Comparing the performances of different energy storage cells for hybrid electric vehicle

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Abstract
Currently, the energy storage systems for hybrid electric vehicle (HEV) are high power-type lithium-ion batteries and super capacitor (SC). In this paper, three commercial high power-type lithium-ion batteries of different electrode materials including Li\textsubscript{4}Ti\textsubscript{5}O\textsubscript{12} (LTO), C/LiMn\textsubscript{2}O\textsubscript{4} (LMO), C/LiFePO\textsubscript{4} (LFP), and a commercial SC are investigated and compared to each other. Through a series of different charge rate currents and discharge rate currents test and the hybrid pulse power characteristics (HPPC) test at different working temperature, the power characteristics, rate capabilities, thermal performance and energy density can be comprehensively compared and evaluated. Test results show that the performance under low temperature and the specific power of the LMO and LFP battery are inferior to those of LTO battery and SC. The specific power of the LFP cell and the LMO cell only account for 49\% and 63\% of that of LTO cell under room temperature, respectively, but the specific energy are 120\% and 190\% of the LTO cell, respectively. According to the open circuit voltage-state of charge (OCV-SOC) curves, 1mV voltage measurement error would cause about 3\% SOC estimation error for the LFP cell but the others batteries’ SOC estimation are less than 0.5\%, which means that LFP cell requires higher cell voltage measurement precision for the battery management system (BMS) than others type of battery. SC cell has excellent specific power, and its performances are almost not depend on the discharge or charge current rate and the working temperature, however, its specific energy is very low. Therefore, when matching hybrid electric vehicle powertrain with SC, the main consideration is that the total energy of SC must meet the requirements of HEV accelerating and regenerative braking, while, matching the HEV powertrain with battery, the power of the battery is the main consideration.

Keywords: Lithium ion battery, Super Capacitor, Performance comparison, Hybrid Electric Vehicle
1 Introduction

Both power type battery and super capacitor are the main primary energy storage devices for HEV. Generally, there are two types of batteries employed in the HEVs, namely Ni-MH battery and lithium ion battery. However, compared with Ni-MH battery, lithium ion battery has received considerable attention due to the high energy density, specific power and long cycle life, and considered to be the best choice for HEV[1-4].

Lithium ion batteries are common classified by cathode electrode materials. And today the main interest for battery manufactures are manganese-based compounds and olivine lithium metal phosphates. In addition, lithium titanium oxide LiTi2O3, one new anode material, also has been proposed for advanced lithium batteries due to no SEI layer occurring on its anode surface[4]. In this paper, the power type lithium ion batteries mentioned above will be selected to compare their capabilities required by HEV.

Besides, super capacitor with quite high specific power, fast rate of charge and discharge and long cycle life is an ideal energy storage for HEV application. But poor energy density is the super capacitor’s disadvantage so the combination of battery and super capacitor proposed by some literatures would be the best choice[5]. However, this combination energy storage device is very complex, so that either batteries or super capacitor may still be the only energy storage device as long as they could meet both the energy and power requirements of the vehicle design even though the designer realized super capacitor plus batteries would have some advantages[6].

So far, few literatures focuses on basic performances of different energy storage devices but from the point of energy storage device selecting for HEV, it is significant and necessary to compare the performances of the power type lithium ion batteries and super capacitor. Through compared with each other it can be obviously found which battery type is more appropriate for HEV application or which hybridization level of powertrain of HEV.

In this paper, the general characteristics of 3 different commercial power type lithium ion cells and 1 commercial super capacitor have been investigated and quantitatively compared under same conditions. Considering the harsh working conditions of the energy storage system (ESS) of HEV, charging/discharging the cells at different C-rates under different ambient temperatures are designed to explore how working temperature and operating load (applied currents) especially high currents affect their capacity retention. Besides, HPPC tests at different temperatures also conducted to compare their resistance characteristics and open circuit voltage, from which the power characteristics also be derived.

