Distributed Power Architecture for Electric Propulsion

Dr. Christian E. Lazarovici – Pratt & Whitney, Space Propulsion
Robert A. Lowell – Science Applications International Corporation
James W. Swonger – Peregrine Semiconductor Corporation

ABSTRACT

Hall Effect Thrusters (HETs), which are presently available in a broad range of power levels, are recognized as one of the economic, efficient, and effective means to perform numerous propulsion functions on commercial and military satellites. The HET technology, which is 5 times more efficient than current chemical systems, represents a viable alternative for stationkeeping, orbit insertion, and de-orbiting functions for GEO applications and future constellations of satellites. Power Processing Units (PPU's) for electric thrusters (HETs and Ion Engines) are very complex designs, which require long and expensive qualification cycles. Traditional PPU custom designs cannot easily accommodate parametric changes, require lengthy and costly development cycles, and become extremely vulnerable to discontinuance of high-reliability radhardened parts. In addition, for high power applications severe thermal and EMI issues must be overcome. The use of the distributed power architecture employing space-qualified high power density DC-to-DC converters (COTS - derived), provides an attractive solution to industry needs for low-cost, light-weight, low-volume, shorter time-to-market, low development risk, and built-in economic redundancy.

INTRODUCTION

The Power Processing Unit (Figure 1) for a Hall Effect Thruster provides electrical power to the thruster, its cathode, and its associated Flow Control Unit (FCU). Depending on the satellite configuration the PPU may serve a redundant arrangement of thrusters, cathodes, and flow control units. In this case the PPU may be equipped with a Thruster Selection Electronics (TSE), which allows selection of the prime or redundant elements under the spacecraft computer telecommands. The PPU Logic Control (usually a Mil-Std-1553B interface) provides communication with the satellite on-board computer (telecommands and telemetry flow). Depending on the satellite configuration the PPU is powered either from an unregulated battery bus or from a regulated power bus.

The core element of a PPU is an assembly of power supplies providing controlled electrical energy to the HET, FCU, and cathode, as well as to the internal PPU electronics. The HET power supplies subassembly is comprised of the Discharge Power Supply (DPS), the Cathode Heater Power Supply, and the Cathode Ignition Power Supply. The FCU power supplies subassembly contains the Valves Power Supply, the Thermothrottle Power Supply or a Multifunction Valve Power Supply, and in certain instances a FCU Heater Power Supply. Also, there is an additional subassembly of power supplies for internal use: the Logic Power Supply to power the PPU Logic Control and the Housekeeping Power Supply for TSE and spacecraft interface operations. These subassemblies of power supplies establish the features of the PPU: size, mass, efficiency, reliability, complexity of the development cycle, and the recurring and non-recurring costs.

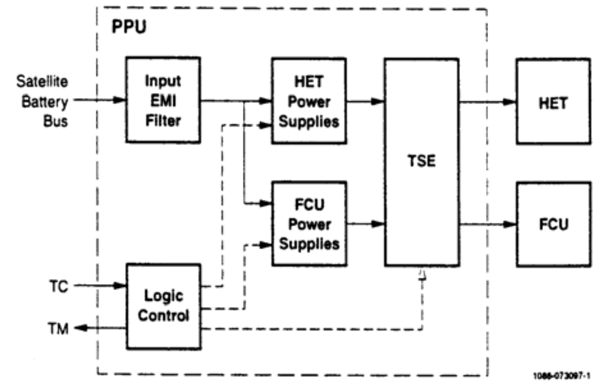

Figure 1. Power Processing Unit Block Diagram

The anode circuit of the thruster is powered by the Discharge Power Supply, which processes most of the PPU input power. This supply powers the thruster at approximately 300V during steady state operation, and must be able to deliver large peak currents during thruster start-up phase. For high power applications the DPS steady state power can go up to 20 kW, while its peak power capability could exceed 30 kW. Because the Discharge Power Supply is the most complex power subsystem of the PPU, its features have a major impact on the PPU characteristics.

