DEVELOPMENT OF AN ELECTRICAL FUNCTIONAL MODEL FOR SPS 2000

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Abstract

SPS 2000 is a study model of 10 Mwatt class Solar Power Satellite on a 1,100 km equatorial orbit. To identify the problems of SPS 2000 on a system level as well as a subsystem level, an electrical functional model has been developed for ground testing. The model includes solar cell arrays and a microwave power transmitter which are assembled on a scale model of SPS 2000. The power level of the microwave transmission is 1-4 watt. The model has been tested in combination with a microwave receiver as the ground segment. In the integration test, the performance of each subsystem of SPS 2000 and its ground segment has been evaluated from a standpoint of system integration and operation. The test results are reflected in the conceptual design of SPS 2000.

1.Introduction

SPS 2000 has been studied by the SPS 2000 task team as a realistic and low-cost SPS model based on the near-term technologies. Figure 1 illustrates the basic concept of SPS 2000. The mission orbit is at an altitude of 1,100km above the equator, which is a compromise of transportation cost and environmental concerns. It has the shape of a triangular prism with a length of 300 m each side. The prism axis is in the north-south direction, perpendicular to the orbital velocity. The solar arrays are attached at the two upper planes of the prism, while the transmitting antenna is installed at the bottom plane, facing the ground all the time. The power generation and microwave power transmission are 18 Mwatt and 10 Mwatt, respectively. To simplify the system configuration, the model SPS has no energy storage, and the attitude is stabilized merely by gravity-gradient force. The total weight of SPS 2000 is estimated to be about 240 ton.

The main structure of SPS 2000 is made of double-bay single-raced beam, which is assembled of 3 meter-long aluminum pipes of 12 mm diameter with quick connection mechanisms. The task analysis for construction has shown that unmanned assembly is feasible under gravity-gradient force. The solar cell arrays consist of 180 rolls of 3 m x 300 m strips of solar cell panel. For transportation from ground and deployment in space, amorphous silicon (a-Si) solar cell, a thin film type, will be used. The voltage of the power generation is 1,000 V to reduce the cable loss. Flat cables made of 1 mm thick copper plate are used for the electrical power collection. For the microwave power transmission, 2.45 GHz is selected as the most practical frequency for the near-future application because of technical maturity and a high transmission capability in the atmosphere. The spacetenna 132 m

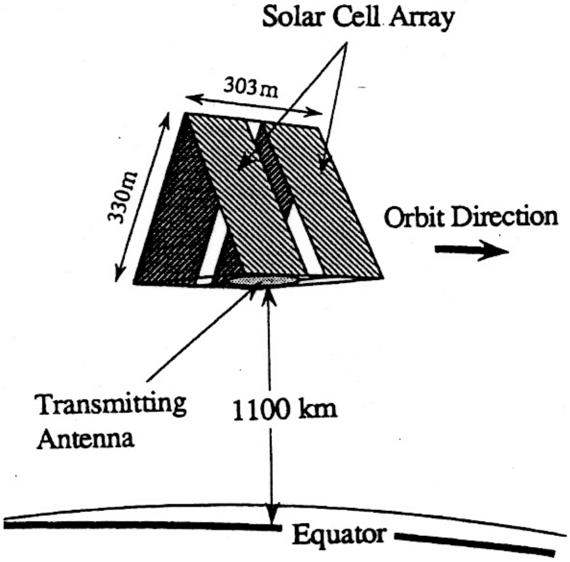

Fig.1 Basic concept of SPS 2000.

