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Battery cell balance of electric vehicles under fast-DC charging

Guido Wager, Jonathan Whale and Thomas Bräunl

Abstract: Electric vehicle (EV) range, recharge opportunities and time to recharge are major barriers to mainstream acceptance. Fast-DC charging has the potential to overcome these barriers. This research investigates the impact of fast-DC charging on battery cell balance, charge capacity and range for an EV travelling long distances on an ‘electric-highway’. Two commercially available EVs were exposed to a series of discharge and fast-DC charge cycles to measure cell balance and charge capacity. The vehicles’ battery management systems (BMS) were capable of successfully balancing individual cells and hence maintaining the batteries’ charge capacity. Although fast-DC charge levels and discharge safety margins significantly reduced the vehicles’ charge capacity and range as stated by the manufacturer, these values remained stable for the test period. In regards to cell balance and charge capacity, our research suggests that fast-DC charging technology is a feasible option for EVs to travel large distances in a day.

1 Introduction

In an electric vehicle (EV) or plug-in hybrid electric vehicle (PHEV), individual battery cells are connected in series to form a battery at the desired voltage. The major types of rechargeable EV batteries are: lead-acid (Pb-acid), nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), lithium-ion (Li-ion), lithium-polymer (Li-poly), sodium-sulphur (NaS) and zinc-air (Zn-Air) (Manzetti and Mariasiu, 2015; Husain, 2003). In the early days of EVs the most popular choice for EVs was lead-acid batteries since they were relatively cheap, could be designed for high power, were safe to operate and had a recycling industry in place. A further benefit was a simple charging procedure where individual cells do not require a complex BMS. However, lead-acid batteries take a long time to recharge and have a short calendar and cycle life. Furthermore lead-acid batteries have a low specific energy density and in contrast to automotive distillate, which has a specific energy of around 12000 Wh/kg (Energy, 2015), a lead-acid battery contains just 50 Wh/kg (Husain, 2003). Even though internal combustion engine (ICE) cars have much lower energy conversion efficiency than EVs, the high specific energy in automotive distillate allows ICE cars a short refuel time and large drivable range.

The energy storage (and hence the drivable range) and the time to recharge an EV are still amongst the most important factors in deciding whether EV technology can become a large-scale feasible alternative to motor vehicles that run on fossil fuels (Ehsani et al., 2009; Lukic, 2008; Heyvaert et al., 2015; Lebeau et al., 2013).

The introduction of lithium-ion batteries has improved the situation. Lithium-ion batteries can store around 170 Wh/kg (Husain, 2003), have high specific power, can be fast charged and have a much longer calendar and cycle life than lead-acid batteries. However, their drawbacks are the relatively high costs and the requirement of a complex BMS to balance individual cells and manage complex recharging techniques. To prevent overcharging, overheating and permanent damage, lithium-ion cells require complex charging algorithms (Hussein and Batarseh, 2011) and smart chargers that communicate with the EV to ensure a safe and efficient charging procedure.

Currently, the most popular charging methods for EVs are home charging (level-1) and public charging stations (level-2, AC or fast-DC following Combo-CCS or CHAdeMO). Depending on the state of charge (SoC), the size of the onboard battery charger and the available electricity source, recharging of a standard EV traction battery can take more than 10 h. The long charging time is a result of the low level-1 charge rate (a maximum of 2.4 kW in Australia) and the time required to balance the cells.

Fast-DC charging for EVs is a new technology that provides a charge rate of up to 120 kW (Motors, 2015). As a result, a standard EV traction battery can be charged to 80% of its battery capacity within as little as 20 min. The short recharge time enables EV drivers to drive large distances with acceptable recharge and travelling times. However, this also means that EV drivers may have to forfeit the 20% of their EV’s charge capacity and consequently driving range, as fast-DC charging cannot deliver energy for the remaining 20% at an equal speed to the first 80%. If fast-DC charging stations are installed along highways between remote towns, this technology has the potential to make EV driving feasible in areas of low population density where EV driving is currently very limited owing to the lack of recharging infrastructure between and within remote towns. In the south west region of rural Western Australia (WA), for example, a number of fast DC charging stations are being installed in country towns that are popular with tourists to form an ‘electric highway’ that will join the city of Perth to these towns (Moodie, 2015; Project, n.d.) When installation is complete, this will be Australia’s first large-scale EV charging network.

