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Enhancing electric vehicle sustainability through battery life optimal charging

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ABSTRACT

In this article, we investigate the potential for battery life prolongation through optimized charging under consideration of individual mobility requirements. Based on a comprehensive battery aging model we introduce a continuous quadratic programming model to derive battery life optimal charging (OPT). The strategy indicates when and how much to charge to maximize the potential range throughout the battery life. We find that OPT has the potential to more than double the expected battery life compared to simple and often abundant recharging activities as observable today. The degree of battery life prolongation strongly depends on the operating temperature. Since optimal charging would require deterministic knowledge of future trips and corresponding charging levels we investigate a more convenient charging heuristic derived from “As-Late-As-Possible” (ALAP) charging. ALAP charging considers range buffers between 5% and 60% over the range required until the next re-charging opportunity. We analyze the trade-off between (long-term) battery life and (short-term) range flexibility. We find that for decreasing temperatures the trade-off between battery life and flexibility is solved with increasing range buffers. From our results battery degradation aware charging heuristics can be easily derived and applied in real-world settings.

1. Introduction

Electric vehicles (EVs) are gaining importance in many developed countries. For instance, Germany intends to have one million EVs on its streets by 2020 (NPE, 2011). Other countries like the USA strive to achieve this number even earlier. The adoption of this technology is currently still delayed due to the high cost of batteries and the limited range as compared to conventional internal combustion engine vehicles (ICEVs). This limited range can further decline during operation due to the degradation of the battery over time, driven in particular by the fade of maximum capacity.

It is known from laboratory aging tests that the major drivers for battery aging are operating conditions related to time, energy throughput, temperature and in particular the state of charge (SoC) (Jossen and Weydanz, 2006; Jossen, 2006; Pelletier et al., 2017). However, recent publications have identified phenomena such as range anxiety that lead to frequent and full recharging and therefore high SoCs.

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1.1. EV user behavior

Uncertainty about the possibility to recharge and the range limitations have led to the observation of *range anxiety* in field studies (Franke and Krems, 2013b; Xu et al., 2017) and user interviews (Eberle and von Helmolt, 2010; Neubauer and Wood, 2014). Franke and Krems (2013a) study EV drivers and their charging behavior and found that users prefer to retain range buffers. Since the observed average daily distance is far below the available range, daily recharging is found unnecessary from a technical perspective.

Rolim et al. (2012) as well as Xu et al. (2017) observed that a large portion of users considered in a similar setting are mostly charging at home and overnight. Other empirical studies from the U.S.A. that estimate the potential of EV applicability show that the average driving distance per day is between 46 km (NHTS[1]) and 52 km (Pearre et al., 2011). Further empirical evidence from field trials in Japan shows that the majority of private users reconnects a vehicle for full-charging after the last trip of the day to have the full range available the next day (Sun et al., 2015). This behavior was also observed in field trials reported in Zoepf et al. (2013) and Jabeen et al. (2013).

While this frequent full-recharging covers the drivers' potential (not necessarily actual) mobility requirements, higher charging states drive battery degradation and shorten the lifetime of the battery. So far this trade-off has not been modeled in a formal fashion, and charging aimed at maximizing battery life received scant attention in the literature.

1.2. Charging management and optimization

There is ample literature about controlled charging and discharging of EVs. Most work focuses on technical and grid integration objectives through shifting of unidirectional charging events. Energy feed-in from EVs to the grid, well known as Vehicle-to-Grid (V2G), was introduced by Kempton and Letendre (1997) and has received increased attention ever since. This body of literature considers battery degradation on different levels but mostly simplistic in nature.

EVs of private customers are–on average–used only around one hour a day (Kempton and Tomic, 2005). Hence, most EVs have temporal flexibility regarding their recharging phases (Wu and Sioshansi, 2017). A significant body of research has been devoted to exploit this flexibility for example to reduce charging costs incurred given a variable pricing scheme (Valentine et al., 2012; Schuller et al., 2014; Wei and Guan, 2014; Flath et al., 2014; Fetene et al., 2016).

Since V2G introduces additional cycles to the battery this also needs to be accounted for in the economic assessment. Current literature in the field of V2G considers battery degradation by simplified assumptions, such as the calendaric part of aging (Dietze, 2015) or penalties for high power charging and discharging (Peterson et al., 2010).

Other, more recent work from Wang et al. (2016) combines semi-empirical battery aging, vehicle and ambient temperature models in order to determine the effect of a constant V2G operation mode for peak shaving or frequency regulation in the Californian energy market. The degradation model employed by Wang et al. (2016) is derived from Wang et al. (2014), which is reviewed in more detail in Section 2.1. In summary, most of the sources mentioned consider battery degradation merely as a simplified, additional cost factor but do not focus on reducing it as a primary objective.

1.3. Aim and organization of this paper

The consideration of user behavior and phenomena such as range anxiety and their impact on battery aging is essential to propose adjustments of utilization patterns in daily operation that prolong the operational lifetime and maximize the cumulated range of an EV. However, by now there is only little guidance on how to appropriately consider battery degradation in charging recommendations.

First, no models have yet been proposed to estimate the sensitivity of battery lifetime in empirical settings on driving and charging behavior. Second, the phenomenon of range anxiety of EV users as well as uncertainty in range predictions need to be considered in any charging strategy recommendation.

To support an informed decision on a beneficial trade-off between range requirements and battery lifetime increase, in this paper we investigate *to which extent battery life can be extended by the application of a degradation optimal charging strategy* and *how the trade-off between range flexibility in terms of buffers and the battery life can be modeled in a formal fashion*.

We contribute to the literature by introducing a continuous quadratic programming model to calculate the battery life optimal charging strategy (OPT). OPT–the decision when and how much to charge–aims at maximizing the time until the end of life (EoL) of a battery.

Since optimal charging would require deterministic knowledge of future trips and corresponding charging levels we investigate the more convenient As-Late-As-Possible (ALAP) charging heuristic, considering range buffers between 5% and 60% over the range required until the next re-charging opportunity ($ALAP_b$). In simulation studies with real-life assumptions on vehicle parameters and mobility requirements based on a representative set of empirical driving profiles from the German mobility panel (BMVBS, 2008), we analyze the trade-off between range flexibility and battery life achievable with $ALAP_b$ in comparison to the optimal solution (OPT).

[1] National Household Travel Survey, http://nhts.ornl.gov