International Journal of Electrical and Computer Engineering (IJECE)
Vol. 14, No. 3, June 2024, pp. 2457~2465
ISSN: 2088-8708, DOI: 10.11591/ijece.v14i3.pp2457-2465

A fast charge algorithm for Li-ion battery for electric vehicles

Sohaib Bouzaid, Laadissi El Mehdi, Abdessamad El Ballouti
Laboratory of Engineering Sciences for Energy, National School of Applied Sciences, University of Chouaib Doukkali,
El Jadida, Morocco

Article Info

Article history:

Received Feb 1, 2024
Revised Mar 8, 2024
Accepted Mar 9, 2024

Keywords:

Battery management systems
Charging time
Electric vehicle battery
Fast charge
Li-ion battery
Li-ion polarization

ABSTRACT

The renewable solar energy industry and electric vehicle industry are today seeking for fast battery pack recharging methods to achieve higher performances, and fast energy recovery for energy storage systems (ESS) and for electric vehicles. The charge rate of batteries impacts directly the temperature which in turn impacts the capacity fade, thus it should be kept low to prevent the cells from warming up. This not only limits the charging rate but also puts us on a trade-off, a long lifetime or a fast recharge. In this study, we tried to achieve fast charging using a new charging method that combine two charging methods, without much deterring the capacity of the battery, in order to be able to maintain a long battery lifetime. Charging time of around 82 min was achieved for a 1.8 Ah battery. We compared our findings with the literature with known charging profiles.

Corresponding Author:

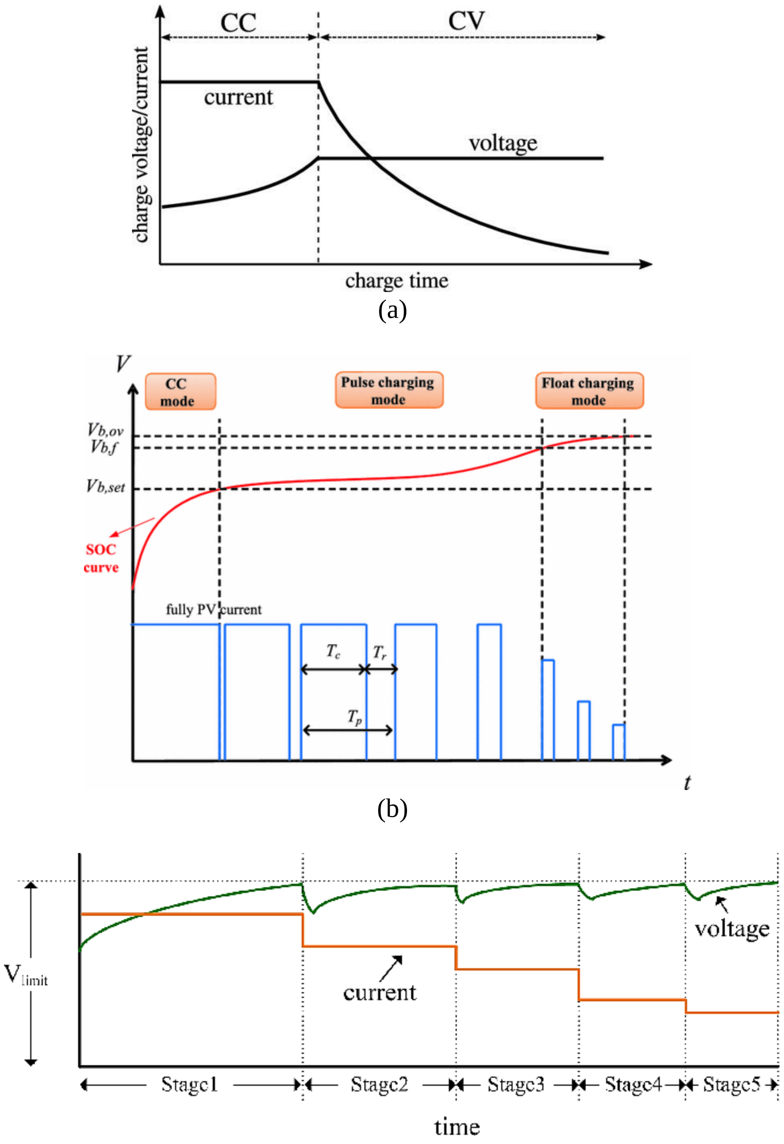
Sohaib Bouzaid
Laboratory of Engineering Sciences for Energy, National School of Applied Sciences, Chouaib Doukkali University
El Jadida, Morocco
Email: bouzaid.s@ucd.ac.ma

