Review of Modern Solar Power Satellite and Space Rectenna Systems

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***Abstract*—This paper presents the review and analysis of modern space solar power satellite system and space rectenna. There is a challenge to collect and transmit large amount of energy from space to earth using microwave power transmission technology without the interference with communication satellites such as military operations systems and aircraft radar systems. This study focuses on Low Earth Orbit (LEO) location of the space satellite for maximum efficiency. Microwaves of 5.8 GHz frequency with efficiency of 85% will be used to transmit the electric power from the space satellite to the rectenna.**

Space-based solar power system is different from the current solar power collection methods. The space solar power method uses a satellite placed on an orbit to collect the solar energy instead of on earth's surface. Research found space-based solar power to be uneconomical but new developments have paved ways for space solar power exploitation. The space-based section of the system consists of a constellation of solar energy collecting satellites called SunSats that collect solar power and transmit it through a suitable frequency to earth. The ground station of the system consists of large receiving antennas known as rectennas which convert the microwave frequency into DC power. The DC power is then transformed into AC and injected into the electrical grid.

Keywords*—*Space, solar, rectenna, microwave, satellite

I. Introduction

An increase in the world's population with the increase in global warming has drawn the attention of the development of a clean and reliable power source to meet the demand of energy. Although numerous alternative energy sources have been pursued, none of the technologies has been successful to meet the world's energy demand [1]. Technological developments have recently made way for space-based solar power systems as a means for meeting energy demands.

Space solar power satellite system is a system whereby large satellites are placed into geostationary orbit to capture and convert a large amount of sunlight into microwave energy which is then transmitted to a rectifying antenna array on earth [2]. The rectenna then receives and converts the microwave power into electrical energy that is pumped into the terrestrial electric grid for use [2]. The applications of space solar power systems include, electric power sources for remote areas, other satellites, a supplement to the terrestrial electric grid and also provide power for certain businesses and domestic use in some countries [3]. To sustain humanity's energy future, and to reduce atmospheric CO_2 over time, it is practical to build a feasible power system that will continually harvest solar energy from our sun. The sun has unlimited energy and an SSPS is a system to achieve just that. Since many researchers have focused on the GEO-SSPS, as well as the ground rectenna array, this work looked at the microwave beam space environment stretching from a GEO-SSPS to Earth or to lower orbiting satellites.

The space solar power system is a free energy source, which has to be considered a feasible method to provide electrical generating capacity due to constant sunshine in space [4]. Due to orbit location, the amount of solar energy received by the satellite during the year is very effective and consistent [5]. Some satellites have the same rotational time as the earth at geosynchronous orbit and therefore, are fixed at a particular location at all times which enables the satellite to deliver constant power to a ground-receiving site [6]. Therefore, it is crucial to establish a space solar system which is cost-effective, feasible and accurate to deliver maximum power.

II. Research Objectives

The research objective is to design an economically feasible, solar power satellite system to collect solar energy from space and transmit it to earth at maximum power efficiency. The various space solar power systems would be investigated under new technologies and the major elements of the ground system would be evaluated to determine an effective viable system design. Though the design focuses on microwave power transmission, laser power transmission system will also be analysed.

III. Background to the Study

The US Department of Energy and NASA made their first significant strive to construct and assess a space-based solar power system from 1977-1980 [7]. They defined a space-based solar power reference system which included all the system configuration and major components [8]. The project was developed to generate a total power of 300 gigawatts from 60 different satellites. The satellites were configured to produce a power generating capacity of five gigawatts each using photovoltaic cells and microwave power transmission at a frequency of 2.45 GHz placed at geosynchronous orbit [8]. Many evaluations were performed on the NASA concept and conclusions indicated that space solar power system was practically viable but the reference system presumptions were not reliable due to components performance over time and the cost of launch [9]. Recommendations were made for further research to be carried out and assessed regularly [10].

Japan developed an interest in space solar power system in the 1981 during the formation of its space agency (Institute of Space and Astronautical Science of Japan) [11]. Japan considered the heavy cost and the practical strain of constructing the Reference system and therefore focused on a cost effective developing of an offshore floating ground receiving system. Japan first developed a 10 MW photovoltaic Space Solar Power Satellite system based on the DOE/NASA Reference System. The second power system that was considered was a solar concentrator to generate 70 MW and a thermal energy conversion satellite with energy storage [12].

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The US National Aeronautics and Space Agency commenced the Space Solar Power (SSP) Exploratory Research and Technology (SERT) program in 1999 to conduct more research on space solar power system [13]. The program continued the satellite concepts and funded fundamental technology research [13]. SERT defined several SSPS applications for science, exploration and other commercial space uses and also addressed analytical technology elements for solar power satellites, including deployment, assembly, power management, distribution and wireless power transmission [10].

