

# Magnetically Inflatable SPS with Energy Storage Capability

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## Abstract

A new approach to Superconductive Magnetic Energy Storage (SMES) for Solar Power Satellite (SPS) with inherent rigidity is introduced in this paper. The rigidity of this SMES originating from the electromagnetic forces within it, can eliminate the need for mechanical building blocks for support structure. This force can also be used for the deployment of the system in space. In addition, the storage capability of the system allows its use in low earth orbit (LEO) which reduces the launching and transmission costs. The paper also discusses the basic design and the operation of the proposed SPS system.

## 1 Introduction

Superconductive Magnetic Energy Storage (SMES) has been studied for ground based electrical power systems for many years [1,2,3]. The application of the same concept to space power systems has also been suggested by some researchers [4,5]. In this paper we will introduce the concept of magnetically inflated (self supporting) SMES to the solar power satellite (SPS). FIGURE 1 shows a schematic diagram of the system. The rigidity of our magnetically inflatable solar power satellite (MISPS) originates from the inherent electromagnetic forces of a SMES ring. This can eliminate the need for mechanical building blocks to support the SPS structure. Thus, the weight and volume of the materials that are needed to be launched can be reduced. Furthermore, the SMES part of MISPS system can be launched in a collapsed form. Once in orbit, it can be “magnetically inflated” by a small source, such as a pilot solar photovoltaic or nuclear-electric energy source.

In addition to the self structural support, the MISPS concept will provide bulk energy storage capability to the SPS system. This will have an even more profound impact on its design and operation. The MISPS system can be built in small units and placed in low earth orbit (LEO). The launching costs to LEO are significantly lower than those of geosynchronous earth orbit (GEO), which are envisioned for the SPS. Furthermore, LEO will also reduce the microwave power transmission system size and complexity. Another advantage of a MISPS in LEO includes the possibility of multiple earth receiving stations from one or more orbiting systems.

A SPS is best assembled in LEO, where astronauts can work. Transfer to GEO is best done with electric propulsion rather than rocket engines. This involves slow transit through the van Allen belts, which degrade the silicon solar cells. In GEO

the array must then be annealed by infrared heating apparatus. LEO operation avoids this problem.

However, a MISPS in LEO will be in the line of sight of a receiving earth station only intermittently. Thus, the transmission from each MISPS unit is by periodic long pulses, while it is in line of sight. This difficulty can be alleviated by installing a SMES in the receiving station as well. Thus, the SMES system will act as a buffer between the intermittent source and independently varying electrical load at the ground station. Similarly, the SMES in MISPS will balance the variations of energy reception and transmission in each orbit.

The details of MISPS orbital behavior and its general design characteristics are the subject of the remainder of this paper.

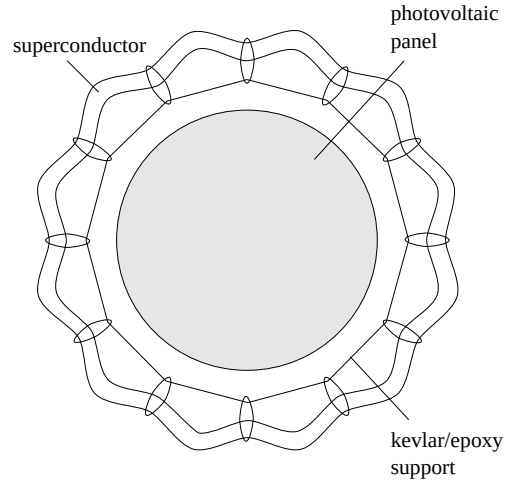


FIGURE 1: SCHEMATIC DIAGRAM OF THE MAGNETICALLY INFLATED SOLAR POWER SATELLITE

## 2 MISPS in LEO

Assuming an approximate equatorial orbital period of  $T \cong 100min$ , the line of sight fraction of the orbit, from a point on the equator, is ideally about 10%. Assuming power transmission during this segment of the orbit, the power transmission duration in terms of the period is

$$t_t = 0.1T \quad (1)$$

For this orbit the dark eclipsed segment in terms of the period is

$$t_D \cong 0.39T \quad (2)$$

Therefore the fraction of the period in which the satellite can receive solar energy will be

$$\begin{aligned} t_r &= (1 - 0.39)T \\ &= 0.61T \end{aligned} \quad (3)$$

When the SPS is in operational equilibrium the total energy received must be equal to the total energy transmitted per period. This implies that

$$P_t t_t = P_r t_r \quad (4)$$

where  $P_t$  is the microwave transmission power and  $P_r$  is the solar electrical received power. Substituting in terms of the orbital period,

$$P_t \cdot (0.1) = P_r \cdot (0.61) \quad (5)$$

$$P_t = 6.1 P_r$$

The power profile for one orbital period under the above scenario is shown in FIGURE 2.

