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The Effect of Pulsed Current on the Performance of Lithium-ion Batteries

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Abstract—The pulsed current is considered to improve the performance of the Lithium-ion (Li-ion) battery. However, the effect of the pulsed current on Li-ion battery performances is inconclusive at present. In this paper, a battery cell was charged by applying a 0.05 Hz pulsed current. Different duty cycles, the current-rates (C-rates), and ambient temperatures were considered in order to obtain a clear impact of the pulsed current on the battery performance during charging. Compared with the constant current, the pulsed current can improve the charging capacity and decrease the maximum rising temperature by 30.63% and 60.3%, respectively. The results obtained were used for the parameterization of a capacity model and charging time model, which are able to express both the capacity and charging time at different charging conditions of the Li-ion battery cell.

Index Terms—Lithium-ion (Li-ion) battery, pulsed current, charging capacity, charging time, thermal behavior.

I. INTRODUCTION

Electric Vehicles (EVs) are expected to be the future of the automotive industry and have become part of modern transportation in our life. Replacing traditional internal combustion engine vehicles with EVs can reduce dependence on oil, and can reduce greenhouse gas emissions to protect the ecological environment [1]. The Lithium-ion (Li-ion) battery is the key battery technology for powering EVs due to their higher energy density and longer lifetime compared to lead-acid batteries. The main concerns of EV users are the limited lifetime, charging speed, the driving mileage after each charge, and safe charging. A longer lifetime of the battery means a longer total mileage of the EVs and the more cost-effectiveness for the user. Charging speed refers to the time required to charge an EV in a single operation. The mileage after a single charge corresponds to the charging capacity of the battery. The safety is related to variable factors, such as overcharge, overdischarge, and operating temperature, etc., thus monitoring the battery cells' states and thermal behavior are important to ensure the safe operation of the EVs [2]. Therefore, research on the advanced charging strategies is necessary to improve the lifetime and performances of the battery system in EVs.

There are three charging levels considered for EVs. Level 1 is applied in household scenarios, which use the standard three-prong household connection and allow the EVs to charge

overnight at home [3]. Thus, there is no special requirement for the charging speed. The charging time of Level 1 is generally about 10 hours due to the low power level, which is used. Level 2 has a higher power level that can decrease the charging time to 2-6 h. Level 3 is the fast charging technology that can control the charging time to be 15-30 minutes [4]. However, the rising temperature during the charging operation is significantly higher than that of Level 1 and Level 2. A higher rising temperature might expose the battery to the danger of thermal runaway and even explosion, and will also reduce the lifetime of the battery. Thus, it is valuable to study how to balance the battery charging time and thermal behavior as well as the battery lifetime [5]. The Constant Current-Constant Voltage (CC-CV) is a practical charging strategy that is widely applied in academia and industry. The CC-CV charging strategy includes two phases, which are the Constant Current (CC) phase and Constant Voltage (CV) phase. At the first CC stage, the battery cell is charged by applying a constant current I_{cha} , and the voltage monotonously increases. When the cell voltage reaches maximum voltage, the charging process enters the CV phase, and the current is gradually decreased. Once the current decreases to the cut-off current, the charging process is completed. The charging time is mostly related to the Current-rate (C-rate) of the CC phase, while the CV phase enables the battery cell to obtain a higher available capacity but prolongs the charging time.

To improve the charge performances of the Li-ion battery cells, various charging strategies were proposed. The Multi-Stage Constant Current (MSCC) was developed to speed the charge time by 12% and improve the efficiency by 1.8% [11]. In [6], the Sinusoidal Ripple Current (SRC) is proposed and verified that the charging time, the charging efficiency, the maximum rising temperature, and the lifetime of the Li-ion battery are improved by about 17%, 1.9%, 45.8%, and 16.1%, respectively. Pulsed current charging strategy, which is previously applied in Lead-acid batteries, is also proposed to be used in Li-ion batteries. Pulsed current can be divided into the Positive Pulsed Current (PPC) mode and Negative Pulsed Current (NPC) mode [12]. The NPC mode is the constant current charging with periodic short discharging pulses and periodic short relaxation time. The NPC charging method can improve active material utilization to provide higher discharge

TABLE I
THE EXISTING STUDY ON THE POSITIVE PULSED CURRENT (PPC) AND ITS IMPACT ON LI-ION BATTERIES.