1. INTRODUCTION

The batteries, especially the secondary type ones, are used today in different apparatus and have a wide range of applications, from energy storage for photovoltaic systems to uninterruptible power sources for hospital devices and electric vehicles. With the repetitive use of batteries for photovoltaic use or electric vehicle, it is discharged because of its chemical reactions and energy loss. It is in some cases easier to change the battery and, while the apparatus is being used, we recharge the used battery outside of its apparatus, but in other cases, recharging the battery without removing it is the only available solution, especially in electric vehicles and photovoltaic systems, where the use of secondary types of batteries is primordial, and the battery may sometimes need to be recharged while it is in use.

For the later, we cannot just sink the energy from the photovoltaic grid to recharge the batteries, proper devices have to be intermediate, besides that fast recharging the batteries will make the system more stable since it will be ready for any high-power demand. For electric vehicles, one of the many causes for the battery swapping difficulties is the lack of consensus about battery standards and technologies used by each manufacturer [1]–[3]. Nowadays we have different charging outlets and power levels for electric vehicle charging. Level 1 charging: uses the lowest charging power, with 120 V alternating current (AC) and less than 10 A with an output power of 1 Kw. Level 2 charging: uses higher power and faster charging than level 1 with 240 V AC and a maximum current of 80 A achieving a power of 19 kW [4]. And direct current-fast charge (DCFC): uses direct current (DC) instead of AC and uses voltages as high as 800 V DC and can achieve a power of 350 kW and down to 50 kW [5].

Charging the battery to 100% state of charge (SOC) takes longer for the level 2 and DCFC charging levels, this is because after 80% SOC the battery management system (BMS) switches from constant current to constant voltage depending on the protocol used for the charge [6], [7]. Achieving extreme fast charging (EFC) is not as easy as it seems. The major limitation to EFC is in the chemical structure of the battery itself, the electrolyte electron transportation cannot follow the chemical reaction rate at high currents, beside that the cathode particle cracking effect causes stability problems [8]. The battery charging is governed by three major parameters, which are the current through the cell, the voltage across the leads of the cell and the power dissipated by the cell. The choice of controlled parameters depends on the operating conditions and compromise between fast charge and battery durability. All charging methods are based on some well-known charging protocols. Different charging protocols were proposed like the standard charging protocol, the constant current constant voltage (CCCV) [9], [10]. This charging method is divided into two phases, the first phase is a constant current phase, the second phase is the end of charge phase where the battery management system keeps the voltage constant (CV) at nearly 4.2 V and the current starts decreasing, the charging process ends when the current going through the cell is bellow a set threshold, called cut-off current. This method has the advantage of not deterring the battery in a drastic manner, Figure 1 shows different charging profiles, and Figure 1(a) shows a typical charging curve. Figure 1(b) shows a typical charging curve using the pulse charge algorithm. Figure 1(c) shows a typical charging curve of multistage constant current for Li-ion battery charging, the charging in this figure was divided into five stages.



