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# Aging and Cost Optimal Residential Charging for Plug-in EVs

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**Abstract**—The scheduling of at-home charging of plug-in electric vehicles (PEVs) normally depends solely on the electricity cost. However, since each charge cycle causes a small degradation of the available capacity of the battery, there is a hidden cost that typically exceeds that of the electricity.

This work presents a method for minimizing the total cost of PEV charging by accounting for both the estimated costs of battery degradation and variable electricity costs.

We show that our solution reaches the bound of 20% loss in capacity with a 46% increase in cycle life with respect to a standard delayed charging scheme.

**Index Terms**—EVs, PHEVs, Li-ion batteries, battery charge, battery aging

## I. INTRODUCTION

The charging of plug-in electric vehicles (PEVs) introduces a new dimension to the process of adding mileage to a car with respect to traditional gasoline re-fueling, i.e., *charge time*. The fact that charging requires non-negligible time (even with the fastest options, this means 5-10x longer than re-fueling) produces an unconventional correlation between charge time and driving range that is peculiar to PEVs. However, the time aspect of charging, which affects the driver in terms of his/her range anxiety, is mostly relevant when charging in public stations. In this case, paradoxically, cost is only a secondary metric and what matters is charging in the shortest possible time.

The picture is totally different for residential (“at-home”) charging; here the time available for charging is usually abundant, causing the driver to re-focus on the *charging cost*. This becomes a priority because the energy required for the charge goes directly on the user’s electricity bill. Besides this intuitive dimension of charging costs, there is another aspect that is usually underestimated by or unknown to the driver but can have an impact on total cost that is at least as important as that of the electricity, i.e., the cost of the *aging* of the battery due to the charging process. In practice, a battery supports a finite number of charge/discharge cycles called *cycle life*. While the discharge phase is determined by the driving patterns, the charge process could be controlled in such a way that the parameters affecting battery aging are mostly kept under control.

There are two reasons why this aging effect is underestimated from the user perspective. Firstly, the user is generally oblivious to such a technical aspect. Secondly, the available chargers have little or no degrees of freedom, which allow the user to control the charging process.

We focus here on residential charging, for two main reasons. Firstly, although the numbers may vary depending on the geographical area, there is general consensus about the fact that the majority of charging events occur at home [1]. Secondly, as mentioned above, non-residential charging is usually dictated by charging time and not by cost. It is worth noticing that the case of long charging events away from home (e.g. at work for the duration of a typical working day) is comparable to the case of at-home charging and our considerations are applicable to such a case as well.

This work proposes a generalized Constant Current-Constant Voltage (CC-CV) charge protocol, in which the *charge start time*, and the *charging current* can be regulated, targeting the optimization of the total (electricity and aging) cost for the user.

Based on the desired plug-off time specified by a user, as in state-of-the-art *delayed charging* schemes [2], we derive a cost and aging-optimal CC-CV charge cycle. The calculation relies on a capacity fade model that accounts for all the relevant parameters, namely the average and variance of the state-of-charge (SOC), depth-of-discharge (DOD), and discharge/charge current. This model has been derived empirically from public data available for the battery pack of a Nissan Leaf [3], [4], [5]. Then, we compare the quality of our solution to traditional delayed charging. Simulation results show that by judiciously scheduling the start of the charge and regulating the charge current it is possible to improve battery life and, therefore, reduce the total cost of the energy per cycle.

## II. BACKGROUND

### A. Battery Charge Protocols

Charging a battery is a delicate operation that may have a noticeable impact on battery health. An appropriate *charge protocol* is thus essential to keep battery performance as unaltered as possible, but also to avoid dangerous side effects, like overcharging.

In Lithium-Ion (Li-ion) batteries the CC-CV protocol is considered the de-facto charging protocol [7] due to its simplicity of implementation and because it guarantees battery safety by protecting from over-voltage and over-current. Figure 1 shows a generic typical CC-CV profile and an instance of the latter for a real-life battery pack.

