

## Research Article

# The Research on Characteristics of Li-NiMnCo Lithium-Ion Batteries in Electric Vehicles

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Received 28 April 2019; Revised 25 December 2019; Accepted 1 February 2020; Published 17 June 2020

Academic Editor: Guobing Zhou

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The energy density of canode materials for lithium-ion batteries has a major impact on the driving range of electric vehicles. In order to study the charge-discharge characteristics and application feasibility of Li-NiMnCo lithium-ion batteries for vehicles, a series of charge and discharge experiments were carried out with different rates of Li-NiMnCo lithium-ion batteries (the ratio of nickel, cobalt, and manganese was 5:2:3) in constant-current-constant-voltage mode. Firstly, a set of charge-discharge experiments were performed on different types of single-cell lithium-ion batteries. The results show that, under temperature conditions, the charge and discharge voltage-capacity curves of the four different types of Li-NiMnCo lithium batteries mentioned in the paper are not much different, and the charge-discharge characteristic curves are similar, indicating that different types of batteries with the same material composition have similar charge and discharge characteristics. Subsequently, a series of charge and discharge tests with different rates were conducted on such ternary lithium batteries. The characteristic curves with different charge-discharge rates indicate that this new type of ternary lithium battery has high current charge and discharge capability and is suitable for use in new energy electric vehicles. In addition, by analyzing the voltage-SOC curve under different magnification conditions, it is known that there is an approximate linear relationship between the battery voltage value and the SOC within a certain SOC range. The SOC value can be evaluated by the battery voltage, which should be controlled within a reasonable range to avoid overcharge or overdischarge of battery, thereby, causing permanent damage to the battery.

## 1. Introduction

Electric vehicles (EVs) are widely regarded as the most promising vehicles and have been developed rapidly in recent years. As a common energy storage link for new energy vehicles, power batteries are the bottleneck restricting the development of new energy vehicles. Their performance has an important impact on the driving range, charge, and safety of electric vehicles. The crucial performance of a power battery includes power density, energy density, cycle-life, cost, and safety [1, 2]. Lead-acid batteries have been widely used in many fields for the advantages of low price, rich resources, stable performance, safety and reliability, recyclable, reusable, etc. However, its specific energy and specific power are low, and its

cycle-life is short. Nowadays, lead-acid batteries are rarely used as energy storage in EVs [3]. Compared with lead-acid batteries, nickel-metal hydride batteries have the advantages of pollution-free, large specific energy, large specific power, and long cycle life, but they have low single voltage, relatively high self-discharge rate, high price, and narrow operating temperature range. Nowadays, some EVs still use nickel-metal hydride batteries as energy storage components. Ultra capacitors have the advantages of long cycle-life, high specific power, fast charge speed, high operating temperature range, and high safety, but with little energy density. Ultra capacitors are widely used in EVs at present [4]. Lithium-ion batteries have excellent comprehensive performance of energy, power density, and cycle-life. Therefore, it is usually the best choice to use

the lithium-ion battery as storage cell based on comprehensive consideration of its energy and power density and cycle-life for battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs). On the other hand, lithium-ion batteries require particular care in EV applications, such as overcurrent, overvoltage, or overcharge/discharge, which can cause significant safety issue to the batteries, noticeably accelerate the aging process, and even cause fire or explosion [5–7]. As one of new energy vehicle’s core technology, lithium-ion batteries may be widely used in the near future.

A lithium-ion single cell usually consists of a positive electrode, a negative electrode, and an electrolyte. The choice of electrode material determines the type and basic performance of the battery. At present, the new cathode materials discovered and synthesized include  $\text{LiMn}_2\text{O}_4$ ,  $\text{LiFePO}_4$ , and  $\text{Li-NiMnCo}$ . Graphite can be used as a negative electrode material. By comparing the performance of several commonly used lithium-ion cathode materials,  $\text{Li-NiMnCo}$  materials have better comprehensive performance in terms of energy density, power density, and lifetime. In the past decade, the research on lithium-ion battery materials has attracted more and more researchers’ attention. Lithium-ion battery can be categorized into a Liquefied Lithium-Ion Battery (or LIB for short) and a Polymer Lithium-Ion Battery (or simply PLIB) according to the electrolyte. The polymer lithium-ion battery (PLB) can be made into an ultrathin battery of wanton form and wanton size. Therefore, it has a broad application prospect. The charge-discharge characteristics and battery management of power lithium battery are the bottleneck of power technology development. The anode material is the core and key material of power lithium battery. The energy density of the anode material is closely related to the range of electric vehicles, and its cost accounts for about 1/3 of the cost of the lithium battery. Therefore, the development of anode materials with high energy density, long life, high safety, and low cost is crucial for the large-scale commercial use of lithium batteries and electric vehicles [8].

With the increasing research in the field of SOC (State of Charge) and SOH (State of Health) [9–17], nowadays improving the accuracy of the charge and discharge model of power batteries, especially lithium-ion batteries, is a crux research target. The available battery capacity can influence and even determine how long a battery can be fully charged and consequently, how far a vehicle can travel. The charge approaches can protect batteries from overheating, improve the capacity utilization, and prolong the service life, which is of great significance. There are four traditional charge approaches in EVs, including constant-current (CC) charge, constant-voltage (CV) charge, constant-current-constant-voltage (CC-CV) charge, and multistage constant-current (MCC) charge [18]. The CC charge is a rough but simple approach which is widely used for lithium-ion batteries [19]. In [20], the CC charge approach is first introduced to charge NiCd or NiMH batteries. Because the behaviours of batteries are highly dependent on the current rate in CC charge, therefore, it is a challenge to search a suitable charging current rate for CC charge. The charge speed is improved, but the battery aging process will be aggravated

TABLE 1: Basic parameters of ternary battery.