Furthermore, through quantitatively comparing and analyzing their available capabilities, it is apparent to determine how the comprehensive performances of different type of cells present

2 Experimental

The 4 commercial power type cells used in the experiment come from 4 different manufactures. The basic parameters of four types of cells are shown in Table 1. All experiments are carried out at an 8-channels battery test bench made by DIGATRON firing circuits. The test bench has a current range of -100A to +100A and a voltage range of 0V to 20V.

To begin with, capacity test was carried out and the test sequence are as follows:

1) Put the cell in the 25°C constant temperature chamber for 4h.
2) Discharge the cell at constant current 1C to discharge cut off voltage.
3) Rest the cell for 1h to let the cell reach internal balancing.
4) Charge the cell at a constant C-rate corresponding to the manufacturer’s specified rate up to the charge cut-off voltage then transfer to constant voltage charging until the current drops to cutoff current.
5) Rest the cell for 1h to let the cell reach internal balancing.
6) Repeat steps (2) – (5) four times.

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Nominal Capacity</th>
<th>Nominal Voltage</th>
<th>Charge/Discharge cutoff voltage</th>
<th>Weight</th>
<th>Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTO</td>
<td>2.9 Ah</td>
<td>2.4 V</td>
<td>2.8/1.8 V</td>
<td>0.150 kg</td>
<td>Prismatic</td>
</tr>
<tr>
<td>LFP</td>
<td>6.5 Ah</td>
<td>3.2 V</td>
<td>3.65/2.0 V</td>
<td>0.384 kg</td>
<td>Prismatic</td>
</tr>
<tr>
<td>LMO</td>
<td>8 Ah</td>
<td>3.6 V</td>
<td>4.2/3.0 V</td>
<td>0.300 kg</td>
<td>Pouch</td>
</tr>
<tr>
<td>SC</td>
<td>1500 F</td>
<td>2.7 V</td>
<td>2.7/1.35V</td>
<td>0.510 kg</td>
<td>Cylindrical</td>
</tr>
</tbody>
</table>
Then the HPPC test at 25℃ referred to the literature[7] is designed to measure the OCV and resistance. The discharge pulse current for LTO, LFP, LMO and SC are 10C, 10C, 5C and 20C. And the charge pulse current for LTO, LFP, LMO and SC are 10C, 10C, 5C and 20C. After that repeat the HPPC test at 45, 35, 15, 0, -10, -20℃, respectively, to find low temperature and high temperature performances of the cells. It has been known that temperature has little influence on the performance of Super capacitor so that the test temperature for super capacitor are 45, 25, 0, -10, -20℃ separately.

Finally, to adequately understand how ambient temperature and applied current rate including charging and discharging affects capacity characteristics, a series of charging and discharging rates are arranged to deliver the cells under different ambient temperatures corresponding to the HPPC tests.

3 Results and discussion

3.1 Comparison of OCV

The OCV-SOC curves could be derived from the HPPC test described in section 2. And the results are shown in Figure 1. The results are tested under temperature 25℃ and without special indication, all the results below are tested at temperature 25℃.

![Figure 1: comparison of OCV](image1)

It is obvious that the OCV of LMO cell is ranked highest, followed by LFP cell, LTO cell and SC cell. The magnitude of OCV is related to the cathode and anode electrode materials used in the battery but it is depend on the polar plate area and the separation distance for super capacitor. The OCV-SOC curve is widely used in SOC estimation. The OCV of battery could be derived by measurement (or other methods like through the battery model), and then the battery SOC could be obtained by interpolation method. Therefore, the shape of OCV-SOC curve may impact the precision of estimated SOC value. The SOC estimation errors caused by 1mV voltage measurement error (which could be also called by dSOC/dOCV) for four types of batteries are shown in Figure 2.

