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Adaptive Charging Protocol (ACP) based on Non-linear Voltammetry (NLV) Charging Patterns for Fast charging Li-Ion batteries.

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Abstract: *The research work presented in this paper emphasis the suitability of the Adaptive charging protocol (ACP) based non-linear voltammetry (NLV) charging patterns for fast charging Li-ion batteries (LIBs). The ACP based NLV charging is a patent pending technology [20] implemented to fast charge the LIBs by non-linearly incrementing the voltage, step by step, adhering to an interdependent relationship [19] based on the product of the "change of current (dI/dt)" and the "change of voltage (dv/dt)"). It has shown a quicker charging ability in fully charging a LIB in just around 22 minutes of charging time. In terms of assessing its safety, stability and the applicability on different battery cells, a number of experiments were performed on four different types of LIBs. These experiments and their expectations have discussed in the second section of the paper and the third section detailed on the results. Out of these aging experiments using the ACP based NLV fast charging, the test modeling the average smartphone users' daily charge-discharge routine is an interesting experiment, which was designed to charge a battery in 30 minutes for three consecutive cycles followed by a slow charging cycle. Most importantly, it showed prominent results in this test which is continued for more than 1000 cycles without degrading its discharge capacity below 80% of the nominal capacity of the battery. The later part of this paper provides a brief discussion on a set of distinctive features of this method such as temperature decrement during charging, the unique charging profiles at each charging attempt and the use of high voltage regions. In an overall, the experimented ACP based NLV method is proven to be an effective fast charging method for a number of different LIBs and indirectly models the natural charging in rechargeable batteries.*

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I. Introduction

The time taken to fully charge a battery is one of the most crucial factors for the wide acceptance of the Li-ion battery powered electronic devices and electric vehicles. For the first decade and a half, since 1991, Li-ion batteries were charged using a constant current constant voltage (CCCV) charging technique, which can be seen in charging a wide range of devices from high-power electric vehicles [1] to the low power coin cell batteries [2]. This CCCV method consists of two stages that initially charges at a constant current (CC) and then at a constant voltage (CV). It encourages slow rate (mostly less than C/2-rate) charging during the initial stage to ensure safety and the maximum cycle life of the battery. However, it is well known to prolong the charging time.

In today's rechargeable battery use case scenarios, such as mobile phones and electric vehicles, users require much faster charging times. The CCCV is not an effective candidate to fulfill those faster charging demands. Thus, there has been a considerable interest in both the research and commercial communities in implementing fast charge technologies beyond the classical CCCV method. As such, numerous algorithms based fast charging methods can be found, and some of those techniques can be seen as statistical [3, 4, 5, 6, 7], responsive & interactive [8, 9,10], design patterns & model based [11, 12, 13] and electrochemical relationships based [14, 15]. These methods mostly focus on gaining quicker charging time with the use of higher current rates and sometimes with higher voltages. In many cases, these current rates and voltages are fixed and selected based on manufacturer data or on statistical factors. Such strategies will stress and harm the internals of the battery in real-time as well as aggregated in a long run. Furthermore, the continuous use of these high currents and/or voltages adversely affect the lifespan of the LIBs.

In this work, an adaptive charging protocol (ACP) based on non-linear voltammetry (NLV) charging pattern for fast charging Li-Ion batteries has presented. Regulating the voltage non-linearly throughout the charging process analyzing its' very present current response is considered one of the main differentiating factor of this method. It prevents stressing the battery with any predefined currents or voltages. Rather, this method tends to model a natural charging, letting the battery to charge with its own favorable current at every charging step. A relationship suggested in Rachid Yazami et al [19] between the change-of-current (dI/dt) versus the change-of-voltage (dv/dt) has used as the fundamental method for the NLV calculations. In addition, a novel strategy of adaptation of the charging process to the real-time state of charge (SOC) and a relaxation in between every charging step is introduced.

Further, a number of extensive experiments were designed to enable an objective comparison & evaluation about the performance of the charging method. For this purpose, different LIBs were tested by using the ACP based NLV method while modeling various charging and discharging patterns. Initial part of this paper discusses the environmental setup and the designed experiments. The next part will provide a detailed analysis of the test results followed by a discussion on the important observations and findings during the tests. Here, the temperature profile and the varying charging profiles at each individual charging cycles [of the same cell] have presented as distinctive features of this method. Finally, the future work and some of the most important findings have discussed in the conclusion.

II. Experimental and ACP based NLV Fast Charging Method

The main hardware components used in this work includes the LIB cells, programmable power supply units, temperature measurement units and computers to run the charging control processes.

Li-Ion Battery Cells

Four different types of LIB cells, LIR13450, ICR14430J, ALT Pouch and LIR18650 with different chemistries, shapes and dimensions were selected to test in this work. Table 1, shows some important information about these LIBs based on their manufacturer's data sheets.

LIB	Type	Nominal Capacity (mAh)	Allowed Voltage (V)	Temperature Range (^{O}C)	Rated Cycle Life
LIR13450	Cylindrical	650	2.5-4.2	0-50	500
ICR14430J	Cylindrical	600	2.5-4.2	0-50	500
ALT Pouch	Pouch	2100	2.5-4.2	0-60	500-1000
LIR18650	Cylindrical	3400	2.5-4.2	0-60	300+

Table 1: The table of LIB battery details

Figure 1: TheLIBs: LIR18650, ALT Pouch, ICR14430J, LIR13450 from left to right.

Cell Preparation

Each of these cells were conditioned for 3 cycles using a standard Arbin cycler [Power Supply from Arbin with 10V & 5A power configurations] at C/6-rate charge and discharge currents. The representative calculated capacity of each cell were taken as the average discharge capacity of the 3 cycles. Then the cells were kept in relaxation for 30 minutes before starting the targeted experiments. All the experiments were conducted at the room temperature (25 ^{0}C) with air conditioning-on.

Power Supply Equipment

Two power supplies were selected based on the varying power requirements of the selected batteries and the programmability of the units.

Figure 2, shows the KEITHLEY 2461 source measurement unit (SMU). This KEITHLEY-Tektronix high current power supply is programmable [16] with a maximum current pulse capability of 10A/100 V and DC at 7A/105V. Its 0.012% DCV accuracy with 6½-digit resolution is an important factor for these experiments.

Therefore, the voltage accuracy is up to 0.1 mV. This unit can be connected to a laptop via a USB 2.0 interface and enable its control for the NLV charging software program.

Figure 2: KEITHLEY, Power Supply with max current of 7A

Figure 3, the KEYSIGHT (previously Agilent) N7951A [17] Dynamic DC Power Supply, 20V, 50A, 1kW was purchased to support the batteries with higher capacities. A separate dissipater unit was used to discharge the cells, as this power supply is only able to charge/power-up a load. The voltage accuracy of this unit is 1mV and an inherent latency was experienced whenever the charging mode was changed from a CV mode to REST & CC mode. Nonetheless, it was easy to program and integrate this unit to a laptop computer through a TCP/IP interface via an Ethernet cable. Here, the NLV charging application was programmed using C#.NET.