While fast-DC charging can significantly reduce the time to recharge, it presents a challenge to the BMSs currently used by EVs. The main task of a BMS is to equalise the individual lithium-ion cells (up to 7000 cells (Wiki, 2014)) in an EV traction battery. Cell equalisation is a complex and important task to maintain cell voltage balance and utilise full battery capacity. The cell voltage is proportional to the cell’s charge capacity and hence the batteries’ capacity is limited to the lowest cell voltage in the battery. A BMS measures individual cell voltages and interacts to balance the individual cells. A sophisticated BMS protects the battery not just from over-charging but also under-charging or temperature related issues and can also report battery health and charge status (Stuart and Zhu, 2010; Chatzakis et al., 2003; Bowkett et al., 2013; Chol-Ho et al., 2013; Bonfiglio and Roessler, 2009; Zhou and Zhang, 2015).

A wide variety of BMSs are implemented for a large number of lithium-ion battery applications. The simplest form of BMS is cell shunt regulators (dissipation type), for example as implemented in a custom converted Lotus Elise ‘REV Racer’ and Hyundai Getz ‘REV Eco’ by the University of Western Australia (UWA) (Oakley et al., 2016). A simple electronic circuit monitors the cell voltage and as soon as a preset voltage level is detected, the shunt becomes an active load and dissipates excessive energy into heat. Although these systems are cheap and comparatively reliable they are inefficient and on large battery banks produce relatively large amounts of heat. Another drawback is that the balancing power is limited to the maximum heat dissipation of the shunt. Hence the balancing is slow and becomes an issue for fast-DC charging applications. More advanced and complex BMS are capable of transferring excessive energy between cells. Each cell is equipped with a micro controller, which communicates to the main BMS controller. The controller monitors individual cells and decides which cell needs be corrected. In contrast to a shunt regulator, excessive energy is not dissipated into heat but stored in an inductive or capacitive energy storage device and transferred between the cells. Such a system ensures that the cells are balanced even when an EV is at the beginning of a charge, driving or just parked. This balancing of individual cells ‘on the fly’ results in higher charge efficiencies and reduced balancing time toward the end of charging (Lukic, 2008; Stuart and Zhu, 2010; Chatzakis et al., 2003; Bowkett et al., 2013; Chol-Ho et al., 2013; Moore and Schneider, 2001). However, even active BMS have limitations and might not be able to complete cell balancing under fast-DC charging. As a consequence if the voltage of a battery cell drifts low and is out of balance with the rest of the cells over time, the overall battery capacity and range are reduced and an efficient utilisation of the battery capacity cannot be maintained.

Although at least one fast-DC charge study has been undertaken (and shown a negative impact on cell capacity (Boesenberg et al., 2015)) and studies have been published on the design and implementation of BMS and cell equalisation methods (Stuart and Zhu, 2010; Chatzakis et al., 2003; Bowkett et al., 2013; Chol-Ho et al., 2013; Bonfiglio and Roessler, 2009), there is little information on realistic fast-DC charging of commercially available EVs. In this paper we are not looking at deterioration of battery cells through fast-DC charging (which very well may be a secondary effect), but we will concentrate on the interaction and impact of realistic fast-DC charging on BMS and battery cell balance and hence on the efficient utilisation of the given battery capacity. The aim of this study is to assess the fast-DC charging impact on the traction battery cell balance and if a BMS can maintain battery capacity and vehicle range under a series of continuous realistic fast-DC charge scenarios on commercially available EVs.