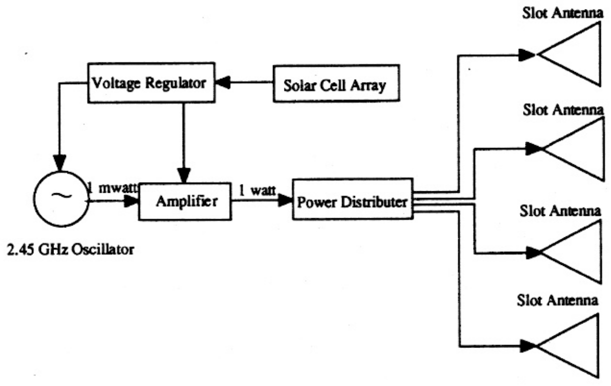

Fig.2 System block diagram of the first functional model.

by 132 m square consists of 2,000 subarrays, each including 1,300 antenna elements. The phased array system is capable of directing the microwave beam ± 30 degrees in north-south and ± 17 degrees in east-west to the normal. The size of rectenna is typically 1 km circular and a power of 300 Kwatt is obtained on average at the rectenna site. Two types of rectenna have been designed ; a simple mesh type called "magic carpet" and a hogline rectenna with circular micro-strip antennas. Both are almost transparent for the sunlight to minimize the environmental impact. More detailed description on the concept of SPS 2000 is given by Nagatomo et al[1].

2. SPS 2000 Functional Model

The functional model simulates the major electrical function of SPS 2000 ; power generation by solar cell arrays and microwave power transmission. Two functional models have been fabricated and tested by the SPS 2000 task team since 1994.

The first model[2], a 1/300 scale model, is a 1-watt transmitting power system without phase control. The block diagram is shown in Fig.2. The frame structure is made of an angle aluminum. Four solar cell modules of polycrystalline silicon type, 494 mm x 424 mm each, are installed on one side of the triangular prism frame of 1m scale. The solar cell module is commercially available for solar cars and planes. It generates a 22-watt power in a 1,000 watt/m^2 solar light. Using two 1 Kwatt Halogen lamps set at 1.8 m apart from the functional model, the solar cell arrays generate an electric power of typically 20 watt. The power is fed to a 2.45 GHz oscillator of 1 mwatt and a 30 dB microwave amplifier. The output power of the amplifier is divided and supplied to four sets of cavity-backed slot antenna.

The second model[3], a 1/200 scale model, is a 4-watt transmitting power system. The length is 1.7 m each side. The instrumentation is almost same as the first model, but it has a capability of phase control for beam steering. The block diagram of the second model is shown in Fig.3. Four 1 Kwatt Halogen lamps are used for the light source. Eight solar cell modules are attached to one side of the triangular prism. The microwave transmitter consists of

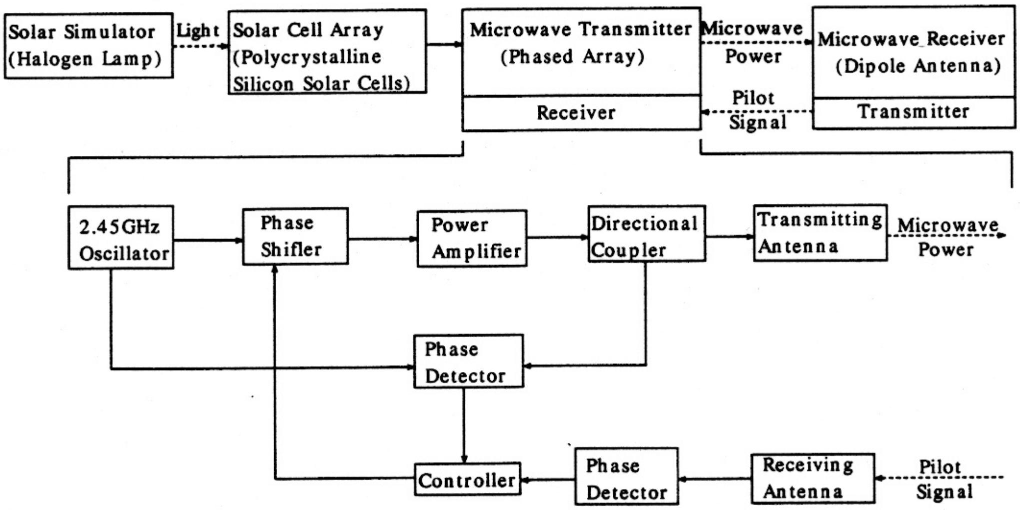

Fig.3 System block diagram of the second functional model.