Figure 3: KEYSIGHT, Power Supply with max Current of 50A

Figure 4: OMEGA, Thermometer

Temperature Sensing Module

The temperature profile was recorded using an external Omega HH520 [18] thermometer data logger, figure 4. This unit provides 4-thermocouples with the accuracy of around 0.7 ^{0}C at a sampling rate of 2 readings per second. It also comes with a separate software, which can be installed, on a computer and use to extract the data that are stored in its internal memory.

Experiment Design

Purpose Of the Experiment	Expected Charging Time	Cell Name	Capacity (mAh)	No. of Cycles
01 Comparison Test	30 Min	LIR13450 Cylindrical	650	035
02 Aging Test	30 Min	ALT Pouch	2100	153
03 Aging Test	45 Min	LIR18650 Cylindrical	2000	297
04 Aging Test	1 Hr	ICR14430J Cylindrical	1200 [Parallel]	122
05 Daily Charge Schedule [Mobile User]	30 Min Fast & CCCV Slow	ALT Pouch Cells	2100	1300

Table 2: The Table of different Experiments.

As shown in the Table 2, five different experiments were designed to evaluate the performance of the charging protocol in different patterns of charging and discharging of LIBs.

01 Comparison Test: Two tests were designed to cross-compare the aging performances of a 30 minutes NLV Charging and a similar charging combination with the standard CCCV method. In both the tests, the LIR13450 cells with 650 mAh nominal capacity was used. This CCCV test was designed to use a CC current of 2.6 C-rate with a CV threshold increased up to 4.45V during the charging steps. Then, both the cells were discharged with a 1C based constant current discharge until the voltage drops down to 2.6V. Accordingly, these charging and discharging steps were cycled and monitored the aging performances to decide which method performs better.

02 Aging Test, 03 Aging Test & 04 Aging Test: These three tests were designed to check the aging performance of the ACP based NLV charging when configured for different charging durations on different LIB cells. The "**02 Aging Test"** was created to charge a pouch cell of a 2100 mAh capacity, within 30 minutes using this method followed by a 1C discharge. The "**03Aging Test"** was designed to charge in 45 minutes while the "**04 Aging Test**" was targeted for 1 hour. In addition, the "**04 Aging Test**" was designed with two ICR14430J cells (each 600 mAh) connected together in parallel mode. The main objective of this parallel connection was to check the applicability of the charging method on battery packs with cells connected in parallel.

05 Daily Charge Schedule [Mobile User]: This is a specially designed test to model the average smartphone users' daily charging behavior. It has assumed that the user wants to fast charge the phone during the daytime but prefers the slow charge overnight. Therefore, 3 consecutive fast charge cycles of ACP based NLV followed by a 1 standard CCCV Charge [slow] were designed. After each of these charge cycles, a 1C Discharge was introduced. Then, this charge-discharge pattern was iterated until its discharge capacity drops below 80% of the nominal capacity of the selected cell. The ALT pouch cell with 2100 mAh capacity was used for the test.

ACP based NLV Fast Charging Method

The ACP based NLV method [20] consists of applying a charging protocol in a "loop" scheme [figure 5] in which the factors such as current, voltage, state-of-charge (SOC) and state-of-health (SOH) of a battery interactively contribute to the charging pattern at every step and finally to the resulting charging time. These factors contributes both directly and indirectly to varying, non-linearly controlled, set-voltage steps to charge the battery. The duration of these steps kept very short and dynamic throughout the entire charging process to self-adjust its steps based on the changes of the aforementioned factors at a finer granularity. As such, the voltage increment at each charge step will depends on the SOC, SOH and the drawn current of the battery during its previous step.

This can also be considered as an adaptation technique where the charging process get adjusted based on the real-time changes in the current response of the battery, and indirectly allowing it to cope with the very dynamic internal status in the battery cell. The non-linear voltage (NLV) regulating intelligence of this method based on a relationship between the "rate of the change in current d [I] /dt" and the "rate of the change in voltage (d [V] /dt)" as described in the patent [19].

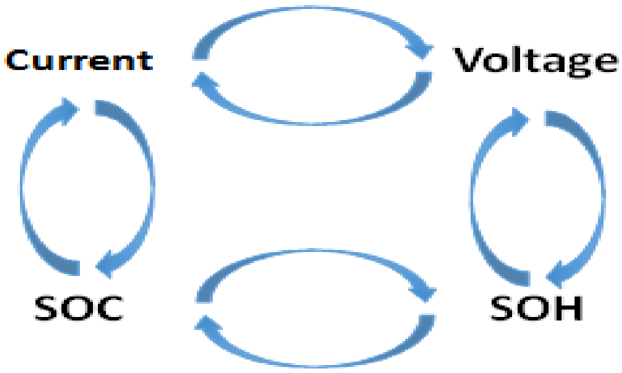

Figure 5: The abstract view of the adaptation relationships in the ACP based NLV charging method.

This relationship can be expressed as below:

$$(K_n) = d[V]/dt * (|d[I]/dt|)^{\alpha}$$

Kn	**:** is a constant within the charging process (n >= 0).
d [V] / dt (volts/ secs)	**:** the rate of the change of Voltage (V) during the charging process. [($V_{step\text{-}end}$- $V_{step\text{-}start}$)/ Step-Time Duration]
d [I] / dt (mA/ secs)	**:** the rate of the change of Current (I) during the charging process. It can be +/- within the process. Therefore, the absolute value is taken.
($\|$d[I]/dt$\|$)$^{\alpha}$	**:** the absolute value of the "d [I] /dt" (α >= 1 , is a non-negative continuous value). We assume as $\alpha = 1$, for all the experiments in this work.

Even though the patent [19] claimed that the **Kn** is a constant, the ACP based NLV charging method uses it differently allowing it to change based on certain regions of the charging process depending on how good or bad the battery cell is willing to charge at that voltage region. This will indirectly allow the intrinsic environmental changes in the battery to impact on its subsequent charging pattern. As the voltage is non-linearly incremented, this charging method will never controls/ impose any current to charge the battery, instead it enables the battery cell to charge with whatever the current favorable to the battery at that very moment (at the particular short voltage step). In case, if the drawn current is considerably higher than the expected-current-rate (the required current-rate to charge, if just a CC is used, within the expected duration), an extra time will be given to charge at that charge step. In addition, it also does not use any predetermined end-voltage. The end-voltage is adjusted based on the gained capacity and the current response during the charging process. However, a safety voltage limit (4.85 V for most of the tests) is used to protect the battery. Therefore, this method indirectly models a natural charging on the battery cell. It has tested through a number of different experiments as mentioned above and evaluated the performances and compatibility of the method on a number of real battery charging situations/modes. Following section will discuss those test results.

