The Design and Investigation of Space Photovoltaic Array Hardware-simulator

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Abstract. A hardware part of space photovoltaic array simulation system is designed in this paper, to realize the actual output characteristics of photovoltaic array. In this paper, the design of a PV array emulator (PVAE) is presented. By analyzing the V-I characteristic curve of solar cell given by the previous software, the simulation scheme is developed. Secondly, the control scheme of the proposed emulator based on DC-DC converter is discussed in detail, than the transfer function of the whole system is established, at last the digital controller based on DSP is designed. A prototype 200W PVAE based on full bridge DC-DC converter has been made, the experimental results show the validity of the controller design. The application of the PVAE can greatly shorten the research and design cycle of photovoltaic array power supply system of spacecraft, improve the research efficiency and credibility of research results.

1. Introduction
The space photovoltaic array provides the basic power source for the spacecraft in orbit. Photovoltaic array is the most effective way to convert solar energy into direct current energy by using photovoltaic effect. The photovoltaic array provides the power required by the load during the sunshine period, and charges the battery group to meet the power supply capacity of the battery group during the shadow period. During the flight of spacecraft in orbit, the working state of photovoltaic array is affected by such environmental conditions as illumination intensity, solar bias angle, environmental temperature, environmental irradiation, attenuation factor and shadow effect. Solar cell power generation system will inevitably have certain changes in its output voltage and power varies with these factors, which needs to be effectively controlled to prevent the impact of unstable system operation on the load equipment. At present, there are many control strategies for the stable, efficient and reliable operation of grid-connected photovoltaic power generation system. But considering the actual requirements of different spacecraft, which control strategy is the most reasonable and effective, requires a lot of research, verification and comparison. If a real photovoltaic array is used to test its performance in space environment, it will not only be expensive, but also increase the difficulty and prolong the research period due to the uncertainty of environmental conditions. At present, there have no real simulated test conditions in the ground test process.

The PV array emulator (PVAE), as a new type specific power supply, can emulate the V-I characteristic of real PV arrays under any working conditions, which makes the all-weather tests and developments of PV systems possible. The application of the PVAE can greatly shorten the research and design cycle of photovoltaic array power supply system of spacecraft, improve the research efficiency and credibility of research results.
Nowadays, there are two kinds of the principles of PVAE. One is that controllable incandescent lamps are used as light source, and the output voltage and current of a small piece of solar cell-chip is amplified to drive the IGBT or MOSFET. The problem is that the process can lost lots of electrical power and generate heat. And the spectrum of incandescent lamps does not match well to the sunlight. The other is digital PVAE that the output characteristic of power electronic equipment is controlled to correspond to the PV array based on the mathematic model of PV array. In most literatures DC-DC switching power supply is usually used, and a resistor is used as the load. Through changing the parameter of resistance, a series of data on work points of load can be acquired. But in real application situations, the PV panel is being connected with a DC-DC converter which is used to perform MPPT algorithm. In this paper, a digital PVAE is designed, and it has been tested in real solar power system[1].

2. V-I characteristic of solar battery
Photovoltaic array simulation system is divided into two parts the software module and the hardware simulator. The pre-stage software module gives the power curves of different states, according to the solar cell array power rating and set by the environmental conditions, through mathematical algorithm calculation. The hardware simulator simulates the solar array power output according to the power curve and load. According to the internal structure and the output V-I characteristic of the photovoltaic array, a mathematical model of solar battery is established, and the voltage-current characteristic curve is given in Figure 1. Isc represents short circuit current, Voc represents open circuit voltage, point M for corresponding solar power points is the best operating point. Im is the output current on maximum power point. Vm is the output voltage on maximum power point[2-3].

![Figure 1. The output volt-ampere characteristics of Photovoltaic Array](image)

3. Emulation scheme
3.1. The structure of the emulator
Then the structure of simulation is established based on the output voltage-current characteristic curve, which is shown in Figure 2. The system consists of a DSP based digital control design and implementation of a high frequency dc-dc full-bridge converter and a given set of performance specifications. The instantaneous output voltage and current are sensed and conditioned by the voltage and current sense circuit and then input to the DSP via the ADC channel. The digitized sensed output voltage Io is compared to the reference Iref, which is obtained by Vo from look-up table store in DSP. The current loop controller Gc is designed to make the output current Io track the reference Iref and at the same time achieve the desired dynamic performance. The digitized output U of this controller provides the duty ratio command for the full-bridge regulator switch. The PWM module uses this value to generate the PWM output, that finally drives the full-bridge converter switches.
3.2. Controller design
A detailed discussion of output current feedback control method is presented, which contains the analysis of the controller parameters tuning. A relationship formula can be derived through the analysis of electrical object:

\[ L \cdot \frac{di_L}{dt} = 2DnV_g - V_a \]  

(1)

The corresponding current controller diagram is given in Figure 3.

The open-loop transfer function of the control system is:

\[ \phi(s) = G_c(s) \cdot K_{pwm} \cdot nV_g \cdot \frac{1}{Ls} \]  

(2)

After repeated correction analysis of the bode graph for open-loop transfer function, finally a bandwidth gain limited one-pole compensation network is used in this system regulator:

\[ G_c(s) = \frac{1}{K \cdot rs + 1} \]  

(3)

Since there is an integral element included in transfer function of the open-loop transfer function, the requirement of static error of the system is met. The response speed of the system can be improved through moving the cross-over frequency by adjusting the value of ratio K. Pole \( s=1/\tau \) acts as the high frequency filter function. Since the parasitic resistor of capacitance is ignored, the pole should be set nearby the switching frequency to increase the rate of decay of high frequency components[4-5].

4. Simulation and experimental results
At last a simulation model under Matlab conducted by the simulation scheme is built. A 200W prototype is built and tested in the lab. The simulation model is shown in Figure 4. The simulation waveform of output voltage and current on maximum power point is given in Figure 5. The experiment waveform of output voltage and current while load changes is given in Figure 6. The V-I characteristic curve of photovoltaic array to be simulated as the input condition of hardware simulator has been given by the software module. Change the V-I characteristic curve needed to simulate, when the photovoltaic array output characteristic curve of spacecraft varies with the space environment. It can be seen that when load of the simulator changes, operating point of Vo and Io changes accordingly.
and the dynamic response time is less than 6ms. Several experiments have been done to investigate validity of the controller and tracking performance of the simulator.

![Simulation model](image)

**Figure 4.** Simulation model

![Simulation waveform of output voltage and current on maximum power point](image)

(a) (b)

**Figure 5.** Simulation waveform of output voltage and current on maximum power point

![Experiment waveform of output voltage and current while load changes](image)

(a) (b)

**Figure 6.** Experiment waveform of output voltage and current while load changes

5. **Conclusion**

A simulation model under Matlab is established, with the full-bridge converter for main circuit and the current feedback adjustment for controlling. A 200W prototype is built and tested in the lab.
Simulation results proved the feasibility of the system principle design. Experimental results proved the correctness of the system, and illustrated its good dynamic performance and accuracy. Good steady state and dynamic tracking performance can be achieved under the control of bandwidth gain limited one pole controller. According to the power requirements of different spacecraft power supply systems, the PVAE designed in this paper can obtain the required voltage of photovoltaic array through series and the required current through parallel connection. The PVAE is applied to realize back-end hardware simulation function in space photovoltaic array simulation system. This PVAE is used as the source of power subsystem or whole satellite hardware simulation, and finally it can realize the normal operation and fault simulation of satellite in orbit.

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