



An Overview: Charging Algorithms of Lithium-Ion Batteries

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Abstract: *This paper presents the overview of charging algorithms for lithium-ion batteries, which include constant current-constant voltage (CC/CV), variants of the CC/CV, multistage constant current, pulse current and pulse voltage. The CC/CV charging algorithm is well developed and widely adopted in charging lithium-ion batteries. It is used as a benchmark to compare with other charging algorithms in terms of the charging time, the charging efficiency, the influences on battery life and other aspects, which can serve as a convenient reference for future work in developing a charger for lithium-ion battery.*

Keywords: Lithium-ion batteries; charging algorithms

I. INTRODUCTION

The rapid development in mobile phones, laptop and tablet devices in recent decades has developed an enormous demand for compact and lightweight batteries. The lithium-ion batteries offer one of the highest energy to weight/volume ratios among current battery systems and display characteristics of long life cycles, no memory and low self-discharge [1], [2]. Those positive characteristics have made lithium-ion batteries a major applicant. More recently, rising environmental and energy sustainability issues, along with the constant decrease in expenses and enhancement of security and reliability in batteries made electric car (EV) industries more sustainable and competitive for standard cars, thereby making EVs more feasible. In about among these applications, a battery system is constructed of the battery as well as battery management system (BMS). Battery charging is actually playing a crucial role within the BMS, in which that the charging algorithms, namely charging profiles as charging currents over time, have a strong influence on the battery efficiency as well as life cycles. As a result, numerous charging algorithms have been designed as well as implemented [3].

The algorithms vary in the charging time, the charging efficiency and the impact on the battery life cycles as well as implementation complexity, sensors required, cost and popularity. They range from the almost obviously simple charging algorithm, such as constant current-constant voltage (CC/CV), to being most creatively complicated one, such as multistage charging algorithm with an ant colony, which is not necessarily the most effective. In fact, so many charging algorithms been developed that it has become very difficult to determine which algorithm is most appropriate for a given application. However, the review of all the algorithms would be very beneficial to researchers and practicing engineers who are working on the areas of battery charging systems. We apologize if one or more important charging algorithms, or significant improvements of, have not been included. The rest of this paper is arranged as follows. Section II discusses and analyze various charging algorithms. Section III provides the summary of the major characteristics of each charging algorithm in terms of their implementation complexity, charging time, charging efficiency, cycle life and sensors required. The conclusion is drawn in Section VI.

II. CHARGING ALGORITHMS OF LITHIUM-ION BATTERIES

The lithium-ion batteries involve a reversible insertion (extraction) of lithium ions into/from two porous electrodes during the discharging (charging) process, where two electrodes are separated by a foil that prevents electrical contact, and both two electrodes and the separator foil are immersed in a liquid electrolyte containing charged species Li^+ ions [4]. Note that some lithium-ion batteries have a solid electrolyte, which serves both as ionic conducting medium and an

electrically insulating separator. These lithium-ion batteries are sometimes called lithium ion polymer batteries or lithium polymer batteries. However, no matter what electrolyte (liquid or solid) is used in the battery, the charged species that intercalates in the battery are the Li^+ ions, and hence they are generally named as lithium-ion batteries.

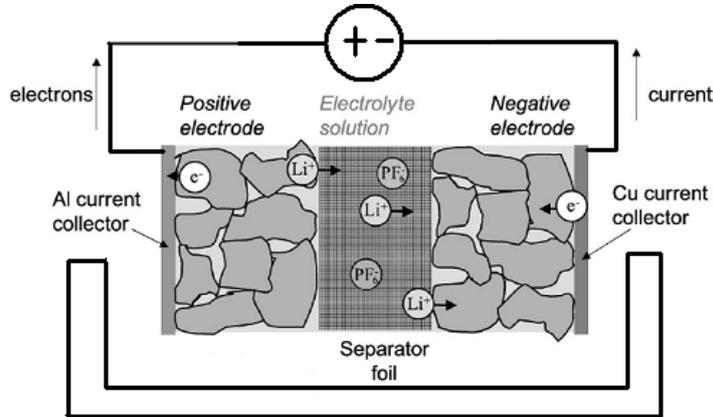


Fig. 1 Charging of lithium-ion batteries

The lithium insertion/extraction process occurring with a flow of ions through the electrolyte is accompanied by a reduction (oxidation) reaction of two electrodes assisted with a flow of electrons through the external circuit. Fig. 1 shows the schematic representation of lithium-ion batteries during charging, where Li^+ ions are extracted from the positive electrode and inserted into the negative electrode. The energy stored in the lithium-ion batteries through the charging process depends on the difference in energy states of the intercalated Li^+ ion in the positive and negative electrodes [5].