The CC-CV protocol consists of two main phases. Initially, the battery is charged with a constant current (CC), until the cell voltage reaches a specified value, smaller than the maximum voltage, in order to avoid over-voltage. Then, the battery voltage is kept constant, resulting in a progressively

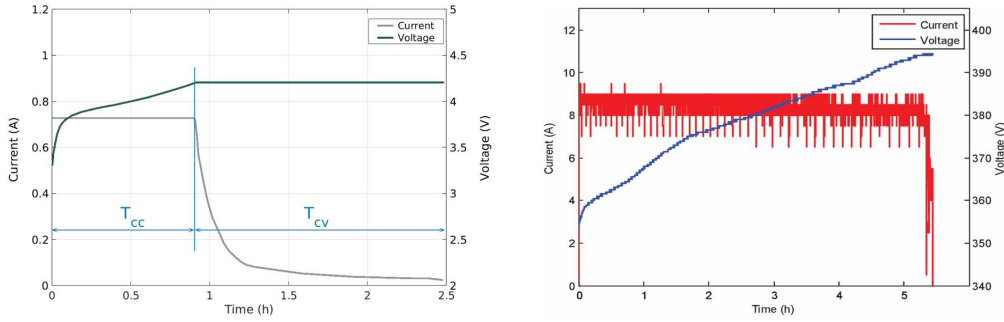


Fig. 1. Typical CC-CV charging profiles: A generic one reporting the most relevant parameters of the protocol (left), and a measured profile relative to the 24kWh Battery Pack for a Nissan Leaf [6] (right).

decreasing charge current. This constant voltage (CV) step is terminated when the charging current drops below a predefined threshold value, or when a predefined maximum charging time is exceeded. Initially, the SOC has a linear growth (integral of the current) and the voltage also increases. When the CC phase is over, the voltage has almost reached its final value, but the charge process continues until it achieves maximum filling.

The power used during a CC-CV charge is therefore not constant, in particular during the CV phase, where it progressively decreases and tracks the shape of current waveform. The actual breakdown of charge time between the CC ( $T_{cc}$ ) and CV ( $T_{cv}$ ) phases depends on various factors. One is the CC current  $I_{cc}$ , which is inversely related to  $T_{cc}$  but correlated with  $T_{cv}$  (a larger  $I_{cc}$  shortens  $T_{cc}$  and extends  $T_{cv}$ ) [6]. In general, however, CC-CV profiles are mostly affected by the battery chemistry. Concerning battery charge, some standards have been defined for automotive applications that are usually grouped into three different levels of charging [2], labeled Type 1–3, and are associated to different power charging levels (Type 1 using the least power).

Besides the CC-CV protocol, other charging schemes are possible, such as pulsed charge, constant power (CP), or multi-stage constant current [7]. Most datasheets however typically report data concerning CC-CV charging since battery chargers traditionally implement the CC-CV scheme. For this reason in this paper we focus on CC-CV and do not consider “alternative” charge schemes.

### B. Battery Aging Issues

When a rechargeable battery ages, its usable capacity decreases. This phenomenon is mainly due to two effects: (i) self-discharge, and (ii) how and how many times the battery is charged and discharged (number of charge-discharge cycles) [5]. The latter is definitely the effect more considered in the literature, because it might be more controlled. The discharge phase of the battery can significantly contribute to its aging. It is, in fact, quite difficult to be controlled as it strongly depends on the behavior of the user. On the contrary, the charging phase is normally fixed, designed a priori and implemented into the charger. For this reason, many studies in the literature are focused on charging.

The aging of a battery can become particularly critical in the field of PEVs, where the cost of the battery pack significantly contributes to the total cost of the vehicle [8]. Therefore, it becomes extremely important to efficiently design the charging scheme so as to delay the time when the battery pack is replaced [9]. For these reasons, the vast literature on customized *charge protocols* to reduce cycle aging is almost entirely focused on the PEV domain.

