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ENERGY SAVING SIMULATION TEST COMPLEX FOR SPACECRAFT POWER SUPPLIES FULL-SCALE ELECTRICAL TESTS

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The aim of this paper is to describe an energy saving automatized simulation test complex used for spacecraft power supplies full-scale electrical ground-based tests. The complex allows you to simulate the operation of solar array, lithium-ion-battery and spacecraft payload. The distinctive features of the test complex are a continuous and impulse control methods combination with an improved dynamic accuracy, and recuperation of consumed energy into its internal DC network for the better energy efficiency. Test complex operational time from uninterruptible power supply accumulator batteries is significantly increased due to the recuperation of excess power into the test complex internal DC network. The results are experimentally proved.

The authors of the paper analyzed dynamic accuracy improvement and energy saving during ground-based spacecraft power system electrical tests. The process of ground-based spacecraft electrical testing includs the following tasks:

– the accurate simulation of static and dynamic characteristics of spacecraft power system energy sources and loads;

– the utilization of energy produced by power system under load and during spacecraft battery charge simulation.

The paper deals with the description of energy saving automatized simulation test complex (ESAST) including complex subsystems structure and experimental study of the test complex characteristics.

Commercially available simulation test complexes usually use continuous or impulse control methods. The continuous control methods decrease energy efficiency, as the most part of energy is dissipated on the regulator, which requires massive heat sink, increasing weight and size. It makes difficult to produce high-power test complexes. The impulse control methods provide better energy efficiency, but limit dynamics and real devices fast response reproduction accuracy. The paper describes the combination of continuous and impulse control methods with the aim of taking the advantages of both.

The energy consumed by the test complex can be utilized either by the heat dissipation in the environment or by the recuperation into industrial AC grid. The heat dissipation reduces the energy efficiency, increases the testing room temperature (in case of high-power spacecraft power system) and an air conditioning system. The recuperation into AC grid is free of specified disadvantages, but it requires the recuperated excess energy parameters matching with AC grid requirements through the network of grid-tied inverters, which leads to the increase of weight and size of the test complex. Moreover, the recuperation into AC grid is difficult during grid emergency shutdown, which can result in long test failure. The paper describes the method of excess energy recuperation into the complex internal DC network. The method significantly reduced test complex energy consumption, which in case of powering test complex from uninterruptible power supply (UPS) notably increase operating time from UPS accumulator batteries during AC grid emergency shutdown.

In conclusion the main advantages of ESAST are given:

– more than twice wattage reduction of test complex main power supply;

– the ability to work during AC grid emergency shutdown with increased operating time from UPS;

– the significant reducing of ESAST main parts weight and size.

Keywords: solar array simulator, battery simulator, electronic load, power supply system, energy saving.

ЭНЕРГОСБЕРЕГАЮЩИЙ ИМИТАЦИОННО-НАТУРНЫЙ КОМПЛЕКС ДЛЯ ЭЛЕКТРИЧЕСКИХ ИСПЫТАНИЙ СИСТЕМ ЭЛЕКТРОПИТАНИЯ КОСМИЧЕСКИХ АППАРАТОВ

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В работе рассмотрен автоматизированный энергосберегающий имитационно-натурный комплекс, предназначенный для наземных испытаний систем электропитания космических аппаратов. Комплекс позволяет имитировать работу солнечной батареи, аккумуляторной батареи и бортовой нагрузки. Отличительной особенностью комплекса является комбинирование непрерывных и импульсных методов управления и использование рекуперации потребленной энергии в собственную сеть постоянного тока с целью повышения динамической точности и повышения коэффициента полезного использования энергии. Также рекуперация в сеть постоянного тока снижает энергопотребление комплекса, что при использовании источника бесперебойного питания (ИБП) позволяет увеличить время работы комплекса от аккумуляторов ИБП.

В статье рассматриваются вопросы повышения динамической точности и снижения энергопотребления при проведении наземных электрических испытаний систем электропитания (СЭП) космических аппаратов (КА). В ходе наземных электрических испытаний СЭП КА возникают следующие задачи:

– необходимо достаточно адекватно воспроизводить статические и динамические свойства как источников энергии СЭП КА, так и потребителей;

– при энергонагружении СЭП и имитации заряда бортовой аккумуляторной батареи (АБ) необходимо утилизировать потребленную энергию.