DISTRIBUTED POWER ARCHITECTURE FOR THE DISCHARGE POWER SUPPLY

For PPUs with power levels above 2 kW, there are concerns related to thermal, EMI, and packaging issues. Traditional spacecraft power processors are in general inflexible: changes in input voltage or power level cannot be accommodated without a major redesign and requalification of the PPU. Recent industry trends impose new cost challenges for the PPU designers and builders. Developing space/aerospace/sea/ground cost-effective systems with little exposure to obsolescence is one of DoD's current efforts. If there is compliance with reliability and screening requirements of the application, military encourages the use of the commercial-off-the shelf (COTS) parts and subassemblies. Cost constraints associated with future constellations of satellites mandate implementation of the economy of scale. There is a strong demand for enhanced reliability, reduced cost, lightweight, and increased power density for PPUs. Of critical importance is the reduction of the costs associated with the program development phase (design and qualification), because customers are no longer willing to pay NRE charges. All of the above motivate the search for new approaches for the design of the power processors. The use of the distributed power architecture for discharge power supplies, employing high power density COTS-based power converters, provides an attractive solution to the challenges imposed by the increased power demand and new market trends.

In the early 1990's, the Ballistic Missile Defense Organization (BMDO) took the lead in identifying and evaluating advanced propulsion technologies. In the late 1990's, the Innovative Science & Technology Office of the BMDO initiated a program to demonstrate the maturity of the Russian Hall Effect Thruster Technology (RHETT) for high power applications. The 4.5 kW T-160E HET System had two major objectives: (i) to demonstrate propulsion component technology in ground testing, and (ii) to assess system components performance in a backup stationkeeping role on the EXPRESS 3A Russian communication satellite. Program management was assigned to NASA GRC, while Schafer Corporation provided system engineering coordination. Space Power Incorporated (SPI), now part of Pratt & Whitney - Space Propulsion, acted as prime contractor managing subcontracts with TRW, Keldysh Research Center (KeRC) and Scientific Production Association of Applied Mechanics (NPO-PM). SPI had the responsibility for the key US component, the development of the PPU. This program was classified as a Class D experiment.

The nominal power of the T-160E HET is 4.5 kW. However, the discharge power supply must be able to provide at least 15% more power under steady-state conditions to cover random power demands caused by the HET oscillations, without reaching a current limit condition. In addition, the peak power capability for short duration must be much higher to allow for a safe start-up of the thruster during the ignition process.

Space Power Incorporated (SPI) engineered the discharge power supply, using a high power array of DC-to-DC power converters. The array's converters were configured in a series-parallel arrangement to create an expandable modular discharge power supply, with built-in redundancy (Figure 2). SPI elected to use the second generation of the Vicor DC-to-DC power converters, which operate at variable switching frequencies up to 1MHz. At the beginning of the program SPI performed a radiation test evaluation of Vicor converters at JPL and University of California Davis. The assessed radiation resistance provides enough margins for 100 hours operation in the first year of the mission (GEO). The selected power converter of 100 Vout has 600 W nominal output power, 800 W peak power for 2 minutes, 110 W/cubic-inch power density and 210 grams mass. Identical converters were configured in strings of 3 converters each, with their outputs connected in series to boost the output voltage to 300 V. Each string has a nominal power capability of 1.8 kW, and 2.4 kW peak power. By paralleling identical strings the output power can be boosted in 1.8 kW power increments. Three strings provide 5.4 kW nominal output power, or 7.2 kW peak power. A series-parallel configuration requires accurate power sharing to maintain identical output voltages for each converter of a string, with good current sharing between strings. The power sharing mechanism is one of the Vicor converters' features. Therefore, an identical switching frequency has to be imposed through synchronization of all converters of the power array.

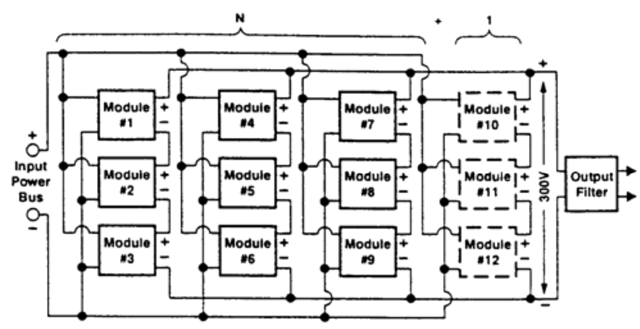

Figure 2. Modular Discharge Power Supply Block Diagram.

