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Indirect measurement of the battery capacity of smart devices

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Abstract. A crucial part of portable electronic devices (smartphones, smart watches, Tablet PCs, GPS devices, etc.) are the batteries. The dominant trend in the design of these devices is such that the users are not supposed to replace the batteries, i.e. the device's battery is meant to last for the entire lifetime of the device. This makes it important to know the capacity of the battery in order to estimate the expected life of the portable device. As there is no access to the terminals of these batteries, it is not possible to use traditional direct methods to evaluate the capacity of the battery and an indirect method needs to be used. The aim of the given research is to propose different indirect methods of battery capacity measurement and assess their accuracy.

Key words: smart device, battery life, capacity, indirect measurement.

INTRODUCTION

The present study focuses on universal indirect capacity measurement methods for lithium-ion batteries. As more and more devices (smartphones, tablets, GPS devices, e-readers, video cameras, etc.) are designed in such a way that their batteries cannot be replaced by the consumer, it is important to know the capacity of these batteries, because the expected life of the equipment is directly dependent on it. The problem with these batteries is, that the terminals of integrated batteries are not accessible for measurement and therefore indirect methods are needed.

The vast majority of portable devices use a Lithium-Ion (Li-on) battery. There is even a need to assess the capacity of unused or less used Li-on batteries, because the capacity of batteries decreases over time, regardless of use (Williard et al., 2013, Keil et al., 2016). Previous research on Li-on battery charging has been done by (Chun et al., 2015; Vo et al., 2015) and specifically on the capacity of Li-on batteries by (Weng et al., 2013; Weng et al., 2016). The algorithms for state of charge and energy estimation of Li-on batteries have been explored by (He et al., 2011; Chaoui & Gualous 2016; Zhang et al., 2017).

Li-on batteries are extremely sensitive to both overloading and excessive emptying and, as a result, are always equipped with a control module. The purpose of the module is to interrupt the connection between the battery and the charger and/or energy consuming device if necessary, depending on whether the battery temperature has risen too high, the battery is fully charged or the battery has emptied to the allowed limit (Chao et al., 2014). Overcharging of Li-on batteries should be avoided, because it leads to a rise of the internal temperature, which can cause the battery to ignite (Wang et al., 2012). Excessive emptying, in turn, can lead to deterioration of the battery (Zheng et al., 2015).

There are several CPU based (software) methods, which measure the capacity of a device's battery (Rong & Pedram, 2006). In these cases, the control module acts as a measurement tool by being in direct contact with the terminals of the battery. As such, these methods should be classified as methods of direct measurement because the calculations are made based on the results measured from the terminals. All devices that use Android or iOS operating systems, and for which numerous applications have been created, belong in this category. However, there also exist many devices, with which these methods cannot be used because the end user is unable to install applications (e.g. GPS devices, power banks).

Consequently the proposed method of capacity measurement for these devices is to measure the energy used in the charging process and assess how much of the energy stored in the battery is usable.

MATERIALS AND METHODS

Method 1

The units Wh and mAh are usually used to describe the maximum usable energy E_n stored in the batteries of the analysed devices e.g. 4,000 mAh /14.8Wh. However, these are units of electric charge and do not directly describe the usable energy in the battery. The more frequently used unit Ah is not a SI unit and describes a situation in which the battery provides the stated current during an hour, operating at the rated voltage V_n. For the purpose of this paper, we will instead use their corresponding energy values. In order to express the receivable energy from the battery in SI units (J), the Ampere hours must be multiplied by the nominal voltage V_n and 3,600 seconds.

The first step in this method for the measurement of the capacity of an integrated battery, is to apply a load to the device until it shuts down. As the device turns itself off before the battery is fully discharged, a residual energy of E_r remains in the battery, which with the usable energy E_{usable} forms the actual energy $E_{actural}$. Since the capacity of each Li-on battery decreases with time, then $E_{usable} < E_N$. By leaving the device in the the off position, and by charging its battery to full capacity, we can measure the energy (E_{charge}) that is used to charge the battery. The energy can be calculated with formula 2.

$$E_{charge} = \sum_{i=1}^{n} I_i \cdot V_i \cdot t_i, \tag{1}$$

where n – number of measurements, I_i – charging current (A); V_i – charging voltage (V); t_i – measurement interval (s).

The stored useful energy can be calculated with the following formula:

$$E_{charge} = E_{usable} + E_{loss} + E_{cm} , \tag{2}$$

where E_{usable} – stored useful energy (J); E_{loss} – energy loss while charging the battery (J); E_{cm} – self-consumption of control module (J). Hence

$$E_{usable} = E_{charge} - E_{loss} - E_{cm}, \tag{3}$$

E_{loss} can not be measured but it is known that the efficiency factor of Li-on batteries typically is in the range of 95 % (Espinar & Mayer, 2011). Hence:

$$E_{usable} = 0.95(E_{charge} - E_{cm}) \tag{4}$$

E_{cm} can be found by measuring the off-mode power consumption of the fully charged device. All energy consumed in that state is used for the self-consumption of the control module, because when the battery is fully charged, the control module disconnects the device from the charger to prevent overcharge.

