Lithium-ion Batteries: Experimental Research and Application to Battery Swapping Stations

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***Abstract*—Wider adoption of electrical vehicles (EVs) is mainly governed by the battery technology which is still unable to provide driving comfort (and expenses) of conventional internal combustion engine vehicles. The paper is concerned with experimental research of lithium-ion rechargeable batteries, with the aim to improve operation of battery swapping stations (BSSs), a concept that represents an alternative to the EV charging stations.**

The paper provides insight into the EV charging, concept of BSS, rechargeable batteries (terminology, technology and attributes), and lithium-ion battery charging procedure (constant-current-constant-voltage). For the purpose of investigating charging/discharging characteristics of various batteries, an advanced bidirectional AC-DC converter has been developed. The converter is presented, along with the experiments which proved its functionality. Experiments are conducted on a lithium-ion battery cell by charging/discharging with different currents. Various battery characteristics are obtained and application of results to BSSs is discussed.

I. Introduction

Battery Electric Vehicles (BEVs) are becoming increasingly popular. Their main advantages over the Internal Combustion Engine (ICE) vehicles are: (i) no CO_2 emissions, (ii) simpler mechanics (simpler maintenance), (iii) better driving performance (acceleration, regenerative breaking).

The biggest obstacle to wider adoption of EVs[1] is (im)maturity of battery technology. Namely, if EVs could provide similar driving comfort (driving range, refueling times etc.) at similar prices as ICE vehicles, there would surely be a lot more EVs on the roads around the world [1], [2], [3]. In reality, batteries for EVs are still pretty expensive (even though the prices are going down) and they constitute a large share of the EV's total price (20%-35%). The percentage is easily calculated from a vehicle's price, rated battery energy in kWh and reported (or estimated) purchase price of the battery expressed in $/kWh (see e.g. [4], [5]). On the other hand, chemical energy that can be stored in a typical EV battery pack is insufficient to provide driving range comparable to that of ICE vehicles, i.e. typical EV driving range is significantly lower compared to the ICE vehicles [6]. This means that EVs need to recharge their batteries more often than ICE vehicles need to stop for refueling. Moreover, recharging the batteries takes more time than refueling, which might be inconvenient. Various fast charging schemes are being developed and implemented, in order to reduce waiting times at public charging stations [7], [8], [9].

An alternative to Battery Charging Stations (BCSs) are Battery Swapping Stations (BSSs), where discharged EV batteries can be quickly swapped for a fully charged ones, thus eliminating long waiting times normally needed for charging [10]. The concept of BSS is based on the idea of battery leasing, in a sense that EV owners buy their vehicle without the battery (thus reducing its initial price by 20%-35%) and then lease the batteries from the BSS for a certain fee. It is assumed that all the battery related costs (maintenance, degradation, etc.) are managed by the BSS. Therefore, it is in BSS's best interest to optimize battery charging procedure in order to prolong battery lifetime, reduce maintenance, and thus, increase profitability. During off-peak hours, BSS charges the batteries in a way to maximize their lifetime. On the other hand, during peak hours, a trade-off has to be made between fast charging and preserving the battery.

Paper is organized as follows. Section II provides insight into basic rechargeable battery attributes. Section III gives brief introduction to battery chargers, followed by the description of a custom-made bidirectional AC-DC converter. Description of experiments, together with the results is given in Section IV. Potential application of the results to BSSs is discussed in Section V, along with the future work plans. Finally, conclusions are drawn in Section VI.

II. Rechargeable batteries

Main rechargeable battery characteristics are voltage and capacity. Capacity represents the amount of energy that can be stored in a battery and it is typically expressed in Ampere-hours (Ah). Ah is the discharge current a battery can deliver over time. Theoretically, a battery of 10 Ah is able to deliver current of 10 A for 1 h, or current of 5 A for 2 h, etc. In practice, the rated capacity can be achieved only with low discharge currents (see Section IV-C).

The speed at which the battery is charged or discharged is specified by the C-rate. At 1C, the battery charges or discharges at a current that corresponds to its Ah rating (e.g.

