J. Electrical Systems 20-2 (2024): 2604-2615

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Intelligent, optimal charging with MSSC and PCM protocols for healthy and long life on Li-ion batteries

Abstract: - MSCC is one of the most efficient charging methods with the appropriate advantages over the CC/CV method most commonly used in the Li-ion battery charger market. Our approach to this optimal charging is based on the weak points of CC/CV charging, as well as the battery's reaction after each CC step in testing the new optimal current. Given the needs of the industrial market, which demands fast charging and safety against overcharging and side effects, we decided to develop a fast, optimal charging method aimed first and foremost at guaranteeing a long battery life cycle. Our intelligent charging strategy uses a combination of two charging protocols, MSSC and PCM, each with functionality and a communication link via an STM32 MCU. The principle is to find the optimum charging current for the battery at each stage of charging, depending on its state of health, and then apply the MSSC with a modern, optimized method based on methodological calculations, always respecting the temperature conditions.

Finally, based on several experimental tests, we were able to prove that the optimal, intelligent method proposed in this article reduces charging time by 16.8% and temperature by 20%, compared with our own intelligent CC/CV+PCM method.

Keywords: Multi-step constant current (MSCC), Pulse charging method (PCM), Constant-current / Constant-voltage (CC/CV), Li-ion battery charging, Optimal current (OC).

I. INTRODUCTION

Li-ion batteries have become indispensable in today's world, as many fields are confronted with their use, especially in EVs, due to their many advantages: long life, high operating voltage, low self-discharge rate, and high power density [1]- [2].

he major challenge imposed by users and manufacturers is to ensure rapid battery charging and protection against overheating and the danger of explosions, with a long life cycle [3]. To meet the needs of the market and the current trend, we aim for a fast-charging method that is efficient but also optimal and intelligent, intending to guarantee a good SOH. The strategy followed is to play on the important point of charge control and the weak points of current conventional CC-CV or MSSC methods.

Constant-current and constant-voltage charging methods are simple and effective, but their speed is no longer sufficient, given the time elapsed in the voltage-constant phase [4]. Also, CC-CV charging with an appropriate rated current is no longer cost-effective, given the aging and SOH of the battery, which results in a non-rapid charge and high temperatures leading to battery destruction. In our conference paper, we proposed a method for optimal CC-CV charging using a combination of the PCM protocol responsible for finding the optimal charging current, the aim of which is to remedy the drawbacks above [5]. Experimental results showed an improvement in charging time at 16,8% and normal temperatures compared with conventional CC-CV.

Based on these studies and experimental results, we propose an intelligent charging method using a combination of the two protocols MSSC and PCM, but in an optimized way aimed at reducing charging time while protecting the battery's life cycle. The strategy is to search for the optimum charging current using the PCM protocol, then deliver it to the MCU, which will initiate charging via MSCC, providing a fast, safe charge adapted to the battery's state of health and offering an extended life cycle. Our challenge was to design the PCM test within a very short timeframe, as this is the key to our method, so it's not just launched to find the optimum current even within the

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transition phase between constant currents.

Implementing this solution with a backup LI-ion battery ensured that this MSCC-PCM method via intelligent control is more reliable than the CC/CV+PCM combination.

In this article, the second part is devoted to examining the various CC-CV, MSCC and PCM charging protocols, detailing their principles and functionalities. Next, we will detail our intelligent charging method based on MSCC and PCM and digital control via an MCU. In part 3, we will illustrate the experimental results and compare them to make the most of this work.

Finally, Part 4 will conclude this study.

II. CC/CV VS MSCC

A. CC/CV inconvenient

This is the most common method of charging Li-ion batteries on the market, due to its simplicity and protection against very high currents. Given the charging process and the time expired by the CV mode, this charging protocol is no longer profitable for the industrial market, especially in the field of electric vehicles, for many reasons:

- Charging time
- Life cycle
- Charging conditions

As the battery ages, charging at nominal current is no longer reliable in terms of time, and even has a negative impact on the life cycle [6].

