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Influence of operational factors on fail-safety and resource of LISB bypass device for spacecrafts

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***Abstract*—To ensure trouble-free operation and lifetime of lithium-ion storage batteries (LISB) for spacecrafts, it is advisable to use bypass devices (BD) with a power element of a thermal drive made of smart material with shape memory effect (SME). The authors presented experimental results of the effect of operational thermal factors and mechanical effects on the operating parameters of BD structural elements (the power element of the thermal actuator and the contact group) and LIAB in general. The authors carried out bench tests in conditions, simulating the operational ones, performed on the experimental base of PJSC "Saturn" (Krasnodar). Thermocycling is in the temperature range from minus 50 ° C to plus 50 ° C. Tests were aimed at revealing resistance to mechanical influences with respect to the absence of resonant frequencies. There were also tests for broadband random vibration; tests for resistance to single shocks, simulating the load caused by a carrier rocket; tests for revealing the resistance to multiple shocks, imitating the impact of transportation. These tests confirmed the working efficiency of the BD. Resource tests were performed at temperature of -50 ° C for 57 days, at temperature of +70 ° C - for 156 days, which corresponded to four years of storage and 11.6 years of unloaded operation. Tests at temperature of + 50 ° C for 68 days, corresponding to 3,4 years of operation under load, confirmed the working efficiency of the BD. Comparative analysis of domestic and foreign BDs by such important indicator as transient resistance showed that the considered variant of the BD design has a clear advantage over its analogues.**

Keywords*— Lithium-ion storage batteries (LISB); Bypass device (BD); Shape memory effect (SME); Contact block; Transition resistance; Operational factors

I. Introduction

At present, lithium-ion batteries (LIB) are used in on-board power supplies of space vehicles (SV) in Russia and abroad, which have rather high specific characteristics and long service life [1,2]. LIBs degrade during the regular operation time [3,4].

Numerous studies have shown that the loss of LIB capacity significantly depends on the operation time. Modeling of LIB degradation processes, carried out in works [5,6] shows the degree of degradation and allows one to determine the functional life of a spacecraft. Due to the fact that accumulators in the battery are connected in series, the degradation of one LIB leads to a capacity decrease in the entire battery. To maintain accumulator battery (AB), it is necessary to remove the degrading accumulator from the battery. This can be carried out with a bypass device (BD). Russian and foreign BDs, existing at present time, including leaders in power supply production "SAFT" (France), "NEA" (USA) and Mitsubishi Electric (Japan), have a significant drawback – it is impossible to carry out reversible testing of their operability at the stage of manufacturing and acceptance testings. This problem can be solved by using functional materials with shape memory effect (SME) [7,8]. To ensure the reliable functioning of the spacecraft power supply system, the design of bypass device has been developed (Patent of the Russian Federation, No. 2392494, 2415489, 127252), as well as the technology of their manufacturing [9], providing the necessary characteristics of power contacts response [10].

The bypass switch is an electromechanical device with a trigger mechanism based on the use of a spring made of an alloy with the shape memory effect (Fig. 1) [7]. The switch consists of housing 1 with working spring 2 placed therein, an actuator with movable contact 4, fixed contacts 5, rod 6, which keeps actuator 3 from moving, the power element of the thermal actuator in the form of concentric spring 7 made of SME alloy, held in a compressed state by a linearly elastic spring (counter element).

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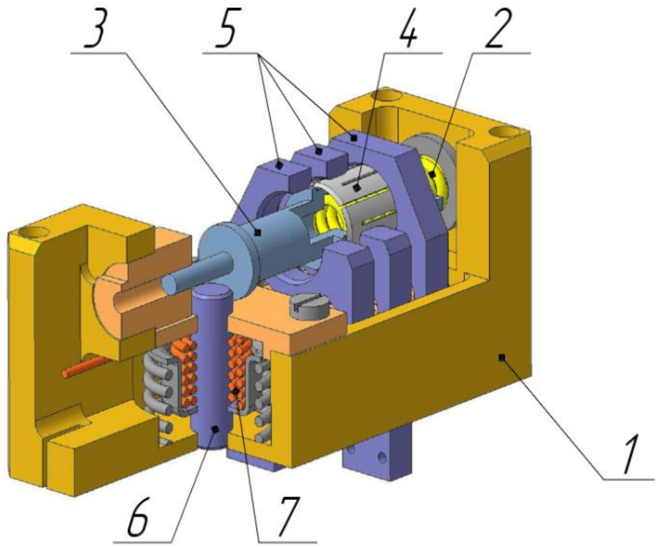