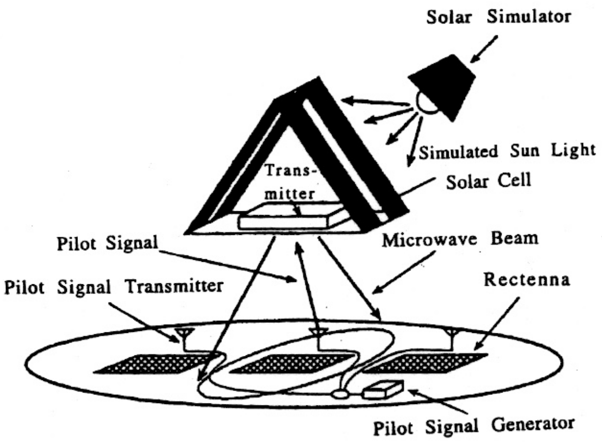

Fig.4 Test configuration of the second functional model in combination with the rectenna.

4 channels of phase-control loop. Each channel is connected to two slot antennas. The phase control loop has an analog phase shifter, an amplifier, a directional coupler and a phase detector. The controller compares the phase signal of the transmitter with that of the pilot signal, and then generates a control signal for the phase shifter to direct the microwave beam toward the pilot signal source. 800MHz is used for the frequency of the pilot signal.

The electrical function models have been tested in combination with rectennas. The typical test configuration for the second model is shown in Fig.4. Three rectenna sites are configured so as to demonstrate the beam steering capability. Three types of receiving antenna have been developed for the test. The separation between the transmitting antenna of the functional model and rectenna was 1-2 meters. The received power was rectified and supplied to dummy loads consisting of LEDs and miniature motors.

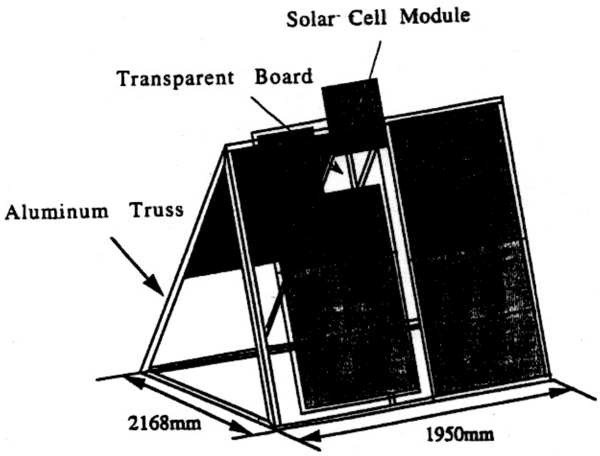

Fig.5 Integration of 32 solar cell modules for the third functional model.

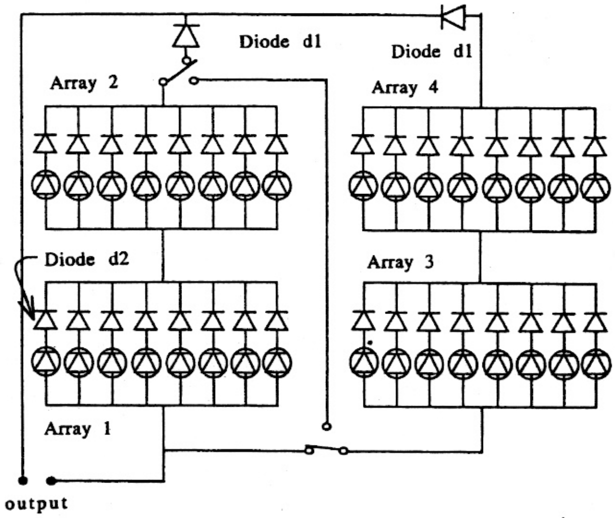

Fig.6 Block diagram of the power generation system for the third functional model.

