Advances in Astronautics Science and Technology (2022) 5:31–37
https://doi.org/10.1007/s42423-022-00099-4

ORIGINAL PAPER

High-Voltage and High-Power Electricity Generation, Transmission and Management of MR-SPS

Xinbin Hou[1] · Li Wang[1] · Zili Liu[1]

Received: 16 September 2021 / Revised: 28 January 2022 / Accepted: 9 February 2022 / Published online: 23 March 2022

Abstract
Space Power Satellite (SPS) is a huge spacecraft to utilize solar energy in space. Because of the huge size, immense mass and high power, there exist many technical difficulties. For a GW SPS system, the generated electric power in space will be over 2 GW, and the whole area of the solar array will be several square kilometers. The high-power electricity generation, transmission and management in space becomes a huge challenge. In the paper, the primary scheme of MR-SPS concept is presented and two important sub-systems, Solar Energy Collection and Conversion (SECC), Power Transmission and Management (PTM) are introduced. The SECC sub-system includes fifty solar sub-arrays. Each solar sub-array is composed of twelve solar array modules. The area of each solar sub-array is about 0.12 km^2. The solar sub-arrays transmit electric power to the cables installed on the main structure of MR-SPS by 100 middle power rotary joints. PTM sub-system converts, transmits and distributes the output electric power of SECC sub-system. Most of electric power is transmitted to the antenna and is distributed in the antenna. The remaining electric power is transmitted and distributed to the service equipments for the operation of SPS. The mix of distributed and centralized high-voltage PTM is adopted to meet the requirement of electric power supply of the electric equipments on SPS. Typical space environment influencing high-power electric system is analyzed. The key technologies need to be researched and solved including high-efficient, long-life thin-film GaAs PV cell, ultra-large–high-voltage (500 V) solar array module, high-power conductive rotary joint, ultra-high-voltage (20 kV) cables, high-power converter, high-power switch, etc., and assembly and maintenance of the sub-systems.

Keywords Space Power · Transmission and Management · Space Environment

1 Introduction

Solar Power Satellite (SPS), proposed first by Dr. Peter Glaser [1], has been regarded as one of the most promising renewable energy projects in the future. It is attracting more attention in recent years. There are lots of related development plans and research activities in the world [2].

In 2016, CalTech proposed the new SPS concept with the support of Northrop Grumman [3]. In 2017, Ian Cash proposed CASSIOPeiASPS concept [4, 5].

In 2017 and 2019, Korea Aerospace Research Institute (KARI) held the International Workshop for Space Based Solar Power (SSPS) in Seoul. Experts from Korea, China, USA, Japan and UK discussed the opportunity of SPS development. In 2018, Korea started the SPS research project and proposed the Korean SPS concept [6].

In 2018, Japan presented the updated roadmap of SPS. In 2019, Japan Space Systems conducted the drone WPT experiments project which transmitted power to the drone flying at altitude of tens of meters under the contract of Ministry of Economy, Trade and Industry (METI) [7].

China started the study in SPS field in 2006 and more and more Chinese scholars and experts began to pay attention to the development of the space solar power. In 2014, two new concepts are proposed in China. One is an innovative non-concentration SPS concept proposed by China Academy of Space Technology (CAST), named the Multi-Rotary joints SPS (MR-SPS) [8, 9]. Another one is an innovative concentration SPS proposed by Xidian University, named SSPS-OMEGA [10].

Lots of SPS concepts have been proposed since 1968 [11–17]. These SPS concepts fall into three categories: Type I, Non-concentration continuous WPT SPS; Type II, Non-

