EVS25
Shenzhen, China, Nov 5-9, 2010

Analysis of the key factors affecting the energy efficiency of batteries in electric vehicle

Rengui Lu[1], Aochi Yang[1], Yufeng Xue[2], Lichao Xu[2], Chunbo Zhu[1]

[1]Harbin Institute of Technology, Harbin, China
[2]First Automobile Works, Changchun, China
E-mail: lurengui@hit.edu.com

Abstract

The energy efficiency for electric vehicle battery is affected by many factors. Through the definition of energy efficiency we find the relationship between energy efficiency, voltage efficiency and coulomb efficiency. The factors such as current, internal resistance, SOC and temperature which affect coulomb efficiency and voltage efficiency, will affect energy efficiency as well. An equation is given to show how internal resistance and current influence the energy efficiency. The relationship between these factors and energy efficiency was analyzed through theory and experimental data. This will show ways to increase battery energy efficiency and improve the battery performance.

Keywords: *Energy efficiency, Coulomb efficiency, Voltage efficiency, Electric vehicle battery*

1 Introduction

An electric vehicle's running cost and service life are affected by the battery performance, and the full use of energy of the battery can reduce the operating cost and prolong the service life. The energy efficiency is a significant parameter for electric vehicle battery. So it is necessary to study the key factors affecting the energy efficiency. The purpose is to reduce the charging time reasonably and increase the discharge energy. And then, improve the whole performance of the electric vehicle.

There are several ways to express the battery efficiency. We usually use coulomb efficiency and energy efficiency for evaluating battery performance. The battery's coulomb efficiency is defined in USABC (1996) as the ratio of the discharged capacity to the capacity needed to be charged to the initial state before discharge. The coulomb efficiency is shown in [1] as:

$$\eta_C = \frac{\int_0^{t_d} I_d dt}{\int_0^{t_c} I_c dt} \tag{1}$$

Where I_d is the discharge current, t_d is the discharge time, I_c is the charge current and t_c is the charge time. The experiment indicates that the coulomb efficiency is different with respect to different current rates. At different state-of-charge (SOC) the coulomb efficiency also changes. Only the average coulomb efficiency in the whole charge and discharge processes are obtained from Eq. (1).

The definition of energy efficiency is similar with the coulomb efficiency. Energy efficiency is defined as the ratio of the discharged energy to the energy needed to be charged to the initial state before discharge. The energy efficiency is shown as:

$$\eta_W = \frac{\int_0^{t_d} U_d I_d dt}{\int_0^{t_c} U_c I_c dt} \tag{2}$$

Where I_d is the discharge current, t_d is the discharge time, U_d is the discharge voltage, I_c is the charge current, t_c is the charge time and U_c is the charge voltage. U_d and U_c are functions of time. Eq. (2) expresses the average energy efficiency in the whole charge and discharge processes.

Compared with coulomb efficiency the energy efficiency is more complex since the voltage is introduced in the definition, besides charging and discharging voltages depend on the rate at which current is entering or leaving the battery as well as the state of charge of the battery, its temperature, age, and general condition.

2 Key factors affecting energy efficiency

2.1 Relationship between three kinds of efficiency

Imagine charging a battery with a constant current I_c over a period of time t_c during which time the voltage is a function U_c . The capacity Q_C and energy E_C input to the battery is thus

$$Q_C = I_c t_c \tag{3}$$

$$E_C = I_c \int_0^{t_c} U_c dt \tag{4}$$

Suppose that the battery is discharged at a constant current I_d over a period of time t_d in order to restore the initial state before charge. During this time the voltage is expressed by U_d . Total capacity and energy E_D during discharge is

$$Q_D = I_d t_d \tag{5}$$

$$E_D = I_d \int_0^{t_d} U_d dt \tag{6}$$

According to the definitions of coulomb efficiency and energy efficiency, coulomb efficiency η_C and energy efficiency η_W can be shown as:

$$\eta_C = \frac{Q_D}{Q_C} = \frac{I_d t_d}{I_c t_c} \tag{7}$$

$$\eta_W = \frac{E_D}{E_C} = \frac{I_d \int_0^{t_d} U_d dt}{I_c \int_0^{t_c} U_c dt} \tag{8}$$