Item	Specification
Nominal voltage	3.7 V
Charge cutoff voltage	4.4 V
Discharge cutoff voltage	2.75 V
Cell weight	195 g $\pm$ 15 g
Cell dimension	Thickness: 5.0 $\pm$ 0.30 mm (full charge)
	Width: 100.0 $\pm$ 2.0 mm (no folding)
	Height: 200.0 $\pm$ 2.0 mm

with large current rate in CC charge. While the high capacity utilization is achieved, too low current rate will slow down the battery charging speed with small current rate in CC charge. The proper battery charge approaches can be effectively designed according to enough accurate estimation of SOC, SOH, and temperature.

Lithium-ion power battery is a kind of high-performance energy storage cell. It is difficult to establish the mathematical model of the battery from the perspective of mechanism due to the complexity and strong nonlinearity of the battery. In order to provide data support and theoretical support for battery management, the test method is generally used to study the performance of the battery and a large number of experimental data are used to summarize the external characteristics of the battery in practical application. Promising applications such as EVs and smart grids have already encouraged many researchers to improve the performance of lithium-ion batteries. One area of research is to study anode battery materials. Previous studies have pointed out that there are a variety of materials can be used in anode materials for lithium-ion batteries. In this paper, we will focus on  $\text{Li-NiCoMn}$  lithium-ion batteries. We conducted a preliminary study on charge and discharge test data of  $\text{Li-NiCoMn}$  lithium-ion batteries, in order to analyze and study the charge and discharge characteristics of  $\text{Li-NiCoMn}$  batteries. A series of experiments were performed under different conditions. The contribution of this paper is threefold as follows.

- (1) A series experiments were designed to determine capacity of  $\text{Li-NiCoMn}$  lithium-ion battery under different conditions in CC charge
- (2) Charge and discharge characteristic curves of lithium-ion battery are obtained under different conditions in CC charge
- (3) The experiments’ results can provide support for searching the proper charge current rate of battery in order to further improve charge performance

This paper is organized as follows. Section 2 details a set of experiments to determine the battery capacity of the  $\text{Li-NiCoMn}$  lithium-ion battery used in this paper. Section 3 describes a series of charge and discharge tests for a single  $\text{Li-NiCoMn}$  lithium-ion battery. Finally, Section 4 concludes this paper with a summary of contributions and with a discussion on possible extensions.

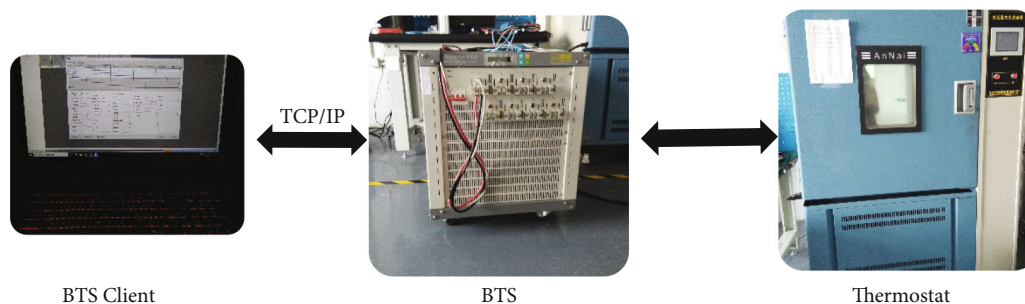


FIGURE 1: The schematic of the battery test bench.

## 2. Charge Characteristic Tests of Single Cell Li-NiCoMn Lithium-Ion Batteries

In this paper, the newly developed ternary Li-NiMnCo (the material ratio of nickel, manganese, and cobalt is 5:2:3) is selected as the test object. Its basic parameters are shown in Table 1. From Table 1, we can see that its nominal capacity is 10.0 AH, the charge cutoff voltage is 4.4 V, and the discharge cutoff voltage is 2.75 V. The other items such as cell weight and cell dimension are also shown in Table 1.

As shown in Figure 1, the schematic of the battery test bench consists of three parts: thermostat, BTS (battery testing system), and BTS Client. The operating range of the thermostat is  $-80^{\circ}$ – $150^{\circ}$  and the accuracy is  $0.1^{\circ}$ , which can provide suitable and stable ambient temperature for the selected lithium-ion battery. The lithium-ion battery which is connected with the BTS through the battery clamp and is placed in the thermostat. The BTS Client is installed on the computer, which communicates with the BTS through TCP/IP. It can set the working condition of the BTS and complete the data collection and analysis functions of a series of experiments in this paper.

The objective of this paper is to study the behaviors of Li-NiCoMn cell. The test content includes the relationship between battery charge voltage and capacity, the relationship between battery charge voltage and SOC, battery charge efficiency, and charge characteristics of different rates in CC charge. The charge characteristics are summarized through a large number of tests, which can support for searching the proper charge-discharge current rate of battery in order to further improve charge-discharge performance.

**2.1. Charge Capacity Tests of Single Cell Ternary Li-NiMnCo Lithium-Ion Batteries.** In order to analyze the capacity of the selected ternary lithium battery material, a set of experiments were designed for different types of batteries in CC charging-discharge mode from different manufacturers. Table 2 shows the test results. In Table 2, the anode materials ZH and PU50D in the second column are from China Zhenhua (Group) Technology Co., Ltd. and Peking University Industrial Co., Ltd., and the third column cathode materials AML402 and YI202 are from Dongguan Kaijin New Energy Technology Co., Ltd., and column 4 materials CG-CS and TCE8633 are two different electrolytes. The capacity in Table 1 is the corresponding charge battery capacity when

TABLE 2: Capacity of single Li-NiMnCo lithium-ion batteries.

Battery model	Anode	Cathode	Electrolyte	Capacity (mAh)
#1	ZH	AML402	CG-CS	11087
#2	ZH	YI202	CG-CS	11001
#3	ZH	YI202	TCE8633	11070
#4	PU50D	YI202	TCE8633	10709

each single cell is charged to a cutoff voltage of 4.4 V with constant rate 1 C.

From Table 2, it can be seen that the four different types of ternary Li-NiMnCo materials have higher charge capacity in the 1 C constant current charge mode. For different battery models, the difference in battery capacity charged is small.