A more powerful functional model, the third model, is now under development supported by an MOE (Ministry of Education, Science and Culture) Grant-in-Aid for Scientific Research. It is a 1/150 scale model with a capability of power generation more than 300 watt in the sunlight. Totally 32 solar cell modules are assembled on the two sides of a triangular prism structure as shown in Fig.5. The side length is about 2 m. The circuit diagram of the power generation system is illustrated in Fig.6. The 32 cell modules are grouped into 4 arrays. Array 1 and 2 are connected in series and installed on one side, and in the same way connected for Array 3 and 4 on the other side. Arrays 1/2 and 3/4 are connected in parallel. Diodes are used to prevent reverse current caused by uneven cell voltage. The picture of the third model in the field test is shown in Fig.7. This system will be combined with the microwave transmitter of the second model which has been recently improved in Hokkaido University. As another type of transmitter for this model, a compact type of transmitting element which contains microwave circuits and a transmitting antenna integrated into a multi-layer struc-

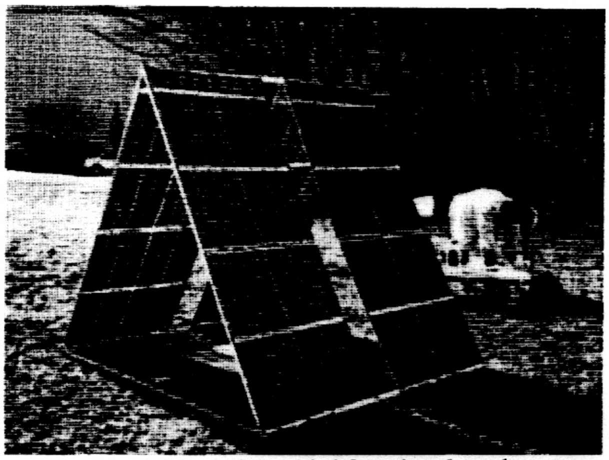

Fig.7 View of the third functional mode.

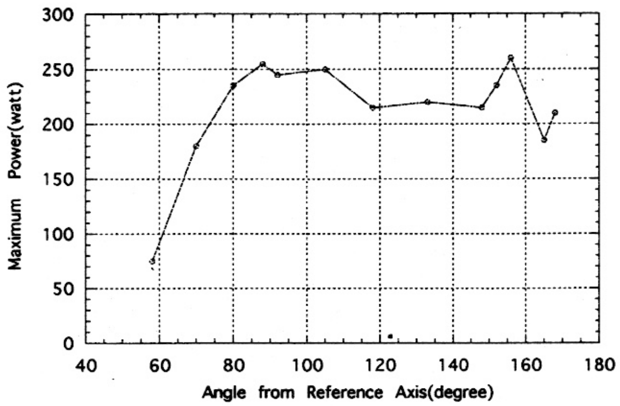

Fig.9 Diural variation of the maximum power for the third functional model.

ture, is investigated in Tokai University.

3. Test Results

3.1 Power Generation

The electrical characteristics of the power generation system consisting of solar cell modules, diodes, and power collecting cables assembled on the scale model were measured using the Halogen lamps or in the sun light. The typical voltage-current and voltage-power characteristics of the third model in the sun light are shown in Fig.8. The maximum power amounts to 330 watt at 30 volt. Since the sun angle to the solar cell arrays on both sides changes with time, the total output power varies with time. An example of diurnal variation measured in January 1997 is shown in Fig.9. The variations include the change of the reflected light from the surroundings as the sun angle changes with time. The power generation was also subjected to the change of the atmospheric condition.

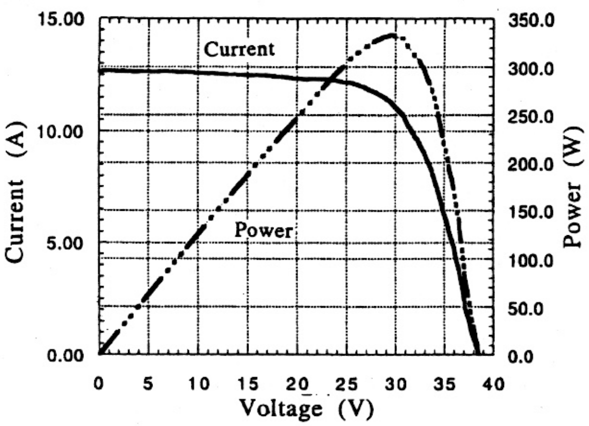

Fig.8 Typical characteristics of the power generation system for the third functional model.