Reference	Test conditions		Study Point					
	frequency [Hz]	Ambient temperature [°C]	Current [C]	Duty cycle [%]	Charging capacity	Charging time	Thermal behavior	Life time
[6]	1, 100, 998, 10k	28	1	50	✓	✓	✓	×
[7]	1, 10, 100, 1k, 10k, 100k	24.8	0.5	50	×	×	✓	✓
[8], [9]	100, 1k, 6k, 12k, 50k, 100k	0, 23, 45	0.5	20, 50, 80	×	✓	×	✓
[10]	1, 25	25	3	50	✓	×	✓	✓
This work	0.05	15, 25, 35, 45	0.5, 1, 2, 3	30, 50, 70, 90	✓	✓	✓	×

capacity and longer life cycles. In [13], the NPC method can complete 1600 full cycling tests, while the CC charging method has only 700 cycles when the battery capacity of in two cases decreases to the same capacity. Moreover, low amplitude and a few numbers of the negative pulse have a positive effect on the capacity fading that decrease the capacity loss around 3% [14]. The PPC mode is the constant current with periodic relaxation time. The existing studies on the PPC charging are listed in Table I. In [6], the battery was tested at different frequencies that range from 1 Hz to 10 kHz. The effect of the pulsed current with different frequencies show similar performances, i.e. the charging capacity, charging time, and the maximum rising temperature. However, when compared to these performances presented by conventional CC-CV charging strategy, the average of the charging capacity, the charging time, and the maximum temperature measured by applying the pulsed current are improved by 1.3%, 16.2%, and 29.8%, respectively. In [7], it is presented that the pulsed current at 10 kHz can slow down the degradation speed of the Li-ion batteries. In [8] and [9], different duty cycles and frequencies of the pulsed current and varied ambient temperatures were considered to test the battery lifetime. The results were that the pulsed current can improve the lifetime by 100 life cycles at a certain test condition (i.e. 12 kHz, 50% duty cycle frequency, 23 °C ambient temperature). Moreover, the charging time decreases by 49% at the same test condition. However, not all pulsed current can improve the performances or lifetime of the Li-ion batteries. In [10], the capacity utilization and charging time of the 1 Hz pulsed current and 25 Hz pulsed current are similar to that of the CC-CV charging, while 1 Hz pulsed current results in a faster capacity fade for Li-ion batteries. For the existing researches on the pulsed current, all of them investigated the range of the frequency is above 1 Hz. Furthermore, the charging capacity is not improved. However, the discharging capacity of the Lithium-Sulfur battery can be extended to more than 20% by introducing relaxation time [15]. Therefore, the pulsed current with a frequency below 1 Hz should be investigated because a lower frequency can provide longer relaxation time for battery cells to recovery its capacity.

The paper investigated the effect of the pulsed current on the charging capacity, charging time, and thermal behavior

(the maximum rising temperature ΔT) of a LiNiMnCoO₂ (NMC) battery. The NMC battery cell was tested considering different duty cycles and different C-rate of the pulsed current as well as different ambient temperatures. The frequency of the pulsed current is 0.05 Hz. The results are compared with the CC charging method. Based on the obtained results, a battery capacity model and charging time model of the pulsed current is developed and parameterized.

II. EXPERIMENT

A. Pulsed current

The charging method studied in this paper is the PPC technique, as shown in Fig. 1. The positive pulsed current is the constant current with periodic relaxation time. The amplitude of the pulsed current is I_p . The pulse period T_p can be obtained by equation (1):

$$T_p = \frac{1}{f} \quad (1)$$

where f is the frequency of the pulsed current. In a pulse period, the width of the pulsed current is t_p , and the relaxation time is t_r . The period is the sum of t_p and t_r . The duty cycle of the pulsed current D can be calculated by equation (2):

$$D = \frac{t_p}{T_p} \quad (2)$$

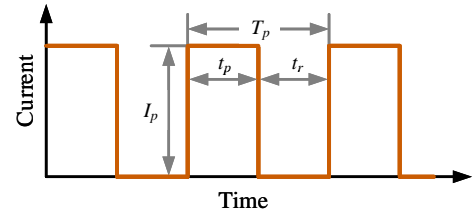


Fig. 1. Positive Pulsed Current (PPC) waveform.

B. Battery cell

The main electrical parameters of the NMC battery cell, which is used in this work, are summarized in Table II. All the experiments are performed using a Digatron battery test station, and the battery cell is placed in a Memmert temperature chamber to ensure a stable and reliable temperature, as shown in Fig. 2.

TABLE II
ELECTRICAL PARAMETERS OF THE TESTED LiNiMnCo (NMC)
BATTERY CELL.

Parameter	Value
Nominal capacity [Ah]	2.2
Nominal voltage [V]	3.6
Maximum voltage [V]	4.2
Minimum voltage [V]	2.5
Maximum charge current [A]	6.6
Operating temperature for charging [°C]	0-55

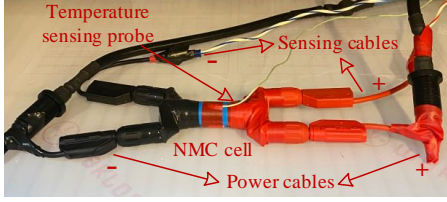


Fig. 2. NMC battery cell during the test.

