[1] Yi Liu

Research on SOP Estimation Based on SOC Constraints under Static Operating Conditions

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Abstract: - In a battery management system (BMS), accurate estimation of system operating power (SOP) is essential to ensure battery performance and extend service life. In this paper, an SOP estimation method based on open circuit voltage (OCV), state of charge (SOC) and battery current is studied. By analyzing the battery data under dynamic stress test (DST) conditions, the estimated value of continuous peak charge and discharge current is calculated, and the corresponding continuous peak charge and discharge power is estimated accordingly. Comparing the estimated charging and discharging power with the experimental value, the results show that the new algorithm can significantly improve the estimation accuracy of SOP. It not only improves the accuracy of SOP estimates, but also helps to optimize BMS, thereby improving the overall performance and service life of the power battery.

Keywords: battery management system, power state, open circuit voltage, charge state, constraint condition

Lithium-ion battery is the core of modern energy storage system, and its state estimation technology is the key to ensure the safe and reliable operation of the battery. Among various state estimation indicators, State of Charge (SOC) and State of Power (SOP) are the two most important parameters[1]. In this paper, we will introduce a joint SOC and SOP estimation method, which improves the accuracy and practicability of the estimation by considering the electrochemical characteristics and real-time operating state of the battery.

1. Introduction

In the field of battery management systems (BMS), accurate estimation of a battery's SOC and SOP has a decisive impact on ensuring battery performance, extending battery life and maintaining its safety[2]. To accurately estimate and manage these parameters, BMS requires the use of data analysis and mathematical modeling techniques. By integrating multiple sensor data such as temperature, voltage, and current, BMS can monitor battery status in real time and apply algorithms to dynamically adjust charging and discharging

1. School of mechanical engineering, Jiangxi Vocational College of Mechanical & Electrical Technology, Nanchang,Jiangxi,330013,China

Corresponding Author: Yi Liu m19979169387@163.com

strategies to optimize performance and extend battery life.

In today's continuous advancement of battery technology, accurate estimation of SOC and SOP not only affects the direct performance of the battery, but also relates to the overall efficiency and reliability of the system [3]. Therefore, the continuous optimization of these estimation methods will provide a solid foundation for the development of electric vehicles (EVs), renewable energy storage, and other battery-dependent applications.

2. Importance of SOC and SOP

SOC is the ratio of the battery's remaining charge [4], which is the percentage of the battery's current stored charge to its maximum storable charge. An SOC is a unitless quantity, usually expressed as a percentage. For example, an SOC of 100% means that the battery is fully charged, while an SOC of 0% means that the battery charge is completely released.

In BMS, accurate estimation of the SOC is a core part of achieving efficient energy management and ensuring battery safety. SOC, as a key indicator to measure the ratio of current remaining battery power to the total, directly affects the operational efficiency, safety, and user confidence in battery endurance [5].

Accurate SOC estimation is essential to prevent battery overcharge and overdischarge. Overcharging the battery may lead to an increase in internal pressure, temperature, and even thermal runaway, while over discharging can cause the battery voltage to fall below the safety threshold, further affecting its performance and lifespan. By accurately monitoring SOC, BMS can ensure that the battery operates within a safe voltage and current range, thereby effectively avoiding these risks [6].

Accurate SOC estimation optimizes battery life. Batteries undergo physical and chemical changes during charging and discharging, which accelerate with the increase of battery usage time. By accurately estimating the SOC and adjusting the charge and discharge strategy accordingly, the aging process of the battery can be slowed down and its service life can be extended. For example, avoiding prolonged exposure to high SOC levels can significantly reduce the stress and capacity attenuation of lithium-ion batteries [7].

Accurate SOC estimates are essential to provide accurate range information. For EV users, accurate battery life prediction is an important basis for their vehicle planning. Inaccurate SOC estimates may lead to errors in driving range, which in turn affects users' vehicle scheduling and trust in EVs[8]. By improving the accuracy of SOC estimates, the user experience and market acceptance of EVs can be significantly improved.

