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NICKEL MANGANESE COBALT OXIDE BATTERY ROUND TRIP EFFICIENCY AT DIFFERENT STATE OF HEALTH LEVELS

This study investigates the influence of battery state of health and discharge rate on the round-trip efficiency of lithium nickel manganese cobalt oxide battery cells used in electric vehicle applications. Experimental testing was performed on individual 18650 size cells using controlled charge and discharge cycles at discharge rates of 1C, 2C, and 3C. Battery round-trip efficiency was evaluated at different state of health levels to determine how battery aging affects overall energy efficiency. The findings indicate that limiting battery discharge rates through battery management system control strategies may improve energy efficiency and extend electric vehicle driving range, particularly for aged batteries.
***Key words**: round-trip efficiency, state of health, electric vehicles, battery aging.*

1 Introduction

The evaluation of lithium-ion battery degradation in electric vehicles is of significant importance for ensuring long-term operational performance, safety, reliability, and energy efficiency. As lithium-ion batteries undergo repeated charge and discharge cycles throughout their service life, a variety of degradation mechanisms occur within the cell structure. These degradation processes gradually reduce the available battery capacity, increase internal resistance, and alter the thermal characteristics of the battery system [1]. Consequently, battery aging directly affects critical electric vehicle performance parameters, including driving range, charging capability, power delivery, thermal stability, and overall energy efficiency [2].

Among the various indicators used to characterize battery performance degradation, round-trip efficiency (RTE) is considered one of the most important parameters for evaluating the overall efficiency of electric vehicle battery system [3]. The RTE of a battery is defined as the ratio of the energy delivered during the discharge process to the total energy required during charging, typically expressed as a percentage. High RTE is essential for maximizing vehicle energy utilization and minimizing energy losses associated with battery operation.

For new NMC batteries, the RTE typically ranges between approximately 85% and 95%, depending on operating conditions such as temperature and charge-discharge rate. However, as the battery ages and its state of health (SOH) progressively declines, the RTE also decreases [4]. Battery aging is primarily characterized by capacity fade and an increase in internal resistance caused by electrochemical side reactions. The increase in internal resistance results in higher resistance losses and elevated heat generation during both charging and discharging processes, thereby reducing the amount of recoverable energy and lowering overall battery efficiency [5].

In electric vehicle applications, the reduction in battery RTE over time can significantly influence total vehicle energy consumption and operational economics. Lower battery efficiency results in increased charging energy requirements for the same usable output energy, ultimately reducing system-level efficiency and affecting vehicle range predictions [6]. Therefore, understanding the relationship between battery aging, discharge rates and RTE is essential for accurate modeling of electric vehicle performance, battery lifetime estimation, and optimization of battery management system (BMS) strategies.

This study investigates the RTE characteristics of lithium-ion NMC battery cells at different SOH levels while discharging at different discharge rates C, in order to evaluate how battery aging influences energy efficiency during different operating conditions. By analyzing the variation of RTE under different degradation conditions, the research aims to provide a better understanding of the efficiency behavior of electric vehicle batteries throughout their operational lifetime and to contribute to the development of more accurate battery performance assessment methodologies.

2 Evaluation of Battery Degradation

2.1 Battery SOH Measurement

Battery state of health (SOH) can be evaluated by monitoring the reduction in battery capacity over repeated charge–discharge cycles. This is typically accomplished by periodically discharging the battery under controlled conditions and measuring the delivered energy and discharged capacity during each cycle (1). As the battery ages, electrochemical degradation mechanisms progressively reduce the available capacity, resulting in a gradual decline in energy storage capability with increasing cycle number.

$$SOH_C = \frac{C_{Measured}}{C_{Initial}} \times 100\ \% \quad (1)$$

Where the battery capacity health SOH_C is the ratio of battery's cell current measured capacity $C_{Measured}$ to the initial capacity $C_{Initial}$ [7].

2.2 Battery RTE Measurement

Battery round-trip efficiency can be determined by measuring the total energy required to charge the battery and comparing it with the total energy delivered during the subsequent discharge process (2). The RTE generally decreases at higher charge and discharge rates, as increased current levels lead to greater internal resistive and thermal losses within the battery.

$$RTE = \frac{Wh_{out}}{Wh_{in}} \times 100\ \% \quad (2)$$

Where the battery round trip efficiency RTE is the ratio of discharged energy from the battery Wh_{out} to the charged energy to the battery $C_{Initial}$ [8].