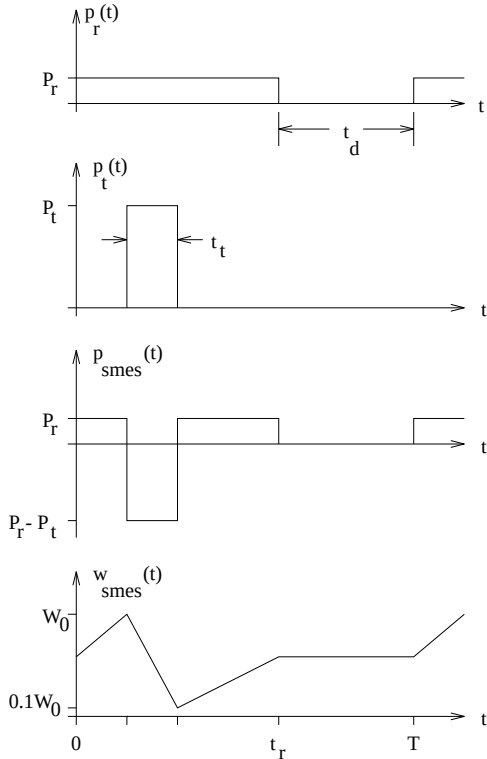


FIGURE 2: THE POWER AND ENERGY PROFILES OF MISPS FOR ONE ORBITAL PERIOD

The SMES power,  $P_{SMES}$ , is the balance between the received and transmitted power at any instant.

For structural integrity of the magnetically inflated SMES, we will assume a magnet current variation of from 100% to 33% of the nominal SMES current,  $I_o$ . The lowest SMES current ( $0.33 I_o$ ) will occur at the end of the transmission period,  $t_t$ . The highest SMES current ( $I_o$ ) will occur at the beginning of the transmission period. This implies that the energy content of the SMES is a maximum of  $W_o$  at the beginning of the transmission and  $0.1W_o$  at the end of transmission.

The energy rating of the SMES can be found from the above discussion as follows.

$$0.9W_o = (P_t - P_r)t_t \quad (6)$$

Therefore,

$$W_o = \frac{1}{0.9}(P_t - P_r)t_t, \quad (7)$$

or in terms of photovoltaic power rating and orbital period:

$$W_o = 0.57 P_r T \quad (8)$$

### Nonequatorial Orbits

The above calculations are for an equatorial orbit and receiving station. For a nonequatorial orbit and receiving station the MISPS's observation angle from the ground station will not be the same for each pass, due to the rotation of earth. This affects the power transmission time  $t_t$ . Furthermore, the solar energy receiving time,  $t_r$ , can increase from  $0.61T$  to  $T$ , as the orbit tends toward the polar. Conversely, the eclipse time,  $t_d$ , changes from  $0.39T$  to  $0$ . For example, in the polar orbit the MISPS can receive sunlight all the time if the orbital plane is normal to the sun rays and the receiving time,  $t_r$  will be equal to  $T$ .

For an SPS in equatorial orbit, receiving antennas are constructed to receive power from one point in the sky. Tracking antennas would be required for efficiently receiving power from an SPS in LEO.

The number of passes per day is also affected by nonequatorial systems. For example, in our example of the equatorial orbit and receiving station, about 14 passes per day occur. The number of passes drop to about 4 per day if the MISPS is in polar orbit. For a typical example of a  $60^\circ$  orbital angle of inclination (the angle between the equatorial plane and the orbital plane), and an earth station, having a  $+30^\circ$  latitude, the number of passes per day is about 8.

LEO satellites are subject to various perturbations. Air drag slows them, resulting in loss of altitude. Solar power with electric propulsion can be used for restoring orbit altitudes. Seasonal changes and other perturbations, such as gravitational, geomagnetic and solar pressure also affect the orbit and the eclipse time. These effects need to be accounted for and corrected by additional work which is outside the scope of this paper. The variations due to nonequatorial orbit and receiving stations also affect the energy storage and power transmission ratings of the MISPS. However, multiple satellite and earth stations will help even out the duty cycles of transmission and storage.