Fig. 1. Design of a bypass switch with a power element of a double coil spring

If it is necessary to activate the bypass switch, an electrical current is applied to the control contacts, which cause the heating of the element made of SME material, so that phase transformations could take place inside. In the martensitic-austenite phase transition, the rigidity of spring 7 increases significantly. The resulting reactive force is sufficient to overcome the force of the counter-element and move rod 6 downward. Having moved, rod 6 releases the path of actuator 3 with movable contact 4 under the action of working spring 2. At first, the movable contact closes the normally open contact and then opens normally closed contact 5. At the same time, the common connection circuit of the batteries is not broken during the switching process, and the time interval from the moment of closing of normally open contacts before opening of normally closed contacts is determined by the length of the movable contact 4 and the speed of movement. Contacts 5 are made of beryl bronze, which, after heat treatment, have good elastic properties, which provide the necessary contraction force of contacts during the entire service life.

The present paper is devoted to the evaluation of the operational factors effect on the functional characteristics of the LISB bypass device with the power element of the thermocouple made of material with SME.

II. EXPERIMENTAL PROCEDURE

Spacecraft accumulator batteries and bypass devices in their composition should remain operational during the performance at the launch site after mechanical impacts. The power element of BD thermal actuator must retain its technical and operational characteristics and must not have any mechanical damage during and after the action of quasistatic loads at acceleration of ± 147.2 m / s2 (± 15 g), as well as vibration (Table 1) and shock (Table 2). Shock loads are given according to each of the three mutually perpendicular axes in the form of shock spectra of accelerations with a Q-quality of resonators Q = 10, (three impacts along each direction along each of the three mutually perpendicular axes). Any changes in acceleration within each frequency subband are linear with a logarithmic scale in frequency and amplitude of acceleration of loads in three mutually perpendicular planes.

TABLE I. SHOCK SPECTRUM OF ACCELERATION

Frequency sub-band, Hz	Impact spectra, м/c^2 (g)
35 – 50	245 - 490.5 (25 - 50)
50 – 100	490.5-1471.5 (50 - 150)
100 – 200	1471.5 – 3924 (150 – 400)
200 – 500	3924- 17167.5 (400 – 1750)
500 - 1000	17167.5-49050 (1750-5000)
1000 - 2000	49050 (5000)

An important condition for maintaining the control unit operability is to observe the temperature regime, since the BD element is made of thermosensitive SME material. Temperature regimes in the process of ground and regular operation are as follows: during storage and transportation from -50 to +50; at regular operation in the composition of AB for 15, 25 years from -10 to +50.

TABLE II. CHARACTERISTICS OF VIBRATION LOADING

Impact	Frequency, Hz	Level
Impact	5 – 10	±10 mm
	10 - 20	from ±4 g to ±15 g ±15 g
	20 – 100	from ±4 g to ±15 g ±15 g
Impact	20	+6 dB/okt
	50	0.2 g^2/hz
	1000	-6 dB/okt
Impact	5 – 10	±10 mm
	10 - 20	from ±4 g to ±15 g ±15 g
	20 – 100	from ±4 g to ±15 g ±15 g

The thermal actuator must be operative in the pressure range over the body from atmospheric one at 1.3·10^{-4} Pa (10-6 mm Hg). The efficiency of the thermal drive at the stage of product testing is confirmed by the preservation of operating parameters in pressure change conditions onto the AB body from atmospheric one to 1.3-10-3 Pa (10-5 mm Hg).

