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(Article begins on next page)

An Aging-Aware Battery Charge Scheme for Mobile Devices Exploiting Plug-in Time Patterns

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Abstract---The aging of a rechargeable battery is mainly due to stress during charge-discharge cycles. Although the discharge phase is difficult to control, the charging phase can be performed in a specific way in order to mitigate the aging of the battery during its usage. It therefore becomes important to select the correct charging algorithm.

In the case of mobile systems, equipped mainly with lithium-ion batteries, the standard widely adopted for charging a battery is the typical constant current/constant voltage (CC-CV) protocol usually based on a linearly regular charge process.

In this work, we propose a charging protocol based on the standard CC-CV method in which the charge start time and the value of the charging current can be programmed in such a way that the aging of the battery is mitigated. To validate this charging scheme we use an aging model that includes the charge/discharge current among the major parameters, and an analytical macro-model for the CC-CV charge time analysis.

I. BACKGROUND AND RELATED WORK

A. Battery Charge Protocols

The aging of a rechargeable battery degrades the usable capacity over time, and is due to either self-discharge (calendar aging) or the stress induced by cyclic charge-discharge patterns (cycle aging). Of the two, cycle aging has been studied in more depth because it is strongly correlated to the battery usage patterns and can therefore be mitigated by acting on these patterns. However, although the discharge phase significantly contributes to cycle aging, it is difficult to control and essentially depends on user “behavior”; for this reason, most studies focus on the charge phase, which is fixed and designed upfront and implemented in the charger circuit.

Battery aging is a particularly critical factor for plug-in electric vehicles (PHEV), where batteries represent a significant share of the vehicle cost: a carefully-designed charge scheme to reduce battery degradation can either delay the time when batteries are replaced or allow the use of a smaller battery [1]. For these reasons, the vast literature on customized *charge protocols* to reduce cycle aging is almost entirely focused on the PHEV domain [2]-[4].

Conversely, in the domain of devices like smartphones or tablets, battery aging issues have not raised much interest essentially for two reasons. Firstly, there is a general acceptance of the fact that the average replacement cycle of these devices is much shorter than the typical lifetime of a battery. Secondly, these devices are bound by stringent constraints related to the use of standardized, inexpensive, and compact chargers. For instance, typical chargers (including

USBs) implement the traditional Constant Current-Constant Voltage (CC-CV) charge protocol, which is recommended for lithium-ion (Li-Ion) cells (in the vast majority of portable devices), due to its simplicity for implementation and because it guarantees battery safety including over-voltage and over-current protection.

Besides the CC-CV protocol, several alternative charging schemes have been proposed in the literature, like pulsed charge, constant power, or multi-stage constant current [3], [5], [6]. Unfortunately, the test of such charge protocols requires measurements since, traditionally, datasheets report data relative to CC-CV protocol.

B. Battery Aging Issues

The degradation rate of a single battery cycle primarily depends on the following stress factors: *temperature*, *Depth-of-Discharge* (DOD), *average State Of Charge* (SOC_{avg}) and *Charge/Discharge Current*. The DOD is the percentage of battery capacity that has been discharged before starting a new charge phase (e.g., a DOD of 100% implies that a battery gets fully discharged before being recharged). The State Of Charge (SOC) is the % of the maximum possible battery capacity. Charge/Discharge current is usually measured in C-rate, a current normalized to the one necessary to charge/discharge the nominal battery capacity in one hour. Aging is accelerated by deeper discharge cycles, higher values of average SOC, and higher charge/discharge currents.

Many researchers have studied aging issues in batteries and have devised various types of aging models [7], [8], [1]. In this work, we extend the aging model of [7] and then we adopt a macro-model for a CC-CV charge time analysis [9].

1) *Aging Model*: In order to analyze the battery life, we adopt the Millner’s model [7], which is a reference on this topic. Although that aging model, as well as most others, considers only SOC, SOC swing or deviation (SOC_{dev}) here considered as DOD, and temperature as main factors for the degradation rate, also the current is an important parameter in the battery cycle life, as also reported in the battery datasheet considered in [7], i.e., the Li-Ion ANR26650m1 by A123 Systems [10]. Therefore, in this work we extend the model of [7] by including the *current rate* as stress factor. The following equation introduces the relationship of the charge and discharge current to the original aging model in order to obtain the battery life degradation rate for a generic cycle m :

$$Life(m) = Life_{Millner} \cdot e^{(K_{ic} \cdot I_{ch} + K_{id} \cdot I_{dis})} \quad (1)$$

In (1), I_{ch} and I_{dis} are the charging and discharging current rates (absolute values), respectively, whose effect on the decay rate is then given by their related parameters, K_{ic} and K_{id} . The values of these two parameters (reported in Section III) are indeed extracted from the manufacturer's data. Instead, the reader may refer to the original document for more details about the Millner's model [7].

