

New Architectures for Space Power Systems

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Abstract

Electric power generation and conditioning have experienced revolutionary development over the past two decades. Furthermore, new materials such as high energy magnets and high temperature superconductors are either available or on the horizon. Our work is based on the premise that new technologies are an important driver of new power system concepts and architectures. This observation is born out by the historical evolution of power systems both in terrestrial and aerospace applications.

This paper will introduce new approaches to designing space power systems by using several new technologies.

1 Introduction

As commercial and military use of space expands, increasing demands are placed on the space power systems. These demands may be summarized as follows:

1. Increasing load power
2. Single power bus rather than multiple buses
3. More efficient use of power generation units
4. High power densities (weight and volume)
5. Improved system stability
6. Reliability

This work is a fundamental search for new power systems to meet these demands [1,2,3,4].

Available technology is generally used as the starting point for developing space power systems. Our initial starting point in searching for new possible architectures for space power systems was the superconductors. The fundamental design in conventional power systems is based on near perfect insulation technology and imperfect conductors. However, in the space environment insulators behave far from perfect and this imposes severe limitations on the magnitude of available voltages. Furthermore, the presence of plasma, which is unavoidable in space environments, adversely affects high voltage configurations, causing large power losses. Therefore, efficient use of high currents is an attractive candidate for building high power systems in space. This, of course, necessitates the use of superconductors. To the authors' knowledge an architectural study to optimally utilize superconductors has not appeared in the literature up to now. At the present time there is intensive research in superconductors all over the world. Also, there is a strong

belief that room temperature semiconductors will be a reality in the not too distant future. Therefore, conceptual design of superconductive power systems for space applications seems timely.

The most common justification for using superconductors in power systems is the elimination of conductor losses. However, superconductors are not merely perfect conductors. They have other properties that may be useful. These are high current carrying capability, magnetic shielding, quenching and Meissner effect. The major benefits of superconducting power systems are:

1. At a given voltage the power capacity of a superconducting cable is much higher than that of a conventional cable
2. The superconducting cable can be built to operate at surge impedance loading and the transmission problems related to reactive power can be eliminated [5].

One of the architectures (Current Source Current Intensive System) proposed in this paper utilizes the first benefit while another architecture (Articulate System) incorporates the second.

2 Basic Architectural Study

Electric power is the product of voltage and current. In general, to transmit a given power the amplitudes, shapes, and frequencies of voltage and current can be selected in many different ways. Voltage-current sizing generally depends on the available technology. TABLE I is a classification of power system architectures based on V-I amplitudes and source behavior. This table shows the positions of the first power system in the U.S. (DC), high voltage AC (HVAC) and high voltage DC (HVDC) systems. Superconducting Magnetic Energy Storage (SMES) is a new architecture and occupies a new place in the table. An extension of the SMES concept leads to the Current Source Current Intensive (CSCI) System which is a subject of our study. Furthermore, given total freedom in V-I source behavior, afforded by the modern power electronics technology, we have arrived at the Articulate power system. The Articulate power system is feasible with extensive use of modern power electronics and microcomputer control technologies [6,7].

Our study has shown that there are many possible power system architectures. However, only three or four of these possible architectures are presently used to technological and historical reasons. TABLE II shows the historical development of new system architectures based on the available technologies

at the time. This table also suggests that power systems history is on the verge of another major leap forward.

TABLE I: POWER SYSTEM ARCHITECTURES

		V - I INTENSITY					
		HIGH VOLTAGE		HIGH CURRENT		MODERATE V-I	
		AC	DC	AC	DC	AC	DC
		High Voltage AC [FACTS]		Voltage Source Current Intensive	[SMES]	Aircraft and Space Power Systems	First Electric Power System
SOURCE BEHAVIOR	STIFF		High Voltage DC	Current Source Current Intensive			
	SOFT	Articulate Power Systems (AC and DC)					

FACTS: Flexible AC Transmission Systems

SMES: Superconductive Magnetic Energy Storage

The quantum leap in power system design will be based on superconductors, power electronics, and computer control. Space vehicles may be among the first to benefit from these new developments due to their unique combination of high constraints and increasing performance demand.

TABLE II: HISTORICAL DEVELOPMENT OF TERRESTRIAL POWER SYSTEM ARCHITECTURES

TECHNOLOGY	ARCHITECTURE
Battery, DC Generator, DC Motor, Incandescent Lamp	First Electric Power System, Pearl Street, New York, 1882
Transformer, Induction Motor, Synchronous Generator	First 3- ϕ AC Power Supply, Germany, 1891
High Power Rectification and Inversion	First HVDC Power System, Sweden, 1954
Superconductors, High Power Processing, New Generators, Computers	?