C. Test procedure

The battery cell was charged by applying the constant current and the pulsed current with different C-rates (0.5 C, 1 C, 2C, 3C) and different temperatures (15 °C, 25 °C, 35 °C, 45 °C.). The effect of different duty cycles of the pulsed current on the performances of the Li-ion battery is also investigated; thus, experiments at 30%, 50%, 70%, and 90% duty cycle were performed. The frequency of the pulsed current is 0.05 Hz. The test procedures are the following:

- 1) Tempering of the battery cell at 25 °C for one hour.
- 2) Full discharging of the battery cell by applying a 0.5 C current until it reaches the discharging cut-off voltage.
- 3) Relaxation of the battery cell at 25 °C for one hour.
- 4) Full charging of the battery cell by applying a 0.5 C pulsed current with 30% duty cycle.
- 5) Relaxation of the battery cell at 25 °C for one hour.
- 6) Full discharging of the battery cell by applying a 0.5 C pulsed current with 30% duty cycle.
- 7) Repetition of step 4-6 for the different C-rate: 1 C, 2 C, and 3 C.
- 8) Repetition of step 4-7 for the different duty cycle of the pulsed current: 50%, 70% and 90%.
- 9) Repetition of step 4-8 for the constant current.
- 10) Repetition of step 1-9 at the different ambient temperature: 15 °C, 45 °C, 35 °C.

The Digatron battery manager is applied for acquiring and logging the measured data.

An example of the pulsed current charging process is provided, as shown in Fig. 3. Fig. 3(a) presents the charging current, the voltage of the battery cell, and the temperature change of the battery cell when the pulsed current is 0.5 C, 30% duty cycle, and the ambient temperature is 15 °C. The extended zoom of this case presents in Fig. 3(b).

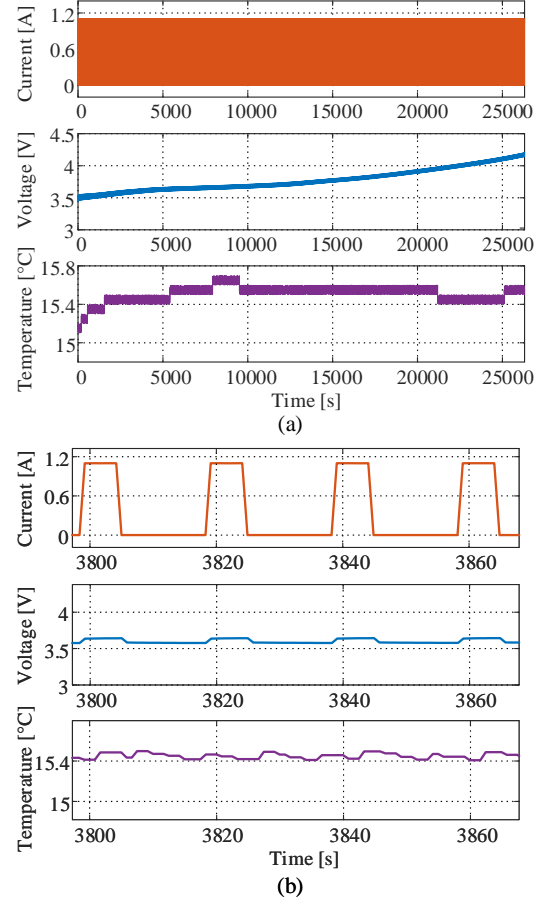


Fig. 3. An example of pulsed current charging process: (a) performance test by applying a 0.5 C, 30% duty cycle pulsed current at 15 °C; (b) extended zoom of (a).

III. RESULTS AND DISCUSSION

To obtain the effect of the pulsed current on the Li-ion battery performances, the battery cell was charged at different temperature conditions, different C-rates, and different duty cycles of the pulsed current. The obtained battery charging capacity, battery charging time, and the maximum rising temperature are compared with the constant current at the same C-rate and the same ambient temperature condition. In the following part, T is the ambient temperature; C is the C-rate; D is the duty cycle. The constant current can be regarded as the pulsed current with a 100% duty cycle.

A. Charging capacity

The effect of the pulsed current on the charging capacity $\Delta Q_{T.C.D}$ is calculated by equation (3):

$$\Delta Q_{T.C.D} = \left(\frac{Q_{T.C.D}}{Q_{T.C.100}} - 1 \right) \times 100\% \quad (3)$$

where $Q_{T.C.D}$ is the charging capacity by applying a pulsed current with different duty cycles (i.e., 30%, 50%, 70%, 90%); $Q_{T.C.100}$ is the charging capacity by applying a constant