From Eq. (7) and Eq. (8) the relationship between coulomb efficiency and energy efficiency is shown as:

$$\eta_W = \eta_C \frac{\dfrac{\int_0^{t_d} U_d dt}{t_d}}{\dfrac{\int_0^{t_c} U_c dt}{t_c}} = \eta_C \frac{\overline{U_d}}{\overline{U_c}} \tag{9}$$

Where $\overline{U_d}$ is the average voltage of the battery in the whole discharge process and $\overline{U_c}$ is the average voltage of the battery in the whole charge process. And the voltage efficiency η_V is defined as the ratio of the discharged average voltage $\overline{U_d}$ to the charged average voltage $\overline{U_c}$. So the energy efficiency is the product of coulomb efficiency and voltage efficiency:

$$\eta_W = \eta_C \eta_V \tag{10}$$

From Eq. (10) we find that energy efficiency is affected by voltage efficiency and coulomb efficiency. Decomposing energy efficiency into two parts will make the analysis of the key factors affecting the energy efficiency easier Through the analysis we find that the significant factors that can affect coulomb efficiency η_C and voltage efficiency η_V are as follows: discharge and charge current , state-of-charge, internal resistance, temperature and the age of battery. The analysis and experiments below eliminate the influence of temperature, SOC and the age of battery and focus on the relationships between current, internal resistance and energy efficiency.

2.2 Factors affecting energy efficiency

First, think about the influence on voltage efficiency η_V caused by different charging and discharging currents. Charging voltage and discharging voltage are the function of state-of-charge, and they also have to do with internal resistance. Consider the simple Thevenin equivalent in [2] for a battery consisting of an ideal battery of voltage V_B in series with an internal resistance, R_i (Fig. 1). Voltage V_B can be considered to be the open circuit "rest" voltage of the battery as measured some hours after either charging or discharging has occurred.

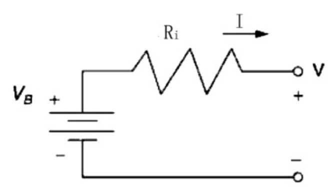

Figure 1: Thevenin equivalent circuit for a battery

According to Thevenin equivalent, internal resistance and current can affect battery voltage during charging and discharging processes. Assuming that during a short period of charging or discharging process the state-of-charge does not change, namely during this period V_B is constant. During the charging period, the average voltage applied to the terminals $\overline{U_c}$ must be greater than V_B. When the battery is discharging, the average output voltage $\overline{U_d}$ will be less than V_B. So the discharged average voltage $\overline{U_d}$ and the charged average voltage $\overline{U_c}$ can be separated as

$$\overline{U_d} = V_B - R_i I_d \tag{11}$$

$$\overline{U_c} = V_B + R_i I_c \tag{12}$$

Thus the voltage efficiency η_V can be shown as

$$\eta_V = \frac{V_B - R_i I_d}{V_B + R_i I_c} \tag{13}$$

From Eq. (13), when internal resistance is constant if discharge current I_d is greater, the voltage efficiency η_V will decrease. With the same discharge current I_d, if internal resistance increases, it will also leads to the drop of voltage efficiency η_V. During those charge and discharge times, there are $I^2 R_i$ power losses in the internal resistance. Since those losses go as the square of current, faster charge or discharge times result in much higher losses.

Coulomb efficiency is influenced mainly by three key factors: temperature, current and state-of-charge. Since when the battery is used in an electric vehicle SOC should be limited from 0.2~0.8 in which the coulomb efficiency approximates 1. The relationship between coulomb efficiency and charge or discharge currents can be deduced by the Peukert equation.

The Peukert equation in [3] gives a relationship between immediately available capacity deliverable as a function of current. It is commonly modeled as

$$Q = KI^{1-n} \tag{14}$$

Where Q, capacity, is measured in Ampere-hours, K and n are the Peukert constant and exponent (characteristic battery constant and the battery discharge rate sensitivity exponent), respectively, and I the current in Amperes. In words, it states that as the discharge current increases, the total capacity of the battery (in Ampere-hours), or the total energy delivered by the battery, decreases disproportionately. So coulomb efficiency can be shown as

$$\eta_C = \frac{Q_d}{Q_N} = (\frac{I_d}{I_N})^{1-n} \tag{15}$$

Where I_d is discharge current, I_N is base current, Q_d is the capacity discharged by I_d and Q_N is the capacity discharged by base current I_N.