III. Results

Figure 6, shows a sample charging profile of the ACP based NLV charging. In this test, a LIR13450 battery cell with 650 mAh capacity has fully charged in just 22 minutes.

Here, the voltage has non-linearly incremented resulting in a dynamic and voluntary variation of the current used to charge the battery. Most interestingly, each charge step has kept very short and has given relaxation (zero current) periods in between. The duration of this relaxation period also changing based on the adaptation intelligence in this method. Further, the capacity gaining seems very slow at the beginning and manages to continue almost linear within the actively charging regions. However, this can be seen as a stair-case in a zoom-in level as there is no capacity gain during the relaxation steps.

The corresponding discharging profile of this fully charged cell is shown in the Figure 7. It can be seen that almost 100% discharge capacity of its nominal capacity is produced even at a rate of 1C constant current discharge. Therefore, the charging efficiency during this test is almost 100%.

In order to compare the charging performances of this method with a similar charging method, based on standard CCCV method, the "01 Comparison Test" was designed. Here, four cells of LIR13450 were used with two cells performing each tests. Then the experiment was cycled and analyzed the aging performances. As shown in Figure 8, the CCCV based fast charging method failed to gain more than 50% of its nominal capacity just after 18 cycles while the ACP based NLV method was able to maintain a discharge capacity well-above 80% of its nominal capacity all the while. Even after the 35 cycles, these ACP based cells were continued for many cycles until it was stopped.

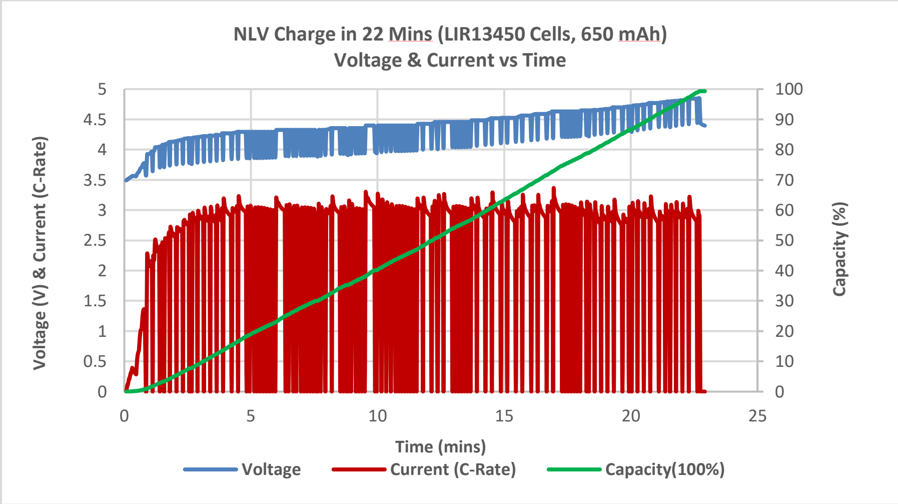

Figure 6: The Voltage, Current & Capacity vs Time profile of an ACP based NLV Charging of a LIR13450.

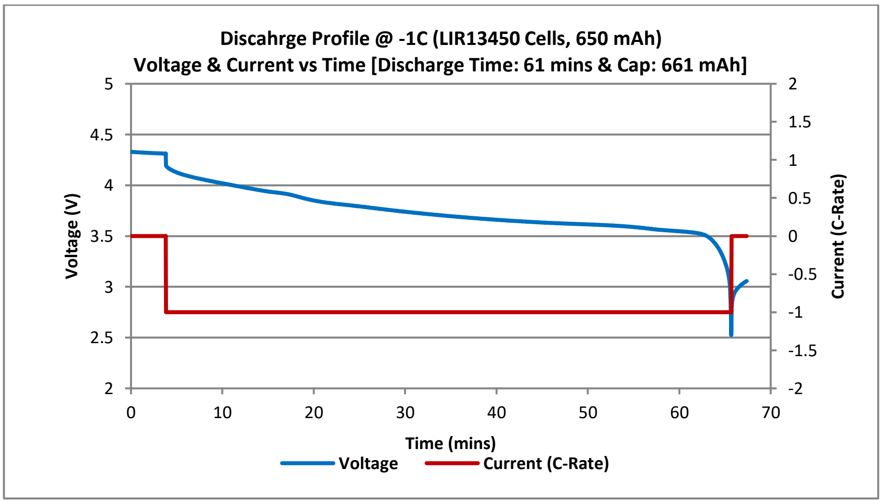

Figure 7: The Voltage & Current vs Time profile during 1C-based Discharge of the LIR13450 battery that was fully charged in 22 minutes using ACP based NLV.

In addition, from the two cells used to charge with CCCV, one was bloated [Figure 9] after about 23 cycles and the other was burned to ashes [Figure 10] during the 36th cycle. Accordingly, this comparison test results shows that the presented ACP based NLV fast charging method is performing a lot better than its reference CCCV. However, to further evaluate the stability and the applicability of this method, for different battery cells, the rest of the aging tests were performed.

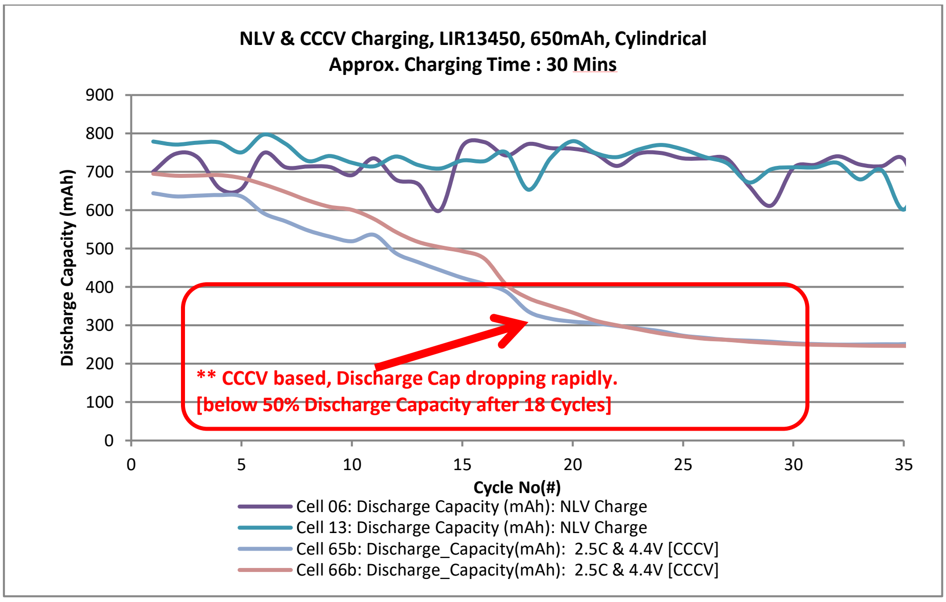

Figure 8: The aging results of four cells of LIR13450, fully charged using ACP based NLV and CCCV in just 30 minutes.