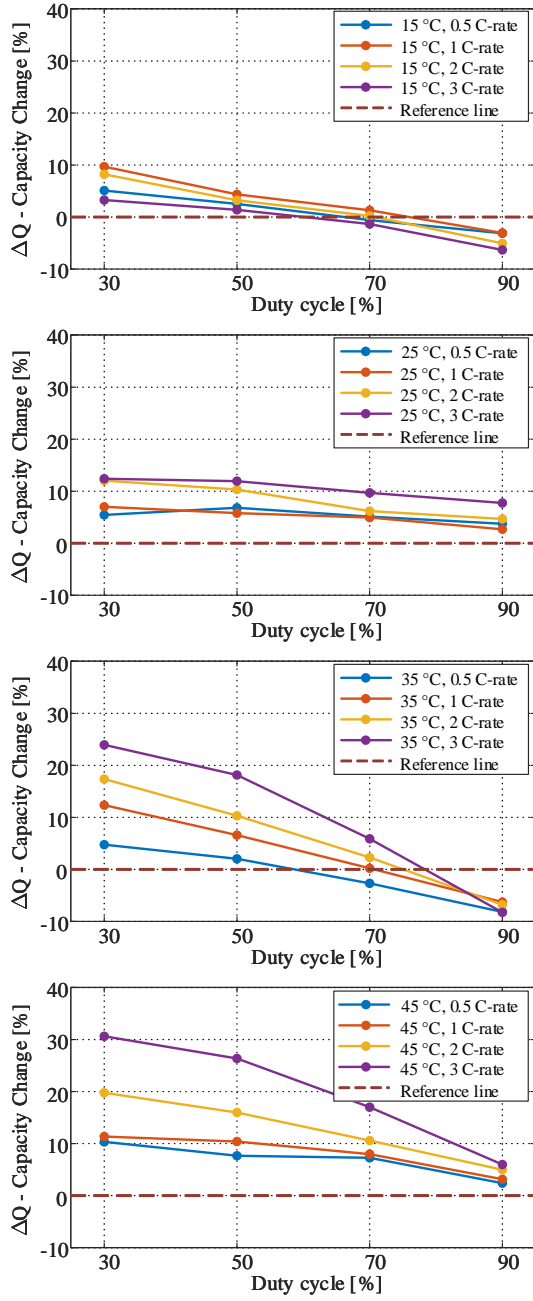


Fig. 4. The effect of the pulsed current on the charging capacity of the Li-ion battery at different test conditions.

current. The C-rate and the ambient temperature are the same for both the pulsed current and the constant current. The effect of the pulsed current at different conditions on the charging capacity is illustrated in Fig. 4. When $\Delta Q_{T.C.D}$ is higher than the reference line, the pulsed current has a positive effect on the charging capacity, i.e., a higher capacity is obtained by pulsed charging. The effect of the pulsed current on the charging capacity can be summarized as follows:

- The duty cycle shows a significant impact on the charging capacity of the tested Li-ion battery, where a 30%-

duty-cycle pulsed current can improve the capacity by 3.3%-30.6%; the higher the temperature, the stronger the positive effect on the charging capacity.

- As the duty cycle increases, the positive effect of the pulsed current on the charging capacity gradually decreases. When the duty cycle is greater than 70%, the pulse current has a negative impact on the battery's charging capacity at 15 °C and 35 °C, independent on the C-rate.
- When the ambient temperature is above 25 °C, higher C-rates have a better impact on the battery capacity.
- Compared with the low temperature, the pulse current has a more positive effect at a high temperature. For example, when the duty cycle of the pulsed current is 30%, the maximum extended charging capacity is 8.2%, 12.4%, 24%, and 30.6% at 15 °C, 25 °C, 35 °C, and 45 °C, respectively.

B. Charging time

The effect of the pulsed current on the charging time can be analyzed by the ratio of the charging time $Rt_{T.C.D}$ based on the constant current, as followed equation (4):

$$Rt_{T.C.D} = \frac{t_{T.C.D}}{t_{T.C.100}} \quad (4)$$

where $t_{T.C.D}$ is the charging time by applying a pulsed current with a duty cycle (i.e., 30%, 50%, 70%, 90%) condition; and $t_{T.C.100}$ is the charging time by applying a constant current. The C-rate and the ambient temperature are the same for both the pulsed current and the constant current. The results of the impact on the charging time are presented in Fig. 5. According to the results of the charging time, the charging time is mostly impacted by the duty cycle of the pulsed current. A lower duty cycle leads to a longer charging time due to the longer relaxation time at every pulse period. Furthermore, at 15 °C and 25 °C, the C-rate and temperature do not have any impact on the battery charging time.

C. Thermal behavior

The temperature of the battery cell was monitored during the test process. The maximum rising temperature $\Delta T_{T.C.D}$ of the battery cell is the difference between the highest temperature $T_{max.T.C.D}$ measured during the charging and the initial temperature $T_{initial.T.C.D}$ as the equation (5):

$$\Delta T_{T.C.D} = T_{max.T.C.D} - T_{initial.T.C.D} \quad (5)$$

Before each measurement, the cell was tempered for one hour in order to ensure thermo-dynamic stability and to provide a base for comparable results. The maximum rising temperature results are provided, as shown in Fig. 6. The result of the 100% duty cycle is represented the maximum rising temperature of the constant current. As expected, a higher C-rate results in a higher rising temperature. Higher increase in the temperature are obtained for low measurement temperature due to the internal resistance of the battery, which increases at low temperatures. The pulsed current can reduce

