Conference Paper

# High-voltage Spacecraft Power System Based on Adjustable Voltage Inverters

M M Chernaya and Yu A Shinyakov

Tomsk State University of Control System and Radio Electronics, Russia

## Abstract

The authors have proposed the solar battery mathematical model based on use of its photoelectric energy converters parameters of any unit area and its experimental current-voltage characteristics, provided by manufacturer of solar batteries. The mathematical model allows drawing current-voltage and voltage-watt characteristics depending on its operation conditions and used to calculate the solar batteries electrical characteristics regardless of the manufacturing technology and the substrate material: Si, GaAs, etc. High-voltage high-efficiency spacecraft power system based on adjustable voltage inverters has been developed. The system provides for simplification of voltage matching of solar battery, accumulator battery and load and allows adjusting solar battery voltage in a range sufficient to implement the maximum power point tracking (MPPT) mode. Calculation of the solar battery parameters ensuring the restoration of the accumulator battery capacity to the beginning of a new calculation cycle for an arbitrarily compiled load curve with allowance for the solar battery maximum open circuit voltage limitation (180 V) with a change of solar battery and load powers. The results of the development and experimental researches of the energy-converting device based on voltage inverter providing a high efficiency (not less than 96 %) are shown.

Corresponding Author:
M M Chernaya
cmm91@inbox.ru

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## 1. Introduction and problem definition

The study and exploration of outer space requires the development and improvement of various spacecrafts (SC). In particular, unmanned spacecrafts designed to create a global communication system, television and navigation, SC designed to create surveillance and data link systems, SC designed to study of weather conditions, natural resources of the Earth, exploration of deep space, etc.

The main primary energy source of the SC power supply systems (PS) are solar batteries. In addition, SC PS of long service life should be equipped with secondary energy sources – accumulator batteries (AB). Solar and accumulator batteries are connected to the output stabilized load bus by means of regulating and stabilizing devices (energy-conversion devices). SB, AB and energy-conversion devices of SC PS require research and development, while for the full use of each it is necessary to study the entire spacecraft power system. Because SC PS reach up to 30 % by mass and cost of SC. Therefore, optimization of existing and development of new SC PS allows to significantly improving the technical and economic performance of the spacecraft.

For a long time the output voltage of the stabilized load bus of SC was equal to 27 – 28 V. Among a large number of SC PS structure parallel and series-parallel structure was most widely used [1]. The choice of SC PS structure is largely explained by the choice of the working orbit, SC operating modes and load curves.

Since the middle of the 90th years of the 20th century the new requirements for the spacecraft power system design began to create. The number of SC tasks, its power-to-weight ratio and output power were increased. Requirements on weight-dimension characteristics of the PS components and its efficiency have increased. There was a requirement to reduce the cost of SC PS of development and manufacturing, to increase reliability and radiation durability, etc. That has promoted to transition from the low-voltage output stabilized power bus of load (27 – 28 V) to the high-voltage output stabilized power bus of load (100 V).

The main problem at use of the solar batteries (with a maximum power point of the volt-watt characteristics) in high-voltage SC power systems is increase of the SB open-circuit voltage when SC output from shadow sites of an orbit that creates conditions for the emergence of electrostatic discharges between the chains of SB photodiodes (for Si SB - up to 300 V, for GaAs SB - up to 245 V). At that time was determined the optimal PS structure for geostationary SC, forcibly limiting the SB voltage by using shunt converters [2, 3]. Examples of such SC power systems may be the Russian platform "Express-2000" performed by JSC "Information Satellite Systems" - name after Academician M. F. Reshetnev", electrical power system of European firms Alcatel performed for the platform for "Spacebus-4000", the power supply system of firm Hughes on the platform HS-702, the system power supply of firm Lockheed Martin on platform for A-2100 AXX and etc.

It is not optimal to use results in the development and creation of high-voltage SC PS with varying loading curve and various operating modes despite the technological advance, the testing of results and the successful implementation of shunt high-voltage SC PS due to its low energy efficiency provided by significant changes in parameters of SB current-voltage characteristics that undergoing changes in the different environmental conditions (temperature, illumination, etc.). And direct application of the technological advance of the low-voltage parallel-sequential SC PS design is not possible because of the possibility of emergencies due to the achievement of critical levels of open-circuit SB voltage (at minimum temperature) and, as a consequence, the low PS reliability.