### 3 Design of the MISPS

The magnetically inflated loop serves two functions:

1. It provides structural support
2. It stores energy

Therefore energy storage capacity and force calculations are necessary for design. To simplify the calculations an ideal circular single conductor loop will be assumed for the MISPS (FIGURE 3).

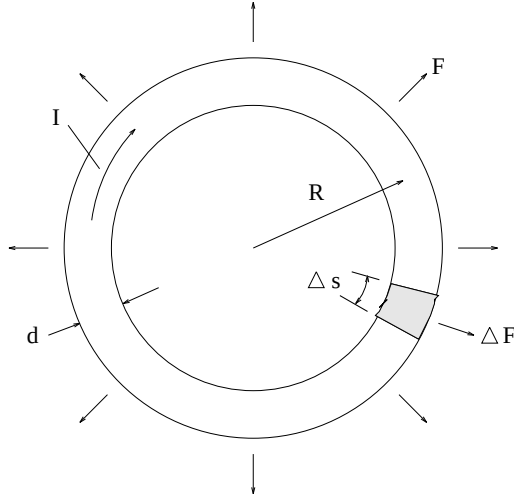


FIGURE 3: CIRCULAR APPROXIMATION OF THE MISPS COIL

The photovoltaic system and microwave antenna will be placed inside the loop as shown in FIGURE 1. Therefore to find the loop radius, the area of photovoltaic system (S) has to be calculated first. Solar intensity in the vicinity of the earth is about  $1.353 \text{ kW/m}^2$ . Therefore, conservatively assuming an electrical output power of  $100 \text{ W/m}^2$  for the P.V. system, its surface area is

$$S = \frac{P_r}{100}, \text{ m}^2 \quad (9)$$

If a disk P.V. panel is used, its radius will be

$$R_{pv} = \sqrt{\frac{P_r}{100\pi}}, \text{ m} \quad (10)$$

The SMES loop radius  $R$  will have to be greater than  $R_{pv}$  in our design.

The loop inductance can be approximated as follows where  $d$  is the conductor cross sectional diameter in meters.

$$L = 4\pi 10^{-7} R \cdot \ln\left(\frac{2R}{d}\right), \text{ H} \quad (11)$$

The above expression is derived under the assumption of a very low aspect ratio coil [6].

The radial force,  $F$ , can be calculated from the energy conservation principle [7].

$$F = \frac{dW}{dR}, \text{ N} \quad (12)$$

This force is the total force around the loop. The radial force on the loop is

$$F_R = \frac{\Delta F}{\Delta S} = \frac{F}{2\pi R}, \text{ N} \quad (13)$$

From (10), (11), (12) and (13) we get,

$$F_{R,MAX} = \frac{2 \times 10^{-7} I_o^2}{R} \ln\left(\frac{2R}{d} + 1\right) \quad (14)$$

If the maximum current density of the superconductor is  $J_c$  and its cross section is  $A$ , the maximum loop current will be

$$I_o = A \cdot J_c = \frac{\pi d^2}{4} J_c, \text{ A} \quad (15)$$

Assuming a maximum energy storage of  $W_o$ , the maximum loop current will be

$$I_o = \sqrt{\frac{2W_o}{L}}, \text{ A} \quad (16)$$

From (13), (14) and (15) we will get

$$d^4 \ln\left(\frac{2R}{d}\right) = 2.58 \times 10^6 \frac{W_o}{J_c^2} \quad (17)$$

This is a useful design equation for finding the total cross sectional diameter of the superconductor and the required current density when  $W_o$  and  $R$  are given.

### 100 MW MISPS

An earth orbiting MISPS having a period of 100 minutes was assumed. The power transfer duration,  $t_t$ , the dark eclipsed segment,  $t_o$ , and the period during which the satellite can receive solar power,  $t_r$ , are as follows

$$\begin{aligned} t_t &= 10 \text{ min} \\ t_o &= 39 \text{ min} \\ t_r &= 61 \text{ min} \end{aligned}$$

From (4) the solar electric power is

$$\begin{aligned} P_r &= P_t \cdot \frac{t_t}{t_r} \\ &= 16.4 \text{ MW} \end{aligned}$$