Finally, actual battery life degradation L (i.e., normalized capacity loss, from 0 to 1) after M cycles is given by the following expression:

$$L = \sum_{m=1}^M Life(m) \quad (2)$$

2) *CC-CV Compact Macromodel*: The model proposed in [9] represents the total charge time, here called T_{charge} , as the sum of two contributions, one for each of the two phases (CC and CV), i.e., $T_{charge} = t_{cc} + t_{cv}$. Indeed, T_{charge} is computed exploiting the principle of the Peukert's law applied to the charge phase, and is thus expressed as:

$$T_{charge}(I_{cc}, k_{cc}) = \frac{C_p}{k_{cc} \cdot I_{cc}^{k_{cc}}} + \frac{C_p(1 - k_{cc})}{k_{cc}} \cdot \frac{1}{I_{eoc}^{k_{cc}}} \quad (3)$$

where I_{cc} , C_p , and k_{cc} denote the constant charging current, the Peukert capacity of the battery, and the Peukert coefficient, respectively, while I_{eoc} corresponds to the current during the CV phase (I_{cv}) when the end-of-charge (*eoc*) time is reached. This formula approximates the CC-CV charging time with a given I_{cc} depending on only three parameters, i.e., k_{cc} , C_p , and I_{eoc} .

II. SCENARIO AND APPROACH

A. Characterization of the Charge Period

Figure 1 shows a generic charge-discharge cycle of a typical device, and specifically the evolution of the battery SOC over time. Since the focus is mainly on the charge phase, the two phases are not in scale; the discharge time, which is normally longer, has been compressed for a better emphasis on the charge phase.

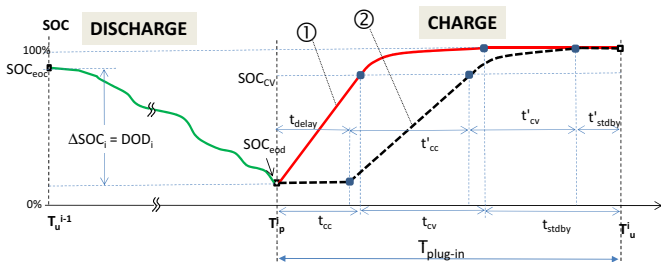


Fig. 1. Generic Charge-Discharge Cycle.

Starting from some value SOC_{eoc} (end-of-charge) at the end of the previous charge period, the discharge will evolve according to the user activity on the device and will reach a value SOC_{eod} (end-of-discharge), at some point in time T_p^i (i -th plug-in time) when the user will connect the device at some charging device and the charge phase starts. The difference $\Delta SOC = SOC_{eoc} - SOC_{eod}$ represents the depth of discharge of the i discharge phase DOD_i .

The curve labeled with ① on the plot identifies the conventional charge implemented by typical chargers: as soon as the device is plugged, the standard CC-CV protocol is applied; in the diagram, we assume that the CC and CV phase lasts t_{cc} seconds and t_{cv} , respectively.

Since typical charge times, with the recommended currents I_{cc} (0.7C--1C), are between 2.5 and 4 hours, in the case of long charge times where the device is plugged to the charger between 7 to 14 hours (usually during nighttime), such charge protocol has a critical drawback.

Calling $T_{plug-in}$ the total time for which the device is kept connected to the charger, whenever $T_{plug-in} \gg T_{charge}$, the battery stays plenty of charge for $T_{plug-in} - T_{charge}$ (the time t_{stdby} in the figure), which can be a significant amount of time in the case of overnight charging.

Although the average SOC (visually identified by the area below the SOC curve) adversely affects the aging of the battery, the aging model of Section I tells us also that the discharge rate matters for the aging.

While we don't have any control on the current used to discharge the battery, we can control the current used for charging. In particular, whenever $T_{plug-in}$ is reasonable long (as in nightly charging), we could also act on the charging current to slow the charge process, thus achieving the two-fold objective of (i) reducing the charge current, and (ii) reduce the average SOC during the charge.

