ARTICLE IN PRESS

Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Active battery cell equalization based on residual available energy maximization

Weiping Diao[a,b,c], Nan Xue[a,b], Vikram Bhattacharjee[d], Jiuchun Jiang[a,b,*], Orkun Karabasoglu[e,f], Michael Pecht[c]

[a] National Active Distribution Network Technology Research Center (NANTEC), Beijing Jiaotong University, Beijing 100044, China
[b] Collaborative Innovation Center of Electric Vehicles in Beijing, Beijing Jiaotong University, Beijing 100044, China
[c] Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD 20740, USA
[d] Department of Electrical & Computer Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[e] Department of Industrial Engineering, Yaşar University, 35100 Bornova, İzmir, Turkey
[f] School of Computer and Information Technology, Beijing Jiaotong University, Beijing 100044, China

HIGHLIGHTS

- The terms AE and RAE are defined for battery packs which incorporate inter-cell parameter variation.
- A novel active equalization strategy based on RAE maximization is proposed.
- Experimental results with cost analysis are shown to prove its superiority and feasibility.

ARTICLE INFO

Keywords:
Active equalization
Residual available energy
Capacity
Internal resistance
SOC
Discharge current

ABSTRACT

The residual available energy (RAE) of a battery pack is an important parameter for determination of the amount of energy left in the battery pack. The RAE is defined as a function of the cell's initial state of charge (SOC), discharge current, cell capacity and internal resistance. Battery management systems achieve active equalization through balancing either the SOC or the terminal voltage of battery packs. Recent research discovered that these equalization schemes cannot maximize RAE of the battery pack due to the variation of internal resistances and capacities of the cells in the pack. On the other hand, terminal voltage equalization is not applicable for batteries having a flat SOC-open-circuit voltage curve. This paper introduces the framework to calculate the RAE of a battery pack incorporating the variation of internal resistance and capacity of the individual cells in a pack. It further proposes a novel active battery cell equalization technique based on an RAE maximization scheme. The effectiveness of the proposed equalization scheme is validated through experimental results with a comparison of the energy utilization efficiency. The solution methodology and the results are discussed in the paper.

1. Introduction

Electric vehicles (EVs) and smart grids have become extremely popular in the recent years due to increasing environmental concerns and shortage of fossil fuels. As a critical subsystem in EVs and smart grids, a battery energy storage system (BESS) plays an essential role in providing a power source and enhancing the stability [1]. Lithium-ion batteries are in extensive use because they offer high energy density and reasonable usage cost [2–4]. When coupled with energy management schemes such as battery management systems (BMSs), these storage systems perform with more controllability and efficiency [5]. However, the BESS suffers from issues such as cell-to-cell parameter variation and inconsistency and these factors can adversely affect the lifetime of the battery pack [6]. Zhou et al. [7] proved that cell inconsistency affects a pack's performances. In EVs, the energy performance - available energy (AE) can indicate the whole driving range, while the state of energy (SOE) is used to estimate the remaining driving range in the BMS [4]. In Plug-in Hybrid Electric Vehicles (PHEVs), the driving range by battery is especially important for their market adoption. It was found that the cost of owning a vehicle, the driving range of the vehicle, and the time it takes to charge the vehicle, play important roles as moderators to be adopted in the EV/PHEV

* Corresponding author at: National Active Distribution Network Technology Research Center (NANTEC), Beijing Jiaotong University, Beijing 100044, China.
E-mail addresses: wpdiao@bjtu.edu.cn (W. Diao), 14121488@bjtu.edu.cn (N. Xue), vbhattac@andrew.cmu.edu (V. Bhattacharjee), jcjiang@bjtu.edu.cn (J. Jiang), karabasoglu@cmu.edu (O. Karabasoglu), pecht@umd.edu (M. Pecht).

http://dx.doi.org/10.1016/j.apenergy.2017.07.137
Received 13 February 2017; Received in revised form 30 July 2017; Accepted 31 July 2017
0306-2619/ © 2017 Elsevier Ltd. All rights reserved.