Preliminary analysis shows that a large number of SC PS structure and absence of a unified approach to its construction overload the electrical engineering industry with permanent developments of solar batteries, accumulator batteries and energy-conversion devices of SC PS. At the same time, the lack of unified solutions does not provide for simplification of voltage matching of SB, AB and load and seriously complicates the spacecraft operation and its application.

Therefore, the design of high-voltage high-power SC PS with variable load curve should be carried out by theoretical, simulation and experimental works, taking into account the fulfillment of energy efficiency requirements, reliability and simplification of energy sources and loads voltage matching in SC PS, which requires new engineering solution and approach.

# 2. Theory

## 2.1. Solar battery mathematical model

The main factors of the environment, leading to a significant change in the non-linear current-voltage and voltage-watt characteristics are temperature and illumination. The SB mathematical model taking into account the effect of SB temperature t, $^0$C and their illumination F, W/m$^2$ based on a mathematical model of SB current-voltage characteristics has developed [4]:

$$I_{sb}(U_{sb}, t, F) = I_{sc}(t, F) \cdot \left(1 - \left(1 - \frac{I_{>}(t, F)}{I_{sc}(t, F)}\right)^{\left(\frac{1}{1-\frac{U_{>}(t,F)}{U_{oc}(t,F)}} \cdot \left(1-\frac{U_{sb}}{U_{oc}(t,F)}\right)\right)}\right), \tag{1}$$

where $U_{sb}$ – SB voltage, $t$ – calculated temperature value ($^0$C), $F$ – calculated illumination value (W/m$^2$), $I_{sc}(t,F)$ – short-circuit current of the photovoltaic cell (A) as a function of t и F, $I_o(t,F)$ – optimal photovoltaic cell current (A) as a function of t и F, $U_o(t,F)$ – optimal photovoltaic cell voltage (V) as a function of t и F, $U_{oc}(t,F)$ – open circuit voltage of the photovoltaic cell (V) as a function of t и F.

$$U_{oA}(t, F) = k_{un} \cdot U_{oA}(t_1, F_1) \cdot (1 + 0,01 \cdot \beta)^{(t-t_1)}, \tag{2}$$

where $t_1$ – nominal temperature ($^0$C), $F_1$ – nominal illumination (W/m$^2$), β – temperature coefficient of $U_{oc}$(%/$^0$C), $k_{un}$ – the voltage factor taking into account the influence of the photovoltaic cell illumination and determined as follows:

1. On the axis of abscissa according to the experimental current-voltage characteristics of the photovoltaic cells (Figure 1), provided by the SB manufacturers, and obtained at different illumination levels of $F_1$… $F_n$and $t_1$, the values of open circuit voltage of the photovoltaic cell $U_{oc1}(t_1, F_1)$ … $U_{ocn}(t_1, F_n)$ are determined.

2. The coefficients $k_{u1}$… $k_{un}$, reflecting the relative change in the open circuit voltages of the photovoltaic cells in the range between $U_{ocn}$ $(t_1, F_n)$ and $U_{ocn+1}$ $(t_1, F_{n+1})$, are calculated as a function of its illumination levels according to the equations:

$$k_{un} = \frac{U_{ocn+1}\left(t_1, F_{n+1}\right)}{U_{oc1}\left(t_1, F_1\right)} + \left(\left(\frac{\frac{U_{ocn}\left(t_1, F_n\right)}{U_{oc1}\left(t_1, F_1\right)} - \frac{U_{ocn+1}\left(t_1, F_{n+1}\right)}{U_{oc1}\left(t_1, F_1\right)}}{F_n - F_{(n+1)}}\right) \cdot \left(F - F_{(n+1)}\right)\right) \tag{3}$$

$$U_{>}(t, F) = k_{un} \cdot U_{>}(t_1, F_1) \cdot (1 + 0,01 \cdot \gamma)^{(t-t_1)}, \tag{4}$$

where γ – temperature coefficient of $U_o$(%/$^0$C).