From Eq. (13) and Eq. (15) the relationship between energy efficiency and discharge current and internal resistance can be given as

$$\eta_W = \eta_C \eta_V = (\frac{I_d}{I_N})^{1-n} \frac{V_B - R_i I_d}{V_B + R_i I_c} \tag{16}$$

So eliminating temperature factor and SOC factor, the energy efficiency can be described in Eq. (16). From Eq. (16), the internal resistance and discharge current are two important factors that decrease the energy efficiency, so during the use of the battery small internal resistance and appropriate charge and discharge current will help to increase the energy efficiency.

2.3 Experimental analysis

Ni-MH batteries from three different companies are tested for analyzing the relationship between energy efficiency; coulomb efficiency and voltage efficiency described in Eq. (10). Three companies are shown as A, B and C.

In the tables below, experiment result of energy efficiency is the quotient of energy discharged and energy charged; calculation result of energy efficiency is the product of voltage efficiency and coulomb efficiency.

Table 1: Experimental data of battery A

Data of battery A	Process of charge			Process of discharge			Results			
	Time (s)	Energy (Wh)	Average Voltage	Time (s)	Energy (Wh)	Average Voltage	Voltage efficiency	Coulomb efficiency	Energy efficiency (Calculation result)	Energy efficiency (Experiment result)
No. 1	2160	31.319	8.407	2071	27.282	7.511	89.34%	97.58%	87.18%	87.18%
No. 2	2160	31.036	8.392	1997	26.075	7.458	88.87%	94.54%	84.02%	84.01%
No. 3	2160	31.033	8.391	1993	26.035	7.566	90.17%	93.02%	83.88%	83.89%
Average							89.46%	95.05%	85.03%	85.03%

Table 2: Experimental data of battery B

Data of battery B	Process of charge			Process of discharge			Results			
	Time (s)	Energy (Wh)	Average Voltage	Time (s)	Energy (Wh)	Average Voltage	Voltage efficiency	Coulomb efficiency	Energy efficiency (Calculation result)	Energy efficiency (Experiment result)
No. 1	2160	33.174	8.407	2071	28.409	7.601	90.41%	94.72%	85.64%	85.64%
No. 2	2160	32.778	8.392	2114	28.745	7.604	90.61%	96.79%	87.70%	87.70%
No. 3	2160	33.151	8.391	2066	28.329	7.595	90.51%	94.48%	85.51%	85.45%
No. 4	2160	32.681	8.471	2120	28.738	7.676	90.61%	97.05%	87.94%	87.93%
Average							90.54%	95.76%	86.70%	86.68%

Table 3: Experimental data of battery C

Data of battery C	Process of charge			Process of discharge			Results			
	Time (s)	Energy (Wh)	Average Voltage	Time (s)	Energy (Wh)	Average Voltage	Voltage efficiency	Coulomb efficiency	Energy efficiency (Calculation result)	Energy efficiency (Experiment result)
No. 1	2160	30.230	8.450	2124	26.565	7.688	90.98%	96.58%	87.87%	87.88%
No. 2	2160	30.704	8.516	2078	26.189	7.744	90.93%	93.81%	85.30%	85.30%
No. 3	2160	29.983	8.380	2134	26.649	7.624	90.98%	97.70%	88.89%	88.88%
No. 4	2160	30.434	8.442	2088	26.312	7.678	90.95%	95.06%	86.46%	86.46%
Average							90.96%	95.79%	87.13%	87.13%

Through the tests for Ni-MH batteries from three different companies, experiment result of energy efficiency and calculation result of energy efficiency are compared in the Figure 2. We can find out that energy efficiency calculated from Eq. (10) and energy efficiency calculated directly from the energy charged and discharged are almost equal. As a result, the relationship shown in Eq. (10) gives us another way to calculate battery's energy efficiency.