The bypass device, which is a part of spacecraft LISB, was subjected to a thermal cycling test. It was tested for resistance to the following types of mechanical effects: acoustic, quasistatic, vibrational, shock, as well as load effects, which simulated transportation. The characteristics of equipment used for mechanical and resource tests are given in Table. 3.

TABLE III. STAND TEST EQUIPMENT

Equipment	Test Modes
Thermocycling	
Thermovacuum chamber “KTHB”- 0,16155X.037.0003  a)	Thermal cycling modes • decrease the assembly temperature up to (0 ± 2) 0C. • withstand the BD at this temperature for at least 2 hours; • increase the assembly temperature to (50 ± 2) °C; • withstand the BD at this temperature for at least 2 hours. • Number of cycles 10
Vibration loads	
Vibrating table Dactron  b)	• The operating frequency range is from 5 to 2500 Hz. • Rated buoyancy force is 58000N. • Weight of the rated load on the vibrator table is not more than 300 kg. • The stand provides the specified vibration parameters when working with the Laser Dactron for vibration testing
Impact loading	
Shoch-mechanical machine UUM 100 / 150-100  c)	• Range of values of peak shock acceleration is from 10g to 150g. • The duration of the shock pulse is from 2 to 13.5 m / s^2. • The repetition rate is from 10 to 100 per minute. • The pulse shock pulse shape is a half-sinusoid wave. • Number of strokes in each direction is 3.
Transportation	
Simulation of transportation SIT-2M  d)	Effects of harmonic vibration: • scan speed 1 octa / min, the test for at least 20 minutes in each of three mutually perpendicular planes. • The test is subject to accidental vibration with a factor of 1.2. Exposure time - 6 minutes in each of three mutually perpendicular planes.
Resource testing	
Chamber of heat and cold “KTH”  e)	Types of tests: • check of storage in the non-activated state. • tests of the non-activated BD at a maximum nominal current of 50 A. • Resource tests in the activated state. • Resource tests in the activated state at the maximum nominal current.

III. STAND TESTS RESULTS

Bench tests are an integral part of the space equipment manufacturing and test conditions are often assigned to be tougher than operational ones. This is due to the definition of constructive reserves in case of contingencies

A. *Temperature tests*

In the process of operation, the elements of the spacecraft are exposed to thermal shifts. On the solar and shady part of the orbit, the temperature of the SC varies significantly. It is known that the element of BD thermal drive is made of SME material, which is very sensitive to thermal changes. The TiNi alloy (TU 1822-038-01538612-10) has the following characteristics of the phase transformations: AH = 80 + 10°C; AK = 100 + 15°C; MH = 65 + 15°C; MK = 25 + 10°C). Thermocycling tests were carried out in two stages. At the first stage, the authors simulated the conditions of the BD LISB storage when the temperature changed from -50 °C to + 50 °C in the heat and cold chamber “KTH-1” with the maximum possible rate of transition to the extreme limits. The second part of the tests consists in simulating the regular BD work under load, and was carried out in a thermovacuum chamber “KTHB -0,16-155 X.037.0003” (Table 3,a) during ten cycles of temperature change from 0 ° C to + 50 ° C according to Mode shown in Fig. 2.

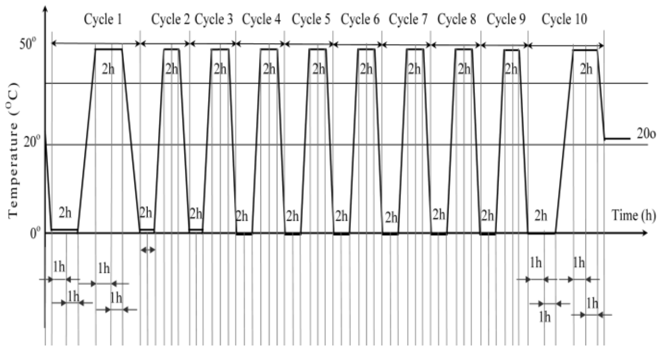


Fig. 2. Bypass Device Test Cyclogram

After thermocycling (10 cycles), control actions were performed to assess the effect of temperature changes on the BD operability and on changes in its parameters. The criterion for evaluating the test results is the preservation of the BD operability. The carried out five control triggers after the thermal cycling confirmed the preservation of the BD operability.