$$I_{sc}(t, F) = k_{in} \cdot I_{sc}(t_1, F_1) \cdot (1 + 0,01 \cdot \alpha)^{(t-t_1)} = k_{in} \cdot I_{sc}(t_1, F_1) \cdot (1 - 0,01 \cdot \alpha)^{(t_1-t)}, \tag{5}$$

where α – temperature coefficient of $I_{sc}$(%/$^0$C), $k_{in}$ – the current factor taking into account the influence of the photovoltaic cell illumination and determined similarly to the method of determining the voltage factor $k_{un}$ and calculated on the axis of ordinates as:

$$k_{in} = \frac{I_{scn+1}\left(t_1, F_{n+1}\right)}{I_{sc1}\left(t_1, F_1\right)} + \left(\left(\frac{\frac{I_{scn}\left(t_1, F_n\right)}{I_{sc1}\left(t_1, F_1\right)} - \frac{I_{scn+1}\left(t_1, F_{n+1}\right)}{I_{sc1}\left(t_1, F_1\right)}}{F_n - F_{n+1}}\right) \cdot \left(F - F_{n+1}\right)\right) \tag{6}$$

$$I_{>}(t, F) = \frac{k_{in} \cdot I_{>}(t_1, F_1) \cdot (1 + 0,01 \cdot \lambda)^{(t-t_1)}}{(1 + 0,01 \cdot \gamma)^{(t-t_1)}}, \tag{7}$$

where $\lambda$ – temperature coefficient of $I_o$(%/$^0$C).

## 2.2. The high-voltage high- efficiency space craft power system structure based on voltage inverters

The high-voltage SC PS that provides for simplification of voltage matching of SB, AB and load by the transformation coefficients is shown in Figure 2. The voltage regulator (VR) and the accumulator battery discharge device (BD) are implemented on the basis of voltage inverters (VI) [5].

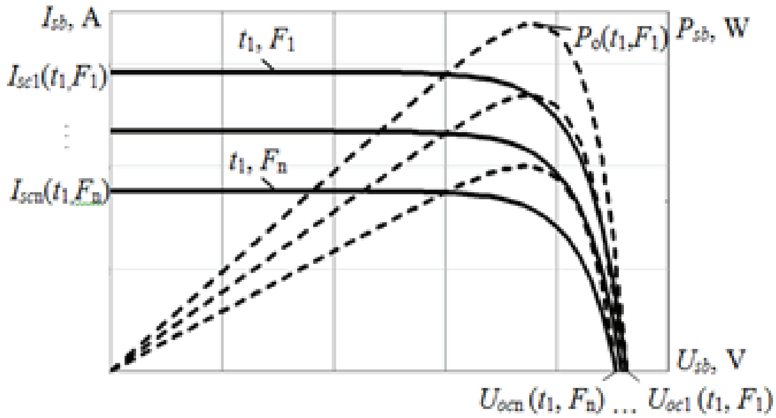


**Figure** 1: Current-voltage and voltage-watt characteristics of the photovoltaic cell with different levels of illumination.