The degradation rate of a single battery cycle primarily depends on the following stress factors:

- **Temperature.** Aging increases as temperature increases.
- **Depth-of-Discharge (DOD).** The DOD is used to describe how deeply the battery is discharged. A DOD of 100% implies that a battery gets fully discharged before being recharged. DOD always can be treated as how much energy the battery delivered. Aging is increased by deeper discharge cycles (i.e., higher DOD values).
- **Average State-Of-Charge (SOC).** The SOC of a battery (or cell) is the percentage of its total energy capacity that is still available to discharge. Aging accelerates with higher values of average SOC.
- **Charge/Discharge Current.** 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 increases with higher charge/discharge currents [10].

Various aging-aware charging protocols have been proposed in the recent years (e.g., [9]). However, implementation of these protocols requires generally a non-trivial settings of the parameters and, furthermore, they requires a higher complexity of the charger.

## III. OPTIMAL CHARGE PROTOCOL

### A. Scenario and Problem Definition

The top plot of Figure 2 shows a conceptual plot describing the evolution of the battery SOC over time in a typical cycle, with the purpose of defining its key quantities. Since in this work we focus on the charge phase, the discharge phase, usually longer than the charge one, has been compacted in order to better emphasize the charge step.

Starting from a given value  $SOC_{eoc}$ , which is the SOC of the battery at end of the previous charge period, the discharge phase

will depend on the user activity on the device and will reach, at some point in time ( $t_{plug-in}$ ), a value  $SOC_{eod}$ , i.e., the SOC when the user connects the car to the power grid. As soon as the device is plugged the CC-CV protocol is applied and the device starts charging. The difference  $\Delta SOC = SOC_{eoc} - SOC_{eod}$  represents the depth of discharge.

All the parameters reported in Figure 2 are summarized in Table I.

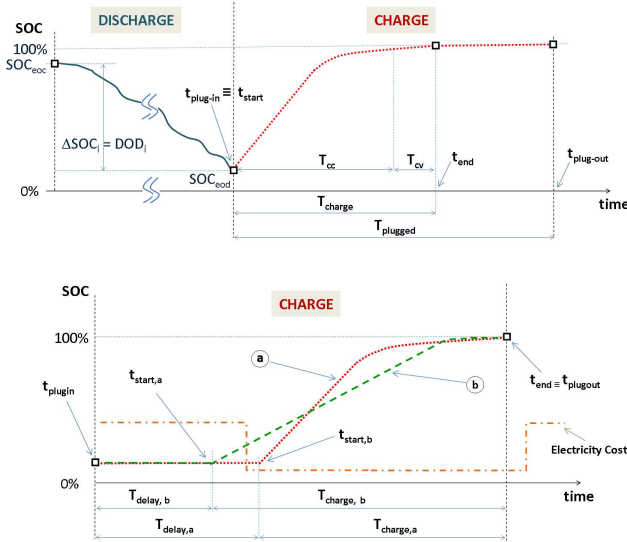


Fig. 2. (Top) Generic charge-discharge cycle and the corresponding relevant quantities (top); (bottom) the charge phases for delayed charging (a) and the proposed scheme (b)

The bottom diagram in Figure 2 zooms into the charge phase to show the CC-CV profiles of the delayed charge (a) and the proposed optimal one (b). Notice that the various terms in the bottom figure have an extra subscript (a or b) depending on the curve they refer to.

The two curves differ in *when* the battery starts charging ( $t_{start}$ ). In general, some time  $T_{delay}$  may elapse between  $t_{plug-in}$  and when it starts charging; this is a typical option offered by most PEVs. As already mentioned, delayed charge targets only the minimization of the electricity cost by trying to include the whole charging time ( $T_{charge}$ ) in the period with the lowest electricity cost. However, in this way no countermeasures to the battery aging are taken (i.e., by acting on the parameters that affect aging).

