

An Adaptive Pulse Charging Algorithm for Lithium Batteries

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Abstract—In this paper, a pulse charge system for lithium based batteries, which adaptively picks the correct charging pulse, is proposed to improve the charging performance in terms of speed and charge efficiency. An experimental setup is designed, implemented and tested on Lithium ion (Li-ion) and Lithium ion Polymer (Li-Po) batteries separately. Both batteries reached up to 3.9 V within 40 minutes and both batteries were able to charged approximately 17 % faster than the conventional Constant Current-Constant Voltage (CC-CV) charger. The proposed system gave 6 % and 5 % of leading charge efficiencies than CC-CV strategy, for Li-ion and Li-Po batteries respectively. Li-Po battery gave slightly leading charging performance by 3 % in terms of charging speed and 2 % in terms of charge efficiency compared to Li-ion battery.

Keywords—Battery Charger; Li-ion battery; Li-Po battery; Pulse; Optimum frequency; Optimum duty;

I. INTRODUCTION

Recently, the increasing demand of home electronics, portable electronics, electric powered vehicles, power tools has heighten the prominence of using lithium batteries as a reliable power source, due to its invincible features such as high energy and power density, longer life time, low self-discharge and flexible geometry. On the other hand, lithium batteries play a key role in electrical power industry in varies ways, some of which are improving power quality of energy harvested from renewable sources and storing electrical energy in micro grid power management systems [1].

The anode electrode and cathode electrode of a lithium cell is made of carbonaceous material and lithium based metal oxide respectively. A semipermeable separator is placed in between electrodes, which allows only lithium ions to pass through. Two electrodes and the separator is soaked in lithium salt based electrolyte [2]. Commonly, cathode in Li-ion battery is a thin film of lithium based crystal, formed with multi-metal oxide of cobalt, nickel and manganese pasted on aluminum current collector foil. Lithium ion (Li-ion) and lithium ion polymer (Li-Po, LIP, Li-Poly) are the most commonly used lithium based battery types in telecommunication devices, smart electronics and Electrical Energy Storage Systems (EESS). The lithium-polymer differs from traditional Li-ion cell by the type of electrolyte used. The main difference between traditional Li-ion battery and Li-Po technology lies in the separator material placed in between electrodes.

Simply, a substance made of microporous polymer, covered in an electrolytic gel acts as both separator and electrolytic medium. The separating polymer can also act as a catalyst to improve the chemical reaction between anode and cathode [3][4]. Due to the catalytic property of polymer electrolyte, Li-Po has slightly higher energy density than standard Li-ion. Furthermore, the flexibility nature of polymer plastic allows to manufacture thin or oddly shaped flexible batteries. However, Li-Po batteries are identical to Li-ion in some ways as they are built with same electrode materials.

II. BACKGROUND

Conventionally, constant current-constant voltage (CC-CV) charging is the most widely spread method in Li-ion battery chargers [5][6]. From the early age of discovery of Li-ion battery, researchers have done comprehensive studies on charging strategies such as Constant Tickle Current (CTC) strategy Constant Current Strategy (CC) prior to modern CC-CV strategy and those strategies were incorporated inadequate charging performances [7]. Multi-Stage Constant Current Voltage (MCC-CV) can be found as another widely spread fast charge method [8][9][10].

Pulse charging of Li-ion battery is proven empirically and experimentally as a promising charging technology, which offers fast and efficient charge performance. Among other different flavors of charging techniques, pulse charging provides bunch of extra advantages such as longer battery life span, maximal battery material utilization, low heating, and low degradation of battery material [11]. Batteries charged with fast chargers, which uses high currents are deteriorated due to the dendritic deposition on electrode surfaces.

Among different practices, scrutinizing the corresponding electrochemical impedance equivalent circuit is a good way of understanding chemical behavioral of Li-ion cell. The resultant impedance of the battery Z_{bat} can be considered as a measure of momentous electrochemical condition. Z_{bat} is a function of the frequency of applied pulse. In order lower the battery impedance, the pulse frequency should be adjusted accordingly to the varying battery conditions [12][13].