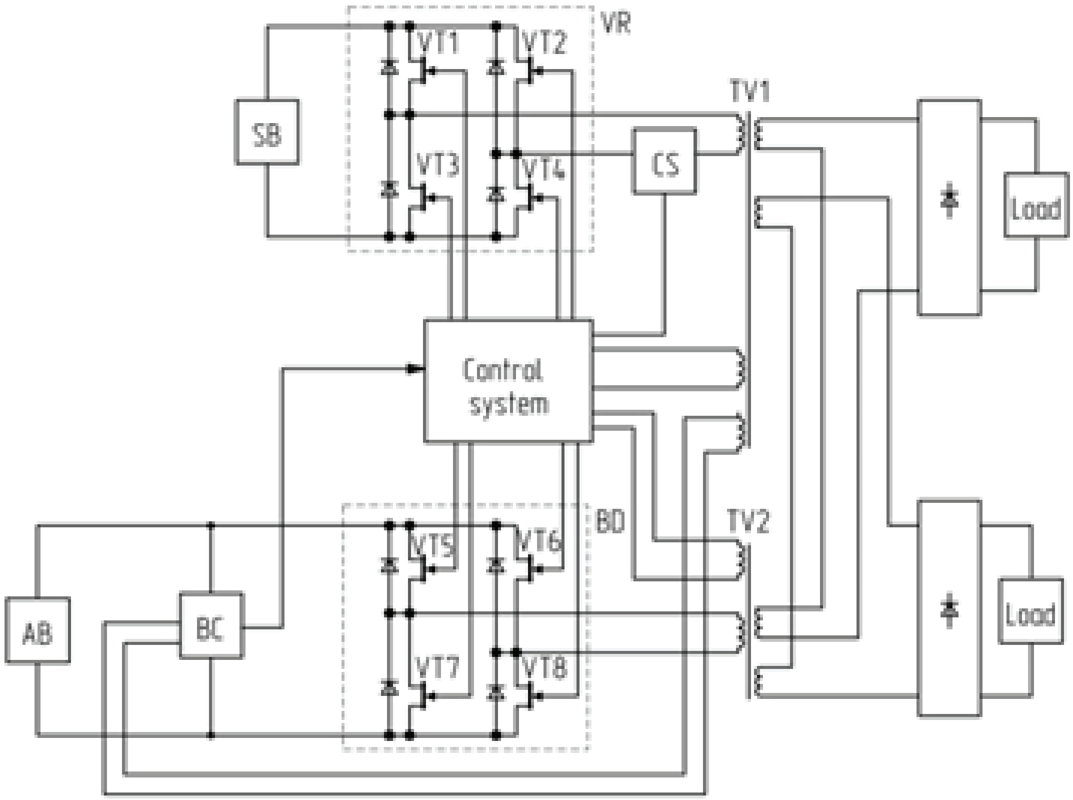


**Figure** 2: High-voltage high-efficiency SC power system based on voltage inverters.

In Figure 2 the following designations are accepted: BC – the AB charge device, CS – the current sensor, TV1 – the first transformer, TV2 – the second transformer.

The SC power system provides power to the on-board consumers at the different ratios of SB power, AB power and load power. Mode 1. The load is powered by SB. Excess SB energy is used to charge AB. Mode 2. The load is powered by SB and AB.

Mode 3. The load is powered by the battery. SB does not generate power. (Spacecraft is on the shadow site of an orbit).

The output parameters of the energy-conversion devices based on VI are related to the input parameters according to equation:

$$k_{tr\_vr} = U_{sb} \cdot U_{out}^{-1} \tag{8}$$

$$k_{tr\_bd} = U_{ab} \cdot U_{out}^{-1} \tag{9}$$

$$I_{out} = I_{sb} \cdot k_{tr\_vr} \cdot \gamma_{vr}^{-1} = I_{ab} \cdot k_{tr\_bd} \cdot \gamma_{bd}^{-1} \tag{10}$$

$$U_{out} = U_{sb} \cdot \gamma_{vr} \cdot k_{tr\_vr}^{-1} + U_{ab} \cdot \gamma_{bd} \cdot k_{tr\_bd}^{-1} \tag{11}$$

According to the equation (11) the load can be powered at different power ratio consumed from the SB and AB. With a phase shift of the control impulse of the VR transistors by an angle of π, the duration $\gamma_{vr} \to 0$, so the load will be provided by AB. The voltage $U_{sb} \to U_{oc}$. When $\gamma_{vr}$ increases, the VR starts to generate a voltage in the summation circuit, which is compensated by a decrease of BD voltage. The SB voltage decreases. And for some $\gamma_{vr}$, the SB voltage is determined by the optimal SB voltage, when the converter is operating in the MPPT mode and SB is fully used on power. BD inverter provides the voltage stabilization on the load [6].

## 2.3. Theoretical research and mathematical modeling of the SC PS with variable load curve

For theoretical research and mathematical modeling a load curve of SC is made with a calculation period equal to 96 minutes. A shadow site of an orbit is 36 minutes. The maximum power of load in the mode 2 is 21 kW. The minimum load power in this mode is 18.5 kW. In the mode 3 the maximum power of load equal to 20 kW and the minimum power of load is 5.5 kW. The space craft power system operates in a MPPT mode throughout the all calculated period of operation.

A calculation of the space craft PS (Figure 2) for an arbitrary made load curve was performed using the technique for SC PS calculating described in [7]. Using the SB mathematical model (equation (1) taking into account the increase in the reliability of the high-voltage (100 V) SC PS by limiting the maximum open circuit voltage of SB at 180 V, the parameters of the solar battery ensuring the recovery of AB capacity by the beginning of a new calculation cycle are received. At the nominal temperature $t_1$ = 25

$^0$C the SB parameters are equal: $U_{oc}$ = 132.93 V, $I_{sc}$ = 90.514 A, $I$ = 84.304 A, $U$ = 108.47 V.

The changes of SB parameters (currents and voltages) with changing environmental factors and load power are shown in table 1.

