

Mission Impossible?

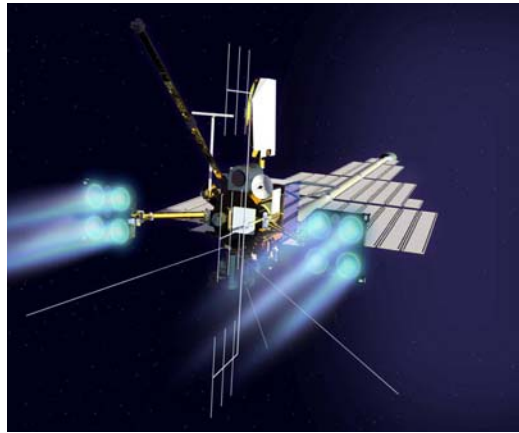
Developing Enabling Technologies for RadHard Space Applications

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ABSTRACT

ZIN Power has successfully designed and built a prototype high-power high-voltage power supply for future NASA nuclear powered deep space missions. This development, which faced serious challenges such as extreme radiation, lacked the necessary technologies required to build a realistic design meeting mission requirements. By implementing a solutions oriented project plan for this development, ZIN was able to develop the enabling technologies required to complete a practical design capable of meeting and exceeding the mission goals. This paper discusses the solutions oriented project implementation which resulted in the development of new (patented) technology for an extreme radiation hardened power supply design.



Prometheus-1 Spacecraft Concept

Introduction

ZIN Power was tasked by NASA's Prometheus-1 project to develop high voltage power supplies and power processing technologies suitable for the Herakles ion thruster and the Brayton power conversion and distribution system (PCAD). The most prominent of these high voltage power supplies is the 27 kW/6500Vdc high voltage Beam Power Supply, which processes more than 95% of the power required by the ion thruster. As a result, the development of this supply required the most effort. This effort faced multiple challenges including developing high voltage power converters with very high power capability and efficiency, while minimizing weight. In addition, the power supply needed to be relatively simple in design for high reliability, as well as being capable of surviving challenging environmental requirements including intense radiation.

Project Implementation

At the project start, the consequences of these challenges were deemed to be a serious impediment to meeting the program goals and that enabling technologies may need to be created in order to ultimately develop a practical design. With this in mind, a project plan was defined to first determine and understand mission critical requirements. Secondly, to identify state-of-art (SOA) applicable technologies including power conversion topologies and components. Next, identify tall pole technology risks followed by performing trade studies on the most viable approaches. Finally, with all technology risks identified, breadboard the approach that provides the best opportunity for meeting the design objectives. This provides a proof of concept for overall feasibility of the approach while identifying strengths and weakness. In addition, a more realistic assessment of what technology gains is required to overcome the present risks of the design. The breadboard also provides an opportunity to clarify its impact on connecting systems.

In parallel with the breadboard development, risks or weak links were continuously addressed by engaging experts. This provided an opportunity to more thoroughly evaluate the potential for eliminating

or minimizing the associated risk. This approach provided the needed impetus for a creative solution resulting in the development of enabling technology.

Beam Power Supply Illustration

Identify Mission Critical Requirements: The design of the Beam Power Supply, as mentioned earlier, had very challenging requirements, including high power, high voltage, high efficiency, minimal weight, low parts count and almost significantly a high radiation environment. The power level requirement was 27kW and the output voltage was 6500Vdc with a $\pm 10\%$ regulation. In addition, the supply had to be short circuit protected with minimized energy transferred to the ion thruster during a “recycle”. A “recycle” refers to when an ion thruster develops a short circuit within its grid. This event occurs frequently.

Identify SOA Applicable Technologies: Applicable technologies for the Beam Power Supply included DC-DC topologies such as the Zero-Voltage Switching (ZVS) full-bridge and boost circuits for a DC based PCAD system. For an AC PCAD system, AC-DC topologies include single phase rectifiers, three-phase six pulse, 12 pulse and 18 pulse rectifier systems. To minimize parts the development of a high voltage DC output would require high voltage power semiconductors.