**2.2. Charge Characteristic Tests of Single Cell Ternary Li-NiMnCo Lithium-Ion Battery.** In order to analyze the charge characteristics of the ternary Li-NiMnCo batteries shown in Table 2, a set of charge experiments for the four types of batteries in CC charge mode is designed in this section. The charge process is under normal temperature conditions and charge the cells with constant rate 1 C to 4.4 V. According to the experimental data, the relationship between voltage and capacity of four different models is obtained, as shown in Figure 2. Figure 3 shows the relationship between the charge voltage and SOC of four different types of ternary lithium batteries.

Comparing the four curves in Figure 2, it can be seen that the voltage capacity curves of different battery models are similar, which indicates that the anode materials are from different manufacturers, but having the same composition ratio of Ni, Mn, and Co has little difference in the charge characteristic curve of the single ternary lithium battery.

As shown in Figure 2, the operating voltage of the ternary lithium battery has gone through three stages: the voltage rises faster in the early and late stages of charge, while in the middle of charge, the charge curve tends to be flat. Based on this charge characteristic of the battery, we can use the piecewise function to estimate the charge capacity of the battery by measuring the voltage value of the battery. During the experiment, it should be noted that the battery voltage cannot be higher than the charge cutoff voltage, which will cause permanent damage to the battery.

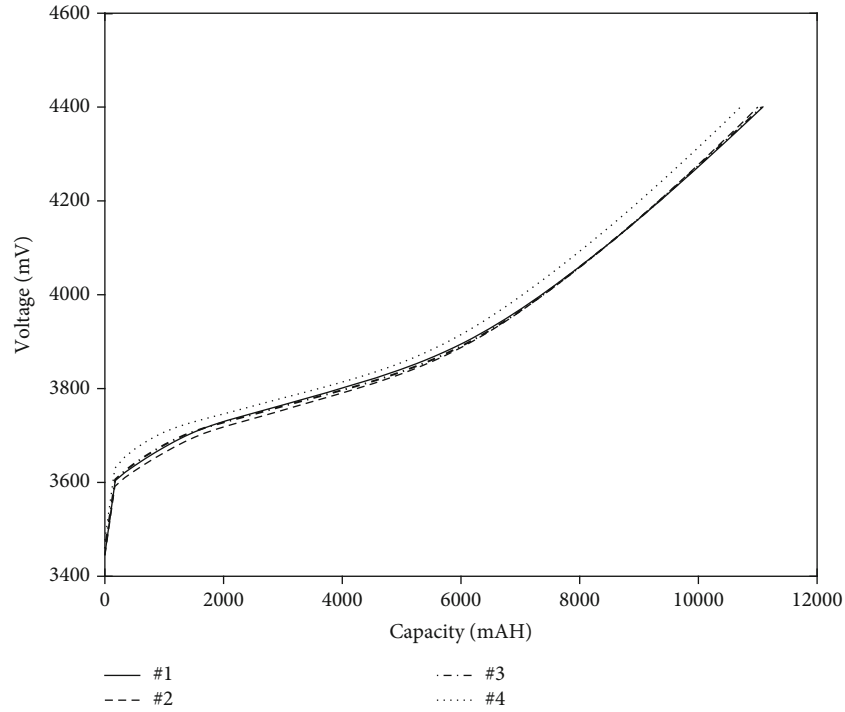


FIGURE 2: Charge characteristic curves of different types of batteries.

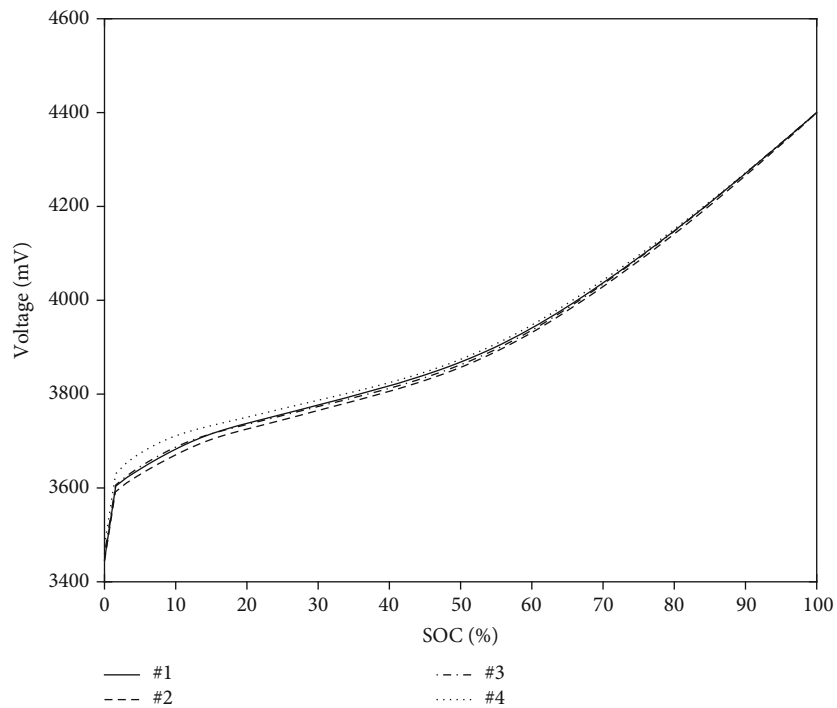


FIGURE 3: SOC-OCV curves of the different types of batteries.

As can be seen from Figure 3, in the range of SOC values of 15%-65%, the curve is approximately a straight line with a small slope. While in the range of SOC values from 65% to 100%, the curve approximation is also approximately a straight line with a slightly larger slope. For a hybrid car,

the battery is often in a nonoperating state even during vehicle operation; the value of the OCV can be measured conveniently. Therefore, the value of the SOC can be predicted by the value of the OCV using the piecewise function according to this characteristic of the curve representation.

