IECON2015-Yokohama
November 9-12, 2015

Energy Efficiency of Lithium-ion Battery Used as Energy Storage Devices in Micro-grid

Kaiyuan Li
School of Electrical and Electronic Engineering
Nanyang Technological University, Singapore, 639798
kli1@e.ntu.edu.sg

King Jet Tseng
School of Electrical and Electronic Engineering
Nanyang Technological University, Singapore, 639798
k.j.tseng@pmail.ntu.edu.sg

***Abstract*—This paper investigates the energy efficiency of Li-ion battery used as energy storage devices in a micro-grid. The overall energy efficiency of Li-ion battery depends on the energy efficiency under charging, discharging, and charging-discharging conditions. These three types of energy efficiency of single battery cell have been calculated under different current rates. The relations of the energy efficiencies with current rate are analyzed using non-linear curve fitting and polynomial equations. Moreover, the Li-ion battery used in the present study has been verified to have low cell imbalance when 10 cells are connected in series without any cell equalizers, and the charging-discharging energy efficiency of the battery pack has been obtained through hardware experiments.**

Keywords—lithium-ion battery; energy storage device; energy efficiency; net energy of lithium-ion battery; OCV-SOC relation; non-linear curve fitting

I. Introduction

Secondary batteries are playing an increasingly significant role in our daily life as energy storage devices in micro-grid and EVs. Battery as energy storage devices for micro-grid are generally used to support the micro-grid by providing contingency supplies. In addition, it can help to allow better integration of renewable energy sources such as solar PV and wind turbine into the micro-grid, and work as grid support during peak consumption hours for load shifting and peak shaving.

Due to its relatively high energy-to-weight ratio, long life span, absence of memory effect and clean environment consideration, Li-ion battery has been the preferred choice among various existing secondary batteries used as energy storage devices in micro-grid. A Li-ion battery is a device that converts chemical energy directly into electricity energy; in the case of a rechargeable system, the battery is recharged by reversing the process [1]. Therefore, energy efficiency represents the utilization rate of energy, including the chemical energy and the electrical energy during processes. Unlike those of tiny-scale Li-ion batteries, the characteristics of large-scale Li-ion batteries, especially power batteries used as energy storage devices in micro-grid, require thorough analysis, not only with regard to basic properties such as voltage, current, and capacity, but also properties concerning the macroscopic operating environment of the battery, such as energy efficiency, temperature, and power. Due to its great significance, energy efficiency is a key parameter for evaluating the working conditions of battery: several research works were done for redox flow battery [2, 3, 4], lead-acid battery [4, 5], fuel cells [6], sodium-sulfur battery [7, 8], and zinc-nickel battery [9]. Moreover, the methods to evaluate battery's energy efficiency vary with the battery types and system composition. Currently, the most commonly adopted method only determines the battery's energy efficiency during discharging [10]. Briefly summarized, the abovementioned literature states that battery's energy efficiency is the ratio of the discharged energy to the recharged energy into the battery. Details of this method will be introduced in Section II A, and this method has two drawbacks: first, it does not offer a way to determine the battery's energy efficiency under charging; second, the recharged energy into the battery is not equal to the chemical energy gained by the battery, i.e., the net energy, because the recharged electrical energy from the power sources could not be 100% converted to the battery's internal chemical energy.

This study on the energy efficiency of Li-ion battery aims to: (1) calculate the utilization efficiency of battery's energy and minimize the energy loss by optimizing the working conditions; (2) predict the remaining discharging time of battery used in powering domestic electrical devices as energy storage devices, assuming the discharging efficiency is given; (3) estimate the internal energy loss of the battery, thus developing the equivalent circuit of the battery, and further predicting the State of Charge (SOC) and State of Energy (SOE) [11] of the battery; and (4) contribute to the thermal management of the battery, since the thermal energy of battery during charging and discharging is related directly to the internal energy loss of the battery, based on conservation of energy.

In the present study, energy efficiency of the Li-ion battery used as energy storage devices in micro-grid is investigated based on electrochemistry and electrical theory, for both single cell and a 10-cell battery pack. The tests are based on a type of large capacity lithium titanate (LTO) rechargeable battery, and the quantitative relations of the energy efficiency are analyzed. This paper is organized as follows: in Section II, the experimental methodology is discussed; Section III and Section IV discuss the experiments set-up and the real time experimental results, respectively. Section V concludes this paper.