![Figure 2: dSOC/dOCV of four types of batteries](image2)

It is clear that the curve of LFP cell sticks out in the four curves and LFP cell has two large peaks in the SOC interval 0.4-0.8 and 0.8-1.0. And the maximum value is 0.03, which means that, while making the SOC estimation by OCV, 1mV voltage measurement error will cause about 3% SOC estimation error. Regarding this issue, in case of an OCV-SOC curve of a battery that does have a relative flat voltage plateau it seems that the battery might requires the management system (BMS) higher voltage measurement precision and more accurate SOC estimation algorithm. However, the peak values of the other three type batteries are entirely less than 0.5%, which means that 1mV voltage measurement error only cause about less than 0.5% SOC estimation error.

For LFP battery, if the voltage measurement precision does not reach 1mV then it is likely that its estimation error of SOC will turn worse further. As shown in the figure 3, it is the estimation error of SOC for LFP at different voltage measurement error corresponding to 5mV, 10mV, 15mV and 20mV, respectively. The SOC estimation error reach up to nearly 10% when the voltage measurement error stays in the 10mV.
3.2 Rate capabilities

3.2.1 Discharge

Rate capabilities play an important role in the energy storage system of hybrid electric vehicles because HEV requires the ESS must be capable of furnishing large currents to accelerate and climb long hill while it operates. Then it is necessary for the auxiliary power source to keep high capacity retention when discharge the battery at high rates in order to supply adequate output energy to propel the HEV. In addition, work temperature can produce a significant effect on the capacity retention of battery, which has also been point out by lots of literatures. Therefore, the multiple discharge rates combined with multiple ambient temperatures from low temperature -20°C up to high temperature 45°C, covering the HEV common operating temperature range, are designed to research the capacity retention. The comparison of capacity retention of the four type cells at 25°C is shown in the Figure 4.

![Figure 3: dSOC/dOCV of LFP battery](image)

By and large, it has the semblable law for the four type cells that the capacity retention decreases more or less with discharge rate gradually increasing. However, in terms of the identical discharge rate, the capacity retention of the four type battery exist large difference. For example, super capacitor (SC) is superior to the others in the capacity retention value and the super capacitor can be discharged at quite high rates up to 60C while the capacity retention still keep about 95% capacity retention so that there is no need to worry about whether the output energies provided by the auxiliary power source are sufficient for acceleration and hill-climbing events. The higher rate capability of super capacitors comes from the electrostatic storage of charge at the electrode surface. In contrast to the super capacitors, the batteries store energy by oxidation-reduction reaction in the bulk electrode, leading to high energy density but slow kinetics. Since the different mechanism of energy storage, the difference in rate capability between electrochemical battery and super capacitor can be explained.

In addition, it is can be found that the rank in rate capability is exactly contrary to its own nominal capacity. Rate capability is clearly important for power type battery because most of discharge operations are done at high current levels with small capacity drains. From the Figure 4 we can find that the LTO battery with new negative material of LTO has outstanding rate capabilities than LFP battery and LMO battery. From a rate capability standpoint, the LTO battery and super capacitor are more suitable for HEV application.

Since the great effects on battery capabilities by working temperature, especially the low temperature that can reduce the conductivity of the electrolyte leading to slow down the electrochemical reaction rate and increase the internal resistance resulting in much loss of energy, discharge performance at low temperature is considered as a very important index to evaluate the batteries technology. Figure 5 (a) to (d) presents the capacity retention profile of the four type batteries at different discharge rates under different temperature.

![Figure 4: Comparison of capacity retention of the four type battery](image)
For the three types of lithium ion batteries, it is clear that capacity retention curves of LFP battery and LMO battery change to worse when temperature turn to cold and discharge rates increase. In some sense, the capacity retention “stiffness” under low temperature reflects the low temperature performance of battery technology. It is expected that working temperature has little effects on battery especially discharging the battery in high rates as the super capacitor presents. As the Figure 5 shows, LMO battery is most sensitive to low temperature, at 0℃ there is almost no energy to deliver at 15C discharge rate. While for LFP battery and LTO battery the situation appear at -10℃ and -20℃, respectively.