A string of converters with outputs connected in series boosts the output voltage, while a parallel combination of converters boosts the output current. In these simplified configurations all modules have their controllers active, and the array elects one of the converters (master converter) to control timing activities needed for synchronization. The master converter forces the other converters to operate at the same switching frequency, allowing all converters to provide identical lumps of energy per cycle. As a result, equal output voltages are forced for all converters of a string (having the same output current), and for the parallel combination of strings (having the same output voltage) an equal output current is forced through each string.

The same power sharing mechanism applies to a series-parallel configuration. However, the series-parallel combination is a more interactive system than a simple series or parallel arrangement, because two parameters (current and voltage) must be controlled. In this particular case there is the risk of degrading the power sharing mechanism under transient conditions. The unstable nature of the HET plasma leads to large current oscillations and voltage transients at the output of the discharge power supply. Under these oscillations and transients a series-parallel array may react by switching the synchronization control from the assigned master converter to another converter in the array. During the transition process both converters are attempting to synchronize the array by sending impulses on the same control bus. This temporary conflict on the control bus leads to an asynchronous mode of operation for the array's converters (no power sharing), and in the worst case can induce control-loop instabilities. No transfer of the synchronization control would occur if the master assignment were preserved. This is achieved by forcing a master-slave arrangement for the array's converters. Under this configuration the synchronization feature of the controller is disabled for all converters but one (the imposed master). Thus, no transfer of the synchronization control between two converters of the array can occur under any transient conditions.

To prevent failure propagation to other strings, isolation diodes are placed on the positive output of the upper converter of each string. To maintain nominal power capability of the array in the event of a converter failure an economic N+1 redundant configuration was implemented paralleling one more string of three converters. If a "slave" converter fails automatically its string is isolated from the array by the isolation diode. The array continues to operate under the synchronization signals provided by the "master" converter. However, if the "master" converter fails, the array switches to an asynchronous mode of operation. A "double master" synchronization scheme (use of 2 masters: prime and auxiliary) was conceived. The "auxiliary master" converter is located in a different string of the array and is maintained inhibited with respect to its supply of synchronization signals. In the event of the "prime master" failure, automatically the "auxiliary master" synchronization control is activated, maintaining the array in a synchronous mode of operation.

POWERING THE T-160E HET WITH THE MODULAR DISCHARGE POWER SUPPLY

The Modular Discharge Power Supply (MDPS) was constructed using two identical Printed Wiring Assemblies (PWAs). Each PWA accommodates two paralleled strings of three 100 Vout converters with their outputs connected in series in order to boost the output voltage to 300 V. A double pole filter π was placed on the output of the MDPS to provide adequate protection against oscillations and transients induced by the thruster plasma instability. Each converter was equipped with an EMI filter to meet Mil-Std-461C requirements. The total mass of the MDPS assembly including the distributed architecture of EMI filters is 4 Kg, which translates into a 0.56 gram/W specific mass.

During ground testing the MDPS behavior was monitored for the start-up mode, steady state operation, and master control transfer. Oscilloscope records of the output voltage and output current of the four-string MDPS (N+1 redundant) during the start-up sequence of the T-160E Hall Effect Thruster are shown in Figure 3. The top curves in the Figure 3 shows the voltage (flat upper trace) and current (lower trace with overshoot transient) at the output of the MDPS array. The bottom curves in the Figure 3 shows the voltage (upper trace) and current (lower trace) downstream of the double pole output filter at the HET anode. Note that voltage at the anode side sags during the startup transient, but the voltage of

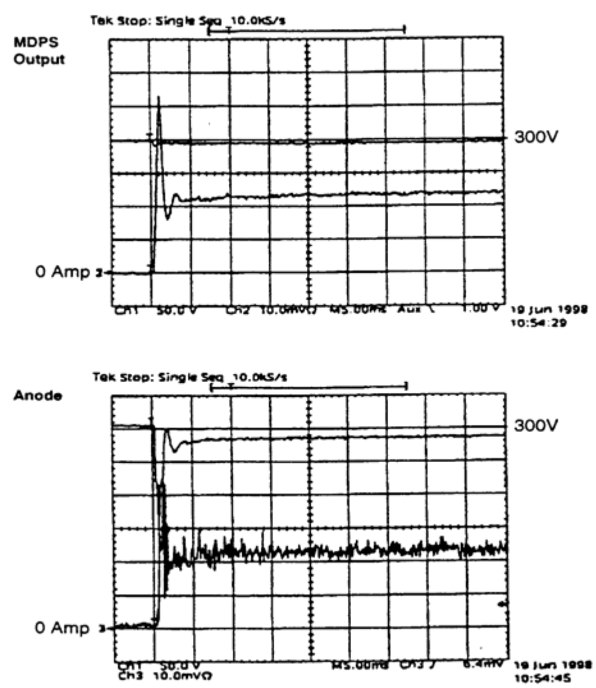

Figure 3. MDPS output voltage and current for the start-up mode.