Figure 9:LIR13450 bloated cell after the cyclic test of CCCV charging in 30 minutes.

Figure 10:LIR13450 burned to ashes cell after the cyclic test of CCCV charging in 30 minutes.

Figure 11 shows the results of a NLV charging ("**02 Aging Test**") of a Pouch cell (2100 mAh) targeted to fully charge in just 30 minutes. Here, the discharge capacity after each NLV charge cycle has recorded and presented. When it was stopped after 153 cycles, the discharge capacity remained a lot more than the 80% of its nominal capacity. In addition, it can be seen that the discharge capacity is considerably consistent throughout the test with only a few deviations.

Afterwards, instead of trying to further reduce the charging time, the tests were targeted to check the performances of the charging solution on commercially available LIB cells. For this, two tests were designed to charge within 45 minutes (the LIR18650, is one of the famous type of battery in Lithium battery world) and 1 hr charging time using NLV Charging method. Here, the time duration was increased as many of the commercially available fast chargers take about 1.5 hours to fully charge a Li-ion battery. Therefore, these test results should also be easily comparable with some of those contemporary fast-charging solutions.

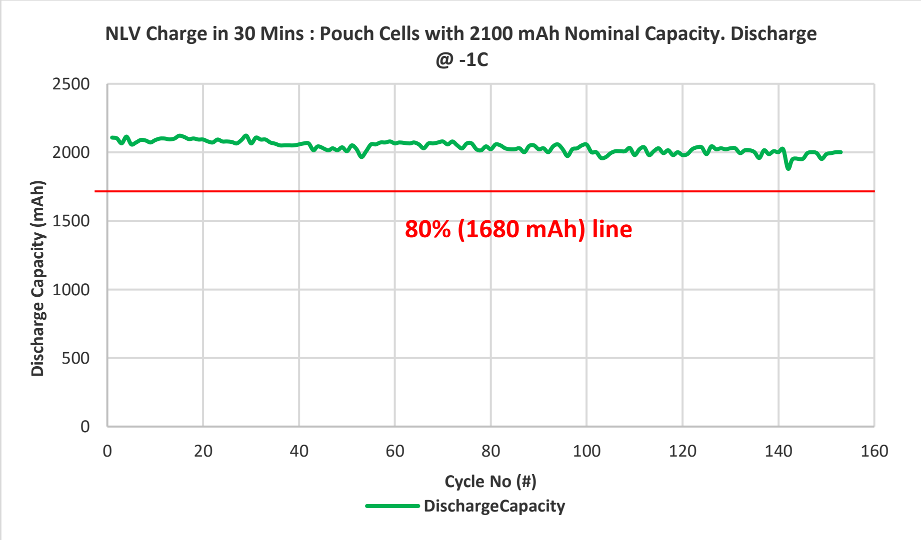

Figure 11: Aging test profile of the ACP based NLV Charge in 30 Mins : ATL Pouch Cells with 2100 mAh nominal capacity & Discharge @ -1C.

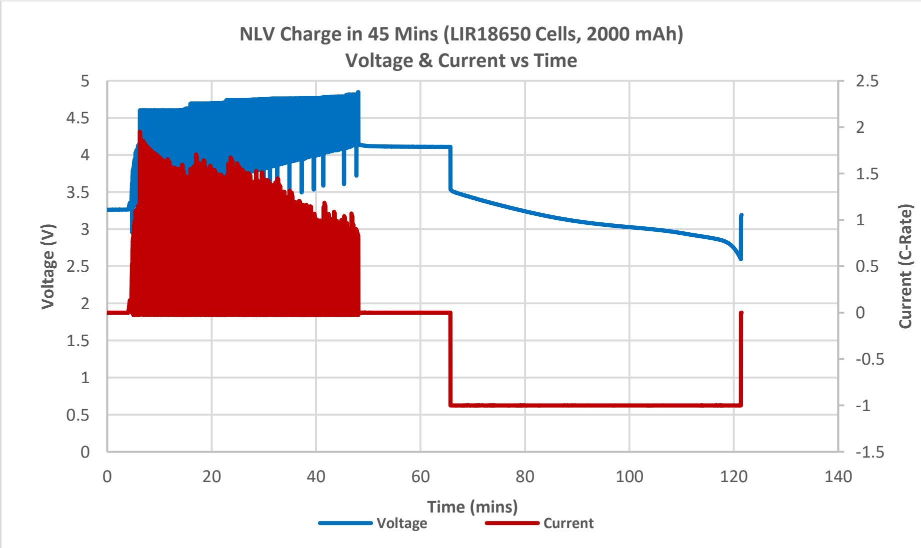

Figure 12: The Voltage &Current vs Time profile of the ACP based NLV Charging in 45 mins and CC Discharging: on a LIR18650.

Even the targeted charging time was 45 minutes; the charge-discharge profile in the figure 12 shows ("**03 Aging Test"**) that it has only taken 43 minutes to charge the battery. Analyzing its discharge profile, it is clear that the 1C discharge was able to constantly provide current for 56 minutes before reaching its lower voltage threshold of 2.6 V. Accordingly to this sample graph, the particular charge-discharge cycle has managed to give a charge efficiency of 93% (56/60 * 100). However, as shown in its aging analysis, figure 13, the discharge capacity has never dropped below the 80% of its nominal capacity.

Considering the battery charging configurations in parallel mode, in some of the battery packs or power banks, the next test ("**04 Aging Test**") was designed to charge a battery module with 2 parallel connected ICR14430J batteries (each with 600 mAh capacity). Therefore, this ICR14430J battery module holds a capacity of 1200 mAh. However, the battery module was just another single load for the ACP based NLV Charger system [Figure 14].

The sample charging-discharging profile seen on the parallel charging test in figure 15 shows a charging time of 63 minutes to fully charge the battery. Further, it has a discharging time of 58.61 minutes and thus holds a capacity of 1172.2 mAh securing a 97.7% charge efficiency. Subsequently, its aging analysis in the figure 16 shows that this test managed to maintain a very good discharge capacity percentage above 80% of its nominal capacity all along the aging process.

