Automotive Lithium-ion Cells: Improving Cell Energy Density and Power Density

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Abstract. In recent years, environmental problems caused by carbon emissions have become increasingly serious, and traditional internal combustion engine vehicles are one of the main contributors to carbon emissions. In order to solve the problem of carbon emissions, electric vehicles have recently attracted public attention. However, electric vehicles still have problems such as short driving time and slow charging speed. Looking back at previous studies, improving the energy density and power density of lithium-ion batteries is still an important direction for the development of electric vehicles. This article reviews the methods of improving battery energy density from the perspective of improving the positive and negative electrode materials of lithium-ion batteries and explains their contributions to improving the power density of lithium-ion batteries from two aspects: improving the use of internal materials of lithium-ion batteries and reasonable battery management technology. With the further in-depth research on lithium-ion batteries, electric vehicles in the future will be more suitable for human use.

Keywords: Electric vehicles, lithium-ion batteries, energy density, power density.

1. Introduction

As climate and environmental challenges become more prevalent, people must face the challenge of how to reduce carbon emissions. As one of the contributors to carbon emissions, humans have begun to seek alternatives to internal combustion engine vehicles. Against this backdrop, electric vehicles (EVs) have begun to develop rapidly. Currently, EVs have become an important form of automobile.

Lithium-ion batteries (LIBs) offer many advantages to EVs compared to traditional internal combustion engine vehicles, such as the ability to charge using cheap electricity at night and the fact that they produce no emissions when in operation. However, EVs have a shorter range and longer charging times than fuel cell vehicles (a new energy vehicle). This problem is primarily related to the limitations of current LIB technology. Overall, if the energy density and power density of LIBs can be effectively improved, many of the shortcomings of current EVs will be significantly addressed.

With the goal of improving the energy density and power density of LIBs, this study explores design techniques. This paper includes the following structure: Section 2 describes the design concept of LIBs. Section 3 discusses the methods to increase the energy density of LIBs. Section 4 aims to improve the power density of LIBs.

2. The Design of Lithium-ion Batteries for Electric Vehicles

The development of LIBs began in the 1980s. Their recognized advantages, such as low energy consumption, high specific capacity and energy density, high operating voltage, long cycle life, low self-discharge, environmental friendliness, robust cycle performance, and extended service life, have promoted their widespread application [1]. To date, EV battery technology is still dominated by the use of LIBs. This means that if the characteristics of LIBs can be fully understood and the design concept of LIBs can be improved, the safety and performance of EVs will be improved.

Battery safety is one of the key issues in EV development. Given the recent increase in attention to battery safety issues, improving the safety performance of LIBs has become a key focus of battery research and development [2].

In addition to safety issues, how to simultaneously improve LIB energy density and power density is the main topic of this research. The fundamental tension between their physical and chemical properties is the main reason for the difficulty in increasing energy density and power density. In order to improve these two key characteristics, more research on battery structure and related topics is still needed in the future.

In summary, the basic idea of battery design is to ensure that LIBs operate stably and safely while working to improve their performance.

3. Energy Density of Lithium-Ion Batteries

3.1. Energy Density

The total quantity of electrical power that a LIB holds per unit of volume or weight is known as its energy density, which is often given in Watt-hours per kilogram (Wh/kg) or Watt-hours per liter. Energy density is an essential performance measure since it has an immediate effect on battery run time and volume/weight appropriateness. If the energy density of the active part of the LIB system can be improved, the battery capacity can be effectively increased without changing the mass, thereby extending the EV's range.

3.2. Applying high-performance material positive cathodes to increase the energy density of LIBs—taking nickel cobalt manganese oxide LIB as an example

A battery's energy density is strongly tied to the material used for its cathode, which is critical in determining the energy density of LIBs [3]. The adoption of high energy density cathode materials has the potential to considerably increase battery energy storage capacity. Among the many LIB technologies, ternary lithium batteries are favored by manufacturers due to their excellent overall performance. In particular, nickel cobalt manganese oxide (NCM) is widely used in ternary lithium battery cathode materials for EVs due to its high energy density.

NCM is one of the most popular cathode materials in the EV field. Its name “NCM” comes from its three main components: nickel (Ni), cobalt (Co) and manganese (Mn). By precisely controlling the ratio of these elements, the battery’s energy density, cost-effectiveness, thermal stability and other key performance indicators can be optimized [4]. The tunability of this material makes it have a wide range of application prospects in battery technology.

The high energy density of NCM batteries is mostly owing to a rise in nickel percentage in their positive electrode materials, which greatly increases the material's specific capacity [5]. The high chemical activity of nickel plays a key role in increasing battery capacity. However, NCM batteries also face some challenges at high nickel content. Specifically, the increase in nickel concentration may have an adverse effect on the thermal and structural stability of the material, leading to rapid degradation of battery performance [5]. In order to meet this challenge, researchers have proposed practical solutions. Through doping technology and modification of single-crystal NCM811 materials, the release of oxygen under high-temperature conditions can be effectively suppressed and the thermal stability of the material can be enhanced [6].