[1] In the remainder of the paper "Battery Electric Vehicle (BEV)" is referred to simply as "Electric Vehicle (EV)".

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1C for a 10 Ah battery is 10 A, 2C for the same battery is 20 A, while 0.5C corresponds to 5 A).

Battery state-of-charge (SoC) is a measure for the amount of energy stored in a battery with respect to the energy that the battery contains when it is fully charged. SoC gives the user an indication of how much longer a battery will last before it needs recharging [11]. A battery that is fully charged is said to have 100% SoC, while a fully depleted battery has 0% SoC. Battery SoC is not straightforward to determine (see Section IV-D). SoC complementary term (an antonym) commonly found in literature is depth-of-discharge (DoD). The following relation always holds for a battery:

$$SoC + DoD = 100\ \%. \qquad (1)$$

Battery state-of-health (SoH) is a measure for the overall battery condition. New, healthy battery has 100% SoH. SoH is not unambiguously related to measurable quantities and there is no universal method for assessing it [11]. Therefore, SoH can only be estimated based on three indicators [12]: (i) capacity, (ii) internal resistance, and (iii) self-discharge.

Different rechargeable battery technologies (chemistries) have different characteristics. The most common technologies are [12]: lead acid, nickel-cadmium (NiCd), nickel-metal-hydride (NiMH) and lithium-ion (li-ion). However, the common characteristic of all rechargeable batteries is that they have a limited lifetime and that their characteristics (in the first place capacity) gradually degrade with time and usage (discharging and charging, also known as cycling). Furthermore, battery degradation and overall lifetime are very dependent on the way batteries are discharged and charged (fast vs. slow, pulse vs. continuous, etc.) [13]. It is therefore important to understand battery characteristics and to choose the optimal charging/discharging pattern. When talking about BCSs, we do not have any influence on the discharge, since that depends only on the drivers and their driving style. On the other hand, when talking about BSSs, the battery discharge pattern may be of interest, as BSSs may operate in battery-to-grid (B2G) or battery-to-battery (B2B) mode (see e.g. [10]).

III. Battery Chargers

All batteries are a DC (direct current) source, so they also have to be charged with DC current. Most consumer batteries are charged from the grid with a dedicated charger which is actually an AC-DC converter. Most consumer chargers are unidirectional which means that electricity can flow only from the grid to the battery. On the other hand, bidirectional chargers (converters) allow the battery to feed the energy into the grid, which in some cases may be desirable.

When talking about EV charging, there are two main types: AC and DC charging. AC charging is usually referred to as ”slow” charging, since it utilizes an on-board converter which typically has small dimensions and low power (with AC charging, AC current enters the vehicle). On the other hand, DC charging is usually referred to as ”fast” charging, as it utilizes an off-board converter (located in the charging station) which may have bigger dimensions and higher power (with DC charging, DC current enters the vehicle).

A. Custom Made Converter

For the purpose of experimenting with various batteries, an advanced grid-tied bidirectional AC-DC converter has been developed. This specially designed converter allows virtually any battery charging/discharging pattern to be implemented and tested. The converter specifications are:

- Nominal output power: 1 kW
- Output voltage: 0 to 20 V DC
- Output current: -50 to 50 A DC
- Input: 50 Hz, 230 V AC.

Input/output current/voltage are measured by analog signals (0-10 V DC) and digital signals (isolated USB or RS-485). Resolutions of the voltage and current measurements are 5.8 mV and 46.56 mA, respectively. Accuracy is improved by remote battery voltage sensing.

The converter is connected to the host PC with the National Instruments (NI) equipment. Communication takes place over NI cRIO[2] via Ethernet, while the converter is supervised and controlled over SCADA[3] system implemented in NI LabVIEW[4].

The converter has three-stage topology which consists of: (i) bidirectional grid inverter, (ii) resonant HF transformer, and (iii) output bidirectional interleaved buck-boost converter. This topology is shown in Fig. 1.