In this project we will investigate the effect of fast-DC charging on cell balance within an EV's battery pack. Cell balance for an EV is essential, as an EV has to stop driving when any cell drops below a certain threshold charge value and likewise has to stop charging once any cell exceeds another threshold charge value. Since fast-DC charging happens in a much shorter time than e.g., home-AC charging (typically 20 min. vs. 8 h), there will be significantly less time for the EV's BMS to achieve an active cell balance through redirecting current-flow during charging. In this paper we investigate the impact of fast-DC charging under different conditions and with two OEM[1]-built EVs.

Please note that this paper does not address any potential long-term battery degradation effects due to high-powered DC charging. The scope of this work is on the short-term charge imbalance of individual cells, which can typically happen on a single longer EV trip with some short stops for fast-DC charging, such as on the WA 'electric highway'. These imbalances are generally reversible, e.g., by conducting a slow-AC charge, giving the BMS more time to balance cells, but they may have a detrimental effect on vehicle range when driving a long distance highway route.

2 Materials and methods

To observe the impact of fast-DC charging on the cell balance in EV batteries, two factory-built EVs were used and their traction batteries were exposed to a series of discharge and fast-DC charge cycles. The test cars used in this study were a pre-used Nissan Leaf (24,000 km) and a pre-used Mitsubishi i-MiEV (5100 km), depicted in Figure 1. The Leaf is manufactured with a 24 kWh battery and the i-MiEV contains a 16 kWh battery. However, in both cases, not all of the nominal battery energy can be used since the BMS protects the batteries from permanent damage due to deep discharge. At a very low battery level the Leaf's and i-MiEV'sBMSs force the cars into 'limp mode'. In 'limp mode' the control system reduces the vehicles' maximum drivable speed significantly, allowing the cars to be driven to a safe location before coming to a full stop (Nissan, 2013a; Mitsubishi, 2015). According to Nissan's specifications, under laboratory conditions the Leaf has a drivable range of up to 199 km (Nissan, 2013b) on full charge, while the i-MiEV claims a range between 150 km (Mitsubishi, 2015) and 160 km (Mitsubishi, n.d.).

Figure 1 Test cars Nissan Leaf (left) and Mitsubishi i-MiEV (right) used for the experiments

A series of 18 discharge and fast-DC charge cycles were carried out on the Nissan Leaf, and eight cycles on the Mitsubishi i-MiEV. For a uniform discharge rate and a uniform SoC, the vehicle batteries were discharged using the cars' internal loads such as the heater or AC system, head lights, demister and fans. As stated previously, the scope of this paper concentrates on short-term imbalance of battery cells, such as experienced on a drive on a long distance highway (e.g., the WA electric highway) and thus a limited series of discharge and charge cycles were carried out. There were also practical reasons that limited the number of cycles including the fact that the EVs were borrowed, which limited the time that the vehicles were available and prevented the authors from sacrificing the batteries through continual degradation over a large number of cycles.

A lithium-ion battery cannot be fully discharged, which means that in a real-world driving scenario, the vehicle cannot be driven to the end of its charge capacity. To prevent the vehicles from the 'limp mode', where the vehicle cannot be driven further, a safety margin was included. For the Leaf with the larger battery, minimum SoCs of 30% and then 20% were used, while for the i-MiEV a minimum SoC of 30% was used. Up to four discharge/charge cycles were conducted per day with the vehicles being recharged using a Veefil fast-DC charger, a 50 kW charger that is installed at the University of Western Australia (UWA). The Combo CCS (SAE, 2012) and CHAdeMO standards (CHAdeMO, 2015) provide a suitable charging interface to the Leaf and i-MiEV.

To monitor the energy consumption and the charging of the batteries, the following variables were read from the vehicle controller area network (CAN) bus during the experiment: battery capacity (Ah), system voltage (V), individual cell voltages (V), charge and discharge power (W), and current (A). In addition, the Leaf gave an indication of battery health status (%). The CAN bus was accessible via an onboard diagnostic connector (OBD2) (Allande et al., 2013; Benders et al., 2013). For the hardware interface, a commercially available scan tool was used and the data from the scanner was transmitted via a Bluetooth terminal to an android computer system.