Lithium ion production, at the cathode in charging mode, which is proportional to the current density (i_o) need to be regulated in order to obtain the maximum charging performance. According to the work done by Chen in [14] the charge

performance can be intensified by maximizing the charging factor (η) as shown in Eq.1. Since, η does not linearly related with duty, an optimal duty should exist, which offers both maximum charge speed and efficiency. Furthermore, Eq.1 has been modified to Eq.2 in [14] for ease of tracking the most suitable duty for a particular moment during charging process. Basically, duty is changed in order to control exchange current density. The best duty, which gives the maximum charging factor can be tracked by applying sequence of pulses with different duties for a small time at fixed frequency as shown in Eq.3. Moreover, the charging factor can further be improved by changing the frequency for fixed duty as shown in Eq.4.

$$\eta = D \cdot i_0 \quad (1)$$

$$\eta_{D_k} = \frac{i_{b,k}}{D_k} \quad (2)$$

$$D_{best} = \{D_k | MAX(\eta_{D_k}, k = 1, 2, 3, \dots K)\} \quad (3)$$

Where, η_{D_k} is pulse charge factor for Duty D_k $\{D_k = 50 + k, k = 5, 10, 15, \dots 45\}$ [14].

$$f_{best} = \{f_n | MAX(i_{b,n}, n = 1, 2, 3, \dots N)\} \quad (4)$$

Where, $f_1, f_2, f_3, \dots f_N$ are testing frequencies while duty is held at the optimal, obtained according to Eq.3, $i_{b,n}$ is the corresponding average current for f_n [12]. Number of pulse charging strategies have been proposed and most of the them are design to track the optimum pulse duty and frequency this study is a further algorithmic improvement of works done in [12][14][13].

III. PROPOSED ALGORITHM

The state diagram of proposed system shown in Fig.1 illustrates a full process of a charging cycle. The proposed system consists of central micro-controller (CM), adjustable pulse generator (APG), Voltage Sensor (VS), Current Sensor (CS), Analog-to Digital Converter (ADC), Electronic Switch and Li-ion/Li-Po batteries as shown in Fig.2. Full process is divided in to several states named as Full Charge Scan State (FCSS), Scan State (SS), and Charging State (CS). These states are executed consecutively for predefined time intervals where, T_{full} is Full Charge Scan Period, T_{sp} is Scan Period, T_{cp} is Charging Period as illustrated in Fig.1.

Prior to initiate the charging process the battery terminal voltage is measured in Full Charge Scan State (FCSS) to ensure that the open circuit voltage is below 4.2 V. If the battery voltage is 4.2 V, the charging process is terminated. In this state, The battery is isolated from the system for T_{full} when this state is in operation [15].

There are two algorithms to track the best frequency and duty based on maximum charging factor. Initially, duty is held at 50 %, and Li-ion/Li-Po battery is pulse charged with varying frequencies ($500 \text{ Hz} \leq f_n \leq 2 \text{ KHz}$). For each step, corresponding average battery current $i_{b,n}$ and voltage V_{avg} are measured (The amplitude of pulses is maintained at 4.2 V/cell). Subsequently, the charging factor is calculated for each frequency as previously explained. The optimal pulse

