A NEW STRUCTRUE FOR SOLAR ENERGY COLLECTION IN SPACE

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Keywords: Space solar power; System configuration; Line focus; Collection stability.

Abstract

Compared to earth-based solar energy, space-based solar energy has the advantages of high efficiency and energy density, continuity and stability, which is promising to be one of the most important energy sources for sustainable development in the future. Several current design concepts for space solar energy collection have disadvantages of low collection efficiency, and/or large fluctuation in solar concentration, large mass, and complicated control system. Some typical solar energy collection systems (SECS) in space are introduced briefly and a new structure for space-based energy collection with line focus region is presented in detail, both the system configuration and operational principle are given. The energy distribution of the energy collection surface of the proposed concept is analyzed. Collection efficiency curve with the change of sun angle is also presented. Analysis shows the proposed concept has good performance in the stability of energy collection.

1 Introduction

For the contradiction between the energy supply and demand, the energy dilemma has great influences on the worldwide economic and social development[1]. Meanwhile, the environment pollution has become one of the world's most concerned problems. Thus, new forms of clean energy resource are urgently needed. Due to its low energy density, restriction by regions, incontinuous irradiation and instable collection efficiency, earth-based solar energy has not been widely used and may not be used as the form of the base energy supplying in the future. Compared to the earth-based solar energy, space-based form avoids all the disadvantages and it is a promising alternative to provide earth with primary power thus, how to make use of this form has been paid great attention to and scientists have implemented great many relative research works.

In 1968, Dr. Peter Glaser[2] put forward the idea of collecting solar energy in space and transmitting into earth, which is known as Space Solar Power Satellite (SPS). The concept is a collecting system gathering and converting space solar energy to electricity, and then transmitting into ground-receiving system with wireless power transmission (WPT) devices.

2 Summary of current concepts

Since the invention of the concept in 1968, dozens of concepts have been proposed, most of which have made innovations on solar energy collection system, for instance, NASA-DOE Reference Model, Integrated Symmetrical Concentrator (ISC), Sun Tower/Sail, Tethered Solar Power Satellite[3], ALPHA[4], etc.

Peter Glaser put forward an original sketch in 1968, which is the earliest version of the concept. The SECS of the original concept is a spherical PV solar array several thousands of meters in diameter, as is shown in Fig.1.

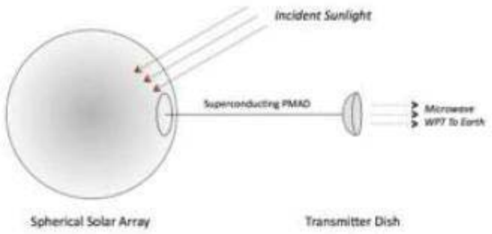

Figure 1. Peter Glaser's original concept[4].

NASA and the Department of Energy (DOE) proposed an model known as the NASA-DOE reference model in 1979, the SECS of which is a huge PV cell plate by 25,000 meters in area and points to the sun via attitude control system, as is presented in Fig.2.

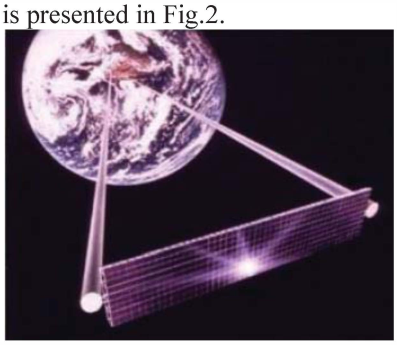

Figure 2. 1979 reference model.

The Sun Tower concept[5] has exploited several innovative approaches to reduce the SPS development and life-cycle cost, which made use of hundreds of small condensation modules for gathering sunlight, as is given in Fig.3. Similar to NASA's Sun Tower SSPS, The Sail Tower, proposed by ESA, used thin-film technology and innovative deployment mechanisms developed for solar sails.

