RESEARCH OF CONTROL SYSTEM STABILITY IN SOLAR ARRAY SIMULATOR WITH CONTINUOUS POWER AMPLIFIER OF PARALLEL TYPE

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Abstract. Solar array simulators are nonlinear control systems designed to reproduce static and dynamic characteristics of solar array. Solar array characteristics depend on illumination, temperature, space environment and other causes. During on-earth testing of spacecraft power systems there is a problem reaching stable work of simulator with different impedance loads in wide range load regulation. In the article authors propose a research method for absolute process stability in solar array simulators and present results of absolute stability research for solar array simulator with continuous parallel type power amplifier.

1. Introduction
Solar array simulators (SAS) [1-8] are widely used during on-earth testing of space power systems. Simulators should reproduce nonlinear current-voltage characteristics [9] (I-V curve) and impedance (admittance) of solar array [10] with given accuracy. During test simulator should reproduce I-V curve characteristics: short circuit current, open circuit voltage, I-V curve shape (figure 1) which can vary in wide range.

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To reproduce solar array admittance-frequency characteristic in range from 0 to 1000 kHz SAS should be implemented with continuous control. In this case SAS can be built using two methods:

- obtaining I-V curve in control circuit
- obtaining I-V curve in load circuit.

Advantages and disadvantages of each method of I-V curve obtaining method reviewed by authors in article [11]. Simulators with control circuit I-V curve obtaining method usually based on control system with nonlinear functional feedback and continuous power amplifier (CPA).

To conform given requirements on solar array static and dynamic characteristics reproduction accuracy, problem of SAS control system absolute stability in condition of wide range nonlinear I-V curve regulation should be solved. SAS with CPA connected in series to load [12] are widely used. SAS with CPA of parallel type are less studied [13].

The purpose of the article is to give survey on absolute stability of electrical process in SAS with parallel type CPA.

2. Preliminary

In accordance with structure (figure 2), SAS is a load current stabilizer with nonlinear I-V curve forming feedback based on functional transformer (FT). I-V curve regulation done by using current scale device (CSD) and voltage scale device (VSD). SAS open circuit voltage range is 20-160 V, short circuit current range is 1-5 A.

![Figure 2. Structure of solar array simulator with parallel CPA.](image)
On figure 2 shown next devices: PS – power source (current source), RPS – PS internal resistance, CPA – continuous power amplifier, CD- serial correction device, VA – error voltage amplifier, CVT – current to voltage transformer, CSD – current scale device, CR – current reference, FT – functional transformer, VSD – voltage scale device, VD – voltage divider, CC – correction circuit, L – load, CS – current sensor.

It is advisable to use absolute stability criteria by Naumov and Cypkin [14] to analyse absolute stability of processes in nonlinear control systems. Due to criteria, functional scheme of SAS should be represented (figure 3) to contain linear part with transfer function (TF) $W_{\text{lin}}(s)$ and nonlinear functional feedback $F_{\text{ft}}(U)$.

![Figure 3](image-url)  
**Figure 3.** Generalized functional scheme of SAS with CPA of parallel type.

According to figure 2 for each SAS device, we can obtain symbolic equation, describing processes in the device.

Let’s represent PS in form of current source $I_{PS}(s)$ with internal resistance $Y_{PS}(s)$:

$$Y_{PS}(s) = \frac{I_{RPS}(s)}{U_{PS}(s)} = \frac{1}{R_{PS}(s)}$$

Then we can write:

$$I_{PS}(s) = I_{RPS}(s) + I_{CPA}(s) + I_{OUT}(s)$$

$$I_{OUT}(s) = I_{CC}(s) + I_{L}(s)$$

According to equations, we can compose functional scheme of simulator (figure 4).

![Figure 4](image-url)  
**Figure 4.** Functional scheme of solar array simulator with parallel CPA.
3. Methodics
Methodic of correction device and correction circuit synthesis providing required admittance-frequency characteristic and stability of linearized SAS control system given in [15].

According to Naumov-Cypkin stability criteria the authors proposed next methodic of SAS stability research:

- Functional scheme should be represented in one loop form (figure 3) with separation of linear part $W_{lin}(s)$ and nonlinear unit $F_{ft}(U)$.
- Determine devices transfer functions using mathematical description, numeric experiments in circuit simulator (for example, Micro-CAP), or using empirical methods. Determine maximum values of scaling devices gain.
- Determine worst-case maximum gradient value $k_{FTmax}$ for nonlinear unit (functional converter). Due to functional scheme:

$$k_{FTmax} = \left( \frac{\partial I_{FT}}{\partial U} \right)_{max} = \frac{k_{IVCmax} W_{CS}(0)}{W_{VSDmin}(0) W_{CSVmin}(0) W_{CVT}(0) W_{VD}(0)}$$  \hspace{1cm} (1)