B. Tests for resistance to mechanical stress

During the manufacture, delivery, launch and operation of the spacecraft, it is subjected to various mechanical influences apart from the effects of space factors and temperature factors. The battery, including the BD, is subjected to vibration and shock loads during transportation and launching into orbit by a launch vehicle, which can lead to their destruction. At the same time, the impact of all factors is impossible. Therefore, the BDs are subjected to loads for each kind of impact in three mutually perpendicular planes. This allows us to assess the stability of the BD with the maximum approximation to real effects. Full-scale tests for strength and resistance to AB mechanical influences (including BD) were carried out using Dactron system (Table 3,b).

Tensile strength tests against vibration loads. Mechanical tests begin with the search for resonant frequencies of the BD. For this purpose, the BD is fixed on the shaker in the rig that simulates the permanent attachment of the BD to the LISB. The authors also install sensors that adjust the amplitude of the system's oscillations and the load (Figure 3, a), which does not exceed a predetermined value of 1 g. Control sensors are also installed. The reference sensor is mounted in the attachment points to the tooling, and the reference sensor is mounted on the test elements of the structure.

Amplitude-frequency characteristics (AFC) are determined at the locations of the sensors in the range of the most dangerous frequencies for 20-150 Hz, which simulate the effect onto the product with an acceleration of 1g and a scan rate of 1 okta / min in three mutually perpendicular planes. The BD is considered to have passed the test provided that: there are no mechanical damages to the BD; no resonant frequencies (the amplitude of the oscillations of the structural elements does not exceed the amplitude of the attachment point oscillation); the resonance frequencies before and after the effects of vibrational loads remain unchanged and the shift of the resonant frequencies does not exceed 10%.

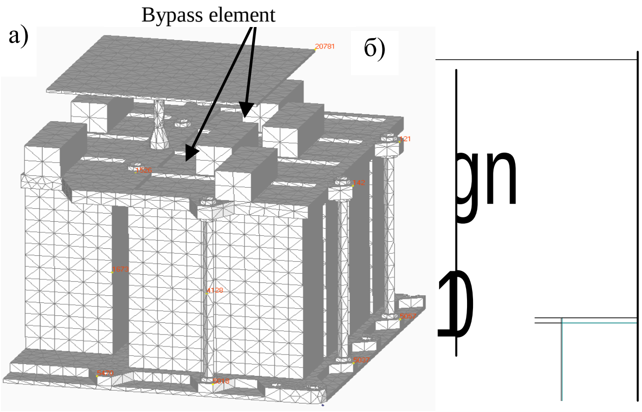


Fig.3. LISB model for constructing BD AFC - a) for determining resonant frequencies - b); the reference sensors are installed at the base of the model at the attachment point

During the test it was established that the resonance occurs at frequencies of the order of 1400-1500 Hz (Fig. 3, b). Analysis of the experimental data made allowed us to conclude that the design of BD is very rigid and can not have a significant effect on the frequency response of other elements of the LISB and the entire spacecraft. Tests under sinusoidal harmonic vibration at frequencies from 5 Hz to 100 Hz have shown that the harmonic vibration of BD does not affect the vibration-sensitive elements of the battery.

One of the most destructive effects is broadband random vibration (BRV), accompanied by significant loads (rms load 18 g) in the entire frequency range of 20-2000 Hz. Studies have shown that at a setting action of 18 g, the reaction of individual nodes reaches 22g and 38 g (Fig. 4). The analysis shows that the spectral density of the acceleration exceeds the value 3, but is in the range of resonant frequencies. The tests for the impact of the BRV showed that BD is resistant to the effects of the given loads. Fig. 3 shows the frequency response of BD in the most loaded direction of the action. In the other two directions, the frequency response is identical, which indicates the high rigidity of BD structure and confirms its considerable margin of safety.