From (7) the maximum energy to be stored is

$$\begin{aligned} W_o &= \frac{1}{0.9} (100 - 16.4) \times 0.167 \\ &= 15.5 \text{ MWh} \end{aligned}$$

Using (8) the required photovoltaic area is

$$S = \frac{16.4 \times 10^6}{100} = 16.4 \times 10^4 \text{ m}^2$$

This is the area of a disk with 228 m radius. The superconductive loop around this circular panel will be far enough away to have a negligible magnetic field effect. The superconductive loop radius is chosen to be  $R = 250 \text{ m}$ . For a  $J_c = 500 \text{ A/mm}^2$  and  $W_o = 15.5 \text{ MWh}$  the loop conductor cross section diameter can be obtained from (17) to be  $d = 13 \text{ cm}$ . From (16) we find,

$$I_o = 6.6 \times 10^6 \text{ A}$$

This current is for single turn superconductive loop. In order to impose a reasonable current, e.g., 1 kA, on the power converter, the loop can be made of 6600 turns.

From (13) the radial force is found:

$$F_R = 30.5 \text{ ton/m}$$

The above force is an approximation for a circular SMES. A practical design would utilize a rippled loop configuration as shown in FIGURE 1. The loop is supported by a polygon of

Kevlar under tension. The details of this basic design will determine the exact tensile forces on the Kevlar and superconducting components.

Assuming a superconductor density of  $3g/cm^3$ , the total weight of the conductor will be

$$M_{sc} = 63 \text{ tons}$$

The 100 MW MISPS specifications are summarized in TABLE I.

TABLE I: 100 MW MISPS SPECIFICATIONS

|                                          |                      |
|------------------------------------------|----------------------|
| Orbital period                           | 100min               |
| Solar Panel Radius                       | 228m                 |
| Superconducting loop radius              | 250m                 |
| Maximum Stored Energy                    | 15.5MWh              |
| Radial Force (max)                       | 30.5ton/m            |
| Total superconducting loop cross section | 133cm <sup>2</sup>   |
| Max superconducting loop current density | 500A/mm <sup>2</sup> |
| Number of turns of the coil              | 6600 turns           |
| Coil current                             | 1kA                  |
| Conductor Weight                         | 63,000kg             |

#### 4 Comparison of SPS in GEO vs LEO

One major difficulty with SPS in geosynchronous is the large spot on earth which is illuminated by the microwave beam. This area must be mostly covered by the receiving rectenna array if the power transmission efficiency is to be high. Thus the area of the rectenna array is fixed by the distance (24000 miles for GEO) and the frequency of the microwave beam (2.45 GHz in the baseline design). Efficient use of the rectenna array then requires an energy density in the beam such that the rectenna elements are loaded up to their ratings. To fit an economically viable design into the above framework, a baseline design of 5000 MW has been suggested. Of course, this also requires a correspondingly large photovoltaic array and transmitting capability on the SPS. Hence, the weight of the SPS which must be placed in geosynchronous orbit is large. Accordingly, the cost of a single SPS is very high and incremented development is really not possible.

However, the advantage of the GEO SPS is the almost 100% utilization of both the transmitting and receiving elements. This follows because the photovoltaic (PV) array in orbit is almost always illuminated by the sun. Considering the LEO SPS, proposed in this paper, the PV array is illuminated only about 2/3 of the time, thereby diminishing the utilization factor of the PV array. Furthermore, the rectenna site on earth is only within view of the orbiting SPS for a small fraction of the orbit. The above window is further constricted if the rectenna and the SPS orbit are not on the equatorial plane. Therefore, the utilization factor of the rectenna site will be very low if only one SPS is in orbit. Clearly the utilization factor of a rectenna site will improve if more than one SPS is in orbit. Furthermore, if more than one rectenna site exists on earth, the SMES capacity of the SPS can be reduced since the collected energy will be transmitted more frequently.

The spot on earth illuminated by a microwave beam of a given frequency with lower orbits, e.g., 2.45 GHz, will be proportionately reduced as will be seen in the following section. Thus, using the argument given earlier, capability, and hence weight and cost, of a LEO SPS will be much less than a GEO SPS. This would reduce the financial (and political) cost of a first SPS launch and would, it seems, facilitate an incremental development of a scheme with multiple SPS in orbit and multiple rectenna sites around the earth.