Overall, excellent low temperature performance and rate capabilities of batteries can enhance the environment adaptable capability and reduce the complexity of BMS, therefore there is also huge potential for large-scale application.

3.2.2 Charge

Though the discharge performance of the batteries attract much attention attributed to the basic power auxiliary function for HEV, the charge performance should not be neglected. With the level of hybridization elevated, more attention should be paid to the charge capability of the batteries. The mild-HEV and medium-HEV not only require ESS supply relative high output power but also requires the rapid energy recovery from the regenerative braking to enable fuel saving. In the particular case of HEV with electric drive capability such as full-HEV and plug-in HEV, the HEV imposes the high rate demands for battery[8] so that a kind of battery whether can be charged at high rate or not directly relating to the drive performance of HEV and market interesting.

Figure 6 presents the charge test results, the different charge current rates, not beyond the range permitted by their own manufacture, were performed for the four type batteries at 25℃. The charge regime adopted is standard constant current charging and constant voltage charge (CC-CV) which is mentioned in section 2. Excessively long constant voltage charging stage is not favored before full charged because that means the available capacity in constant current charging stage reduces.
Figure 6: Comparison of charge test

Figure 7 is a qualitative representation of ESS performance demands in a typical HEV duty cycle[9]. The realistic operation window for HEV is 30-70% SOC to avoid overcharge or over discharge resulting in the battery cycle life reduction.

In addition, it should be noted that the battery supplied current rates in HEV usually more than 15C, even 20C. Consequently, it imposes the strong charge acceptance for high rates on the battery.

As the Figure 6 shows, for the three kind of lithium ion battery except for the super capacitor, the LTO battery can be charged at up to 25C rate, even higher, which should be owed to the advanced negative material of LTO, and keep well voltage distribution in the 30-70% SOC as charge current increases.

For LFP battery, when charged at 10C rate, only about 60% capacity can be charged into the battery during the CC stage and the rest approximate 40% capacity has to rely on the CV charging section, which indicates the poor fast charging performance and the weak regenerative braking capability related to the fuel saving.

For LMO battery, the voltage section below 60% SOC exhibits considerable variation and nonlinear characteristics so that it is hard for voltage regulation. Independent of the charging current rates, the charging performance of super capacitor is obviously superior to the other three electrochemical batteries.

In fact, the charge acceptance in working temperature is more rigorous than discharge. Because the carbon material used as negative electrode, LMO battery and LFP battery are not suggested to be charged in low temperature to
protect lithium metal plating at the anode. But for LTO battery, the LTO anode can accept lithium at a high rate so that there is no question of charging under low temperature. Due to the different mechanism of energy storage from electrochemical battery, the charge acceptance for super capacitor is independent on temperature. Therefore, the conclusion can be deduced that super capacitor and LTO battery owe better charge performance than LMO battery and LFP battery.

Figure 8 and Figure 9 present the charging test results of LTO battery at 1C current rate under different temperature. Figure 8 shows the voltage change process and the Figure 9 records the time change process. At the same condition, the low temperature prolongs the full-charging time and CV stage.

3.3 Resistance and power characteristics

3.3.1 Resistance characteristics

The internal resistance of the battery is one of the most important evaluating indexes for battery characteristics, which also reflects the state of health (SOH) of the battery. As power type battery, the amplitude of battery resistance value directly influences its output power and heat generation. The small internal resistance implies the low transport resistance and high electrical conductivities in the electrode and electrolyte which is related to the cathode material structure that can be modified to improve kinetics by applying the nanostructure on the electrode material or using conductive additive like carbon black[10]. Once the electronic transport within lithium battery electrode is improved, the internal resistance will decrease followed by an increase of charge and discharge current rates as well as the output power of the battery.
Figure 10: discharge and charge resistances of the four type batteries

The Figure 9 shows the 10s discharge and charge resistance of the four types of batteries at 25℃, which can be derived from the HPPC test.

