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Fast charge implications: Pack and cell analysis and comparison

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HIGHLIGHTS

- Implications of direct current fast charging on pack and cell.
- Minimal impact to performance due to direct current fast charging.
- Pack degradation cannot be directly inferred from cell evaluation.
- Delayed charging improves battery life across multiple charging regimes.

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ABSTRACT

This study investigates the effect of 50-kW (about 2C) direct current fast charging on a full-size battery electric vehicle's battery pack in comparison to a pack exclusively charged at 3.3 kW, which is the common alternating current Level 2 charging power level. Comparable scaled charging protocols are also independently applied to individual cells at three different temperatures, 20 °C, 30 °C, and 40 °C, to perform a comparative analysis with the packs. Dominant cell-level aging modes were identified through incremental capacity analysis and compared with full packs to gain a clear understanding of additional key factors that affect pack aging.

While the cell-level study showed a minor impact on performance due to direct current fast charging, the packs showed a significantly higher rate of capacity fade under similar charging protocols. This indicates that pack-level aging cannot be directly extrapolated from cell evaluation. Delayed fast charging, completing shortly before discharge, was found to have less of an impact on battery degradation than conventional alternating current Level 2 charging.

1. Introduction

Production of electric drive vehicles (EDVs) has doubled every year since 2010 [1]. New releases of EDVs almost exclusively rely on lithium-ion battery (LIB) technology due to the high power and energy density of this class of battery. Since 2010, the average price for the automotive LIB pack for EDVs has fallen roughly by 80%, which is a key factor behind the upward trend of EDV sales and driving range [2]. In concert with these factors, the increasing availability of direct current fast charging (DCFC) stations is working as a catalyst, increasing EDV adoption and utility. The increased range and easy access to DCFC stations are encouraging consumers to drive further without the fear of being stranded. For instance, a 25% increase in annual electric vehicles miles is recorded in areas where drivers have access to 50–120-kW fast charging stations [3,4]. Continued expansion of the DCFC network could significantly increase the utility of battery electric vehicles and alleviate consumers' “range anxiety,” which often discourages consumers from buying battery electric vehicles [5].

Automotive original equipment manufacturers and electric vehicle supply equipment (EVSE) companies are constantly expanding their fast charging networks. As of August 2017, 6372 Tesla Superchargers [6]; 2215 CHAdeMo chargers [7]; and 1500 combined charging system fast chargers [8] have been installed in the United States. Despite this progress in adding more charging stations, EDV charging speed is not yet comparable to the fueling speed of conventional gasoline engines, which is typically under 10 min [9]. Currently, the Tesla 120 kW Supercharger recharges 80% of battery capacity in 40 min [10], Nissan Leaf's CHAdeMo 50-kW DCFC recharges the battery pack from nearly empty to 80% in less than 30 min [11], and the Chevrolet Bolt battery pack takes an hour to recharge up to 80% with a 50-kW combined charging system charger [12]. Higher-power charging stations up to 400 kW and compatible vehicles are necessary to make the battery electric vehicle's recharge time comparable to the refueling time of gasoline engines [9]. Additional challenges will be encountered in realizing this extreme charging speed, from battery cells to vehicle systems and from charging infrastructure hardware to charging

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Acronyms

AC	alternating current
BMS	battery management system
CHAdeMO	CHArger de MOve
DCFC	direct current fast charging
DOD	depth-of-discharge
EDV	electric drive vehicle
EVSE	electric vehicle supply equipment
EOC	end of charge
EOD	end of discharge
HPPC	hybrid pulse power characterization
IC	incremental capacity
LLI	loss of lithium inventory
LAM	loss of active material
LMO	lithium manganese oxide, $LiMn_2O_4$
LIB	lithium ion battery
NE	negative electrode
OEM	original equipment manufacturer
PE	positive electrode
RCV	rest cell voltage
RPT	reference performance test
RPV	rest pack voltage
SOH	state-of-health
SOC	state-of-charge

network economic feasibility. The U.S. Department of Energy recently performed a technology and economic gap assessment to identify challenges in realizing extreme fast charging up to 400 kW [9,13–15]; some automotive OEMs and EVSE companies have already started working on solving these challenges [16–18].

