Performance Analysis of Three Energy Storage Components for Wide Temperature Range EV Applications

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Abstract
As the working temperature range of electric vehicles is wide (from -30 °C to 50 °C), analyzing the performance of energy storage components at different temperatures is a fundamental process for the design of the energy storage system, state estimation algorithm, and optimization of control algorithm. In this paper, a Li(NiCoMn)O$_2$/Graphite battery, a LiMnO$_2$/Li$_4$Ti$_5$O$_{12}$ battery and a super capacitor are selected as the research objects. The capacity, open circuit voltage, internal resistance and power characteristics are compactly analyzed. After the data unitization was implemented in the form of unit weight and unit volume, our team conduct a comparison of the electrical characteristics of the three energy storage components. Moreover, the appropriate function form for fitting temperature characteristics curve are discussed. The result will provide some support for subsequent electric vehicle power system modeling and SOC/SOE/SOH estimation.

Keywords: wide temperature range, performance, battery, super capacitor

1. Introduction
Due to the demands of the low-carbon environmental protection, energy saving and emission reduction, the development of electric vehicles is widely concerned in the world[1, 2]. Owing to the development of the electric energy storage technology, the reliability and the maximum driving distance of electric vehicles continue to increase in recent years. However, as the temperature of driving environment changes with the areas and seasons, electric vehicles will experience alternating high and low temperatures during use[3], which will bring great challenges to the performance of electric vehicle energy storage systems. It’s of great importance for the energy storage systems of electric vehicles to be able to adapt to a wide temperature range[4]. Nevertheless, a number of energy storage components, such as lead-acid battery, lithium cobalt oxide battery, lithium manganese oxide battery, lithium iron phosphate battery, etc., have poor temperature adaptability. Therefore, if the energy storage systems are used in a fairly extreme environment, the performance can be seriously degraded. In addition, the system will be confronted with safety risks. In order to make the entire energy storage system work properly, it relies on the battery management system with a complicated thermal management module. A large and complex auxiliary system is needed urgently to optimize the temperature of the energy storage component working environment, which will increase the cost of production and reduce system reliability. Thus, selecting the energy storage components with good temperature adaptability, analyzing their temperature characteristics and applying them to the electric vehicle systems will help with the reduction of system cost and reinforcement in system reliability[5]. Hence, this paper carries out a performance analysis of three types of energy storage elements for wide temperature range electric vehicle applications.

In our work, a Li(NiCoMn)O$_2$/Graphite battery (NCM), a LiMnO$_2$/Li$_4$Ti$_5$O$_{12}$ battery (LTO) and a super capacitor [6-9] are selected as research objects. Temperature characteristics of the above energy storage components were analyzed from four aspects: open circuit voltage, internal resistance, capacity and maximum power capability. The second section introduces the need of the temperature performance analysis of the energy storage components. The third section introduces the battery experiment and data processing methods. The fourth section analyzes the temperature characteristics of the three energy storage components separately. The fifth section compares the temperature performance of the energy storage components horizontally to judge the applicability of these energy storage components. The final section is the conclusion of the full paper.
2. Demand for Temperature Performance Analysis of the Energy Storage Components

The main reasons for temperature performance analysis on electric vehicles are: high temperature will accelerate the aging of the energy storage system, lower the safety of the battery pack, and may even lead to the burning and explosion of the automobile in severe cases. Also, low temperature will slow down the electrochemical reaction in the energy storage components, and the battery capacity will also decline sharply, which will make a straight influence on the driving performance of the electric vehicle. As a result, if the energy storage system of an electric vehicle can be matched with a suitable energy storage component that can work well over a wide temperature range, it can obtain a good driving performance under high temperature or cold temperature. Accordingly, the improvement and optimization of the performance of electric vehicles have very urgent requirements for the analysis of the temperature characteristics of energy storage components.

3. Experiments and data processing

The shape and main performance of the energy storage components are shown in Figure 3-1 and Table 3-1.

![Figure 3-1 Three energy storage components (NCM, LTO, and Super capacitor)](image)

<table>
<thead>
<tr>
<th></th>
<th>NCM</th>
<th>LTO</th>
<th>Super Capacitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>5.3Ah</td>
<td>16Ah</td>
<td>1.33Ah</td>
</tr>
<tr>
<td>Temperature</td>
<td>-20~70°C</td>
<td>-30~55°C</td>
<td>-40~65°C</td>
</tr>
<tr>
<td>Current</td>
<td>±15.9A</td>
<td>±160A</td>
<td>--</td>
</tr>
<tr>
<td>Voltage</td>
<td>2.75~4.2V</td>
<td>1.6~2.7V</td>
<td>0.5~2.7V</td>
</tr>
<tr>
<td>Weight</td>
<td>117.5g</td>
<td>672g</td>
<td>550g</td>
</tr>
<tr>
<td>Volume</td>
<td>0.042L</td>
<td>0.3136L</td>
<td>1.96L</td>
</tr>
</tbody>
</table>