A proposal of a design prototype by Professor Kaya Nobuyuki was analysed in the study of space solar power system in Japan [14]. The investigation concluded that the Sun Tower middle-earth-orbit system was not feasible. The main features of the system were to place a photovoltaic array directly behind the stationary transmitting antenna, pointing at earth and use concentrator to direct the sun's energy to the photovoltaic array [15]. The principal wireless radio frequency solar energy transmission satellite concepts that originated from the SERT program were, a conventional perpendicular to orbit plane configuration and the Integrated Symmetric Concentrator configuration [16]. This concept was based on an altered prototype concept in which two photovoltaic array are placed at the front of the concentrator array [16]. The method removed the heat management problems but increased the power distribution and management complexity [15].

Technology has improved in the development of space solar power satellite system since the Reference System [10]. Africa is still not within realistic reach of space travel yet, but South Africa and Nigeria have the most advanced space programs on the continent. NASA and Roscosmos are the major space programs in the world and China national space agency (CNSA) is the fastest rising space agency. India space program has also undergone a rapid expansion in recent years due to the growing economic power and influence. The Japan Aerospace Exploration Agency (JAXA) have made some very impressive gains in recent years.

IV. Demonstrated Projects

A. SPS 2000

The Japanese SPS 2000 project was the most aspiring wireless power transmission experiment since before World War I [17]. The main aim was to construct a functioning space solar power satellite system. The ground infrastructure was to consist of several rectenna geographical locations to lay out the foundation to promote space solar power systems. The concept was to use a satellite that can deliver electrical power of 10 MW from a spherical 1100 km east-to-west equatorial orbit [17]. The transmitting phased array antenna was designed to steer at ±30° along the orbital path and ±16.7° perpendicular to the orbital path [17].

B. The Grand-Bassin Project

The project was designed for France La Réunion to provide electricity for Grand-Bassin remote areas [18]. The main purpose was to perform an actual demonstration of a viable point-to-point wireless power transmission. The area is isolated by a river valley which hinder access to the place. Numerous options were considered to provide power of up to 10 kW to Grand-Bassin. The wireless power transmission from an available station was used but there was a cost restriction on the system [18].

C. Retro-directive Phased Array Antenna/Rectenna Demonstration

The Kobe University developed a 5.8 GHz retro-directive phased array power system [11]. This system used a solid state amplifiers which were connected directly to the transmitter to decrease weight [11]. The receiving antenna for the pilot beam was essential with the transmitter and the 5.8 GHz oscillator determined the phase of the pilot beam. Phase shifters were combined with the conjugate phase to steer the beam accurately onto the rectenna. The system has an advantage of small in size and less weight as compared to 2.45 GHz. The second advantage was an accurate pointing control and effective efficiency of the power amplifiers [11].

D. The SPS End-to-End Terrestrial Demonstration

This project was proposed to design and experiment the major elements of a space solar power system. The demonstration used the photovoltaic array DC output to power a transmitting array at certain power range. The receiver, which was located at a 1 to 5 km distance from the transmitter converted the RF power to DC for a power utility grid [19]. The aim was to prove a feasible wireless power transmission system and to also determine the components reliability over time [19].

E. ISPER Project

A Japanese space agency conducted an experiment to test new technologies for a viable space solar power satellite system. The idea was to develop a protoype system using the retro-directive solid state phased array transmitter integrated with solar cells which are directly connected to the power amplifiers [14]. Inflatable concentrators were used to direct the sunlight to the solar cells. The experiment was a prototype which consisted of a transmitting antenna photovoltaic array to transmit power to other smaller satellites in low earth orbit and to the ground receiving station. The Japanese Space Flyer Unit [14] deployed this project in low earth orbit (LEO). The main objective of this experiment was to prove the operation of the antenna-photovoltaic array concept in space.

V. Space Solar Power Satellite System Design Requirements

A System Tool Kit (STK) would be used to design both the SSPS and low earth orbit satellite system and simulated using software packages such as CST Microwave/Ansys Ansoft HFSS. The CST Microwave Studio is a tool for simulating high frequency devices and the Ansys hfss is a simulation software used to design and simulate high-frequency electronic products such as antennas, antenna arrays and RF or microwave components [20]. Experimental validation will be undertaken using physical models of an actual design system. This will be achieved using field experiments, measured field data and engagement with the South African National Space Agency (SANSA). The entire system consists of two modules, namely:

1. The space solar power system (Spacetenna/Sunsat)
2. The ground power system (Rectenna)

A. Space satellite (SUNSAT)

The SunSats are required to produce radio frequency power at a constant rate with minimum interruptions. The main components of the system include: the solar cell arrays, the power conversion hardware, and a battery backup system [19]. The solar arrays will be paired with a reflector array to help concentrate solar energy onto the photovoltaic cells. The DC power produced by the SunSats will be transmitted to Earth at a frequency of 5.8 GHz. This frequency compared to 2.4 GHz has less attenuation by atmospheric conditions. The higher frequency of 5.8 GHz instead of 2.4 GHz, increases the gain of the antennas used in the design and thereby the efficiency of the system. The elements of the system are given in Fig. 1.