These considerations bring us to the dashed curve labeled ②, which represents the most general shape of a charge profile for a given plug-in time $T_{plug-in}$.

This curve is composed by four main parts.

- 1) **Delay phase**: An initial interval in which the battery, even if attached to a charger, is not actually charged. Let us call this time t_{delay} ;
- 2) **CC phase**: the CC phase. According to the chosen charge current I_{cc} , the SOC will increase linearly until reaching the level corresponding to the activation of the CV phase. The time t'_{cc} will be roughly proportional to the supplied current.
- 3) **CV phase**: the CV phase. Notice that the CV time is not a constant. It is a well-known fact that the CV phase increases as I_{cc} increases. We denote this time by t'_{cv} .
- 4) **Standby phase**: the time t'_{stdby} between the end of CV phase and the unplug time. We assume that the SOC stays approximately at 100% during this phase.

At a more careful analysis, we can observe that the standby phase is always a penalty in terms of aging. Firstly because, as already observed, it implies a 100% SOC for the corresponding time; secondly, it arises as a consequence of a I_{cc} larger than needed; as I_{cc} decreases, the slower the charge, the shorter t_{stdby} .

Therefore, we can immediately rule out the standby phase from the parameters to be considered in the analysis; aging-optimal charge profiles to be considered will have $t_{stdby} \equiv 0$, i.e., that will complete the charge just-in-time.

As a result, these just-in-time aging-aware protocols will lie between the two extremes depicted in Figure 2, which

represent therefore the solution space to our problem. Subscripts (a) and (b) on the time quantities refer to the these two extremes cases. Protocol (a) (“Slow just-in-time charge”) starts as soon as the device is plugged ($t_{delay,a} \equiv 0$) and uses the smallest current that allows to reach 100% SOC at unplug time ($T_{plug-in} \equiv t_{cc,a} + t_{cv,a}$). Protocol (b) (“Delayed just-in-time charge”), delays the charge until a time at which, by using the rated charging current, the charge will finish just in time. In practice, this is simply a delayed version of the standard charge (curve ① in Figure 1).

For a given value of $T_{plug-in}$, its actual breakdown in the three phases (delay, CC, CV) is entirely determined by two parameters, i.e., t_{delay} and I_{cc} . This is because from I_{cc} we can determine t_{cc} and t_{cv} using the macro-model of [9].

B. Problem Formulation and Algorithm

The problem we are trying to solve can be stated as follows:

Given a discharge profile and an estimate of the plug-in time, determine a charge schedule (i.e., t_{delay} and I_{cc}) that minimizes the battery aging.

The problem is not trivial because there is an inherent trade-off between two contrasting factors affecting aging. As it can be seen in Figure 2, a delayed charge (dashed curve) yields the least average SOC (area below the curve), but it achieves that using a larger current. Conversely, the slow charge (solid curve) stores more charge over time, but it charges the battery using a moderate current. It is therefore intuitive to expect that an aging-optimal solution will lie in between these two extremes and will carefully balance the effects of load current and average SOC.

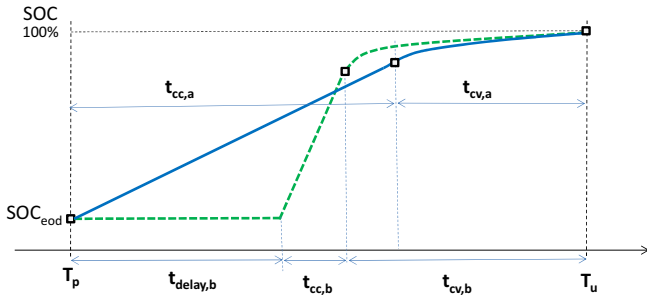


Fig. 2. Solution Space for the Just-in-Time Charge Protocols.

The input data are SOC_{eod} and $T_{plug-in}$. There is actually a third input, namely, the maximum charge current $I_{cc,max}$, which is extracted by the battery datasheets and implies no approximation or estimation whatsoever.