Статья представляет собой описание автоматизированного энергосберегающего имитационно-натурного комплекса (ЭИНК), структур его подсистем, экспериментальное подтверждение характеристик. Приведен внешний вид ЭИНК.

Промышленно выпускаемые имитационно-натурные комплексы, как правило, используют непрерывные или импульсные методы управления. Использование непрерывных методов управления снижает коэффициент полезного использования энергии, поскольку относительно большая часть энергии рассеивается в виде тепла на регулирующих элементах, а также приводит к увеличению массогабаритных показателей из-за необходимости применения теплоотводов. Это затрудняет создание мощных имитационно-натурных комплексов. Использование импульсных методов управления обеспечивает высокое значение коэффициента использования энергии, однако не позволяет получить высокого быстродействия и адекватного воспроизведения быстропротекающих процессов реальных устройств. В данной статье рассмотрено комбинирование непрерывных и импульсных методов управления, что позволяет объединить их преимущества.

Для утилизации избыточной энергии в промышленно выпускаемых имитационно-натурных комплексах используется или рассеивание энергии в виде тепла или рекуперация в промышленную сеть переменного тока. Сброс избыточной энергии в виде тепла снижает коэффициент полезного использования энергии, приводит к повышению температуры в помещении (при испытании мощных СЭП), может потребовать систем вентиляции и кондиционирования воздуха. Рекуперация энергии в сеть переменного тока лишена этих недостатков. Однако она требует согласования параметров рекуперируемой энергии с требованиями промышленной сети посредством ведомых сетью инверторов, что приводит к ухудшению массогабаритных показателей комплекса. Кроме того, рекуперация в сеть переменного тока затруднена при аварийном отключении сети. Это может привести к срыву длительных испытаний. В данной статье рассмотрен метод рекуперации избыточной энергии в собственную сеть постоянного тока комплекса. При этом снижается энергопотребление комплекса, что при использовании источников бесперебойного питания (ИБП) повышает время работы ЭИНК от аккумуляторов ИБП при аварийном отключении сети переменного тока.

В выводах статьи подчеркивается, что разработанный ЭИНК обладает следующими преимуществами:

– возможность уменьшения мощности источника электропитания комплекса минимум в два раза;

– сохранение работоспособности и увеличение длительности работы от источника бесперебойного питания при отключении промышленной сети переменного напряжения;

– существенное уменьшение массы и габаритов составных частей ЭИНК.

Ключевые слова: имитатор солнечной батареи, имитатор аккумуляторной батареи, нагрузочное устройство, система электропитания, энергосбережение.

Introduction. The automatized simulation test complex (AST)), which contain simulators of the primary energy source (solar battery), rechargeable battery (RB), and various load devices are used to carry out the ground-based tests of the power supply systems (PS) of the spacecraft (SC). To ensure the required test quality the simulators must reproduce the static and dynamic characteristics of the prototypes with a sufficiently high accuracy.

While creating AST of powerful (more than 10 kW) SC power systems and conducting long-term (resource) tests two problems arise:

– to ensure the required accuracy of simulating the static and dynamic characteristics of power sources of the PS, which is important for the adequacy of the tests performed;

– to save energy and reduce the heat generation of the complex subsystems , which is important for improving the functional and operational characteristics of the complex, its weight and dimension.

In the existing AST, the first problem is solved by applying continuous control laws [1–3], which leads to a low coefficient of electricity use (no more than 50 %) and, as a result, to a large heat emission.

While solving the second problem, the pulse control methods [4] and power recovery to the AC network are used. At the same time, the dynamic characteristics of simulators worsen, while meeting the requirements for the quality of electricity, the recuperator schemes become more complicated and their cost increases. To improve the quality of complex power supply the uninterruptible power supplies (UPS) have been used lately. But even in this case the significant disadvantage of this method is that, when the AC power is switched off in an emergency, recovery becomes impossible.