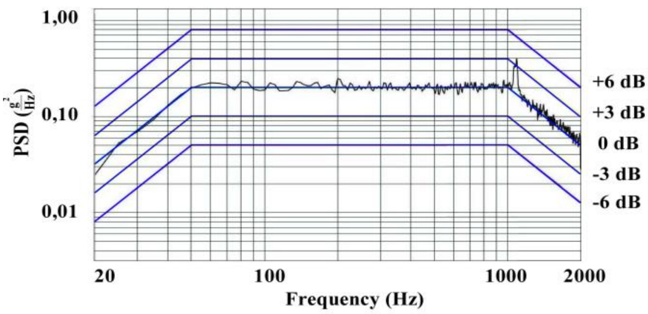


Fig. 4. The diagram of the amplitude-frequency characteristic of the control unit at the control panel according to the readings of the sensors (M1, M2 - upper and lower tolerance limits, average reproducibility)

The tests for strength and resistance to single shocks, (Table 3,c) mimic the loads caused by the carrier rocket. BD together with AB experience shocks during the launch of the rocket engines, undocking of its stages, the accelerating module and the apparatus itself. These loads are of impulse nature, but the values of the developed accelerations reach 300 g. During the test, the duration of such pulses is 2 ms, three hits in each of the mutually perpendicular planes.

Tests for strength and resistance to multiple shocks (transportation) (Table 3,d). Tests for resistance to multiple impacts simulate the effects of BD and LIAB transportation, which can be carried out by road, rail and air transport. The values of the overload during such tests are much lower than for single shocks and are 5g, but their number increases up to 40,000 strokes with duration of 2-10 ms. After tests for resistance to single and multiple shocks, the characteristics of BD remained in the allowable range.

C. Functional tests after completion of tests and defect

The checking of functioning after the tests included the following steps: checking the appearance; checking of electrical circuits (when the BD is not activated); checking of operation; checking of electrical circuits (with activated BD); checking of the springs forces and the effort of closing the control contacts; checking of the attachment of power contacts; diagnostics of non-destructive testing and destroying physical analysis of samples that have been tested for strength and resistance to mechanical stress.

To assess the operability of the BD after storage and during the entire life-span, which is intended for 15 years, the authors carried out accelerated resource tests that simulate the entire period of storage and operation of the BD in orbit in a relatively short period of time. This is achieved by increasing the temperature in the thermo-chamber and, consequently, accelerating the degradation processes in structural materials, of which the BD parts are made. The authors carried out tests for two cases. The first case is four-year storage and operation in non-activated state for fifteen years. The second case is simulation in the activated state, i.e. the case when activation is required immediately after the launch of the spacecraft. From the viewpoint of ensuring the reliability of the power element of the control unit thermal drive, it is of interest that the activation is at the end of the service life. The test at a temperature of + 50 °C for 68 days corresponds to 3.4 years of operation under load. Accelerated resource tests were conducted under the following regimes:

- Checking of storage in non-activated state: it is kept at a temperature of -50°C for 57 days, then at a temperature of 70°C for 156 days (the regime corresponds to storage stability in storage conditions for 4 years and 11.6 years of operation in solar sections of the orbit);

- Resource tests in the activated state: stand at a temperature of -50°C for 45 days, then at a temperature of 70°C for 116 days. This mode of accelerated testing should correspond to the storage capacity of the BD during 11.6 years of operation in the solar sections of the orbit.

