Lithium-Ion Battery Management

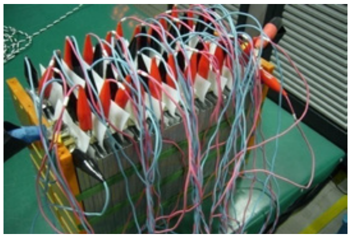
Control and monitoring remain outstanding challenges in lithium-ion batteries for high-power applications despite the progress of the technology.

Since the commercialization of lithium-ion rechargeable batteries by Sony Corporation in 1991, the basic principles of lithium intercalation and rocking-chair operation have remained unchanged, but new material types and enhanced chemical compounds for electrodes and electrolytes are being continuously introduced.

Capacity improvements have been incremental, and commercially available 200-Wh/kg cells are still far from the theoretical values of about 600 Wh/kg for current chemistries and up to 11 kWh/kg for the holy grail of lithium-air cells (an energy capacity that is close to gasoline's 13 kWh/kg). Specific power, on the other hand, has significantly improved and is getting close to a milestone of 100C for charge and discharge current (i.e., current limit in amperes is a hundredfold of cell capacity in ampere-hours).

High energy and power density make lithium-ion a technology of choice for automotive and aerospace applications; however, safety issues and susceptibility to rapid aging are drawbacks, which are currently addressed by conservative control strategies that sacrifice battery capacity and power.

Lithium-Ion Battery Safety

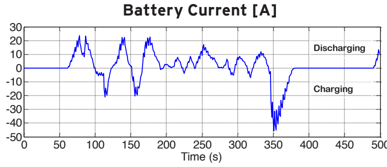


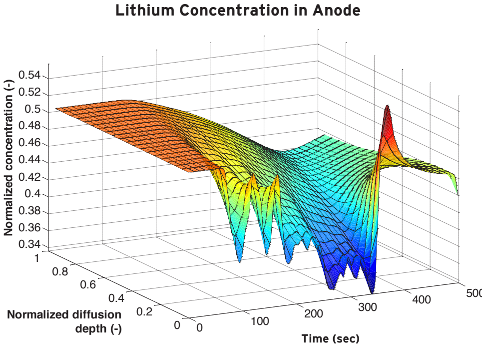
Experimental 24-V/100-Ah lithium-ion battery pack with 40 cells for automotive applications

Lithium-ion technology is prone to thermal runaways with low temperature threshold. In combination with a flammable organic electrolyte solvent and metal-oxide content in electrodes, these runaways can lead to violent self-sustaining fires that can spread rapidly among cells in a battery pack (a phenomenon that has prompted the recall of tens of millions of Sony batteries, concerns about the Chevrolet Volt fire risk, the grounding of Boeing 787s, etc.). Safety problems arise from both design/manufacturing issues (contamination of metallic particles leading to slow dendrite formation and short-circuiting of separators) and also from insufficient insight into battery operation and battery internal state. Protection systems should not rely solely on measurements, but should be able to estimate and predict internal state for early detection of hazardous events.

Lithium-Ion Battery Aging

Lithium-ion batteries have a tendency toward rapid aging (capacity and power decrease, internal resistivity increases) if used close to operational constraints (overcharging, full discharge, excessive current and temperature, etc.). Since battery cost is a significant part of the total electric or hybrid vehicle cost, the powertrain controller should optimize for mileage and battery amortization jointly. This requires modeling battery aging and battery state-of-health estimation; however, aging is a combination of complex mechanisms (formation of ion transport inhibiting deposits, lithium plating, passivation, crystal grid collapse, etc.).





Under high-current operation, high variation of lithium concentration on the anode surface (normalized diffusion depth of 0) creates "hidden waves" in the internal lithium concentration profile (normalized diffusion depth >0). Knowledge of the internal profile is essential for estimating parameters such as state of charge, but voltage measurements only reflect the surface concentration.