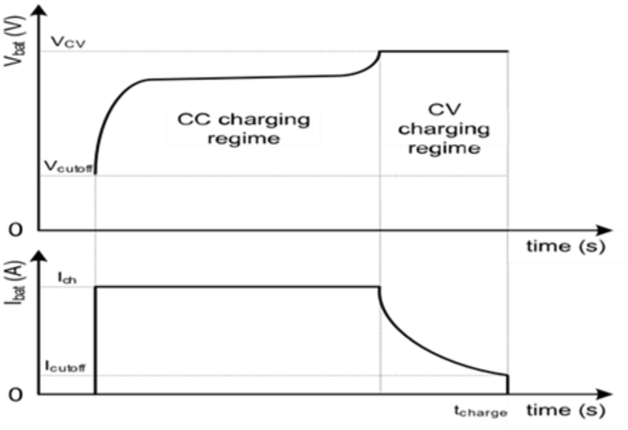


Fig. 1: Protocol CC/CV charging

As illustrated in Fig. 1 [7], the charging method consists of 2 regimes: CC charging and CV charging. CC charging is the most important, accounting for 80% of the charge percentage in a short time, compared with CV charging, which slows down the rate of charge.

With a standby battery used in different climatic conditions, the CC charging regime launched with a nominal current appropriate to the battery at the time of manufacture will give unsatisfactory results in terms of charging time and high temperature.

Based on these shortcomings of the classic CC/CV charging method, and after several experimental simulations, we have remedied the problem with an intelligent, fast charge that respects the battery's SOH.

B. MSSC basic strategy

This method has been imposed to solve the problems of the CC/CV technique, its ease of implementation, and its gain in terms of charging time imposing it as the primary technique for the Li-ion battery charger market.

This protocol has been developed by TAGUCHI as already described, a series of constant currents is applied with precise calculations of the current and period of each series to offer the best performance to the battery.

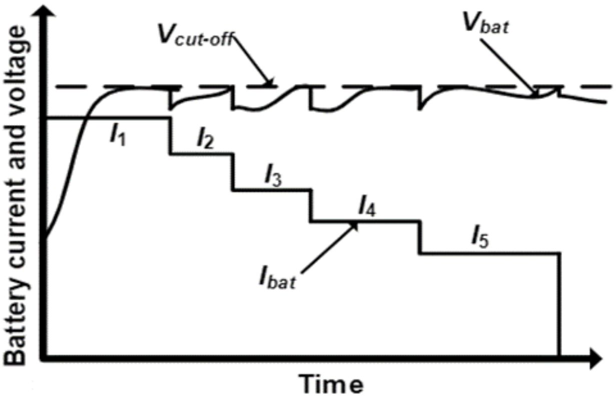


Fig. 2: Protocol multi-step constant current charging

Figure 2 illustrates the basic multi-stage constant-current method, containing 5 series of constant currents. Each time the number of constant currents is increased, the adjustment and control design of this method becomes more complex [8]- [9].

When the predefined switching condition is reached, the charging process proceeds to the next charging step until all charging steps have been completed. Depending on the switching condition, the MSCC charging strategy can be divided into two categories: voltage-based MCC charging and state-of-charge-based MCC charging.

Switching conditions and constant current values are very important for this charging method:

- The upper voltage value is always the same, and as soon as it is reached, we notice that we switch to the next constant current stage.
- The charging current of the current stage must not exceed the charging current setting of the previous stage, otherwise, the battery terminal voltage will immediately reach the voltage limit, and the duration of this phase will be very short.

$$I = [I1, I2, \ldots\ldots\ldots, In]$$
$$\text{Subject to: } Ii \geq Ij \quad \text{if } i < j, \quad i, j = 1 \ldots n$$
$$I_2 = \sqrt{I_1 I_3}$$
$$I_3 = \sqrt{I_2 I_4}$$
$$\ldots \ldots \ldots \ldots$$
$$I_{n-1} = \sqrt{I_{n-2} I_n}$$

III. ALGORITHM-BASED SMART CHARGING

Our design consists of two parts: Hardware and Software. The hardware design will be described in detail in the experiment section, while the software design is the most important and is responsible for managing the operating modes and safety of our system and analog components. In this section, we'll take a closer look at the MCU's charging modes and management for proper operation.