✉ Zili Liu
ronger2007@126.com

1 QianXuesen Laboratory of Space Technology, CAST, Beijing 100094, China

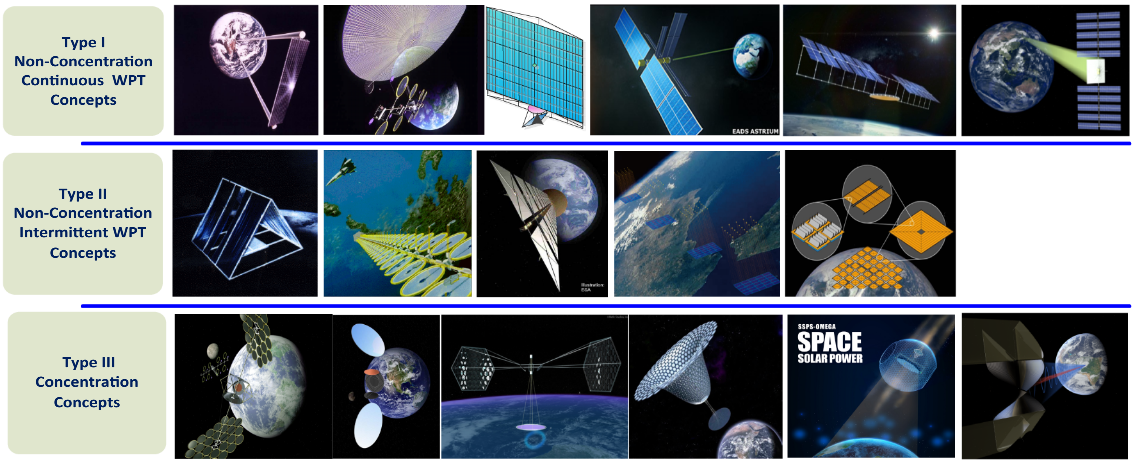

Fig. 1 SPS concept categories

concentration intermittent WPT SPS; Type III, Concentration SPS (Fig. 1).

The type I SPS relies on the conductive rotary joint to keep the solar array Sun-pointing and the antenna Earth-pointing to generate power continuously and steadily. The extremely high-power conductive rotary joint is the biggest technical challenge.

For type II SPS, the position of the solar array is fixed relative to the antenna. The angle between the solar array and the Sun changes from zero degree to 360 degree. Therefore, energy will fluctuate between zero and maximum during the orbit period.

The type III SPS uses special reflectors to change the direction of sunlight. The design avoids the high-power conductive rotary joints and shortens the transmission electric cables largely to simplify power management and distribution. But the high precise concentration system and the cooling of solar array become two intractable technical challenges.

2 MR-SPS concept

2.1 Introduction

MR-SPS is a type I SPS and is mainly designed to solve the extremely high-power conductive rotary joint problem. Multiple independent solar sub-arrays point to the Sun and convert solar energy to electric power continuously and steadily (Fig. 2). Each solar sub-array transmits electric power to the main structure by its two independent conductive rotary joints. The main structure and the transmission antenna are connected and without relative motion between them.

The electric power generated by the solar sub-arrays is transmitted to the antenna by the cables along the structure

Fig. 2 MR-SPS concept

trusses. Then the electric power is converted to microwave energy and transmitted to the rectenna on ground. The rectenna receives the microwave energy and converts it to electric power conversely. Then, the electric power is connected to the grid. The typical power of a SPS is 1GW. The total energy efficiency of the SPS is about 13.8%.

2.2 Configuration of MR-SPS

The MR-SPS functionally consists of Solar Energy Collection and Conversion (SECC) sub-system, Power Transmission and Management (PTM) sub-system, Microwave Power Transmission (MPT) sub-system, Structure sub-system, Attitude and Orbit Control (AOC) sub-system, Thermal Management (TM) sub-system, and Information and System Operation Management (ISRM) sub-system. The MR-SPS configurationally includes three key parts: solar array, microwave transmission antenna and main structure. The SPS platform service equipments, including AOC, TM and ISRM equipments, are installed on the solar array, microwave transmission antenna and main structure. Figure 3 shows the configuration and size of a typical 1GW MR-SPS.

