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Control strategies and cycling demands for Li-ion storage batteries in residential micro-cogeneration systems

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HIGHLIGHTS

- Canadian home energy system modeled with PV, ICE CHP, battery and power grid.
- Battery function is modeled on fundamental electrochemical principles.
- Techno-economics of control strategies assessed.
- Impact of control strategies battery cycles is developed for wear analysis.
- Non-monotonic nature of battery cycles with transient renewables is discussed.

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ABSTRACT

Energy storage units have become important components in residential micro-cogeneration (MCG) systems. As MCG systems are often connected to single residences or buildings in a wide variety of settings, they are frequently unique and highly customized. Lithium-ion batteries have recently gained some profile as energy storage units of choice, because of their good capacity, high efficiency, robustness and ability to meet the demands of typical residential electrical loads. In the present work, modeled scenarios are explored which examine the performance of a MCG system with an internal combustion engine, photovoltaic input and a Li-ion storage battery. An electricity demand profile from new data collected in Ottawa, Canada is used to provide a full year energy use context for the analyses. The demands placed on the battery are examined to assess the suitability of the battery size and performance, as well as control related functionalities which reveal significantly varying battery use, and led to a quantitative expression for equivalent cycles. The energy use simulations are derived from electrochemical fundamentals adapted for a larger battery pack. Simulation output provides the basis for techno-economic commentary on how to assess large-scale Li-ion batteries for effective electrical storage purposes in MCG systems, and the impact of the nature of the control strategy on the battery service life.

1. Introduction

Lithium ion batteries at ratings around a 2 kW/6 kW h level are expected to play a role for residential power supply and storage. It is envisioned that they can provide some economic benefit under time-of-use (TOU) pricing structures. Storing energy can also reduce peak power demands as well as offset costly infrastructure upgrades to electrical power grid networks [1]. Rechargeable large-scale lithium ion batteries with good capacity and cyclability are among the most promising choices for residential energy storage (RES) applications. Lithium ion batteries have many characteristics which make them highly suitable for being the electrical storage components of choice. These characteristics include very high energy density, good power output, good cycle life with a broad cycling range, high coulombic efficiencies and comparatively low heat output. For prolonged intensive use, such as a in a micro-cogeneration system, proper control and management of a lithium-ion battery is crucial to ensure high capacity retention, as well as to operate the unit in a safe manner. A common mixed metal spinel, lithium nickel manganese cobalt oxide (LiNMC) is the cathode material in the battery pack prototype developed by Electrovaya, a Canadian battery company, which is modeled in this study.

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Nomenclature

c_i	lithium ion concentration in electrode (mol m^{-3})
$\mathrm{cap}_{\mathrm{ref}}$	reference capacity of cell (A h)
D_i	solid phase diffusion coefficient in electrode (m^2 s^{-1})
$E_{\mathrm{ref},i}$	electrode reference potential (V)
F	Faraday's constant = 9.648534 × 10^4 (C mol^{-1})
$i_{0,1}$	exchange current density in Butler-Volmer expression (Eq. (4)) (A m^{-2})
I_{tot}	applied current (A)
J_i	intercalation current density (mol m^{-2} s^{-1})
k_{ct}	rate of intercalation reaction (mol$^{0.5}$ m$^{2.5}$ s^{-1})
L_i	load profile demand (W)
P	power (W)
r	electrode particle radius position (m)
R	gas constant = 8.314 (J mol^{-1} K^{-1})
$R_{\mathrm{film},i}$	film resistance on the electrode particle (V A^{-1})
R_{int}	internal resistance of battery (Eq. (8)) (V A^{-1})
R_P	electrode particle radius (m)
S_i	internal specific surface area of the electrode (m^2 m^{-3}) = (m^{-1})
t	time (s)
T	temperature (K)
V	voltage (V)
α	stoichiometric coefficient in Butler-Volmer expression (Eq. (4)) (–)
α	temperature related parameter (Eq. (11)) (–)
β	capacity fade parameter (Eq. (11)) (–)
θ	electrode state of charge (–)
η	electrode overpotential (V) (Eq. (6))
η	unit efficiency (–) (Section 2.3)
Φ	electrode potential (V)