The experimental equipment for the energy storage components includes a battery test system produced by Sunwood, Dongguan, China and a temperature chamber produced by Sunwood, Dongguan, China. The battery test system provides the energy and discharge release path for the energy storage components. and the temperature chamber simulates the working environment temperature of the energy storage components. The main parameters of the battery test system are: current ranges from -100A to 100A, the voltage ranges from 0V to 30V. The main parameters of the temperature chamber are: temperature ranges from -40℃ to 150℃ with the accuracy of ±1.5℃. The schematic diagram of energy storage component experimental system is shown in Figure 3-2.

![Figure 3-2 Schematic diagram of energy storage component experimental system](image)

Battery experiments include the constant current and constant voltage charging experiment (CCCV charging test), constant current discharging experiment (CC discharging test), hybrid pulse power characterization (HPPC) test[10] experiments. According to the characteristics of the energy storage component, an appropriate current multiplier is selected for the experiment.

To extract the critical parameters, it is indispensable to use the battery model technology. The common used first-order RC circuit including a variable voltage source is selected as the equivalent model for the dynamic characteristics description for the battery. The first-order RC circuit without a voltage source as the equivalent model is for the description of super capacitor [7][8]. The equivalent models are shown in Figure 3-3.

![Figure 3-3 Equivalent models for the components](image)

The state space equation of the two types of equivalent models are written as:

\[
\begin{align*}
\text{Battery:} & \quad \begin{cases} 
V(t) = I(t)R_p + E_{oc} + U_p(t) \\
\frac{dU_p(t)}{dt} + \frac{U_p(t)}{R_p} = I(t) 
\end{cases} \\
\text{Super capacitor:} & \quad \begin{cases} 
V(t) = I(t)R_p + U_p(t) \\
\frac{dU_p(t)}{dt} + \frac{U_p(t)}{R_p} = I(t)
\end{cases}
\end{align*}
\]
4. Temperature Characteristics of Energy Storage Components

4.1 Temperature performance of the NCM battery

The change of the open circuit voltage of the NCM battery in a wide temperature range is obvious. According to the OCV-SOC curves from 0 °C to 45 °C, the voltage drop is about 100mV. When the environment temperature decrease to -15 °C, the gap between the open circuit voltage curve and the other curves increase to 350 mV. The main reason for this phenomenon is that the phase change process of the material is affected by the temperature, which causes the positive electrode potential to deform at low temperatures. The characteristics of the open circuit voltage determine that a more complex open circuit voltage model needs to be established when estimating the battery SOC/SOE/SOH, etc., to ensure the accuracy of the OCV-SOC relationship.

The Ohmic internal resistance of the ternary lithium battery does not change significantly with the SOC when the temperature is between 0 °C and 45 °C. As the temperature decreases, the entire curve moves upwards, indicating a large increase in the internal resistance. When the ambient temperature is lowered to -15 °C, the Ohmic internal resistance increases from tens of milliohms to 200 mΩ. The temperature also has a large effect on the polarization internal resistance of the NCM battery. The polarization internal resistance increases with the decrease of temperature. When compared with the Ohmic internal resistance, the polarization internal resistance is a little smaller.

Figure 4-1 (d ~ f) show change in battery capacity and charge/discharge peak power as a function of temperature/SOC. When the temperature is higher than 0 °C, the capacity of the ternary battery decreases with the decrease of temperature, but it is not obvious. When the temperature is lower than 0 °C, the capacity is obviously reduced. At -15 °C, the capacity reduced to 75% of the nominal capacity. Seen from the peak power curves in Figure (e) and (f), the peak charging power and the peak discharging power change significantly with temperature. Compared to the capacity characteristics, the peak power characteristics of the battery are more pronounced at low temperatures, and the peak power at -15 °C is only 30% and 12% of the peak power at 30 °C. In the low temperature condition, the NCM battery can only charge and discharge with low current rates.
4.2 Temperature performance of the LTO battery

The change of open circuit voltage curves of the LTO battery is obvious in the wide temperature range of -15 °C ~ 45 °C, the gap of the open circuit voltage-SOC curves data is about 100mV. Unlike the NCM battery, the shape of the voltage curve does not change significantly. It can be inferred that the main reason for the voltage curve change with temperature is the reduction of the available capacity of the LTO battery. The relationship between capacity/temperature/open circuit voltage should be modeled when estimating the SOC/SOE/SOH, etc., to ensure the correct relationship of OCV-SOC. When the temperature is between 30 °C and 45 °C, the Ohmic internal resistance is similar. However, the Ohmic internal resistance is quickly increased from 1 mΩ to 9 mΩ as the ambient temperature decrease from 30 °C to -15 °C. It can be summarized that it is also necessary to take into account the effect of temperature on the internal resistance of the LTO battery when estimating the state of the LTO battery over a wide temperature range. The temperature change has a large influence on the polarization internal resistance of the LTO battery as well.