Therefore, the importance of SOC in BMS is self-evident. It is not only the basis for ensuring the safe operation of batteries, but also the key to optimizing battery life and improving user experience[9]. With the continuous advancement of battery technology and management systems, the accuracy of SOC estimates will be further improved in the future, laying a more solid foundation for the development of battery-dependent applications.

SOP refers to the maximum power that a battery can safely deliver or absorb at a specific SOC. SOP reflects the load capacity of the battery over a short period of time, including both discharge power (that is, the ability to provide energy) and charge power (that is, the ability to absorb energy). Accurate estimation of the SOP helps to optimize the performance of the battery and ensure that the battery can perform at its maximum performance under different operating conditions[10].

SOP is the ratio of peak power to nominal power. According to the literature definition[11], under the design voltage, current, SOC and power constraints, the maximum power that the battery can continuously provide in T seconds is defined as the peak power. After the peak power of the battery is obtained, the power state of the battery can be calculated by equation (1)[12].

$$\begin{cases} SOP_{chg} = \frac{P_{min}^{chg}}{P_{n}^{chg}} \times 100\% \\ SOP_{dis} = \frac{P_{max}^{dis}}{P_{n}^{dis}} \times 100\% \end{cases} \#(1)$$

SOP_{chg} indicates the charging power status, SOP_{dis} indicates the discharge power status, P_{min}^{chg} indicates the peak battery charging power, P_{max}^{dis} indicates the peak battery discharge power, and P_{n} indicates the nominal battery power.

In the design and operation of electric vehicles, the BMS plays a crucial role in the accurate estimation of the battery SOP. SOP reflects the maximum power that a battery can safely deliver or absorb in a short period of time and has a direct impact on the acceleration performance of an electric vehicle and the optimization of regenerative braking systems. Through accurate SOP estimation, BMS can ensure that electric vehicles maintain high performance while not exceeding the safe operating range of the battery[13].

Accurate estimation of SOP is crucial for the optimization of EV acceleration performance [14]. The power of an EV comes mainly from its battery system, so it requires a large amount of energy to be released by the electric fast pool during acceleration. If the SOP estimation is too low, it may limit the acceleration capacity of the electric vehicle; On the contrary, excessive estimates may lead to excessive battery discharge, increasing safety risks. By accurately estimating the SOP, BMS can maximize the power output of the electric vehicle while ensuring safety and improving the user's driving experience.

For regenerative braking systems, accurate estimation of SOP is equally crucial. The regenerative braking system effectively improves energy utilization by recovering energy into the battery during the braking process. However, the energy that batteries can safely absorb in a short period of time is limited, which requires BMS to accurately estimate this maximum capacity to avoid damage to the battery during regenerative braking. It not only protects the battery, but also ensures the efficient operation of the regenerative braking system[15].

Accurate estimation of the SOP is also critical to the design of thermal management systems for electric vehicles. Under high load conditions, the heat of the battery will increase sharply. If not controlled through effective thermal management, it may lead to a decrease in battery performance or even damage. Accurate estimation of BMS through SOP can predict and manage the heat generated by batteries, optimize the design of thermal management systems, and ensure the safety and performance of batteries [14].

In order to achieve accurate estimation of SOP, researchers have developed a variety of methods, including prediction based on electrochemical models, real-time monitoring techniques of empirical models and estimation methods based on machine learning[17]. These methods improve the accuracy and reliability of SOP estimation and provide technical support for performance optimization and safety management of electric vehicles.

Therefore, the evaluation of SOP in BMS is of great significance for the performance optimization and safety management of electric vehicles. By accurately estimating the maximum power output of the battery, it is possible to maximize the performance and energy efficiency of the electric vehicle while ensuring safety.