Nomenclature

U_O	terminal voltage (V)
U_{OCV}	open-circuit voltage (V)
$U_{OCV\ dis}$	open-circuit voltage at cut-off time
U_r	ohmic voltage (V)
U_P	polarization voltage (V)
C_j	nominal capacity (Ah)
R_j	internal resistance (Ω)
μ_1	mean of maximum capacities (Ah)
μ_2	mean of internal resistances (Ω)
${\sigma_1}^2$	variance of maximum capacities
${\sigma_2}^2$	variance of internal resistances
$f_1(y)$	density function of nominal capacities
$f_2(y)$	density function of internal resistances
I	discharge current of the battery pack (A)
U_{OCVdis}	discharge cut-off voltage (V)
$U_{cut\text{-}off(dis)}$:	discharge cut-off voltage (V)
$SOC_I(j)$	initial SOC of the jth battery
$SOC_L(j)$	lower limit of SOC of the jth battery discharged individually at current I
$\Delta SOC(j)$	the available SOC range of the jth battery discharged individually at the current I
Q_j	the available capacity of the jth battery discharged individually at the current I (Ah)
Q_A	the residual available capacity of the battery pack at the current I (Ah)
$SOC_0(j)$	the lower limit of SOC of the jth battery discharged in the battery pack at the current I
$E_a(j)$	the residual available energy of the jth battery cell discharged in the battery pack at the current I (Wh)
N	the number of battery cells in the pack
E_A	the residual available energy of the battery pack discharged at the current I without equalization (Wh)
E_m	the total energy stored in a battery pack (Wh)
E_{AE}	the residual available energy of the battery pack at the current I with equalization (Wh)
$I_b(j)$	the current that flows through the jth battery cell during discharge
$I_t(j)$	the equalization current of the jth battery cell (A)
T_E	the time used to fully discharge the battery pack (h)
U_{pack}	the average terminal voltage of the battery pack (V)
$E_t(j)$	the energy to be transferred of the jth battery cell (Wh)
$\varepsilon(ji)$	the error of the ith calculation and $(i+1)$th calculation of $I_t\ (j)$ (A)
$I_t(j,i\text{-}1)$	the $(i\text{-}1)$th calculation of $I_t\ (j)$ (A)
$I_t(j,i)$	the ith calculation of $I_t\ (j)$ (A)

Abbreviations

SOC	state of charge
EV	electric vehicle
BESS	battery energy storage system
BMS	battery management system
SOE	state of energy
PHEV	Plug-in Hybrid Electric Vehicle
AE	available energy
RAE	residual available energy
EUE	energy utilization efficiency
SOH	State of Health

markets [8,9]. Therefore, it can be inferred that the estimation and optimization of the energy performance is indispensable for the battery system.

In this context, the AE of a battery cell is defined as the energy released during the whole discharge process after being fully charged (i.e. to a SOC of 100%). If the initial SOC is not 100%, the energy released during the whole discharge process is denoted by the residual available energy (RAE). In a pack where hundreds of batteries are connected in series or parallel, the AE and RAE are often limited by the inconsistency of the capacities, internal resistances, and imbalances of SOCs. A battery pack with a maximum RAE will offer more advantages by ensuring a larger reduction of purchase cost. As an important objective, loss/cost minimization has been widely studied in the energy and automotive sectors [10,11]. Hence there is a need to consider and analyze the factors that can determine the RAE in a battery pack.

Recent studies have focused on the factors influencing energy performance, but they do not consider the cumulative effect of the discharge current, distribution of capacities, internal resistances and SOC on the performance of the battery pack for analyzing its AE and RAE. Recent research has investigated the impact of parameter inconsistency on the energy performance of a battery pack. In [12], researchers carried out a qualitative analysis of how the SOCs, internal resistances and capacities made cells' voltages different respectively. They concluded that a low charge current helped to maximize the pack's available capacity. However, terminal voltage is only one of the factors that affect the energy performance of the battery pack. Researchers in [13] measured and calculated the energy efficiency of a battery and the battery pack, relying totally on the measurement of the terminal voltages and current of the batteries in actual operation. The estimation process based on multiple experiments lacks theoretical analysis and is time-consuming with limited scope for real-time applications [14]. Hence a mathematical formulation incorporating inter-cell variations is necessary for analyzing their effects and adopting in the equalization schemes.

It is observed that the energy dissipated or utilized in an equalization device also depends on the type of equalizing strategy used. Cell equalization is usually categorized as passive or active equalization [15]. In passive equalization (also known as dissipative equalization) technique, the available capacity of a battery pack is limited by the battery cell with the minimum capacity. Additionally, the inconsistency of the capacities and internal resistances is caused by manufacturing defects and is further aggravated due to random degradation [16,17], which cannot be equalized by passive equalization.

On the other hand, active equalization transfers energy between battery cells. Equalization circuits and strategies are both studied to optimize this process. Firstly, some papers focus on the equalization topologies to increase the efficiency [18,19]. For example, a bi-directional isolated Cuk equalizer and some reconfigurable battery packs were proposed in [20,21], respectively. In [22], an equalization circuit using bidirectional switch sets and a multi-winding transformer were used and their operating principles were investigated. This topology can make a short energy transfer-path for two arbitrary cells thereby ensuring a faster rate of equalization. However, fast equalization does not necessarily help in increasing the energy utilization efficiency (EUE). Secondly, many researchers have designed active equalization strategies for cell balancing. A current equalization method for balancing serially connected battery cells was proposed in [23]. Taking only capacity variation into account, this method does not reflect the overall increase in energy level due to the equalization. In [24], a novel active equalization method was devised where the remaining capacity and the SOCs were measured at the moment of initiation. In [25] the active cell-balancing strategy was based on equalization of the SOCs of the battery cells by disconnecting cells with the least SOC. In [26], an active cell balancing approach for equalizing the terminal voltages of different battery modules was executed by changing the amplitude of each module's carrier wave. From the literature it is clear that active

Download English Version:

https://daneshyari.com/en/article/6681335

Download Persian Version:

https://daneshyari.com/article/6681335

Daneshyari.com