Our intelligent charger is based on a digital control (MCU STM32) which ensures optimal and safe charging by combining the two protocols used. This combination of PCM and MSCC protocols offers optimal, fast charging and protects the battery against overcharging and high temperatures to guarantee a long life cycle. The PCM protocol is launched with a very short delay before charging begins, the principle being to specify the optimum charging current according to the battery's state of health. The MSCC protocol is then responsible for the battery charging phase.

A. PCM (Optimal current)

This is a method well-established in the industrial market for recharging small electronic devices. It is technically difficult and very costly, requiring the use of a sophisticated charger to retain its benefits. In the TPC method, current is sent in pulses leaving short intervals with zero current pumped into the battery. Several studies agree that pulse charging reduces charging time by eliminating the CV mode, but does not benefit battery life or health.

Fig. 3 below illustrates the PCM method with a series of pulses separated by rest periods [10].

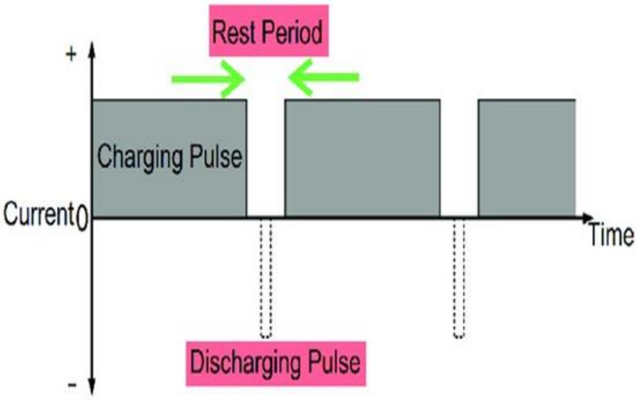


Fig. 3: Pulse Method

Our strategy is based on this principle but attacks the battery with a series of 9 pulses with different current values (1C, 1.2C, 1.4C, 1.6C, 1.8C, 2C, 2.2C, 2.5C, 3C) with a period of 0.04s for each pulse and a rest period of 0.1s between pulses.

Fig. 4 below shows the structure of the PCM test pulses and their periods [11].

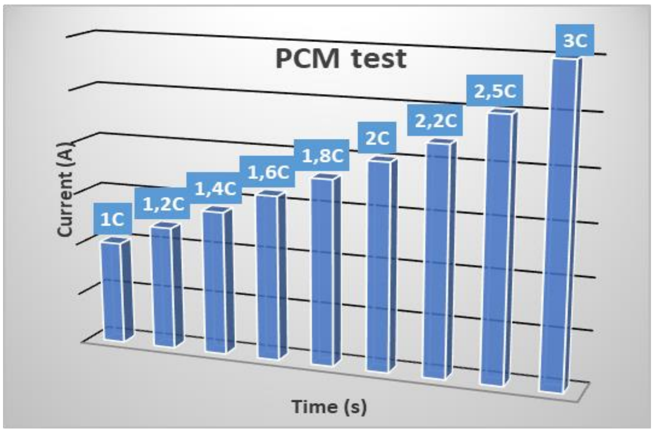


Fig. 4: Test PCM to choose the optimal current

The test steps digitally controlled by MCU are classified:

- Calculate $EMF_{(SOC)}$ and store it in table
- Attack the battery with pulses and store the V_{Bat} and I_{Bat} values appropriate to each pulse
- Calculate each pulse $Rdc = \frac{Vbat - EMF(soc)}{Ibat}$
- Compare the R_{DC} of the 8 pulses and select the optimum current corresponding to the small resistor

Table 1: Template of the table test PCM

Pulse	EMF	V_{Bat}	I_{Bat}	R_{DC}
1C				
1,2C				
1,4C				
1,6C				
1,8C				
2C				
2,2C				
2,5C				
3C				

B. MSCC Optimal simulation

In this document, our method contains a load with 5 series of constant currents using the MSCC protocol, but in an optimized way.