Conversely, the proposed charging scheme does still follow a “delayed” charge approach, but chooses an optimal  $T_{delay}$ , to account for the tradeoff between electricity cost and battery aging. As it can be observed in the figure, the green dashed curve (b) has a more gradual slope of the SOC compared to curve (a), implying a lower charging current and consequently, a smaller battery aging. Average SOC (area below the two curves) is instead approximately the same.

This anticipation of  $t_{start}$  does not come for free; the charging period may start in a time period that is subject to a higher electricity cost. It is thus essential, as explained in the next sections, to correctly play with the  $t_{start}$  in order to optimize

the tradeoff between electricity cost and aging.

TABLE I  
PARAMETER DEFINITIONS

Parameter	Description
$t_{plug-in}$	Time when the user connects the device to the power grid.
$t_{start}$	Time when the device starts charging.
$t_{end}$	Time when the charging period ends.
$t_{plug-out}$	Time when the device is disconnected from the power grid.
$T_{CC}$	Time period in which the battery is charged with a Constant Current (CC).
$T_{CV}$	Time period in which the battery is charged with a Constant Voltage (CV).
$T_{delay}$	Time period in which the device is plugged in but not charged.
$T_{charge}$	Time period in which the device is charged; it is computed as $T_{CC} + T_{CV}$ .
$T_{plugged}$	Total time period in which the device is plugged in; it is computed as $T_{delay} + T_{charge}$ .

## B. Models

1) *Aging Model*: We adopt the widely used aging model of [11], which relies on a modular template in which each of the parameters affecting aging (Section II-B) corresponds to an independent term that causes a loss in capacity. For a given cycle  $m$ , the loss of capacity can be conceptually expressed as

$$L_m = \prod_i f_i(X_i) \quad (1)$$

where  $f_i(X_i)$  is a function describing the aging incurred to a given parameter  $X_i$  (e.g.,  $X_i = SOC_{avg}$ ). Functions  $f_i$  are typically empirically fitted to measured data to determine their actual expression. With respect to [11], we consider the extended model with two extra factors  $f_i$  relative to charge and discharge currents [10].

The total normalized capacity loss  $L$  (0 = no loss, 1 = no capacity available) after  $M$  cycles is then simply obtained by summing over the  $M$  cycles, i.e.,  $L = \sum_{m=1}^M L_m$ .

2) *Cost Model*: There are two main contributions to the total cost of the charge: aging cost  $c_{aging}$  and electricity cost  $c_{elec}$ . Aging cost of a generic cycle  $m$  is simply defined as follows:

$$c_{aging,m} = c_{batt} \cdot \frac{L_m}{L_{max}} \quad (2)$$

where,  $c_{batt}$  is the battery cost,  $L_m$  the capacity loss in a cycle as defined previously, and  $L_{max}$  is the maximum acceptable degradation before replacing the battery pack (typically 0.2). Electricity cost for a generic cycle  $m$  is defined as:

$$c_{elec,m} = \int_{T_{charge}} e(t)P(t)dt \quad (3)$$

where  $e(t)$  is the electricity cost (per kWh), and  $P(t)$  is the instantaneous charge power (kW). In most cases,  $e(t)$  is a stepwise function with step values associated to different times of the day.

The total (aging+electricity) cost in a cycle is obviously obtained by summing  $c_{aging,m}$  and  $c_{elec,m}$ . Summing over multiple cycles yields the total cost.

Notice that while  $c_{elec,m}$  accrues only during charge time,  $c_{aging,m}$  is cumulated during both charge and discharge.

After considering the current cost of the battery pack in U.S. and Europe, and also the related electricity pricing, which depends on specific Country legislation and provider's policy, in general the aging cost is about double, or even more, than the electricity cost. For this reason, we focus on the optimization of the battery life degradation and minimization of the total cost.