2.1 Constant Current-Constant Voltage

Among all charging algorithms, the constant current-constant voltage (CC/CV) charging algorithm is well developed and widely adopted in charge in lithium-ion batteries because of its simplicity and easy implementation. Under the arrangement of the CC/CV charging algorithm, a constant current is applied to charge the battery until the battery voltage rises to a pre-set maximum charging voltage ($V_{pre\ set}$), then the charging algorithm is very easy and cheap to implement as it does not necessarily require a microcontroller

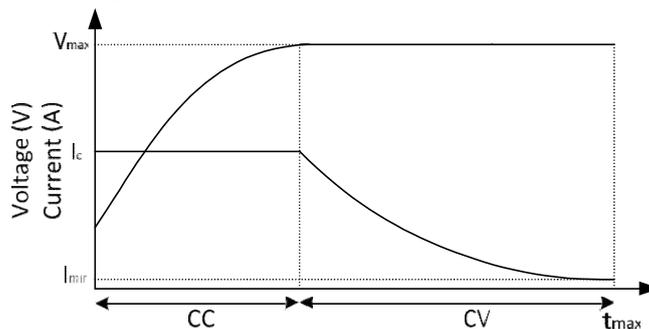
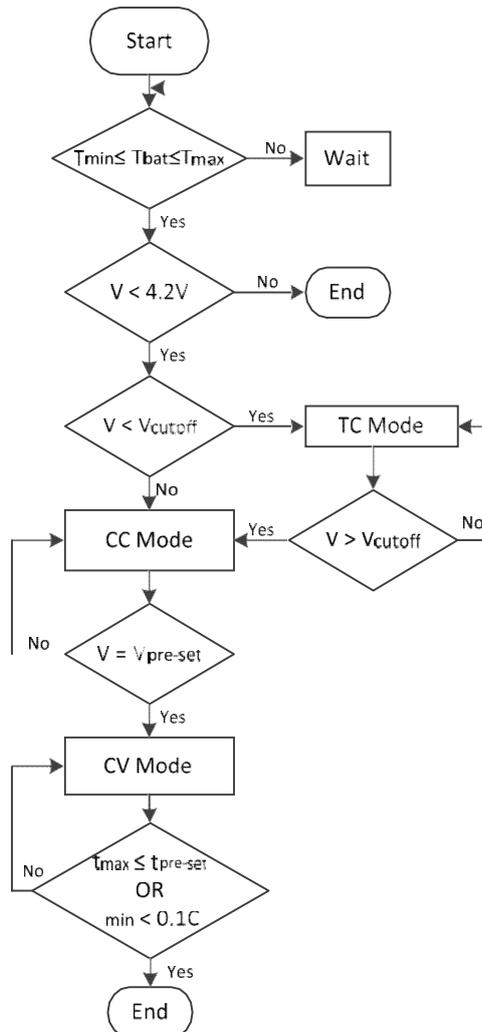


Fig. 2 Charging profile of CC/CV

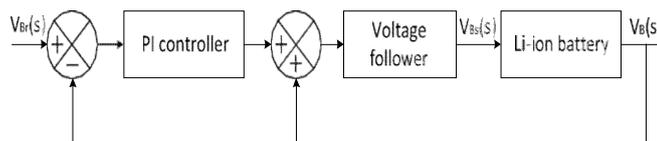
Charging voltage is held constant at $V_{pre\ set}$ and correspondingly the charging current is reduced exponentially. The charging process stops when the charging current reaches a pre-set small current. Fig. 2 shows the charging profile of the CC/CV [6]. When the CC/CV was used to develop a charger for a lithium-ion battery, a few protection measures have to be taken to protect the battery. Fig. 3 shows the flow chart of the charging process of a charger based on the CC/CV [7] including the safety and protection check. It shows that the charging process of the CC/CV consists of three steps. First, the battery initial conditions, such as temperature and open-circuit voltage (OCV), are checked if they are in the normal range. If the OCV is less than a pre-set cut off voltage (V_{cutoff}), the battery is charged by trickle charge (TC) mode with small current (e.g. 0.1C) until the battery voltage rises to the cutoff voltage, where 0.1C represents the charging current