(a)

(b)

(c)

Figure 1. Typical charging profiles: (a) CCCV Li-ion charging curve [11], (b) pulse charging Li-ion battery [12], and (c) multistage constant current charging [13]

Another known charging method is the pulse charging like discussed in [14] where using a 50% duty cycle at 1 Hz, the cycle life was improved by 4 times and charging time reduced by 17% compared to the CCCV charging protocol. Kannan and Weatherspoon [15] used a Li-ion cell with Nickel Manganese Cobalt Cathode with a slightly different method, pulsed-CV, and charged the cell at frequencies of 50 Hz, 100 Hz and 1 kHz. The reduced charging time is between 14 min and 23 min, and the charging time using pulsed-CV has not changed a lot over the 250 cycles, whereas for the constant current constant voltage method, the charging time increased suddenly after 125 cycles. The advantage of this method is that the concentration polarization is reduced and this improves the electrochemical performance. Figure 1(b) shows a typical charging curve using the pulse charge algorithm, the current pulse width gets narrower with the increased cell voltage and the charge rate (i.e. the derivative $CH_r = \frac{dSOC}{dt}$) goes to 0.

The multistage constant current charging (MSCC) is an amelioration to the CCCV standard charging protocol, where the constant voltage phase is replaced by multiple constant current values that are decreasing [16], [17]. Zhang *et al.* [18] used a model of 26650 LiFePO4 battery, applied constant current charging at different C-rate, the multi stage charging was segmented according to the SOC of the cell and the charging current at each interval decreases by a calculated amount, the maximum reduction in charging time was 3.42%, or 2.13 min reduced. Choosing the right number of steps is still a research topic and many optimization algorithms are used to calculate it [13], [19]–[21].

Figure 1(c) shows a typical charging curve of multistage constant current for Li-ion battery charging, the charging in this figure was divided into five stages. For each stage, the current is fixed at a constant value and for each next step; we reduce the current until reaching the end of charge. Other charging protocols are used like pulsed charging [22], constant current combined with pulsed charging [23], pulse charging [24], and boost charging [25], [26].

The combination of different charging profiles is not mentioned enough in the literature. In this research article, we are going to address a common problem in battery management, the long charging time of the batteries, we are going to combine two charging methods, the pulsed charging and the constant voltage at the end of charge to reduce charging time. In the next section, we will show the equations and the circuitry used for the experiment as well as the software algorithm, and then we will conclude, compare and discuss about the results gathered.

2. MATERIALS AND METHOD

To validate the proposed hypothesis about the positive effect on combining two charging methods, and since we cannot try fast charging on an electric vehicle's battery pack because of its non-availability in the facility, we used a real commercial cell token randomly from a battery pack; its characteristics are shown in Table 1. The experimental setup consists of a charging station (EA-PS 9080-340) that we controlled using a virtual instrument we developed with LabVIEW version 17.0f2 software. In the instrument's graphical user interface (GUI), we provided the different current profiles, and saved the cell voltage and actual current into a file and used separately an electronic load to discharge the cell after each test, the LabView instrument GUI is shown in Figure 2.

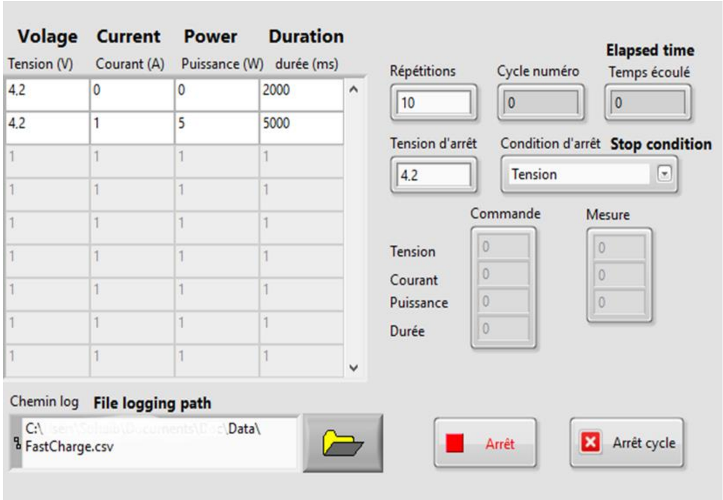
The first step of the experiment protocol is charging the cell to 4.2 V until the current is below 100 mA, which we defined as the cut-off current, the second step is discharging the cell at its nominal current until the cut-off voltage of 2.5 V. At the first and last discharges only, we measured the capacity of the cell, for the first discharge it is 1.84 Ah. We then charged the cell using the recommended charging profile in the datasheet, the CCCV with a cut-off current of 0.1 A since it is the minimal current measured by the machine. Then we discharged the battery again using the second step of the protocol. For each of the proposed charging methods, we used a profile to charge the cell, then used step 2 to discharge the cell.