II. Experimental Methodology

A. Definition of terms related to energy efficiency of battery

The USA PNGV Battery Test Manual [10] provided by the US Department of Energy (DOE) discussed the formula for calculating the round-trip energy efficiency of the battery as the ratio of the discharged energy removed to the regeneration energy returned during the process:

$$\text{Round trip efficiency} = \frac{watt \times hours\ (discahrge)}{watt \times hours\ (regen)} \times 100\% \qquad (1)$$

The regeneration energy in Eq. (1) is the recharged energy input with given steps. Note that only the discharging energy efficiency of the battery could be calculated from the above equation, and that the regeneration energy is not equal to the internal chemical energy gained by the battery itself because of the occurrence of polarization during the charging process. The demerits of the above method are discussed in Section I.

In the present study, 3 types of energy efficiency are defined according to the different battery working conditions: energy efficiency under charging (η_{cha}), energy efficiency under discharging (η_{dis}), and energy efficiency under charging-discharging ($\eta_{battery}$). They are defined as:

1) Energy efficiency under charging η_{cha} is the ratio of chemical energy gained by the battery during charging, i.e., the net energy ($\Delta E_{battery}$), over the energy extracted from power sources to charge the battery (ΔE_{in}).

$$\eta_{cha} = \frac{\Delta E_{battery}}{\Delta E_{in}} \qquad (2)$$

The method of calculating the net energy $\Delta E_{battery}$ will be discussed in details in Section II B. The value of the charged energy ΔE_{in} is calculated as:

$$\Delta E_{in} = \int_{t_0}^{t} V_{Cha} I_{Cha}\, dt = \int_{SOC(0)}^{SOC(t)} V_{Cha} C_n\, dSOC \qquad (3)$$

In Eq. (3), V_{cha} is the battery's close circuit voltage (CCV) during charging and I_{cha} is the charging current, C_n is the battery's standard capacity, SOC(0) is the battery's state of charge in terms of capacity when the charging starts, and SOC(t) is the SOC when the charging is completed. In the present study, C_n will be calculated in Section III C for higher precision instead of using the value given by the battery manufacturer.

2) Energy efficiency under discharging η_{dis} is calculated in the similar way, as the ratio of discharged energy from battery (ΔE_{out}) over the net energy of battery $\Delta E_{battery}$.

$$\eta_{dis} = \frac{\Delta E_{out}}{\Delta E_{battery}} \qquad (4)$$

The value of ΔE_{out} is calculated using the following equation:

$$\Delta E_{out} = \int_{t_0}^{t} V_{dis} I_{dis}\, dt = \int_{SOC(0)}^{SOC(t)} V_{dis} C_n\, dSOC \qquad (5)$$

In Eq. (5), V_{dis} is the battery's CCV during discharging and I_{dis} is the discharging current. SOC(0) and SOC(t) are the battery's SOC when the discharging starts and completes, respectively.

Environmental data such as time, ambient temperature, battery's surface temperature, terminal voltage and the charging/discharging current will be monitored and recorded during the experimental process, and the values of ΔE_{in} and ΔE_{out} can be calculated easily from Eq. (3) and (5). As to the state of charge, SOC(0) is calculated by the open circuit voltage (OCV) method [12] during the stabilization phase of the battery, and the equation to calculate SOC(t) is given in [13] as follows, using the Coulomb Counting method:

$$\text{SOC(t)} = SOC(0) + \frac{\int I dt}{C_n} \qquad (6)$$

In Eq. (6), the sign of I is positive during charging and negative during discharging.

3) Energy efficiency under charging-discharging $\eta_{battery}$ is calculated as the ratio of ΔE_{out} over ΔE_{in} when the battery is under charging-discharging cycle.

$$\eta_{battery} = \frac{\Delta E_{out}}{\Delta E_{in}} \qquad (7)$$

B. Calculation of the net energy of battery

The input or output energy of battery should not be considered as the internal chemical energy gained by the battery attributed the polarization from the charging and discharging process [14]. According to [14], the Gibb's free energy ($|\Delta G|$) of battery, which represents the stored internal chemical energy of battery, is given by:

$$|\Delta G| = \text{Charge passed} \times \text{Reversible potential difference} \qquad (8)$$