Initially, from $T_{plug-in}$ we compute a lower bound $I_{cc,min}$ for I_{cc} , obtained as the value that correspond to a t_{delay} of 0. Similarly, we compute an upper bound $t_{delay,max}$ for t_{delay} , obtained as the as-late-as-possible charge using the maximum possible current $I_{cc,max}$. These bounds for the two variables will be useful for the optimization of the cost function. Then, we calculate the other parameters required by 1 and 3 to determine the capacity fade. The SOC_{dev} is trivially calculated as 100% minus the entry charge level SOC_{eod} . The SOC_{avg} is slightly more elaborate to calculate; it corresponds to the area below the charge curve divided by the total charge time $T_{plug-in}$. In the CV region, although it could be possible

to do a more accurate calculation by expressing the SOC behavior analytically, we approximate it by assuming a linear increase, yielding an area of $(SOC_{cv} + 100) \cdot t_{cv}/2$. By summing the three contributions and dividing by $T_{plug-in}$ we get SOC_{avg} , a function of the two variables I_{cc} and t_{delay} . Then, we plug all the values into the extended aging model yielding a function $Life$ that depends on I_{cc} and t_{delay} . Finally, we calculate the values of I_{cc} and t_{delay} that minimize the life degradation.

III. EXPERIMENTAL RESULTS

The proposed methodology has been applied to the A123 Systems lithium-ion ANR26650m1 [10] having 2.3Ah nominal capacity. The parameters for the extended aging model have been extracted and calibrated from its datasheet and from [7]. The operating temperature is set to $35^\circ C$ as in [7]. Table I reports all the other setting values for the model parameters.

TABLE I
AGING MODEL PARAMETERS SETTING.

K_{co}	3.66e-5	K_{ex}	0.71700	K_{SOC}	0.91600
K_T	0.04621	K_{ic}	0.19804	K_{id}	0.04951

The battery datasheet reports an average capacity degradation of about 10% after two years, i.e., more than 700 cycles, assuming that the battery is charged once every day.

The typical Li-Ion battery capacity degradation in mobile devices could be higher; nevertheless, we assume that the battery under test shares the same aging mechanisms, since its cell chemistry is Li-Ion as well. Therefore, although the model of [7] was developed for an electric vehicle battery, the reported results still help us to evaluate the proposed methodology.

We considered three different battery usage patterns related to three progressively higher DOD average values: *conservative*, with $DOD = 20\%$, *moderate*, with $DOD = 50\%$, and *aggressive*, with $DOD = 80\%$. We analyzed usage patterns having a fixed time period of 12h, as mobile devices are commonly used during daytime. This results in discharge profiles having equal discharge times, but different average discharge currents.

We estimated the aging-minimizing charge schedule with our framework for each usage pattern using plug-in times ranging from 3h to 8h. The charge current values considered in our framework range from 0.05C (since the current value used to detect the end-of-charge for the battery is 0.02C), to 2C (the typical charge current limit in order to avoid accelerated battery aging). Then, we compared the obtained charge schedule in terms of battery capacity degradation to the charge method recommended by the battery manufacturer, i.e., the standard CC-CV protocol with a charge current of 3A, hence with no initial delay phase ($t_{delay} = 0$).

Table II reports the reduction percentage of the capacity degradation obtained with the proposed just-in-time charge protocol with respect to the standard charge method for each usage pattern and $T_{plug-in}$ value in a single discharge/charge cycle. Table III reports the corresponding (t_{delay} , I_{cc}) values for each charge schedule.

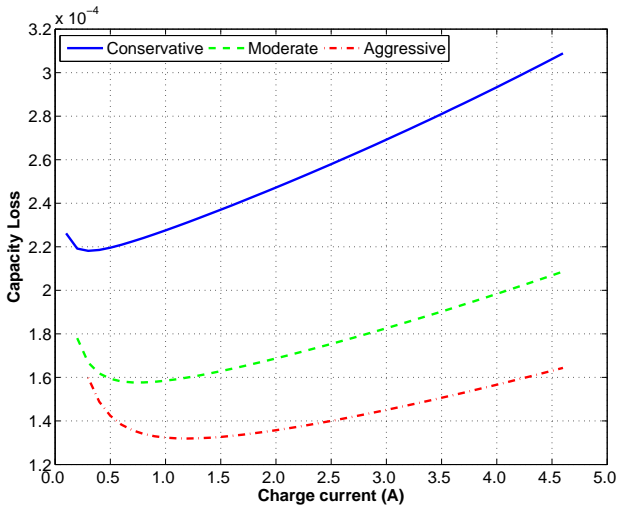


Fig. 3. Capacity Loss in a Single Cycle vs. Charge Current for the Different Usage Patterns with $T_{plug-in} = 8h$.