The experimental setup is shown in Figure 3, the cell is permanently connected to the power supply, the power supply charges the cell. We did not turn off the power supply while discharging the cell. For the discharge process, we configured the power supply at the minimum cell's voltage so when this voltage is achieved by the cell at the discharge, the power supply will start supplying current for the electronic load, and thus preventing the cell from going into deep discharge situation. The power supply circuit has a constant voltage (CV) system that switches automatically on when the cell's voltage reaches the preset charging voltage of 4.2 V. At this phase, the current starts decreasing until reaching a minimum of 0.1 A as end of charge current. The charging process ends then. For higher currents, a voltage drop is noticed across power cables, so we used a special sensing input available from the power supply, it helps get accurate voltage measurements across the cell.

Figure 4 shows a typical current profile that we will use for the dynamic pulse charging. The dynamic pulse charging used is not a standard one. Instead of having one pulse of current I_H for T_H seconds and 0 A for T_L seconds, the current at T_L is higher than 0 A but no more than the maximum allowable current by the manufacturer. Having a low current leaves the cell already polarized, so we do not waste much energy at the next pulse. In the second phase, we used a constant voltage charging for end of charge.

Table 1. Characteristics of the cell used for the experiment

Nominal voltage (V)	Measured capacity (mAh)	Internal resistance (Ω)	Polarization resistance (Ω)	Time constant (s)
4.2	1,843	0.15	0.2	600



Volage Tension (V)	**Current** Courant (A)	**Power** Puissance (W)	**Duration** durée (ms)
4,2	0	0	2000
4,2	1	5	5000
1	1	1	1
1	1	1	1
1	1	1	1
1	1	1	1
1	1	1	1
1	1	1	1
1	1	1	1

Répétitions: 10
Cycle numéro: 0
Elapsed time Temps écoulé: 0
Tension d'arrêt: 4.2
Condition d'arrêt **Stop condition**: Tension

	Commande	Mesure
Tension	0	0
Courant	0	0
Puissance	0	0
Durée	0	

Chemin log **File logging path**: C:\[redacted]\Data\FastCharge.csv

Figure 2. LabVIEW GUI for current profile generation

Figure 3. Experiment for fast charge

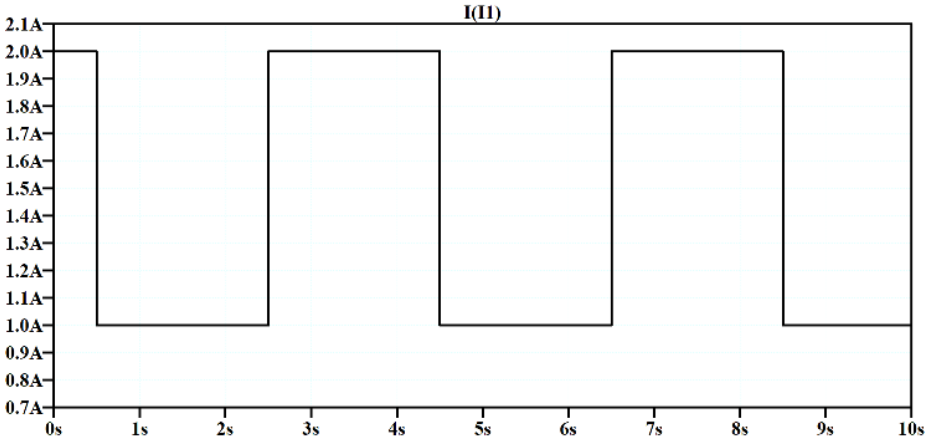


Figure 4. Typical dynamic pulse current profile

The charging time ends after the constant voltage phase has begun and when the current going through the cell is lower than 0.1 A. We used different current profiles for the experiment; each profile is defined by four parameters: the duration of the high current and low current, and the value of high current and low current. The rise time and fall time cannot be changed, they are fixed by the machine manufacturer and are not included in the profile parameters. Table 2 shows the different profiles proposed, the CCCV is used as charging time reference with charging current of 0.5 A, and the 1 A and 2 A pulsed charging profiles are used to compare with the new proposed methods, the duration of high current was limited to only 2 seconds for the 2 A profiles to prevent the cell from heating. We calculated the SOC using the Coulomb counting method, we used (1) for that.