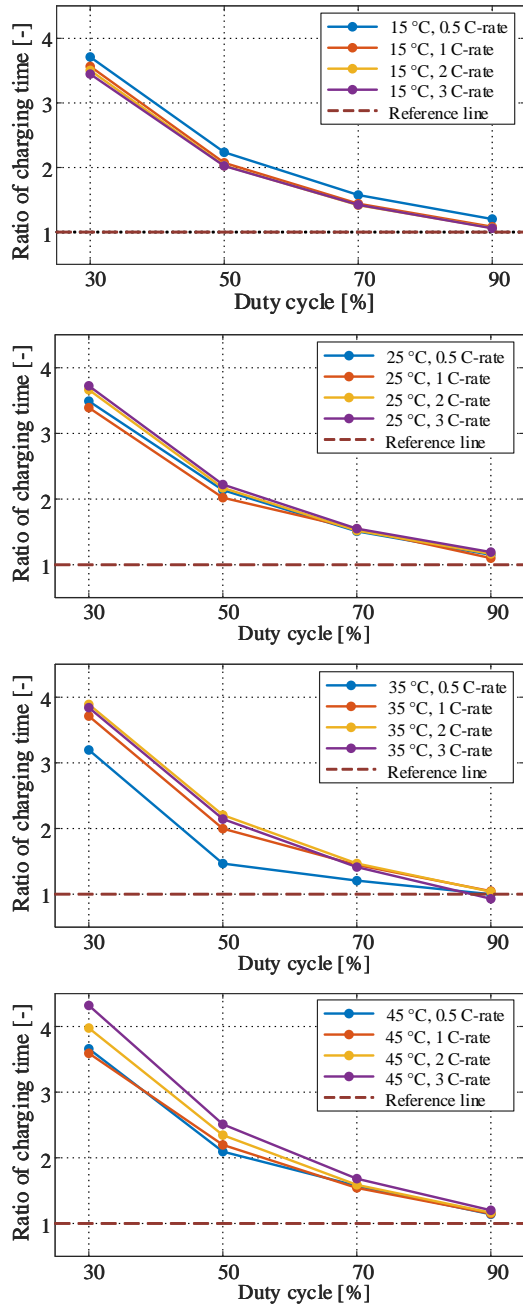


Fig. 5. The effect of the pulsed current on the charging time of the Li-ion battery at different test conditions.

the maximum rising temperature because the relaxation period of the pulsed current offers the cell a periodic time for cooling. Moreover, a lower duty cycle means a longer pause time, which provides more relaxation time for cooling the cell. One can notice as well that the increase in the temperature during the measurements depends linearly on the duty cycle. The rising temperature of the cell charged by a pulsed current can be reduced by 60.3% on average compared with that of the constant current.

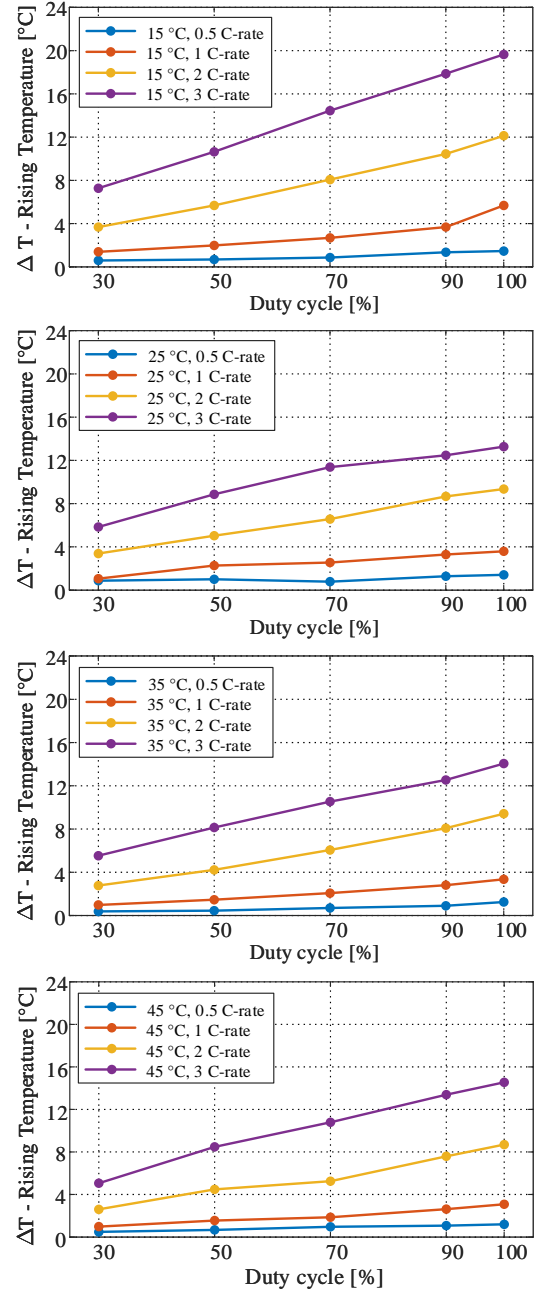


Fig. 6. The effect of the pulsed current on the maximum rising temperature of the Li-ion battery at different test conditions.