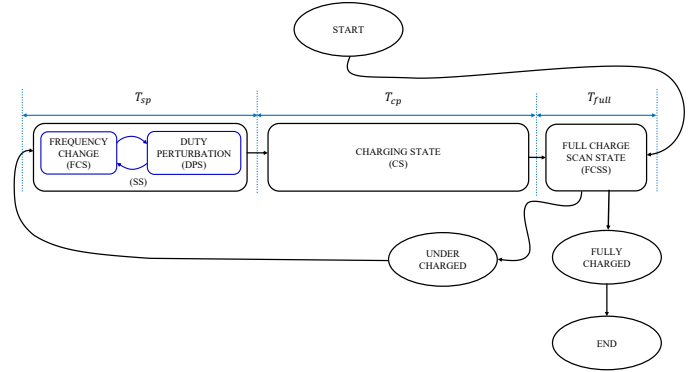


Fig. 1. State Diagram of proposed algorithm

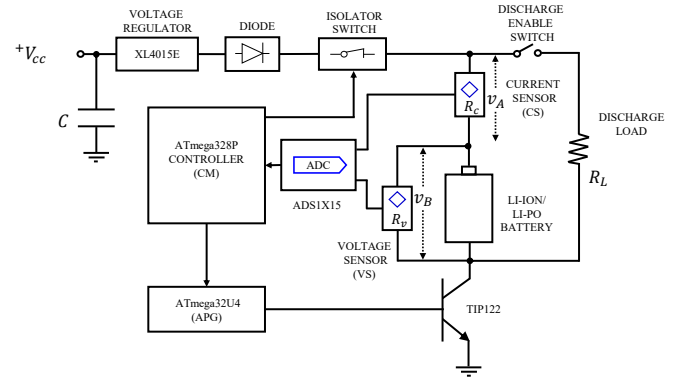


Fig. 2. Circuit design of experimental setup

frequency f_{best} gives maximum average battery current $i_{b,n}$ as well as charging factor. After determining the suitable frequency, Li-ion/Li-Po battery is pulse charged with varying the duties D_k by 5 % steps, i.e. ($50 \% \leq D_k \leq 95 \%$) at fixed frequency f_{best} . To avoid slow charging, lower duties (less than 50 %) were not tested. Then, similar procedure is carried out to find the best duty D_{best} as shown in Eq.3.

Above mentioned approach needs a considerable time to finish the scanning and calculation process. Therefore, second algorithm is proposed to minimize the calculation time in SS. Once the previous best duty is known, a perturbation and observation algorithm is used to track the best duty as shown in Fig.3. In this algorithm, the perturbation starts with the last known best duty and decrease duty by 5 % to check that charging factor is increasing. If so, the duty is further reduced by 5 % and this loop continues until the charging factor is not rising up any more. If lowering the duty does not making the charging factor better, duty is then increased by 5 % and observe whether charging factor is higher. This loop runs between 500 Hz to 2000 Hz with 500 Hz and selects the best frequency and best duty that provides the maximum pulse charging factor.

After obtaining the most suitable frequency and duty, the battery is pulse charged with f_{best} and D_{best} for time T_{cp} . Concurrently, the average battery voltage and currents are recorded in a PC to examine the charging response. After pulse charging for T_{cp} , the system come back to the FCSS and runs

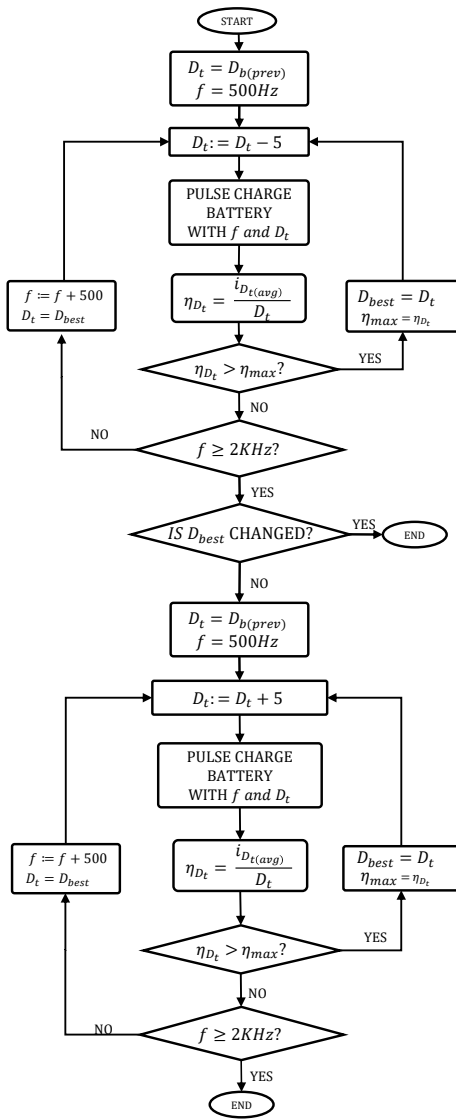


Fig. 3. The block diagram of proposed method

the states sequentially until the battery voltage is risen up to 4.2 V.

