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Spacecraft Electrical Power Management Systems – System Review

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***Abstract*—This paper presents space electrical power management and energy storage systems. For any space satellite system to be effective, an electrical power supply system is required to supply constant power to all the components and subsystems. The main purpose of the electrical power system is to provide regulated power to space satellites loads during launch. The effective construction of the electrical power system determines the space system life span. The lifetime of the system is affected by the debilitation of the solar arrays with time. The battery capacity is also deteriorated when run over an extended number of cycles. This study explores possible methods to an effective electrical power system design that would alleviate space satellite system failures.**

***Keywords*—Space, battery, energy, hybrid, storage, solar**

I. INTRODUCTION

The decline of available resources to produce constant electrical power to supply the world's energy demand has inspired researchers to determine alternative energy sources. Solar energy in space is one of the effective and attractive alternative resources that can produce sufficient and sustainable power to fulfil all the needs of energy demand. Solar energy in space solar power is the concept of harnessing solar power in space using a satellite power system. Space-based solar power system uses embedded solar arrays to harvest the energy of sun which can be converted to DC to supply other systems with power. The system has the benefits of a higher harness rate and a longer collection time due to the lack of a dispersing atmosphere and weather conditions. The harnessed solar energy is converted to microwaves and transmitted back to the Earth's surface via a rectifying antenna called rectenna.

The launch of this satellite system requires an on-board electrical power system to supply power to all the subsystems and components of the spacecraft during mission. The electrical power system is a critical unit for any space mission as any electrical failure will lead to the failure of the mission or unsuccessful launch. Fig.1 shows the block diagram of a space-based solar power satellite system (SSPS). The system comprises of a space antenna also known as Sunsat and a rectifying antenna known as rectenna. Advance space power and energy storage systems will improve the performance of spacecraft even if it is further away from the sun where solar energy is not accessible. The design of the space power system is required to withstand any environmental conditions which can range from high radiation levels to very high or low temperatures. The power system should be able to operate under any challenging environment to prevent mission failure.

Electrical power supply system is one of the key sections of any space satellite. Mass is the main design parameters for the construction of any space satellite system [1]. The electrical power system can consume a mass in the range from 20% to 75% of the total space system mass [2]. The reduction of mass in the solar array reduces drag in lower orbits satellite level [3]. There is a need to explore possible solutions to reduce mass in the electrical power system and one of the solutions would be the insertion of hybrid PV and rectenna array power supply system. Insufficient power system would lead to the failure of any space satellite system. Analyses done on Earth-orbiting space satellite systems indicated that electrical power system failures contribute to a quarter of most space systems failures in space [4]. Tafazoli also analyzed 130 spacecraft and discovered that most power failures are caused by the deterioration of the solar array and battery failure also accounts for less than a quarter of failures [5].

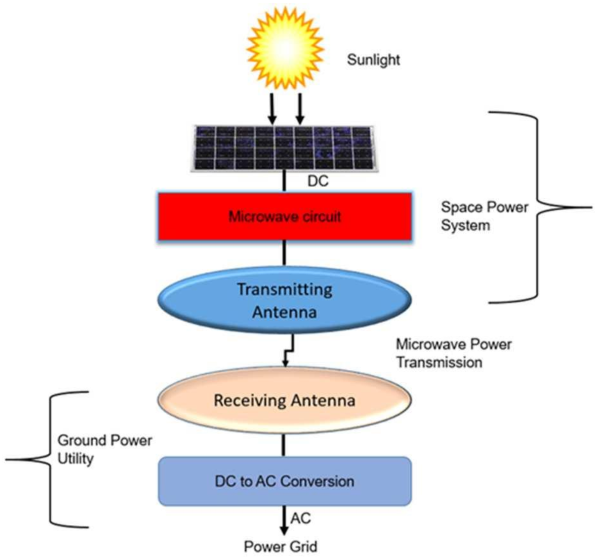

Fig. 1: SSPS block diagram

II. SPACE ELECTRICAL POWER SYSTEM

This system controls the electrical power to all space satellite systems. The system design is a key parameter to determine the satellite life span. A successful launch of any space mission required continuous supply of power to all the subsystems of the spacecraft. The size of power controllers and regulators also affect the efficiency of the system [1].

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The electrical power system contributes to the reliability of any space system. Most of the power failures involves the solar arrays of the system. Rectenna array, solar photovoltaic array and a combination of hybrid solar photovoltaic and rectenna array are the main power generation systems in any space satellite mission [1]. These systems have to be analysed to determine the best system that can gain from the changing power beam medium.

Photovoltaic solar arrays are widely used as the primary energy source for earth orbiting satellite systems. Satellite systems in low earth orbit mission are exposed to 15 eclipse periods every day which degrades the performance of the solar cells due to solar radiation and temperature changes [6]. The GaAs solar cells have high efficiency and radiation resistance and therefore are mostly preferred for space systems applications [6].