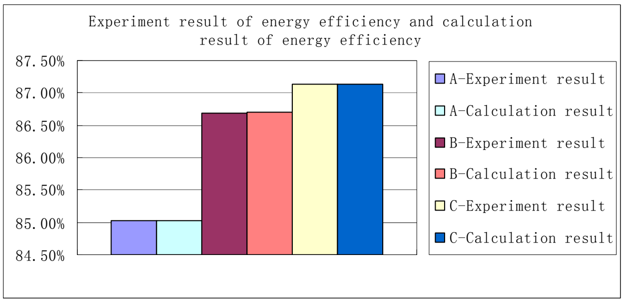

Figure 2: Comparison between experiment result of energy efficiency and calculation result of energy efficiency

For further analysis the relationship between voltage efficiency and internal resistance, the internal resistances are tested. The internal resistance of there three companies are respectively 21.86mΩ, 17.15mΩ and 16.8mΩ as shown in Figure 3. In order to show voltage efficiency better, voltage efficiency of A, B and C companies is given again in Table 4 and compared in Figure 4 below.

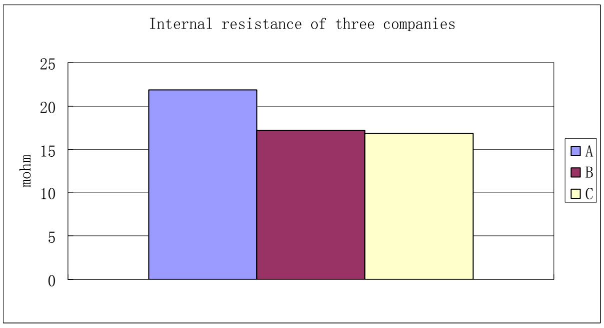

Figure 3 Internal resistances of three companies

Table 4: Voltage efficiency of three companies

A	Voltage efficiency	B	Voltage efficiency	C	Voltage efficiency
1	89.34%	1	90.41%	1	90.98%
2	88.87%	2	90.61%	2	90.93%
3	90.17%	3	90.51%	3	90.98%
		4	90.61%	4	90.95%
Average	89.46%		90.54%		90.96%

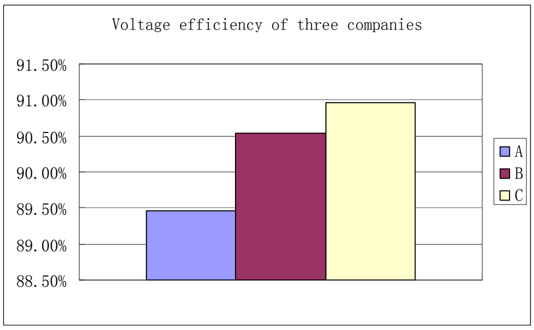

Figure 4 Voltage efficiency of three companies

From the comparison between Figure 3 and Figure 4, it is easy to see that the experimental results correspond to the Eq. (13). With the increasing of internal resistance, voltage efficiency of the battery will decrease. From the comparison between Figure 2 and Figure 3, we can also see the relationship between internal resistance and energy efficiency: when the internal resistance increases, energy efficiency decreases as a result.

3 Conclusion

Through the analysis, energy efficiency can be separated into two parts: voltage efficiency and coulomb efficiency. The key factors such as charge and discharge current, internal resistance, SOC and temperature affecting coulomb efficiency and voltage efficiency will influence the energy efficiency as well. The relationship between current, internal resistance and energy efficiency is given. Reducing internal resistance and control charge and discharge current appropriately will help to increase the energy efficiency.

References

[1] Junping Wang, Binggang Cao, Quanshi Chen, Feng Wang, *Combined state of charge estimator for electric vehicle battery pack*, Control Engineering Practice Vol. 15, 2007, pp:1569-1576.

[2] Gilbert M Masters, *Renewable and efficient electric power systems*, 2004, pp:566-569.

[3] Ahmed Fasih, *Modeling and Fault Diagnosis of Automotive Lead-Acid Batteries*, College of Engineering, The Ohio State University, 2006, pp:14-16.

Authors

Ph.D. Rengui Lu
Rengui Lu received Ph.D. in Instrument Science and Technology from the Harbin Institute of Technology in 2008. Since 2005, he was Associate Professor of School of Electrical Engineering and Automation in Harbin Institute of Technology. His research interests include batterymanagement; EV and HEV Control.

Graduate student. Aochi Yang
Aochi Yang received the B.S. degree in electrical engineering from the Harbin Institute of Technology in 2009. Now he is a graduate student and his main research direction is battery management including battery state monitoring and cell balancing.

Engineer Yufeng Xue
Yufeng Xue received the master degree from the Harbin Institute of Technology. His researches mainly focus on the development and test of the power battery system.