Our added value compared to the basic MSCC method is to start the load with an optimal current found using the PCM test, so the transition between multi-steps is controlled by the PCM test which defines the next constant current. This transition only occurs when the charging voltage V_C is equal to the nominal battery threshold voltage V_S. All these operations are well handled and controlled by MCU, which represents the heart of our system. This technique will give us a fast, optimal charge, depending on the battery's state of health.

The diagram in Fig. 5 describes the charging procedure and the link between PCM and MSCC techniques and their control by MCU.

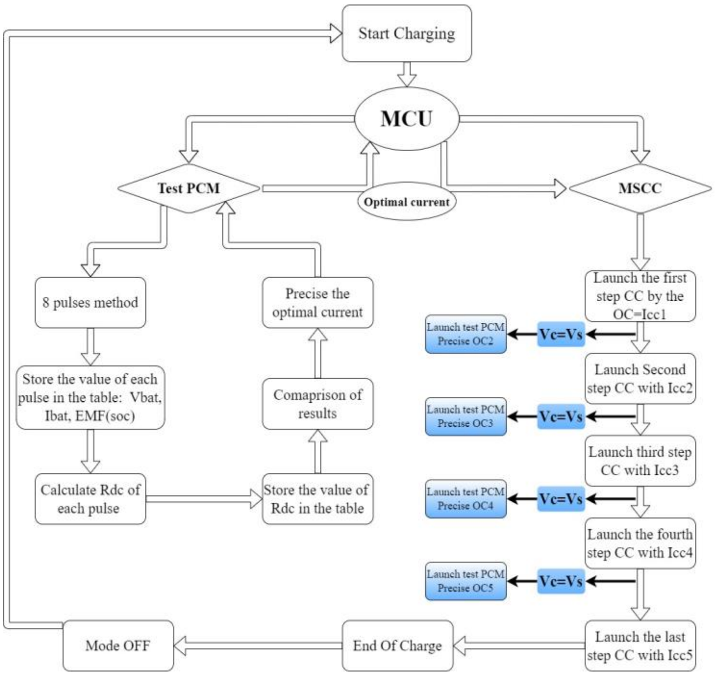


Fig. 6: Flowchart of optimal MSCC charging

C. Battery characteristics

The battery used in this experiment is a SONY LIS1551ERPC standby battery whose specifications are described in Table 2 below.

Table 2. Li-ion battery specification

Characteristic	Value
Nominal capacity (Ah)	**2,33**
Nominal Voltage (V)	**3,7**
Min Discharge Voltage (V)	**2**
Max Current Charging (A)	**8**
Charging Temperature Range (°C)	**-20 - 50**
Internal Resistance (mΩ)	**5,5**

D. *Temperature Sensor*

One of the most important safety criteria when charging Li-ion batteries is temperature control. To measure the battery temperature and also visualize its reaction during transitions between CC multi-steps, we used a sensor linked directly to the battery.

Fig. 6 shows the temperature sensor used in our proposed charger, which is linked to the MCU to inform the system of the battery's condition and ensure its safety. In the event of a high temperature exceeding the threshold range supplied to the MCU, the system goes directly to the End-Of-Charge phase [12].

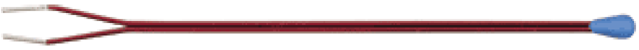


Fig. 6: NTC thermistor

The advantage of this sensor is the high accuracy and high sensibility temperature available by the small size and high accuracy NTC Thermistor, and large operating temperature range -40°C to +125°C.