Table 1: Calculated values of SB and AB currents and voltages with varying load power and temperature.

| Mode | $T$, $^0$C | $P_{out}$, W | $P_{sb}$, W | $U_{AB}$, V | $I_{AB}$, A | $U_o$, V | $U_{oc}$, V | $I_o$, A | $I_{sc}$, A | $\gamma_{vr}$ | $\gamma_{bd}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | + 60 | 5500 | 18338.44 | 69.6 | 165.225 | 161.47 | 180 | 113.573 | 118.508 | 0.595 | - |
| 1 | + 60 | 4000 | 11050.25 | 69.6 | 90.199 | 96.042 | 124.834 | 115.057 | 124.834 | 1 | - |
| 1 | + 60 | 6500 | 11050.25 | 69.6 | 56.0751 | 96.042 | 124.834 | 115.057 | 124.834 | 1 | - |
| 2 | - 70 | 18500 | 11050.25 | 58.56 | 149.323 | 96.042 | 124.834 | 115.057 | 124.834 | 0.573 | 0.427 |

According to the table 1 the optimal value of $\gamma_{vr}$ensuring MPPT mode for energy load supply and battery charging equal to 0.595 when $U_{sb}$ = 161.47 V and $\gamma_{vr}$ is 1 when $U_{sb}$ decreasing to 96.042 V.

The SB operates in the voltage source mode and the optimum voltage of the SB current-voltage characteristics varies from 96.042 V, which is less than the output stabilized voltage value of the load power bus (100 V) to 161.47 V. The characteristics of the power, voltage and current distribution in SC PS at $P_{out}$ = 5500 W and $P_{sb}$ = 18338.44 W according to the table 1 are shown in Figure 3 and Figure 4.

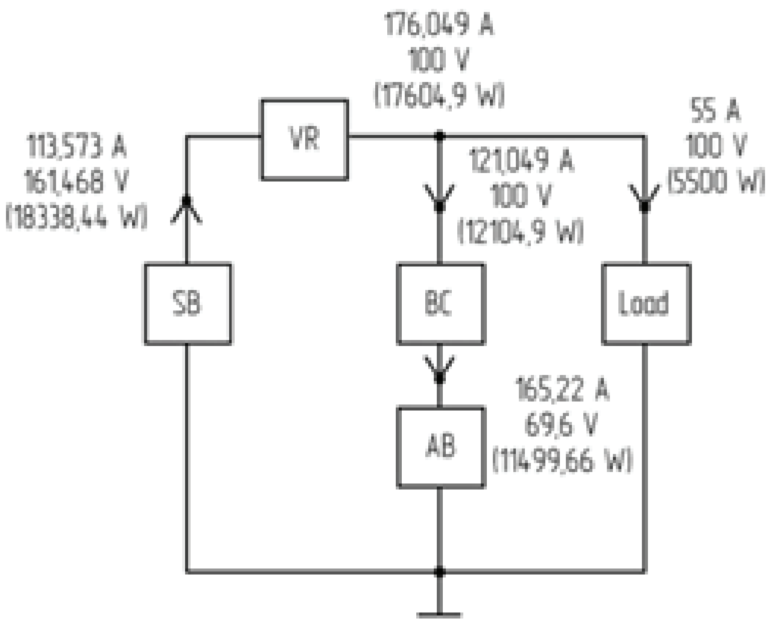


**Figure** 3: Powers, currents and voltages distribution in the SC PS.

In Figure 4 the following designations are accepted: $I_{vr\_out}$– VR output current, $I_{bc\_out}$– BD output current, $I_{sb}$ – SB current, $I_{bc\_in}$ – BD input current, $I_{out}$ – load current. The

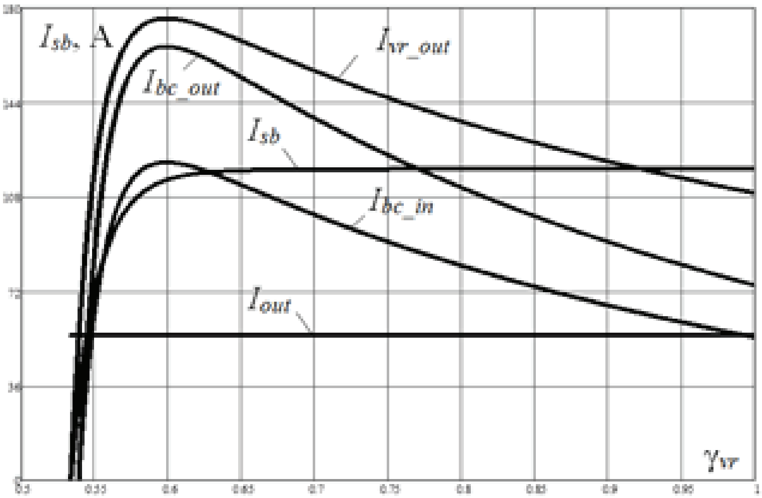


**Figure** 4: Mathematical simulation of current distribution in the SC PS.

construction of the powers, current and voltages of distribution characteristics in the SC PS for any mode of its operation can be carried out in a similar way.

