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Adjustment, error analysis and modular strategy for Space Solar Power Station

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ABSTRACT

Space Solar Power Station (SSPS) is a very potential candidate for supplying abundant electrical energy. Symmetrical two-stage flat reflected concentrator (STFC) has many advantages when used in SSPS. However the steady performance and control method on orbit has become a big problem which will be discussed in this paper. The actual posture of entire station is analyzed in detail due to the requirements of good flux uniformity, circular concentrated spot and controlled concentration ratio. Here two regulating directions are studied. And the most optimal method in multidimensional space of adjusting parameters is developed. In order to verify the correctness and reliability, the concentrating characteristics in different cases are simulated by Monte-Carlo ray tracing method (MCRTM). Based on the optimal adjusting parameters, solutions for the arrangement of transverse truss are proposed. After that the effect and regulating method for tracking error is investigated to improve the tolerance performance as highly as possible. Finally the construction of concentrators is much important to the realizability, cost and working performance. A flat hexagon module concept and the regular pattern are investigated to build the optical model. The flux distribution on solar panel based on different big number of modules is simulated, which provides certain reference for the build of SSPS.

1. Introduction

The prospect of delivering solar power to the earth from platforms in space has been paid attention in recent years [1], which is still facing many problems, such as steady performance and control method on orbit, the weight and cost. The tremendous concentrated solar energy can be used as generating electricity [2] or hydrogen production [3]. From the perspective of Concentrator photovoltaic (CPV), engineers try to explore a more effective, stable and realizable solution.

The incident solar rays and light path are dynamic, so the operation of SSPS on orbit becomes important but a difficult task. The 1.2-GW "Abacus Reflector" satellite configuration is a single sun-oriented array fixed to the transmitter by a slip ring, and a rotating RF reflector that tracks an antenna sites on Earth [4,5]. It can apparently reduce the cable lengths between the arrays and transmitter. Simultaneously, the rotating RF reflector could provide the smooth running on orbit. SolarDisc is a single and large-scale (1–10 GW) solar power system constructed by a sun-pointing PV disc [6]. The PV disc and RF generator are rotated to keep a constant generation on orbit. As a result multiple ground rectenna sites must be served for sharing a single SolarDisc SPS with time-phased power transmission [7].

Another concept is the Integrated Symmetrical Concentrator (ISC), composed of two symmetrical clamshells which rotate to collect and reflect the incident sunlight onto two centrally-located photovoltaic arrays [8,9]. The joint between the clamshells and the mast provides rotational capability for the once-a-day orbital tracking, and the seasonal beta tilt. The disadvantage of ISC lies in the thermal control problem for the centralized solar panel and transmitter. Rather, to reduce the geometric concentrating ratio, the mast becomes overlong which is up to 10 km [10]. The Sun Tower adopted a series of earth-pointing 'sunflower' and corresponding transmitter arrays. It would be an intermittent duty system, requiring a ground-based energy storage system, unless multiple satellites orbit to maintain constant power at that level [11].

To control the light path and obtain appropriate concentrated solar power on solar cells, engineers adopted the two-stage reflectors, called 'Cassegrain-type concentrators' [12,13]. The existence of secondary mirrors makes the regulating operation possible. In 2001, the NASDA (JAXA) SPS model was proposed as a two-stage reflected system [14]. In this concept, the conversion module is

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always pointed at the receiving site, and the mirrors must rotate and constantly receive solar radiation. Sandwich structure makes the power generator and antenna components together. After that it was utilized fully for the tethered-SPS [15,16], a simple and practical configuration constructed by an assembly of equivalent miniature elements. In 2003, the primary mirror was physically separated from the conversion module with the help of Formation Flying [14]. Cassegrain structure had also been improved by US in 2007, illustrated in the official website of NSS [8]. The latest Alpha SPS [17] is composed of numerous hexagonal reflectors that act as individually pointing heliostats. These mirror facets are connected by 'HexBus' and would be controlled flexibly on orbit. Table 1 briefly presents the concepts of typical SSPS, including their different configurations and tracking methods on orbit. However for all of the above, especially the Cassegrain-types, the details of the variable structure parameters and flux transmission for orbital tracking have not been studied or published.