The recharged energy was averaged over the charge cycles and the uncertainty was estimated by the associated standard deviation. The calibration and accuracy of all instrumentation used in the experiments was limited to the manufacturing standards of the EVs and the fast-DC charging station.

3 Results

During all discharge-charge cycles on the Nissan Leaf and i-MiEV the traction battery charge capacity and cell balance were recorded.

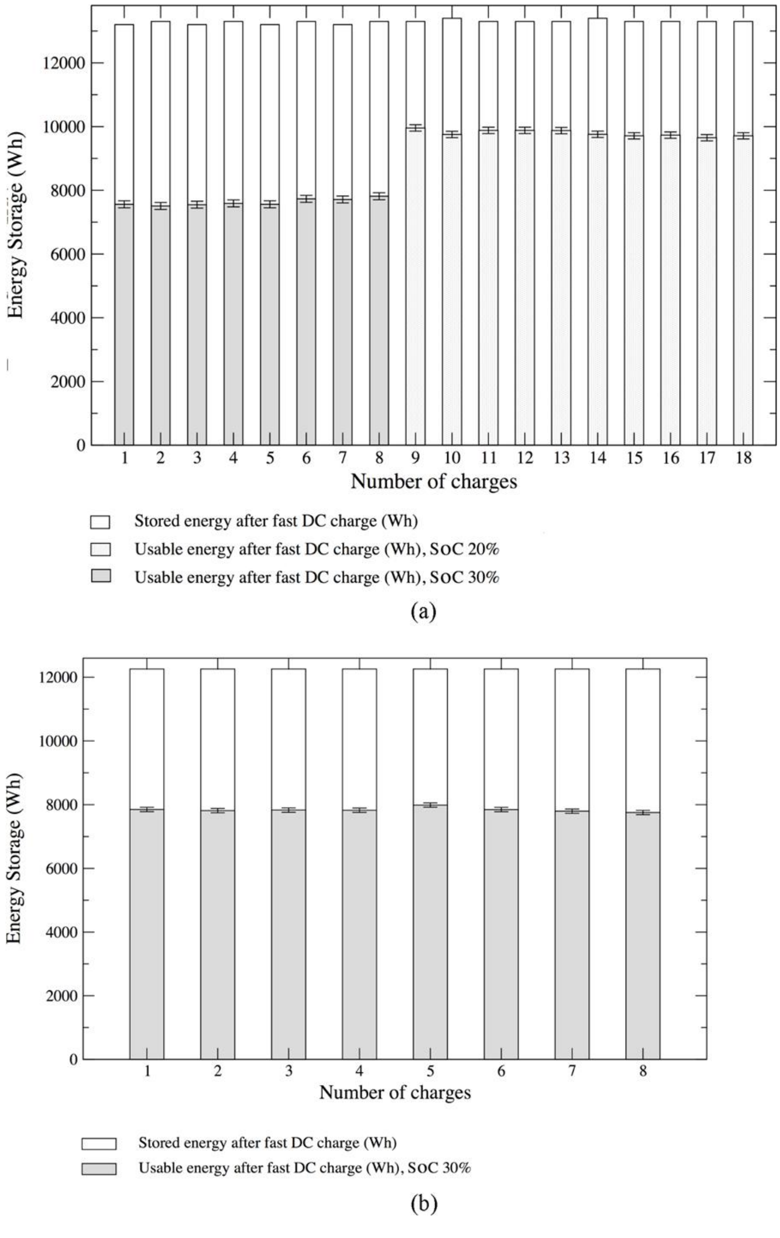
The total applied charge energy to the Leaf over 18 charges was 159 kWh. Assuming an energy consumption of 150 Wh/km (Nissan, 2013b) this is equivalent to over 1000 km of real road driving. The total applied charge energy to the i-MiEV over eight charges was 62.7 kWh, which is equivalent to over 500 km of road driving, assuming an energy consumption of 125 Wh/km (Mitsubishi, n.d.).