### C. Calculation of the Optimal Charging Protocol

The charging algorithm (Figure 3) is invoked for a given cycle  $m$  at plug-in time  $t_{plug-in}$  and receives two inputs: (i) the SOC at the time of plug-in  $SOC_{eod}$ , and (ii) the plug-out time  $t_{plug-out}$ ; it returns the cost-optimal charge profile that, as an instance of CC-CV, is uniquely defined by (i) a value of  $I_{cc}$ , and (ii) a delay  $T_{delay}$  from the plug-in time  $t_{plug-in}$  as defined in Section III-A. Moreover, it also return the total cost (aging+electricity) for the current cycle.

The algorithm is based on a simple exhaustive exploration of the values of the only "free" parameter of a CC-CV protocol, i.e.,  $I_{cc}$ . Given the scales of the current magnitudes in play, the exploration step can be relatively coarse: we chose a discretization step of 0.1 A.

```

// invoked at charge cycle m
Inputs:  $T_{plug-out}$ ,  $SOC_{eod}$ 
Outputs:  $T_{delay}$ ,  $I_{cc}$ ,  $C_{tot,m}$ 

1. Compute max CC charge current  $I_{cc,max} = (P_{charge,max}/E_{pack}) * Q_{nom}$ 
2. Compute min CC charge current  $I_{cc,min} = (P_{charge,min}/E_{pack}) * Q_{nom}$ 
3. foreach  $I_{cc} = [I_{cc,min} \dots I_{cc,nom}]$  // in steps of 0.1A
4.   Calculate  $T_{cc}$  and  $T_{cv}$  from  $I_{cc}$  using a simulation model
5.   Calculate  $T_{delay} = T_{plugged} - T_{cc} - T_{cv}$ 
6.   Calculate  $SOC_{avg}$  as a function of  $I_{cc}$  and  $T_{delay}$  (Figure 4-(a))
7.    $\Delta SOC = SOC_{eoc} - SOC_{eod}$ 
8.   Compute  $L_m(I_{cc}, SOC_{avg}, \Delta SOC)$  using (1) and  $c_{aging,m}$  using Eqn. (2)
9.   Compute  $P(I_{cc})$  as the product of current and voltage (Figure 4-(b)) and  $c_{elec,m}$  using (3)
10.   $C_{tot,m} = C_{aging,m} * C_{elec,m}$ 
11.  if  $C_{tot,m} < C_{tot,best}$  store configuration ( $T_{delay}$ ,  $I_{cc}$ ) as  $C_{tot,best}$ 
12. endfor
13. return  $T_{delay}$ ,  $I_{cc}$ ,  $C_{tot,best}$ 

```

Fig. 3. Aging and Cost-Optimal CC-CV Charging Algorithm

$I_{cc}$  ranges between a lower and an upper bound that are obtained from the constraints on the charge power. Charge current is obtained from the charge rate  $P_{charge}$  as  $I = (P_{charge}/E_{pack}) * Q_{nom}$ , where  $E_{pack}$  is the total energy of the pack and  $Q_{nom}$  the nominal capacity of a single cell. Using the maximum and minimum charge power (6.16 kW and 1.41 kW) specified for the 2015 Nissan Leaf battery in [12], we get  $I_{cc,max} = 7.5A$  and  $I_{cc,min} = 1.5A$  (Lines 1–2). The two values are not proportional to charge power because efficiency of the charge is not constant and decreases for lower currents. Moreover, these bounds are an approximation since they are calculated assuming a constant charge power, which is not exactly true for a CC-CV profile. With these current bounds, the exploration space consists of  $(7.5 - 1.5)/0.1 = 60$  current values to be evaluated.

Notice that we include points with lower efficiency (and therefore not to be used if considering only energy costs) in the

exploration because by using lower current we may decrease the aging cost.