One of the important characteristics of the NTC thermistor shown in Fig. 7 is its ability to repeatedly and predictably change its resistance in relationship to its body temperature [13].

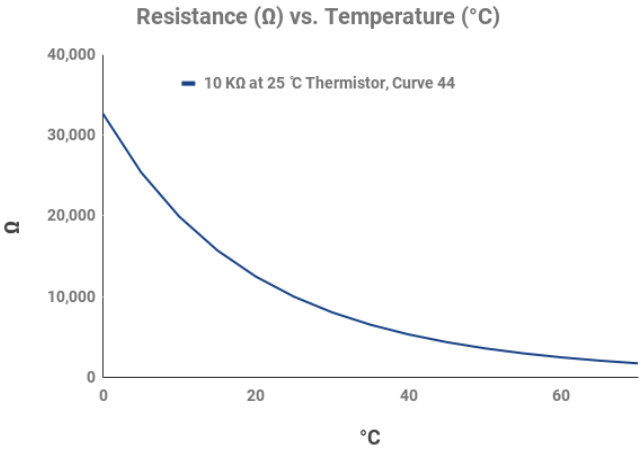


Fig. 7: Resistance/Temperature characteristic

IV. EXPERIMENTAL VALIDATION AND COMPARISON

A. *Hardware conception*

The heart of our proposed charger is its digital control system, which enables us to manage all the charging stages, as well as the combination between the two protocols, and finally to secure the charge by controlling the temperature. Fig. 8 shows the various components of our circuit and their links with the STM-type controller. We chose the STM32F1xx MCU because of its high performance, first-rate peripherals and low-power, low-voltage operation, simple architecture, and easy-to-use tools. The system's charging circuit includes a Buck-Boost converter that gives us a wide range of current-voltage variations for charging multiple batteries**.** Our linear charger also contains an important component TL494 with two different roles: the first connects the MCU with the Buck converter as a PMW modulator, and the other connects BOOST with the MCU to control charging current and voltage.

The TL494 has everything needed on the chip to generate and control a PWM signal. This in turn can provide the ability to drive heavier current carriers such as transistors. The chip has two error amplifiers that can be used to control the output and an internal voltage reference and oscillator. The flexible output stage has 2 uncommitted transistors that can be hooked up as either common-emitter or emitter-follower configurations [14]- [15].

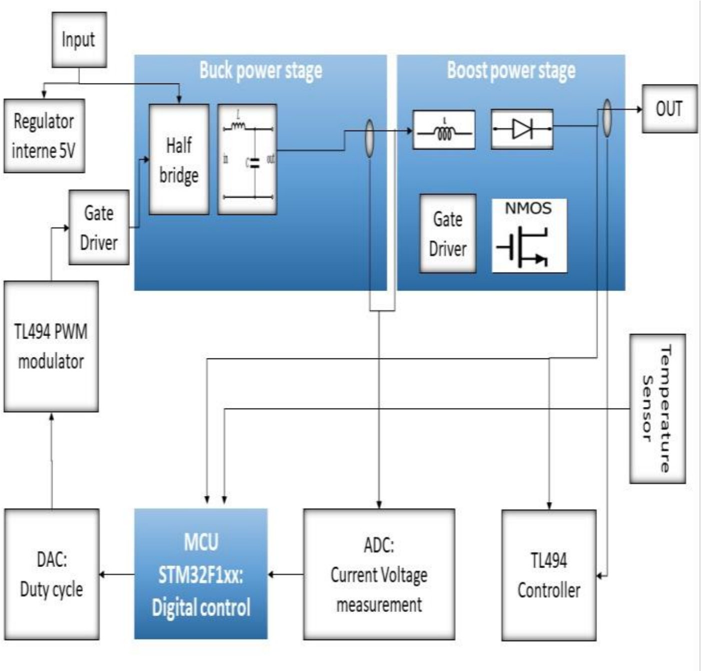


Fig. 8: Schematic block diagram of the intelligent charge

Fig. 9 shows the components and their configurations and connections for each block listed in Fig. 8.