The results show that our algorithm allows to find a just-in-time charge schedule that reduces the battery capacity degradation with respect to the standard charge conditions. Moreover, such aging-optimal charge schedule is not simply the delayed just-in-time charge, but it is the outcome of a careful trade-off between the effects of average SOC and the adopted charge current. In fact, the combination of delayed charge and lower charging current values results in lower SOC_{avg} and SOC_{dev} and lower current rate stress in a given plug-in time. As an example, Figure 3 shows the capacity loss adopting the proposed just-in-time charge protocol in a plug-in time of 8h for the analyzed usage patterns.

Referring to Table II, the reduction of capacity degradation generally increases as the plug-in time increases, and it takes quite large values when the battery is deeply discharged.

In Table III, the best just-in-time charge schedule for the aggressive usage pattern with $T_{plug-in}$ equal to 3h and 4h uses a lower current than in the other plug-in times, as the average SOC is very similar when charging at 1.1A and 1.2A, but the lower current results in a lower capacity degradation.

Using the aging-optimal just-in-time charge schedules reported in Table III, we also estimated the resulting battery

TABLE II
REDUCTION OF THE CAPACITY DEGRADATION ON A SINGLE CYCLE FOR DIFFERENT USAGE PATTERNS AND PLUG-IN TIMES.

Usage Pattern	$T_{plug-in}$ (h)					
	3	4	5	6	7	8
Conservative	28.9%	31.2%	33.8%	35.5%	37.6%	38.9%
Moderate	35.9%	41.6%	46.5%	50.5%	53.5%	56.2%
Aggressive	41.9%	49.7%	56.2%	61.1%	65.1%	68.4%

TABLE III
CHARGE SCHEDULES (t_{delay} (h), I_{cc} (A)) MINIMIZING CAPACITY DEGRADATION FOR DIFFERENT USAGE PATTERNS AND PLUG-IN TIMES.

Usage Pattern	$T_{plug-in}$ (h)					
	3	4	5	6	7	8
Conservative	(1.4, 0.3)	(2.4, 0.3)	(3.4, 0.3)	(4.4, 0.3)	(5.4, 0.3)	(6.4, 0.3)
Moderate	(1.5, 0.8)	(2.5, 0.8)	(3.5, 0.8)	(4.5, 0.8)	(5.5, 0.8)	(6.5, 0.8)
Aggressive	(1.2, 1.1)	(2.2, 1.1)	(3.4, 1.2)	(4.4, 1.2)	(5.4, 1.2)	(6.4, 1.2)

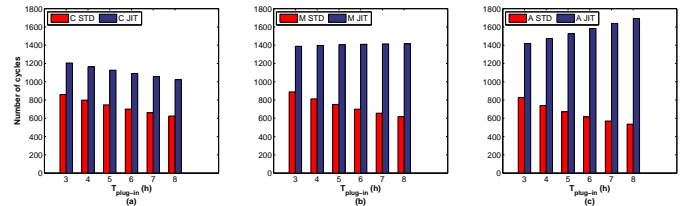


Fig. 4. Number of cycles vs. plug-in times for the three usage patterns Conservative (a), Moderate (b), and Aggressive (c): comparison between the standard CC-CV charge protocol (*STD*) and the proposed aging-optimal just-in-time charge protocol (*JIT*).

cycle life, i.e., the number of cycles that the battery can achieve before the capacity fades to 80% of its nominal value. We compared the computed number of cycles with those obtained using the standard charge method.

Figure 4 reports, for each usage pattern and each plug-in time, the estimated number of cycles obtained with the standard charge protocol *STD* and the aging-optimal just-in-time charge protocol *JIT*. In general, the proposed charge scheme extends the battery cycle life achieving a higher number of cycles with respect to the standard charge protocol. Indeed, the chart shows that the number of cycles achieved with the standard CC-CV charge protocol globally decreases as the plug-in time increases. On the contrary, the number of cycles increases along with the plug-in time in the case of moderate and aggressive usage patterns with the just-in-time charge scheme.

IV. CONCLUSION

Battery aging is a critical factor to be kept under control since it leads, over time, to the decrease of the usable battery capacity. In this paper we propose an aging-aware CC-CV-based charging protocol that minimizes battery aging by controlling the charge start time and the charging current. Simulation results show that a careful selection of such parameters can reduce battery degradation on a single cycle by 46.2% and improve battery cycle life by 96.3% on average with respect to the standard CC-CV charging protocol.

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