3 The Current Source Current Intensive Power System

This new concept has a single line (one conductor) power transmission and distribution configuration. A Current Source Current Intensive (CSCI) system with Superconductive Magnetic Energy Storage (SMES) is shown on FIGURE 1. It is seen that there is only one current path in this series system. When the SMES is not used it is crowbarred (short circuited). When the circuit operates without SMES, its current is controlled by one of the converters. Each converter can be either a rectifier or an inverter. Converters can easily be added or removed by shorting out and power can be quickly reversed. Therefore, direct current circuit breakers are not needed. However, in a CSCI system, an open-circuit fault would be catastrophic, and circuit makers (crowbars) would be needed to clear such faults.

Independent power control is achieved at each terminal without the requirement for a high speed load dispatch control. Power variations at various terminals are automatically compensated for at the current controlling terminal. However, in the series system without SMES enough inductance should be added in the loop to help stabilize the loop current.

When a SMES is used in the series system for energy storage it can be connected without an interface converter. In this case short term current can be controlled by the SMES. The SMES will be charged when the power demand is lower than generation and will be discharged when the demand is higher. Therefore load leveling is possible. This will help reduce the size of generating units. For example, when a rotating generator is used it can be operated at its most efficient power rating. Furthermore, when a solar generating unit issued, stored energy will be able to supply energy to the system while the space is in the shaded area of the orbit.

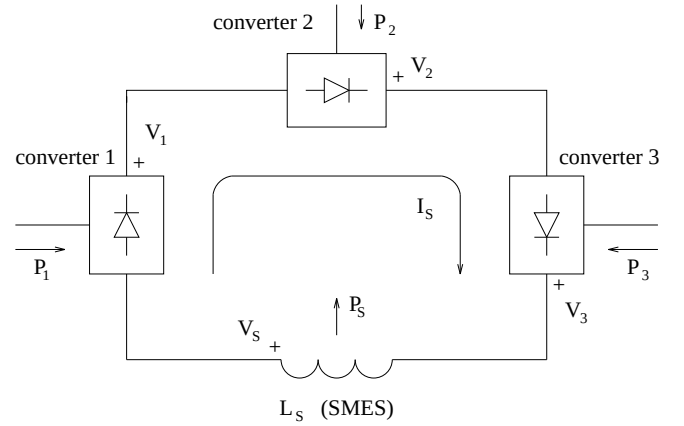


FIGURE 1: CSCI POWER SYSTEM ARCHITECTURE

A CSCI system with SMES will not operate at constant current over a long period of time. In general, current will change very slowly with time. However, a ratio of one to three current change is enough to discharge 90% of the SMES energy because the solar energy is proportional to the square of the system current:

$$W = \frac{1}{2} L I^2 \quad (1)$$

The performance of the system can be characterized by the following equations for the configuration given in FIGURE 1.

$$P_1 = V_1 I_d \quad (2)$$

$$P_2 = V_2 I_d \quad (3)$$

$$P_3 = V_3 I_d \quad (4)$$

$$P_s = V_s I_d \quad (5)$$

$$P_1 + P_2 + P_3 + P_s = 0 \quad (6)$$

$$L_s \frac{dI_d}{dt} = \frac{P_s}{I_d} \quad (7)$$

where power electronic voltage variations are assumed virtually instantaneous in comparison with I_d variations.

Space Application of CSCI

In certain applications, such as on a space platform, the superconductive transmission line can also serve as an integral

superconductive magnetic energy storage device for the system. Thus, the CSCI power system can supply large variable loads from a small continuous power source. Furthermore, the inherent magnetically stored energy of the system can be used to supply pulsed loads for civilian and military applications.

In addition, the electromagnetic forces (Lorenz Force) generated by the high currents in this system can be utilized for structural support in space. For example the CSCI transmission line can be transported into space in collapsed form. For deployment a low power source, e.g. solar photo voltaic collectors, “charge up” the system to its operating high current (FIGURE 2). Thus, an operational CSCI power system will not only store energy and distribute electric power to the loads in the space structure, but will also expand to a predestined rigid structure under stress.