## 3. Practical implementation results and experimental researches of the energy-converting device based on voltage inverter

The developed breadboard model of energy-converting device based on voltage inverter in the power supply channel of the load from AB is shown on Figure 5 and has technical characteristics: output voltage 100 V, AB discharge voltage varies from 96 V to 55 V. The maximum output power is 1400 W. The AB discharge current is 15 A. The operating frequency is 100 kHz.

Oscillograms of the breadboard model when the AB discharge voltage is changed are shown in Figure 6 and Figure 7. The stabilization of output voltage (100 V) is achieved by $\gamma_{bd}$regulation.

The power converter device efficiency is not less than 96 % if AB discharge voltage more than 70 V and $P_{out}$ is more than 450 W (Figure 8). The power efficiency decreases if AB discharges voltage less than 70 V especially with relatively small values of $P_{out}$ and AB discharge voltage.

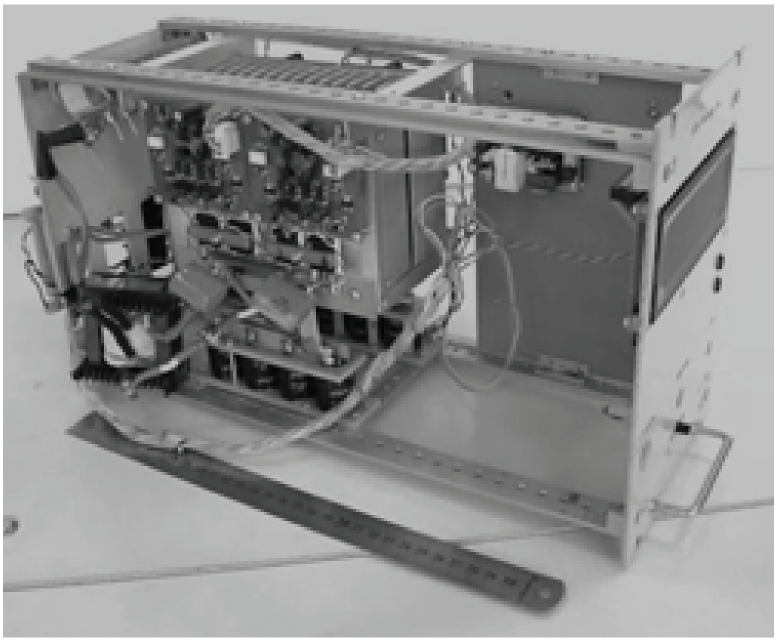

**Figure** 5: The breadboard model of energy-converting device.

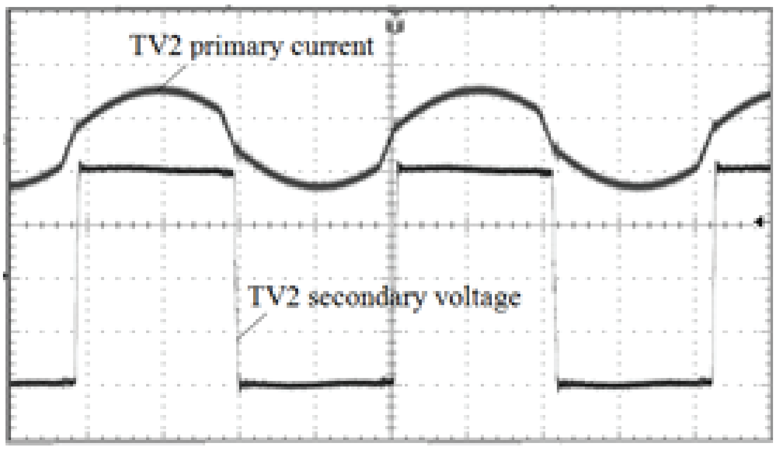


**Figure** 6: The primary current and secondary voltage of transformer TV2 ($U_{AB}$ = 55 V, $\gamma_{bd}$ = 1).

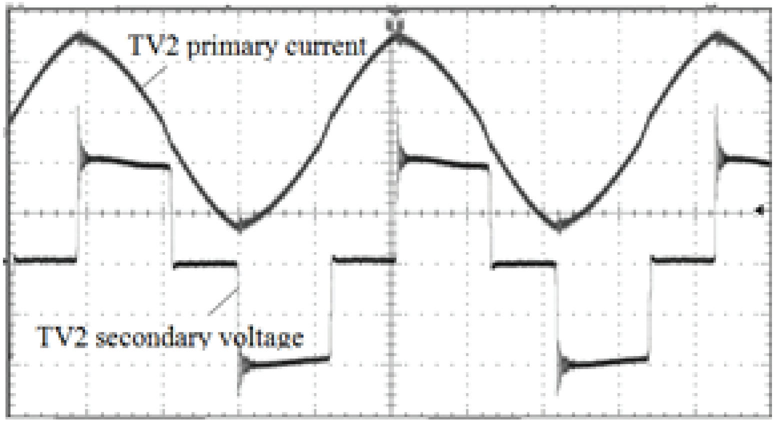


**Figure** 7: The primary current and secondary voltage of transformer TV2 ($U_{AB}$ = 96 V, $\gamma_{bd}$ = 0.573).

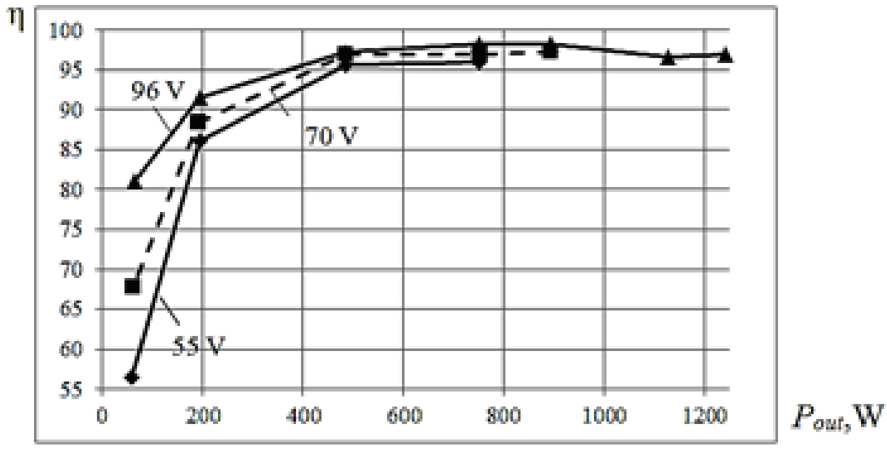


**Figure** 8: Dependence diagrams of the breadboard model of energy-converting device based on VI in the power supply channel of the load from AB with different AB discharge voltage and $P_{out}$.