3. SOP joint estimation method based on SOC constraints

SOP estimation cannot directly utilize real-time collected data such as current and voltage for calculation. The estimation methods of SOP can be mainly divided into two categories, one based on characteristic curve graphs, and the other relying on electrochemical models. As a result, the accuracy of SOP estimation is largely influenced by the accuracy of SOC estimation. The characteristic curve graph method determines SOP by interpolation or function operation of SOC, therefore, the accuracy of SOP estimation based on characteristic curve graphs closely depends on the accuracy of SOC estimation. The error in SOC estimation based on electrochemical models can directly affect the accuracy of model parameters, open circuit voltage (OCV), etc., thereby affecting the accuracy of SOP estimation results [16].

Therefore, SOP estimation based on battery SOC constraints is essential for the design and optimization of BMS. The SOC of a battery, as a measure of the battery's remaining power, is directly related to the maximum power that the battery can output. At different SOC levels, key parameters such as the internal resistance, voltage and temperature of the battery change, which in turn affects the SOP. As a result, accurate estimation of SOP under a given SOC constraint is of great significance for efficient utilization and life extension of the battery. In addition, accurate SOP estimation can guarantee the safe operation of the battery under high power demands, avoiding damage caused by excessive discharge or charging.

N is defined as the number of cells in a series battery pack, the voltage of the NTH cell in the battery pack is $\mathrm{v}_n(\mathrm{t})$, and for all cells, the charge off voltage of the cell voltage is v_{max}, and the discharge off voltage of the cell is v_{min}; If the SOC of the battery is set to $SOC(t)$, then the maximum is SOC_{max} and the minimum is SOC_{min}. $\mathrm{P}_n(\mathrm{t})$ represents the power of the battery, P_{max} represents its maximum value, P_{min} represents its minimum value, $\mathrm{i}_n(\mathrm{t})$ represents the battery current, i_{max} represents its maximum value. i_{min} represents its minimum value. Because the battery discharge current is positive and the charging current is negative, the absolute value of i_{min}^{chg} actually represents the peak charging current, and P_{min}^{chg} actually represents the peak charging power

The estimation of the maximum discharge current of the battery is based on ensuring that the voltage of the battery remains within the safe range (i.e. between v_{min} and v_{max}). Under discharge conditions, if the internal resistance of a single battery pack is set as $R_{dis,\Delta t}$, considering that the terminal voltage $v(t)$ of the battery should meet the voltage range for safe operation, it can be obtained:

$$v(t) = U_{OC}\left(SOC(t)\right) - i(t)R \tag{2}$$

This method takes into account the various constraints of the battery in actual operation, especially the limitation of the battery terminal voltage.

The basis for estimating the maximum power of the battery pack is to maintain the voltage range of the battery between v_{min} and v_{max}.

Under discharge conditions, the internal resistance of a single battery pack is set to $R = R_{dis,\Delta t}$, then the maximum discharge current of the battery is:

$$i_{max,n}^{dis,volt} = \frac{OCV\left(SOC(t)\right) - v_{min}}{R_{dis,\Delta t}} \#(3)$$

The maximum power output of the battery pack is:

$$P_{max}^{dis} = Nv_{max} \times i_{max,n}^{dis,volt} \tag{4}$$

Under charging conditions, the internal resistance of the battery pack is set to $R = R_{chg,\Delta t}$, , and the maximum charging current of a single battery can be calculated according to formula (3) :

$$i_{min,n}^{chg,volt} = \frac{OCV\left(SOC(t)\right) - v_{max}}{R_{chg,\Delta t}} \tag{5}$$

The maximum charging power of the battery pack is:

$$P_{min}^{chg} = Nv_{max} \times i_{min,n}^{chg,volt} \tag{6}$$

In the above estimation, the terminal voltage constraint is added to the charging current constraint. In this paper, SOP estimation based on battery SOC constraint is carried out to predict the maximum power output capacity of the battery under different energy states. This approach helps to optimize the use of batteries, extend their service life, and ensure safety and reliability in a variety of applications. Future research will further explore more complex battery models and high-precision estimation algorithms to adapt to the growing needs of battery applications.