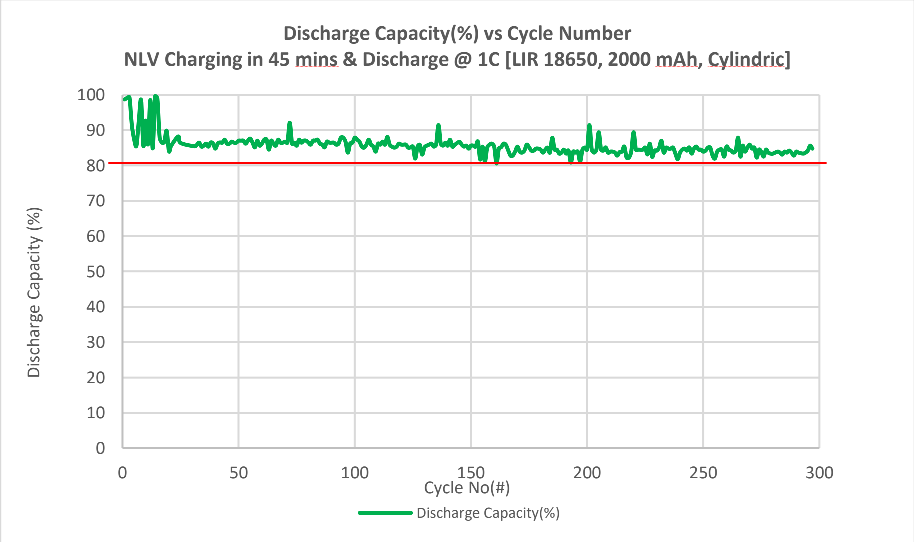

Figure 13: Aging test profile of the ACP based NLV Charge in 45 Mins & Discharge @ -1C: LIR18650 Cells with 2000 mAh capacity.

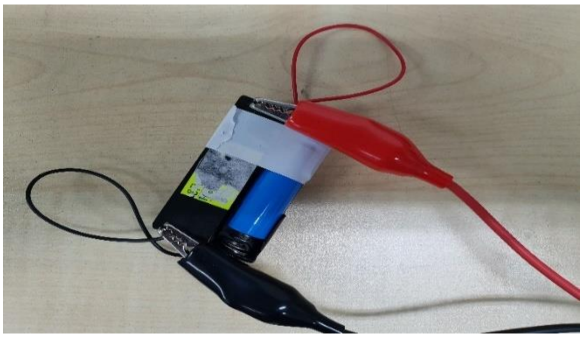

Figure 14: Two parallel-connected ICR14430J batteries attached to the charging clips.

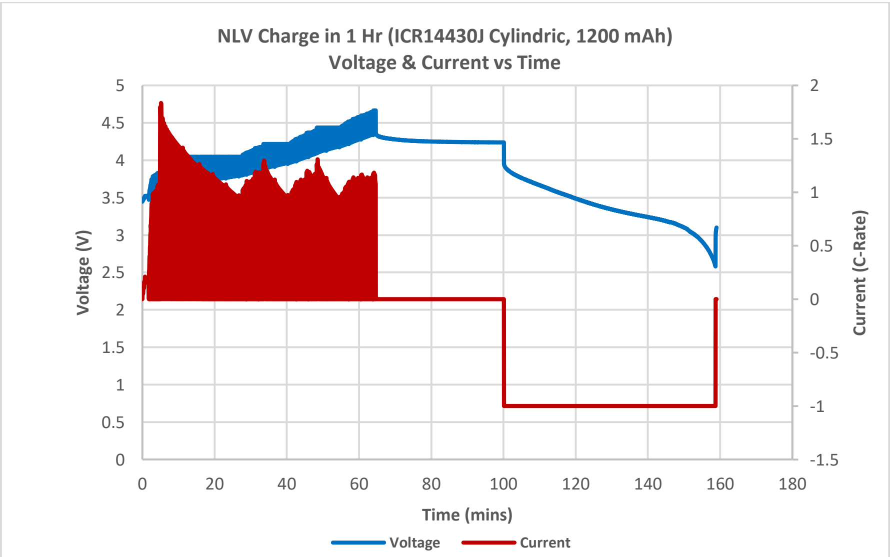

Figure 15: The Voltage & Current vs Time profile of the ACP based NLV Charging in 1 Hr & Discharge @ -1C: on a ICR14430J.

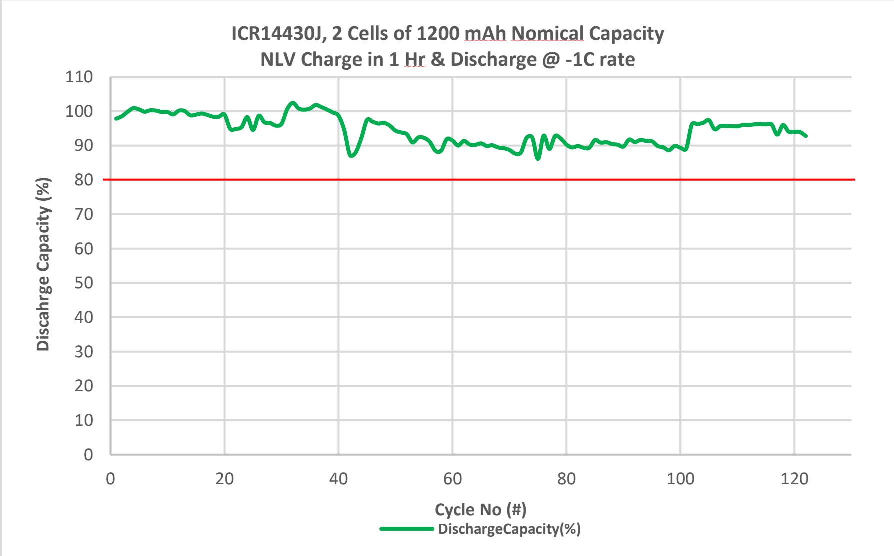

Figure 16: Aging test profile of the ACP based NLV Charge in 1 Hr & Discharge @ -1C: ICR14430J Cells with 1200 mAh capacity.

After considering a normal smartphone users daily routing, it is likely that the phone may charge frequently during the day time than a longer charging at night where slow charging is possible. Therefore, a separate test was designed as “3 NLV + 1 CCCV charge schedule” to model this daily charge routine. Here, the 3 NLV means to fully charge the battery using ACP based NLV Charging method and the 1 CCCV meant for a standard CCCV based slow charging with C/4-rate CC stage and 4.2V CV stage constant voltage charging. Also, during each NLV charge process, the battery was set to charge only upto 95% of its nominal capacity. This is also due to the fact the most of the mobile rarely charges a battery until its 100% capability [86]. As usual in all other test in this work, a 1C constant current discharge is used to discharge the charge battery. Further, a rest time of 30 minutes was assigned in between every charge-discharge and discharge-charge processes.

Figure 17 (“**05 Daily Charge Schedule [Mobile User]**) clearly shows that after 3 cycles of ACP based NLV fast charging, a slow charging with standard CCCV has applied. The discharge capacity was recorded at each cycle and continued cycling this charging-discharging pattern expecting the battery to drop its discharge capacity below 80% of its nominal capacity. More interestingly, the aging results in Figure 18 shows that this test managed to continue more than 1000 cycles without degrading the discharge capacity below the minimum expected.