In the present study, the Gibb's free energy is substituted with net energy because the former item is a thermodynamic term, which is very hard to evaluate within our laboratory. The reversible potential difference that is a constant for the given battery is replaced by battery's OCV. In fact, all activities are changed during the charging and discharging. Kang et al. proposed in [15] that owing to the OCV varying with the SOC, the net energy, $\Delta E_{battery}$, is given by

$$\Delta E_{battery} = \int_{t_0}^{t} V_{OCV} I dt = \int_{SOC(0)}^{SOC(t)} V_{OCV} C_n dSOC \qquad (9)$$

The value of V_{OCV} at different SOC are obtained in two ways. The conventional method is to measure the terminal voltage of the battery after certain time period of charging/discharging for the cell to reach to a certain SOC and longtime relaxation. For example, after charging/discharging, battery's terminal voltage might take about 1 hour to reach to a steady state value, which is OCV, at which time the battery's internal activities are almost stabilized. This method is accurate but not suitable for online applications and is very time-consuming. The preferred way is proposed by S. Abu-Sharkh et al. in [16]: the battery is pulse charged and then pulse discharged at rated current with an off time of 1 minute in order to measure the initial voltage of the cell. Cell voltage, as functions of SOC under discharging and charging, are averaged to compute battery's OCV.

III. Expermentation

In order to obtain the energy efficiency of Li-ion battery at different operating conditions, the following experiments are conducted.

A. Battery specification

A type of LTO Li-ion battery with large capacity of 20.0 Ah is selected for all the experiments, Table 1 shows the specification of the LTO Li-ion battery cell provided by the manufacturer.

TABLE I. Battery specification

Battery	*Characteristics*
Chemical system	Lithium Titanate (LTO) rechargeable battery
Nominal voltage	2.3 V
Capacity	20.0 Ah Typical
Charging condition	CVCC 2.7 V 20.0 A, 1.0 A cut-off 25 °C
Discharging condition	Constant current 6.67 A, 1.5 V cut-off 25 °C
Maximum charging voltage	2.7 V
Discharge cut-off voltage	1.5 V
Operating temperature	-30 to 55 °C

B. Apparutus

HIOKI measurement stations LR8410-20 are used as data logger for the experiments. The ambient temperature, battery's surface temperature, terminal voltage and operating current are monitored and recorded to prevent overheating of the battery and to collect data. The experimental data is stored in the database of HIOKI measurement station and copied to PC via a SD card.

Chroma programmable AC/DC electronic load Model 63803 3.6KW/36A/350V is able to keep the current through it at a constant value; thus this E-load is connected in series with the battery in order to maintain the charging/discharging current at a constant value.

C. Charging and discharging setting

A general pre-set-up for all experiments are detailed as follows:

- All fresh battery cells are firstly set to 0% SOC by discharging at 6.67A (0.33C, and C means the discharging current that discharges the nominal battery capacity in 1h time) till the threshold 1.5V as stated in the battery's specification. These cells are then charged to 100% SOC after 2 hours' relaxation, and the charging process is carried out at a fixed rate of 20.0A (1.0C) in constant current (CC) mode and a fixed voltage of 2.7V in constant voltage (CV) mode with a charging termination current of 1.0A, according to the manufacturer's specification shown in Table I.
- All battery cells are relaxed for 1 hour for stabilization of their internal chemical reactions and terminal voltage.
- Surface temperature, terminal voltage and operating current of each battery cells are continuously monitored and recorded for every 1 second to obtain sufficient numbers of data points used in the energy efficiency calculation and the curve fitting process.
- All the charging and discharging experiments are done under constant current conditions, i.e., the charging and discharging current rates are constant. The battery used for charging are set to 0% SOC and rested for 1 hour before the charging experiments. Similarly, the battery for discharging are set to 100% SOC and rested for 1 hour before the discharging experiments.
- In the present study, charging experiments are performed at different current rates, and the current are held constant by the E-load. Each charging experiment will be cut-off when cell's CCV reaches the threshold 2.7V, at which point the cell's SOC is around 94%. However, CV charging will take about 20 minutes to fill the rest of the 6% SOC, thus for the operating and calculating simplicity in the present study, the battery will not undergo CV charging and therefore will not reach 100% SOC. All the charging will be cut off when the cell's terminal voltage reaches 2.7V after CC charging.
- Discharging experiments are performed with different current values, and the current are kept constant. Each discharging experiments will be cut-off when the cell's CCV reaches 1.5 V.
- All the cells are rested for 2 hours after each discharging and charging experiments, and are recalibrated to 0% or 100% SOC respectively for other experiment usage.
- The standard capacity C_n of the Li-ion battery is measured by firstly charging the battery to 100% SOC by the rated method, and then discharging the battery by the rated current rate after 1 hour's rest, and C_n is calculated by the Coulomb Counting method given in [13]; C_n is calculated to be 20.22 Ah, which is close to the value of 20.0 Ah provided by the manufacturer shown in Table I.
- All the experiments are performed under lab's constant ambient temperature of 23.0±0.2ºC.
- There is no power electronics used in the present study, future research will focus on the addition of power electronic devices in order to minimize energy loss and improve the energy efficiency of the battery.