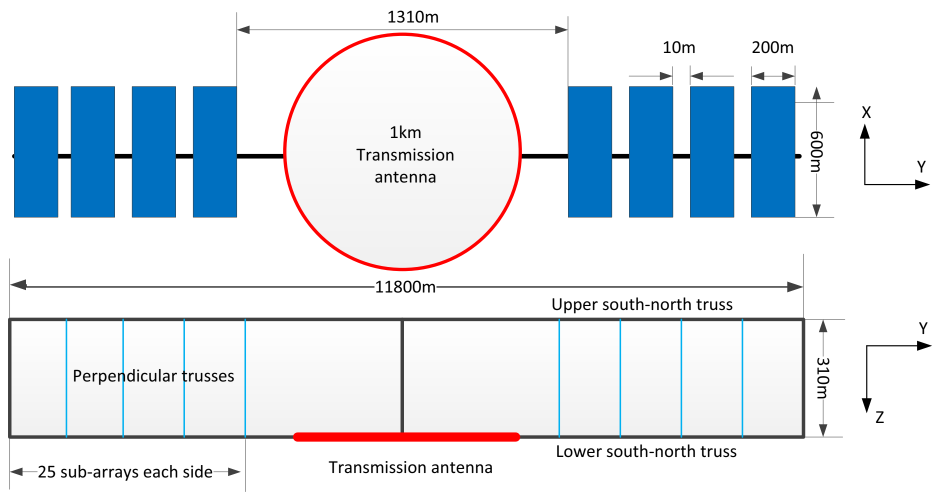

Fig. 3 Configuration of MR-SPS

The solar array consists of 50 solar sub-arrays. The solar sub-arrays are 10 m apart. The distance between the two solar sub-arrays close to the antenna is 1310 m to avoid the effect of eclipse of the antenna. So, the total length of a SPS is about 11,800 m.

To reduce the impact of the atmospheric transparency and the size of antenna, 5.8 GHz is chosen as the frequency of transmission microwave. An antenna with 1000 m diameter is selected based on the factors of energy density and transmission distance.

The main structure connects the solar array and the microwave transmission antenna. The upper south–north truss supports the solar sub-arrays, while the solar sub-arrays rotate around the truss in the orbit to point to the Sun. The lower south–north truss supports the microwave transmission antenna. The upper south–north truss and the lower south–north truss are connected by the perpendicular trusses.

The specifications of a typical 1GW MR-SPS are summarized in Table 1.

3 High-Power Electricity Generation, Transmission and Management of MR-SPS

3.1 Solar Energy Collection and Conversion (SECC) Sub-system

The SECC sub-system collects and converts solar energy to electricity in space. According to the MR-SPS configuration and efficiency chain analysis, SECC sub-system needs to supply 2 GW electric power for the MPT sub-system. The SECC sub-system includes fifty solar sub-arrays and each solar sub-array is composed of twelve solar array modules that are divided into two groups. All modules will be assembled in space. The area of each solar sub-array is about 0.12 km^2 and the output power is about 48 MW. The structure of the solar sub-array is a 200 m × 600 m crisscross truss (Fig. 4). The 200 m truss connects the conductive rotary joints at two ends and the 600 m truss connects twelve solar array modules symmetrically. First, the electricity generated by each module is transmitted to the conductive rotary joints. Then, the electricity is transmitted to the microwave transmission antenna by the cables installed on the main structure of SPS.

The thin-film structure is important to decrease the weight of the solar array [17]. Each solar array module is a 100 m × 100 m thin-film PV array that is composed of thin-film PV cells, trusses and deployment mechanism (Fig. 5). It is folded before launch and is deployed automatically in orbit. It weighs about three tons. The high-efficiency thin-film GaAs cell is chosen and the prospective efficiency is over 40% [18]. Considering the gaps between cells, the output power of each solar array module is about 4 MW. The total output power of all 600 solar array modules of the SECC sub-system is about 2.4 GW, while the total weight is about 1800 tons.

Because of the interaction of special space environment and solar array, high voltage is a huge technical challenge for the high-power solar array. Lots of studies have focused on the high-voltage solar array [19–23]. HORYU-II mission demonstrated the solar array over 350 V in space in 2013. Based on these studies, it is believed feasible to develop 500 V high-voltage solar array module.

3.2 Power Transmission and Management (PTM) Sub-system

PTM sub-system converts, transmits and distributes the output electricity of SECC sub-systems. Most of the electricity is transmitted to the antenna. The remaining electricity is transmitted and distributed to the platform equipments of SPS for normal operation of SPS. The particular mix configuration of distributed and centralized PTM is adopted for MR-SPS to meet the requirement of power supply of the elec-