In this paper, we propose the solution of these problems: providing the required dynamic properties and increasing energy use in high-power AST

For the solution of the problems with the energy-saving AST (ESAST) developed by the authors the new approaches are used:

– the combination of pulse and continuous control methods for simulators of power installations and subsystems of PS, which allows to increase the coefficient of electricity use and provide the required dynamic properties of simulators;

– the recovery of excess power of the load devices in the DC circuit of the complex power supply system , which allows to increase the of electricity use rate, reduce power consumption from the AC mains and the capacity of the power source of ESAST and increase the working time of ESAST from the battery when you unplug the AC.

The proposed device structure. Fig. 1 shows a block diagram of the ESAST [5], which explains the use of the electricity recovery method in the DC network.

In the first mode of operation (the illuminated section of the SC flight path, the RB charge), the PS receives electricity from the SAS and supplies the load and the LibS charge. LDER sets the power loading mode of the PS and returns the consumed energy to the general DC power supply network of the ESAST. The LibS operates in the RB charge simulation mode and recovers excess energy to the general DC power supply network of the ESAST.

In the second mode of operation of the PS (the shadow section of the flight path of the SC), the SAS stops power supply to the PS. The LibS operates in the RB discharge simulation mode and provides power to the PS. LDER sets the power loading mode of the PS and returns the consumed energy to the general DC power supply network of the ESAST.

In the third mode of operation (the illuminated section of the SC flight path, the peak power consumption), the PS is powered from the SAS and the LibS together. The LibS also, as in the previous case, operates in the RB discharge simulation mode. LDER sets the power loading mode of the PS and returns the consumed energy to the general DC power supply network of the ESAST.

The following advantages of the ESAST structure should be considered: a relatively simple implementation of LDER, recovering the consumed energy in single SAS and LibS power supply, and relatively high specific energy characteristics of LibS using a bidirectional switching converter (PC).

The combination of pulse and continuous simulators control methods, which allows providing high dynamic characteristics with relatively high energy efficiency, is as follows. Simulators (SAS, LibS and LDER) contain high-speed continuous regulators that regulate the output parameter of the simulator (voltage, current, power, etc.), and pulse regulators that limit the power dissipation on continuous regulators and increase the energy efficiency.

The solar array simulator. The basis of the SAS (fig. 2) is a continuous current stabilizer with the parallel control element (ACE) switching on. The CCS consists of the following devices: ACE, SA1, and CS1. To reproduce the required nonlinear current-voltage characteristics of the SB, the continuous current stabilizer (CCS) is covered by functional voltage feedback (FFD). The use of a pulsed current stabilizer (PCS) for the current flowing through the ACE allows us to limit the power dissipated by the ACE. The PCS consists of the following devices: PC, PWM, SA2, CS2, Vref.

The principle of operation of the SAS: SA1 compares the voltage with CS1, proportional to the output current of the SAS, with the voltage at the output of the FFD and generates a control signal for the ACE. The FFD generates a set point for the continuous current stabilizer in accordance with the specified current-voltage characteristic and the current voltage value measured by the VD. SA2 compares with the reference (Vref) voltage proportional to the current through the ACE obtained from the CS2, and generates a control signal for the PC proportional to the deviation of the current through the ACE from the required value.

The lithium-ion-battery simulator (LibS). The basis of the Lithium-ion-battery simulator structure (fig. 3) [6] is a continuous voltage stabilizer with parallel switching on the ACE. The continuous voltage stabilizer consists of the following devices: ACE, SA1, VD to reproduce the required nonlinear charge-discharge characteristics of the AB, the continuous voltage stabilizer is covered by functional current feedback (CS). The use of a pulsed current stabilizer for current flowing through the ACE allows you to limit the power dissipated by the ACE. Pulsed current stabilizer consists of the following devices: BPC, PWM, SA2, CS2, Vref.