Where maximum slope of I-V curve defined by:

$$k_{IVCmax} = \left( \frac{\partial I}{\partial U} \right)_{max}$$

$W(0)$ is a transfer coefficient of the element at frequency $\omega=0$.
- Draw normalized Bode magnitude plot (BMP)

$$L_0(\omega) = 20 \log \left( k_{FTmax} \left| W_{lin}(j\omega) \right| \right)$$

and Bode phase plot (BPP) $\phi_{lin}(\omega)$ of linear part.
- Draw BMP of critical transfer coefficient

$$L_{CR}(\omega) = -20 \log \left( \left| \cos(\phi_{lin}(\omega)) \right| \right)$$

- Verify criteria of absolute stability:

$$L_{CR}(\omega) > L_0(\omega)$$  \hspace{1cm} (2)

in frequency range where next requirement is met:

$$-(4m+1) \frac{3\pi}{2} \geq \phi_{lin}(\omega) \geq -(4m+1) \frac{\pi}{2} \hspace{1cm} m = 0, 1, 2, ...$$  \hspace{1cm} (3)

If normalized BMP $L_0(\omega)$ will not cross BMP of critical coefficient $L_{CR}(\omega)$, processes in SAS will be asymptotically stable in case of I-V curve deformation within given current and voltage ranges.

To get transfer function of linear part Mason formula used [16]. Analyzing part of scheme (figure 4) which does not contain nonlinear unit $F_{ft}(U)$ with input signal $I_E(s)$ and output signal $U(s)$ on FC input, we can write:

$$W_{lin}(s) = \frac{I_E(s)}{U(s)} = \frac{H_1(s)}{\Delta(s)}$$  \hspace{1cm} (4)
Where

\[ H_1(s) = W_{CSD\text{max}}(s)W_{CVT}(s)W_{CP}(s)Z_L(s)W_{VD}(s)W_{VSD\text{max}}(s) \]

\[ W_{CP}(s) = W_{iA}(s)W_{CD}(s)W_{CPA}(s) \]

\[ \Delta(s) = 1 - (H_{11}(s) + H_{12}(s) + H_{13}(s) + H_{14}(s) + H_{15}(s) + H_{16}(s)) \]

\[ H_{11}(s) = -W_{\text{NL}}(s)W_{CS}(s) \]

\[ H_{12}(s) = -W_{CS}(s)Y_{CPA}(s) \]

\[ H_{13}(s) = -Z_L(s)Y_{CPA}(s) \]

\[ H_{14}(s) = -W_{CS}(s)Y_{PS}(s) \]

\[ H_{15}(s) = -Z_L(s)Y_{PS}(s) \]

\[ H_{16}(s) = -Z_L(s)Y_{CC}(s) \]

To determine transfer function for devices without analytical description authors created SAS circuit model in Micro-CAP circuit simulator (figure 5). The circuit model is equivalent to SAS structure shown on figure 2. In the circuit model next PSPICE models are used: AD8066 operational amplifier (X1-X3), complementary pair of IRF7309 FET (VT1-VT2), IRF740 (VT3), bipolar transistors BC107 (VT7-VT9), BC309 (VT4-VT6).

Using frequency analysis program (AC-Analysis) of Micro-CAP together with Invfreqs MATLAB function we can determine transfer functions:

\[ W_{CSD\text{max}}(s) = 1 \]

\[ W_{CVT}(s) = \frac{4000}{(9.6 \times 10^{-9} \cdot s + 1)} \]

\[ W_{CP}(s) = \frac{216}{(1.6 \cdot 10^{-3} \cdot s + 1)(1.6 \cdot 10^{-8} \cdot s + 1)(1.3 \cdot 10^{-8} \cdot s + 1)} \]

\[ W_{VD}(s) = 0.05 \]

\[ W_{VSD\text{max}}(s) = \frac{8}{(2.65 \cdot 10^{-8} \cdot s + 1)} \]

\[ W_{CS}(s) = 0.4 \]

\[ Y_{CPA}(s) = \frac{303 \cdot 10^{6} (2.87 \cdot 10^{-4} \cdot s + 1)}{(3.18 \cdot 10^{-8} \cdot s + 1)(3.18 \cdot 10^{-8} \cdot s + 1)} \]

\[ Y_{CC}(s) = \frac{C_{CC}s}{(C_{CC}R_{CC} \cdot s + 1)} = \frac{2 \cdot 10^{-6} s}{2 \cdot 10^{-6} \cdot 0.1s + 1} \]

\[ Y_{PS}(s) = \frac{(C_{PS}R_{PS} \cdot s + 1)}{R_{PS}} = \frac{5 \cdot 10^{-3} s + 1}{10 \cdot 10^{3}} \]
Current scale device has maximum transfer coefficient $k_{CSD_{\text{max}}}=1$ with maximal current $I_{sc}=5$ A. Voltage scale device has maximum transfer coefficient $k_{VSD_{\text{max}}}=8$ with minimal voltage $U_{dc}=20$ V.