3.2 Power Transmission

The amplifier in the microwave transmitter of the first model was commercial one without phase control, but the transmitter with a capability of phase control for the second one was newly developed for the SPS 2000 functional model in Hokkaido University[4]. The design target for the transmission power of the second model was 30 dBm each channel and 36 dBm (4 watt) total. The actual transmitting power was found to be from 23 dBm to 29 dBm each channel. The radiation pattern from the transmitting antenna was measured for the array of 8 antenna elements integrated in a plane of 300 mm x 180 mm. The maximum gain and beam divergence of the antenna array were 14 dBi as shown in Fig.10 and 20 degrees, respec-

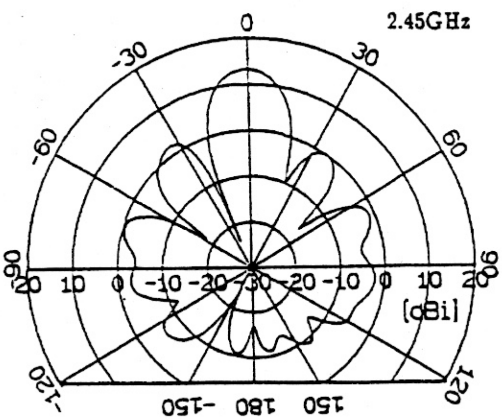

Fig.10 Characteristics of the array antenna[4].

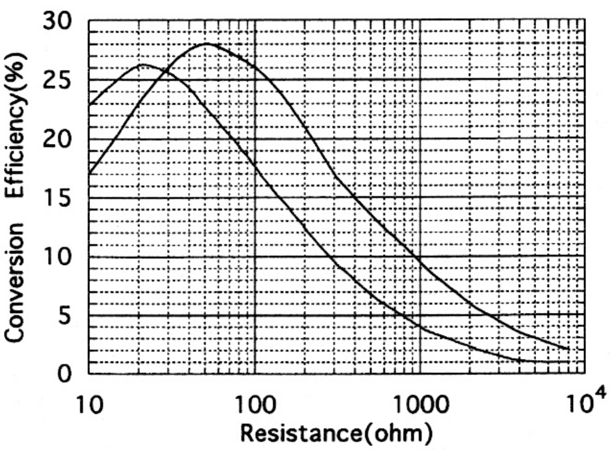

Fig.11 Conversion efficiency of the H-type dipole antenna array.

tively. The beam steering capability up to 15 degrees was demonstrated in the integration test.

3.3 Power Reception

Three types of the rectenna have been tested[5] ; H-type dipole antenna with a reflector mesh, copper foil dipole antenna on a flexible structure with an Al foil reflector (magic carpet) , and circular micro strip antenna combined with a wire grid reflector. The number of antenna element distributed on a 50 cm x 50 cm unit area is 24, 45, and 24, respectively for each type of rectenna. They were tested in a microwave field of 3.4 watt/cm^2. The conversion efficiency versus load resistance for two sets of H-type antenna is shown in Fig.11. The maximum efficiency was 26-28 %. It is noted that the characteristics of the conversion efficiency are different for the two sets, which means that there is some unknown factor which is sensitive to workmanship. In the combination test with the functional model, the rectennas were set at 1-2 m apart from the transmitting antenna array attached at the bottom of the functional models. A dc power of 100-200 mwatt was obtained at the rectenna site and fed to LEDs and miniature motors for demonstration of wireless power transmission.

4. Discussion

In the test using the SPS 2000 functional models, several research subjects have been identified concerning power generation, microwave power transmission, and microwave power reception.