Table 1 Specifications of a 1GW MR-SPS

SPS system	Operating orbit	GEO
	Supply power	~ 1 GW
	Total efficiency	~ 13%
	Total mass	~ 10,000 t
Solar Energy Collection and Conversion sub-system	PV cell	Thin-film GaAs
	Efficiency	~ 40%
	Total area of solar array	~ 6 km^2
	Output power	~ 2.4 GW
	Voltage of solar array module	~ 500 V
	Total mass	~ 2000 t
Microwave Power Transmission sub-system	Frequency of microwave	5.8 GHz
	Efficiency of WPT	~ 54%
	Diameter of transmission antenna	1000 m
	Number of antenna modules	128,000
	Power of an antenna module	12.5 kW
	Total mass	4000 t
	Diameter of receiving antenna	5 km
Power Transmission and Management sub-system	Style	Mix of distributed and centralized
	Voltage of solar sub-array	5 kV
	Voltage of main bus	20 kV
	Number of conductive rotary joints	100
	Total mass	2500 t
Structure sub-system	Module	Deployed truss
	Total mass	1200 t
Attitude and Orbit Control sub-system	Thruster	1 N electric thruster
	Total mass	100 t
Other sub-systems	Mass of Thermal Management	150 t
	Mass of ISRM	50 t
Operation mode		Continuous transmission

tric equipments. The solar sub-arrays transmit the electricity to the cables by 100 middle power conductive rotary joints. The cables are connected to two interfaces of the antenna and then, the electricity is distributed in the antenna (Fig. 6). The power transmission and management includes three segments as follows.

The first segment is power transmission and management on the solar array. Its function includes converting, regulating and transmitting the electric power generated by the solar array modules. The output voltage of the solar array modules is 500 V. To decrease electric current, the electric power is converted to 5 kV and transmitted to the conductive rotary joints. Each solar sub-array has two output power buses of 5 kV and 4800 A.

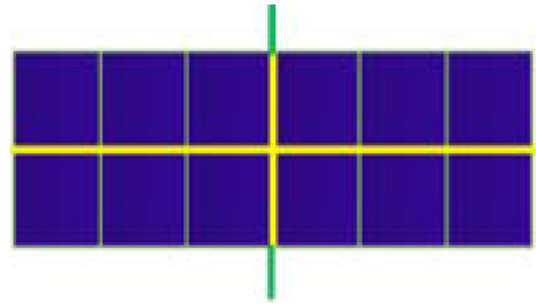

Fig. 4 Configuration of a solar sub-array

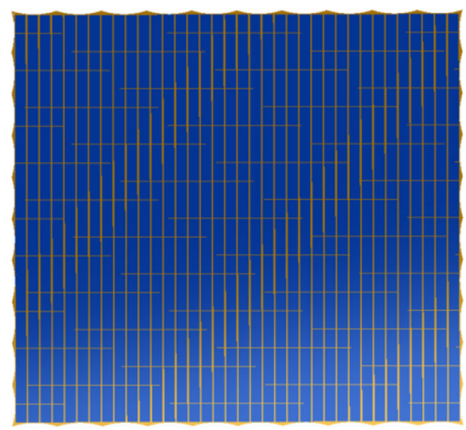

Fig. 5 Configuration of a solar array module

The second segment is power transmission and management on the main structure. Its function includes converting, regulating and transmitting the electricity of the solar sub-arrays. The output voltage of the solar sub-arrays is 5 kV. The voltage is boosted to 20 kV to reduce transmission loss before being transmitted to the antenna. The antenna has two main buses (multiple cables) of 20 kV and 50 kA.

The third segment is the power transmission and management on the antenna. Its function includes converting, regulating and transmitting the electricity of the antenna modules. The input voltage is 20 kV. The majority of the electricity is converted to about 5 kV before being transmitted to the antenna modules for microwave generation.

For each segment, parts of electricity are distributed to the service equipments (including electric thrusters) and parts of electricity are stored to supply power for service equipments during eclipse. The power needs to be converted to adaptive voltage according to different requirement.