The next power generation system to consider is the rectenna array. This generation method can achieve an efficiency of 85-92% at the frequency of 2.45-GHz [7]. The last system to be considered is the combination of hybrid photovoltaic and rectenna array power system [8]. This system can generate power from solar and microwave sources [9]. The integration of the solar arrays on the radiating system of the radio frequency collector maintains the system compactness [9]. The combination of these structures would reduce the space satellite mass without affecting the performance of the solar array or antenna [10]. Fig. 2 shows a block diagram of space electrical power system. The rectifier is determined by the power density and frequency range. A low-pass filter is connected to the output of the rectifier to restrict any RF energy from flowing into the power management system [11].

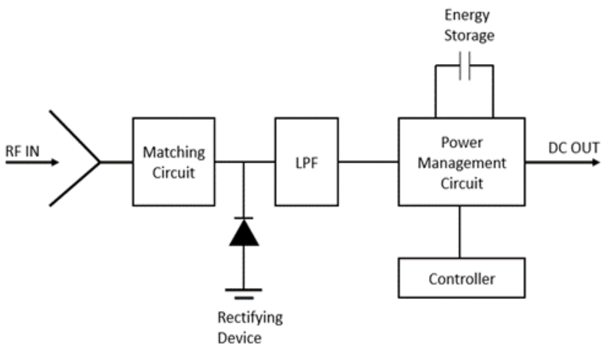

Fig. 2: Space Electrical Power System [11]

III. Electrical Power Management System

The power management system attributes to the power conditioning, charge and discharge control. The methods that are used in this system include the directive energy transfer and the peak power tracker. Electrical energy is sent directly from the photovoltaic panels to the loads without any control system in the directive energy transfer system [12]. The solar array is conditioned to work at the same voltage level with the bus in this system. Peak power tracker technique has an additional regulator placed between the photovoltaic panels and the load. In the peak power tracker method, the bus and solar array operate at different voltage levels. The peak power tracker architecture is more reliable for missions in low earth orbit which has huge solar flux variations [12]. The directive energy transfer system can be utilized in a rectenna array equipped with space satellite system but the power density flux can cause large ranges of voltage variations. Fig. 3 indicates the block diagram of the power management system.

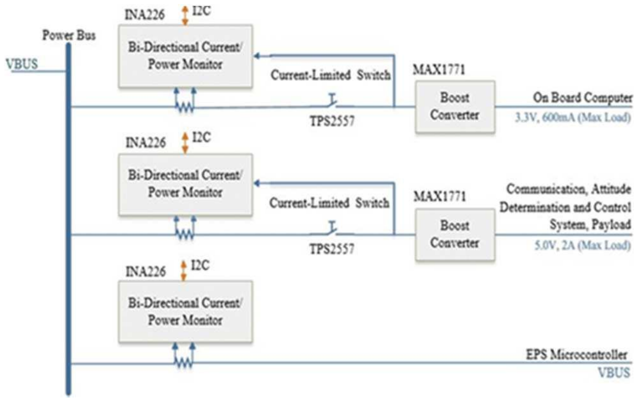

Fig. 3: Block Diagram of Power Management System.

The power monitor is equipped with a DC regulator which stabilizes the voltage to the power bus. The charging system regulates the voltage from the bus to supply allowable output charge to all equipment of the power storage system. The current and voltage levels are monitored from the storage system to trace any system failure and maintain the storage components charge and discharge rate within the design parameters. If a fault occurs in any of the subsystems of the satellite, a control switch isolates the power to that load. This is controlled by the set parameters in the microcontroller.

The peak power tracker has an advantage of tracking the solar energy at all times but system requires an advance circuit design which makes it complex [12]. This system can also increase the weight and heat dissipation in the satellite system [3]. The importance of peak power tracking is the utilization of maximum incident solar energy. Another power management technique which is the gimbal system, can be connected to the photovoltaic array to rotate it to track the sun during orbit. This allows the system to capture massive amount of solar energy to compensate for any power losses [13]. This is one of the advance electrical power design system which is not widely used due to its complexity. Table I indicates the advantages of solar tracking mechanisms.

TABLE I. Advantages of Solar Tracking Mechanisms [14]

System	Advantages	Applications
Gimbal	Constantly tracing the sun for maximum energy harvesting	Large variations in solar array
Regulated Direct Energy Transfer	More efficient and provides regulated voltage.	Large solar array power/voltage variations
Un-regulated Direct Energy Transfer	It has a very high power transfer.	Small load and power variation for most of Sunlight period.

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Peak Power Transfer	Maximum use of solar energy and therefore battery charge regulator is not required.	Large variations in solar array illumination during launch.