$$SOC = \int_{t_s}^{t_e} \frac{i(t)dt}{C} \tag{1}$$

The integral limits of integration, t_s and t_e are the charging start and end time, $i(t)$ is the current passing through the cell, positive for charging, and negative for discharging. C is the capacity of the cell. In our case C=1.84 Ah, $t_s = 0$ and t_e is the time at which the cell's voltage is 4.2 V at cut-off current.

To verify that the profiles have no severe impact on capacity degradation, we calculated the capacity one last time by discharging the cell at 0.5 A to compare it with the first calculated capacity. We found that the capacity is 1,716 mAh, which corresponds to 6.9% capacity loss. This shows that none of the profiles is deterring aggressively the capacity of the cell.

Table 2. Current profiles characteristics

Profile proposed name	Duration of high current (s)	Duration of low current (s)	Value of high current (A)	Value of low current (A)
1A/0A@5s/2s	5	2	1	0
1A/0.5A@5s/2s	5	2	1	0.5
2A/0A@2s/4s	2	4	2	0
2A/0.5A@2s/4s	2	4	2	0.5
2A/1A@2s/4s	2	4	2	1
2A/1A@2s/2s	2	2	2	1
CCCV	-	-	0.5	0.1

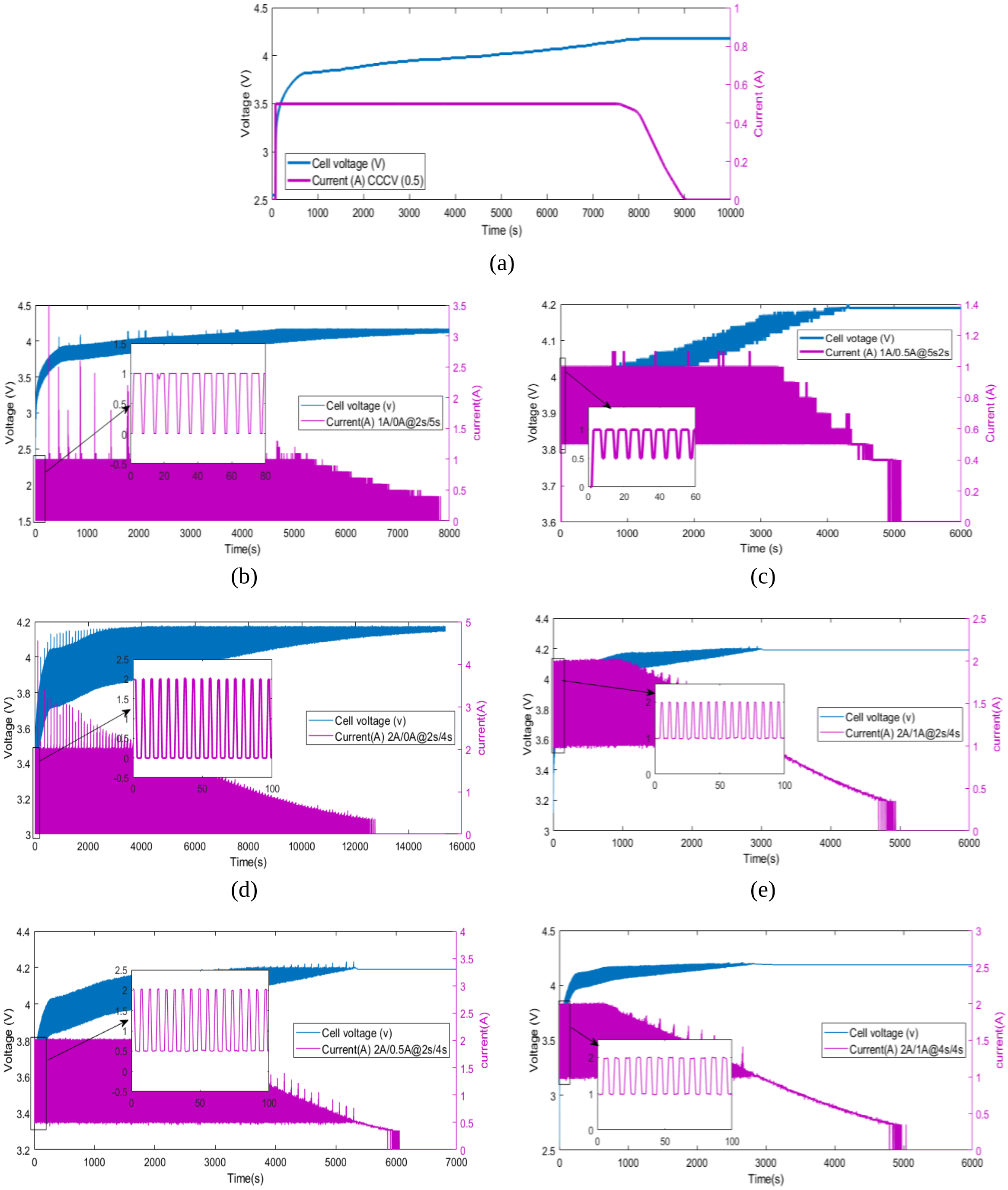
3. RESULTS AND DISCUSSION

Figure 5 shows the plots of the cell voltage for different current profiles versus time during charging. Figure 5(a) shows the reference charging profile, Figure 5(b) shows standard pulse charging, Figure 5(c) shows the proposed charging method to compare with the plot (b), Figure 5(d) shows pulsed charging and Figure 5(e), Figure 5(f) and Figure 5(g) show the proposed charging methods to compare with plot (d). for the CCCV, we charged the cell according to the manufacturer technical document. The time elapsed until CV phase starts is 136 min, and the full charge is achieved in 150 min. The charging time for pulsed charging is 167 and 211 min for 1 A (plot b) and 2 A (plot d) respectively, the 2 A pulsed charging took longer because the off time is much longer than the on time. Comparing these charging times with each other, the CCCV was faster than the pulsed charging.