For the Leaf’s first series of discharges to 30% SoC, the average remaining energy in the traction battery was 5.3 kWh. Assuming a New European Driving Cycle NEDC (UN-Vehicle-Regulations, 2013) energy consumption of 150 Wh/km (Nissan, 2013b) the remaining range would be 35 km before the system would switch into ‘limp mode’, which is a reasonably large safety margin compared to the range of ‘up to 199 km’ published by Nissan for the Leaf (Nissan, 2013b). However, independent road testing performed at UWA has shown that when driving under realistic highway conditions energy consumptions on both cars can exceed 250 Wh/km and driving at higher speeds with an assumed energy consumption of 250 Wh/km reduces the safety margin to 21 km. For the second series of discharges down to 20% SoC, the average remaining energy in the traction battery was 3.2 kWh. Based on the energy consumptions of 150 Wh/km and 250 Wh/km assumed above, this corresponds to remaining drivable distances of 21.2 km and 12.8 km, respectively.

A similar scenario was observed on the i-MiEV. Discharging to 20% SoC, the average remaining energy in the traction battery was 4.6 kWh and, based on an energy consumption of 125 Wh/km reported by Mistsubishi (n.d.) above, the remaining drivable distance before the vehicle enters ‘limp mode’ would be 36.8 km. Compared to a range of 150 km for the i-MiEV published by Mitsubishi (2015) this is also a relatively large safety margin. However, assuming continuous, real road driving on a highway at a speed of 110 km/h and an assumed energy consumption of 250 Wh/km the safety margin reduces to just 18.4 km.

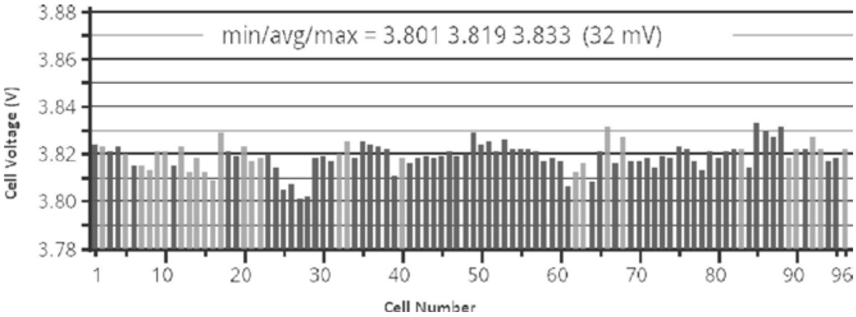
Figure 2(a) and (b) show the stored and usable (recharged) energy over the 18 discharge-recharge cycles for the Nissan Leaf and the eight cycles for the i-MiEV, respectively. For the Nissan Leaf, Figure 2(a) clearly shows that the stored and usable energy remain stable over all cycles. By recharging the battery from a SoC of 30% the average usable energy was 7628 ± 109 Wh. By recharging the battery from a SoC of 20%, the average usable energy was 9790 ± 99 Wh. For both combined recharge scenarios, SoC 20% and SoC 30%, the average energy stored in the battery after the charge was 13,300 ± 58 Wh. Similarly, the data in Figure 2(b) shows that the battery energy remained stable over the eight discharges and fast-DC charges applied to the i-MiEV. By recharging the battery from a SoC of 30%, the average recharged energy was 7837 ± 68 Wh. The average energy stored in the battery after the charge was 12,261 Wh.

Figure 2 Stored and usable energy during a series of fast-DC charges: (a) Nissan leaf stored and usable energy and (b) MiEV stored and usable energy over the charge cycles



For both EVs, the amount of usable energy did not change significantly over the recharge cycles. This is likely to be a result of well-performing BMSs and the findings indicate that the BMSs were capable of efficiently balancing the charge across individual cells. This is supported by the trends of the chart shown in Figure 3 that show the activity of the Leaf's BMS during the discharge at a SoC of 68%. The light grey on the individual columns indicates an active shunt and transferring of energy between traction battery cells. Such an active BMS ensures balanced cells all the time, i.e., during both discharge and charge and not just at the end of a charge as on a simple shunt BMS. During all charges and discharges, a very low cell voltage deviation was observed (maximum of ±25 mV).