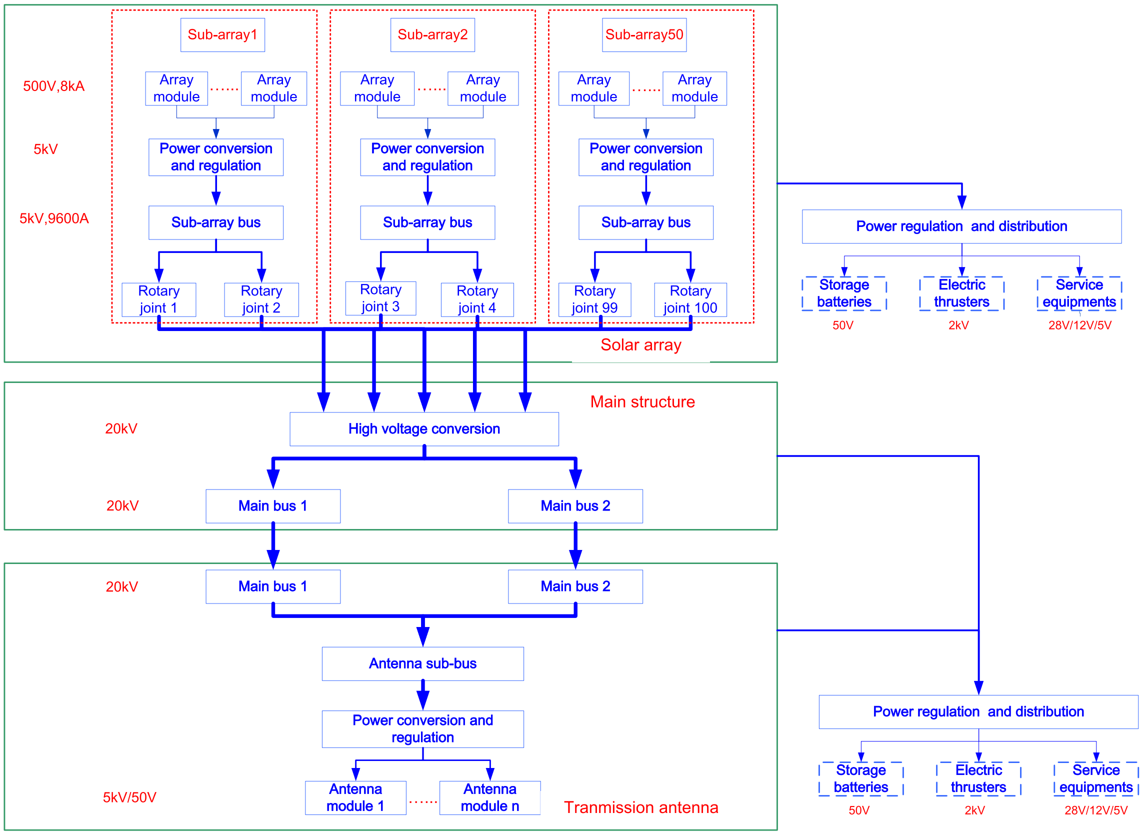

Fig. 6 Mix configuration of distributed and centralized PTM

4 The Space Environment Influence

4.1 Typical Space Environments Influencing High-Power Electric System

Tens of thousands volts is used wildly in electric grid on ground. But it is inconceivable in space because of the special space environment.

The space environment is different in diverse orbit. Typical space environment factors influencing electric system include ultraviolet, plasma, high-energy electron, high-energy proton and heavy ion. These environment factors come from Van Allen radiation belt, sun radiation and galactic cosmic ray [24, 25]. Different space environment factors will influence different electric power units. The typical relation between space environment factors and electric power units are summarized in Table 2.

First, space radiation environment will affect insulation materials and power equipments and will decrease their performance seriously, even conduce to failure. Another important problem is the electrons accumulation and electrostatic discharge. Especially, integration effect of high-voltage and space radiation will make it very difficult to develop high-voltage solar array, cable and conductive rotary joint.

4.2 Radiation Protection Requirement of Electric Power Units

1. High-Voltage Solar Array.

The potential high-voltage solar array is the thin-film GaAs array. The protection requirement includes two aspects, PV cell and solar array. First, innovation lightweight radiation protection layer of PV cell needs to be studied to replace traditional cover glass to avoid the serious efficiency decrease of PV cell. Second, for large area thin-film solar array, the electrons accumulation will be more serious. Traditional RTV adhesive is not feasible for thin-film solar array, new cover film needs to be developed to prevent arcing, for example, the special Ethylene-Tetra Fluoro Ethylene (ETFE) film used in HORYU-II mission.

2. High-Power Electric Cable.

The voltage requirement of high-power electric cable in space should be over 1–10 kV. The key technology is to decrease the accumulation of electric charge and to increase the performance of radiation protection of insulation material. An possible method is to change the performance of

Table2 The main space environment factors influencing high-power electric system

Space environment factors	PV cell	High-voltage array	Rotary joint	Cable	Power equipments
Ultraviolet		★		★	
Plasma		★		★	
High-energy electron	★	★	★	★	★
High-energy proton	★				★
Heavy ion	★				★

the insulation material by adding nanometer materials, for example, the special non-linear conductivity polymer dielectric materials [26, 27]. But more researches need to be done to understand whether it is suitable for high-voltage system.