As shown in plot (c), we achieved full charge at nearly 85 min, which is 51 min less than CCCV charging time. Almost half the time needed to charge the cell using the 1 A pulsed charging. Whereas in plot (e) on same figure, charging time is 82 min, while the standard 2 A pulsed charging needed 211 min to achieve full charge, almost three times longer. In plot (f), the charging time is 100 min, almost half the time needed for the 2 A pulsed charging. A comparison between plot (e) and (g) on the same figure shows that changing the duty cycle from 33.33% to 50% did not impact the charging time too much, but had an impact on the CC phase duration, the constant current phase for the 1/3 duty cycle is nearly 16.67 min (1,000 sec), whereas the constant current phase for the 50% duty cycle is 12.5 min (750 sec). This result shows that the duty cycle impacts the constant current duration, the higher the duty cycle, the less the duration of constant current. Table 3 recapitulates these results.

From Table 3 we can see that pulsed charging is not all the time faster than the CCCV, the standard pulsed charging using maximum current of 2 A for 2 seconds needed more than 3 h to fully charge the cell whereas the CCCV needed only 2 h 30 min. But when using pulsed charging with a lower current and longer time, 1 A for 5 seconds, the charging time decreased to only 2 h 40 min, still slower than constant current but faster than the 2 A pulsed charging, this is mainly caused by the short duration of the on time for the 2 A pulsed charging. Changing the duty cycle may not have a direct impact on charging time as we can see in charging time between the profiles 2A/1A@2s/4s and 2A/1A@4s/4s. Besides that, the proposed method (1A/0.5A and 2A/0.5A) is remarkably faster than their respective standard pulsed charging (1A/0A and 2A/0A).