Identify Technology Risks: The single greatest technology risk associated with this design was the lack of radiation hardened high voltage power semiconductor devices. At the time, the only commercially available radiation hardened 1 MRad high voltage power semiconductors were MOSFET devices with voltage ratings of 400V or less. Some higher voltage parts existed but were not readily available (600V and 500V) or had very high loss (1000V). For even higher voltages, other types of power semiconductor devices such as IGBTs and Silicon Controlled Rectifiers (SCR) had shown potential to fail under radiation exposure.

Perform Trade Studies on Viable Approaches: An extensive DC-DC and AC-DC trade study was performed to evaluate various power topologies and high voltage active and passive components relevant to the scope of the mission. Advantages and disadvantages of the different schemes were evaluated. From the trade study, it was concluded that the optimum design for the Beam Power Supply would be a multiple stage AC-DC power supply with a 400V three phase 2 kHz AC input feed from a nuclear powered Brayton-alternator system. This AC Beam Power Supply (ACBPS) would consist of several series stacked stages with approximately 1400Vdc output to generate the required 6500Vdc. Each stage would contain three “delta” connected single phase transformers and three “wye” connected single phase transformers configured as a 12 pulse rectifier. Most of the stages would be uncontrolled with high voltage power diodes performing the rectification. One stage would be a controlled stage with SCR devices performing the rectification to DC and phase control would be used for output regulation. This 12 pulse scheme provides harmonic reduction sufficient enough to meet design margins and evolved from the basic design objectives of minimizing weight, parts count and simplicity of design.

Although the weight of the 2 kHz transformers for the AC-DC approach would at first glance appear to be a much heavier option than utilizing high frequency DC-DC converter topologies, the trade study showed otherwise. Actually both approaches were similar in weight. The DC-DC approach, with its lower efficiency and its higher susceptibility to radiation damage, required more thermal control and shielding mass. The 2 kHz transformers had one more benefit in that they could be configured as additional shielding to the remaining electronics. This approach minimized the weight impact and provided greater packaging flexibility.

Identify Weak Links: The critical weakness of this approach included the radiation susceptibility of the high voltage SCRs used for the controlled stage and that the system required SCRs in the AC input lines to provide the required short circuit fault protection. In addition, the weight of the 2 kHz transformers was included although the system weight was found to be equivalent to a DC-DC solution.

Breadboard Most Viable Approach: At this point, the project effort was focused on implementing the ACBPS concept. The ACBPS, as shown in Figure 1, which consisted of 4 uncontrolled power stages combined with a single controlled stage, was built. Testing of the design successfully demonstrated the conversion of three phase 2 kHz to 6500VDC at an efficiency of 95% including the necessary front-end SCR AC line fault circuit.



Figure 1. ACBPS Breadboard

Engaging Experts: With regard to the most prominent technology risk, which was the lack of radiation hardened high voltage power semiconductor devices, NASA put together a radhard high voltage parts panel of expertise, which consisted of members from various NASA Centers and ZIN Technologies. This panel reviewed the Prometheus requirements, the state-of-art in radiation hardened components and high voltage power switching semiconductors from which the panel prepared technology development decision gate milestones for NASA management. In conjunction, NASA invoked an extensive radiation testing program for evaluating commercially available high voltage power switching semiconductors for the required environment. This work was performed by the Systems Development Branch at NASA Glenn Research Center (GRC) and by the Jet Propulsion Laboratory (JPL) Electronic Parts Engineering Office - Radiation Effects Group. The overall results of this work confirmed that devices such as IGBTs and SCRs were unsuitable for the application and that radhard MOSFETs rated for voltages above 400V would be difficult to obtain without an extensive and costly development program.

An ACBPS design using only 400V rated power switching semiconductors (MOSFETs) could be implemented, however, many more lower voltage stages would be required thus dramatically increasing the number of parts and adversely affecting the reliability. Ultimately, the AC input line fault protection circuit with its higher voltage requirement would be unachievable.