3. Conductive Rotary Joint.

The conductive rotary joint is the key part to transmit electric power from solar array to the cable. Because the transmission power will be over tens of MWs and the voltage will be over thousands of volts, the possibility of fatal short circuit breakdown arisen by deep dielectric charging needs be researched specially [28, 29].

4. High-Power Equipments.

High-power equipments include high-voltage power converter, high-voltage switch, high-voltage circuit breaker, high-power conditioner, high-power control unit and so on. The protection requirement includes two aspects, radiation hardening component and insulating protection. New generation SiC and GaN components should be adapted. New electric package materials should be researched to avoid various single event effects. New circuit design and software design should be adapted to detect and correct errors arisen by single event events. The tradeoff of the shell and new insulation materials will decrease the possibility of electrostatic discharge.

5 The Key Technologies

As discussed in the paper, SPS is an extreme high-power spacecraft. High-power electric power generation, transmission and management is an important technical challenge. Many key technologies need to be solved.

1. High-power solar power generation
   SPS needs ultra-large solar arrays to generate several GWs electricity. Therefore, PV cells need to be high-efficient, ultra-light and long life. Thin-film GaAs PV cell might be potential candidate with the expected efficiency over 40%. Ultra-large and high-voltage solar array module is another key requirement. The total area might be as large as 10,000 m^2 with about 500 V voltage, new cover film needs to be developed to avoid electrons accumulation and serious arcing.
2. High-voltage electric power transmission
   SPS needs long-distance electricity transmission in space. To minimize the power dissipation, electricity transmission voltage needs over 20 kV, which is a big challenge in space although trivial on ground. The high-efficiency converters, switch and ultra-light cables are needed. MR-SPS concept reduces the power of the conductive rotary joint from 1.2 GW to 24 MW, but the high-power rotary joint is still a big problem compared with the existing 100 kW rotary joint.
3. Special material and component
   New material and component are important for the high-power electric system in space. New high-conductive conductor materials, for example, graphene, are needed to decrease the weight of cables. High-temperature superconductive material over 200 K may be the best way to transmit high power in space. New radiation hardening insulation dielectric materials are needed to endure high voltage in space. New generation SiC and GaN power electronics components are needed to develop high-power, high-temperature and radiation hardening power equipments.
4. Assembly and maintenance

Even though single module is very large, the solar array of SPS must be assembled in space. All electric power equipments need to be installed in space. The assembly of tens of km cable in space is also a big challenge. The complexity and hazard of assembly exceed that of ISS greatly.

6 Conclusion

MR-SPS is a new concept and the high-power electricity generation, transmission and management is an important technology challenge. Primary MR-SPS concept and the particular configuration of high-power electricity generation, transmission and management are introduced firstly and the typical influences of space environment factors on high-power electric system are analyzed. At last, several key technologies to achieve high-power electricity generation, transmission and management in space are presented. The conclusions are as follows.

1. MR-SPS is a new non-concentrator SPS concept and can provide electricity continuously and steadily in GEO.
2. The main innovation of MR-SPS is that the huge sq.km scale solar array is broke up into 50 disjunctive solar sub-arrays and each sub-array transmits electricity by two independent conductive rotary joints. Such design reduces the power of the conductive rotary joint and avoids the single point failure problem.
3. Based on the multi-rotary joints design, the mix configuration of distributed and centralized PTM is adopted for MR-SPS.
4. The high-efficiency thin-film GaAs cell is chosen for the ultra-large flexible solar array module. The output voltage is 500 V.
5. The transmission power of a conductive rotary joint is about 24 MW. The transmission power can be reduced further by adding more solar sub-arrays.
6. The power of the solar sub-array is transmitted to antenna by cables fixed on the structure trusses. The long-distance high-voltage (20 kV) electricity transmission cables are needed.
7. The space radiation environment will affect insulation materials and power electronic equipments seriously. The integration effect of high-voltage and space radiation will make it very difficult to develop the high-voltage solar array, cable and conductive rotary joint.