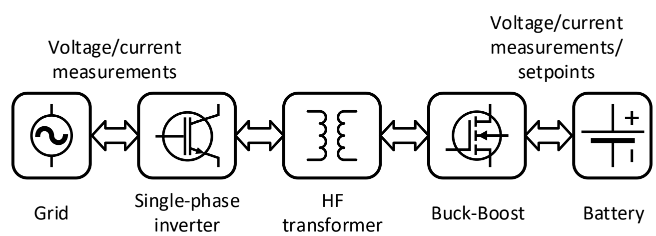

Fig. 1. Topology of the converter

IV. Experimental Research

Early EVs were powered mainly by lead-acid and nickel-metal-hydride batteries. However, all of the recent EV models (from year 2000 onwards) use li-ion batteries almost exclusively [13]. Therefore, this paper is concerned with experimental research of li-ion batteries. Experimental results are in general much more reliable and plausible compared to results gained through various computer simulations.

Experiments are conducted on a 18650[5] li-ion cell, a type of cell which is used in a renown Tesla Model S, but also in laptop computers, power tools, flashlights etc. Specific cell

[2]cRIO (Compact Reconfigurable Input Output) is a real-time industrial controller

[3]SCADA (Supervisory Control and Data Acquisition)

[4]LabVIEW (Laboratory Virtual Instrument Engineering Workbench)

[5]18650 is a cylindrical cell which measures 65 mm in length and 18 mm in diameter

model that we used in the experiments is Samsung ICR18650-32A which is shown in Fig. 2. Manufacturer's specifications for this cell [14] are given in Table I.

Fig. 2. Samsung ICR18650-32A li-ion cell

TABLE I
SPECIFICATIONS OF SAMSUNG ICR18650-32A

Chemistry	LCO (ICR)
Nominal capacity	3.2 Ah
Nominal voltage	3.75 V
Charging voltage	4.35 V
Discharge cut-off voltage	2.75 V
Charging current (standard)	1.6 A (0.5C)
Charging current (rapid)	3.2 A (1C)
Charging time (standard)	3 hours
Charging time (rapid)	2.5 hours
Max. charge current	3.2 A (1C)
Max. discharge current	6.4 A (2C)

Considered cell is made in Lithium Cobalt Oxide ($LiCoO_2$) chemistry[6] which is abbreviated as "LCO" or "ICR". For other common li-ion chemistries see e.g. [13]. Nominal voltage of typical li-ion cells is said to be 3.6 or 3.7 V. However, during regular cell operation its voltage floats between the charging value and the discharge cut-off value, depending on the present SoC and the charging/discharging current. When its voltage drops below the discharge cut-off value, the cell is considered to be fully depleted, even though some current could again be drawn after a period of rest.

A. *Charging Characteristic*

Li-ion batteries are typically charged with constant-current-constant-voltage (CC-CV) characteristic [12], [13]. This characteristic consists of two phases:

1) In the first phase, the charging current is kept constant while the voltage rises to a certain predefined threshold (charging voltage).
2) In the second phase, the voltage is kept constant at the threshold value, while the current gradually decreases. Full charge is reached after the current drops to cca. 3-5% of the battery's Ah rating.

Adjustable parameters in CC-CV charging procedure are: (i) constant charging current (phase 1), (ii) constant charging voltage (phase 2), and (iii) cut-off current (at which charging terminates).

In order to obtain charging characteristic for the observed Samsung-32A cell, we completely discharged it (until the voltage has dropped below 2.75 V) and then applied full charge according to the manufacturer's specifications: we used standard charging current of 1.6 A, charging voltage of 4.35 V and we terminated the charge after 3 hours (instead of using a low cut-off current threshold). The recorded characteristic is shown in Fig. 3.