IV. Energy Storage

A space satellite system that uses photovoltaic array method requires energy storage for eclipse periods [6]. Space satellite system that uses a rectenna array technique stores power for use outside the microwave beam. The main secondary energy sources to consider as energy storage system are batteries and super-capacitors. The photovoltaic energy source systems are recharged using the sun's energy while rectenna arrays are recharged within the microwave beam. The space satellite depends highly on the pre-charged secondary power source during eclipse periods. Lithium Ion (Li-Ion) is mostly used as rechargeable battery for space satellite missions [6]. The depth-of-discharge is the main characteristic for batteries. Li-Ion has a depth-of-discharge of 20-40% in low earth to prevent overcharge of the batteries [15]. To maintain a longer mission life, the following options have to be considered; (a) batteries with higher power irradiance and depth-of-discharge, (b) adequate and flexible mission profiles and (c) use more efficient cells or enlarge the solar array area. The efficiency of the system increases when the satellite reaches the power beam center and decreases at lower power density levels [16].

Rectifiers have the characteristics to operate within certain power levels for wireless energy applications. The power density levels change when the satellite passes through the power beam [17]. The diode impedance varies which gives a different value as compared to the actual design impedance of the circuit. Resistance compression networks can be placed before the rectifier to reduce the load sensitivity [17]. Fig. 4 shows a schematic diagram of the energy storage system.

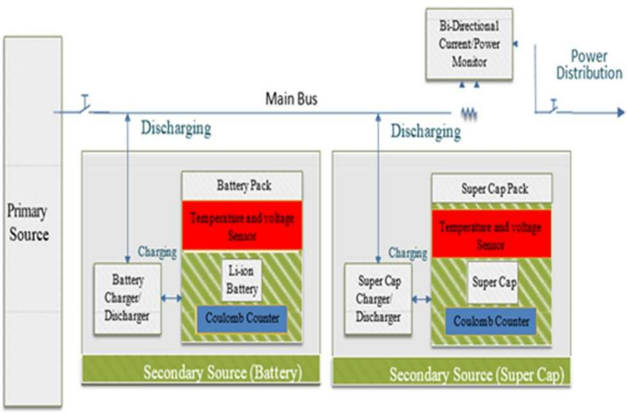

Fig. 4: S Energy Storage Subsystem

Increasing battery capacity through the installation of super-capacitors needs extra mass. Since rectenna arrays are much lighter than the photovoltaic array, the reserved mass can be used to maximize the power storage capacity. The combination of super-capacitor and battery increases the power of the system during peak-power periods [18]. Energy storage devices can be compared based on energy and power density, endurance and the cost as indicated in Table II. The energy density is the amount of energy that the device can hold per unit mass or volume which has a critical effect on efficiency and performance of the system. For batteries, the input and output power is different depending on the present level of charge and the technology used [19]. The endurance determines how long the device can store and reproduce its energy capacity. The super-capacitor technology is a high density capacitor where charge and discharge rates can be very high and can be repeated often without damaging the device. There is no conditioning of the input and output energy flow required for this type of energy storage system. Table III shows the comparison of different types of batteries.

TABLE II. Energy, Power Density and Endurance of Energy Storage System [19]

Type	Energy $Wh.kg^{-1}$	Power $W.kg^{-1}$	Number of cycles
Lead Acid battery (Panasonic,2022)	18 - 40	25 - 80	200 - 600
Ultra Capacitors (Maxwell Technology, 2022)	2-30	150 - 5 100	200 000
Nimh battery (Battery space, 2022)	40 - 85	200 - 600	2 000
Li-polymer battery (Dixon Batteries, 2022)	60 - 130	300 - 2 800	600
H_2fuel Cell[2] (Ebay, 2022)	33 600	$8.4MW\ell^{-1}\ s^{-1}$	N/A

TABLE III. Comparison of Different Types of Batteries [20]

Battery Type	Advantages	Disadvantages
Lead-Acid (sealed)	Very cheap and reliable.	Has low energy density and cannot be stored when discharged.
Lithium-Ion	Has very high energy density. Has a better cost-performance ratio.	Needs a protection circuit to avoid overheating.
NiCD	Has Fast and simple charge. Has good load performance and Cheapest.	Has low energy density and high self-discharge.
NiMH	Has very high energy densities. Environmentally friendly.	Limited service life, High self-discharge. Performance degrades at high temperatures. High maintenance.

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Another option to provide constant power supply to the system is to reduce the batteries usage when the temperature is very high or low to allow the super-capacitor to reboost. The stored power in the energy storage facility is used on peak power periods. Rectenna array section of the hybrid energy system can be used to redirect power to the super-capacitor system for peak periods usage.

V. Conclusions

Space satellite missions require effective power systems and components to survive the different types of extreme environmental conditions. Electrical power supply is a critical limitation for any space exploitation and the availability of constant power supply paves way for many space missions to be accomplished. This calls for the development of high efficient cells that can effectively operate under low intensity and solar arrays that can operate at high temperatures for a longer period of time. The harvesting of constant solar energy available in space can actually be used to supplement the electrical power system of space satellites. This energy source can also be beamed to the ground station to provide electrical energy for use. This system can also be used as a power supply system to other spacecraft in orbit.

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