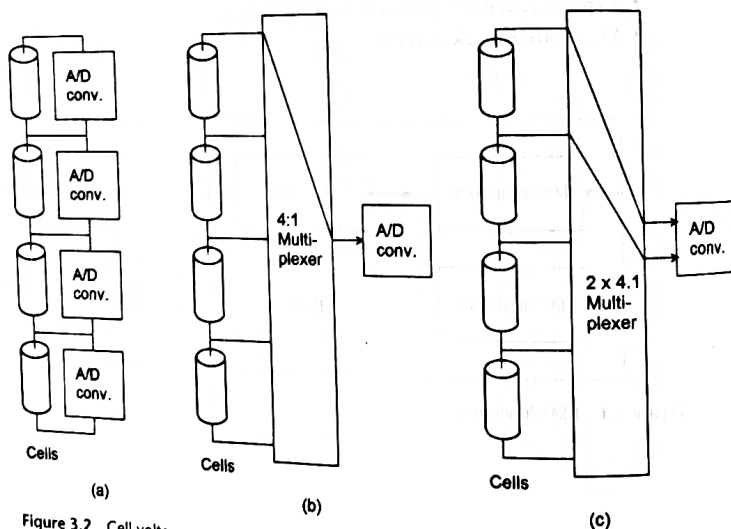


Figure 3.2 Cell voltage measurement methods: (a) discrete, (b) single-end multiplexed, and (c) differential multiplexed.

- For research application, scientists may like to see 10 to 100 readings per second.

If the BMS must calculate the internal resistance of the cells, and the pack current varies rapidly, the voltages of all cells should be measured simultaneously, or almost simultaneously, so they may all be correlated to what the pack current was at the time of measurement. Otherwise, there will be errors in the calculations of resistance for the cells whose voltage was measured at a different time than when the pack current was sampled. As long as the readings were all taken simultaneously, they may be reported sequentially, afterwards.

3.1.1.3 Accuracy

The required accuracy for the reading depends on its use.

- To simply detect when a cell is fully charged or discharged, an accuracy of 100 mV is sufficient, because the OCV versus SOC curve for a Li-Ion cell is very sharp at the top and bottom ends. The voltage rises some 200 mV at the charged end and drops on the order of 500 mV at the discharged end.
- To top balance a battery while charging, an accuracy to 50 mV is sufficient to match the SOC of the cells. Any higher accuracy in the reading may be lost in the errors due to cell resistance.
- To accurately estimate a cell's SOC from its real or estimated open circuit voltage (OCV) at the either end of the OCV versus SOC curve, an accuracy of 10 mV or better is required. Otherwise, the SOC estimate will suffer from errors on the order of 10%.
- To accurately estimate a cell's SOC from its OCV in the central plateau of the OCV versus SOC curve (20% to 80% SOC) an accuracy of 1 mV or better is required. This is a requirement for BMSs that are able to estimate the cell's SOC without knowing its previous history. For example:
 - Products that have a BMS that stays with the product (not with the removable battery);
 - An HEV, whose pack never becomes fully charged or discharged, and therefore is not able to calibrate the SOC at the end of charge or discharge.

Table 3.1 lists the required A/D resolution (based on a 5-V full scale) and total tolerance in the reference and voltage dividers to achieve the accuracies listed previously.

The accuracy of most BMSs is between 10 and 30 mV. Very few BMSs have the high-precision electronics that are required to achieve higher accuracy.

3.1.1.4 Isolation

Cell voltages are, of course, at high-voltage potential, which, in a large pack, must be isolated from the low-voltage, ground-referenced signals. Therefore, measuring the cell voltage brings the challenge of doing so without introducing a loss of isolation in the pack. We will explore this issue in more detail when discussing BMS