A practicable Cassegrain-type concentrator, STFC had been designed to determine the optimal structure parameters for SSPS. It is composed of two symmetrical off-axis concentrators and inclined flat reflectors. Analysis in many respects revealed that STFC has several exclusive advantages [18]. The flux distribution uniformity gets highest and the energy concentration ratio (ECR) becomes modest when the parameters of STFC satisfy the range of formula (1).

$$\begin{cases} \varphi + \theta_s < \phi \leqslant \pi/2 + \varphi - \theta_c - \theta_s \\ \frac{2\phi+\theta_c}{4} < \varphi \leqslant \frac{\phi+\theta_s+\theta_c}{2} \end{cases} \quad (1)$$

In this range, the symmetrical structure makes the gradient distributions of focal spots from both sides overlap with each other, and the spot's nonuniformity could reach below 5%. However the situation in space operation is much more complicated. On geosynchronous orbit, the primary off-axis concentrators continually keep track of the solar, meanwhile the back of solar panel must keep its face to the earth's surface and transmit microwave energy.

On the other hand, the truss between two primary mirrors exceeds 8000 m. Under the adjustment of huge primary mirrors, the solar radiation pressure and centripetal force bend the truss seriously. This causes problems such as tracking error and reducing optical efficiency. In addition, the optical path for a two-stage concentrator is much longer than a single one, which badly enhance the influence of tracking error. The steady tolerance performance is of great necessity for SSPS on orbit. So the effect and regulating method is important and need to be studied.

Lastly, because the large area needed for the concentrators, the parabolic concentrator must be constructed as the joining of several facets. This is much important to the realizability, cost and working performance of SSPS at space.

This paper focuses on the adjustment, error analysis and modular strategy of SSPS which provides important reference for its building. The adjustment method for STFC when it travels on orbit will be discussed. The fundamental requirement for regulating is the axis of angular bisector must be perpendicular to the optical axis [18]. Based on this, the actual posture and adjustment of the entire station would be analysed detailedly due to the requirements of good flux distribution uniformity, circular concentrated spot and controlled concentration ratio. Thus the most optimal method in multidimensional space of adjusting parameters will be developed. After that, the effect and regulating method for tracking error would be investigated. And the mathematical partition model of a flat hexagon module concept is built carefully. The flux distribution on solar panel based on different number of modules will be simulated.

2. Adjusting method of STFC on orbit

SSPS is often given the geostationary orbits, like communications satellites. The transmitting antennas can be pointed permanently at the fixed receiving ground station. The directions of incident solar rays change at every moment. A principal advantage of SSPS is the flexible targets of transmission. Due to the vast territory and great differences between regions, people deeply feel the energy poverty. SSPS provide the solution to these problems:

(1) Through design, SSPS can easily provide the tracking of 23.5° seasonal motion. It is a good candidate for supplying abundant electrical energy in the whole year.
(2) Energy shortages are always caused by the overwhelming disaster. The earthquake and flowing mud in remote mountain area are quite likely to destroy transmission lines. The adjustable microwave transmission system in SSPS can provide timely energy supplies.
(3) In some remote regions, SSPS can also power large-scale equipments when necessary.

The efficiency of dc – microwave – dc (2.45-GHz unit) process is about 54% according to the NASA laboratory test [19]. Assuming that 20% solar power can be converted into electric current by a solar array of 500 m radius, the GCR of a 1 GW objective CPV system (when the actual power generation on the ground is 540 MW) should be designed as 5 times. Taking these data into account, the optimal length of the mast between primary dish concentrators is 8967 m for the STFC model. And the large area of single primary reflector reaches up to 2.8 km^2 – this is why the adjustment strategy of orbital tracking becomes significant. During the orbit operation, the solar panel will naturally point at the earth's surface, needing no adjustment because of the inertia force. Conversely the

Table 1
Typical SSPS concepts.

Model		Organization	Configuration	Output power	Tracking method
Non-concentrator	Tethered-SPS	USEF	Simple 'Sandwich' panel	1.2 GW	No track control
	Abacus Reflector	NASA	Solar panel with sun-oriented array transmitter	1.2 GW	Use rotatable RF reflector to track the earth
	SolarDisc	NASA	Rotated PV disc and RF generator	1–10 GW	Multiple ground sites to share time-phased power transmission
Concentrator	Sun Tower	NASA	Tree-like tower, highly modular structure, fresnel thin film concentrator	250 MW	Need multiple ground sites and storage system
	ISC	NASA	Two symmetrical off-axis dish concentrators	1.2 GW	Flexible joint and mast ensure the orbital tracking
	NASDA 2001	NASDA (JAXA)	Cassegrain-type concentrator, Sandwich panel	1 GW	Use rotatable two stage mirrors to track
	Alpha SPS	NASA	Bodymounted, axisymmetric structure, large number of heliostats	0.01–1 GW	Each heliostat smartly keeps tracking the sun