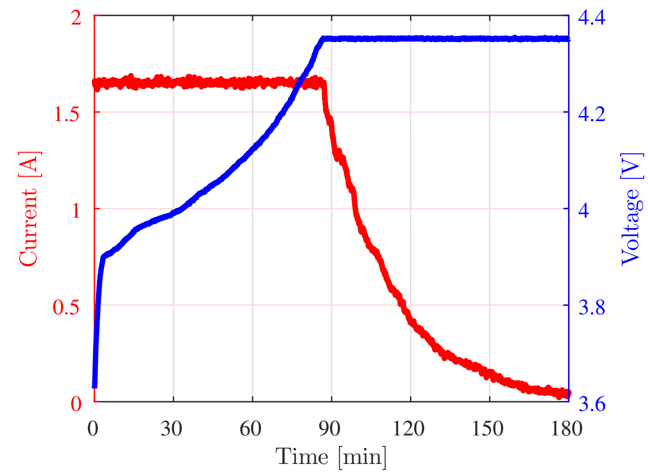

Fig. 3. Charging characteristic with 0.5C charging current

Fig. 4 displays charging characteristics for different charging currents: 3.2 A (1C), 1.6 A (0.5C) and 0.64 A (0.2C). What all the characteristics have in common is that after the voltage saturates, the current can no longer be maintained at the constant charging value and it starts to decrease. For higher charging currents, phase 1 (constant current) is shorter and phase 2 (constant voltage) longer.

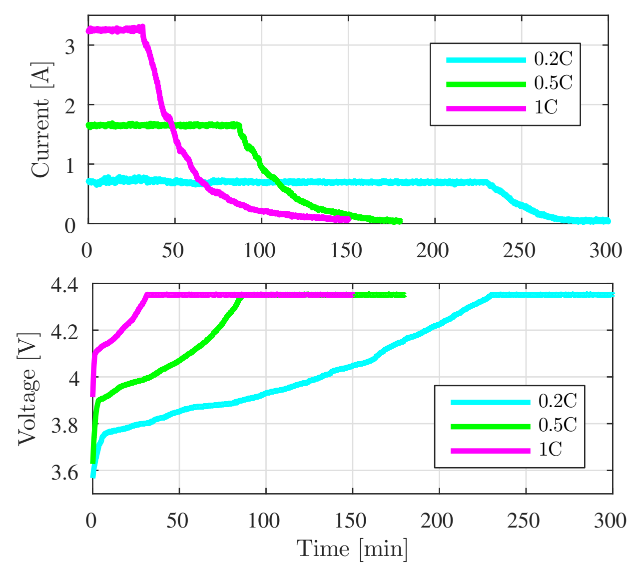

Fig. 4. Charging characteristics with different charging currents

[6]"Lithium-ion (li-ion)" is a generic name, while the exact cell chemistry may vary.

B. Discharging Characteristic

Discharging characteristics of Samsung-32A cell are shown in Fig. 5 for different (constant) discharging currents: 3.2 A (1C), 1.6 A (0.5C) and 0.64 A (0.2C). A typical nonlinear voltage curve (which drops sharply near the end-of-discharge) is seen in all three cases. End-of-discharge is reached when the voltage drops below the specified value of 2.75 V.

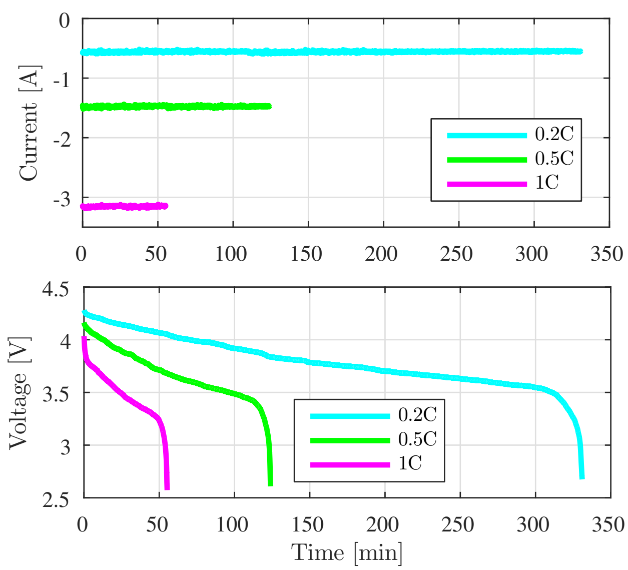

Fig. 5. Discharging characteristics with different discharging currents

C. Capacity

Cell capacity is the maximum number of Ampere-hours (Ah) that can be drawn from a cell during a single discharge. Capacity is typically obtained by applying a full charge which is then followed by the controlled discharge during which the current is measured and logged. Integral of current over the whole discharge time equals capacity:

$$C = \int_0^T I(\tau) d\tau, \tag{2}$$

where C is the cell capacity (Ah), I the discharge current (A), and T time (h) of the full discharge (following the full charge).

