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Review article

# A comprehensive review of on-board State-of-Available-Power prediction techniques for lithium-ion batteries in electric vehicles

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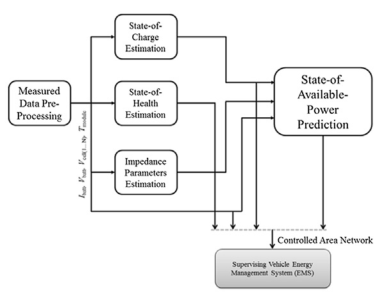
## HIGHLIGHTS

- Challenges and issues of on-board SoAP prediction are discussed.
- All available techniques recently applied for SoAP estimation are discussed.
- For every technique the pros and cons of the proposed method are described.
- Examples of existing research results and patents are given.

## GRAPHICAL ABSTRACT

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## ABSTRACT

This study provides an overview of available techniques for on-board State-of-Available-Power (SoAP) prediction of lithium-ion batteries (LIBs) in electric vehicles. Different approaches dealing with the on-board estimation of battery State-of-Charge (SoC) or State-of-Health (SoH) have been extensively discussed in various researches in the past. However, the topic of SoAP prediction has not been explored comprehensively yet. The prediction of the maximum power that can be applied to the battery by discharging or charging it during acceleration, regenerative braking and gradient climbing is definitely one of the most challenging tasks of battery management systems. In large lithium-ion battery packs because of many factors, such as temperature distribution, cell-to-cell deviations regarding the actual battery impedance or capacity either in initial or aged state, the use of efficient and reliable methods for battery state estimation is required. The available battery power is limited by the safe operating area (SOA), where SOA is defined by battery temperature, current, voltage and SoC. Accurate SoAP prediction allows the energy management system to regulate the power flow of the vehicle more precisely and optimize battery performance and improve its lifetime accordingly. To this end, scientific and technical literature sources are studied and available approaches are reviewed.



## 1. Introduction

Partial or full electrification of the vehicle powertrains opens a wide range of opportunities to implement more consumer-friendly, security-relevant functions and to discard or reduce the vehicle's

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local emission. In this regard, lithium-ion batteries (LIBs) are favored as promising alternative to other energy storage systems (ESS) such as lead-acid batteries or nickel-metal hydride batteries in automotive applications. In the long term, LIBs are a worthy replacement for fossil fuels and traditional energy sources for use either in mobile or stationary applications [1,2].

High level of gravimetric and volumetric energy and power density, low self-discharge, high cell-voltage (depending on the used active materials) and high cycle and calendar lifetime are among the main advantages of LIBs [3–7]. Considering the growing amount of patent applications of lithium-based technologies from both research institutions and industry in the recent past, a high interest in pushing LIB-based ESS forward can be observed [8].

In order to fulfill specific power and energy requirements in electric vehicles (EVs) generally specified by car manufactures, LIBs are connected in series and/or in parallel (depending on topology), thus forming a large lithium-ion battery pack [9]. The performance of LIBs and their operation are controlled and diagnosed by means of so-called battery management systems (BMS) consisting of both software and hardware [10]. In other words, protection against battery over-voltage, under-voltage, over-current, over-temperature, under-temperature and cell balancing are among the main tasks of the BMS.

Fig. 1 illustrates schematically a simplified lithium-ion battery pack including the following BMS electric and electronic components [11]:

- Cell Controller Board (CCB),
- BMS Master,
- Low-voltage (LV) and high-voltage (HV) interfaces,
- Fuse, contactors etc.

The main task of the CCB is to measure a particular number of cell voltages and temperatures (e.g., 1–12 cells) [11]. In fact, the CCB is the only physical interface between the BMS and the battery cells. Furthermore, cell balancing is performed by means of balancing resistances implemented on each CCB and controlled by an algorithm implemented on the electronic control unit (ECU) in the BMS master. Depending on the topology of the lithium-ion battery pack and the number of LIBs which have to be monitored, one or more CCBs are required. Each CCB communicates with the other CCBs via Controlled Area Network (CAN) or Isolated Communications Interface (isoSPI). Measured cell voltages and temperatures are then submitted via CAN to the BMS Master and analyzed, respectively. On the one hand the BMS Master is responsible for evaluating the measured battery pack's current and voltage as well as triggering the contactors (opening, closing) during pre-charge phases or when a crash or fault is detected, and on the other hand it performs plausibility checks and diagnoses of the battery states and parameters. Furthermore, monitoring algorithms implemented for battery state estimation (BSE) are running on the ECU. Submitting or receiving data to/from the vehicle EMS as well as the electronic power supply are all performed over a designed low-voltage (LV) interface.