The exploration of  $I_{cc}$  values in the range (Line 3) consists of the calculation of several intermediate quantities needed to arrive at the total cost of the charge. First (Line 4),  $T_{cc}$  and  $T_{cv}$  are computed. We run an electrical circuit model of the battery to derive them:  $T_{cc}$  is first computed as the time at which the voltage reaches the  $V_{CV}$  value under application of a constant  $I_{cc}$  current (Figure 2). Similarly,  $T_{cv}$  is then obtained by applying a voltage source  $V_{CV}$  at the output of the circuit model and monitoring when current reaches the  $I_{eoc}$  value that determines the end of the charge. Knowing  $T_{cc}$  and  $T_{cv}$ , we calculate  $T_{delay}$  as  $T_{plugged} - T_{cc} - T_{cv}$  (Line 5).

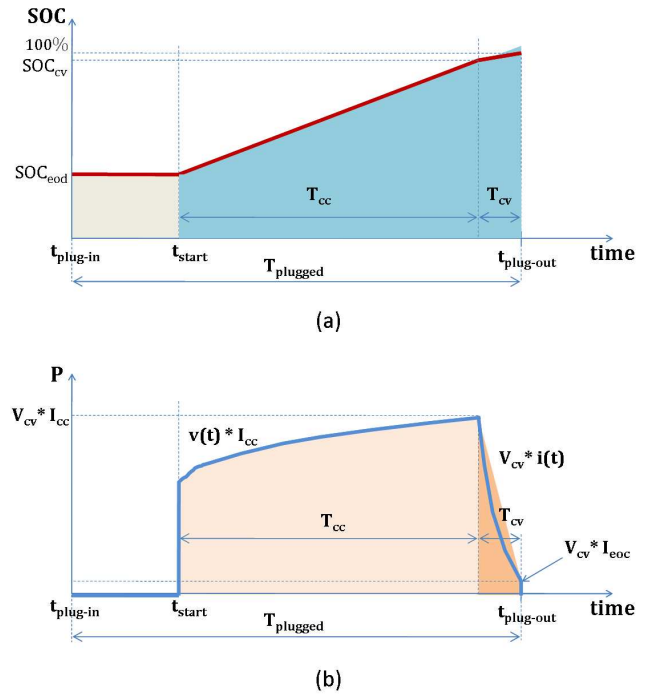


Fig. 4. SOC (a) and Energy (b) Calculation for a Charge Profile.

In Lines 6 and 7 the SOC-related parameters to be used in the aging model are computed. The calculation of the average charge SOC is done by approximating the SOC profile with piecewise segments as shown in Figure 4-(a). Since a constant current implies a linear increase of the SOC in the CC phase, the approximation only involves the short CV phase. The area below the curve divided by  $T_{plugged}$  yields the average SOC. Using  $\Delta SOC$ ,  $SOC_{avg}$  and  $I_{cc}$  we can evaluate the aging and its relative cost  $c_{aging}$  (Line 8).

Then, the total charge power is computed using the actual current and voltage profiles tracked by the simulation model and stored during the calculation of  $T_{cc}$ . As for the SOC, we simplify the calculation during the CV phase due to its small impact on the total (Figure 4-(b)). The area under the power waveform is the total charge energy, which yields the total electricity cost  $c_{elec}$ .

Finally (Lines 10-11), the total cost of this charge profile is stored as the new optimum value if it improves the current one.

## IV. SIMULATION RESULTS

### A. Setup and Characterization

For the validation of the model, we chose the battery pack of the *Nissan Leaf*, with nominal voltage of 360 V and nominal capacity of 24 kWh. It consists of 48 smaller modules, each consisting of four individual pouch cells; the four cells are configured in a 2-series, 2-parallel organization [3]. The list price of the pack is approximately 5,000 Euros.

Our simulations were carried out on a single cell with nominal voltage of 3.75 V and nominal capacity of 122 Wh, and then reflected on the entire pack by appropriately scaling current and voltage values.

We used the method described in [13] for deriving the circuit equivalent battery model to track voltage and current and so compute the charge power.