Figure 3 An interactive BMS during a discharge of a Leaf traction battery



4 Discussion of results

Assuming an energy consumption of 150 Wh/km as reported by Nissan (2013b) and an average usable energy from Figure 2(a) of 9790 Wh (20% SoC), the theoretical drivable range of the Leaf is 65.2 km. From the experiment results, 9790 Wh of usable energy corresponds to only 40% of the nominal battery capacity of 24 kWh. This suggests a very inefficient utilisation of the built-in battery capacity. In the case of recharging a battery with remaining 30% SoC, the usable energy is 7628 Wh, the theoretical driving range is 50.8 km and the usable energy is 32% of nominal battery capacity.

Assuming an energy consumption of 125 Wh/km as reported by Mitsubishi (n.d.), and an average usable energy from the experiment of 7837 Wh (30% SoC), the theoretical drivable range of the i-MiEV is 62.7 km. The average usable energy of 7837 Wh is also very low. This value is just 49% of the built-in capacity of 16 kWh and could also be considered an inefficient utilisation of the battery's capacity since around half of its full battery capacity is not used but still contributes significantly to the vehicle's weight (Gissing et al., 2015). Despite the Leaf having a much larger nominal battery capacity, comparison of results for same safety margin of 20% SoC, indicate that the Leaf actually has a shorter driving range than the i-MiEV due to a higher energy consumption (Mitsubishi, 2015, n.d.) and lower battery capacity utilisation.

Although the drivable range on both vehicles remained stable, EV drivers and electric highway designers should be aware that under fast-DC charging, batteries can be charged only to 80% of full capacity. Furthermore, under realistic conditions, EVs being driven between towns cannot fully discharge batteries as this will drive the cars into 'limp mode', which will consequently lead to system shutdown. The process of discharging thus requires a safety margin so that not all the nominal stored energy can be taken from the battery. The combination of a reduced charge level of 80% and a safety margin reduces the usable energy from traction batteries significantly and hence a vehicle’s drivable range appears to be markedly lower than that published by the car manufacturer.

The fast-DC charging experiments on the Leaf and i-MiEV have shown that continuous discharge and fast-DC charge did not influence the cell balance. The BMS of both cars efficiently prevented a cell voltage drift and balanced each individual cell regardless of charging or discharging. The level of stored energy was relatively low but did not change significantly over time. The findings suggest that, even during a long distance drive with several discharge-recharge cycles per day, the charge capacity and drivable range remain stable. In regards to cell balance and charge capacity, fast-DC charging technology is a feasible option for EVs to travel larger distances. EV drivers and electric highway designers, however, should be aware of the lower drivable range associated with realistic real road scenarios and fast-DC charging.

5 Conclusion

Drivable range and recharge time are amongst the largest barriers to the adoption of EVs, particularly in remote areas. Not much is known about the impact on battery cell balance and thus the drivable range of commercial EVs undergoing non-laboratory, realistic fast-DC charging. The aim of this study was to investigate the impact of fast-DC charging on EVs’ traction battery cell balance and vehicle drivable range. For the two commercial EVs investigated no short-term negative impact on traction battery cell balance was observed during the fast-DC charging experiments. The vehicles were subjected to a series of continuous battery discharge-charges cycles using fast-DC charging. The results found unchanged traction battery charge capacities and the level of usable energy from the battery (and hence the drivable range) remained stable over time in the short-term scenario of a long drive on an electric highway. EV drivers and electric highway designers, however, should be aware that fast-DC charging to 80% on EV traction battery results in reduced charge capacity and hence reduced drivable range than what is currently stated by EV manufacturers. Further research is required to investigate the impact of fast-DC charging on EV energy consumption and drivable range at higher speeds.

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