## 4. Discussion of results and conclusion

The development and creation of high-voltage spacecrafts power supply systems with variable load curve based on voltage inverters allows to provide for simplification of voltage matching of SB, AB and load by the transformation coefficients and provide redistribution of the generated SB and AB power by changing of the energy-conversion device transistors pulse width, and allows to use any type of SB and AB. Thus, solar batteries voltage regulates in the wide range including a point with the maximum power on the SB current-voltage characteristic and can be below and above of the output stabilized power bus of load voltage value. The converters with high frequency link are capable to work in the output voltage stabilization mode and in the MPPT mode which in turn increases the energy efficiency of spacecrafts power systems.

The developed solar battery mathematical model is differs availability of data necessary for the calculation, allows drawing current-voltage and voltage-watt characteristics depending on its operation conditions and used to calculate the SB electrical characteristics, regardless of the technology of its production (manufacture) and the substrate material: silicon, gallium arsenide, etc. Thus, developed SB mathematical model is used to calculate the SB electrical characteristics for ground and space applications. The SB mathematical model allows to calculate the SB parameters for a high-voltage SC PS which provides recovery of the AB capacity by the beginning of a new calculation cycle, taking into account the possibility of limiting the SB maximum open circuit voltage at the required level, which provides an increase in SC PS of reliability. Experimental studies of the breadboard model of the energy-converting device in the power supply channel of the load from AB confirmed the possibility of stabilizing the required level of the output voltage of the load power bus and achieving efficiency in the AB discharge mode more than 96 %.

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