It is a well-known fact that a number of Ah which can be drawn from a fully charged cell is very dependent on the discharge current. This is verified experimentally on our Samsung-32A cell and the results are shown in Fig. 6.

Capacity of 3.3 Ah has been obtained with 0.1C discharge current and this we proclaim to be 100% capacity. The higher the discharge current, the lower the capacity and this is why manufacturers always declare capacity obtained with a low discharge current. Remember that Ah-rating is valid only for a new and healthy cell, as capacity fades with usage [13].

D. State-of-Charge

SoC characteristic for our Samsung-32A cell has been obtained for two charging currents (0.5C and 1C). This is done by measuring cell SoC against charging duration, as follows.

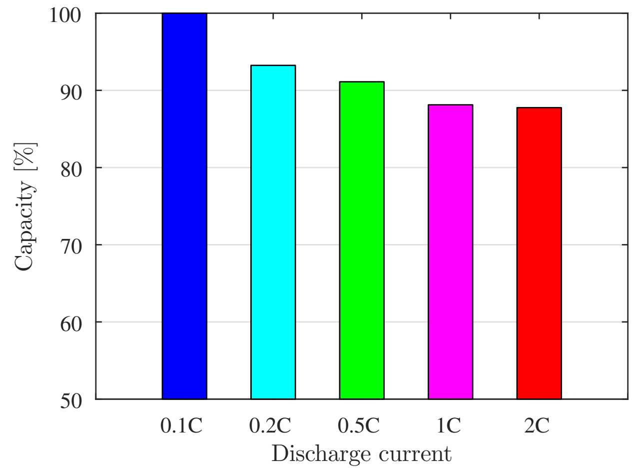

Fig. 6. Capacity measured against discharge current

A series of partial charges has been applied (in 10 minute steps) followed by immediate discharge during which the SoC is obtained by virtue of (2). Discharge current is always 0.5C (for both charging currents). The obtained characteristics are shown in Fig. 7[7]. Seemingly illogical results for 80-110 minutes charging at 1C (longer charging, smaller SoC) are a consequence of a current measurement error[8].

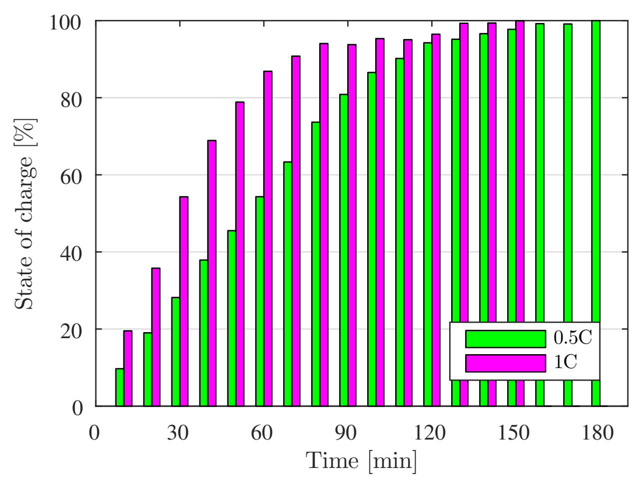

Fig. 7. State-of-charge measured against charging time

From Fig. 7 it is seen that SoC characteristics are nonlinear, i.e. cell (or battery) charges faster at the beginning and slower towards the end of the charging process. With 0.5C charging current, cca. 50% SoC is reached after one hour, while two more hours are needed for the other 50%. With 1C charging current, cca. 50% SoC is reached in the first half an

[7]According to manufacturer's specifications full charge with currents of 0.5C and 1C is achieved after 150 and 180 minutes respectively.