- Resource tests in the activated state at the maximum nominal current: temperature (50 ± 2) °C, atmospheric pressure; the test is conducted for at least 68 days (1632 hours) at a current value (50 ± 2.5) A; this accelerated test mode is based on work under maximum load, i.e. at the maximum nominal current, in the shadow areas of the orbit. In addition, this regime, due to an increase in temperature to 50°C, corresponds to 3.4 years of the total service life at currents much lower than the maximum ones (in the intervals between the shadow areas of the orbit).

The greatest concern was caused by the test regime at a temperature of plus 70°C. This temperature is in the immediate vicinity to the martensitic transformation interval of SME material, which is the material of BD element of the thermal drive [9]. As the experiment showed, the BD after the completion of the resource tests, retained its operability and functional characteristics.

IV. Comparative Evaluation of Design and Experimental Parameters of BD Power Contact Block

The main parameter of the bypass device and the contact block is the value of its transient resistance R_{tran}. Although BD is designed to exclude, if necessary, a faulty battery from the serial AB chain, the battery current will be switched through the BD contacts and the losses in these contacts must be minimal.

Determination of the transient resistance value is carried out by the method of recalculation. The current is passed through the closed contacts (for convenience of calculation by the force 10A) and the magnitude of the voltage drop is measured. Measurements are made in two positions: in activated and inactivated ones, because the switching must also be carried out after the operation of the control unit. The results of these measurements, as well as their comparison with samples of other manufacturers are shown in Fig. 5. It can be seen from Fig. 5 that BD in the proposed structural design, manufactured according to the used technology [7-10], significantly exceeds the known analogs in the basic parameter - the transition resistance of the power contact block.

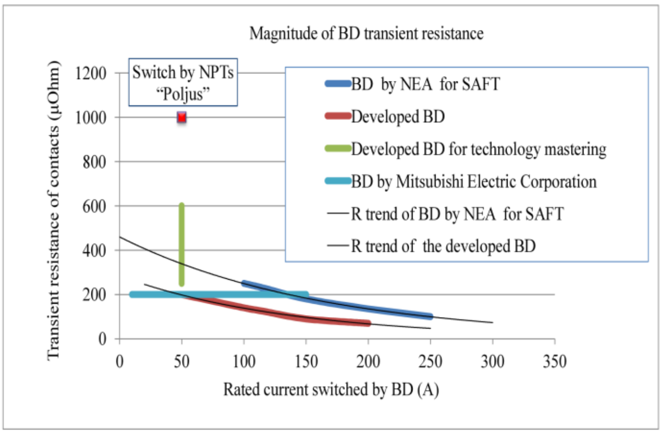
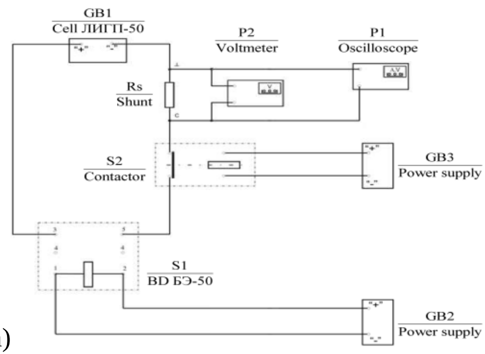
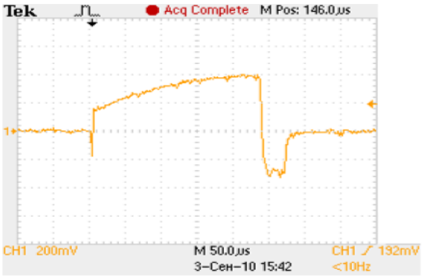


Fig. 5. Comparative evaluation of the value R_{tran} of the developed BD of the best foreign and domestic manufacturers

In addition to the multiple checks of the transient electrical resistance, which are performed at all stages of manufacturing and testing, it is important to study the behavior of the contact block under conditions of direct operation on the space vehicle. If it is necessary to activate BD onboard the spacecraft, the condition of continuity of the common power circuit must necessarily be fulfilled, which leads to a short circuit (SC) of the excluded battery. It is difficult to predict the residual capacity and short-circuit current. Therefore, tests were carried out on a fully charged model of the LIGP-50 battery with a capacity of 25Ah (Fig. 6,a).