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Challenges: Control-Oriented Modeling for High-Power Applications

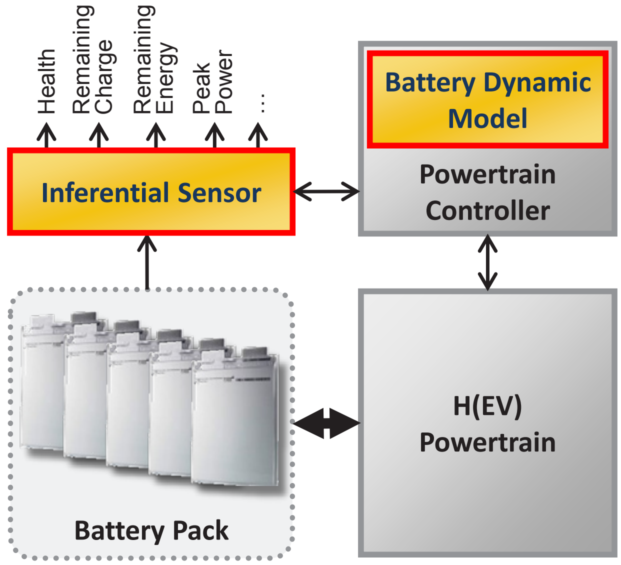
- High current density causes spatial imbalance of active species resulting from fast electrochemical phenomena and slow diffusion kinetics. This distributed-parameters behavior cannot be ignored.
- Accurate electrochemical models are based on partial differential algebraic equations driven by the Butler-Volmer kinetic equation and diffusion laws; these models are too complex for closed-loop control.
- Modeling of the aging mechanism is not tractable even on the level of electrochemical models (e.g., phenomena on the solid-electrolyte interface) and has to be approximated by empirical models.
- Successful single-particle models have limited applicability for high-power applications.
- The main challenge is bridging the gap between high-fidelity electrochemical models and control-oriented models targeted to embedded applications.

Challenges: Experiment Design

- Battery experiments consume substantial time and resources, especially lifetime cycling and testing under a wide range of conditions.
- Parameter identification of electrochemical models is difficult.
- Electrochemical impedance spectroscopy only captures steady-state behavior.
- Major challenges are the design of reasonable experiments for aging models and parameter identification algorithms.

Challenges: Battery Aware Optimization

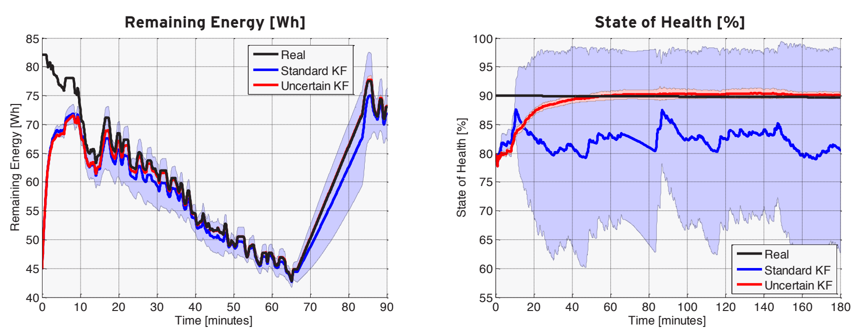
- Powertrain optimization with a criterion combining mileage and battery amortization.



An inferential sensor for a Li-ion battery pack is needed for several variables in hybrid or electric vehicle powertrains.

Challenges: Inferential Sensor Design

- Design of an inferential sensor must be robust to manufacturing variability (see graphs below).
- Variables of interest, apart from state of charge, include remaining energy, current peak power, heat production rate, and remaining effective charge capacity.
- Early detection of thermal runaways is necessary.
- Observability issues arise from limited measurements and distributed-parameter-based models.



Inferential sensing of battery remaining energy (left) and state of health (right) under manufacturing variability. The black trajectory is a simulated model with "real" parameters. The blue and red trajectories show estimation with a standard Kalman filter (KF) and a Kalman filter for uncertain models over multiple runs with model parametrization taken randomly from manufacturing uncertainty. Solid lines are mean values, and shaded bands illustrate the standard deviation range in each case. Knowledge of, and design for, manufacturing uncertainty is essential for accurate estimation.