[8]Measurement range of presently used current sensor is -50 to 50 A, which results in the resolution of 46.6 mA (due to quantization in microcontroller). Since we are using smaller currents (3.2 or max. 6.4 A), better resolution (and thus measurement accuracy) could be achieved with current sensor of smaller range.

hour, while two more hours are needed for the other 50%. This is a consequence of the voltage and current charging characteristics displayed in Fig. 4: decreasing current of the constant voltage phase means slower charging. Therefore, the higher the charging current, the higher SoC percentage can be reached quickly, e.g. with 2C charging current, 70% SoC is reached in the first half an hour. This property is used for fast EV charging. However, higher charging currents do not shorten the full charging time by much. Namely, higher current ensures that the voltage threshold is reached faster (constant current phase), but in that case the saturation phase (constant voltage phase) lasts longer and the total time to reach 100% SoC is not changed by much. It is also worth noting that too high charging (and also discharging) currents cause the stress to the battery thus reducing its lifetime [12].

Method we used for determining SoC characteristics is time consuming as it requires repetitive charging/discharging and it is thus suitable only for laboratory conditions. Determining SoC in real-time (during battery operation) is more complex. An idea that comes to mind is to simply integrate the current on-line, as the battery is being charged or discharged. This method is known as ”coulomb counting” and can be expressed as:

$$SC(t) = SC(t-1) + \frac{100}{C} \cdot \int_{t-1}^{t} I(\tau) d\tau, \tag{3}$$

where SC is the state-of-charge (expressed in percentages), C the cell capacity (Ah), and I (A) current (assumed positive for charge and negative for discharge). The problem with coulomb counting is that it quickly accumulates error due to the current measurement uncertainty, charging/discharging efficiencies, etc.

Another idea for determining SoC in real-time is to simply measure the battery voltage and correlate it with SoC. However, battery voltage is not a good representative of the SoC for the reasons explained in the sequel. Open-circuit voltage (OCV), a voltage under no-load condition, must be differed from the close-circuit voltage (CCV), a voltage under load condition (charging or discharging). CCV rises with the charging current and drops with the discharging current, i.e. voltage measured in real-time is very dependent on the battery charging/discharging current. OCV may be used to determine SoC, but it may take hours for OCV to recover, after the load has been removed [15]. Therefore, a battery must rest for a long period before you can reliably determine SoC simply by taking the OCV reading.

Special algorithms are being used in order to determine battery SoC. Typically, battery SoC is estimated by using various battery models which combine coulomb counting with other available measurements (voltage, temperature, etc.) [16], [15], [17], [18].

E. Power and Energy

Charging power characteristics during full charge (0%-100% SoC) of Samsung-32A cell is shown in Fig. 8. In the constant current phase of the charging process, power rises as the voltage rises. In the constant voltage phase, power

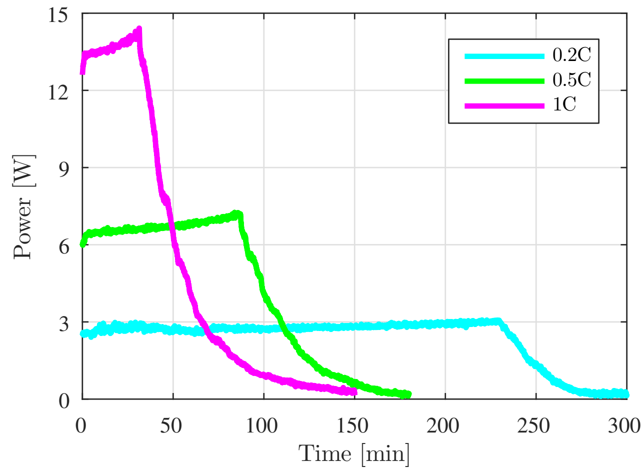

Fig. 8. Charging power with different charging currents

drops as the current drops. Peak power is reached at the intersection of the two phases. Generally, it can be said that power characteristics resembles current characteristics. The lower the charging current, the greater the resemblance, as the voltage rises slower during the first phase.

Electrical energy (Wh) is defined as an integral of electrical power over time:

$$E = \int_{0}^{t} P(\tau) d\tau. \tag{4}$$

This actually means that the energy corresponds to the surface under power-time graph. Surfaces under all three graphs from Fig. 8 are about the same which means that similar amounts of energy are required in order to obtain full charge, regardless of the charging current.

