Thesis: Evaluation of Key Indexes and Characteristics of Lithium-Ion Battery for Management in Building Smart Grid

Li Kaiyuan G1401060E

Abstract

Energy storage has been considered as an imperative enabling technology to improve the energy sustainability in the traditional building power grids. Among all the energy storage techniques, Li-ion based rechargeable batteries are recognized to be the most promising solution, due to their outperformed performance such as high gravimetric and volumetric energy density, great cycle life, enhanced safety and low self-discharge rate. With the increasing vehicle-to-grid synergy and renewable energy sources imports, Li-ion batteries are positioned uniquely to act a crucial role. Despite the remarkable progress achieved in the material and chemistry of Li-ion batteries, that battery systems are always oversized and underused still remains a problem, i.e., 20%-40% excess energy and capacity was idle, and evoking superfluous weight and volume augment, as well as purchasing costs. Attenuation of this conservatism has necessitated and efficient and intelligent battery management system (BMS), where the key indexes, e.g., state of charge (SOC), state of health (SOH), state of energy (SOE), are monitored precisely on the fly. In particular, proper BMSs facilitate avoiding premature battery failure and catastrophic hazards, and therefore enhancing the durability, efficiency, and reliability of Li-ion battery systems.

Motivation of this research work is to scrutinize and to achieve a holistic understanding of the characteristics and electrical behaviors of Li-ion type battery utilized as energy storage applications in the building environment, and the overall challenge the author trying to solve is to design and develop an intelligent and efficient battery management system for Li-ion batteries used as energy storage devices in built environment, thus propelling the thriving development of the energy

sustainability as a pivotal pillar. In the past three years' research, characteristics of the Li-ion batteries such as the energy efficiency, modelling, estimations of SOC, SOE, SOH, and instantaneous terminal voltage responses were studied. Additionally, the author also paid attention to fast charging technique of Li-ion batteries as an emerging technology.

Chapter 1 is an introduction of the energy storage technology, battery energy storage systems, and Li-ion battery. Chapter 2 is the literature review part and introduces the related research and engineering proceedings of Li-ion battery as energy storage device in grid applications. In specific, related works of energy efficiency, modelling, estimation of SOC, SOH, SOE of Li-ion battery are reviewed in detail. Meanwhile, as a promising and booming technique, fast charging technique for Li-ion battery is also reviewed.

In Chapter 3 the energy efficiency of Li-ion battery used as energy storage systems in built environment is investigated based on electrical and electrochemical theory, for both single cell and a 10-cell battery pack. The equations and the calculation procedures of the energy efficiency of Li-ion battery are provided. The proposed method and the results could be used for the determination of the energy efficiency of the Li-ion battery in the cases of high-current fast charging applications. This chapter serves as a preliminary study of the electrical characteristics and behaviors of Li-ion batteries.

Chapter 4 investigates the estimation of the online SOH of Li-ion batteries exploited as energy storage devices in a practical smart grid. Realistic profiles of the smart grid such as load current and temperature are utilized in this study. Two approaches for online SOH estimation are developed and the validation tests verify the good efficacy and robustness of both the approaches. Moreover, we also study the capacity degradation of the Li-ion batteries from the electrical perspective and the experimental results show that, at least for the type of Li-ion batteries that are tested, their capacity fade extent is not correlated with the ageing conditions, which is generally in line with the conclusion of some research works in the literature emphasizing on electro-chemistry. This inference is of great significance in both the

industrial and research work on the capacity degradation of Li-ion batteries, in light of that almost all the ageing models of Li-ion battery use the accelerated ageing test profile for cycling.

Chapter 5 focuses on another two critical indexes of the battery system, i.e., the SOC and SOE. SOC depicts the residual available capacity of the battery, while SOE is introduced recently for better description of the battery residual assessable energy and energy state. SOE generally differs from SOC by considering energy throughput of the battery more directly. In actual battery operations, the dramatic variation of load current puts forward challenges to the energy management of batteries. In the SOE estimation, energy loss in the electrochemical reactions, the internal resistance, and the decrease of battery's open circuit voltage are considered more comprehensively. It is suggested, therefore, that a better analogue to the extent of the energy throughout and runtime of the practical battery-based energy storage devices is perhaps the measure of battery energy, thus the index of SOE. Three hybrid battery models of Li-ion batteries, one for online SOE and SOC estimation based on the kinetic and electrical circuit battery models, one aiming at prediction of the terminal voltage responses and the SOE via the combination of an analytical and an electrical battery model, another for terminal voltage and SOE estimation by combining an electrochemical and an electrical model are presented. All the three models are capable of estimating the SOE and residual endurance time of the Li-ion batteries with high accuracy and reliability, based on the results of the validation tests.

Last but not least in Chapter 6, a charger for fast charging a lithium titanate (LTO) type battery cell (or cell strings connected in series and parallel) with accurate estimation of online SOC is disclosed. The charge system includes: a circuit for charging the LTO battery via the traditional constant current constant voltage (CCCV) way, and the monitor system includes monitoring of cell's voltage, current, surface temperature and particularly the online SOC based on a previously unknown feature in LTO cell's surface temperature-SOC characteristic which is discovered recently. Differentiating from the prior arts, the invented fast charger is able to

provide precious estimation of the cell's online SOC, and the LTO batteries are expected to be fast charged safely to at least 90% SOC with precious online SOC identification, thus providing more confidence and better user friendliness for consumers in utilizing fast charging on their energy storage devices.

Finally, the conclusion is given in Chapter 7 and the future work is also addressed. After the careful scrutinization of the related literature, the electrical characteristic and behaviors of Li-ion batteries utilized as energy storage devices in built environment such as, study on energy efficiency, online estimation of SOH, SOC, SOE, and terminal voltage responses, are deeply investigated. Plenty of cells have been cycled in the laboratory under realistic load condition and large amounts of experimental data of diverse load and ambient temperature profile were collected in the laboratory for model construction and validation processes. This multi-cell setting provides a more valuable and significant scenario than the conventional single-cell setting. The author has basically realized the objectives of the holistic understanding and the design of the intelligent and efficient battery management system. Furthermore, the study and the demonstration of the novel fast charger for the LTO type batteries in Chapter 6 helps to propel the development of the fast charge technique of Li-ion batteries as a thriving area of research in both academic and industrial sectors.

The proposed future work includes the development of the online battery estimators for SOH, SOE, and SOC with less computational burdens and higher precision. Further, influences on the battery behaviors and characters of the factors such as the ageing extent of the battery, the temperature, the initial status, and the load condition will be studied more thoroughly. The influencing factors for cycle-ageing of Li-ion batteries will be explored, such as the battery chemistry, type, rated capacity and voltage, rest time, etc. In addition, other brands of LTO batteries and other types of Li-ion batteries will also be tested in future work in terms of fast charging technique and applications.