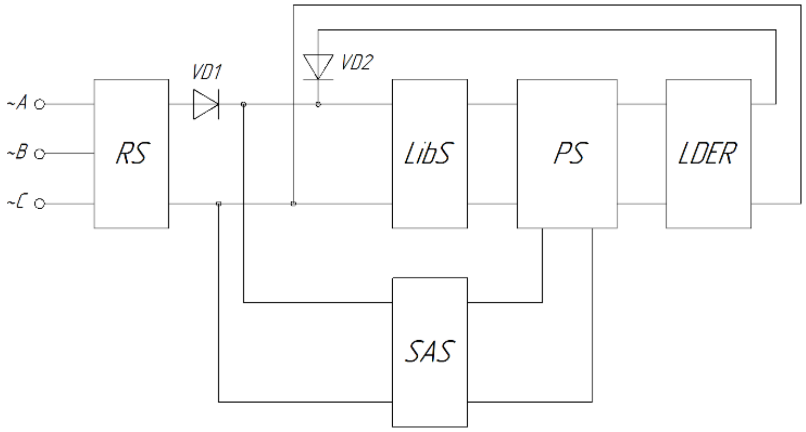

Fig. 1. ESAST structure:
RS – rectifier stabilizer; SAS – Solar array simulator;
PS – tested power supply; LDER – load device with energy
recuperation; LibS – Lithium-ion-battery simulator

Рис. 1. Структурная схема модуля ЭИНК:
ВС – выпрямитель-стабилизатор; ИСБ – имитатор солнечной
батареи; СЭП – испытываемая система электропитания;
НУРТ – нагрузочное устройство рекуперативного типа;
ИАБ – имитатор аккумуляторной батареи

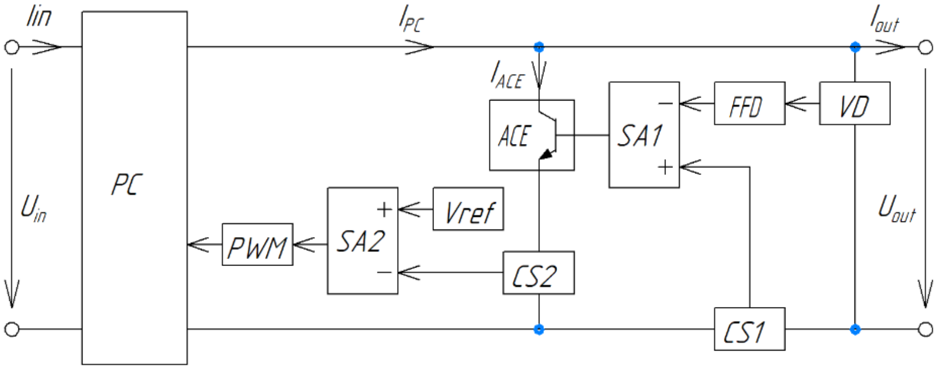

Fig. 2. Solar array simulator structure (SAS):
PC – pulse converter; PWM – pulse width modulator; SA – summing amplifier;
Vref – voltage reference; ACE – analogue control element; FFD – functional feedback;
VD – voltage divider; CS – current sensor

Рис. 2. Структурная схема ИСБ:
ИП – импульсный преобразователь; ШИМ – широтно-импульсный модулятор;
УС – усилитель-сумматор; ИОН – источник опорного напряжения;
НРЭ – непрерывный регулирующий элемент; УФОС – устройство функциональной
обратной связи; ДН – датчик напряжения; ДТ – датчик тока

The operating principle of the LibS: SA1 compares the voltage with the VD, proportional to the output voltage of the LibS, with the voltage of the FFD and generates a control signal for the ACE. The FFD generates a set point for continuous voltage stabilizer in accordance with the specified charge-discharge characteristic (CDC) and the state of charge measured by the AHS. SA2 compares the voltage proportional to the current through the ACE obtained from the CS2 with the reference one and generates a control signal for the BPC proportional to the deviation of the current through the ACE from the required value.

Load device with energy recuperation. The LDER basis (fig. 4) is the continuous current stabilizer with parallel inclusion of the ACE. The continuous current stabilizer consists of the following devices: ACE, SA1, and CS1.

To reproduce the required nonlinear current-voltage characteristics of the simulated load, the CCS is covered by functional voltage feedback (FFD). The use of a pulsed current stabilizer (PCS) flowing through the ACE allows you to limit the power dissipated by the ACE. Pulsed current stabilizer consists of the following devices: PC, PWM, SA2, CS2, Vref.

The principle of operation of the LDER: SA1 compares the voltage with CS1, proportional to the input current of the LDER, with the voltage at the output of the FFD and generates a control signal for the ACE. The FFD generates a set point for the continuous current stabilizer in accordance with the specified VAC and the current voltage value measured by the VD. SA2 compares the voltage proportional to the current through the ACE obtained from the CS2 with the reference one and generates a control signal for the PC proportional to the deviation of the current value through the ACE from the required value.