3 Research Methodology

In this study, experimental investigations were conducted using individual lithium-ion battery cells rather than complete battery packs. This approach was selected in order to reduce overall energy consumption during testing procedures and to minimize the financial costs associated with experimental research, as commercially available full-scale electric vehicle battery packs are significantly more expensive. Furthermore, testing at the cell level enables more precise control of operating conditions and allows the electrochemical performance of each cell to be evaluated independently, without the influence of battery management systems or inter-cell balancing effects typically present in battery pack configurations.

The experiments were performed using cylindrical 18650-format lithium NMC battery cells. Each cell was subjected to individual charge and discharge cycles while continuously monitoring and recording the electrical energy supplied to and extracted from the cell. All measurements were carried out using the EBC-A40L battery testing system in combination with the EB Tester software platform, which enabled automated control and data acquisition throughout the experimental procedure.

To evaluate the RTE of the cells under different operating conditions, discharge tests were performed using the constant current (CC) method at multiple discharge rates corresponding to 1C, 2C, and 3C. These discharge rates were selected to investigate the influence of increasing current load (simulated higher acceleration in electric vehicle) on battery efficiency and energy losses. During each experimental cycle, the cells were discharged from a fully charged state of 100% state of charge (SOC), corresponding to a terminal voltage of 4.2 V, down to 0% SOC, corresponding to a cutoff voltage of 2.5 V.

Following the completion of each discharge cycle, the cells were recharged using a two-stage charging protocol commonly applied to lithium-ion batteries. Initially, the charging process was conducted in constant current (CC) mode at a charging rate of 1C until the cell voltage reached the upper charging limit of 4.2 V. Subsequently, the charging process transitioned to constant voltage (CV) mode, during which the voltage was maintained constant while the charging current gradually decreased. The charging cycle was terminated once the charging current dropped to 250 mA, indicating that the cell had reached a fully charged condition.

4 Results and Their Analysis

4.1 NMC Battery Round Trip Efficiency analysis

The experimental results revealed a clear relationship between battery SOH, discharge rate, and RTE of the investigated lithium NMC cells. A progressive decrease in RTE was observed with declining SOH

across all tested discharge rates, indicating that battery aging significantly reduces energy conversion efficiency.

At a discharge rate of 1 C, the measured battery RTE decreased from 91.7% at 100% SOH to 85.6% at 65% SOH, as presented in Table 1. This reduction demonstrates the impact of battery degradation on energy losses during charge-discharge cycling, even under relatively moderate current loading conditions.

Table 1. NMC round trip efficiency test results at different SOH levels

SOH	Charged energy (1 C), Wh	Discharged energy (1 C), Wh	RTE (1 C), %	Charged energy (2 C), Wh	Discharged energy (2 C), Wh	RTE (2 C), %	Charged energy (3 C), Wh	Discharged energy (3 C), Wh	RTE (3 C), %
100	10,2	9,4	91,7	10,1	9,2	91,1	10,1	8,8	86,8
95	9,7	8,9	91,2	9,6	8,7	90,7	9,6	8,3	86,5
90	9,2	8,3	90,1	9,2	8,1	88,4	9,2	7,8	84,9
85	8,8	7,9	89,7	8,7	7,6	87,0	8,7	7,3	84,6
80	8,3	7,4	88,6	8,3	7,1	85,4	8,2	6,9	83,5
75	7,9	6,8	86,8	7,8	6,6	84,5	7,8	6,3	81,3
70	7,4	6,3	85,5	7,3	6,1	82,8	7,3	5,9	80,4
65	6,8	5,9	85,6	6,9	5,6	82,1	6,8	5,4	79,8

A more pronounced efficiency reduction was observed at higher discharge rates. At a discharge rate of 2 C, the RTE decreased from 91.1% for a new battery cell at 100% SOH to 82.1% at 65% SOH. Similarly, at the highest investigated discharge rate of 3C, the RTE declined from 86.8% at 100% SOH to 79.8% at 65% SOH (Figure 1).