Taking into account the time spent on charging, we can calculate the E_{cm}:

$$E_{cm} = \sum_{i=1}^{n} I_{cm} \cdot V_{cm} \cdot t_i, \tag{5}$$

where n is the number of measurements; I_{cm} – charging current of disconnected battery (A) ; V_{cm} – charging voltage of disconnected battery (V); t_i – measurement interval (s).

How much of the initial capacity of the battery is maintained can be calculated with the following equation:

$$\frac{E_{cm}}{E_N} \cdot 100\%, \tag{6}$$

How much of the initial capacity of the battery is maintained depends on the number of cycles that the battery has underwent and on the age of the battery.

Method 2

The second method (Method 2) uses a separate power bank to measure the battery (Table 1). For this purpose the test device is burdened until it switches off, the power bank is fully charged and used to charge the test device, and after the charging is complete, the remaining energy in the power bank is measured.

Table 1. Used equipment

Equipment	Method 1	Method 2
Tested device	Sony Xperia V	Sony Xperia V
Battery	E_N = 1,700 mAh and V_N = 3.7 V	E_N = 1,700 mAh and V_N = 3.7 V
Charger	LG, 5 V, 0.7 A	LG, 5 V, 0.7 A
Measurement device	Agilent 34972a	Agilent 34972a
Power bank	-	RIVACASE VA2004 4,000 mAh
Additional load	-	USB powered lamp, P_N = 3W
Used software	Spreadsheet software	MathCad

Knowing the capacity of the power bank, we can easily calculate the amount of energy spent on charging the device. Since it is possible to burden the power bank with a USB device, then by knowing the power it consumes (P_N) and measuring the time until it shuts down, we can calculate the total receivable energy E_{pb} from the power bank.

$$E_{pb} = P_N \cdot t, \tag{7}$$

The residual energy (E_r) in the power bank after charging the test device can be calculated similarly by using the time (t_r) during which the residual power is consumed.

$$E_r = P_N \cdot t_r, \tag{8}$$

Energy spent on charging test device (E_{charge}) can be calculated with:

$$E_{charge} = E_{pb} - E_r, \tag{9}$$

It is not possible to measure the self-consumption of the control module (E_{cm}) using this method, so it will not be taken into account for this experiment.

$$E_{usable} = 0.95 \cdot E_{charge}, \tag{10}$$

$$\frac{E_{usable}}{E_N} \cdot 100\%, \tag{11}$$

The phone's battery (described in Table 1) was previously burdened with an electrical load to a state, where it had shut off automatically (the battery control module had disconnected the battery from the device before it was fully discharged. The phone was connected to the charger through the measuring device and the voltage and current were measured with 2 second intervals. The experiments were held at room temperature 20 °C.

RESULTS AND DISCUSSION

Method 1

The course of the charging process in relation to the power consumption is characterized by Fig. 1. The total· E_{charge} calculated according to Eq. (2) is 19,350.55 J. We can see from Fig. 2 that the current stabilizes at 0.075 (A) at the end of the charging, which is the self-consumption of the control module (I_{cm}), therefore according to Eq. (6) E_{cm} = 3,631.76 J and according to Eg. (5) E_{usable} = 14,932.85 J. On the basis of the aforementioned findings the the maximum usable energy (E_N) is 22,644 J. Hence E_{usable}/E_N =65.95% (Eq. 10). So 65.95% of the initial capacity has remained. Fig. 1 shows the strength of current during the charging process.

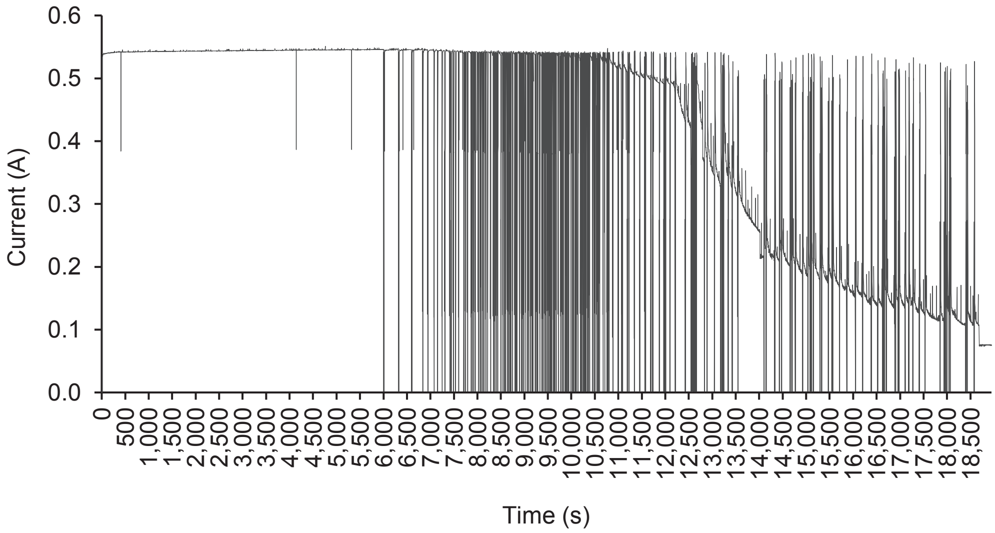

Figure 1. Current during the charging process.