Energy-saving simulation and full-scale complex. ESAST developed by the authors (fig. 5) contains: SAS, LibS, LDER, high-speed protection device (HSPD), specialized hardware and software complex (HSC). The SAS module consists of 4 independent channels that allow both parallel, serial connection of two channels and mixed connections. Each channel provides: the no-load voltage changing from 20 to 200 V; the short-circuit current from 0.1 to 7 A changing; the VAC shape setting mathematically, using a table, slopes for voltage and current branches and a non-linear transition zone; changing the output capacitance from 500 to 1000 nF with a step of 100 nF.

The module of the lithium-ion battery simulator (LibS) includes the following blocks: simulation of charge-discharge characteristics of the LibS; simulation of analog voltage sensors changes of each battery; simulation of analog temperature sensors.

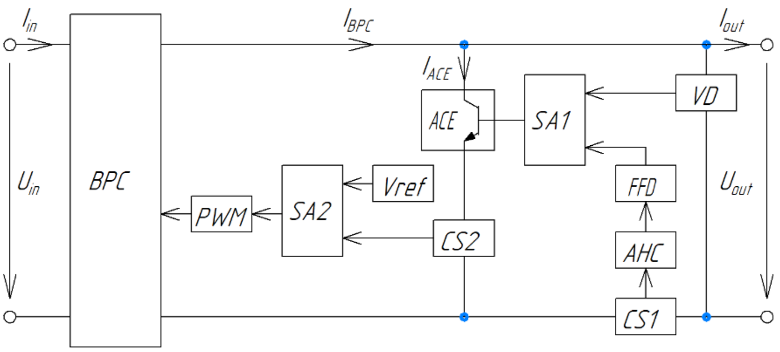

Fig. 3. Lithium-ion-battery simulator structure:
BPC – bi-directional pulse converter; PWM – pulse width modulation; SA – summing amplifier; Vref – voltage reference; ACE – analogue control element; CS – current sensor; VD – voltage divider; FFD – functional feedback; AHC – amp hours counter

Рис. 3. Структурная схема ИАБ:
ДИП – двунаправленный импульсный преобразователь; ШИМ – широтно-импульсный модулятор; УС – усилитель-сумматор; ИОН – источник опорного напряжения; ДТ – датчик тока; НРЭ – непрерывный регулирующий элемент; ДН – датчик напряжения; УФОС – устройство функциональной обратной связи; САЧ – счетчик ампер-часов

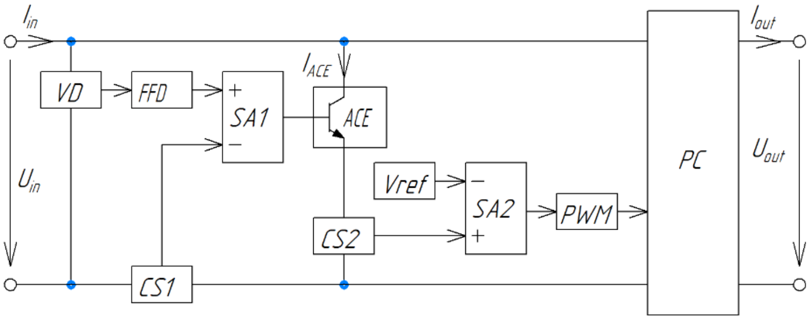

Fig. 4. Structure of load device with energy recuperation:
PC – converter; PWM – pulse width modulation; SA – summing amplifier; Vref – voltage reference; ACE – analogue control element; FFD – functional feedback; VD – voltage divider; CS – current sensor

Рис. 4. Структурная схема НУРТ:
ДН – датчик напряжения; ДТ – датчик тока; УФОС – устройство функциональной обратной связи; УС – усилитель-сумматор; НРЭ – непрерывный регулирующий элемент; ИОН – источник опорного напряжения; ШИМ – широтно-импульсный преобразователь; ИП – импульсный преобразователь