a)



b)

Fig. 6. Measuring scheme of parameters (current, switching time) when the BD is triggered (a); measuring oscillogram of voltage drop and the switching time of the bypass device (b)

The circuit of the experiment is a circuit in which the LIGP-50, BD, shunt battery is included, on which a voltage drop during a short-circuit current flow is measured with a digital oscilloscope. Safety contactor S2 is connected to the circuit, which, if necessary, must break the short-circuiting circuit (Fig. 6,a). The contactor is necessary during the experiment in the case if, for some reason, the movable contact of the BD is jammed or welded under the action of short-circuit current. With an incomplete switching of BD, on tester P2, connected in parallel with the shunt, one can see that the current flows through the circuit. In this case, it is necessary to break the circuit by contactor S2 and after that the GB3 power supply will be disconnected. The voltage drop across the shunt during the tests was 400 mV (Fig. 6, b), and the duration of the fault is 250 • 10-6s.

Knowing the resistance of the shunt (750 μΩ), it was determined by calculations that the short-circuit current is 533 A. When this current was applied to the surface of the contact block, damages appeared (Fig. 7).

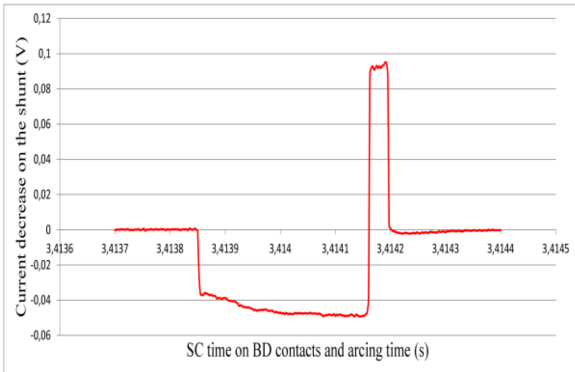
a)

b)

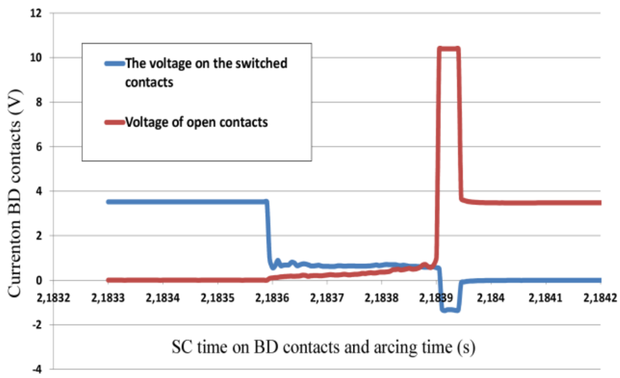
Fig. 7. Video capture of the moment of closing (a) and opening (b) of the battery

The video recording made during the experiment allowed one to fix the flash at the moment of battery closing and opening (Fig. 7). Usually such flashes are accompanied by a darkening of the origin place of the spark and have an effect on transient resistance – BD R_{tran}. In the considered case the BD contact block is designed in such a way that the burning zone is outside the spark zone.

After checking the BD operation, a test was performed to activate the BD with a standard LIGP-50 battery with a nominal capacity of 50Ah. In this experiment, the LTR-EU-2-5 recording device was used, with a recording period of 5 μs. In the experiment, the short-circuit current was fixed as 656A for a time of 345 microseconds. The results of the experiment are shown in Fig. 8, a.



a)



