Study of a lithium-ion battery charge-discharge test unit characteristics*

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Abstract. The article describes the structure of a charge-discharge unit which allows to perform electrical, resource and thermal testing of several lithium-ion batteries simultaneously. The principle of operation of a one battery research channel (BRC) is shown. This study evaluated the stabilization error and rate of change of charge/discharge currents, the switching time from the charge mode to the discharge mode and vice versa for a single BRC and parallel BRCs. The possibility of increasing the maximum battery testing current due to the parallel connection of multiple BRCs without using a current alignment device between channels was discussed.

1. Introduction

In electric power systems (EPS) of the satellites have been widely used rechargeable batteries (RB) based on lithium-ion technology. Battery resource determines the duration of the spacecraft as a whole. On development stage the manufacturer typically perform electrical, thermal and other kinds of battery tests to estimate battery resource. Battery resource tests [1, 2] are performed under laboratory conditions through reproduction of battery charge/discharge modes and through maintaining the battery temperature at the values corresponding to operating modes. In addition, an indirect estimation of battery resource is possible by changing the output impedance of the battery.

These tests allow to estimate the following resource characteristics of the battery:

- number of charge/discharge cycles;
- battery capacity degradation dynamics during operation;
- variation of the output impedance during operation.

Quicker resource tests can significantly speed up and reduce the cost of designing and testing of the spacecraft power system. To reduce testing time, the specific battery testing methods were developed. [3, 4] These methods are based on the idea of stress tests. Reducing of the testing time is achieved by increasing the charge/discharge currents up to the maximum battery currents, including constant power discharge modes.

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As equipment for battery resource tests are often used the elements of spacecraft PSS such as battery charge/discharge unit (CDU) [5] or their simulators. The disadvantages of this method include:

- charge/discharge currents and discharge powers for testing is limited by standard operation modes of systems;
- the duration of the test is comparable with the normal battery operating time;
- only a fixed number of series-connected batteries from battery pack can be tested which does not allow to test particular advanced batteries;
- all batteries in tested pack have common charge/discharge current so it is not possible to use a single battery discharge mode by constant power and to provide negative voltages on the battery.

2. The structure and operation principles of the charge-discharge test unit

To overcome the above drawbacks, the authors developed a charge-discharge test unit which allows to perform electrical, thermal and resource tests of twelve lithium-ion batteries simultaneously.

The block diagram of the proposed system is shown at figure 1. Uninterruptible power supply (UPS) powers the primary energy source (PES) and prevents unscheduled completion of the tests in the case of emergency AC network shutdown. Charge and discharge modes of the battery provided with the appropriate switching of it in the electrical circuit formed by controlled voltage stabilizer (CVS) and a switched-mode voltage converter (SVC) using switches S1-S4. Application of the CVS allows to ensure the normal operation of the SVC because the battery has a relatively low voltage and must be tested in the reverse polarity mode. Excess energy, consumed by SVC, dissipated in the load unit (LU).

![Figure 1. The block diagram of the charge-discharge test unit for the battery resource tests](image)

Measuring and registering device (MRD) registers changes in current, voltage and temperature of the battery in time (battery temperature stabilization and measurement system are not shown in block diagram).

Necessity of battery current regulation in the wide range (0-160 A), the need for electrical isolation between SVC and LU and complexity of power high-frequency transformer manufacturing, designed for maximum battery current, made it necessary to use two...
stabilizers in the SVC: switched-mode stabilizer of input current (SCS) and switched-mode stabilizer of SCS input voltage (SVS). SCS consist of switched-mode current regulator (SCR), which is based on boost converter, current sensor (CS) and CU. SVS consist of switched-mode voltage regulator (SVR), which is based on full-bridge buck converter, voltage sensor (VS2) and control system [6].

A control unit (CU), in accordance with predetermined patterns and the measured values of battery voltage and current, control switches S1-S4, generates control signals for SVC, set reference for PES, and provides safe completion of tests if charge of the UPS batteries is low and if voltage in AC network is absent. CU includes a device which protects battery against charge/discharge currents and battery voltages that exceeds their maximum permissible levels. One battery research channel (BRC) consists of four switches S1-S4, voltage sensor (VS1), MRD, CU and SVC.