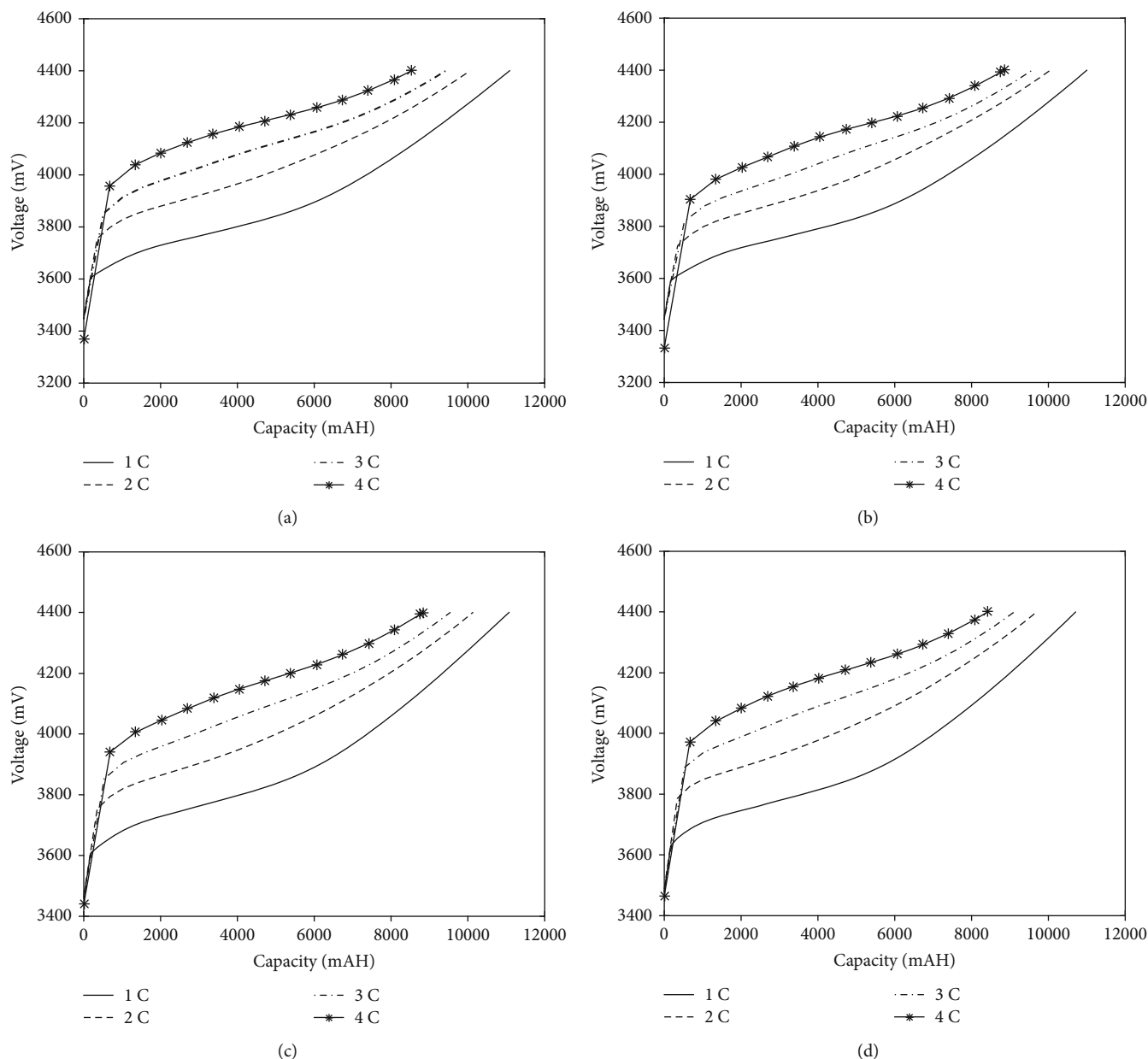


FIGURE 4: Charge curves with different rates: (a) #1 battery; (b) #2 battery; (c) #3 battery; and (d) #4 battery.

**2.3. Rate Charge Characteristic Tests of Single Cell Ternary Li-NiMnCo Lithium-Ion Battery.** The rate charge tests are carried out using single cell ternary Li-NiMnCo lithium-ion batteries in this section. Figures 4(a)–4(d) show the voltage capacity curves of four different types of lithium batteries; Figures 5(a)–5(d) show the SOC-OCV curves for four different types of lithium batteries.

As can be seen from Figures 4(a)–4(d), the ternary lithium batteries used have better charge characteristics, which can be charged at a higher rate. Comparing Figures 4(a)–4(d), it can be found that the battery charge curves are similar for 4 different types of batteries and each type of battery can accept 4 C constant rate charge. In addition, the charged battery capacity decreases with the charge rate increases.

Similarly, from Figures 5(a)–5(d), we can get that, under 4 C constant rate charge conditions, when the SOC value is greater than about 8%, the curves approximate straight lines. Correspondingly, the SOC value can also be estimated by measuring the voltage.

### 3. Discharge Characteristic Tests of Single Cell Li-NiCoMn Lithium-Ion Batteries

A series of discharge experiments are designed in this section, and the experimental objects are the same as in Section 2. The experimental process: discharge the cells with constant rate 0.5 C to cutoff voltage 2.75 V. Correspondingly, the test content includes the relationship between the discharge voltage and the capacity of the battery, the relationship between the