We extracted the charger efficiency as a function of current from data provided in [12]. We empirically fitted data to a cubic curve, yielding  $\eta(I) = a_1 \times I^3 + a_2 \times I^2 + a_3 \times I + a_4$ , with  $a_1 = 0.000217, a_2 = -0.00593, a_3 = 0.0563, a_4 = 0.736$ . The SSE and RMSE of the fitting are  $5.04 \cdot 10^{-4}$  and  $2.51 \cdot 10^{-3}$ , respectively.

For the electricity cost, we used time-of-use (TOU) pricing most widely used in Italy, which features three fares that are summarized in Table II.

TABLE II  
ELECTRIC CHARGE WITHIN ONE WHOLE DAY

Prices (Euro/kWh)	Time Segment
$F1 = 0.0896$	8:00 – 19:00
$F2 = 0.0786$	7:00 – 8:00 & 19:00 – 23:00
$F3 = 0.0580$	23:00 – 7:00

### B. Charge and Discharge Profiles

For the discharge phase, we generated various values of  $SOC_{eod}$  according to the distribution of the initial SOC for a charge event reported in [14] (top plot of Figure 5).

We assumed that  $t_{plug-in}$  is between 18:30 and 24:00. It reflects the time when users arrive home and plug the charger, with a log-normal distribution in which the early hours are more likely to occur (middle plot Figure 5). On the other hand, we simply set  $t_{plug-out}$  at 7:00 (bottom plot Figure 5).

### C. Simulation Results

We compared the proposed aging-aware charge against the default “delayed” charge as implemented in the *Nissan Leaf*, using the same parameters described in Section IV-A. We applied multiple charge/discharge cycles until the battery reached a loss of capacity of 20% (*state of health* = 80%).

TABLE III  
SIMULATION RESULTS: LIFETIME AND ELECTRIC CHARGE

Protocols	Lifetime (Cycles)	Electric Charge (Euro)
Delayed Standard CC-CV	977	625
Cost-Optimal CC-CV	1428	671