IV. PULSED CHARGING CAPACITY MODELING

A. Charging capacity

Fig. 7 shows the charging capacity of the NMC battery cell that was measured at different temperatures and different pulsed currents (see points in Fig. 7). A first degree polynomial function was found to fit the measured charging capacity for all duty cycles of the pulsed current (see continuous line in Fig. 7). The pulsed charging capacity can be expressed as a

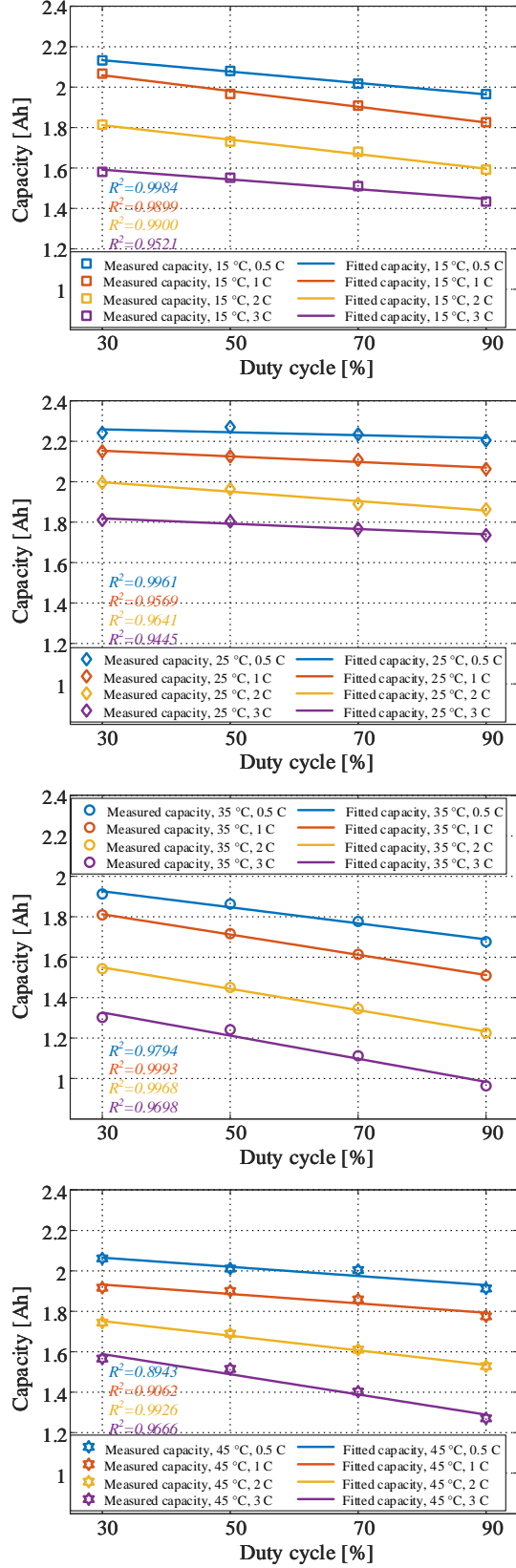


Fig. 7. Measured and fitted charging capacity of the NMC battery at different conditions of the pulsed current.

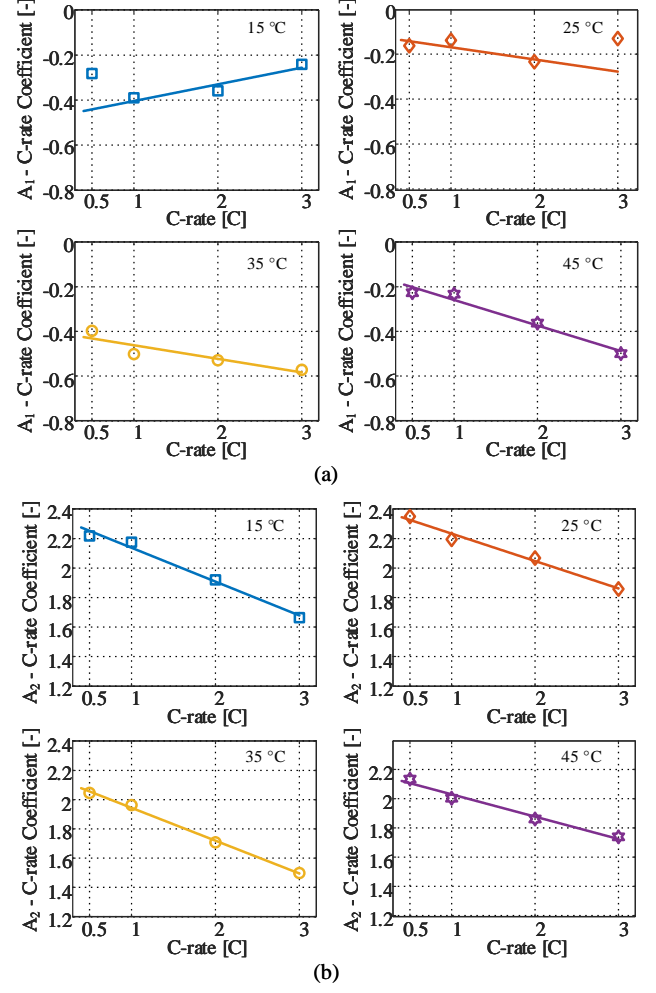


Fig. 8. (a) Relationship between the coefficient $A_1(C, T)$ and the C-rate; (b) relationship between the coefficient $A_2(C, T)$ and the C-rate.

function of the duty cycle, temperature, and C-rate as given in equation (6):

$$Q(D, C, T) = A_{1 \times 2}(C, T) \cdot \begin{bmatrix} D \\ 1 \end{bmatrix} = [A_1(C, T) \quad A_2(C, T)] \cdot \begin{bmatrix} D \\ 1 \end{bmatrix} \quad (6)$$

where $A_{1 \times 2}(C, T)$ represents the C-rate and temperature fitting coefficient; The accuracy of the fitting was quantified by the R^2 coefficient.