IV. EXPERIMENTAL RESULTS

To examine the experimental performance of the proposed method, a prototype charger as shown in Fig.2 was designed and implemented for 600mAh Li-ion and Li-Po battery. The main processing unit is ATmega328P micro-controller chip based on 16MHz clock speed. Pulse generator was realized using ATmega32U4 micro-controller separately, to reduce the cost of main micro-controller. The 12 bit A-to-D controller was run in differential mode in order to read the current and voltage signals at 3300 samples per second. I2C communication interface was used to transmit the pulse parameter to the pulse generating unit and to receive the converted values from A-D converter unit. A-to-D converter and pulse generator were purposely separated from the main controller for smooth individual control in experimental conditions, but they can be realized within one unit in commercial implementations.

The experiment is conducted in room temperature of 25 °C. Fully discharged (at 0.7 C) 600mAh Li-ion and Li-Po were tested. Two batteries were always kept in rest for 60 minutes before subjected to the experiment. Although both batteries were fresh, Li-ion battery is slightly used for few cycles. Open circuit battery voltage and instantaneous average current is always recorded in a PC.

T_{sp} depends on the current electro chemical condition of the battery. For an instance, refer the cycle of tracking optimal duty and frequency shown in Fig.4 between minutes of 31.1 and 31.5 performed on Li-ion battery. The previous optimal condition was maintained 55 % of pulse width at 1000Hz with $\eta = 2.2$. Firstly, the battery was pulse charged with decreased duty down to 50 % while, frequency being held at 500Hz and η was calculated as 2.13. Since, 2.13 is lower than the previous η , duty was then increased up to 60 %, while the frequency was maintained unchanged. The battery gave the maximum charging factor of 2.3 for this setting as illustrated by a rounded rectangular in the Fig.4. The frequency and the duty is stored in the micro-controller. The duty was further stepped up to 65 % at the same frequency, and η for this setting was 2.14, which is lower than 2.3. Thus, the frequency was shifted up to 1000Hz and duty perturbation was performed again assuming that the best duty is 60 %. Ultimately, the loop continues for all frequencies between 500Hz 2000Hz and no setting was able to give a charging factor larger than 2.3. Thus, the optimal duty and frequency was obtained as 500Hz, 60 %. In this particular case T_{sp} is about 12 s.

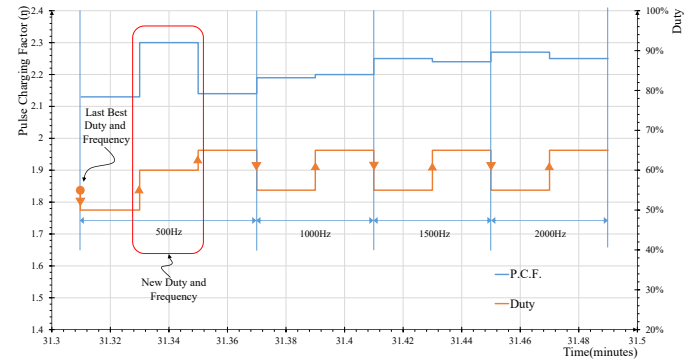


Fig. 4. An instance of scan state

According to the Fig.5 and Fig.6, it can be observed that the switching frequency and the duty are selected eventually to perform maximum possible charge injection so that less energy loss and less damage is taken place in the cell. Fig.7 and Fig.8 shows the current variation of the two batteries through the full cycle.