To provide high current at low battery voltage is necessary to maintain the SVS input voltage at the relatively high level. To this end, the stabilization of the SCS input voltage is provided by CVS, for which the feedback signal is formed by SCS input voltage. Therefore, regardless of battery voltage and the operating mode (charging or discharging of the battery) CVS stabilizes the SCS input voltage at the level of 4 V. In addition, the stabilization of the SCS input voltage enables to discharge the battery until changing the polarity.

In the boost converter voltage conversion ratio varies over a wide range depending on the current and the load impedance. [7, 8] To maintain the relatively high value of the SCS voltage conversion ratio a SVS is introduced in circuit. This SVS stabilizes the SCS output voltage.

In the charge mode (fig. 2) CU closes switches S2 and S3 while the battery and the CVS are switched to opposite-series connection. In this mode CU performs the following functions:

- setting of the SCS control law: the stabilization of the charging current or stabilization of the charging power;
- providing the stabilization of the SCS output voltage;
- setting of the CVS parameters.

![Figure 2. Battery charge mode](image)

In the discharge mode (fig. 3) CU closes switches S1 and S4 while the battery and the CVS are switched to agree-series connection. CU performs functions similar to those described above, but corresponding to the discharge mode.
The unit is implemented for parallel operation of the two BRC in the discharging mode. In this mode, the power outputs of both modules are connected to the battery and the provided discharge current range is 2...320 A. There is also the independent BRC connection mode in which provided discharge current range is 1...160 A.

An implementation of the stand is shown at figure 4. It has twelve BRC modules and the separate rack which includes CU, LU and test load for the unit testing. CU is implemented on the basis of the measuring platform National instruments NI PXIe-1082. As UPS were used EATON 9130.
With the development of technology and the increasing of total capacity of the batteries, the maximum allowable battery charge/discharge currents are also increasing. In this connection there is a need for charge/discharge devices with the maximum currents above hundred amperes. Time intervals of the discharge and charge cycles under stressful conditions may be relatively small and may be about a few seconds. Therefore, performance (delay) of the converters which are used in load units must be sufficiently large (small) that does not significantly affect the magnitude of the calculated capacity or battery power. Measurement errors accumulated over several months of the resource tests and may affect the accuracy of the resource tests that requires greater accuracy.

The stand is designed with consideration of these comments and each BRC has the following specifications:

- battery voltage variation – from −5 V to +5 V (minimal step – 0.05 V);
- battery charge/discharge current variation range from 1 A to 80 A (minimal step – 0.1 A);
- battery discharge current variation range from 1 A to 160 A (minimal step – 1 A);
- time interval variation – from 1 s to several hours in increments of no more than 1 s, the interval representation error within ± 0.6 %.

CU in combination with the battery current and thermal sensors processes the errors:

- charge/discharge current recording error – within ±0.2 %;
- battery voltage recording error – within ±5 mV;
- time interval recording error – within ±0.1 s (in accordance with the duration of the intervals in the program).

3. Experimental results

During the test stand performs the program recorded in the CU. The program is executed step by step. The desired values of stabilized current or power and the duration of the step are set at each step. Thus, it is necessary to evaluate for compliance with the technical requirements:

- charge/discharge current stabilization error at each step in the prescribed current range for single BRC;
- the rate of change of the charge/discharge current for a single BRC;
- the total charge/discharge current stabilization error in parallel BRC operation;
- current mismatch between the modules in parallel operation of BRC;
- switching time from battery charge to discharge mode, and vice versa, in parallel BRC operation.

To measure the charge/discharge current stabilization error the short-circuit tests were performed on single BRC. The duration of the program step – 5 s, a discrete battery current level step - 0.5 A, current range - 0...160 A. After starting the program, the CU recorded the predetermined current and the voltage value from the sensor at each step with the period of 0.1 s.

Reduced charge/discharge current stabilization error of the single BRC (figure 5) calculated as:

\[ \gamma_1 = \left( \frac{I_p - U_m}{I_{max} \cdot k} \right) / I_{max} \cdot 100\%, \] (1)
where \( I_p \) – predetermined discharge current, \( U_m \) - current sensor voltage measured on the resistance \( R_m = 12.5 \, \text{Ohm} \); \( k = 1000 \) – current sensor convert ratio, \( I_{\text{max1}} = 160 \, \text{A} \) – the maximum current of the single channel.

**Figure 5.** Reduced charge/discharge current stabilization error of the single BRC

The short-term deviation of the BRC current is observed when the discharge current changes discretely which leads to additional lag and overshoot. This deviation leads to short-term increase in the current error. However, resulted reduced charge/discharge current stabilization error of the single BRC over the entire range of the current does not exceed 0.16%.