For constant current charging experiments, operating current rates are set to 0.33C, 0.5C, 0.75C, 1C, 1.25C, 1.5C and 1.75C separately; as to constant current discharging experiments, current values are the same as that of constant current charging. The CCV of the cell is recorded by the data logger and η_{cha} is calculated from Eq. (2), (3) and (9), while η_{dis} is calculated from Eq. (4), (5) and (9).

The energy efficiency under charging-discharging $\eta_{battery}$ is calculated from Eq. (3), (5) and (7). It can be expected that $\eta_{battery}$ is simply the arithmetical product of η_{dis} and η_{cha} at the same passing current.

IV. Results and Discussion

A. OCV and SOC relationship

Open circuit voltage represents the voltage between the battery's positive and negative terminals when no load is applied [17]. OCV is dependent on battery's SOC, and generally increases with the increasing SOC. However, the measured terminal voltage at the breaking of current cannot be considered as battery's OCV since the electrochemistry reactions inside the battery have not eased, and battery's electrodes are not in equilibrium state. In the present study, battery's terminal voltage is not found to reach to an equilibrium value until 1 hour of relaxation after cut-off. Therefore, measuring terminal voltage after 1 hour's relaxation

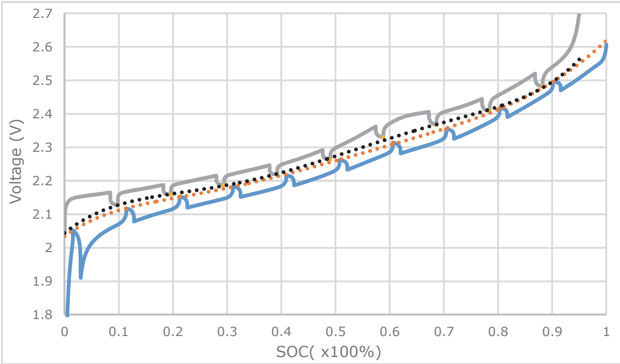

Fig. 1 The OCV curve obtained by averaging 1.0 C pulsed charging and pulsed discharging with 1 minute off time.

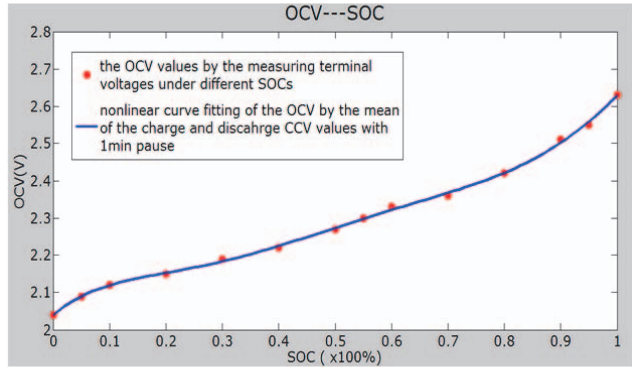

Fig. 2 Comparison of the OCV curve using non-linear fitting and the OCV dots by measuring the terminal voltages.

would be too time-consuming to determine battery's OCV at different SOCs.

As mentioned in Section II B, S. Abu-Sharkh et al. proposed a good way to estimate battery's OCV under different SOCs in [16]: for the high-energy solid-state Li-ion battery, the battery is pulse charged and then pulse discharged at rated current with an off time of 1 minute in order to measure the initial voltage of the cell. The cell voltage, as functions of SOC under discharging and under charging, are averaged to compute OCV values. Fig. 1 gives the OCV-SOC relationship curve by averaging the pulsed charging/discharging CCV curves at rated current 1.0 C with the off time of 1 minute.