The maximum charging capacity of the battery can be estimated based on the charging power and discharge power of the lithium-ion battery. The relationship between the SOC of a battery and the current i_n is:

$$SOC(t + \Delta t) = SOC(t) - \frac{\eta_n i_n \Delta t}{Q} \tag{7}$$

Where η_n represents charging efficiency. Assuming that in the process of discharge $\eta_n = 1$, in the process of charging $\eta_n \leq 1$, then the maximum discharge current and charging current of each battery is:

$$i_{max,n}^{dis,SOC} = \frac{(SOC(t) - SOC_{min})Q}{\Delta t} \tag{8}$$

$$i_{min,n}^{chg,SOC} = \frac{(SOC(t) - SOC_{max})Q}{\eta \Delta t} \tag{9}$$

Given the uncertainty in the estimate of the battery SOC, the confidence is 99.7% according to the 3σprinciple. This is a conservative estimate. The maximum discharge and charging current formula are as follows:

$$i_{max,n}^{dis,SOC} = \frac{\left(SOC(t) - 3\sigma_{SOC,n} - SOC_{min}\right)Q}{\Delta t} \tag{10}$$

$$i_{min,n}^{chg,SOC} = \frac{\left(SOC(t) + 3\sigma_{SOC,n} - SOC_{max}\right)Q}{\eta \Delta t} \tag{11}$$

After calculating the current limit of a single battery, the maximum discharge current and maximum charge current of the battery pack can be determined according to (10) and (11) :

$$i_{max}^{dis} = max\left(i_{max}, i_{max,n}^{dis,SOC}, i_{max,n}^{dis,volt}\right) \tag{12}$$

$$i_{min}^{chg} = max\left(i_{min}, i_{min,n}^{chg,SOC}, i_{min,n}^{chg,volt}\right) \tag{13}$$

The power of the battery can be expressed as the product of current and voltage, and the charge and discharge current of the battery can be calculated by formulas (12) and (13). The terminal voltage value of the battery can be obtained by modeling the equivalent circuit of the battery, and the peak current and terminal voltage can be multiplied to obtain the SOP estimated value based on the SOC constraint of the battery.

$$\begin{cases} P_{min}^{chg,L} = v(t) \times i_{min}^{chg} \\ P_{max}^{dis,L} = v(t) \times i_{max}^{dis} \end{cases} \#(14)$$

Where $P_{min}^{chg,L}$ is the continuous peak charging power, and $P_{max}^{dis,L}$ is the continuous peak discharge power. The obtained power value is the estimated SOP value required.

The battery itself has a design current limit, which can be considered to combine with SOC and terminal voltage to estimate SOP. When the lithium battery is discharged, the current is positive, and the minimum value under the three constraints is taken. When the lithium battery is charged, the current is negative, and the maximum value under three constraints is taken. That is,

$$\begin{cases} P_{min}^{chg,L} = v(t) \times i_{min}^{chg} \\ P_{max}^{dis,L} = v(t) \times i_{max}^{dis} \end{cases} \#(15)$$

Accurate estimation of battery SOP is important for BMS design and battery performance optimization, especially in applications that ensure safe battery operation and maximize battery efficiency.

4. Simulation verification of SOP estimation under SOC constraints

4.1 Determination of constraints

In this paper, the lithium-ion battery capacity is set at 100Ah, and the SOC is controlled at 10%-90% (positive and negative) to meet the needs of electric vehicles for power performance. Charge/discharge cut-off voltage, maximum current and other limitations are listed in Table 4.1.

Table 4.1 Constraint conditions of Li-ion battery parameters in SOP estimation

Parameter	Maximum value	Minimum value
U_d	4.2V	2.5V
I	120A	-60A
SOC	90%	10%

4.2 SOP estimation and verification under DST conditions

Analyze the system SOP under DST conditions. By analyzing the data, under DST conditions, as the experiment progresses, the peak current and peak power of the battery during the charging phase show a significant increase, and the corresponding SOP also shows an upward trend. In contrast, the performance during the discharge stage is exactly the opposite, with a gradual decrease in peak current and peak power, and it is at a higher level in the early stages of the experiment.