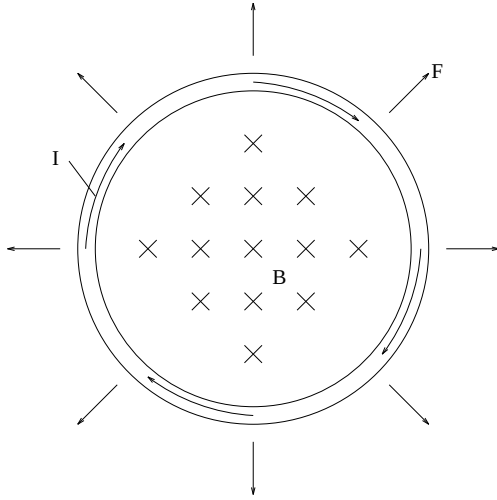


FIGURE 2: MAGNETICALLY INFLATED LOOP

Such a “magnetically inflated” structure which is also integral to the CSCI power system can save on weight and volume of structural materials in space. The above CSCI power system concept will have the following characteristics:

1. eliminate chemical energy storage with associated maintenance and replacement needs
2. reduce the generation unit size
3. can supply pulsed power
4. can provide inherent mechanical rigidity
5. has reduced insulation requirements

However, the intense magnetic field near the CSCI conductor may create safety and technical problems. These problems can be eliminated by superconductive shielding of the conductor [7]. The shielded CSCI power system loses its inherent ability to store energy. However, this can be remedied by discrete SMES units which can be connected to the system without any power electronic interface. Another solution may be separation of the loads from the CSCI system by use of “umbilical cords.”

Problems with Super High Currents

Superconductors might be well utilized for high currents. However two main problems arise:

1. Switching of high currents for power transfer to and from the CSCI loop is problematic. Semiconductor switch losses become significant due to conduction voltage drops. One solution to this problem may be to use superconductive switches [9,10]. A superconductor can be operated as a switch in two ways.

- (a) Heat injection technique: a small amount of heat is injected into the superconductor to cause some resistance. Super current causes additional heat. Therefore a positive feedback cycle starts and the superconductor goes into normal regime quickly.
- (b) Magnetic quenching method: a magnetic field greater than critical magnetic field of superconductor is applied, the superconductor goes into normal regime and circuit opens.

2. High magnetic field due to high currents may be hazardous to the personnel and instruments around. As in the switching problem, superconductivity can offer a solution to this problem [8]. Using superconductive shielding techniques most of the magnetic effects can be eliminated. This principle is as follows. When a magnetic field exists on the surface of the superconductor, surface currents are created. These currents impose an equivalent opposite field; therefore, the outside field can not cross through the superconductor. In other words, the superconductive surface behaves as a magnetic mirror. Shielding the superconductor can be accomplished in a coaxial structure. The example circuit given in FIGURE 1 is modified to a coaxial transmission as shown in FIGURE 3.

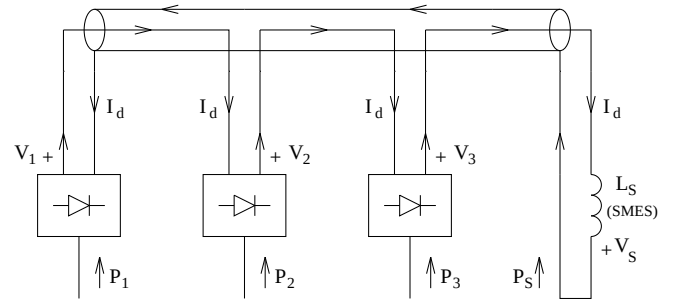


FIGURE 3: SHIELDED CSCI POWER SYSTEM

4 Articulate Power Systems

This architecture can be applied with or without superconductive technology. In the articulate system, voltage, current, and frequency are all flexible and can be controlled, in real time, to optimize the power system performance under varying conditions. For example, in an AC Articulate Power System, it may be desirable to operate the transmission line with continuous natural loading, even as the load varies randomly and the system frequency is varied to continuously minimize the generation losses. In this case the system performance equations will be:

$$\frac{V(t)}{I(t)} - Z_0 = 0 \quad (8)$$

$$V(t)I(t) - P(t) = 0 \quad (9)$$

where $V(t)$ and $I(t)$ are the power system operating voltage and current, Z_0 is the transmission line surge impedance and $P(t)$ is the load power demand. Solution of the above equations gives,

$$V(t) = \sqrt{Z_0 \cdot P(t)} \quad (10)$$

$$I(t) = \sqrt{\frac{P(t)}{Z_0}} \quad (11)$$

Therefore, the system voltage and current is continuously optimized (by power electronic means) in accordance to the above expressions. The system frequency is independently optimized in response to the generator state vector and the load demand.