with the C representing the nominal capacity of the battery. Second, once the battery voltage exceeds V_{cutoff} , the CC mode starts to charge the battery. The charging current is chosen by referring to the specification of the lithium-ion batteries, its range can be varied from 0.5C to 3.2C [8]. Third, when the battery voltage charges to V_{preset} (e.g. 4.2V), the charging process switches to the CV mode, the battery is charged at the constant voltage of 4.2V and the charging current is reduced correspondingly. The charging period is terminated by either the minimum charging current (I_{min} 0.1C) or the maximum charging time (t_{max} t_{preset}) is reached.



Based on the charging current in the CC mode, the total charging time is varied from 1 hour to 2.5 hours. In general, the lower the charging current of the CC mode is, the higher the charging efficiency and longer the charging time and the battery life. Three sensors are usually required to measure the battery voltage, current and surface temperatures. TheCC/CV



2.2 Variants of CC/CV charging algorithms

Many variants of the CC/CV charging algorithms were developed. There are two of them by slightly modifying the standard CC/CV charging algorithm. One is the double-loop control charger (DL-CC/CV) [9], as shown in Fig. 4. With positive and negative feedback of the battery voltage (V_B (s)), the DL-CC/CV can obtain the charging profile very similar to the standard CC/CV without sensing the charging current. As a result, the need for a current sensor is eliminated while still achieving the similar performance of the CC/CV with the simplest and lowest cost in hardware implementation. complexity and the requirement of high computation power, a microcontroller is more suitable for implementing both charging algorithms.

There is one more charging algorithm based on the principle of the phase-locked loop (PLL) control [13]. The PLL process naturally coincides with the requirement to f the charging profile of the CC/CV (PLL-CC/CV). Fig. 7 shows the block diagram of the PLL-CC/CV.

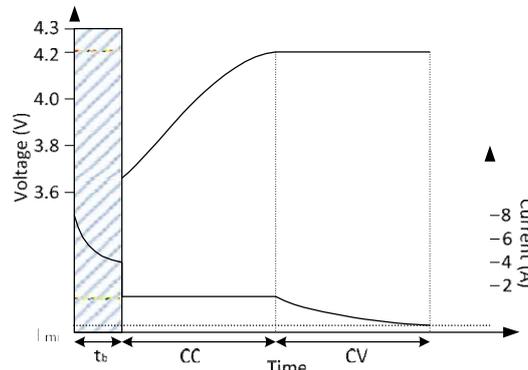


Fig. 4 Block diagram of the double-loop control charger

The other is the boost charger (BC-CC/CV) [10], where the battery is required to be fully discharged before charging. For the BC-CC/CV, the CV mode of the maximum charging voltage V^{max} (e.g. 4.3V which is 0.1V higher than 4.2V) is initially used to charge the battery in the boost charging period t_b (e.g. 5 min.) and the charged capacity can reach around 30% of its nominal capacity. It shows that a significant amount of charge has been stored in the battery within a relatively short period t_0 . If this period is extended to 10 minutes, about 60 % of its nominal capacity can be charged into the battery. After this period, the charging algorithm is the switched to the standard CC/CV. Fig. 5 shows the charging profile of the BC- CC/CV. Due to the initial higher charging voltage, the BC- CC/CV can charge the battery faster than the CC/CV, but it is required to fully discharge the battery before charging which requires the discharge circuit. This will increase the number of components and cost. The necessity of discharge before charging also makes this charging algorithm inefficient. The effect of initial higher charging voltage on the battery life has been investigated. It shows that there is no obvious degradation within 500 testing cycles.

There are other two algorithms which use the advanced control to implement the CC/CV. In these two charging algorithms, the fuzzy-logic control and the grey- predicated control were used to optimize the charging current in the CV mode of the CC/CV, which are named as the FL-CC/CV [11] and the GP-CC/CV [12], respectively. The essential part of these two charging algorithms is to use the open- circuit voltage to replace the voltage incharge as the change over voltage from the CC mode to the CV mode so that the charging current of the CV mode is larger at higher current part and smaller at the From Fig. 7, the output of the VCO oscillates a feedback phase P that reflects on the battery voltage V. P is then compare lower current part than the current in the CV mode of the standard CC/CV charging algorithm. As a result, more the input reference phase P_i to produce the phase error capacity is able to be charged into the battery within the same P_e . This phase error P_e is sent to the current pump to period of the CV mode.