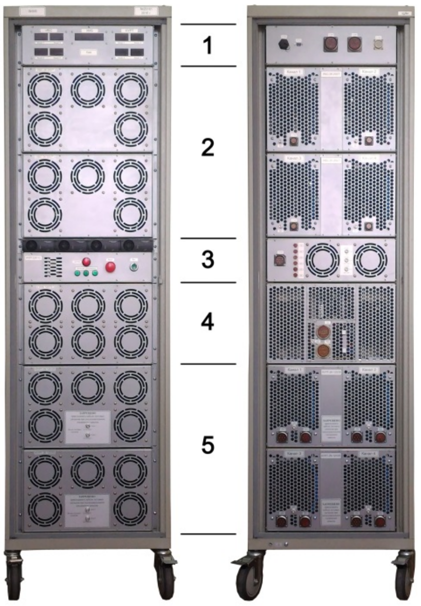

Fig. 5. ESAST:
1 – Hardware and software complex; *2* – Four SAS channels;
3 – PS; *4* – LibS; *5* – four LDER channels

Рис. 5. Внешний вид ЭИНК:
1 – АПК; *2* – четыре канала ИБС; *3* – источник электропитания;
4 – ИАБ; *5* – четыре канала НУРТ

The LibS module provides: changing the voltage from 10 to 105 V; changing the charge current from 0 to 25 A; the discharge current changing from 0 to 70 A; the shape of the charge discharge characteristics (CDC) setting mathematically, using a table; changing the active component of the internal resistance from 5 mohm to 50 mohm, the inductive component – from 8 mgN to 80 mgN.

The LDER module contains 4 independent channels that allow both parallel, serial connection of two channels and mixed connections. LDER provides: maximum channel power of 1500 W; voltage change from 20 to 120 V; current change from 0.1 to 20 A; guidance of harmonic interference with an amplitude of 5 A in the band up to 300 kHz.

To confirm the effectiveness of the pilot images of the main subsystems ESAST a comparative analysis of the technical and price characteristics of subsystems EINK modular characteristics of the subsystems of foreign companies [7–9] and energy saving subsystems of the test systems manufactured was carried out by NIIAM TUSUR (The Research Institute of Automation and Electro mechanics) [10–12], the testing equipment for spacecraft production leader in Russia.

It should be noted that the main advantages of the EINK with the recovery of excess electricity to the DC network of the power supply system of the complex are:

– the ability to reduce at least twice the power source force of the complex;

– keeping the operability and increasing the operation duration from an uninterruptible power supply when the industrial AC network is disconnected;

– the significant mass and dimension reduction of the ESAST components.

Tab. 1 shows the technical characteristics of lithium-ion battery simulators: BIAB-200LI [10], manufactured by NIIEM –TUSUR, Tomsk; LibS with two modules parallel connection, manufactured by Reshetnev Siberian State University of Science and Technology, Krasnoyarsk and a battery simulator manufactured by AMETEK [7], USA.

Tab. 1 shows that the main technical characteristics of the Libs developed by Reshetnev Siberian State University are at the same level, and in terms of weight and size characteristics it is even ahead.

Tab. 2 shows the technical characteristics of simulators of solar cells of comparable capacity: SAS-200/7-4 [11], produced by NIIEM –TUSUR, Tomsk; ISB-200-4K with parallel connection of two modules, produced by Reshetnev Siberian State University, Krasnoyarsk and E4360 Keysight Technologies [8] with parallel connection of four modules containing eight channels.

Tab. 2 shows that in terms of technical characteristics and functions the SAS developed by Reshetnev Siberian State University occupies the intermediate position between the SAS produced by TUSUR and Keysight Technologies. The Keysight Technologies SAS disadvantages are the greater heat capacity when working on the current branch WAC , the WAC insufficient slope on the branch voltage, determined by the value of series resistance RS, low voltage-170V.

Tab. 3 shows comparable in power load device simulators technical characteristics: BIN-100 [12], produced by NIIEM-TUSUR, Tomsk; NUK-120-4K with parallel connection of two modules, produced by Reshetnev Siberian State University, Krasnoyarsk and EA-ELR 9250-70 Elektro-Automatik [9], Germany.