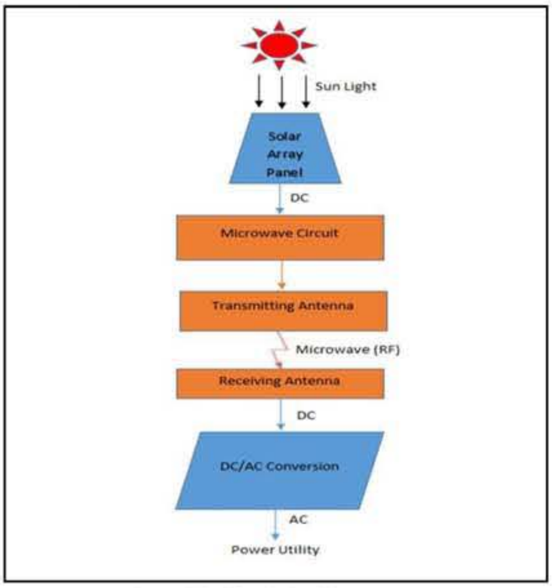

Fig. 1: SSPSS Block Diagram

B. Telemetry and Control system

The telemetry system will be used to deploy the SunSats into their proper orbits. The system will communicate with the earth station under any condition and must be persistent throughout all weather conditions. S-band frequencies of 3.2/3.5 GHz will be used as the carrier frequencies for the link.

C. Power Transmission system

Transmitters used for microwaves includes klystron, magnetron and travelling wave tube. Magnetrons are mostly used since they are efficient and cheaper. Magnetrons can convert power into electron beam and transmit it within a microwave frequency range [22]. Space-based solar power system design depends on the ability to effectively transmit power from space back to earth. This transmission system must be very efficient so that large percentage of the energy harvested can be recovered on Earth. Therefore, an efficiency of 85% is determined for the rectenna to harvest the transmitted power. The main feature of the transmitter dish will be its ability to minimize side lobe levels to prevent unwanted radiating on the ground [24]. The parameters that can be used for the power transmission link are shown in Table I.

TABLE I. PARAMETERS FOR POWER TRANSMISSION SYSTEM [23].

Parameter	**Value**
Transmitter Antenna Efficiency (t)	90%
Main Lobe Efficiency (L)	84%
Transmitter Antenna Power (Pt)	10 GW
Magnetron Efficiency (m)	86%
Rectenna Harvest Efficiency	50%
Rectenna Efficiency	82.7%
Frequency	5.8 GHz

D. Ground Antenna

For the ground station, a parabolic antenna with the ability to track the satellite will be used. This antenna will have the ability to transmit maximum power using a travelling wave tube amplifier [21]. Space-based solar power system design is mainly dependant on the ability to transmit power from space to earth as efficiently so that a large percentage of the power harvested is recovered on earth. The rectenna should be able to harvest approximately 85% of the transmitted power and convert the RF energy back into DC power [22]. The type of rectenna to be used will be determined by its efficiency. The rectenna developed by Suh and Chang which is cable of converting RF to DC at 5.8 GHz with 82.7% efficiency will be used for experiments. [23]. The design will be based on the use of a printed dipole antenna attached to a series of filters that block the re-radiation of higher order harmonics. After passing through the filters, the signal is then directed through a schottky diode, capacitor and load-matched resistor where it is rectified into DC power [24].

E. Ground Rectenna

The 2.45 GHz Reference System by DOE/NASA, placed a space solar power system into GEO orbit within a transmitter array diameter of 1 km to deliver 5 GW of power to Earth [24]. The system proposed a peak power density of 23 mW/cm^2 at the center-of-beam on the rectenna on Earth. The reference systems calculations are used to determine the power irradiance levels and the beam diameter for different orbits that satellites pass through [24]. Three diameters of 342 m, 319 m, and 226 m of the transmitters are chosen to analyse the irradiance levels. The frequency of 5.8 GHz is chosen as opposed to 2.45 GHz, since researchers in the SSPS suggested that 5.8 GHz is cost effective and provides high efficiency.

$$P_d = A_t P_t / \lambda^2 D^2 \quad (1)$$

This formula is used to determine the power, where A_t is the total area of the transmitter, P_t is the total power radiated from the transmitter, λ is the wavelength, and D is the separation distance between the apertures [27].