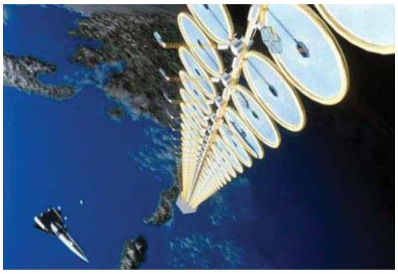

Figure 3. Illustration of Sun Tower.

Shown in Fig.4, Integrated Symmetrical Concentrator (ISC) uses 24 or 36 plane mirrors of 500 m diameter for a concentration factor of two or four. Importing the secondary reflectors and integrating the PV Cell array and transmitting antenna into "Sandwich" structure, symmetrical two-stage flat reflected concentrator (STFC) is good for receiving a high degree of distribution uniformity [6] and a suitable condensation ratio via adjusting the tilt angles of primary off-axis concentrator and secondary flat mirror and the height of receiving region.

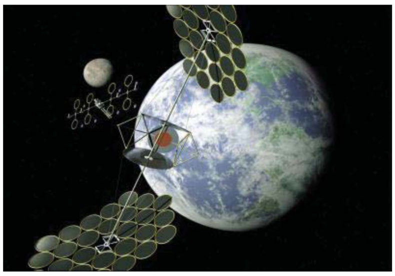

Figure 4. Illustration of ISC concept.

JAXA proposed the Tethered Solar Power Satellite concept to reduce the system complexity and its mass. As is shown in Fig.5, the system consists of a large power generation/transmission panel suspended by multi-tether wires from a bus system above the panel [7]. The attitude is automatically stabilized by the gravity gradient force in the tether configuration without any active attitude control. However, large fluctuation of energy collection is the biggest drawback.

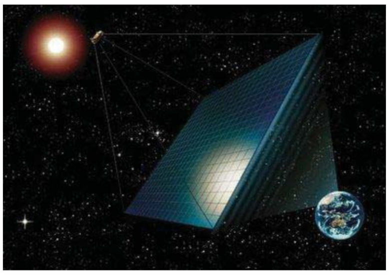

Figure 5. Illustration of tethered solar power satellite.

The Solar Power Satellite via Arbitrarily Large Phased Array [8], abbreviated ALPHA, was proposed by John C. Mankins in 2012. The concept is a high modular design scheme, with thousands of individually pointed light weight thin-film mirrors redirecting sunlight to a high-efficiency photovoltaic array. Both the PV cell, energy conversion devices and transmitting arrays are integrated with sandwich structure, as is presented in Fig.6.

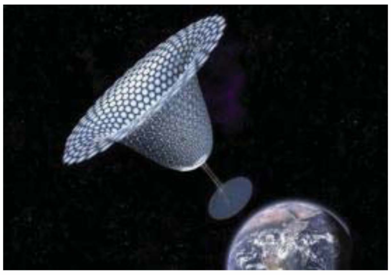

Figure 6. ALPHA concept.

3 Design of New Collection Structure

The system of space solar energy collection has a dimension of km scale, which requires the knowledge of optics, mechanics, thermology, control, and other disciplines. The existing schemes have disadvantages of low efficiency and/or large fluctuation in solar concentration, large mass, and complicated control system. Thus, new scheme with high efficiency, light weight and simple control strategy needs to be proposed.

3.1 Principles of optics

The focus mode of spherical reflector is line focusing. For example, sampling in a two-dimensional plane, according to the law of geometrical optics, the incident light (Parallel light) paralleling to the z-axis is reflected by the reflecting surface and converges to the region from R/2 to R, where R is the spherical radius, as is described in Fig.7. M is the boundary point, the incident sunlight will reach the focal region with reflecting only once if the x-coordinate of the intersection of the x-axis and the direction vector of sunlight $x_{in} \in (0, R\cos 30°)$, while $x_{in} \in (R\cos 30°, R)$, two or more times of reflecting is needed.