In order to verify the accuracy of the OCV-SOC curve obtained by the S. Abu-Sharkh method, the conventional OCV capturing method is implemented to determine the OCV at several SOC points. The implementation is set as the following steps: firstly, the battery is fully charged as specified, and battery's terminal voltage is measured after 1 hour's rest as the OCV value at 100% SOC; afterwards, the battery is discharged at 0.33C to different SOCs (0%, 5%, 10%, 20%, 30%, 40%, 50%, 55%, 60%, 70%, 80%, 90% and 95%, respectively) and the terminal voltage is also measured artificially after 1 hour's rest at each SOC respectively. The red circles in Fig. 2 represent the measured values of OCV at different SOCs by the conventional method and the figure indicates that the measured OCV values coincide perfectly with the OCV-SOC curve obtained before, thus verifying the good accuracy of the S. Abu-Sharkh method.

K. Smith et al. [18, 19] investigated and proposed several models regarding the equilibrium potential at the negative electrode (U_-) and positive electrode (U_+) of a Li-ion battery, of which the active materials of the positive electrode are $Li_yMn_2O_4$, Li_yCoO_2, Li_yNiO_2, $LiFePO_4$ or some combination of metal oxides, serving as a function of the solid Li-ion concentration in the negative (x) and positive (y) electrode. J. Kang et al. [15] proposed and derived the relationship as follows:

$$U_-(x) = 8.00229 + 5.0647x - 12.578x^{1/2} - 8.6322\times10^{-4}x^{-1} + 2.1756\times10^{-5}x^{3/2} - 0.46016\exp[15.0(0.06 - x)] - 0.55364\exp[-2.432(x - 0.92)] \quad (10)$$

$$U_+(y) = 85.681y^6 - 357.70y^5 + 613.89y^4 - 555.65y^3 + 281.06y^2 - 76.648y - 0.30987\exp(5.657y^{115.0}) + 13.1983 \quad (11)$$

However, no literature describes the function concern on LTO battery. Note that, although relative, the solid Li-ion concentration and the SOC are not equivalent. In the present study, the quantitative relation Eq. (12) displays the function of OCV (y) to SOC (x) based on the above theory, but ignores U_-, and it is graphically shown by the OCV-SOC curve in Fig. 2.

$$y = p_1x^6 + p_2x^5 + p_3x^4 + p_4x^3 + p_5x^2 + p_6x + p_7 + p_8e^{(p_9x)} \quad (12)$$

The values of the parameters p_1 to p_9 are -6.7744, 25.436, -35.284, 23.05, -7.1542, 1.324, 2.036, 0.007 and -80 respectively, and the correlation coefficient of the fitting is 0.998. Thus, the quantitative relation of OCV to SOC can be obtained based on the above results.

B. Energy efficiency of single battery cell

As expected, cell's CCV during different operating current is different with each other. It is caused by the over-potential resistance, which will be studied further in the following research regarding to the equivalent circuit of the battery.

The cell's CCV curve under different charging current, as well as the OCV curve, are shown in Fig. 3(a). As can be seen from the figure, starting from the same voltage value at 0% SOC, battery's CCV is higher with higher charging current values. Since the rated charging method is in CCCV mode, it can be expected that battery's SOC cannot reach 100% after each charging in the present study, which is shown in the figure by the black dotted line; when the 1.5 C charging is terminated, battery's SOC only gets to about 92%. Calculated from Eq. (2), (3) and (9), battery's energy efficiency under different charging current η_{cha} is illustrated in Fig. 3(b). The blue line in the figure is the polynomial fitting of η_{cha}, which describes the energy efficiency under charging (y) and current (x) with the fitting equation y = $0.0033x^2 - 0.0297x + 0.99814$. The correlation coefficient of the fitting is 0.99, proving the validity of the outcome. Again, due to the fact that the energy loss is mainly on the over-potential resistance, the value of η_{cha} is unsurprisingly higher with lower charging current values.