In summary, NCM is a cathode material with a fairly high energy density, which is very suitable as the positive cathode for LIBs. Although it may bring battery thermal management issues, these can be solved by developing technologies to realize its full potential of high energy density.

3.3. Improve battery negative electrode materials to increase battery energy density

In the research of improving the energy density of LIB, improving the negative electrode material is a very valuable research direction. At present, the negative electrode material of LIB is usually graphite, but the theoretical capacity of graphite is small, which limits the total energy density of the battery.

In order to increase energy density, using negative electrode materials with larger capacity, such as silicon-based negative electrodes, is an effective way. Theoretically, silicon has a specific capacity of up to 4200 mAh/g, which is much larger than the 372 mAh/g of graphite [7]. In contrast, silicon has a stronger ability to embed and deintercalate lithium ions and can store more lithium ions, thereby significantly improving the battery energy density. In particular, if lithium ions are repeatedly intercalated and deintercalated in the silicon anode, the energy output of the battery can be increased, allowing the silicon anode to hold more charge [8]. Choosing LIB-negative electrode materials with a larger particular capacity is an effective way to increase battery energy density. By changing the type of negative electrode material, LIB energy density can theoretically be significantly increased.

4. Power Density of Lithium-Ion Batteries

4.1. Power Density

The power density of a battery relates to how much power it can produce per unit volume or mass. It is a crucial characteristic for measuring a battery's ability to rapidly release energy in a short amount of time. The unit of power density is usually watts per kilogram (W/kg) or watts per liter (W/L). The power density determines the performance of the battery under high power demands (such as acceleration, starting power tools, fast charging, etc.). For example, when an EV is accelerating, the battery needs to be able to quickly release a large amount of electrical energy, so the LIB carried by the EV needs to have a higher power density to meet people's needs.

4.2. Methods to improve LIB power density

There are many ways to improve the power density of LIB, such as improving battery materials, electrolyte modification, and battery management technology optimization. For NCM batteries used in EVs, the first important factor to consider when improving battery power density is battery energy density. If the cost of improving battery power density is to sacrifice battery energy density, this upgrade plan should be further evaluated. This section will take NCM batteries as an example to discuss some upgrade plans that are effective for LIBs without sacrificing battery energy density to help LIBs improve their power density.

4.3. Applying high-conductivity electrolyte and battery management system (BMS) to improve battery power density - taking NCM battery as an example

Highly conductive electrolytes are critical for increasing the power density of LIBs. The electrolyte is the medium for ion conduction inside the battery. The higher the conductivity of the electrolyte, the faster the lithium ions migrate inside the battery, which means that the time required for the battery to charge or discharge will be reduced. Highly conductive electrolyte reduces the internal resistance of the battery, thereby reducing energy loss and improving the power density of the battery. For NCM batteries, improving the conductivity of its electrolyte is one of the important research directions. A study showed that by adding ethyl 3-methyl-3-phenyl-glycidate (EMP) to the electrolyte of NCM batteries, the internal impedance of the battery can be reduced and the power density of the battery can be improved [9]. The additive EMP will decompose itself during the high voltage stage of battery operation and form a stable electrolyte interface (CEI) layer on the surface of the battery positive electrode. The CEI layer minimizes the connection between the positive electrode and the electrolyte of the NCM battery, lowers the impedance at the battery interface, and increases the battery's power density.

In addition to improving the internal structure of the battery, improving the battery management system (BMS) can also improve the charging and discharging efficiency of the battery. In recent years, BMS technology has been studied by major companies and many scholars. Its main purpose is to more effectively control the working state of the battery to help it perform well. For NCM batteries, it is very important to ensure that their operating temperature is within the optimal temperature range, otherwise their performance will be reduced or their life will be shortened, or even irreversible damage will occur. According to a study on NCM-21700 batteries, it was found that in NCM battery applications, after thermal analysis of the high specific energy NCM-21700 LC unit using a hybrid battery thermal management system, it was found that through effective thermal management, the battery can be kept within the optimal operating temperature range at high power output, thereby increasing the power density and longevity of the battery [10].

In summary, improving the power density of LIBs often requires methods that do not affect the energy density of the battery. Improving the electrolyte composition in the battery to increase its conductivity and improving BMS technology are two effective solutions to improve battery power density.

5. Conclusion

This article provides some optimization ideas for LIB by finding some shortcomings in the performance of automotive LIBs and reviewing the research results of others and the latest scientific research progress. After comparing different types of new energy vehicles, it is shown that although EVs equipped with LIBs have some advantages, they also generally have shortcomings such as low charging and discharging efficiency and short battery life. In order to solve such technical problems, improving the energy density and power density of LIBs is an important direction for improvement. The energy density of LIBs may be greatly increased by choosing a negative electrode material with a larger specific capacity and by enhancing the positive electrode material, according to a study of existing studies on NCM batteries. At the same time, the selection of electrolytes with higher conductivity can help NCM batteries improve their power density, and the reasonable application of BMS technology can help NCM batteries work in their optimal temperature range. Both measures are undoubtedly applicable to improving the charging and discharging efficiency of LIBs. Through continuous research on the improvement of LIB energy density and power density in the future, it can be predicted that more excellent batteries will enter the market, making great progress in the development of EVs.

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