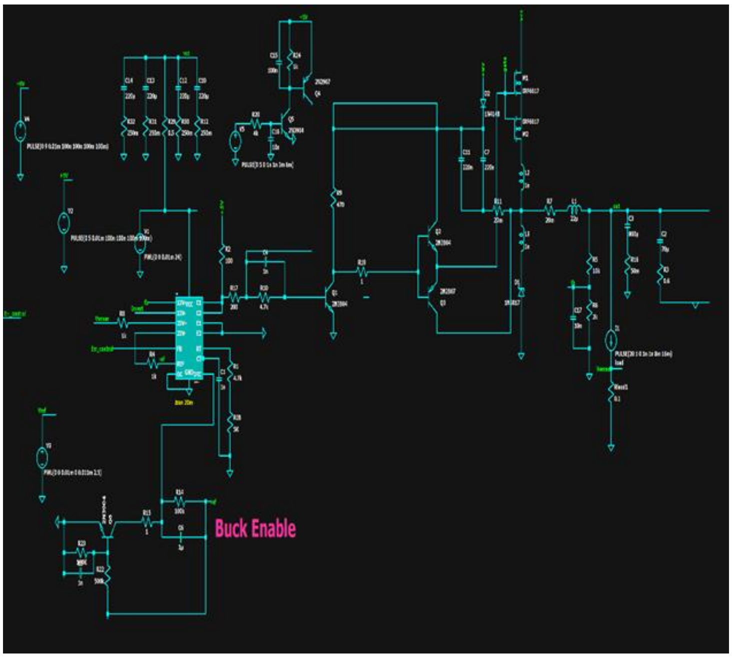


Fig. 9: Schematic of the linear proposed charger

B. *Implementation*

Fig. 10 below shows the actual simulation of our load system using the test instruments.

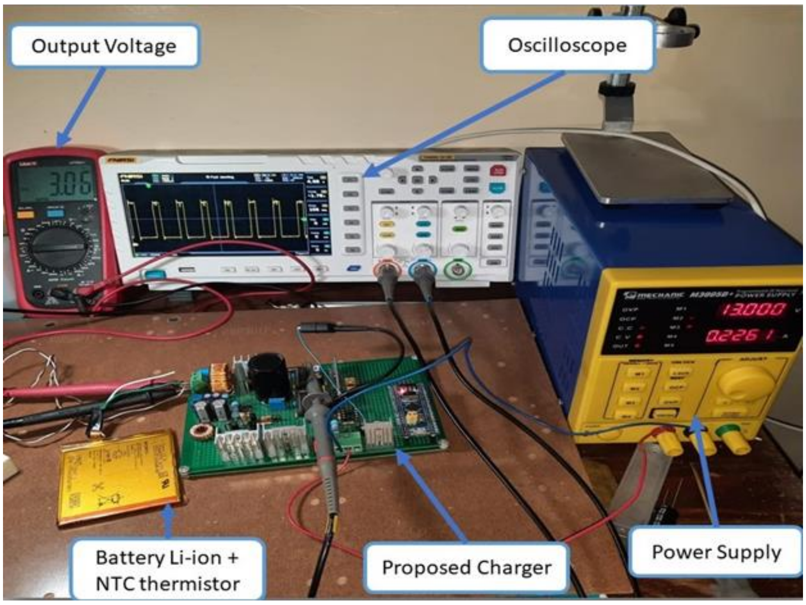


Fig. 10: Implementation test

C. *Test results*

a) *Test PCM*

The following figure shows the actual simulation of the PCM test using oscilloscope visualization. The challenge is to simulate nine pulses each with a defined current in a very short time. To specify the optimum load current among these nine pulses, the microcontroller performs calculations and comparisons to determine the lowest internal resistance to apply the current corresponding to the MSCC phase.