To find a function that is able to express the charging capacity measured by different pulsed current, the dependence of $A_{1 \times 2}(C, T)$ coefficient on the C-rate had to be found as presented in Fig. 8. The relationship between $A_{1 \times 2}(C, T)$ and the C-rate can be described in equation (7):

$$\begin{bmatrix} A_1(C, T) & A_2(C, T) \end{bmatrix} = \begin{bmatrix} C & 1 \end{bmatrix} \cdot B_{2 \times 2}(T) = \begin{bmatrix} C & 1 \end{bmatrix} \cdot \begin{bmatrix} B_{11}(T) & B_{21}(T) \\ B_{12}(T) & B_{22}(T) \end{bmatrix} \quad (7)$$

where $B_{2 \times 2}(T)$ represents the temperature-dependent fitting coefficient of $A_{1 \times 2}(C, T)$. The coefficient $B_{2 \times 2}(T)$ at different temperature are the following:

$$\begin{cases} B_{2 \times 2}(T = 15^\circ \text{C}) = \begin{bmatrix} 0.02562 & -0.2297 \\ -0.3594 & 2.368 \end{bmatrix} \\ B_{2 \times 2}(T = 25^\circ \text{C}) = \begin{bmatrix} -0.02704 & -0.1648 \\ -0.09992 & 2.368 \end{bmatrix} \\ B_{2 \times 2}(T = 35^\circ \text{C}) = \begin{bmatrix} 0.0722 & -0.3154 \\ -0.6929 & 2.368 \end{bmatrix} \\ B_{2 \times 2}(T = 45^\circ \text{C}) = \begin{bmatrix} 0.009368 & -0.2375 \\ -0.416 & 2.368 \end{bmatrix} \end{cases} \quad (8)$$

Then, the charging capacity at the full condition considering duty cycle, C-rate, and ambient temperature, can be expressed:

$$Q(D, C, T) = [C \quad 1] \cdot B_{2 \times 2}(T) \cdot \begin{bmatrix} D \\ 1 \end{bmatrix} \quad (9)$$

Fig. 9 shows the charging capacity of the NMC battery cell, where the black points are the measured capacity and the colored surface is the fitted capacity based on the proposed battery model.

The coefficient of temperature should be further fitted to obtain the relationship between the temperature-dependent fitting coefficient and capacity; nevertheless, this could not be realized with a high accuracy. This might be caused by the fact that the tested NMC battery has a data-sheet life of 800 cycles and at each temperature, the battery was subjected to approximately 20 cycles while performing the described tests. Although it can be roughly assumed that the capacity has not faded, the battery was subjected to at least 80 cycles, which had an effect on the battery capacity.

B. Charging time

Fig. 10 shows the charging capacity of the NMC battery cell that was measured at different temperatures and different pulsed currents (see black points in Fig. 10). A function was found to fit the measured charging time for all duty cycles and C-rates of the pulsed current (see the colored surface in Fig. 10). The charging time can be expressed by equation (10):

$$t(D, C, T) = 60 \cdot N_{1 \times 3}(T) \cdot \begin{bmatrix} \frac{1}{D \cdot C} \\ -3 \cdot D \\ 2 \end{bmatrix} \quad (10)$$

where $N_{1 \times 3}(T)$ represents the temperature-dependent fitting coefficient. The coefficient $N_{1 \times 3}(T)$ at different temperature are the following:

$$\begin{cases} N_{1 \times 3}(T = 15^\circ \text{C}) = [0.6705 \quad 0.9678 \quad 1.0642] \\ N_{1 \times 3}(T = 25^\circ \text{C}) = [0.7207 \quad 1.075 \quad 1.2067] \\ N_{1 \times 3}(T = 35^\circ \text{C}) = [0.5912 \quad 0.7039 \quad 0.7472] \\ N_{1 \times 3}(T = 45^\circ \text{C}) = [0.653 \quad 0.9317 \quad 1.0192] \end{cases} \quad (11)$$

