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Rapid restoration of electric vehicle battery performance while driving at cold temperatures

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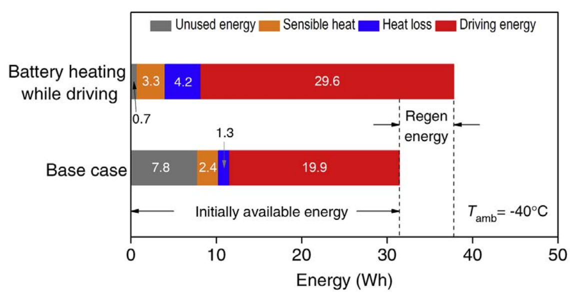
HIGHLIGHTS

- A control strategy that rapidly restores EV battery power while driving in cold.
- It also enables full recovery of regenerative braking energy.
- It could increase EV cruise range in cold, e.g. 49% at −40 °C in US06 drive cycle.

GRAPHICAL ABSTRACT



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ABSTRACT

Electric vehicles (EVs) driven in cold weather experience two major drawbacks of Li-ion batteries: drastic power loss (up to 10-fold at −30 °C) and restriction of regenerative braking at temperatures below 5–10 °C. Both factors greatly reduce cruise range, exacerbating drivers' range anxiety in winter. While preheating the battery before driving is a practice widely adopted to maintain battery power and EV drivability, it is time-consuming (on the order of 40 min) and prohibits instantaneous mobility. Here we reveal a control strategy that can rapidly restore EV battery power and permit full regeneration while driving at temperatures as low as −40 °C. The strategy involves heating the battery internally during regenerative braking and rest periods of driving. We show that this technique fully restores room-temperature battery power and regeneration in 13, 33, 46, 56 and 112 s into uninterrupted driving in 0, −10, −20, −30 and −40 °C environments, respectively. Correspondingly, the strategy significantly increases cruise range of a vehicle operated at cold temperatures, e.g. 49% at −40 °C in simulated US06 driving cycle tests. The present work suggests that smart batteries with embedded sensing/actuation can leapfrog in performance.

1. Introduction

Drastically reduced driving range [1–4] is a major challenge for electric vehicles (EVs) operating at subzero temperatures as it exacerbate drivers' range anxiety [5]. Two technical problems of Li-ion batteries are particularly long-standing. First, regenerative braking is restricted or completely turned off at cold temperatures due to the phenomena of lithium plating that could severely reduce battery life and increase safety hazards [6,7]. Second, there is significant power loss, up to 10 fold at −30 °C [8], due to sluggish reaction kinetics, slow diffusion, reduced electrolyte conductivity, and increased solid-electrolyte interface (SEI) resistance at low temperatures [9–13]. Great

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efforts have been made to increase battery power at cold temperatures, notably reformulating electrolytes [14–18], hybridizing batteries with high-power supercapacitors [19], and preheating batteries before driving [20–27]. Among these approaches, battery preheating has been extensively investigated [22–27] due to its relatively simple implementation. But preheating is slow, typically tens of minutes [23–25], and inconvenient, prohibiting instantaneous mobility of EVs. Here we demonstrate an active control strategy that can rapidly restore EV battery power while driving, which eliminates any need to wait for preheating. This control strategy represents a new paradigm allowing batteries to be actively controlled and manipulated. We also demonstrate, through simulated US06 driving cycle tests and an energy balance analysis, that power restoration while driving could significantly increase EV driving range by fully recuperating braking energy and significantly increasing utilization of energy stored.

2. Experimental

2.1. Experimental system

Self-heating Li-ion battery (SHLB) cells with two embedded nickel foils, schematically shown in Fig. 1c and same as that reported earlier [28], are used as experimental cells. Each cell has a 152 × 75 mm footprint area, has nominal capacity of 9.5 Ah and weighs 210 g. Two pieces of polyethylene terephthalate coated nickel foil, each with resistance of 78 milli-Ohm at 20 °C, are stacked at ¼ and ¾ of cell thickness for uniform heating. The two pieces of nickel foil are connected in parallel with their total resistance of 39 milli-Ohm at 20 °C. The added weight and cost due to nickel foils are about 1.5% and 0.4% of the baseline battery [8]. $LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$ and graphite are used as cathode and anode active materials, respectively. More details about SHLB cell fabrication and materials can be found in our previous work [28]. One end of the nickel foils are connected to the negative terminal of SHLB cell while the other end extends out of the cell as an activation terminal (ACT). A switch is placed between positive terminal and ACT terminal. When the switch is ON, the SHLB cell works at heating mode as high current passes through the nickel foils and generates heat very rapidly [28]. When the switch is OFF, the SHLB cell works at normal mode just like a conventional cell without embedded nickel foils. In this study, the switch will be controlled according to EV load profile using a simple yet novel strategy. More details about the control strategy are in section 3.1. If the switch is constantly OFF, the SHLB cell works as a baseline cell.