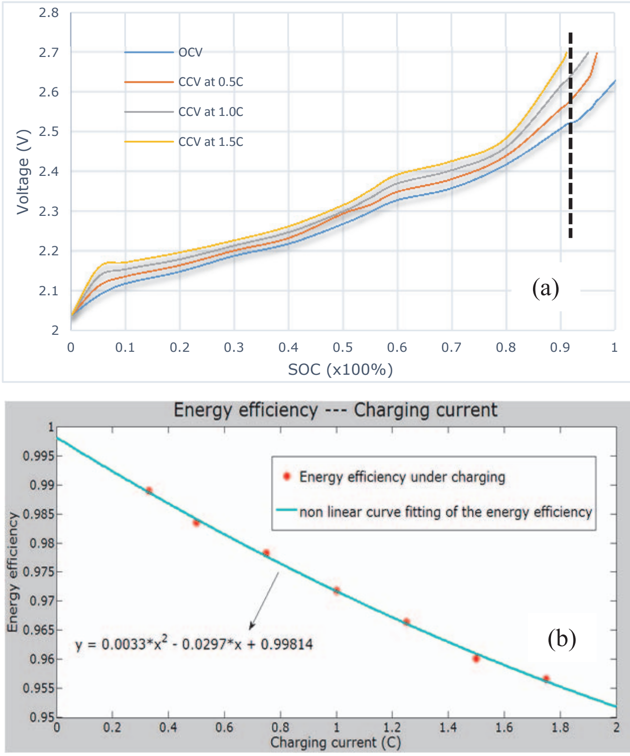

Fig. 3 The charging curves and the energy efficiencies, (a) the voltages (per cell) varied with SOC under different charging current rates, the black dotted line shows the SOC when the charging is complete for the 1.5 C curve, (b) the energy efficiencies under charging η_{cha} varied with the current rates and the corresponding fitting results.

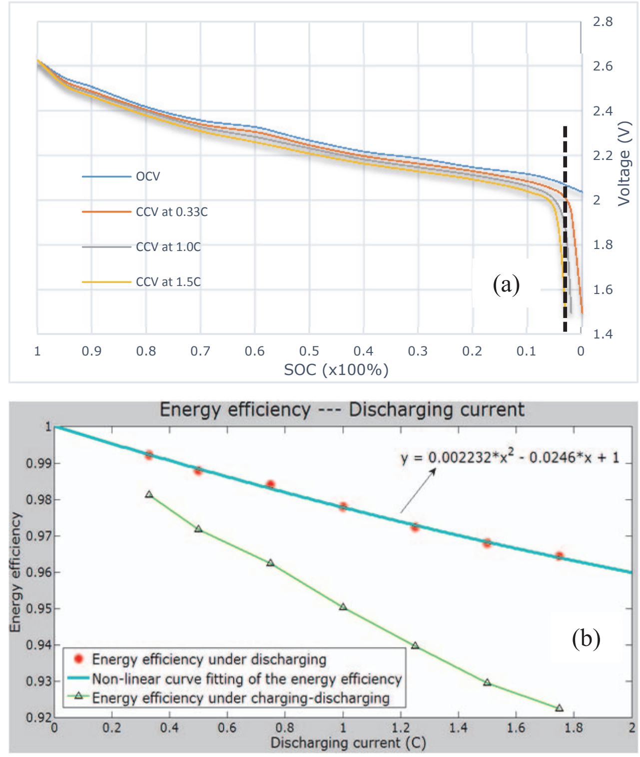

Fig. 4 The discharging curves and the energy efficiencies, (a) the voltages (per cell) varied with SOC under different discharging current rates, the black dotted line shows the SOC when the discharging is complete for the 1.5 C curve, (b) the energy efficiencies under discharging η_{dis} and charging–discharging $\eta_{battery}$ varied with the current rates and the corresponding fitting results of η_{dis}.

Similarly, battery's CCV curve during different discharging rates and the OCV curve are drawn in Fig. 4(a). Similar to the charging curves, battery's SOC at high discharging rates cannot reach 0% when the process is completed. As indicated by the black dotted line, battery's SOC after 1.5 C discharging is around 3%. η_{dis} is shown in Fig. 4(b), which is calculated from Eq. (4), (5) and (9). The blue line in Fig. 4(b) denotes the polynomial fitting of η_{dis} with the equation y = $0.002232x^2$ - 0.0246x + 0.1, and the correlation coefficient is 0.994.

Battery's charging-discharging energy efficiency $\eta_{battery}$ is also plotted in Fig. 4(b), calculated from Eq. (3), (5) and (7). As shown in the figure, it is verified that $\eta_{battery}$ is simply the arithmetical products of η_{dis} and η_{cha}, and $\eta_{battery}$ decreases gradually with the increasing current rates.