References

1. Glaser PE (1968) Power from the sun: its future. Science 162:867–886
2. Mankins JC (2018) Fifty years of space solar power. In: 69th International Astronautical Congress, Bremen, Germany
3. Arya M, Lee N, Pellegrino S (2016) Ultralight structures for space solar power satellites. In: 3rd AIAA spacecraft structures conference, San Diego
4. Ian Cash (2017) CASSIOPeiA Solar Power Satellite, WISEE
5. Ian Cash (2018) CASSIOPeiA—A new paradigm for space solar power. In: 69th International Astronautical Congress, Bremen, Germany
6. Choi J-M (2019) Conceptual design of Korean space solar power satellite. In: 70th international astronautical congress, Washington D.C.
7. Mihara S, Mae Kawa K, Nakamura S et al (2018) The road map toward the SSPS realization and application of its technology. In: 69th international astronautical congress, Bremen, Germany
8. Xinbin H, Li W, Xinghua Z, Zhou Lu (2015) Concept design on Multi-Rotary joints SPS. J Astron 36:1332–1338 **(in Chinese)**
9. Hou X, Li M, Niu L, Zhou L (2015) Multi-rotary joints SPS. In: ISDC 2015, Toronto, Canada
10. Yang Y, Baoyan D, Jin H (2014) SSPA-OMEGA: a new concentrator for SSPS. Chin Space Sci Technol 34:18–23 (**(in Chinese)**)
11. Lyndon B (1980) Johnson space center, satellite power system concept development and evaluation program, NASA-TM-58232
12. Mankins JC (1997) A fresh look at space solar power: new architectures, concepts and technologies. Acta Astronaut 41:347–359
13. Mankins JC (2002) A technical overview of the SUNTOWER solar power satellite concept. Acta Astronaut 50:369–377
14. Sasaki S, Tanaka K, Higuchi K, Okuizumi N (2006) A new concept of solar power satellite: tethered-SPS. Acta Astronaut 60:153–165
15. Seboldt W, Klimke M, Leipold M, Hanowski N (2001) European sail tower SPS concept. Acta Astronaut 48:785–792
16. Sysoev VK, Pichkhadze KM, Feldman LI, Arapov EA, Luzyanin AS (2012) Concept development for a space solar power station. Sol Syst Res 46:548–554
17. Mankins JC (2012) SPS-ALPHA: the first practical solar power satellite via arbitrarily large phased array, Artemis Innovation Management Solutions LLC
18. Sproewitz T, Grundmann J-T, Haack F (2018) GoSolAr—a Gossamer solar array concept for high power spacecraft applications using flexible thin film Photovoltaics. In: 69th International Astronautical Congress, Bremen, Germany
19. Herron BG, Creed DE, Opjorden RW, Todd GT (1970) High voltage solar array configuration study, Hughes Aircraft Company, NASA CR-72724
20. Springgate WF (1970) High voltage solar array study, The Boeing Company, NASA CR-72674
21. Seri Y, KIT Satellite project, Masui H, Cho M (2013) Mission result and anomaly investigation of HORYU-II. In: Small Satellite Conference, Logan, Utah
22. Cho M, Saionji A, Toyoda K, Hikita M (2003) High voltage solar array for 400V satellite bus voltage: preliminary test results. In: 41st aerospace sciences meeting. Reno, Nevada
23. Tanaka K, Toyota H, Tajima M, Sasaki S (2007) Basic experiment of plasma interaction with high voltage solar array. In: 45th AIAA aerospace sciences meeting, Reno, Nevada
24. Shen Y, Yan D (2014) Present status and prospects of space radiation environmental engineering. Spacecr Env Eng 31:229–240 (**(in Chinese)**)
25. Zhao W et al (2012) High voltage engineering and design handbook. ECSS-E-HB-20-05A
26. Jinfeng W, Xiaoquan Z, ShengtaoJiang LW (2011) Internal charging protection technology of typical space polymer dielectric material. J Beijing Univ Aeronaut Astronaut 37:180–184 (**(in Chinese)**)
27. Wang X, Zheng S, Min D, Li S, Hou X, Wang L (2019) Study of deep dielectric charging characteristics and suppression method under space irradiation environment. In: The 21th international symposium on high voltage engineering (ISH), Budapest, Hungary
28. Wang X, Min D, Li S (2020) Charging and discharging mechanism of polyimide under electron irradiation and high voltage. Polyim Electron Electr Eng Appl 2020:5
29. Pan S, Min D, Wang X, Hou X, Wang Li, Li S (2019) Effect of electron irradiation and operating voltage on the deep dielectric charging characteristics of polyimide. IEEE Trans Nucl Sci 66:549–556