Fig. 6 shows the schematic representation of the charging profiles for the both algorithms, where a fuzzy-controlled active state of charge controller for the FL- CC/CV and a grey-predicted technique for the GP- CC/CV have been used to dynamically determine the appropriate charging current with the OCV of 4.2V in the CV mode. Thus, the FL-CC/CV and the GP-CC/CV have a shorter charging time and a higher charging efficiency. Due to their produce a suitable

current to charge lithium-ion batteries. The battery can be fully charged after many cycles.

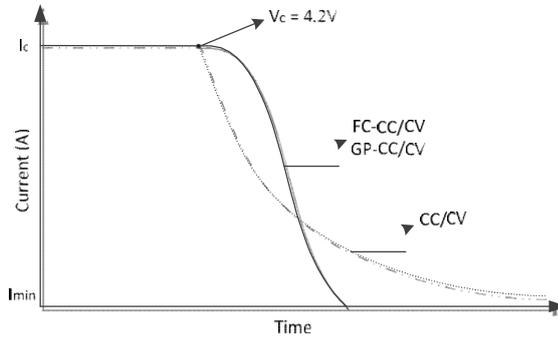


Fig. 5 Charging profile of BC-CC/CV

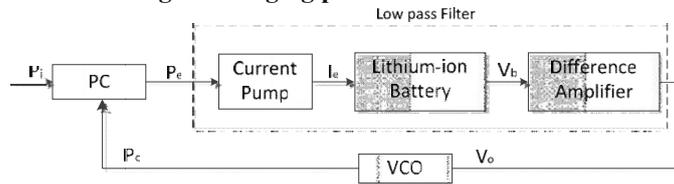


Fig. 6 Charging profile of FL-CC/CV and GP-CC/CV

Under this PLL-CC/CV arrangement, the auto-tracking process (the frequency-tracking) is corresponding to the bulk charge which is similar to the CC mode of the CC/CV. The auto-locking process (from the phase-tracking to the phase-locked state) is corresponding to the variable current charge and float charge which is similar to the CV mode of the another. This was solved by setting the maximum charging CC/CV. Fig. 8 shows the flow chart for the charging process of voltage V_{ma} (e.g. 4.2V) and whenever the battery voltage is the PLL-CC/CV. Later, an improved PLL-CC/CV [14] was proposed (IPLL-CC/CV). The complete charging process consists of the bulk current charge (CC mode) which remains the same as that of the PLL-CC/CV and the pulsed current charge and the pulsed float charge (CV mode) which were modified from the variable current charge and the float charge, respectively, as shown in Fig. 9. As the internal pressure charged by a pulsed current is smaller than that charged by constant current, the charging efficiency of the improved IPLL-CC/CV is higher than that of the CC/CV. The total charging time is similar to that of the CC/CV. Both the PLL- CC/CV and the IPLL- CC/CV can be easily implemented by using the IC chip with the PLL function. Charged to, the charging process will switch over to the max next stage.

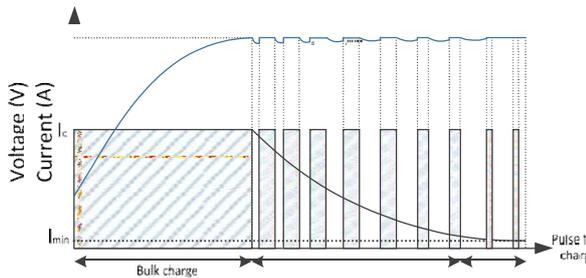


Fig. 7 Flow chart for charging process of PLL-CC/CV

2.3 Multistage current charging algorithm

Multistage current charging (MSCC) algorithm was developed to charge the battery, where various methods were proposed to determine the optimal charging currents in each charging stage of the battery. Fig. 10 illustrates the charging profiles of the MSCC with 5 charging stages. It is clear that there are two issues in the MSCC. The first issue is that at what time the charging process switches from one stage in to