In present days' industry, large current fast charging of Li-ion battery as energy storage devices in such as micro-grid and EVs is drawing more and more attentions, and the above method and the curve fitting results could serve as an estimation method for the determination of the energy efficiency of the Li-ion battery, which will provide a better understanding of the fast charging technique from the macroscopic perspective, i.e., the energy efficiency of the power Li-ion batteries during the charging, discharging and charging-discharging conditions.

C. *Energy efficiency of the battery pack*

Due to the low terminal voltage of a single cell, multiple cells are usually connected in series and parallel as a battery pack and functioned as energy storage devices in practical applications. In the present study, 10 Li-ion battery cells are connected in series as a battery pack for our experiments with no battery equalizers. All the 10 cells are set to 100% SOC separately before connected together. Several tests are done on the battery pack, among which the charging tests are cut-off when the CCV of any cell reaches 2.7V, and the discharging tests are cut-off when the CCV of any cell reaches 1.5V. Terminal voltage of each cell is monitored and recorded by the data logger, and after over 100 times of charging/discharging tests, the deviation of the CCV of the 10 cells between each other are within ±0.83%.

The 10 Li-ion battery cells are tested with suitably-spaced pulse discharging current (6.67A in this case) at room temperature. The pulse width is chosen to guarantee enough "humps" (6–10) for sufficient data points and the off time is selected to allow the battery voltage to reach steady-state conditions (10 min in this case). The pulse discharging curves of the 10 Li-ion battery cells under the same conditions (i.e., the same current, temperature, and the initial SOC) stay very close to each other. As shown in Fig. 5, the 6.67A pulse discharging curves of the ten battery cells show runtime

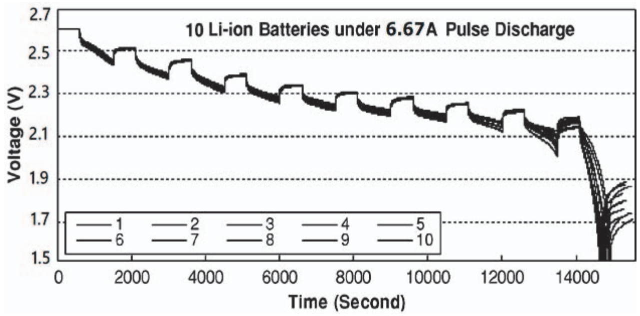

Fig. 5 The 6.67A pulse discharging curves of 10 Li-ion batteries

variation within 2% and error voltage less than 30 mV at 10%–100% SOC. A big error voltage close to fully discharged states (0%–10% SOC) is caused by the sharp OCV drop that influences battery runtime and the instability of the battery's internal reaction near fully discharged states.

The parameters of the battery pack during charging and discharging are monitored and recorded. Based on Eq. (3), (5) and (7), the charging-discharging efficiency $\eta_{battery}$ of the battery pack is calculated to be about 88%. Much energy is lost on the connection between cells and the slight imbalance though. Further research will focus on developing equivalent circuits for Li-ion battery from the in/out energy perspective, as well as the addition of power electronics as interface between the Li-ion battery and the grid for better battery performance as energy storage devices in micro-grid.

V. Conclusion

In the present study, the energy efficiency for Li-ion battery as energy storage devices in micro-grid is investigated. The energy efficiency of Li-ion battery depends on the energy efficiency under charging, discharging, and charging-discharging conditions. The equation related to OCV and SOC in the present study are based on the electrical and electrochemistry theories. Moreover, the quantitative relationship of OCV and SOC is computed using non-linear curve fitting. Based on the results, the three types of energy efficiency of a single cell are calculated under different current rates. The relations of the energy efficiencies and current rates are also analyzed using non-linear curve fitting. The above methods and the curve fitting results could serve as an estimation method for the determination of the energy efficiency of the Li-ion battery in the case of large current fast charging in the industry. Furthermore, good performance of the Li-ion battery with regard to imbalance issues in series-connection has been verified and the charging-discharging energy efficiency for the battery pack is calculated from hardware experiments.

Acknowledgment

This research is funded by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. BEARS has been established by the University of California, Berkeley as a center for intellectual excellence in research and education in Singapore.

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