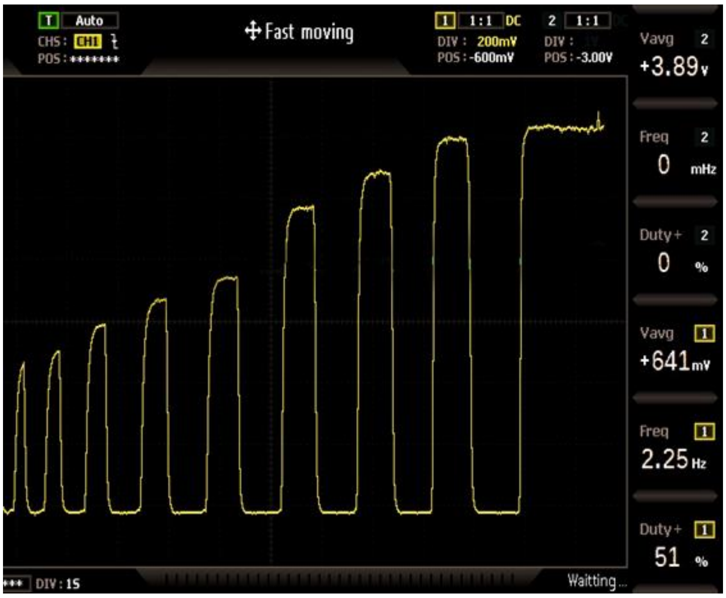


Fig. 11: Test PCM with nine pulses

The following table shows the results of the PCM test applied to the battery using the proposed charger. The table is created by the MCU and compares the calculated resistances of each pulse.

The optimum current is equivalent to the lowest resistance, OC = 1.8C. The first MCC stage is simulated by the optimum current I_{CC1} = 1,8C= 1,8*2,33 = 4A.

Table 3: Results of test PCM to determine the optimal current

Pulse	R_{DC}
1C	0,41
1,2C	0,38
1,4C	0,34
1,6C	0,30
1,8C	0,25
2C	0,30
2,2C	0,31
2,5C	0,45
3C	0,46

b) Optimal MSSC results

Figure 12 shows the reel simulation of the proposed charger with optimized MSCC which contains 5 Constant-Current stages.

Fig. 12: Experimental optimized MSCC test

- Green curve: Current charge
- Red curve: Voltage charge
- Bleu curve: Voltage Seuil

When V_{charge}=V_{seuil} the charger changes the current by using the test PCM again to find the new optimized current.

c) Results temperature sensor

Monitoring the battery temperature during charging is very important for validating the efficiency and performance of our intelligent, optimal method. Fig. 13 shows the temperature values during simulation throughout the charging phase. The temperature range varies between 30.4°C and 33.2°C.