The accurate estimation of battery states, such as State-of-Charge (SoC), State-of-Available-Power (SoAP) or State-of-Health (SoH), is still a challenging task, keeping in mind that the implemented monitoring algorithms have to work accurately over years in the particular application. Monitoring algorithms use on-board measured values such as battery temperature, battery voltage and current for BSE. However, since a direct insight into electrochemical processes inside the LIBs in the field is not possible, estimated battery states or parameters may differ from real values. For example, according to Ref. [12], the difference between the measured cell temperature on the surface and in the core may be approximately 10 K. Keeping in mind that often one single temperature sensor is used in a battery module for monitoring the module's temperature[1] and the measurement accuracy of implemented temperature sensors are often low, it becomes obvious how challenging the task of reliable and accurate battery monitoring is considering all uncertainties and disturbances.

The electrical and thermal performance of the battery is mainly influenced by the following factors:

- Topology of the lithium-ion battery pack [13,16].
- Internal and external factors, such as unequal aging behavior of the LIBs over the battery lifetime (capacity and impedance spread between each individual LIB in the battery module/pack) [9,14],
- Inconsistency of the SoCs [13,15],
- System losses occurring in the battery pack (e.g., power rails, contactor resistances etc.) [9,15],
- Limitation of the use of the battery's maximum power and energy capacity, caused by the increase of battery impedance and decrease of available battery capacity over the battery lifetime [13],
- Distribution of the temperature in the battery pack[2] etc. [7,15].

Therefore, it is necessary to consider these factors during the system design phase in order to prevent oversizing the system and reduce costs, respectively, while specified requirements are fulfilled.

One of the state-of-the-art approaches used for static power capability determination is the hybrid pulse power characterization (HPPC) method presented by the partnership for new generation vehicles (PNGV) battery test manual, published by the Idaho National Engineering & Environmental Laboratory of the U.S. Department of Energy [17]. An improved method for the determination of power capability by means of pulse tests with some modifications regarding applied current rates, resting time etc., is presented in our previous work [18]. In fact, accurate results may be achieved by applying this technique in laboratory environments. But under real conditions, such as in vehicles where available peak current or voltage for a specified time horizon need to be known, accurate power values are not provided and the results are mostly overestimated since only the operational design limit of battery voltage is considered [4,21–23]. Fig. 2 shows the dependence of battery power capability on battery SoC over the battery lifetime at 23 °C in an example of a battery electric vehicle (BEV) prototype using $Li(NiMnCo)O_2$ (NMC)/$Li_4Ti_5O_{12}$ (LTO) LIBs. The available battery power is determined based on resistance values obtained as a voltage value reached after 20 s from the beginning of the current pulse divided by the current.

The power fade occurred over the battery lifetime directly influences the driving performance of the vehicle in terms of acceleration or battery charging during regenerative phases and charging periods [24]. From the relationship between battery SoC and power capability shown in Fig. 2, it becomes obvious that the charging power capability decreases with the increase of SoC and vice versa. The maximum available power of a lithium-ion battery pack (Fig. 2) is derived by investigating the battery's open-circuit voltage ($V_{OCV}$) and resistance as follows [25–27]:

$$P_{discharge} = [V_{cell,min} \cdot (V_{OCV\ cell,charge} - V_{cell,min})/R_{cell,discharge}] \cdot n_{cell,series} \cdot n_{module,parallel} \quad (1.1)$$

[1] Each battery module consists of several cells connected in series or parallel.

[2] Temperature differences between individual LIBs must be kept in a range of 3 °C–5 °C [19,20].