Example of an Articulate System

An example AC articulate power system is shown in FIGURE 4. When the transmission voltage and current satisfy equations (10) and (11), the generator at the sending end has to supply only the real load power. Transmission voltage can be adjusted by controlling the field winding current of a synchronous generator or by a sending end power converter. At the receiving end a Unity Displacement Factor Frequency Charger (UDFFC) [11] presents a unity displacement factor load (resistive load) to the receiving end transformers and a constant frequency and voltage to the load regardless of the load power factor. Since the line voltage is set at an optimal value, a wide range tap changing transformer is required to regulate the output voltage or this task may also be performed by the receiving end converter. Thus, the generator sees pure resistance. Furthermore, line reactance does not affect the stability margin. A communication link between the receiving end and sending end may be necessary to control the total power system.

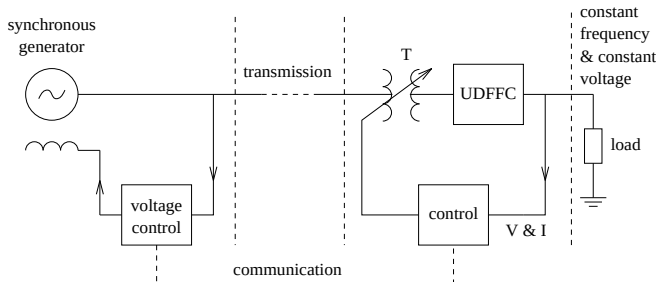


FIGURE 4: AN AC ARTICULATE SYSTEM

In the following, some major advantages of the above system are described.

1. Transmission cable loadability may be increased to $P_m = V_m I_m$ where V_m is the insulation limit (breakdown limit) and I_m is the quenching limit of the superconductor or thermal limit of the normal conductor. In space power systems, to reduce the volume and weight of magnetic materials, it is desirable to increase power system frequency. As frequency goes up, line capacitance and inductance limit the power transmission before insulation and thermal (quenching for superconductor) limits are reached. In an articulate system this effect is eliminated by continuously adjusting V and I to their optimal values for a given power.

2. Because UDFFC is a frequency changer it can keep the output frequency constant regardless of the input frequency. Therefore the synchronous generator does not need an accurate speed control and can operate at variable frequency and due to natural loading, transmission becomes independent of frequency. Therefore, frequency control is not necessary and system control will be more robust compared to the conventional systems. It is, however, important to ensure that constraints on the frequency ranges of turbo-generators, imposed by their critical speeds, are not violated.

Load Coupling to the Articulate Transmission

One way of load coupling to the articulate transmission system was shown in FIGURE 4 where it was done by UDFFC and a variable tap changer. UDFFC is a unity displacement power factor frequency converter. Mathematical analysis of this converter is done in the literature [9]. A more sophisticated version of UDFFC is also capable of direct voltage conversion without using a tap changing transformer.

In FIGURE 5 another coupling circuit with static switching converter is proposed. In this system voltage is converted to DC by a PWM rectifier. The system voltage is dictated by equation (11). To keep the output voltage constant, the inverter gain is controlled by Pulse Width Modulation (PWM) techniques. The switching frequency or output frequency in this configuration can be controlled independently of the line frequency.

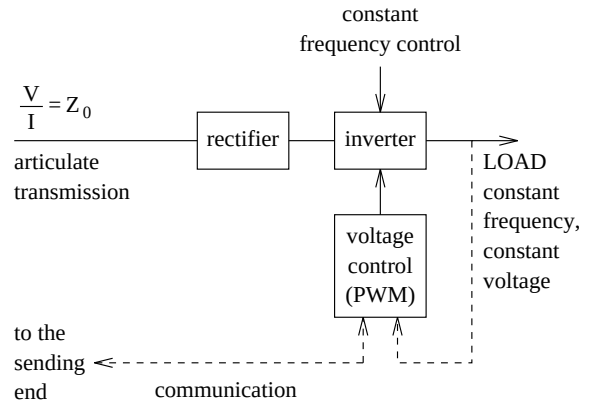


FIGURE 5: FULLY ARTICULATE STATIC LOAD COUPLING

5 Conclusion

Preliminary results have been presented on new approaches to designing power systems for space applications. Two new architectures are introduced: The Current Source Intensive System (CSCI) and the Articulate System. Basic characteristics of these systems have been investigated.

It appears that the CSCI is the more ambitious of the two architectures. By this virtue it will also be realizable in a more distant future. However, some aspects of the articulate system architecture, as discussed in this paper can be implemented in the short term. Flexible AC transmission systems (FACTS) [12] which are now undergoing rapid development and implementation, can be regarded as a subset of the family of control methodologies which constitute the realm of articulate systems. Undoubtedly as the CSCI and Articulate system designs progress, problems will arise. However, the developments

in superconductors, superconducting magnetic energy storage, and power electronics will provide a wide technical base to solve these problems.

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Biographies

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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.