4.1 Power Generation and Collection

Different from the US Reference system with a gimbal to direct the solar panel toward the sun while the microwave antenna to the earth, the SPS 2000 is controlled by the gravity gradient force to keep the transmitter antenna facing the ground with no gimbal mechanism. Then the generated power varies with time by the change of the sun angle with respect to the solar cell arrays on the triangular prism. The analysis result for the power generation of SPS 2000 from 4 a.m. to noon local time is shown in Fig.12. In the power generation test using the scale model, the power profile deviates by 20-30 % from the analytical model. The possible reason for the discrepancy is that the effects of blocking diodes and surface reflection at an oblique incidence of the light are not correctly evaluated in the model calculation. It is planned to measure the power loss at each diode which changes dynamically according to the variation of the power generation. The change of the power generation with the sun angle will be measured using a single cell for further analysis. The data will be referred in evaluation of the capability of the power generation for SPS 2000.

4.2 Electrical Interface between Power Generation and Microwave Power Transmission

As is described in 4.1, the output power from the solar

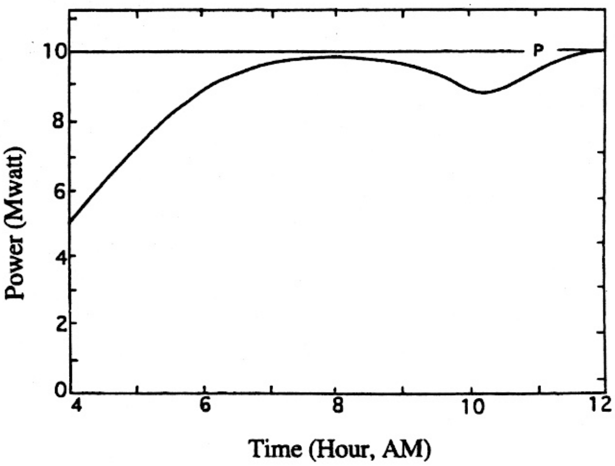

Fig.12 Diural variation of the power generation for SPS 2000.

cell arrays of SPS 2000 varies with time. In the functional model, the power from the solar cell arrays is regulated at a constant voltage and provided to the oscillator and the amplifiers of the microwave transmission system. The voltage regulation results in a power loss more than 20% in the regulators. This corresponds to a 3.6-Mwatt power loss for SPS 2000, which is undesirable from a standpoint of heat rejection. In order to reduce the power loss and to get the maximum power at any solar angle, the input circuit of the transmitter needs to accommodate the voltage variation, which means the microwave power directly depends on the input power. Since the power generation system of SPS 2000 will use a high voltage of 1,000V, accommodation of high voltage must be also considered in the design of the transmitter circuit.

4.3 Microwave Power Transmission and Reception

The direction of the microwave beam is controlled by the pilot signal from the rectenna site. In order to know the direction of the rectenna site, it is necessary to detect the phase of the pilot signal by the antennas on the satellite. However, this has not been successful in the integration test because the phase of the pilot signal was unexpectedly modified by the metal frame of the model. Special consideration is required for the configuration of the receiver of the pilot signal.

There are two major problems to be solved for the microwave transmitter of the functional model. The size of the electronics for the power transmitter is much larger than the slot antenna, contrary to the basic design concept of SPS 2000. The conversion efficiency from DC to RF is less than 10%. For SPS use, both circuit integration and conversion efficiency need to be greatly improved. One of the potential candidates for miniaturization is to integrate the circuits into multi-layer thin structure together with the transmitting antenna, which is now under investigation for the third model.

For the rectenna, the conversion efficiency of 30 % from RF to DC is practically too low. A systematic study for the antenna shape, selection of diode and capacitance, geometry of reflector, and connection of antenna elements is further required. It is also necessary to establish the fabrication process to assure reproduction of the same performance for the rectenna.

5. Conclusion

Electrical functional models of SPS 2000 have been fabricated and tested as a practical approach for the research of SPS 2000. Several research subjects have been identified in the integration tests. They are concerning evaluation of power generation depending on the sun angle, lossless interface between the power generation and transmission systems, and configuration of the pilot signal receiver not to interfere with other systems. It is also noted that improvement of conversion efficiency from DC to RF and vice versa, and miniaturization of power transmission system are essentially required. Besides the usage of the functional model as an experimental setup for the SPS research, the models have been exhibited at the ISAS annual open house and the Wireless Power Transmission Workshop at Reunion Island in 1994 and 1995, which have contributed to spreading scientific knowledge of SPS to public.

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