Figure 5. Micro-CAP circuit model of SAS with parallel CPA.

Maximum I-V curve gradient is

$$k_{IVC_{\text{max}}}=0.35 \text{ A/V}$$

By substitute of static TF coefficient in equation (1) we can get maximum functional transformer gradient

$$k_{FT_{\text{max}}}=700 \cdot 10^{-6} \mu\text{A/V}$$

One of the main requirements to SAS is stable work with PWM based spacecraft electrical power system converters, namely with step-down or step-up converters. Due to step-down input capacitance filter, input impedance of converter has generally capacitive form. Input impedance of step-up converter has inductance form [17]. Also during SAS verification resistance load used to obtain I-V curve. So, to verify absolute stability criteria we should review three types of load:

- Resistant
  
  $$Z_R(s)=R_L$$

- Resistant-capacitive
  
  $$Z_C(s)=\frac{R_L}{R_L C_L \cdot s + 1}$$

- Resistant-inductive
  
  $$Z_L(s)=L_L \cdot s + R_L$$
4. Results
Now it is possible to do a verification of absolute stability criteria. In MathCAD we draw normalized BMP $L_0$ and BMP of critical coefficient $L_{cr}$, and BPP of linear part for each of three types of load.

Analysis of absolute stability criteria fulfillment in case of resistant load done with next assumptions. Maximal transfer coefficient of nonlinear functional converter unit reached in open circuit mode or maximal load resistance, which determined by feedback voltage divider resistance connected parallel to infinite load resistance. From that

$$R_L = R_{VD} = 4 \text{ kOhm}$$

To compare fulfillment of absolute stability criteria in case of different load types, we analyze SAS performance near I-V curve maximum power point, because voltage converters usually works in maximum power point (capacitive-resistant and inductive resistant loads). Maximum power point obtained with load resistance of $R_L = 28.5$ Ohm.

![Bode plot of SAS with parallel CPA for resistant load $R_L=28.5$ Ohm (a), $R_L=4$ kOhm (b).](image)

**Figure 6.** Bode plot of SAS with parallel CPA for resistant load $R_L=28.5$ Ohm (a), $R_L=4$ kOhm (b).
Figure 7. Bode plot of SAS with parallel CPA for capacitive load $C_L=5$ µF (a), $C_L=150$ µF (b).

Bode plot analysis (figure 6) shows that requirements of absolute stability criteria (2) and (3) fulfilled, meaning that processes in SAS in case of resistant load are asymptotically stable during I-V curve regulation within given ranges.

Verification of absolute stability criteria fulfillment in case of capacitive-resistant load (figure 7) done for two $C_L$ values. Load capacitance $C_L = 5$ µF, $C_L = 150$ µF and $R_L = 28.5$ Ohm.

Label with $\Delta L$ stability reserve:

$$\Delta L = (L_{CR}(\omega) - L_0(\omega))_{\text{min}}$$

From figure 7 we can see that in case of $C_L = 150$ µF, normalized BMP $L_0(\omega)$ passes much below BMP $L_{CR}(\omega)$ of critical coefficient, than in case of $C_L = 5$ µF, i.e. requirement $\Delta L_{5} < \Delta L_{150}$ fulfilled.

From above we can conclude that absolute stability criteria (2) and (3) fulfilled in case of capacitive-resistant load with different capacitance and increase of load capacitance comes to increase of stability reserve $\Delta L$.

We can verify absolute stability criteria in case of inductive-resistant load (figure 8) with inductance $L_L = 30$ µH, $L_L = 200$ µH and $R_L = 28.5$ Ohm. Value of inductive part is the same order with input choke of step-up stabilizer of converter.
Figure 8. Bode plot of parallel type CPA SAS for inductive load $L_d=30 \, \mu\text{H}$ (a), $L_d=200 \, \mu\text{H}$ (b).

From analysis of Bode plot (figure 8) we can conclude that with increase of inductance value processes in SAS became absolute stable furthermore, increase of load inductance comes to frequency range widening as of expression (3), i.e. it has effect on linear part BPP and critical coefficient $L_{CR}$, but stability reserve $\Delta L$ remains the same.

On figure 9 presented transient process of output current and voltage for one channel of solar array simulator in wide-range load switching mode on current segment of I-V curve from short circuit to maximum power point of I-V curve with $U_{OC}=160\text{V}$ and $I_{SC}=5\text{A}$. From figure 9 we can see that processes are stable. Time of transient process of 60 microseconds is equal to transient time of real solar array.

Figure 9. Transient process of SAS with parallel CPA in wide-range load switching mode on current segment of I-V curve from short circuit to maximum power point.
5. Conclusion
Summarizing above analysis we can obtain next conclusion about absolute stability of solar array simulator with parallel CPA: processes in solar array simulator can be considered stable in case of I-V curve given range regulation with three typical load types if simulator reproducing admittance-frequency characteristic of solar array with given accuracy.

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