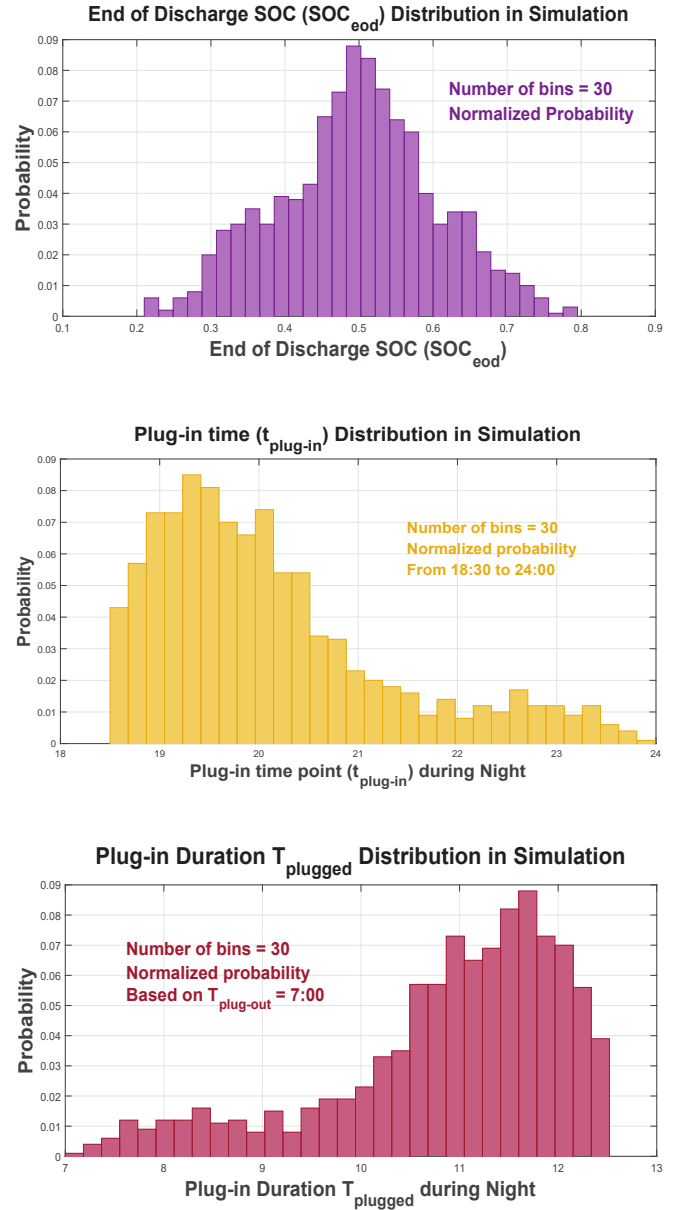


Fig. 5. Distributions of  $SOC_{eod}$  (top),  $t_{plug-in}$  (middle), and  $T_{plugged}$  (bottom), using 1500 cycles.

Table III shows the battery lifetime and electric charge costs for the two charging schemes. The proposed cost-optimal CC-CV protocol allows a much larger number of cycles (1428 vs. 977) with a minimal increase of the electricity bill (671 vs. 625 Euros).

Figure 6 shows the cycle-by-cycle capacity loss of the two schemes; the plot stops at cycle 977, when the delayed charge exhausts the battery capacity. It is clear how the aging degradation under the delayed CC-CV protocol is always larger than the proposed one; the two curves actually diverge, with the top one increasing faster than the bottom one.

Figure 7 shows the cumulative saving in Euros over the 977 cycles; the total saving is about 560 Euros.

Notice that the proposed method, thanks to the use of a circuit



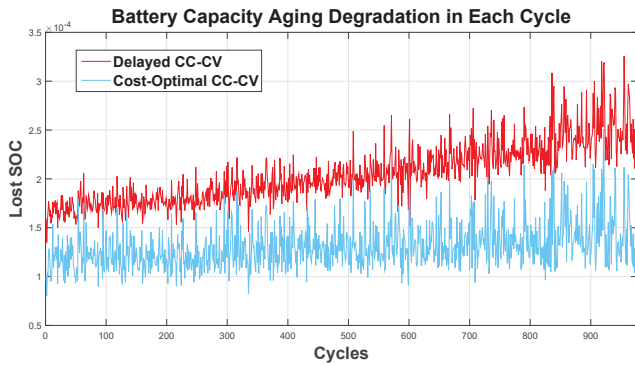


Fig. 6. Battery capacity aging degradation in each single cycle.

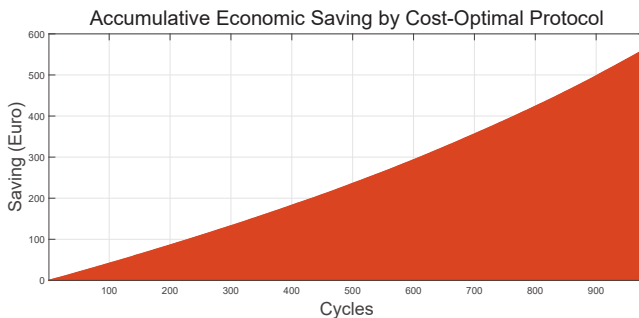


Fig. 7. Cumulative Saving obtained by the proposed charge policy.

equivalent for deriving the relation between  $I$  and  $V$  during the charging phase, is suitable for any charge profile, e.g., constant power - constant voltage (CP-CV).

## V. CONCLUSIONS

The cost of battery aging is essential in determining the total cost of a charge cycle in PEVs. Only considering the electricity cost, as occur in default cost-optimized charge schedules in commercial PEVs, does not actually minimize the *total* cost. We have proposed a total cost-optimized charging scheme based on a standard charger implementing CC-CV protocol, achieving an optimal balance between electricity and battery aging costs by appropriate tuning of the charge current. Simulation results show that a judicious selection of the charge current can lead to a 46% longer cycle life of the battery.

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