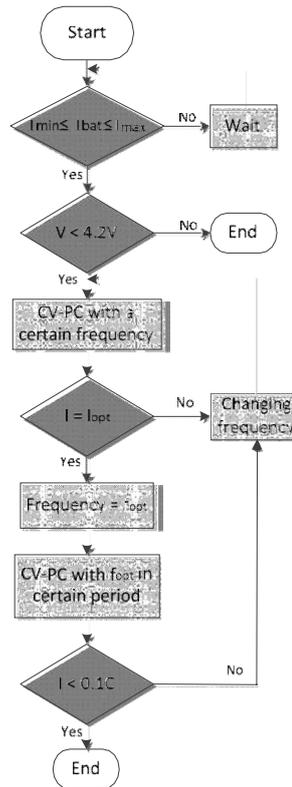


Fig. 8 Charging profile of IPPL-CC/CV

The second issue is that the appropriate charging current in each stage should be must be determined to charge the battery. So far, five approaches were used to determine the optimal charging current for each stage. The first approach used a fuzzy logic controller to determine charging current [15], where the inputs of the fuzzy controller are the temperature and the change of the temperature, and the output of the controller is the charging current. The effectiveness of the approach depends on the knowledge of the user in choosing the right error computation and membership functions and coming up a proper rule basetable.

The second approach adopted the consecutive orthogonal array (or Taguchi method) to search an optimal charging current profile [16], [17]. The third approach applied the ant colony system to optimize a charging current profile [18]. The fourth approach used an integer linear programming to search an optimal charging current profile [19]. The above-mentioned three approaches were implemented with properly designed experiments with a computer. No matter what approaches are used, the general flow chart to implement each charging algorithm is shown in Fig. 11. In this flow chart, the block highlighted by the shaded area may vary from one to another as various optimization approaches are chosen, the rest of them are remaining the same. Generally, the implementation of this charging algorithm has required a microcontroller or a computer. The charging speed is faster and charging efficiency is higher than those of the CC/CV.

2.4 Pulse charge

The pulse charge has been claimed to be a fast and efficient charging algorithm for lithium-ion batteries. The effects of pulse charge on lithium-ion batteries were evaluated using an electronic network model. Simulation results provide insight into the effect of the pulses on the internal process, such as diffusion, migration, electrochemical reactions and heat generation [20]. Also, the effect of pulse charge on the cycle life of lithium-ion batteries was investigated using the experimental approach[21].

Many pulses charging algorithms were developed. Basically, they can be divided into two groups. The first group is the pulse charge with the constant voltage (CV- PC) in the entire Highest charging current. A prototype of these two charging algorithms was implemented.