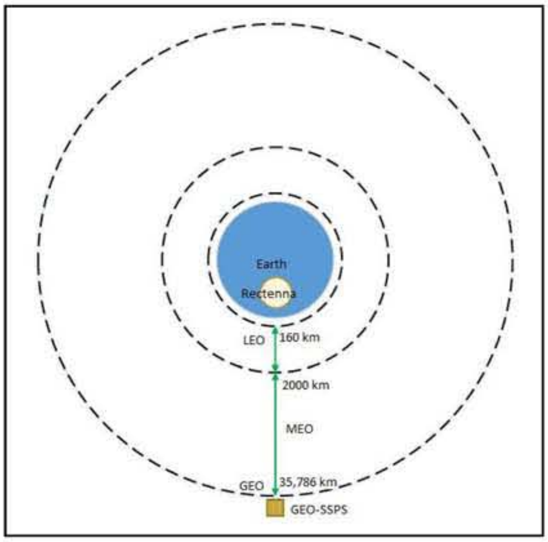

Fig. 2: LEO, MEO and GEO altitutude from Earth [25]

Fig. 2 shows the distance between the different orbits from Earth. The area for the microwave beam at different orbits is determined by the spot diameter. The diffraction pattern, which constitutes the Airy diffraction disk, is produced from a uniformly illuminated circular aperture whose area contains 84% of the beam energy [27] as seen in Fig. 3.

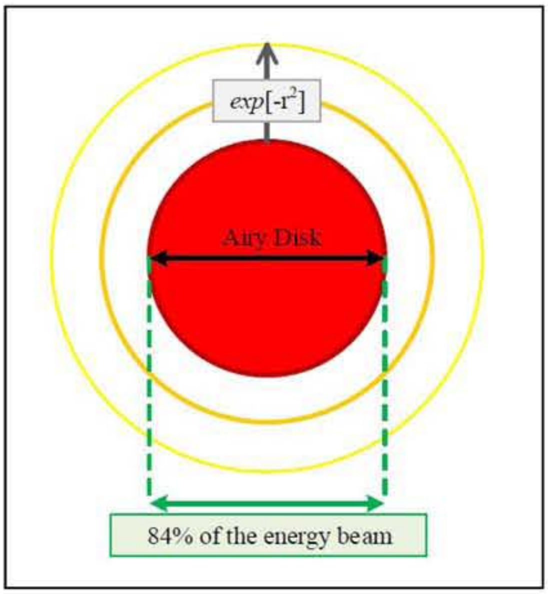

Fig. 3: Airy diffraction disk [27]

The diameter of the Airy diffraction pattern is calculated from:

$$d_{spot} = 2.44\, \lambda D / d_{transmit} \quad (2)$$

where, $d_{transmit}$ is the diameter of the transmitting aperture. The distances for transmitter diameters of 342 m, 319 m, and 226 m are 4531 km, 3940 km, and 1970 km respectively at 5.8 GHz [27].

The exposure time experienced by a satellite has to be calculated to determine the total accessible solar energy and the required radio frequency. The velocity of the satellite is divided by the beam diameter to give the transit time [27]. If low earth orbit is considered as circular, then the velocity of the satellite can be determined from the formula below:

$$V = \sqrt{\frac{\mu_{Earth}}{R}} \quad (3)$$

where, μ_{Earth} and R are the gravitational constant and mean radius of the Earth respectively including the altitude of the orbit from Earth's surface in kilometres [27]. Elliptical orbits require additional orbital parameters to determine the velocity of the satellite [27]. Table II shows data for power irradiance and Airy disk (diameter) for MEOs.

TABLE II. DISTANCE, POWER DENSITY, AIRY DISK, SATELLITE VELOCITY, AND TIME OF RF EXPOSURE FOR A SATELLITE IN LEO AND MEO (GPS) FOR SERT HIGH [27].

Altitude (km)	**Power Density (W/m2)**	**Airy Disk (km)**	**Average Velocity of Satellite (km/s)**	**Maximum Time of Exposure (s)**
0 (at Earth)	200	14.14	N/A	N/A
500	205	13.95	7.62	1.83
1000	211	13.75	7.35	1.87
1500	217	13.55	7.11	1.90
2000	224	13.35	6.90	1.94
20200 (GPS)	1054	6.16	4.96	1.24

CONCLUSIONS

The decline of available resources of fossil fuels and the persistent rise in the prices of oil and gas solidly inspires consumers to hunt for alternative sources of energy. Space solar power is the most productive and attractive sources of free, constant and reliable power. SBSP, at the present trend, uses solar mirrors or panels to collect the available sun's energy and deflect it to earth through wireless power transfer. This paper demonstrates the past research, methods and devices designed. The SPSS will be a central attraction of space and energy technology in future. Space-based solar power transmissions are yet to be proven in Africa to alleviate the constant energy crises and needs further developments around the world.

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