The battery is charged with current pulses with changing frequency during the charging process. The frequency is high until the middle and begins to drop towards the end of the charging process. The charging rate is controlled by varying the width of the pulses. Rest periods between pulses allow chemical reactions to stabilize in the battery. This enables to charge the battery faster and with higher efficiency (Yin et al., 2015). Fig. 2 shows a close up of the current strength at the end of the charging process.

The current drops when the charging process reaches its end (Fig. 2).

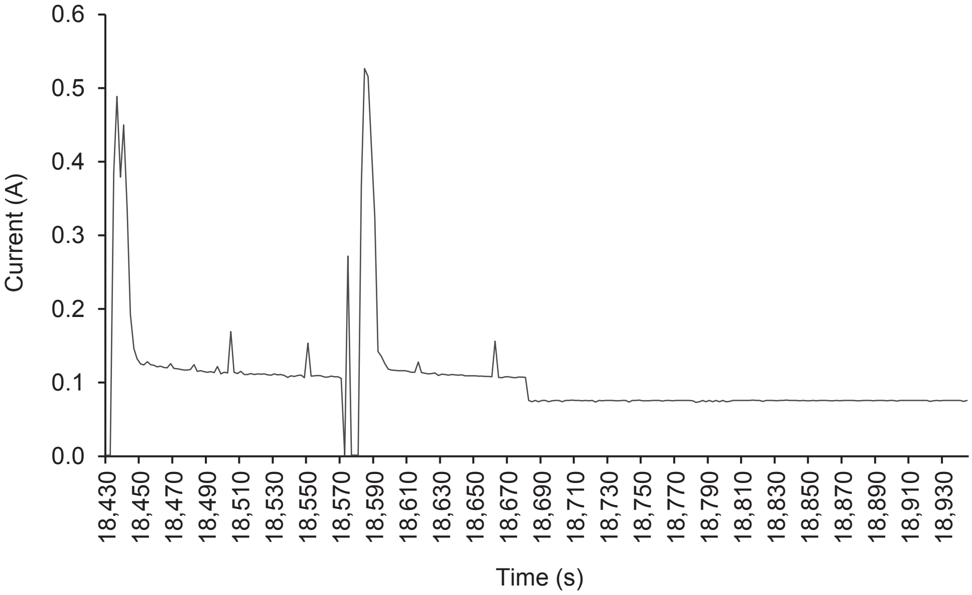

Figure 2. Current at the end of the charging process.

Method 2

The second method involved the discharging of the fully charged power bank. The power bank was connected to a 3 W lamp until it was discharged, which took 13,306 seconds. Thus, the receivable energy from the power bank is E_{pb}=3·13,306=39,918 J.

The test device was burdened until the battery was fully discharged and was then charged using the precharged power bank until the test device signalled that the battery was fully charged. The power bank was then again burdened with a 3W lamp until it was discharged, which took 8,014.00 seconds (2 hours and 14 minutes). The experiments were made at room temperature 20 °C.

Consequently:

$E_r = 8{,}014 \cdot 3 = 24{,}042.00$ J;

$E_{charge} = 39{,}918 - 24{,}042 = 15{,}276.00$ J;

$E_{usable} = 0.95 \cdot 15{,}276 = 14{,}512.20$ J;

$E_{cm}/E_n \cdot 100\% = 64.00\%$.

From Table 2 can be seen that the both applied methods give similar results. The differences were insignificant. Despite that, it has to be considered that method 2 is designed to be used by everyone, and therefore there is some trade-off in accuracy.

Table 2. Comparizon of results from the applied methods

	Method 1	Method 2
E_{usable}, J	14,932.00	14,512.20
E_{usable}, mAh	1,121.15	1,089.50
E_{usable}, %	65.95	64.00

CONCLUSIONS

Despite the different degrees of precision between methods, the results were within the error margin, so that reasonable assumptions can be made about the supposed service life of the test device. An interesting result is that the capacity results were lower using the second method than with the first method. In theory, the second method should have shown a higher result than the first method, as the self-consumption of the control module was included in the useful energy. The reason for this not being the case is probably a result of the test device prematurely signalling that the battery is fully charged.

For further research, different devices should be tested numerous times using both methods in order to gain more information about the precision of the measurements. In this study, it can be said that the second method is accurate enough to measure the capacity of the test device, especially if a power bank with a marginally bigger capacity is used, which shortens the time spent on testing the battery.

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