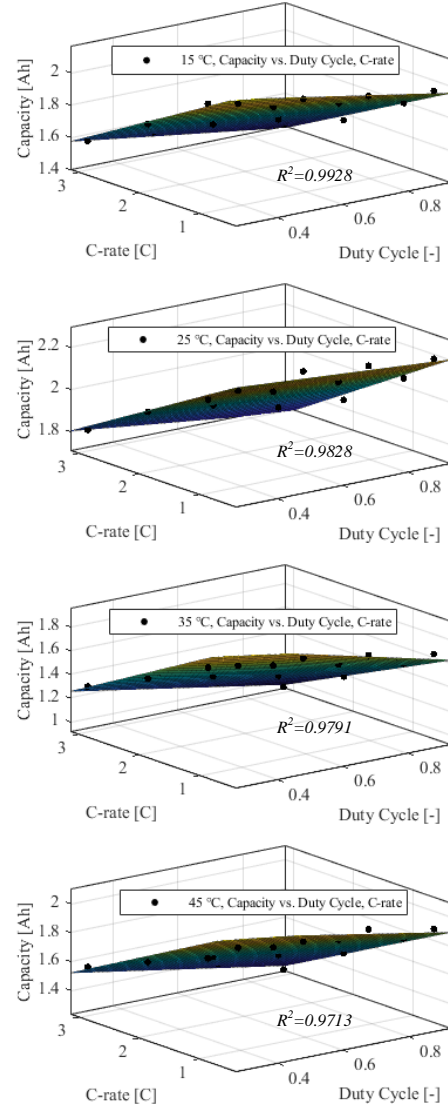


Fig. 9. Measured and the fitted charging capacity based on the proposed pulsed charging capacity model considering the duty cycle and the C-rate.

V. CONCLUSION

In this paper, the effect of the pulsed current on battery performance, including the charging capacity, charging time, and thermal behavior, are investigated. The frequency of the pulsed current is 0.05 Hz. The NMC battery cell was tested in different ambient temperatures (15 °C, 25 °C, 35 °C, 45 °C), different charging current (0.5 C, 1 C, 2 C, 3 C), and different duty cycles (30%, 50%, 70%, 90%). The obtained results of the charging capacity, the charging time, and the maximum rising temperature by the pulsed current are compared with the results of that obtained by the constant current charging. The pulse current can improve the charging capacity of the NMC battery. A lower duty cycle of the pulsed current can obtain a higher charging capacity. Especially when the cell was at a higher temperature condition, the battery capacity can be increased to more than 30%. This is because a lower duty cycle

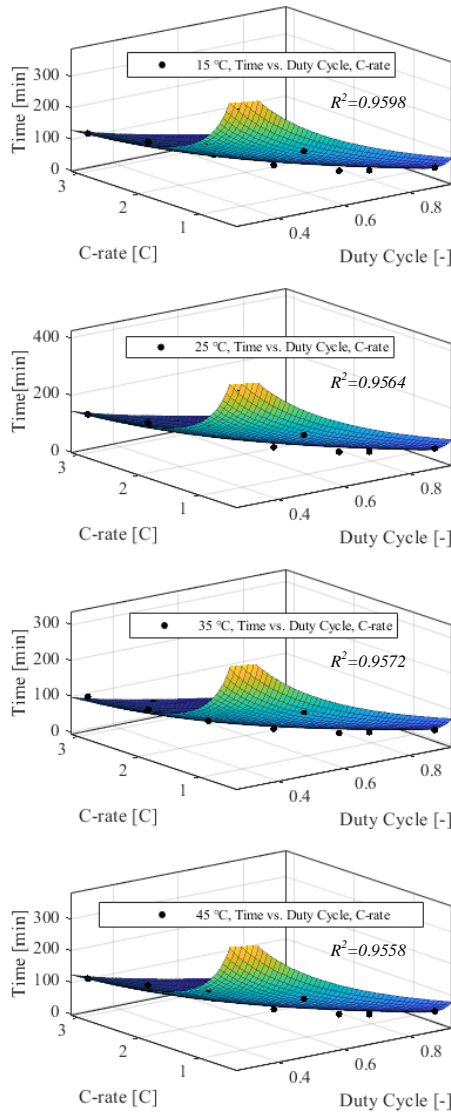


Fig. 10. Measured and fitted charging time based on the proposed pulsed charging time model considering the duty cycle and the C-rate.

means that the battery has more rest time to recover its voltage, and therefore can charge more capacity/energy. However, a longer rest time results in a longer charging time. As the duty cycle increases, the positive effect of the pulse current on the capacity gradually decreases, and even at some temperature conditions, the pulse current will reduce the charging capacity. For example, when the ambient temperature is 15 °C or 35 °C, a 90% duty cycle pulse current will reduce the battery's charging capacity. On the other hand, the time will decrease as the duty cycle increases. Pulse currents can also reduce the maximum rising temperature during battery charging. When the charging current is 3 C, the maximum rising temperature can be reduced by 60.3% on average. This will also have a positive impact on ensuring the safety of the battery during the charging operation and extending the lifetime of the battery. Finally, a model which is able to accurately estimate the

battery capacity at different C-rates, temperatures and duty cycles was developed. Furthermore, a fitted function is given to estimate the charging time on different conditions of the pulsed current.

For future work, the NMC battery cell will be tested by applying the pulsed current with different frequencies. Then, a pulsed current charging strategy that can balance the charging capacity and the charging time will be developed.

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