Elektro-Automatik load devices have good weight and size characteristics, but the reason is ,that the function of directing test sinusoidal and pulse currents on the buses of power sources is limited to a frequency band not exceeding several kilohertz by the use of pulse converters. It is necessary to increase the frequency band to hundreds of kilohertz and measure the impedance frequency characteristics of power sources in order to study the noise immunity, while the use of continuous load devices is required, which significantly worsens the weight and size characteristics of the devices. This is illustrated by the load devices production TUSUR and Reshetnev Siberian State University.

Table 1

Energy and mass-dimensional characteristics of lithium-ion battery simulators

№	Parameter	Dimen tion	BIAB-200LI NIIEM TUSUR	Libs Reshetnev Siberian State University	Battery String Simulator, AMETEK
1	Charge/ discharge voltage range	Volt	40–110	10–120	120
2	The maximum power in the discharge mode	Watt	12000	14700	18000
3	Discreteness of charge/discharge voltage adjustment	Volt	0.1	0.1	No data
4	The magnitude of the output voltage ripple, not more	мVolt	50	500	No data
5	Maximum charging current	Amp	30	50	50
6	Maximum chargig current	Amp	200 voltage not more than 60 Volt. 109 voltage 110 B	140 over entire voltage range	150
7	Charge/discharge characteristics simulation	---	no	yes	no
8	Recuperation in charge mode	---	no	yes	no
9	Voltage sensors simulation	---	yes	yes	yes
10	Temperature sensors simulation	---	yes	yes	yes
13	Specific volume	m^3/Watt	79.56×10^{-6}	16.46×10^{-6}	114.76×10^{-6}
14	Specific gravity	kg/Watt	33.33×10^{-3}	8.84×10^{-3}	31.25×10^{-3}

Table 2

Energy and mass-dimensional characteristics of lithium-ion battery simulators

№	Parameter	Dimention	SAS-200/7-4TUSUR	SAS-200-4К Reshetnev Siberian State University	E4360 Keysight Technologies
1	Control range Uxx	Volt	40–210	20–210	20–170
2	Adjustment discreteness	Volt	0.1	0.1	0.048
3	Single-channel icz current adjustment range	Amp	0-8	0–7	0–3.8
4	Icz current adjustment discretness	Amp	0.01	0.01	0.0012
5	VAC reproduction error	%	5	2	No data
6	Frequency band for admittance playback	Гц Hz	No data	100000	No data
7	Frequency band for admittance playback not more	%	No data	5	No data
8	Resistance serial RS minimum	Ом Om	0.3	0.3	1.72
9	Specific volume	m^3/Watt	87.71×10^{-6}	43.20×10^{-6}	30.36×10^{-6}
10	Specific gravity	kg/Watt	32.74×10^{-3}	16.43×10^{-3}	14.75×10^{-3}

Table 3

Energy and mass-dimensional characteristics of the regenerative-type load devices

№	Parameter	Dimen-tion	BIN-100 TUSUR	NUK-120-4К Reshetnev Siberian State University	EA-ELR 9250-70 Elektro-Automatik
1	Maximum input voltage	Volt	100	120	250
2	Input current range	Amp	0–65	0–80	0–70
3	Adjustment discreteness	Amp	0.01	0.01	No data
4	Range of sinusoidal load test current	Amp	0–15	0–16	No data
5	Adjustment discreteness	Amp	0.1	0.1	No data
6	Frequency range of the test signal	кГц kHrz	0.02–100	0–300	No data
7	Constant resistance load simulation	---	no	yes	yes
8	Constant power load simulation	---	no	yes	yes
9	Recovery of excess energy	---	To the industrial AC network	To the DC network of the test complex	To the industrial AC network
10	The ability to work when disconnecting the commercial power supply AC voltage	---	No, without additional devices	yes	no
11	Specific volume	m^3/Watt	90.68×10^{-6}	40.32×10^{-6}	22.36×10^{-6}
12	Specific gravity	kg/Watt	33.85×10^{-3}	18.33×10^{-3}	9.72×10^{-3}

Conclusion: The main subsystems of the ESAT developed by Reshetnev Siberian State University in most parameters are at the world manufacturer technical characteristics level, and in a number of functions it is sometimes higher. In particular, it concerns the dynamic properties: the frequency band for reproducing the AB impedance, the SB admittance, the frequency range for inducing the test current of the sinusoidal form of the LDER, and the power utilization coefficient.

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