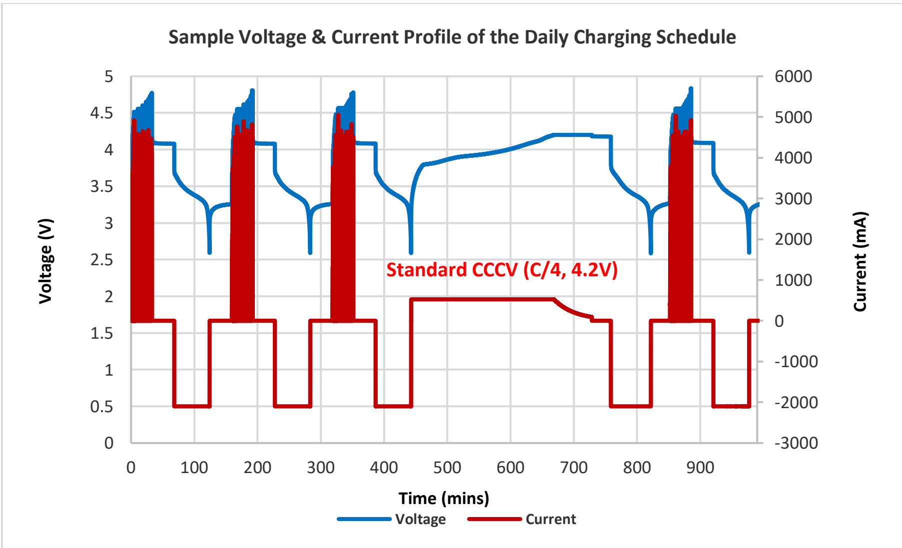

Figure 17: The Voltage &Current vs Time profile of the “Daily Charge Schedule [Mobile User]”Charging in 30Mins ACP based NLV and & Discharge @ -1C CC: on a ALT Pouch Cell [2100 mAh].

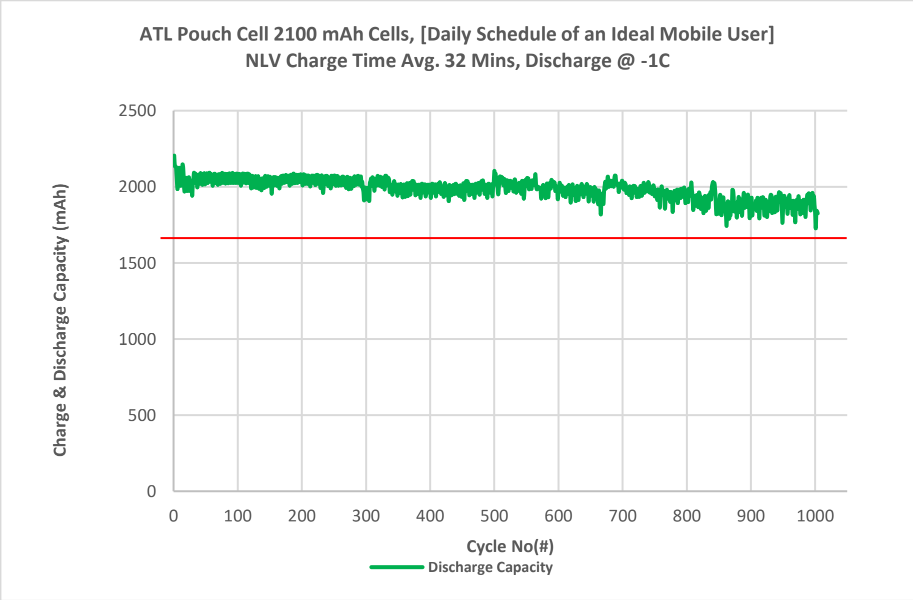

Figure 18: Aging test profile of the "Daily Charge Schedule [Mobile User]" Charging in 30 Mins ACP based NLV & CCCV, & Discharge @ -1C CC: on a ALT Pouch Cell [2100 mAh].

Considering all these test results, it is very clear that the ACP based NLV Charging method for fast charging is a very effective fast charging method. Further, the above experiments on different LIBs has verified that this method is not dependent on a particular battery type or chemistry and rather applicable to many LIBs. It can also be used with different expected charge time durations that may allow some flexibility in designing fast chargers focused on different requirements.

IV. Discussion

In a nutshell, the ACP based NLV Charging method for fast charging LIBs shows very significant charging performances on different types of LIBs. While it holds a competitive faster charging time of around 30 minutes, no considerable degradations in the cycle life is observed. From the experiments with commercial LIBs, it shows a clear competitive advantage in reducing the charging time below 1 hour that is not practically available in today's fast chargers in the market.

Furthermore, there are two major distinctive features in this charging method. One is the lower footprints of the temperature variations and the reduction of the temperature during charging. The second is the unique charging profiles for each different charge cycle even for the same battery. Following sections will discuss these features briefly.

Temperature Decreases while Charging

The kinetics of the internal battery-particles and their reactive processes, such as lithiation/ de-lithiation (intercalation/ de-intercalation), shooting/floating the ions/electrons through the solvents & separators and transporting the charged particles (both mass transfer and charge transfer driven resistances) against the internal impedance (IR) affects the final outcome of the charging process. This internal impedance causes the joule effect and heat up the entire system resulting an exothermic reaction. However, the chemical reaction that takes place during the charging of a lithium ion battery cell is endothermic and it absorbs the heat. However, the collective outcome of these two heat components mostly resulted in an exothermic reaction. Therefore, the battery seems to heat-up during the charging process. In most of the fast charging solutions with high current rates, this joule effect seems to be increased and resulted in more heat causing adverse effects, and sometimes even causing explosions.

However, the ACP based NLV fast charging method shows a significant temperature decrement in some cases, while finally resulted in only a small temperature increment in most cases. This can be realized with what could happen inside the battery cell within the iconic relaxation steps introduced in this method. Within these relaxation steps, there is no chance of propagating a joule effect anymore (zero current), but the automatic stabilization with the intercalation and diffusion in the anode can result in an endothermic outcome. Therefore, the total outcome of the temperature can get endothermic. This is a very important feature for a fast charging.