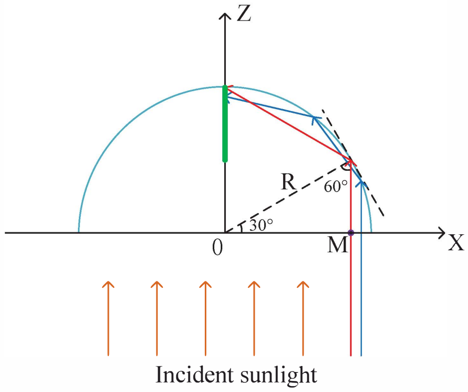

Figure 7. Reflector light path in 2D.

For multiple reflection regions, on the one hand, the reflectivity of a thin-film is impossible to achieve 100% for its physical properties. On the other hand, surface precision of multiple reflection area is of high requirement, which certainly would increases the manufacturing difficulty. Therefore, removing the multiple reflection area to ensure the efficient utilization of the reflector is available, which certainly would reduce the area and quality of spherical reflector to some extent, as is shown in Fig. 8. It must be pointed out that if the surface accuracy, reflectivity and the production cost meet the requirements, can the areas of two or more times reflecting be persisted.

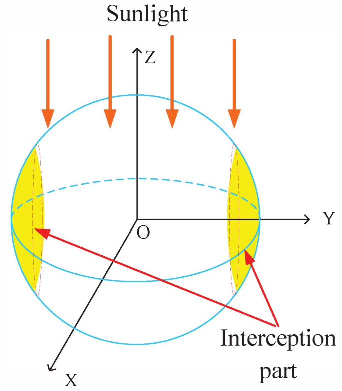

Figure 8. Illustration of multiple reflection area.

3.2 Design of the structures

Due to its large size in km scale, the main reflector must be constructed via assembly. The original spherical reflector is promising to be assembled from different kinds of large thin-film hexagonal reflectors (the specific number and form of the reflectors are all variables to be analyzed in greater detail for efficient light propagation), as is shown in Fig.9.

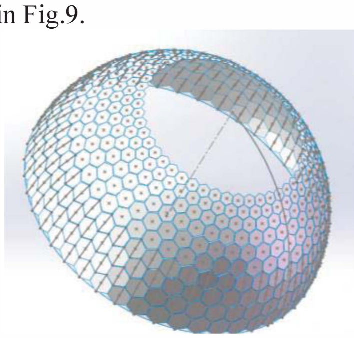

Figure 9. Construction of spherical reflector.

Each hexagonal reflector is controlled independently by Attitude Control System (ACS). Reflectors belonging to the hemisphere facing to the sunlight are rotated to the attitude which the normal vector of the reflector plane is perpendicular to the direction vector of the sunlight, as is presented in Fig.10, so that the sunlight could enter into the spherical system. The sunlight could be reflected by the inner face and converged into the focus region, both for heat-to-dc or light-to-dc conversion.

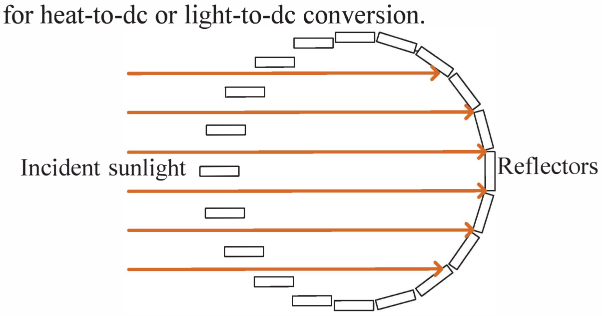

Figure 10. Attitude control of the reflectors.

4 System Analysis

To fully understand the system configuration and system performance of the new concept, detailed analysis is described, with structure geometrical parameters, energy distribution on receiving region (PV cell array) and collection stability.

4.1 System parameters

All the energy losses caused by the processes of energy transmission and conversion should be taken into consideration. According to these, the total energy gathered by the spherical system should be calculated to determine the size of the main reflector and other parameters. The radius of the system is given in (1) if the overall region is made use of.

$$R = \sqrt{W / C\eta\pi} \tag{1}$$

where η is the reflectivity of the thin-film reflecting material. The space solar light power density C=1368W/m^2, W is the receiving power needed, determined by the design requirement. According to the efficiencies of each section of power transmission and conversion, and the ground-receiving power needed, W is theoretically determined.