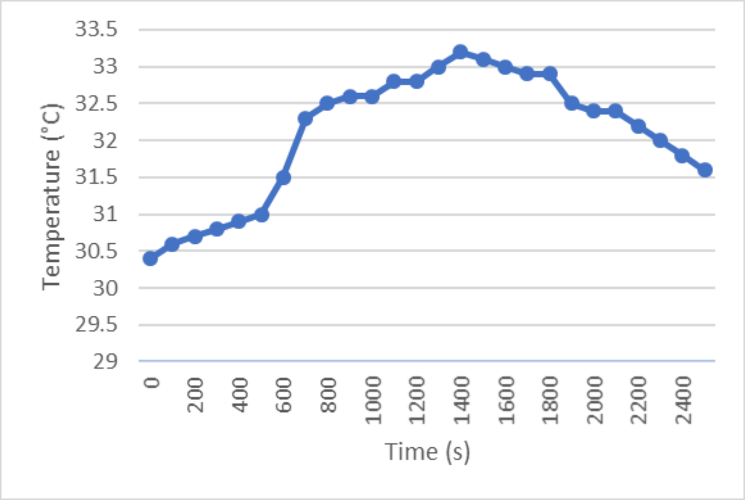


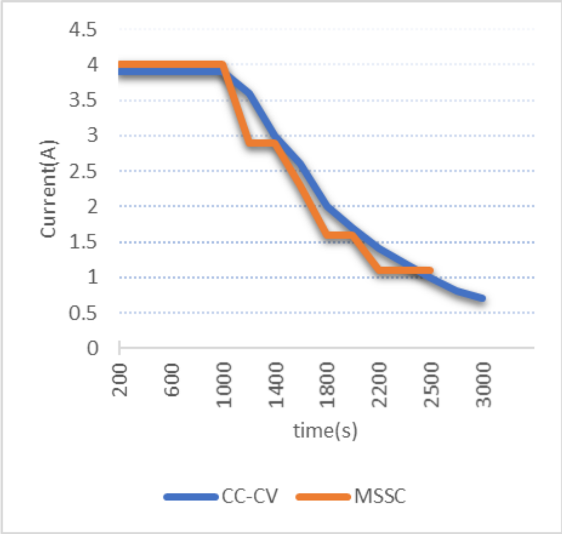
Fig. 13: Battery temperature

D. Comparison

This curve shown in Fig. 13 represents a simulated comparison between our MSSC+PCM and CC/CV+PCM intelligent, fast-charging systems. The results give a good account of the MSSC method in terms of time and even temperature, calculated using a heat sensor on the battery.

In the charging process battery with CCCV and MSCC methods, the MSCC method required (2500 seconds) to fully charge the battery, which was reasonably faster than the CCCV method (3000 seconds).

Fig. 14 shows a detailed comparison of battery temperature during charging as a function of time. It is clear from the graph that the optimal and intelligent MSSC method was able to reduce the temperature, with a difference of 0.9°C between the peak of the two methods.



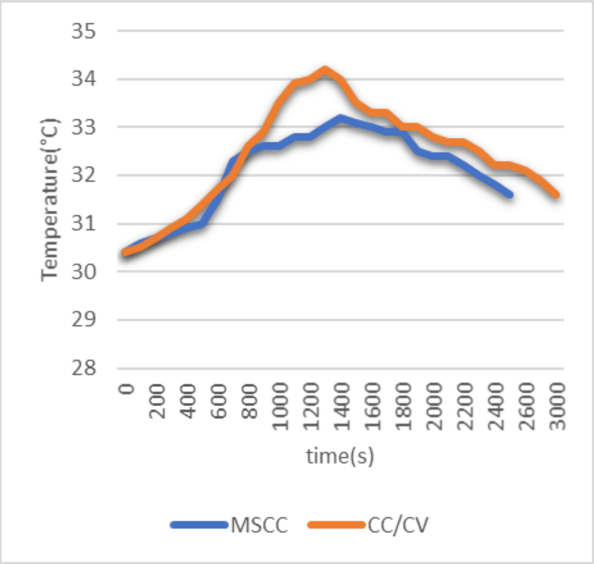


Fig. 13: Comparison of the battery time charging Fig. 14: Comparison of the battery temperature

for intelligent MSCC and CC/CV

V. CONCLUSION

In conclusion, the results of the tests and comparisons showed that the CCCV method is no longer reliable and effective for fast charging while monitoring battery conditions. Intelligent charging has become the trend for Li-ion batteries due to the advantages of digital control (MCU).

Our optimal MSCC smart charging method with a combination of two protocols has optimized charge time by 16,8%, and temperature by 20% with good operation at the end of the storm, extending the battery's life cycle.

These advantages have enabled our proposed charger to establish itself in a variety of Li-ion battery applications in many fields: EVs, medical devices, electronic appliances, etc.

ACKNOWLEDGMENT

This work was supported by the National Center for Scientific and Technical Research (CNRST Morocco) under the APR&D 2020 program.

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