Abstract

MICROWAVE POWER TRANSMISSION FOR SOLAR POWER SATELLITES

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In the years 1978 1981 and 1998 1999, a microwave power beaming system for a Solar Power Satellite (SPS) was analyzed, simulated, and partially demonstrated. These microwave system studios were a collaboration effort with NASA, the Department of Energy (into the environmental and societal impacts of a power beaming system), multiple aerospace/electronic companies, and universities. This paper reviews the simulations for S-band and C-band frequencies, discusses the relative importance of the microwave error parameters and their degradations to the system, the environmental impacts, what advancements have been achieved since 1981, suggestions for demonstrations, and lessons learned.

Environmental Concerns

The Department of Energy (DOE) was responsible for assessing environmental impacts from the proposed 5 gigawatt (GW) S-band microwave system. These concerns included: (1) Power Beam Wander – which was probably the problem of most public concern. What happens to the power beam, which has a power density of 23 milliwatts/cm^2 at the center of the beam and 1 milliwatt/cm^2 at the edge of the rectenna (receiving antenna) in the event of a complete or a partial failure, either intentional or accidental, of the beam steering system? The proposed beam steering system, using retrodirective phase control for electronic steering, has a fail-safe mechanism. In the event of the loss of the uplink pilot beam signal from the center of the rectenna, the individual subarrays on the satellites one Km array antenna are no longer phase coherent, thereby defocusing the main beam by 1/# subarrays. This feature seemed to allay the concerns about beam wander. It also provided a method for turning on and off the power beam for maintenance and the times when the satellite is shadowed from the sun, (2) Grating Lobes – Grating lobes, which are replicas of the main beam at periodical spatial intervals, are dependent upon the mechanical alignment of the satellite's antenna and the size of the subarrays. This problem is greatly reduced by going to the higher frequency C-band system which has smaller subarrays and by imposing mechanical pointing requirements. Performance curves are shown later in the paper, (3) Power beam interactions with the ionosphere. Two concerns were: (a) burning a hole in the ionosphere, and (b) the excited region of the ionosphere would disrupt the uplink pilot beam signal. These issues were addressed in theoretical studies at Princeton University and experimental studies at the Arecibo Observatory in Puerto Rico by the Rice University. A test was performed using the 1000 foot Arecibo receiving antenna, a 30 meter high gain receiving antenna located 10 kilometers away, an ionospheric heater (antenna plus high-power transmitter operating at approximately 5.6 MHz) and a radio star which was the transmitter. The ionospheric heater heated the ionosphere above one of the two receiving antenna to an equivalent 23 milliwatt/cm^2 power density expected from an SPS. The signal from the radio star was received at both antenna which were coherently phase-locked. The two received signals were then compared to determine the relative phase jitter. The measured phase jitter was less than one degree RMS, which was within the phase error budget of the microwave system. The other concern of burning a hole in the ionosphere was theoretically analyzed. The heated area in the ionosphere would be swept away by the ever moving magnetic field lines and continually replaced by the particles outside the 10 kilometer area of the microwave beam, (4) Real estate for rectennas was a concern. This problem is reduced by operating at high frequencies, i.e., 5.8 GHz, and using larger satellite antennas which can handle multiple simultaneous beams, (5) Electronic out-of-band noise and far-side lobes from the main beam – A simulation was performed at the Johnson Space Center in which 100 SPS systems were operating incoherently. By accounting for the far-side lobes expected from the error budget for the microwave systems, the grating lobes, and the out-of-band noise generated by the klystron power tubes, the expected power density at every county-seat in the United States was determined. These levels (different for each county-seat location) were all less than the power density levels measured by the EPA in seven major United States cities in 1976. Thus the SPS microwave levels should not have been a factor for concern in 1981 and even more so now with the proliferation of cell phones, wireless networks, etc.

System Simulation Results

A phased array simulator program was developed to determine the microwave beam performance as a function of error parameters and configurations. Inputs to the program included: number and size of subarrays; amplitude and phase taper across the antenna surface; phase error due to jitter on the power tubes, retrodirective phase control distribution system, and ionospheric jitter; random subarray failures; subarray mechanical tilt; and antenna tilt. From these simulations, the error parameter budget, the main beam collection efficiency, the efficiency chain, the power scattered, the mechanical alignment requirements, and the antenna illumination functions were determined for both S-band and C-band systems. These results are presented in the main paper.

In addition a "super" SPS was developed using a larger transmit antenna which provided simultaneous power beams to multiple locations. The overall transmission efficiency could be improved significantly together with a reduction in rectenna sizes. This larger antenna used a complex antenna illuminator function to reduce the side-lobe levels and improve rectenna collection efficiency. Some of this date is presented.

Retrodirective Phase Control

A discussion of retrodirective phase control for electronically steering a singular beam or multiple beams is given. The main problem in 1980 was distributing a phase stable reference to each of the subarrays within the antenna. Fortunately, since that time the development of photonics has evolved to simplify the phase distribution. A scheme for compensating differences in time delay in the photonic distribution system due to the heat variations on the antenna has been developed at JSC.

Technical Improvements Since 1980

Several technical developments have occurred since 1980 which should enhance the SPS concept. In particular, the above mentioned photonic distribution scheme has been developed and solar cell conversion efficiency has greatly improved. The initial SPS design had thin silicon sheets of solar cells with conversions efficiencies of less the ten percent. Now multiple layer semiconductor cells with associated concentrators projected to have 50 – 60 percent conversion efficiency.

Demonstrations

In the late 1970's several power beaming demonstrations were very beneficial in bringing the SPS to the public. In particular, Richard Dickenson of the Jet Propulsion Laboratory developed a power beam test using a 30 foot Goldstone antenna to a rectenna and lighting a bank of lights. Other tests over a one mile range included Bill Brown's measurements of rectenna conversion efficiency and later, his Amplitron tests.

Before the SPS in geosynchronous orbit was fully defined, NASA initially designed a one megawatt "pilot plant" satellite for demonstrating power transmission from low earth orbit (LEO) to a ground rectenna. This idea was discarded due to costs. From a microwave system standpoint this demonstration did very little to solve the technical problems. The problems to be solved in this LEO satellite were not the same as in a GEO system's microwave system.

An outline of low cost demonstration tests to solve the problems in a microwave power beaming system is discussed.

Lessons Learned

- System transmission efficiency is very important for economic payback. A one percent increase in system efficiency provides a $160,000,000 increase in economic return over a 30 year lifetime.

- The public has to be involved and accept the idea of high power beamings with its risks, safeguards, and costs.

- Unfortunately, bigger microwave systems are better from an economic viewpoint.