In the Experiment, The Li-ion battery was pulse charged approximately at 0.276C, and Li-Po was pulsed charged at 0.283 C. The open circuit voltage variation during charging shown in Fig.9 illustrates that Li-ion is fully charged approximately within 240 minutes while the Li-Po was fully charged in 232 minutes. However, both Li-ion batteries came 3.7 V and Li-Po came to 3.9 V within 40 minutes. At the beginning Li-Po showed higher charging speed and after the open voltage came near 3.9 V both batteries showed slower charging speeds. To compare the charge performance, standard CC-CV charger

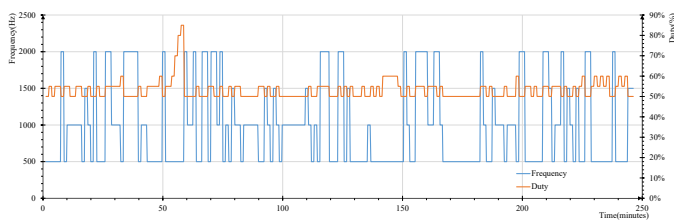


Fig. 5. Duty frequency selection of Li-ion battery

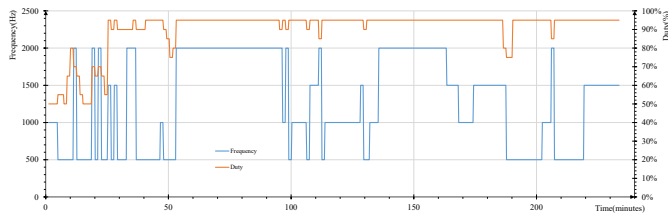


Fig. 6. Duty frequency selection of Li-Po battery

was set to ($\approx 0.3C$). CC-CV charger charged Li-ion battery within 290 minutes and Li-Po battery within 281 minutes. Roughly, the proposed system is 17 % faster than the CC-CV charger for both batteries. In addition to that, the proposed method charges Li-ion battery 4 % faster than the Adaptive Pulse Charge System (APCS) in [13], which completed the charging within 250 minutes, due to the improvements done in SS state. In put charge capacities with the proposed system for Li-ion and Li-Po are 678 mAh and 662 mAh respectively, while CC-CV is 722 mAh and 698 mAh. The proposed system has improved the charging efficiency by 6 % and 5 % higher than CC-CV strategy for Li-ion and Li-Po respectively.

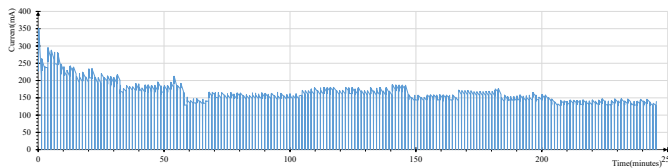


Fig. 7. Li-ion battery current

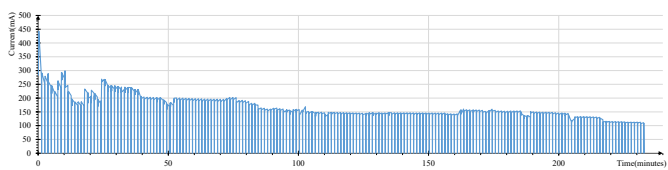


Fig. 8. Li-Po battery current

V. CONCLUSION

In this study, a pulse charging algorithm is proposed, implemented and tested on Li-ion and Li-Po batteries separately. Mainly, an adaptive approach is followed to pulse charge the battery with most preferable duty and frequency to ensure higher charging speed and improved charging efficiency compared with other charging techniques. Compared with Li-ion case, Li- case gave slightly leading charging performance

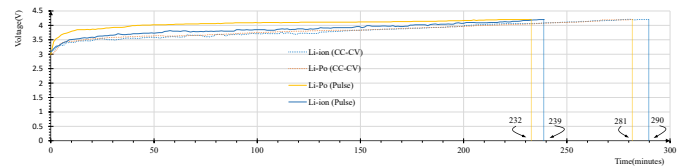


Fig. 9. Open circuit voltage for full charging cycle

in terms of charging speed and charge efficiency by 3 % and 2 %, respectively. However, Li-ion battery can be charged 17 % faster and 6 % efficiently compared to standard CC-CV.

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