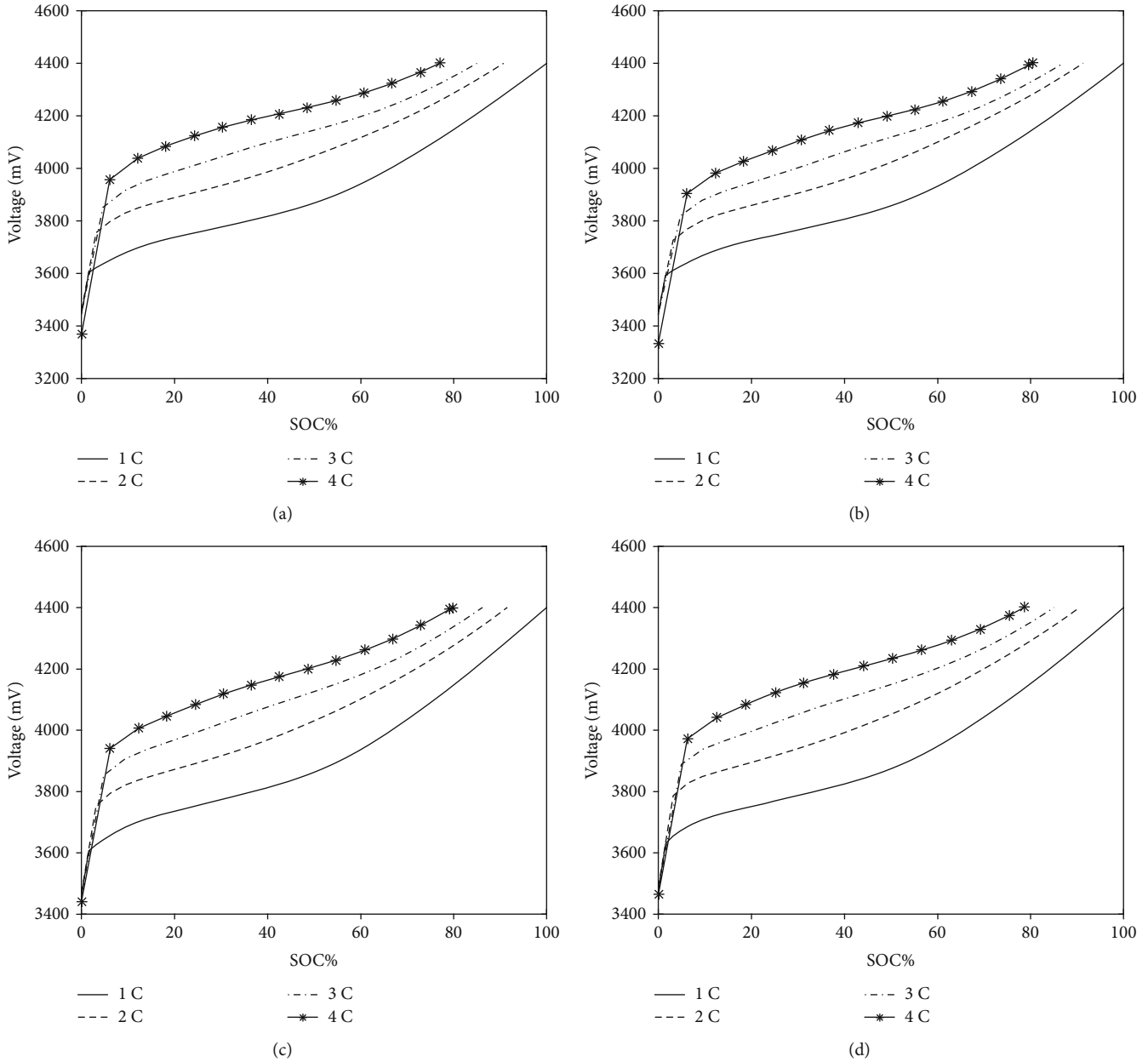


FIGURE 5: SOC-OCV curves with different rates: (a) #1 battery; (b) #2 battery; (c) #3 battery; and (d) #4 battery.

TABLE 3: Discharge capacity of different types of Li-NiMnCo batteries.

Model	Anode	Cathode	Electrolyte	Capacity
#1	ZH	AML402	CG-CS	12142
#2	ZH	YI202	CG-CS	11785
#3	ZH	YI202	TCE8633	12002
#4	PU50D	YI202	TCE8633	11614

discharge voltage of the battery and the SOC, the discharge efficiency of the battery, and the discharge characteristics of different rates. The battery discharge performance is obtained through these tests, and the discharge characteristics of the battery are summarized, which lays a foundation for battery state estimation and health estimation, and

provides a theoretical basis for rational and effective use of the battery.

3.1. Discharge Capacity Tests of Single Cell Ternary Li-NiMnCo Lithium-Ion Batteries. Table 3 shows the capacity of the four different types of ternary materials studied in this

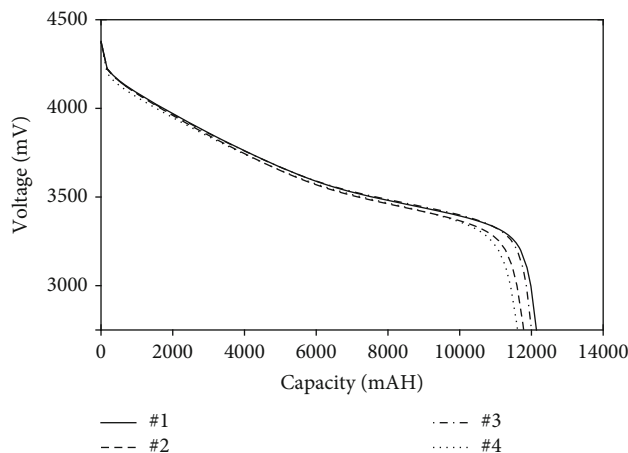


FIGURE 6: Discharge curves with the different types of batteries.

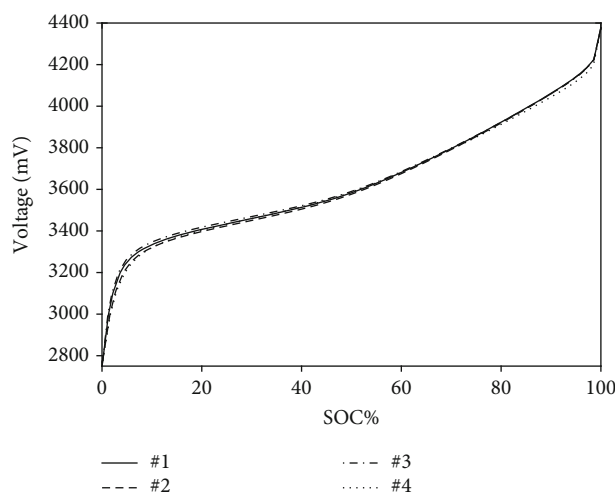


FIGURE 7: SOC-OCV curves with the different types of lithium batteries.

paper. The capacity in the table is the corresponding discharge battery capacity when each single cell is discharged in the 1 C constant current discharge mode to a cutoff voltage of 2.75 V.