While ongoing efforts to increase charging speed and expand the network of charging stations are reassuring for consumers, the increased charging rate associated with fast charging could adversely affect battery performance and life. Thus, it is paramount to understand the effects of fast charging on LIB's performance and life (i.e., state of health [SOH]), from the pack to cell level and to identify the most critical factors affecting battery SOH. Knowledge about the extent of the effects of fast charge on battery SOH would aid battery developers, OEMs, and EVSE developers in judicious design and management of the LIB pack to achieve the anticipated life and desired performance in a cost-effective way.

Lithium plating in the negative electrode has been reported as one primary concern about fast charging LIBs [19–24], especially at low temperatures. Plating at the negative electrode becomes thermodynamically favorable when the over potential (i.e., the difference between solid phase and liquid phase potential) reaches or crosses zero. This usually occurs at or near the interface of the electrode and separator where surface over potential is the largest [24–26]. Graphite, a widely used negative electrode material, is particularly susceptible to lithium plating, due to the proximity of its reversible potential to that of lithium. While the plated lithium is partially reversible, a significant portion of the plated lithium is irreversible [26], which could cause accelerated performance decay (e.g., increased capacity fade and impedance rise). Part of the irreversible or residual lithium could also become isolated, potentially changing the abuse response of the battery. The plated lithium may grow dendritically, developing internal short circuits and leading to major reliability concerns and, in the worst case scenario, catastrophic safety consequences.

The magnitude of the performance and life decay due to fast charging depends on many interrelated battery design parameters from the materials and electrode level to the cell and pack level, as well as the charging protocol and operating temperature. From the materials point-of-view, the selection of anode material, anode particle size, particle shape, and electrolyte play a vital role in minimizing the effects of fast charging [20,25,27]. From the electrode point-of-view, thickness, porosity, and tortuosity are critical design parameters [22,25,28] for avoiding accelerated fade during fast charge. Similarly, both loading

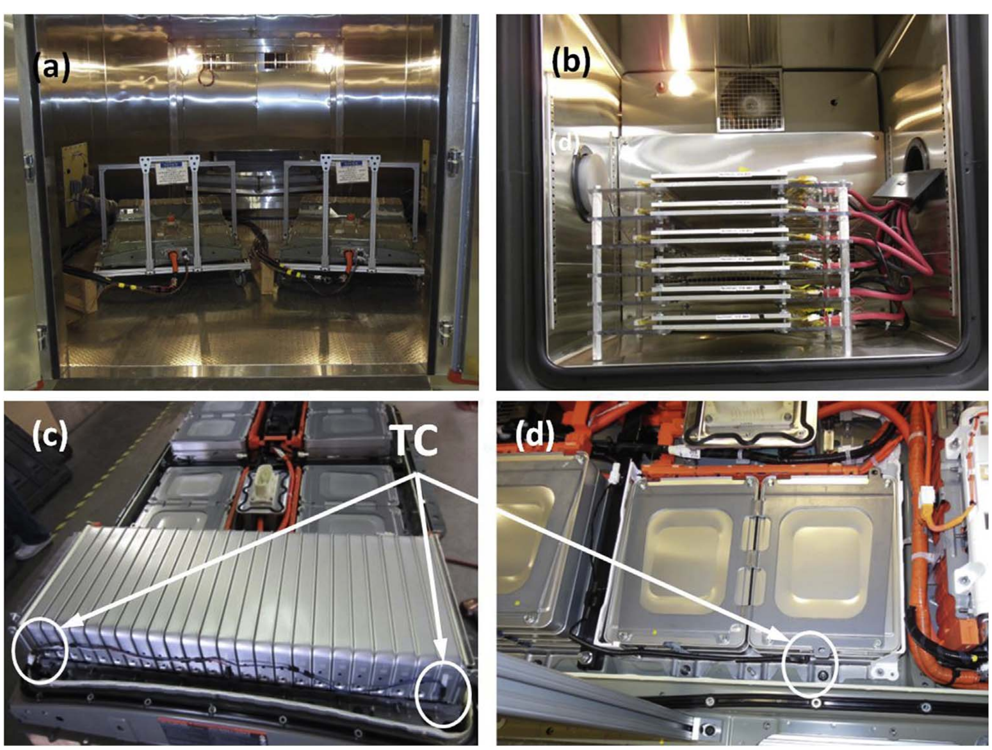

Fig. 1. Test setup: (a) pack, (b) cell, (c) thermocouple location at the rear module stacks, and (d) thermocouple location at one of the side module stack.