Before comparing their resistances, it is noted that the discharge resistance, on the whole, is consistent with the charge resistance except for the LMO battery in the low SOC interval. According to the research by Donald W. Corson[11], the inconformity between the discharge resistance and charge resistance of battery is not beneficial to achieve the best fuel consumption for HEV.

In addition, it could be found that the resistance couldn’t be compared directly because different types of batteries have different capacity and voltage, thus the resistance of different batteries are quite different.

To compare the resistance of different capacity and different voltage more simply, a new parameter should be introduced.

As shown in Figure 11, a battery of nominal voltage 3V, capacity 20Ah, resistance $R$, could be equivalently considered as a battery pack, which includes 60 cells of 1 V, 1 Ah. Specifically, 3 cells are connected in series and 20 in parallel. The resistance of this 1 V, 1 Ah ‘virtual cell’ $r=20R/3$. This resistance could be called as virtual resistance.

For a battery of nominal voltage $U$, capacity $C$, resistance $R$, the virtual resistance could be calculated as: $r=RC/U$. It should be noticed that here $C$ and $U$ may not be integer.

For different batteries with different capacity and different voltage, the resistance couldn’t be compared directly, but the virtual resistance could be compared directly and also reflect the real resistance of the batteries. The virtual resistance at comparisons 25℃ of the 4 types of battery are shown in Figure 12.
It can be easily found that the virtual resistance of super capacitor is very low nearly vanishing, followed by the LTO battery’s virtual resistance which is more smaller than LFP and LMO battery’s in the wide common 30-80% SOC range. The charge and discharge virtual resistance of LTO battery is about $3 \text{ mΩ} \cdot \text{Ah} \cdot \text{V}^{-1}$. And the resistances value of LFP and LMO battery is more than $10 \text{ mΩ} \cdot \text{Ah} \cdot \text{V}^{-1}$ which are relatively high compared with LTO and SC. At different temperature, the resistance of the battery is very different. With the temperature increases, the resistance would decrease; with the temperature decreases, the resistance would increase. The discharge resistance of 4 types of battery under different temperature are shown in Figure 13. But for the life and safety reasons, the LFP and LMO battery couldn’t charge below 0°C so that we do not exhibit the charge resistance of the four types of battery at different temperature. Through observing the discharge resistance distribution under different temperature, the resistance of LFP and LMO battery scattered around in the figure, especially for those resistances below 0°C also illustrate the low temperature performance not as good as the performance under normal atmospherically temperature. When attention switched to the resistance of the LTO battery and super capacitor, the resistance presents regular variations.
3.3.2 Power characteristics

For HEV application, the energy storage system power characteristics are absolutely a significant evaluation indicator. And the level of powertrain hybridization also depends on the power level of ESS. Meanwhile, the higher ESS power level enable higher fuel saving benefits and lower exhaust gas emissions. As noted earlier, the realistic operation of battery of HEV is dynamic which can be explained that the discharge or charge current is intermittent. Therefore, the HPPC test may accurately evaluate the power capabilities of HEV batteries to a certain degree. In addition, the discharge or charge peak current during operation is of intense amplitude more than 20C rates. On basis of the equation (1) and (2) the 10s maximum discharge and charge specific power as a function of the SOC can be obtained from the HPPC test.

\[
P_{dch} = \frac{U_{ocv} - U_{min}}{R_{dch}} \times U_{min} \times \frac{1}{m} \quad (1)
\]

\[
P_{cha} = \frac{U_{max} - U_{ocv}}{R_{cha}} \times U_{max} \times \frac{1}{m} \quad (2)
\]

Here, \( P_{dch} \) and \( P_{cha} \) are the maximum discharge and charge specific power as a function of SOC, \( U_{min} \) and \( U_{max} \) are the discharge and charge cut-off voltage, \( m \) is the mass of cell, \( R_{dch} \) and \( R_{cha} \) are discharge and charge resistance as a function of SOC, and the \( U_{ocv} \) is the open circuit voltage as a function of SOC. Figure 14 presents the 10s maximum specific power of four types of battery at 25°C. Because specific power of super capacitor is extremely higher than other three batteries, the Figure 15 is the results of 3 types of lithium ion battery after the Figure 14 enlarged.