It can be seen from Table 3 that under the full power state, four different types of ternary Li-NiMnCo batteries can discharge a large amount of electricity when discharged to a cutoff voltage of 2.75 V in 1 C constant current discharge mode. The battery capacity difference of the four types of batteries is small.

**3.2. Discharge Characteristic Tests of Single Cell Ternary Li-NiMnCo Lithium-Ion Battery.** Similar to Section 2.2, in order to analyze the discharge characteristics of single Li-NiMnCo batteries, a set of discharge experiments were carried out for four types of batteries in this section. The discharge process is under normal temperature conditions, the batteries are discharged to a cutoff voltage of 2.75 V at a constant current with 1 C rate. According to the experimental data, the relationship between the voltage and the discharge capacity of four different models is obtained, as shown in Figure 6.

Figure 7 shows the OCV-SOC curves for four different types of lithium batteries discharged to cutoff voltage of 2.75 V.

By comparing the curves in Figure 6, the voltage drops rapidly in the initial stage of battery discharge, and then the discharge curve gradually becomes flat, and in the later stage of discharge, the voltage curve decreases linearly. Different types of batteries have certain differences in the later stage of discharge. Based on this discharge characteristic of the battery, we can use the piecewise function to estimate the discharge capacity of the battery by measuring the voltage value of the battery. From the characteristic curve of the later stage of discharge, it should be noted that the battery voltage cannot be lower than the discharge cutoff voltage; otherwise, overdischarge will occur, causing permanent damage to the battery. Figure 6 shows the discharge voltage as a function of SOC. As can be seen from Figure 7, in the range of the SOC of about 15% to 95%, the curve is approximately a straight line, and the slope is small, which has stable discharge performance. While the slope of the initial stage of discharge and the later stage of discharge is large. The SOC-OCV discharge curves of different types of batteries

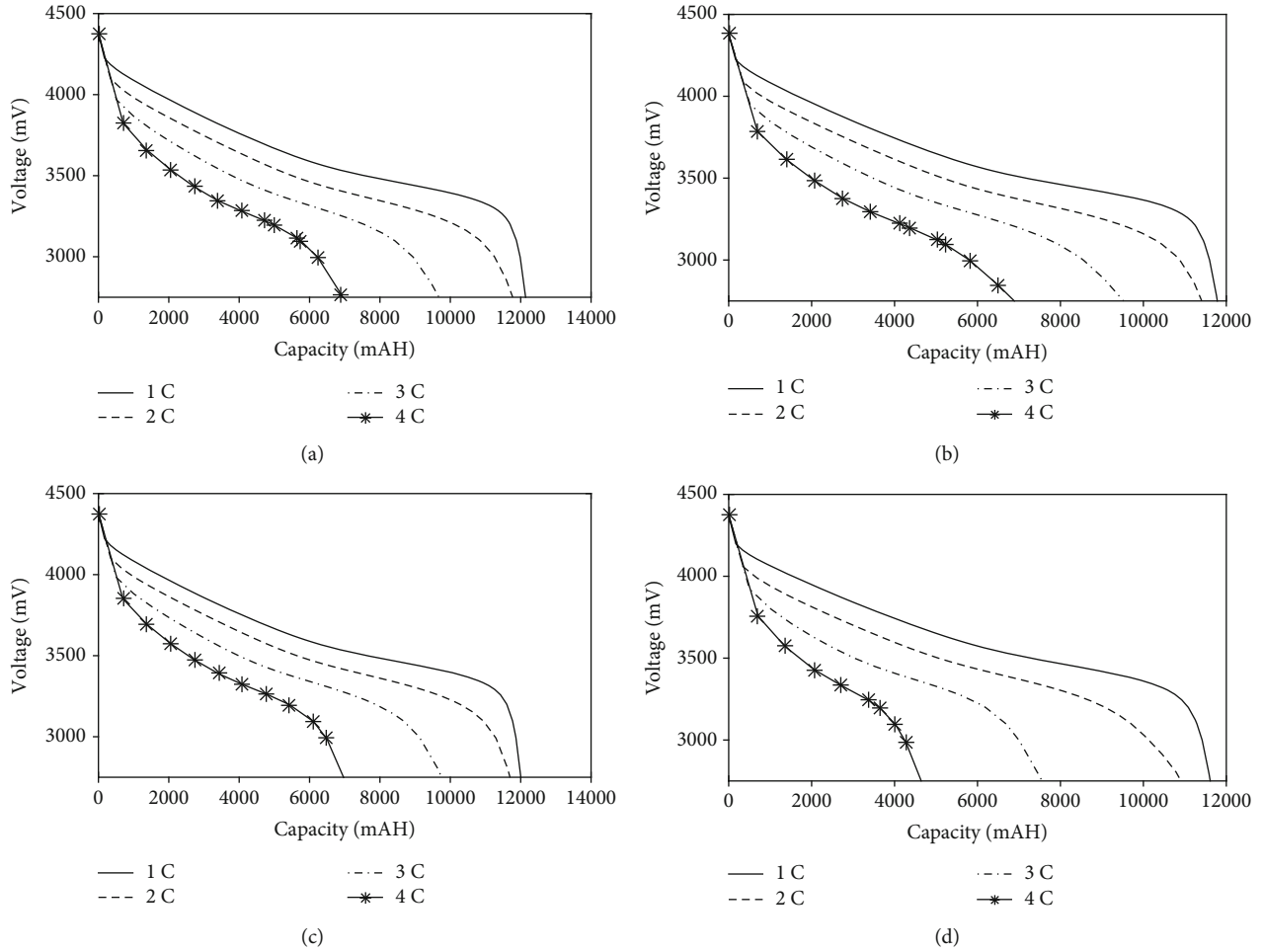


FIGURE 8: Discharge curves with different rates: (a) #1 battery; (b) #2 battery; (c) #3 battery; and (d) #4 battery.

are similar. We can use the piecewise function to predict the value of SOC by the value of OCV according to the characteristics of the curve representation.