To measure the accuracy of the BRC in parallel mode tests were performed on a similar program: the step duration is the same but the range of current change was 70-320 A. In addition, each BRC had stabilized the current in a half of the predetermined value \( I_p \). During the test with period of 0.1 s the voltage was recorded by the first BRC current sensor (\( U_{m1} \)) and by the second BRC current sensor (\( U_{m2} \)).

For each measured value (figure 6) was calculated the total reduced current stabilization error \( \gamma_2 \):

\[
\gamma_2 = \frac{(I_p - (U_{m1} - U_{m2}) / R_m \cdot k) / I_{\text{max2}} \cdot 100\%}{100\%},
\]

(2)

where \( I_{\text{max2}} = 320 \, \text{A} \) – the maximum discharge current.

In addition, the mismatch between discharge currents \( \delta \) of parallel BRC was calculated:

\[
\delta = \frac{(U_{m1} - U_{m2}) / R_m \cdot k / I_{\text{max2}} \cdot 100\%}{100\%}.
\]

(3)
The total reduced current stabilization error $\gamma_2$ of parallel BRC in the second range does not exceed 0.16 %. The mismatch between discharge currents $\delta$ of parallel BRC in the second range does not exceed 0.03 %.

Since the total reduced current stabilization error and the mismatch between discharge currents in both ranges are small, in parallel operation of BRC (as well as for a single channel) is provided high precision of stabilization of the total discharge current and good current equalizing between the two BRC.

Since the currents of several parallel BRC are nearly equal, the overload is eliminated in parallel BRC as well as the need to use a special device to equalize the currents between the BRC.

To evaluate the switching time between the charging and discharging modes for the single BRC the short-circuit test have been performed. The program switched charging mode to discharge mode at charge current of 50 A, then - vice versa, at discharge current of 25 A (figure 7a), the program switched discharge mode to charge mode at discharge current of 50 A, then - vice versa, at charging current of 25 A (figure 7b).

**Figure 6.** The total reduced current stabilization error and the mismatch between discharge currents

**Figure 7.** Switching (a) from the charging mode (50A) to discharging mode (25A), (b) from the discharging mode (25A) to charging mode (50A) (1 (blue) – BRC current, 2 (green) – SVC voltage),
scale: x-axis – 100 ms/div, y-axis – 20 A/div
The switching time from the charging mode to discharging, and vice versa, is the sum of the BRC turn-off time, delay time and turn-on time and does not exceed 0.6 seconds. The BRC turns off fast enough but turn on of the BRC is delayed since the CU sends a command to switch the channel only when the SVC voltage is reached a desired level. The delay time is the major part of the switching time and is determined by inertial properties of the SVC.

To evaluate the switching time between the charging and discharging modes for the parallel BRC operation the short-circuit test have been performed. The program switched charging mode to discharge mode at charge current of 50A, then - vice versa, at discharge current of 50A (figure 8a), the program switched discharge mode to charge mode at discharge current of 50A, then - vice versa, at charging current of 50A (figure 8b).

![Figure 8](image)

**Figure 8.** Switching (a) from the discharging mode (50A) to the charging mode (50A) during the parallel operation of the two BRCs, (b) from the charging mode (50A) to the discharging mode (50A) during the parallel operation of the two BRCs (1 (blue) – BRC 1 current, 2 (green) – BRC 2 current, 3 (red) – SVC voltage of BRC 1, 4 (magenta) – SVC voltage of BRC 2), scale: x-axis – 100 ms/div, y-axis – 20 A/div

As in the previous case, the switching time from the charging mode to discharging, and vice versa, is the sum of the BRC turn-off time, delay time and turn-on time and does not exceed 0.6 seconds. Time and rate of switching are largely depending on the inertial properties of the SVC. The delay time is most of the switching time and can be reduced by using a high-speed SVCs and by enhancement of SVC control methods.

4. **Conclusion**

In this study the charge-discharge test unit was described. This unit allows to perform electrical, resource and thermal testing of several lithium-ion batteries simultaneously. The achieved accuracy of the unit is relatively small and corresponds the requirements for the resource tests. The switching time from charging mode to discharging, and vice versa, depends on the delays introduced by the power source. Excluding these delays will reduce the switching time to 0.2-0.3s. Parameters of parallel operation of the modules confirm the prospect of increasing the maximum testing current for even larger values of the total battery charge than currently in use.
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