Nevertheless, we cannot say that the pulsed charging 2A/0A is not fast since we only tried one duty cycle and the corresponding on time was less than 50%. The proposed charging method is faster than their respective standard pulsed charging, the 1A/0.5A is 55% faster than 1A/0A, whereas the 2A/0.5A is 52% faster than 2A/0A, and 2A/1A is 61% faster than the standard 2A/0A. Calculating the capacity charged for each case gives us the results shown in Table 4. The least charged capacity corresponds to the 1A/0.5A profile that represents 58.6% of total capacity. The 1 A pulsed charging on the contrary has achieved 73.9% of total capacity. The 2 A pulsed charging achieved 86.4% of total capacity but with a charging time of more than 3 h, the 2A/1A@2s4s achieved 74.4% of total capacity, changing the duty cycle from 2/6 to 3/6 increased charged capacity to 77.1% of total capacity for an increased charging time of 2min. Figure 6 shows the charged capacity as a function of charging time.



(a)

(b) (c)

(d) (e)

(f) (g)

Figure 5. Cell charging voltage with different current profiles, (a) CCCV, (b) 1A/0A@2s5s, (c)1A/0.5A@5s2s, (d)2A/0A@2s/4s, (e) 2A/1A@2s/4s, (f) 2A/0.5A@2s/4s, (g) 2A/1A@4s/4s

Table 3. Comparing different charging profile

Profile (plot)	Charging time (min)	Remarks
CCCV (a)	150	Used as reference to compare
2A/0A@2s/4s (d)	211.87	Slower than CCCV
2A/0.5A@2s/4s (f)	100.92	Uses only half time compared to 2 A pulsed charging
2A/1A@2s/4s (e)	82	The fastest charging method among all tried
2A/1A@4s/4s (g)	83.95	Slightly slower than the previous profile
1A/0A@5s/2s (b)	130	faster than the CCCV
1A/0.5A@5s/2s (c)	85	Faster than the precedent

Table 4. Charged capacity for each profile

Profile	Charged capacity (Ah)	Pi
CCCV	1.81	1.21
2A/0A@2s/4s	1.59	0.75
2A/0.5A@2s/4s	1.35	1.34
2A/1A@2s/4s	1.37	1.67
2A/1A@4s/4s	1.42	1.71
1A/0A@5s/2s	1.36	1.04
1A/0.5A@5s/2s	1.06	1.25