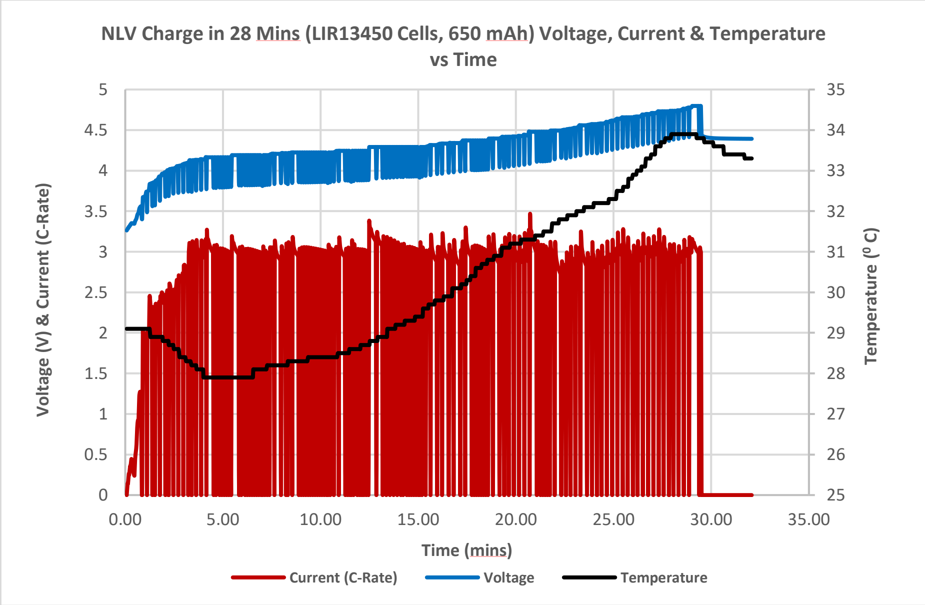

Figure 19: The Voltage, Current and Temperature vs Time profile of the ACP based NLV Charging in 28 mins: on a LIR13450.

Figure 19 shows a clear drop in the temperature followed by a considerably low increment in the end. This cell is a LIR13450 with 650 mAh nominal capacity and expected to have a cathode of **LCO : $LiCoO_2$.** In figure 20, it can be seen that the overall temperature increment is very small and thus it can expect that the relaxation has played a key role during the charging process. An ATL Pouch cell with 2100 mAh capacity is used in this test, and expected to have a cathode of **NMC: $LiNiMnCoO_2$**. Accordingly, it is also clear that the internal battery chemistry and the kinetics together plays a key role in the variation of the temperature.

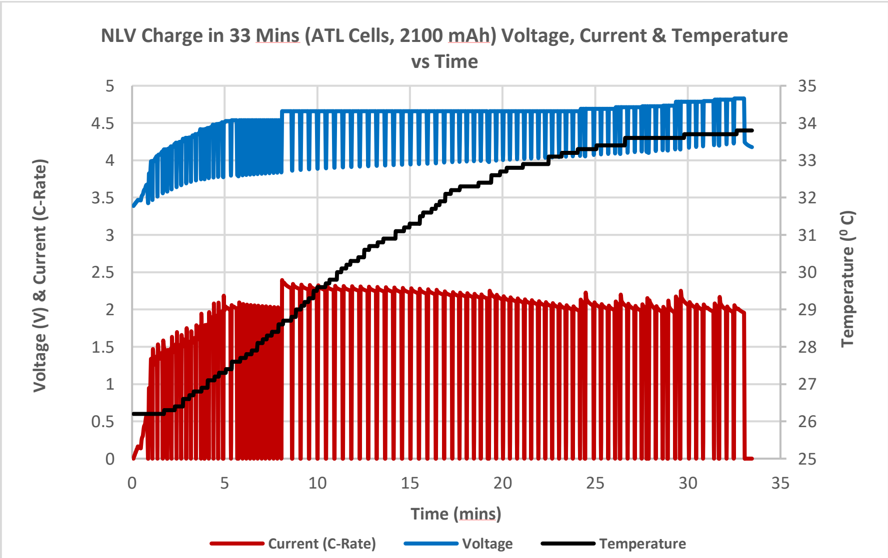

Figure 20: The Voltage, Current & Temperature vs Time profile of the ACP based NLV Charging in 33 mins on a ATL Pouch Cell [2100 mAh nominal capacity].

Unique charging Profiles

The internal operations of a battery during the charging process depends on a number of engineering disciplines, and it is rapidly changing almost all the time. During this process, the ions and electrons transport within their designated trajectories resulted by the cumulative impacts of different factors such as, both the mass and charge transfer potentials and resistances, the ionic concentration near the SEI surfaces, the diffusions and absorption coefficients of active materials in electrode surfaces, and the ionic concentration in the electrolyte solvents. Therefore, the exact amount of restorable Li-ions at a particular time depends on the very specific internal status (state of health - SOH) of the battery at that time. Hence, if the battery is enabled with natural charging, it can expect the charging current profile will be changed in every cycle.

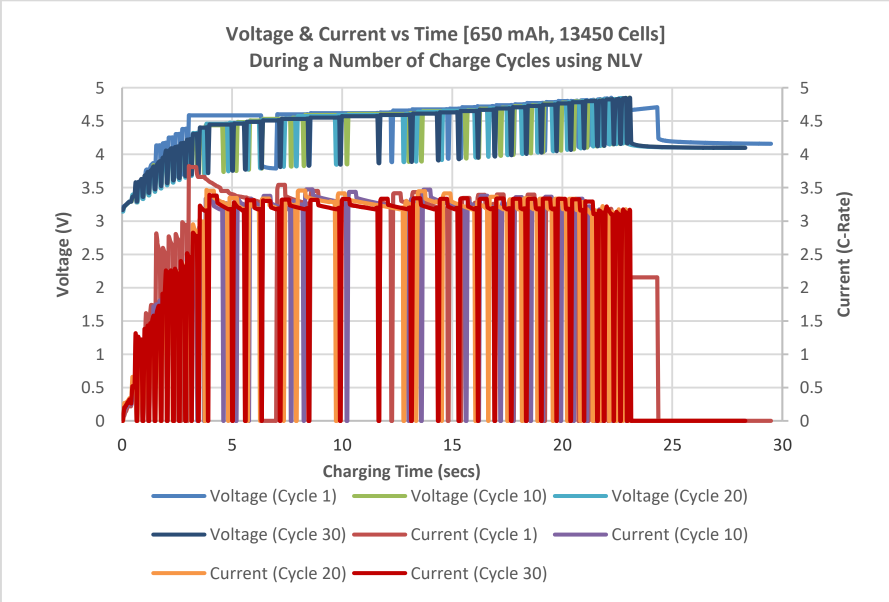

Figure 21: The Voltage & Current vs Time profile of the ACP based NLV Charging in 30 minutes on a LIR 13450 cell.

As the battery tends charge with its naturally chargeable current with the ACP based NLV charging, it resulted in unique charging profiles even in an iterative charging of the same cell. Figure 21, shows a set of charging-profile comparisons of a single cell of LIR13450 [from the same experiments above, "**01 Comparison Test"**] on different charging cycles of 01, 10, 20 & 30. From this, it is clear that the charging profile is unique. It is another distinctive feature in this NLV method and shows that there is no enforcement on voltage or current during the charging process.