**3.3. Rate Discharge Characteristic Tests of Single Cell Ternary Li-NiMnCo Lithium-Ion Battery.** In this section, the selected lithium battery are subjected to rate charge tests. Figures 8(a)–8(d) show the voltage capacity relationship of the four different types of batteries. Figures 9(a)–9(d) show the SOC-OCV relationship curves for the four different types of batteries.

It can be seen from Figures 9(a)–9(d) that the ternary Li-NiMnCo lithium-ion batteries studied have better discharge characteristics which can be discharged at a large rate. From the comparison of Figures 8(a)–8(d), it can be found that the discharge rate curves of the four different types of batteries are similar, and each type of battery can accept the 4 C discharge rate. In addition, it can be seen that the larger the discharge rate is, the smaller the discharged battery capacity is when discharged to a cutoff voltage of 2.75 V.

It can be seen from Figures 9(a)–9(d) that, under 4 C discharge rate conditions, correspondingly, we can also estimate the corresponding SOC value by measuring the voltage.

## 4. Conclusions

In this paper, the characteristics of different Li-NiMnCo lithium batteries are analyzed through a series of charge and discharge experiments. The results from experiments indicate that (1) at room temperature, the charge voltage of the Li-NiMnCo lithium batteries we studied in this paper increase rapidly in the early and late stages of the charge process, while the charge curves are smooth in the middle of the charge process. Based on these characteristics, the battery capacity can be accurately predicted by the terminal circuit voltage. Noticeably, the battery voltage must not exceed a preset threshold to avoid permanent damages to the battery. (2) Similarly, the discharge voltage curves of a Li-NiMnCo lithium battery has similar properties during discharge process at room temperature. The battery capacity also can be predict precisely by the terminal voltage according these characteristics. It concludes that the driving range of a lithium battery electric vehicle after a single charge should be controlled within a reasonable range charge to prevent permanent damage to the battery caused by excessive voltage decay in the later stage of discharge. (3) The Li-NiMnCo lithium battery studied in this paper has good rate charge



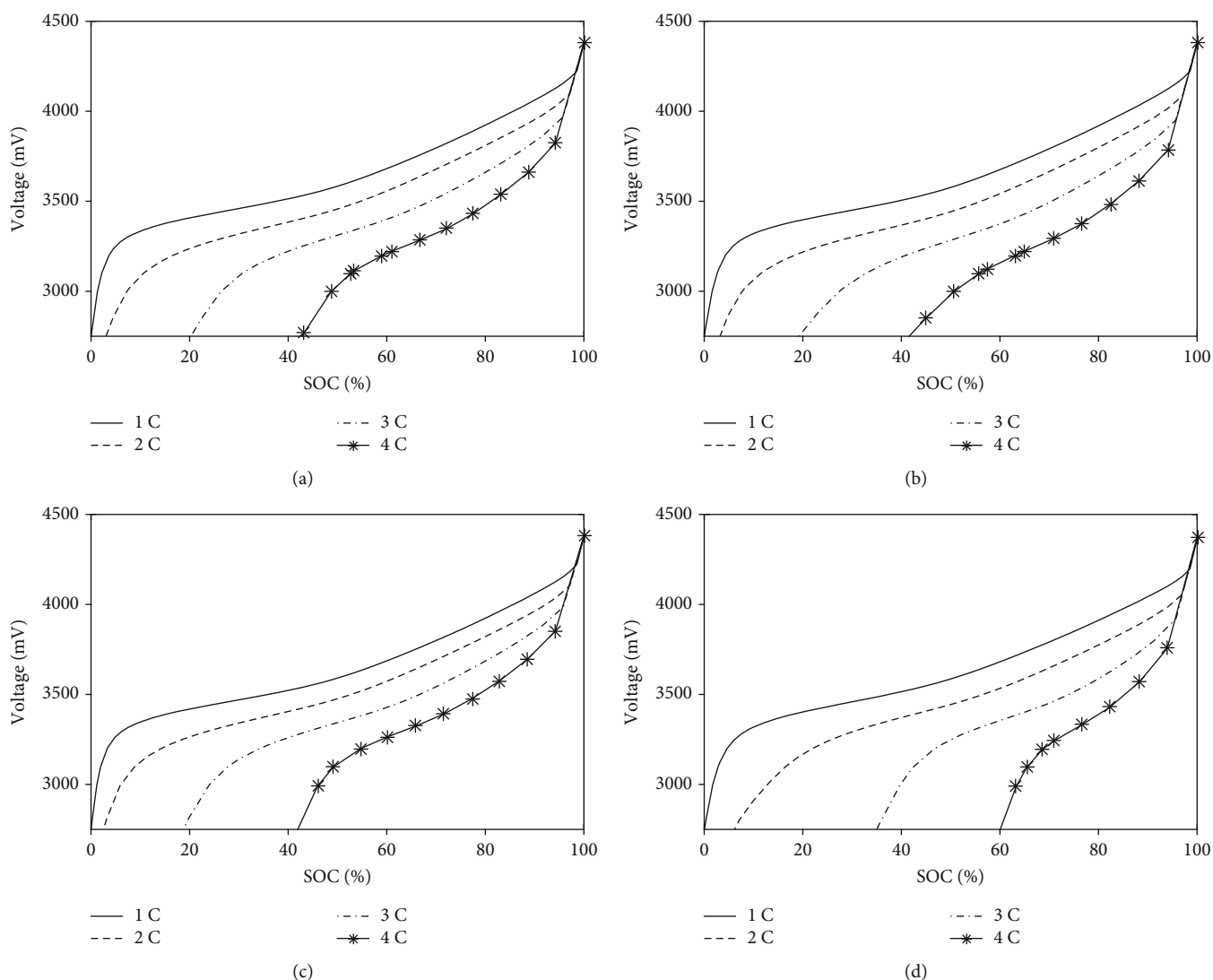


FIGURE 9: SOC-OCV curves with different rates: (a) #1 battery; (b) #2 battery; (c) #3 battery; and (d) #4 battery.

and discharge performance, as well as high current charge and discharge performance, which is suitable for electric vehicles. The results studied in this paper will provide a reference for searching proper charge-discharge current rate which can improve charge-discharge performance. In future work, we will focus on modeling and SOC estimation of Li-NiCoMn lithium-ion battery.