Figure 4-3 shows the change in capacity and charge/discharge peak power with temperature/SOC of the LTO battery. The capacity of the LTO battery decreases with decreases of the ambient temperature. The capacity becomes 65% of the nominal capacity at -15 °C. The environment temperature has a significant influence on the peak charging power. The peak power characteristics of the battery are more obvious under low temperatures, and the peak power at -15 °C is only 17% of the power at 30 °C. It can be concluded that the LTO battery can only be charged and discharged with low current rate in low temperatures.
4.3 Temperature performance of the super capacitor

In Figure 4-4, there are almost no changes in the open circuit voltage over a wide temperature range. From the OCV-SOC data of -15 °C to 45 °C, the voltage gap is only about 5 mV. Due to the voltage change is about 2250 mV corresponding to the SOC from 0 to 100%. As a result, when estimating the SOC/SOE/SOH for the super capacitor, the OCV-SOC relationship at different temperatures can be described using the normal temperature OCV-SOC relationship model. The complexity of the OCV-SOC/temperature model is very low. When the ambient temperature between -30 °C and 45 °C, the Ohmic internal resistance just increases from 4 mΩ to 4.5 mΩ. The relationships between the Ohmic internal resistance and SOC at different temperatures can be described with the normal temperature R_{ohm}-SOC relationship model.

Figure 4-5 show the capacity and charge/discharge peak power of the super capacitor. The performance doesn’t decline drastically under high and low temperature conditions. From the energy storage characteristic, the capacity inconspicuous decreases as the temperature decreases. When the temperature decreased to -30 °C, the capacity becomes 98% of the capacity at 30 °C. From the peak power curves, the charging power and the discharging power also have no significant change with temperature. Compared with the NCM battery and the LTO battery, super capacitor has the best temperature adaptability.

5. Performance Comparison

In order to carry out the comparative analysis on the three energy storage components, the three energy storage components are subjected to unit weight normalization and unit volume normalization processing. Data with SOC=50% was selected as the data for the comparative analysis.

Figure 5-1 (a) and (d) compares the Ohmic internal resistance of three energy storage components with temperature. It can be seen that the Ohmic internal resistance of the three energy storage components is in the same order of magnitude. The Ohmic internal resistance of the LTO and NCM batteries exhibits an exponential change characteristic with temperature. The Ohmic internal resistance of the super capacitor is approximately constant. When characterizing them, it is suitable to use the Arrhenius equation to describe the internal resistance characteristics of the two batteries. When it comes to the super capacitor, the mean of the internal resistance or a linear function is enough to characterize it.

Figure 5-1 (b) and (e) compare the capacity characteristics of the three energy storage components. It can be seen that the super capacitor’s unit weight capacity value and unit volume capacity value are much less than the NCM battery and the LTO battery over the wide temperature range. In the above energy storage components, the NCM battery have the highest energy density. Then, the LTO battery is next to it. When selecting the energy storage components of an electric vehicle, it is very necessary to make decisions on the base of the temperature characteristics of the commercial energy storage components.

Figure 5-1 (c) and (f) make comparison in the power characteristics of the three energy storage components. It can be seen that the super capacitor’s unit weight power value and unit volume power value are similar to those of the NCM battery and the LTO battery over the wide temperature range. When the temperature is lower than 15 °C, the super capacitor has better power characteristics than the NCM battery and the LTO battery.

6. Conclusion

In this paper, the performance of three commercial energy storage components (Li(NiCoMn)O_{2}/Graphite battery, LiMnO_{4}/Li_{4}Ti_{5}O_{12} battery and super capacitor) at different temperatures from (-15 °C ~45 °C) is researched intensively. The open circuit voltage, internal resistance, capacity and power characteristics are compactly analyzed. What’s more, the appropriate function form for temperature characteristics curve fitting are discussed. According to the work, the temperature performance of NCM battery and LTO battery are comparatively different from the super capacitor. NCM battery and LTO battery have relatively high energy density than the super capacitor, but their performances are affected by temperature, especially under low temperature. However, temperature almost has no
effect on the performance of the super capacitor. In view of the comparison and analysis of the experimental data, the result provides support for subsequent electric vehicle power system modeling and SOC/SOE/SOH estimation.

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References