Use of High Voltage

One another different feature of this charging method is the use of the high voltages. Normally, it is widely accepted that the use of high voltages for charging is adversely impact on the battery performances. This is mostly due to the accelerated oxidation at the cathode at high potentials.

However, the use of high voltage region in the NLV method is different from that of continuous use in some of the CV based fast charging solutions. As such, this method uses high voltage only for a very short period in which it can expect that the possibility of aggregating adverse effects would be minimized. To a certain extent, this can be assured by the experiment that continued more than 1000 cycles without any safety issues while using the high voltage of up to 4.85V.

Controlling the Charging Time

It is observed that the charging time of this method is ranging around the expected charging time (+/- 5 minutes) and not exact in many cases. This also shows the natural charging tendency of the method. In terms of consistency aspects, this can be considered as a weakness. Anyhow, it is also understood that this may be able to control only to minimize the deviation but not to confirm on any exact time duration.

V. Conclusion

This research work shows a comprehensive analysis of the use of ACP based NLV charging method for fast charging LIBs. The results presented in the paper on different types of LIB cells targeting different charging times show the compatibility of the charging method with different batteries. In addition, modeling the charge-discharge behavior of a smartphone users' daily charging routine is an important reference point to consider this method for the mobile phone chargers.

Further, a brief analysis of the temperature profiles during the charging of different batteries were discussed. Here, it is also identified that the decrement in temperature is something very special in this charging method. In addition, the unique charging profiles encourages natural charging at every charging attempt and avoid stress on the battery. In an overall, the results show that the charging performance of this method is very positive.

References

[1]. Field test of charging management system for electric vehicle, State of the art charging management using ISO 61851 with EV from different OEMs. Michael Dronia, Marc Gallet, Research Center for Energy Economics e.V. Am Blütenanger 71, 80995 Munich, Germany. https://www.ffe.de/attachments/article/607/2016_CoFAT_MDronia_Field_test_of_charging_management_system.pdf

[2]. Smart charger for Dual Li-Ion Button Cells 3.6V LIR 2032. http://www.batteryspace.com/smartchargerforduallli-ionbuttoncells36vlir2032.aspx

[3]. Zhao, Yanfei & Lu, Bo & Song, Yicheng & Zhang, Junqian. (2018). A modified pulse charging method for Li-ion batteries by considering stress evolution, charging time and capacity utilization. Frontiers of Structural and Civil Engineering. 10.1007/s11709-018-0460-z.

[4]. Rapid Charging of Li-ion Batteries Using Pulsed Currents: A Theoretical Analysis, B. K. Purushothaman* and U. Landauz, http://jes.ecsdl.org/content/153/3/A533.abstract

[5]. Cheng, Y.-S & Young, C.-M & Liu, Y.-H & Chen, G.-J & Yang, Z.-Z. (2015). Design and implementation of Li-ion battery charger using state-of-charge estimation with fuzzy temperature control. Proceedings of the IEEE International Conference on Industrial Technology. 2015. 2075-2079. 10.1109/ICIT.2015.7125402.

[6]. A Review on Li-Ion Battery Charger Techniques and Optimize Battery Charger Performance by Fuzzy Logic, Houshyar Asadi, S.Hr.Aghay Kaboli , Maysam oladazimi and M.J.Safari. 2011 International Conference on Information and Intelligent Computing, IPCSIT vol.18 (2011) © (2011) IACSIT Press, Singapore. http://www.ipcsit.com/vol18/14-ICIIC%202011-C045.pdf

[7]. Optimal Charging of Batteries via a Single Particle Model with Electrolyte and Thermal Dynamics. H.E. Perez, X. Hu, and S.J. Moura. 2016 American Control Conference (ACC).

[8]. Efficient fast-charging strategies for Li-ion batteries, D. Anseán, V.M. García, M. González, J.C. Viera, J.C. Antón, C. Blanco, EVS28 KINTEX, Korea, May 3-6, 2015.

[9]. Fast charging technique for high power lithium iron phosphate batteries: A cycle life analysis. D. Anseán,*, M. González, J.C. Viera, V.M. Garcí, C. Blanco, M. Valledor. Journal of Power Sources 239 (2013) 9e15.

[10]. iCharge: User-Interactive Charging of Mobile Devices, Liang He, Yu-Chih Tung, Kang G. Shin, MobiSys 2017, https://www.semanticscholar.org/paper/iCharge%3A-User-Interactive-Charging-of-Mobile-He-Tung/115a2c6ba5e481fab47f8a9baf7629621cacde1d.

[11]. Polarization based charging time and temperature rise optimization for Li-ion batteries, Caiping Zhang, Jiuchun Jiang, Yang Gao, Weige Zhang, Qiujiang Liu, Xiaosong Hu, CUE2015-Applied Energy Symposium and Summit 2015: Low carbon cities and urban energy systems.

[12]. Charging optimization in Li-ion batteries based on temperature rise and charge time. Caiping Zhang, Jiuchun Jiang, Yang Gao, Weige Zhang, Qiujiang Liu, Xiaosong Hu. Applied Energy 194 (2017) 569–577.

[13]. I. Abou Hamad, M. A. Novotny, D. O. Wipf and P. A. Rikvold, Physical Chemistry Chemical Physics, 12, 2740 (2010).

[14]. Fast-charging of lithium iron phosphate battery with ohmic-drop compensation method. M.H. Noh, P.X. Thivel, C. Lefrou, Y. Bultel, Journal of Energy Storage 8 (2016) 160–167.

[15]. State of Charge (SOC) Governed Fast Charging Method for Lithium Based Batteries (Patent Pending). Fahmida Naznin, TVS Motor Company Ltd. Post Box No. 4, Harita, Hosur, TN-635109, India.

[16]. SourceMeter ® SMU Instrument, 1000 Watts, 10 Amps Pulse, 7 Amps DC. https://www.tek.com/sites/ default/files/media/media/ resources/ 2461-DataSheet.pdf

[17]. The Agilent Advanced Power System, N6900 and N7900 Series Power Supplies Data Sheet, Agilent Technologies. https://datasheet.octopart.com/ N7951A-Agilent-datasheet-17852704.pdf

[18]. Four Channel Handheld Data Logger Thermometer, OMEGA Engineering inc. https://sea.omega.com/sg/pptst/HH520.html

[19]. SMART BATTERY CHARGING SYSTEM, Rachid YAZAMI, Los Angeles, CA. United States, Patent Application Publication, Pub. N0.: US 2012/0043929 A1.

[20]. "Patent Application No: 10201710151Y" under the title of "Adaptive Charging Protocol (ACP) for Fast Charging of Batteries" in Singapore.