### Data Availability

The data used to support the findings of this study are included within the supplementary information file.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

### Acknowledgments

This work was sponsored by the Educational Commission of Jiangsu Province of China (grant no. BE2017008-3), the Qing Lan Project, and the Science and Technology Innovation Fund of Nanjing Institute of Technology (grant no. YKJ201434).

### References

- [1] B. Kennedy, D. Patterson, and S. Camilleri, "Use of lithium-ion batteries in electric vehicles," *Journal of Power Sources*, vol. 90, no. 2, pp. 156–162, 2000.
- [2] J. Speirs, M. Contestabile, Y. Houari, and R. Gross, "The future of lithium availability for electric vehicle batteries," *Renewable and Sustainable Energy Reviews*, vol. 35, pp. 183–193, 2014.
- [3] R. M. S. Santos, C. L. G. D. S. Alves, E. C. T. Macedo, J. M. M. Villanueva, L. V. Hartmann, and S. Y. C. Catunda, "Lead acid

- battery SOC estimation based on extended Kalman filter method considering different temperature conditions,” in *2017 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, pp. 1–6, Turin, 2017.
- [4] L. Zhang, Z. Wang, X. Hu, F. Sun, and D. G. Dorrell, “A comparative study of equivalent circuit models of ultracapacitors for electric vehicles,” *Journal of Power Sources*, vol. 274, pp. 899–906, 2015.
- [5] A. Bartlett, J. Marcicki, S. Onori, G. Rizzoni, X. G. Yang, and T. Miller, “Electrochemical model-based state of charge and capacity estimation for a composite electrode lithium-ion battery,” *IEEE Transactions on Control Systems Technology*, vol. 24, no. 2, pp. 1–399, 2015.
- [6] K. Liu, K. Li, Q. Peng, and C. Zhang, “A brief review on key technologies in the battery management system of electric vehicles,” *Frontiers of Mechanical Engineering*, vol. 14, no. 1, pp. 47–64, 2019.
- [7] L. Lu, X. Han, J. Li, J. Hua, and M. Ouyang, “A review on the key issues for lithium-ion battery management in electric vehicles,” *Journal of Power Sources*, vol. 226, pp. 272–288, 2013.
- [8] R. Huggins, *Advanced Batteries: Materials Science Aspects*, Springer, 2009.
- [9] Z. Chen, X. Li, J. Shen, W. Yan, and R. Xiao, “A novel state of charge estimation algorithm for lithium-ion battery packs of electric vehicles,” *Energies*, vol. 9, no. 9, pp. 710–785, 2016.
- [10] C. Lin, Q. Yu, R. Xiong, and L. Y. Wang, “A study on the impact of open circuit voltage tests on state of charge estimation for lithium-ion batteries,” *Applied Energy*, vol. 205, pp. 892–902, 2017.
- [11] Y. Zheng, M. Ouyang, L. Lu, J. Li, Z. Zhang, and X. Li, “Study on the correlation between state of charge and Coulombic efficiency for commercial lithium ion batteries,” *Journal of Power Sources*, vol. 289, pp. 81–90, 2015.
- [12] J. Li, L. Wang, C. Lyu, and M. Pecht, “State of charge estimation based on a simplified electrochemical model for a single LiCoO<sub>2</sub> battery and battery pack,” *Energy*, vol. 133, pp. 572–583, 2017.
- [13] R. Xiong, F. Sun, and Z. Chen, “Each of lithium-ion polymer battery in electric vehicles,” *Applied Energy*, vol. 113, no. 1, pp. 463–476, 2014.
- [14] M. Ye, H. Guo, and B. Cao, “A model-based adaptive state of charge estimator for a lithium-ion battery using an improved adaptive particle filter,” *Applied Energy*, vol. 190, pp. 740–748, 2017.
- [15] C. Zou, C. Manzie, D. Nešić, and A. G. Kallapur, “Multi-time-scale observer design for state-of-charge and state-of-health of a lithium-ion battery,” *Journal of Power Sources*, vol. 335, pp. 121–130, 2016.
- [16] R. Mingant, J. Bernard, and V. Sauvant-Moynot, “Novel state-of-health diagnostic method for Li-ion battery in service,” *Applied Energy*, vol. 183, pp. 390–398, 2016.
- [17] M. Gholizadeh and F. R. Salmasi, “Estimation of state of charge, unknown nonlinearities, and state of health of a lithium-ion battery based on a comprehensive unobservable model,” *IEEE Transactions on Industrial Electronics*, vol. 61, no. 3, pp. 1335–1344, 2014.
- [18] K. Liu, K. Li, Q. Peng, and C. Zhang, “A brief review on key technologies in the battery management system of electric vehicles,” *Frontiers of Mechanical Engineering*, vol. 14, no. 1, pp. 47–64, 2019.
- [19] A. C. C. Hua and B. Z. W. Syue, “Charge and discharge characteristics of lead-acid battery and LiFePO<sub>4</sub> battery,” in *The 2010 International Power Electronics Conference - ECCE ASIA*, pp. 1478–1483, Sapporo, 2010.
- [20] D. Berndt, *Maintenance-Free Batteries: Lead-Acid, Nickel-Cadmium, Nickel-Metal Hydride*, Research Studies Press, Taunton, 1997.