During start-up mode (thruster cold condition) the amount of current demanded by the thruster is very high. In some instances the current exceeded 100A, causing sags of the anode voltage. The capacitive elements of the output filter and the peak power capability of the MDPS supply the high start-up current. The output voltage of the MDPS was not affected due to the rapid response of the converters to the load demand. The same behavior was noticed when the thruster was powered from a three-string array simulating a non-redundant configuration. The voltage distribution, between converters in any particular string, and the current sharing between strings were measured, and found better than 1%. Also, simulations of one converter failure were conducted, indicating no transient for the output voltage when the "prime master" was artificially disabled. Overall test results indicated flawless operation of modular discharge power supply. Ground testing conducted by NASA technical staff at GRC facilities validated the distributed power architecture concept for multi-kilowatt discharge power supplies.

ADVANTAGES OF THE DISTRIBUTED POWER ARCHITECTURE

The concept of the distributed architecture employing COTS high power density converters can be beneficial for space applications if properly implemented. Numerous power configurations can be engineered without a major design effort by employing the same "off-the-shelf" qualified power converter. System reliability is enhanced when redundancy is implemented. Distributed power architecture lends itself to economic redundancy schemes (N+1, N+2). High power density and low-specific mass leads to light PPU constructions. Problems associated with the heat rejection of the kilowatt power supplies can be managed. Insurmountable thermal and packaging problems associated to EMI filters handling hundreds of amperes are eliminated by the distributed architecture of filters. An individual EMI filter handling low currents serves one converter. Numerous advantages derive from the use of already developed and qualified power blocks. The design cycle is shortened, and qualification by similarity may be used. Volume discount and repetitive manufacturing lead to economy of scale. Automation is perfectly suited for fabrication of large numbers of identical subassemblies. All of the above allow for risk mitigation, and important cost and schedule savings.

POWER CONVERTERS MARKET NEEDS FOR SPACE AND MILITARY APPLICATIONS

Present market needs for DC-to-DC power converters for space and military applications are: enhanced radiation hardness, increased power density, higher efficiency, reduced weight, higher reliability, lower cost, and long-term availability. Current offerings exhibit radhardness/power-density/mass limitations, carry a high price tag, and are based on old silicon technologies. There is a stringent demand for DC-to-DC power converters with survivability to strategic radiation levels. In addition, for critical military applications there is a particular need for DC-to-DC power converters achieving operation-through at strategic radiation levels. Obsolescence of the high-reliability radhard parts, as well as a possible discontinuance of old radhard silicon processes, is a major concern for space and military.

POWER TECHNOLOGY ISSUES

Most of DC-to-DC power converters for space and military applications are custom products. Catalog offerings are available from a limited number of manufacturers. Because the pound-to-thrust cost ratio of the payload is a major concern for all space applications, converter's mass and power density are features of critical importance. Most of the current offerings of DC-to-DC power converters for space and military applications employ a hybrid construction as a means of miniaturization to increase power density or to decrease mass. The approach for the power conversion control is based on catalog offerings of PWM controllers that have little immunity to nuclear weapons environment. Some manufacturers elected to develop proprietary controllers using discrete element evaluated active parts with high tolerance to nuclear events. In both cases converters parts count is in between 150 to 200. High parts count combined with the hybrid approach have a negative impact on converters cost and failure rate. The hybrid substrate reliability is very poorly rated in MIL-HDBK 217F. The cost associated with the procurement of numerous active parts processed to JAN S flow (MIL-M-38510) and the hybrid approach implementation per MIL-PRF-38534 is quite high. Some of the current offerings come at a specific price between $200/W and $300/W, and calculated failure rates as high as 100 fits. Discontinuance of the high reliability radhard parts force power converter manufacturers to allocate large budgets for lifetime buys.