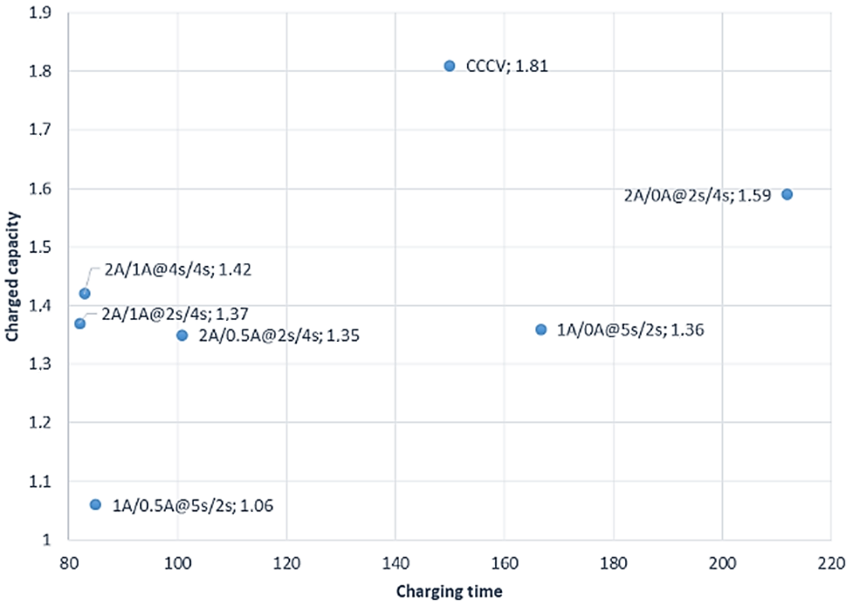


Figure 6. Charging time versus charged capacity

Charged capacity depends on charging time, but the same duration will not give the same charged capacity for all the profiles since they are not the same. To find the better profile we need a formula to normalize the charging time and charged capacity. Comparing two profiles, the better profile is the one who will charge the cell to a certain capacity with the least needed time, and the worst is the one that will need a longer time to charge the cell to the same capacity, the formula bellow describes well this performance indicator. The highest Pi correspond to the profile 2A/1A@4s/4s, outclassing the 2A/1A@2s/4s by higher charged capacity in less time, 2 minutes difference in our case, making these two profiles better than all the experimented profiles, and the 2 A pulsed charging with the lowest Pi making it the slowest profile.

$$Pi = \frac{Charged\ capacity(\ Ah)\times 100}{charging\ time\ (\text{min})} \tag{2}$$

Comparing these results with [15] we can see that the CCCV charging needed 97 min and the pulsed-CV at 50% duty cycle achieved 82 min for both 50 Hz and 1 Khz, the pulsed charging is 15 min faster than CCCV. What is interesting is that battery capacity did not degrade much with the pulsed charging compared to CCCV profile, which makes the pulsed charging more suitable than CCCV for battery fast charge. In [6], a MSCC charging profile was used, the charging time for CCCV at 25 °C was 61 min whereas using MSCC increased the charging time by 4 min. At temperatures of 5°C, the charging time for the CCCV was 66 min whereas the MSCC needed 91 min to get to 90.4% SOC. This indicates that at low temperatures, it may be more efficient to charge the cell using CCCV instead of a fast-charging method.

4. CONCLUSION

In this study, we proposed a new charging profile based on a widely known charging method. Using a constant current to let the cell pre-polarized helped increase charging speed and helped achieving promising results with this proposed profile. Nevertheless, further studies have to be made on battery capacity degradation after each profile to make sure it is still better than the standard pulsed charging profiles and to know which profile is harvesting the cell’s capacity. This study also showed an interesting result about the impact of the duty cycle on the constant current phase. In a further study, we can integrate a charge equalization algorithm to decrease the heat generated when multiple cells are used, it can help increase the efficiency of this method compared to other methods.

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BIOGRAPHIES OF AUTHORS

Sohaib Bouzaid received the B.Eng. degree in electronic and automatic systems engineering from National School of Applied Sciences of Tangier, from Abdelmalek Essaadi University, Morocco, in 2019. Currently, he is a PhD student at the Laboratory of Engineering Sciences for Energy, Chouaib Doukkali University. He is currently working on battery management systems for electric vehicles applications, his research interests include battery management systems, battery fast charge, battery protection algorithms and methods, battery data acquisition. He can be contacted at email: bouzaid.s@ucd.ac.ma.

Laadissi El Mehdi holds a PhD from Mohammed V University. He is currently editor in chief of the International Journal of Engineering and Applied Physics and a professor at the University Chouaib Doukkali. With more than 12 invention patents registered with the World Intellectual Property Organization (WIPO), professor Laadissi is recognized as an international inventor, thus consolidating his position as a leader in the field of engineering and innovation in Morocco and beyond. He specializes in electrical engineering, with a particular focus on battery system management, battery modeling, power electronics, and renewable energy. His academic affiliation also extends to the Laboratory of Engineering Sciences for Energy (LabSIPE) of the same university. He can be contacted at: elmehdi.laadissi@gmail.com.

Abdessamad El Ballouti received the Ph.D. degree in physics at the faculty of sciences of El Jadida, Morocco. He was a professor at technical high school Errazi of El Jadida. He is currently a professor at the National School of Applied Sciences of El Jadida, at Chouaib Doukkali University. He holded previously the head of Department of Sciences and Industrial Technologies at the same school. His research interests include supply chain, analytic hierarchy process, capacitated vehicle, capacitated vehicle routing problem, communication technologies, complex supply chain. He can be contacted at email: elballouti@hotmail.com.