Also, while only the region of one-time reflecting is used, the radius will be given in (2)

$$R = \sqrt{W / (C\eta(\pi + 4\int_{\pi/6}^{0} \sin^2 \varphi d\varphi))} \tag{2}$$

Based on the SPS power transmission hypothesis [9], if one-time reflecting and photoelectric conversion are used, the radius of the main reflector is about 1540 m.

4.2 Energy distribution

The receiving surface is a cylinder, as is shown in Fig.11.

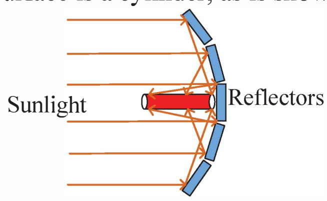

Figure 11. Illustration of receiving surface.

The energy distribution of the energy receiving surface was calculated, as is presented in Fig.12.

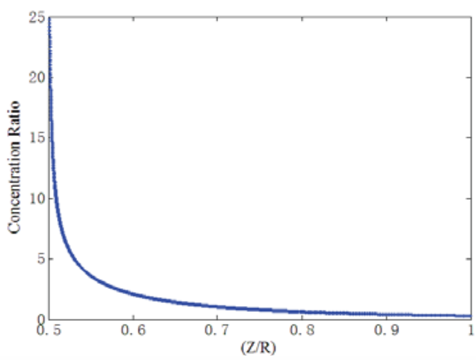

Figure 12. Energy distribution on receiving surface.

If solar thermal power generation is chosen, the result is satisfied with the demand, but such problems as precise sun pointing control, light concentration, heat rejection, and life extension should be solved, which are not feasible in the near future. If photovoltaic generation method is used for dc generation, the energy distribution should be designed in great detail for better irradiance uniformity via structure design.

4.3 Collection stability

Collection stability is another sign of high performance energy collection system. The stability has serious influence on the overall system, on the one hand, system restart is a technical changeling while system shutdown due to the very low energy, on the other hand, large numbers of storage batteries are need to keep the continuous power supply, which will greatly increase the total mass. For instance, the Tethered Solar Power Satellite concept is unable to collect solar energy at 6 a.m. and 6 p.m. every day. Thus, stability is one significant factory in design stage. The collection surface of the proposed system is assumed to rotate in one dimension. The power generation varies with the sun angle change is shown in Fig.13.

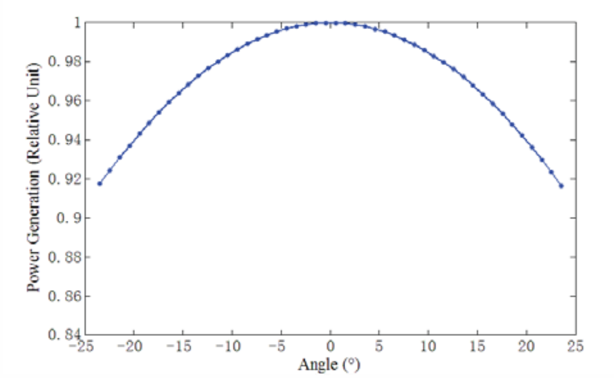

Figure 13. Collection efficiency via sun angle change.

5 Conclusion

A new concept for solar energy collection in space is put forward, with system configuration and operational principle presented. The analysis shows good performance on the stability of collection efficiency, while structure design will be needed to keep good flux uniformity if photoelectric conversion is chosen. Both the assembly of main reflector, attitude control of main reflector and PV cell array, and influence of space environment on system properties are under to be further studied.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of Chinaunder Grants 51490660 and 51405361 and in part by the Fundamental Research Funds for Central Universitiesunder Grant SPSZ011401. The authors would also like to express their gratitude to the staff of Key Laboratory of Electronic Equipment Structure Design of Ministry of Education, Xidian University, China for their help in completing this paper.

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