Creative Thinking: At this time, it was suggested by NASA that perhaps magnetic amplifier (old) technology might be able to perform the function of the AC input line fault protection. This technology can perform a switching function without power semiconductors via magnetics, but typically has a very low control gain from full-on to full-off. With this idea in hand, ZIN began to apply new magnetic materials and winding techniques to develop a prototype device that significantly increased the control gain from full-on to full-off (approximately 15,000 to 1). After several iterations, a new electrically regulated transformer technology (ERT) emerged as a versatile AC power control module. In the ERT, control and switching of power is achieved through an internal low voltage control winding. This “enabling” technology has the advancement that allows the use of low voltage power semiconductor switches, which are readily available in radiation hardened versions, to control high voltage and high power. The application of the ERT to the ACBPS design was to implement all the 12 pulse stages with ERT modules. This approach allowed for a much simpler and much more rugged ACBPS design that could regulate from 0 to 100% (previously 10% was the benchmark) with inherent fast shutdown for fault protection. Besides controlling output voltage and current, the ERT could also control and limit in-rush current.

Final Design Demonstrated with New Enabling Technology: Figure 2 shows one of the 12-pulse ERT module stages developed under NASA’s Prometheus-1 project as the main power conversion, control and fault protection element for the power processing unit (PPU) of an ion propulsion thruster. The beam operated off a three phase, 400 Vrms line-to-line, 2 kHz AC input. This new AC beam power supply design meets and exceeded all of the key NASA requirements, including: minimize the stored energy in the output of the beam supply while maintaining the ripple voltage specification, very high efficiency

(>96%), minimizing complexity and parts count for high reliability, voltage regulation and fault protection under thruster grid faults. Most importantly this new design uses only low voltage power semiconductor switching components which are readily available in 1 Mrad versions.

Conclusion

This paper summarizes a solutions oriented approach to implementing a project which had significant technology risks associated with it. This approach was applied by ZIN Technologies to the development of a Beam Power Supply for NASA. Although a significant technical risk was identified, the project worked towards designing and building the best approach as identified through an extensive trade study. A great deal of valuable information was gained through the first breadboard.

Experts were also engaged to determine how to minimize or eliminate the primary technology risk. Finally, new technology and techniques were applied to an old idea, which resulted into a vastly improved approach. This “enabling” technology eliminated the primary technical risk in the design of the Beam Power Supply.

ZIN’s Electrically Regulated Transformer (ERT) technology can also be applied to numerous commercial and industrial AC-AC and AC-DC applications as a regulation, fault management and power control device. A viable example is utility power grid fault management applications. ERT technology is a more efficient, reliable and rugged approach to providing fault management and control than traditional terrestrial approaches of high voltage IGBT and SCR circuits. This is due to the elimination of all power switching semiconductors from the high-voltage, high-power conduction paths. ERT technology has the following attributes making it a key building block for extremely fault tolerant power and control systems:

- Capable of:
 - regulating and controlling high voltage and high power
 - providing and controlling low voltage buses
 - controlling and limiting in-rush current
 - controlling and limiting output current
 - fast shutdown for fault isolation
 - handling all types of loads
- Scalability and modularity
- High reliability and long life
- High efficiency
- Utilizes low voltage power semiconductor switching devices
- Low Electrical Magnetic Interference
- Intelligent controls easily incorporated for autonomous control

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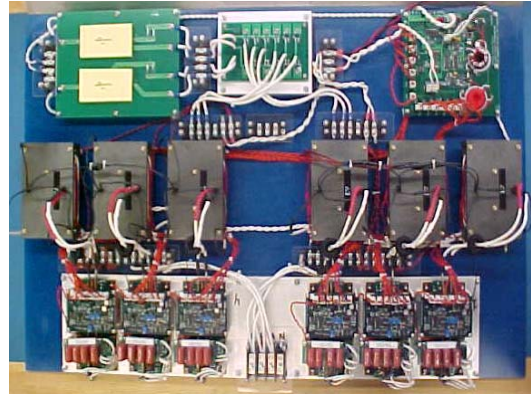


Figure 2. Single ACBPS Beam Module utilizing ERTs.