#### The Impact of Orbital Radius on the Antenna

The size of sending and receiving antennas are dramatically reduced by the concept of magnetically inflated solar power satellite (MISPS) in LEO, as compared to GEO. This is evident from the following. At a given frequency, the efficiency,  $\eta$ , of a microwave transmission is approximately given by

$$\eta \leq k \frac{A_s A_r}{D^2} \quad (18)$$

where  $A_s$  and  $A_r$  are the sending and receiving antenna areas,  $D$  is the separation distance and  $k$  is a constant [9]. For example, from GEO to a LEO of 480 miles, the distance is reduced by a factor of 46. Therefore, both sending and receiving antennae areas will be reduced by about 7 times. However, the line of sight fraction of the orbit for a point on the ground will also be substantially reduced; e.g. by a factor of 3. Therefore, for the same amount of energy, transmission has to be tripled. This will also modify the antenna sizes to some extent.

A problem with the GEO antenna is side lobes and refractions. With careful phased-array design, earth-impinging side lobes can be avoided. Any metal object exposed to the beam will refract 2.45 GHz power, scattering RF power with intensity high enough to swamp nearby receiver inputs. Glint from the receiving antennas contains significant RF power. Also, RF power can affect pacemakers.

#### 5 Superconductor, Cryogenic and Support Material

*NbTi* can be chosen for the superconductor material. It has a critical current density,  $J_c$ , greater than  $3000A/mm^2$  [8]. In our design  $J_c$  is assumed  $500A/mm^2$  for quench protection.

The cryogenic system will use liquid *He* to keep *NbTi* below  $4^\circ K$ . The helium can be placed between the superconductor and an aluminium vacuum jacket.

The superconductor is subject to a high tensile force in normal operation. *NbTi* with copper or aluminum stabilizer can not withstand this force. Therefore Kevlar/epoxy tensile supports must be used. This material has excellent tensile strength and fatigue properties [4].

#### 6 Conclusion

In this paper we have introduced the concept of superconductive magnetic energy storage to the solar power satellite. The potential benefits of this concept are manifold, as described in the paper. All of these benefits stem from the two basic characteristics of MISPS which are energy storage and structural self support.

Perhaps the most important benefit of the MISPS concept is its economic flexibility. The system can be composed from several smaller orbiting units. The number of these units can be gradually expanded from one to the minimum number needed to have one MISPS in the line of sight of an earth station at all times. This evolutionary expansion can be financed by a bootstrapping strategy, where part of the payback of the installed system is reinvested in the next MISPS unit. This economic strategy can be enhanced by selling power to several isolated earth receiving power stations.

Several disadvantages can also be envisioned for the MISPS concept, perhaps the most prominent among them being the application of an unproven SMES technology and its associated complexities. Furthermore, the mechanical forces resulting from the interaction of the SMES magnetic dipole and the earth's magnetic field can destabilize the MISPS. However, spin stabilization and active timing should provide adequate means of correcting this problem.

A significant amount of basic research remains to be done on the MISPS concept. Among these are conceptual design of the magnet and its tensile support structure, the cryogenic and other support requirements of the SMES and the power electronics required for electrical energy conversion on both receiving and transmission sides of the orbiting MISPS.

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## Biographies

**M. Ehsani** (S'70-M'81-SM'83) received the Ph.D. degree from the University of Wisconsin-Madison in 1981, in Electrical Engineering.

Since 1981 he has been at Texas A&M University, College Station, Texas, where he is now a Professor of Electrical Engineering. He is the co-author of more than 95 technical papers and one book and an IEEE Standards book, over the past twenty one years. Three of these papers have received prize paper awards in IEEE-IAS. He has also been honored by Texas A&M University as Halliburton Professor and Dresser Industries Professor. His current research work is in power electronics, motor drives, hybrid vehicles and their control systems.

Dr. Ehsani has served on the Ad Com of Power Electronics Society, Executive Council of Industry Applications Society, and as chairman and member of several technical committees, in both societies. He is a Distinguished Speaker of Industrial Electronics Society and a registered Professional Engineer in the state of Texas.

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**Joydeep Mitra** (S'94) received his B.Tech.(Hons.) degree in Electrical Engineering from the Indian Institute of Technology, Kharagpur, in 1989. From 1989 to 1991 he worked with TATA Steel, India, as an Electrical Engineer. Since 1992 he has been pursuing his Ph.D. degree at Texas A&M University. His doctoral research focuses on the areas of power system reliability analysis and production cost analysis. His research interests also include unconventional power resources, space power systems, and power system analysis, optimization and control.