Whether the discharge power or the charge power, their maximum values all do not appear in the specified operation 30-70% SOC range of the battery resulting in that the HEV could not take advantage of the energy storage and achieve maximum utilization. In addition, the charge power value of LFP battery is only about 600W/kg far from its own discharge power brought about the bottom position compared with other battery.
As noted earlier, the battery is operated at a nominal SOC level near 50% determined by the unique demands of HEV thus the charge and discharge power at 50% SOC is considered to be the most representative key point of the charge and discharge power curves. According to the HPPC test performed under different working temperature, the discharge and charge specific power at 50% SOC under different temperature can be obtained by interpolation method the comparison results are shown in the Figure 16. On the one hand, with temperature decreases, the charge and discharge power decreases and power level within them is quite clear. On the other hand, it seems that the charge and discharge specific power change trends as a function of temperature coincided with some regular laws which can be used to build the model of maximum discharge and recharge power estimation.

3.4 Comparison of specific energy

High specific energy is the outstanding aspect of lithium ion battery which making it attractive for both EV and HEV application. Figure 17 shows the specific energy of 4 types of energy storage at 1C discharge rate under 25°C. Though the super capacitor characterizes the excellent power capability, the poor specific energy, about 4.8Wh/kg, offset its advantage in power aspect.

The rank of specific energy is : LMO > LFP > LTO > SC. It should be noted that due to the realistic operation window of the battery is 30-70%, which is assumed to be extended to 30-80%, thus the available energy is only about one-half of the total energy. Therefore, the specific energy and available specific energy of the four types of the energy storage is shown in the Table 2.

<table>
<thead>
<tr>
<th>Energy Storage</th>
<th>Specific Energy (Wh/kg)</th>
<th>Available Specific Energy (Wh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTO</td>
<td>52.1</td>
<td>26</td>
</tr>
<tr>
<td>SC</td>
<td>4.8</td>
<td>2.4</td>
</tr>
<tr>
<td>LFP</td>
<td>63</td>
<td>31.5</td>
</tr>
<tr>
<td>LMO</td>
<td>101</td>
<td>50.5</td>
</tr>
</tbody>
</table>

Due to the low specific energy, thus super capacitor must be considered to meet the energy required of the HEV during acceleration and long hill-climbing. While for lithium ion battery, there is no need to worry because of the high specific energy.

3.5 Comprehensive comparison

Through several aspects discussed above, it has been proved that none of the four types of energy storage can be characterized by best performance in all aspects. There always exit shortcomings in each type of energy storage to counterbalance their good characteristics in other respects. Under the circumstances, we attempt to find an energy storage with a compromise in various aspects performance by the comprehensive which is shown in Figure 18.
According to the figure 18, it can be easily found that the main drawbacks to super capacitor are low specific energy and low voltage. Compared with other battery, the power type LFP battery is inferior performance. For LMO battery, it has typical high specific energy but poor rate capability and poor low temperature performance. And the LTO battery has a relatively wide range in every way without major defects. Consequently, considering the comprehensive performance, the LTO battery is raised above the four types of energy storage.

4 Conclusion

In this paper, four commercial power type energy storages: LTO battery, LFP battery, LMO battery and super capacitor, were researched for HEV application. A series of discharge and charge current rates under different ambient temperature were designed test the performances of the 4 types of energy storages. Test results demonstrate that the LTO battery and super capacitor are superior to LFP and LMO battery in rate capability, particularly in low temperature, and have the capable of absorbing and furnish the peak current surge during braking, accelerating and long hill-climbing of HEV. In addition, the resistance level and power characteristic of the LTO battery and super capacitor also imply the excellent power performance. However, the poor specific energy of SC offsets its outstanding power performance. By the performances comprehensively compared, the LTO battery should be the best choice for HEV.

5 References


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