Fig. 9 displays ratio between charging energy and the corresponding SoC. Energy-SoC samples are obtained from a series of partial charges/discharges (the experiment is described in Section IV-D). Energy is obtained by integrating charging power, while SoC is measured during discharge. A line is

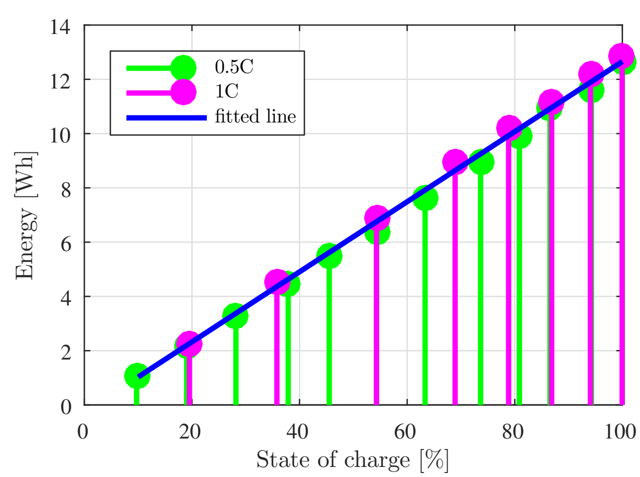

Fig. 9. Charging energy

fitted through all the samples to show that the relationship is approximately linear. Nevertheless, energy consumed with higher charging current is a bit higher: full charge energies at 0.5C and 1C amount to 12.6 and 12.9 Wh respectively.

V. Application of the Results and Future Work

Even though experiments are conducted on li-ion cells only, results can be applied to li-ion battery packs as well. All the characteristics and nonlinearities remain the same, the only difference being the current and voltage levels. Battery packs are formed by connecting cells in series (which increases voltage) and in parallel (which increases capacity and allows for higher currents). By combining series/parallel connection of the cells, batteries of desired power and capacity characteristics are obtained.

Results presented in this paper can be applied to improve operation of EV BCSs and BSSs. For example, decisions about charging durations and powers (currents) can be made. In this context, it is worth noting that, unlike other battery chemistries, li-ion batteries do not need to be fully charged. Moreover it is desirable that li-ion batteries are neither overcharged, nor overdischarged, as both extreme situations have negative influence on li-ion cells [12], [13]. Our future work plan includes further investigation of different charging/discharging patterns, with the aim to find optimal trade-off between battery charging time, battery runtime and, in the long term, battery lifetime.

A typical example for application of the results to BSS operation is during peak hours when not fully charged batteries are swapped at a reduced price which is dependent on the SoC shortage [10]. For example, characteristic shown in Fig. 9 can help model the discount function.

Many optimization models of BCSs and BSSs assume that batteries are charged and discharged at constant power in the whole SoC range (0%-100%). We showed that this is not realistic, especially not for higher charging currents. With lower charging currents (e.g. 0.2C) constant charging power may be assumed for relatively wide SoC range. This can be seen from Fig. 8: At 0.2C, constant current charging phase (which is approximately constant power phase) ends after 230 minutes with the SoC being cca. 85 %. We plan to address this issue in our further research with the intention to bridge the gap between the achievable battery charging pattern and the pattern used in optimization models.

VI. Conclusion

Characteristics of li-ion batteries are experimentally investigated by using the custom-made bidirectional AC-DC converter which allows complete control over charging/discharging process and which proofed to work very good.

Li-ion battery cell is charged/discharged with different currents and the following characteristics are obtained: (i) constant-current-constant-voltage (CC-CV) charging, (ii) discharge capacity, (iii) state-of-charge (SoC), and (iv) power and energy. It is demonstrated that the battery SoC has linear dependence on the charging energy and nonlinear dependence on the charging duration, and that the electrical power is never constant during CC-CV charging, particularly not when charging with higher currents. Finally, application of results to EV BCSs and BSSs is discussed.

Acknowledgment

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