Further analysis finds that the charge cycle has a direct impact on key indicators of battery performance, including peak current and SOP. Specifically, with the extension of the charging cycle, these indicators show an increasing trend; When the charging cycle is shortened, they decrease accordingly. In addition, with the passage of experimental time, the depth of discharge of the battery continues to deepen, and the voltage in the charging stage gradually drops to the discharge termination voltage, thus achieving the maximum limit on the current.

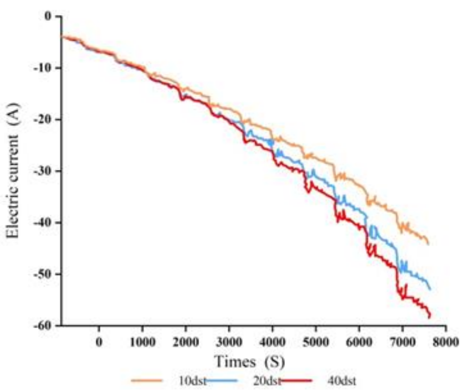


Fig4.1 Charging peak current at different durations

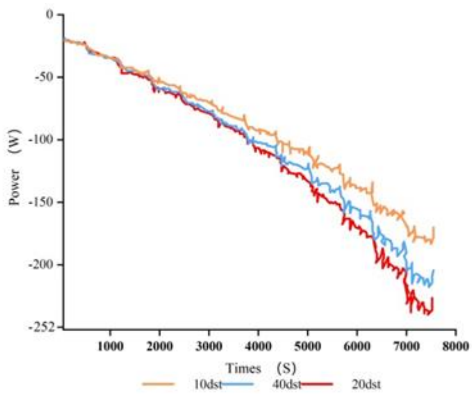
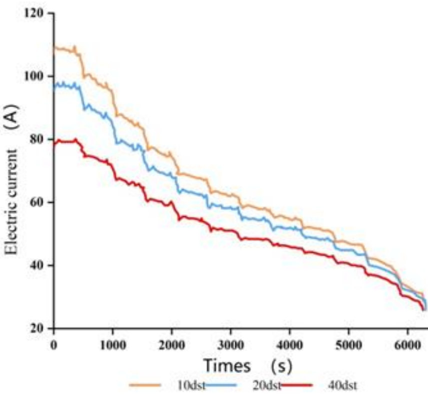


Fig4.2 Charging peak power at different durations



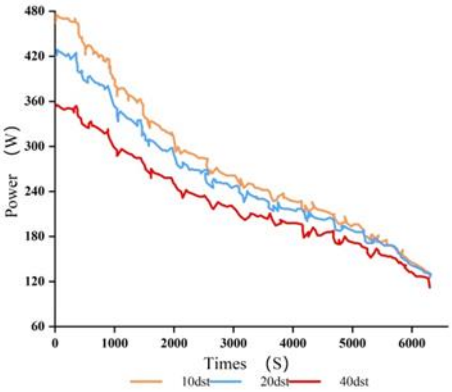


Fig4.3 Peak discharge current at different durations

Fig4.4 Peak discharge power at different durations

5. Summary

This paper explores an innovative approach to SOP estimation based on SOC constraints. An algorithm is proposed to accurately predict the maximum power output of the battery at any given point in time by analyzing the charge and discharge cycle of the battery and the corresponding SOC changes. The core of this method is to use the dynamic SOC data of the battery combined with advanced mathematical models to accurately estimate the real-time power capacity of the battery. The experimental results verify the effectiveness of this method under various working conditions. This estimation method maintains a high degree of accuracy and reliability even when batteries age or environmental conditions change significantly. This research can be widely applied in electric vehicles and renewable energy storage systems, and SOP estimation based on SOC constraints is of great significance and practical value for optimizing battery performance and prolonging its service life.

References:

[1] Hu, X., et al. "A review on state-of-charge and state-of-power estimation techniques for lithium-ion battery management systems." Energies 10.10 (2017): 1471.