Subscripts

i	indicates anode (neg) or cathode (pos)
1	ionic phase in electrode
2	electrolyte phase in electrode
bat	battery
elec	electrical
th	thermal

Abbreviations

BESS	battery energy storage system
CHP	combined heat and power
DOD	depth of discharge
ICE	internal combustion engine
MCG	micro-cogeneration
NMC	nickel manganese cobalt oxide
NRC	National Research Council of Canada
OCV	open-circuit voltage
SOC	state of charge

Micro-cogeneration devices are making inroads for electricity generation at the residential level. These devices include internal combustion engines (ICE), solid oxide fuel cells, proton exchange membrane fuel cells, or Stirling engines. They typically generate less than 15 kW of electricity and are located within the household. When producing electricity alone, micro-cogeneration devices yield poor efficiencies, however when configured in systems that recover thermal energy generated in the electrical conversion process, the efficiency can rise to over 80%, referenced to the higher heating value of the fuel [2].

Annex 54 of the International Energy Agency's Programme on Energy Conservation in Building and Community Systems (IEA/ECBCS) has been focussed on reducing residential electric demand using micro-cogeneration devices through study with whole-building computer simulation software [3]. Within the scope of this Annex a residential micro-cogeneration system consisting of a CHP unit, PV panels and a Li-ion storage battery was simulated under various scenarios. This study, described in this paper, aimed to proscribe suitable large-scale battery sizes and architecture for overall energy use efficiency, as well as to gain insight on the nature of the battery interactions with the rest of the energy use system, such that control algorithms could be designed to provide best overall function and efficiency. A principal novel contribution of this present paper is to examine the details of the load demands placed on batteries in a residential energy system context, in order to better appreciate design considerations which encompass their function, capacity, durability and economy. In particular, the nature of their use on fine time scales is investigated, a topic which to this point has not been seen in the literature.

There is considerable choice of scope for incorporating clean energy technologies into residential energy systems. As an introduction to the subject, a good overview is provided by Desideri and Yan [4]. In a similar vein, storage batteries are presented among a wide range of technology options for storage units in systems with intermittent renewable sources [5]. There has been considerable interest in battery management systems and control strategies for batteries, but to date, much of the work devoted to advanced algorithms has been in the automotive sector. Much of the early focus here was on vehicle to grid (V2G) schemes to ease distribution instabilities that could arise with sudden widespread electric vehicle uptake in the market [6–8]. In the residential sector, effort has been directed at incorporating batteries into multi-component energy systems, with emphasis on sizing the battery packs to adequately handle the power inputs and demands for given configurations ie [9]. The storage of electricity for residential or building energy systems with renewables is recognized as paramount [10]. Further, from the perspective of utilities, demand side management is critical when transient components exploiting wind or solar power are included in the energy systems [11]. Some recent studies have begun to consider the complexities of managing batteries in residential energy systems. A paper by Leadbetter and Swan [12] investigated a battery energy storage system (BESS) used for peak shaving purposes in a residence. It was recognized that a short 5 min time step (as was employed here) in load data was required for proper analysis. Leadbetter and Swan however, only considered interactions with the distribution grid, so comments regarding battery control and effects on service conditions on battery wear did not account for the kinds of power spikes associated with variable transient inputs and domestic loads as considered in the present paper. Another paper by Clemmer et al. [13] which described developing a demand side energy management tool, took a broader overview of inputs for an energy use system which included a storage battery. The controller featured a modular customisable architecture able to account for PV generation, user input, hardware status and load profile information, as well as a TOU pricing schedule as inputs to a system management algorithm. This study focussed on energy use minimization without considering the costs associated with the extent of the battery use required. A study by Geth et al. [14] presented life cycle analysis for a building system with PV and a BESS. In this case, the study only considered monotonic charge or discharge phases and used a 15 min time step. Some other authors have examined