A T-type thermocouple (SA1-T, OMEGA Engineering) is placed at the center of cell outer surface for monitoring cell surface temperature. A battery tester (BT2000, Arbin) is used to control power output of experimental cell according to profile of US06 driving cycle test, which is derived proportionally from the power profile developed by Keil et al. [19] for 3.3 Ah Li-ion cells. The battery tester is also used to measure external voltage and external current. A relay (EV200, TE Connectivity) is used to work as the switch between positive terminal and activation terminal of the SHLB cell. It is controlled by the battery tester so that it closes only during regen and rest periods of US06 driving cycle. When the cell reaches a desired temperature, 10 °C in this study, the relay is powered off and kept open. A shunt resistor (SHT1-500C075DE, Ohmite) is connected between positive terminal and activation terminal to measure cell current during self-heating. An environmental chamber (Tenney SPX, Thermal Product Solutions) is used to control the ambient temperature. The experimental cell is placed in a home-made thermal insulation box inside the environmental chamber to simulate cooling conditions in EV applications. A data acquisition unit (USB-2408, Measurement Computing Corporation) is used to record cell temperature, current and voltage at 5 Hz during US06 driving cycle tests.

2.2. Test protocol

For all low temperature tests in this study, the protocol is as follows: (1) Fully charging cell at 20 °C (1C, 4.2 V, C/20 cutoff); (2) Cooling cell to desired temperature for at least 6 h to ensure thermal equilibrium; (3) US06 driving cycle testing with first self-heating at the beginning and second self-heating after 5 cycles (50 min into testing), with cutoff voltage at 2.7 V; (4) Warming up cell to 20 °C; (5) Further continue US06 driving cycle test at 20 °C. Note that step (1) provides information on initially available energy; step (3) provides information on the regenerative breaking energy and driving energy; and step (5) provides information on unused energy.

3. Results and discussion

3.1. Control strategy of "battery heating while driving"

Fig. 1a shows the measured internal resistance of a 9.5 Ah Li-ion pouch cell during 1C discharge at different temperatures. As can be seen, the cell resistance increases exponentially as temperature decreases. The resistance at −40 °C is about 30 times higher than that at room temperature, indicating proportional power loss. Fig. 1b schematically depicts the load profile scaled for a 9.5 Ah Li-ion cell during a US06 driving cycle test as adapted from that of Keil et al. [19]. Three regimes can be observed from the profile: battery discharge for vehicle driving (power is negative), regenerative braking (power is positive) and rest (power is zero). Energy from the regenerative braking, which is up to 22% of energy for driving in the US06 profile, can be used to charge the battery for later use if the battery is warm enough. But if the battery is too cold, regenerative braking must be much restricted or completely turned off to avoid lithium plating, wasting a significant amount of energy. To fully recuperate this braking energy without lithium plating and restore battery power at low temperatures, we propose a new active control strategy, named "Battery Heating While Driving", where braking energy is used for internal heating. Once the battery is sufficiently warmed, the braking energy is subsequently used to charge battery active materials. This control strategy not only enables full recovery of braking energy, but also rapidly restores battery power performance without interrupting vehicle functionality and mobility.

The active control strategy is implemented on a recently discovered self-heating Li-ion battery (SHLB) [8,28]. As schematically shown in Fig. 1c, a SHLB cell has a nickel foil embedded for highly efficient and rapid self-heating [28]. One end of the foil is connected to the negative terminal while the other end extends out of the cell as an activation terminal (ACT). A switch is placed between positive terminal and ACT terminal. During regenerative braking (indicated by positive value of external current) and when the battery is cold (indicated by $T_{cell} < T_{critical}$), the switch is turned ON. External current from regenerative braking is thus diverted to the nickel foil for heating the battery, instead of being wasted on charging the battery materials which could cause lithium plating. Simultaneously the battery may discharge the current through the nickel foil to augment rate of battery heating and power restoration. When the vehicle needs power for acceleration or driving (indicated by negative value of external current), or the battery is already warm enough (indicated by $T_{cell} \geq T_{critical}$), the switch is turned OFF so that the SHLB functions just like a conventional two-terminal battery. To accelerate battery heating and power restoration, the switch may also be turned ON during rest periods.

Experimental results of executing the "Battery Heating While Driving" control strategy in a simulated US06 driving cycle test at −40 °C are shown in Fig. 1(d)–(g). It can be seen from Fig. 1d that not only is the cell discharge current (blue) equal to the external current (black) during driving periods to provide traction power, but also the cell undergoes high-rate discharge during rest and regen periods (hatched area) for rapid self-heating. Note that cell current automatically