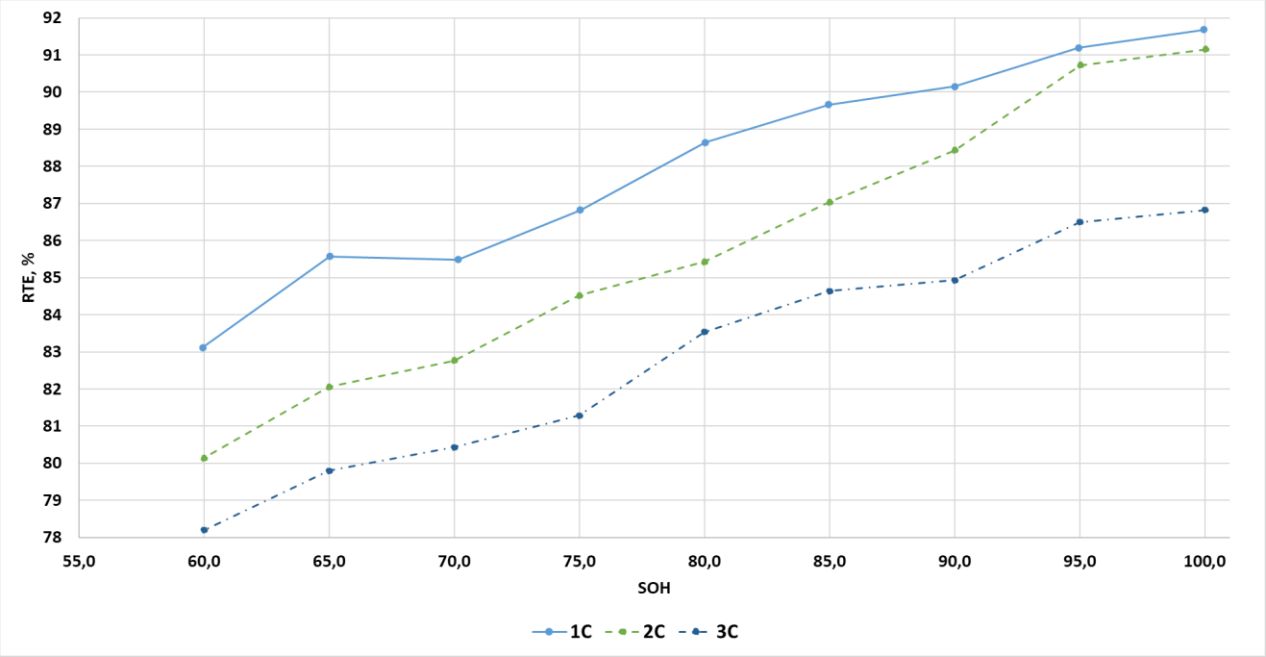

Figure 1. NMC battery round trip efficiency dependency on battery the state of health at different discharge rates C

The obtained results indicate that both battery aging and increased discharge currents contribute to lower round-trip efficiency. Higher discharge rates intensify internal resistive losses and heat generation within the cell, while aging-related increases in internal resistance further amplify these effects.

5 Conclusions

This study demonstrated that the state of health of lithium nickel manganese cobalt oxide battery cells has a significant influence on battery round-trip efficiency. As battery degradation progresses, the RTE decreases due to increased internal resistance and higher energy losses during charging and discharging processes.

The experimental results also showed that battery RTE is strongly dependent on the discharge rate. Higher discharge currents resulted in lower efficiency because of increased resistance and thermal losses within the cell. Therefore, limiting the discharge rate can improve the overall energy efficiency of aged lithium-ion batteries.

The findings suggest that, in electric vehicle applications, the battery management system can improve energy utilization by reducing the allowable discharge rate as the battery ages. Such control strategies may help maintain higher RTE values and increase the achievable driving distance by up to approximately 6%, despite reduced battery capacity at lower SOH levels.

In addition, the results indicate that energy-saving vehicle operating modes, such as “ECO” mode, can further improve electric vehicle efficiency and driving range by limiting battery power demand and reducing discharge rates.

Further research is required to investigate the influence of depth of discharge (DOD) and dynamic operating conditions on battery RTE in order to better adapt these findings for real-world electric vehicle battery management systems.

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