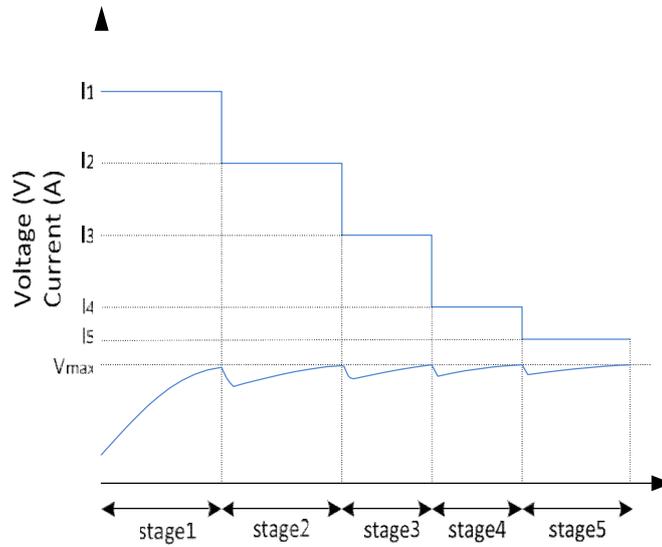


Fig. 9 Charging profile of MSCC

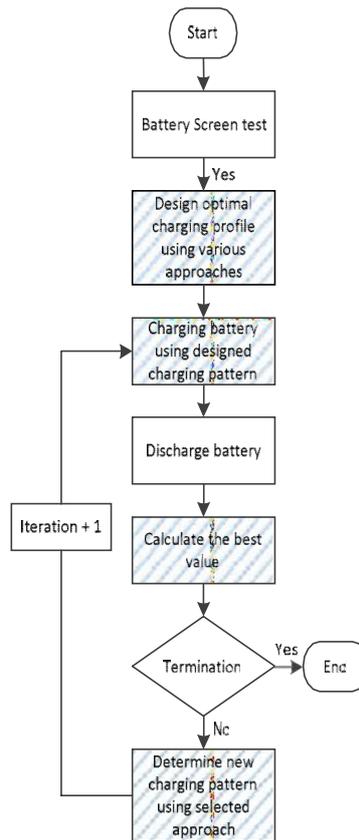


Fig. 10 Flow chart of MSCC

charging process while the frequency of the pulse (FCV-PC) [22] or the duty cycle of the pulse (DCV-PC) is changed [23]. The basic idea of the FCV-PC is to adjust the frequency of the pulse with inaccurate in range and observe the response of the charging current. The optimal frequency (optimal) is obtained when the battery impedance is minimized and the highest Charging currents achieved. Fig.12 shows the flow chart of the FCV-PC. The DCV-PC is very

similar to the FCV-PC, the only difference is that, instead of changing the frequency of the pulse, it changes the duty cycle of the pulse to achieve the Flow chart of FCV-PC It demonstrated that the charging time is shorter than that of the CC/CV [22], [23] and the charging efficiency is higher and the cycle life is longer.

The second group is the pulse charge with the constant current in the entire charging process (CC-PC) while the battery voltage is monitored to make sure that the voltage is always lower than the preset maximum charging voltage. The charging profile can be varied by changing the amplitude and width of the pulse and the relaxation period between the pulses [24], [25]. Fig. 13 shows the charging profile of the CC-PC. With the help of the simulation, the charging time (t_c) is selected when the maximum concentration is reached and the relaxation period (t_r) is determined such that it provides sufficient time to a reset concentration

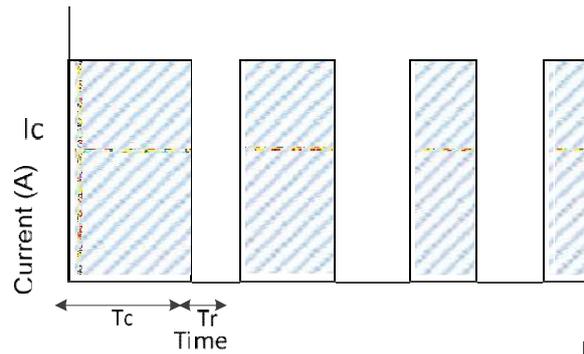


Fig. 11 Charging profile of CC-PC

As a result, electrochemical reactions neither produce heat nor cause the accumulation of pressure inside the battery. Since this charging algorithm is designed to establish the link between the pulse charging current profile and the chemical reaction process, in principle, it can charge the battery faster and more efficient as well as extend battery cycle life. However, no hardware of this charging algorithm for the lithium-ion battery has been implemented so far [15]-[16].

III. DISCUSSIONS

With so many charging algorithms available to charge lithium-ion batteries, it might not be obvious for the users to choose which one better suits their application needs. However, Table I summarizes the major aspects of these charging algorithms which should help in choosing an appropriate charging algorithm.

Table I. Major Characteristics of Charging Algorithms

Charging algorithm	Analog or digital	Ch. time	Ch. Eff.	Imp. Comp.	Cycle Life	Sensed Para.
CC/CV	Both	L	L	M	L	V, I, T
DL-CC/CV	Analog	L	L	L	L	V, T
BC-CC/CV	Both	H	L	M	L	V, I, T
FL-CC/CV	Digital	M	M	H	M	V, I, T
GP-CC/CV	Digital	M	M	H	M	V, I, T
PLL-CC/CV	Analog	L	M	M	L	V, I, T
IPLL-CC/CV	Analog	L	M	M	M	V, I, T
MSCC	Digital	M	M	H	M	V, I, T
FCV-PC	Digital	H	H	H	H	V, I, T
DCV-PC	Digital	H	H	H	H	V, I, T
CC-PC	Digital	H	H	H	H	V, I, T

Notes: H: high, M: medium, L: low, Ch.: charging, Eff.: efficiency, Imp.: implementation, Comp.: complexity, Para.: parameters

IV. CONCLUSION

This paper discusses and analyzes the existing charging algorithms for lithium-ion batteries in the literature. Their major characteristics are compared in terms of implementation, charging time, charging efficiency, cycle life and sensed parameters, which serves as a useful guide in choosing the right charging algorithms for particular applications

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