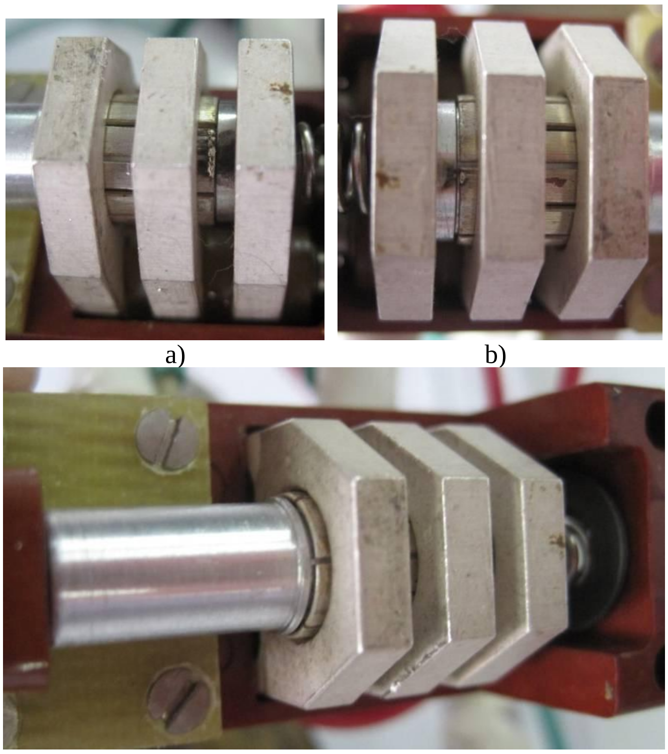
b)

Fig. 8. Changes in voltage on the shunt during the passage of currents SC - a); Voltage changes on the power contacts of the BD at the time of currents CS - b)

The analysis showed that the work of the contacts always takes place stably, without sudden changes in the transient resistance. The formation of the arc is connected with overvoltages that arise as a result of the high inductance of the battery system, which is the BD. The values of these overvoltages are clearly visible when measuring the voltage at normally closed and open contacts.

Photos of moving contacts after the test are shown in Fig. 9, a, b where the traces of the electric arc that appeared when the battery is disconnected are clearly visible. When the normally-open contacts are closed, the consequences of the occurrence of a spark discharge are detected (Fig. 9,c), on normally open contacts (Fig. 8, b).

To assess the operability in a vacuum, the BD was subjected to an additional study. The efficiency of the control unit under reduced pressure does not cause any doubts. However, it is necessary to evaluate the possibility of an electric arc at the time of battery disconnection, which could lead to failure of the BD and AB in general. Connection scheme for current measurement and switching time during the test is similar to the above one, and was characterized by the presence of a recorder P3, designed to fix the electric arc (in case of its appearance). The experiment was carried out in a vacuum chamber at a pressure of 6.5 • 10-3 Pa (5 • 10-5 mm Hg). The voltage drop across the shunt in a vacuum was 452 mV, and the short-circuit duration did not exceed 500 • 10-6s. During tests, the value of the fault current was 602 A, while there was no electric arc.



a) b) c)

Fig. 9. Movable contacts with traces of arc burning (a, b); absence of spark traces when closing normally open contacts c)

The conducted experiments show the stable work of the contact BD block at all verification types. The data obtained during the tests are almost identical to the process time for various short-circuit currents obtained by calculation in the working simulation of BD contact block.

V. CONCLUSION

The results of the study allow us to draw the following conclusions:

- Investigation of operational factors (cyclic temperature changes, harmonic and random vibrations, single and multiple impacts) and space factors on the power elements of the thermal converter of BD made of SME material confirmed the preservation of the BD functional properties.
- Investigation of operational factors (cyclic temperature changes, harmonic and random vibrations, single and multiple impacts) and space factors on the power elements of BD thermal converter made of SME material confirmed the preservation of the BD functional properties
- Conservation tests (resource tests) at minus 50 ° C for 57 days, at a temperature of plus 70 ° C for 156 days, which corresponded to four years of storage and 11.6 years of unloaded operation, tests at a temperature of plus 50 ° C for 68 days corresponding to 3.4 years of operation under load confirmed the working efficiency of BD
- Calculation and experimental studies of operation of the power contact block showed the coincidence of the results. The tests showed that the work of the contact block passes stably, without sudden changes in the transient resistance.

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