[2] Wang, Y., Chen, M., Yu, L., & Deng, Q. (2023). "Battery state-of-charge and state-of-power estimation: A comprehensive review." Journal of Power Sources, 519, 230774.

[3] Zhang, Y., Zhang, C., Hu, J. (2023). "Recent Advances in State-of-Charge and State-of-Power Estimation Techniques for Lithium-Ion Batteries." Renewable and Sustainable Energy Reviews, 151, 111840.

[4] Zhang, Shengyi, et al. "State of charge estimation for lithium-ion batteries: A review." Renewable and Sustainable Energy Reviews 44 (2015): 272-287.

[5] Li, Xinlei, et al. "A Comparative Study of State-of-Charge Estimation Methods for Lithium-Ion Batteries Used in Electric Vehicles." Energies 14.18 (2021): 5632.

[6] Wang, Y. F., et al. "An Improved Lithium-Ion Battery State-of-Charge Estimation Method Based on the Fused Data Model." Energies 14.1 (2021): 179.

[7] Ding, Weimin, et al. "Adaptive Particle Filter-Based State of Charge Estimation for Lithium-Ion Batteries Considering the Variation of Discharge Current." IEEE Transactions on Industrial Electronics 69.2 (2022): 1336-1345.

[8] Yang, Xinyi, et al. "State-of-charge estimation for lithium-ion batteries: A review." Journal of Power Sources 456 (2020): 228074.

[9] Li, Xinlei, et al. "A Comparative Study of State-of-Charge Estimation Methods for Lithium-Ion Batteries Used in Electric Vehicles." Energies 14.18 (2021): 5632.

[10] Tang, Tian, et al. "Adaptive state of charge estimation method based on improved particle filter for lithium-ion battery." Journal of Power Sources 455 (2020): 227941.

[11] Plett G L. High-Performance Battery-Pack Power Estimation Using a Dynamic Cell Model[J].IEEE Transactions on Vehicular Technology. 2004, 53(5): 1586-1593.

[12] Xiang S, Hu G, Huang R, et al. Lithium-Ion Battery Online Rapid State-of-Power Estimation under Multiple Constraints[J]. Energies. 2018, 11(2): 283.

[13] Liu, Yulong, et al. "Online state of power estimation of lithium-ion batteries for electric vehicles using an improved unscented Kalman filter." Applied Energy 233-234 (2019): 15-25.

[14] Yang, Cheng, et al. "A review of state-of-charge estimation methods for electric vehicle batteries based on LiFePO4." Applied Energy 279 (2020): 115810.

[15] Zhang, Haotian, et al. "Optimal Power Split Strategy for Energy Management of Plug-In Hybrid Electric Vehicles Considering Driving Style and Traffic Conditions." IEEE Transactions on Vehicular Technology 70.4 (2021): 4147-4161.

[16] Chen, Ming, et al. "A review of the latest research on battery thermal management in electric vehicles." Journal of Energy Storage 35 (2021): 102080.

[17] J. Doe and A. Brown, "Enhancing Electric Vehicle Performance through Improved Battery Power State Estimation," Journal of Power Sources, vol. 450, 2021.

[18] Yin, Chengliang, et al. "An online state of power estimation method for lithium-ion battery based on improved extended Kalman filter." Applied Energy 265 (2020): 114841.

[19] X. Liu et al., "A comprehensive review on the state of charge of batteries," Journal of Power Sources, vol. 400, pp. 457-467, 2018.

[20] Y. Wang et al., "State of Charge Estimation for Electric Vehicle Batteries: A Review," IEEE Transactions on Intelligent Transportation Systems, vol. 20, no. 5, pp. 1623-1636, 2019.

[21] Arasteh H, Mirsaeedi H. Parallel GA-PSO Algorithm to Solve the Unit Commitment Problem. sjis 2022; 4 (3) :1-9

[22] Azarshab M, Ghazanfari M, Heidarpoor F. An Intelligent Fuzzy Logic Based Traffic Controller. sjfst 2021; 3 (1) :10-17