RAD HARD SILICON TECHNOLOGY ISSUES

Radiation hardened electronic power systems must resist multiple forms of harmful radiation. Exposure to high-energy radiation environments can result in transient or permanent changes to semiconductor's material and electrical properties, which can cause electronic systems malfunction or failure. The power system must be dependable.

The predominant radiation effects for the natural space environment are the Total Ionizing Dose (TID) and the Single Event Effects (SEE). TID degradation or drift of component parameters causes changes to circuit supply and leakage currents, threshold voltages, gains and propagation times. Single Event Effects responses can include non-destructive effects (upset, multiple-bit upset, or analog transients), or destructive effects (latchup, gate rupture, burnout).

The military environment is additionally concerned with the effects of a nuclear event. Besides high levels of TID, neutron (displacement damage) and high dose rate effects must be mitigated. Neutron irradiation produces crystal lattice defects, which cause degradation or possible failure of the semiconductor devices. Dose Rate effects produce functional upset, or latchup / burnout. Military satellite and exo-atmospheric systems may combine exposure to all of the radiation environments mentioned.

Radiation-hardened survivable systems require use of semiconductors components retaining parametric integrity over the entire mission. A high level of radiation tolerance is required for long-duration space missions as well as for strategic applications. The inherent rad hardness exhibited by contemporary silicon technologies is insufficient to provide a high tolerance to radiation effects without special processing or design modifications. Thus, for standard integrated circuits additional shielding and redundancy schemes have to be employed, that causes an increase in system mass and cost.

The majority of digital, and nearly all analog integrated circuits manufactured in older rad hard silicon technologies are incapable of uncompromised operation at higher radiation levels. Even true strategic hardened systems have an upper limit of proper operation, which is orders of magnitude below the worst case exposure used for survivability analysis. Yet, certain critical subsystems must remain functional for the assembly to survive and recover within mission envelope. This is especially true of power supplies, upon which everything else depends.

The limitations of older ICs as regards dose rate operation lie with their processing. The dose rate induced photocurrents scale with device volume. Non-insulating-substrate technologies exhibit aggregate photocurrent responses in the tens of amperes, in products designed for milliamp operation. Not surprisingly, even those which survive do not produce valid function meanwhile. This drives the use of silicon-on-insulator (SOI) technologies. The strategic systems of yesteryear perform analog signal processing using higher voltage, deep-junction bipolar analog SOI circuits. A CMOS device (when properly constructed) does not amplify the primary photocurrent. In bipolar technologies, the natural BJT current amplification requires photocurrent compensation schemes to maintain analog signal quality. Large devices' photocurrent is able to overstress interconnect, so older technologies, for survivability, require extensive and careful insertion of current limiting resistors. This works against circuit dynamic range and is one limiter of analog circuit performance at higher dose rates.

Ultrathin CMOS analog circuits can operate with at very low values of photocurrent per device at what have been considered survivability levels. At this range, it is entirely practical to design analog circuits with negligible external-parameter deflection under high dose rate.

High voltage bipolar devices prove very sensitive to neutron degradation, as they depend critically on minority carrier lifetime, and in turn on the crystalline material quality which displacement damage disrupts. The majority-carrier MOS device is much less sensitive to neutron damage. Low voltage processes use higher-doped devices and this further extends the advantage.

The residual advantage of the high voltage analog bipolar circuits is, simply, high voltage. In the context of power supplies and, in fact, most analog circuitry, it is only a few nodes which exhibit large-scale voltage deflection; the majority move only slightly. However, all devices are sized by the highest working voltage driven groundrules. In the commercial power supply IC arena, a different tack is common; the ICs are implemented in low voltage CMOS based technologies, upon which a limited set of high voltage DMOS devices has been grafted. This combines functional density (several op amps in the space of a bond pad) with the same high voltage capability where, and only where needed. This has pushed power supply IC density to embody the functionality of tens of old-style analog SSI ICs along with significant digital content.

It is reasonable to pursue the same direction using similar, but radiation hardened, SOI CMOS technology. The high piece part price of individual hardened components, and the high reliability impact of reduced component count magnify the value of doing so.

Diminishing sources of supply for standard and custom rad hard integrated circuits is a concern for the space / military industry. Presently, in excess of 18% of the military standard semiconductors are obsolete parts. Obsolete parts are still available from aftermarket manufacturers, but at prices of 10 to 15 times the original cost and with serious delivery schedule disruptions. Many manufacturers of radhard integrated circuits have closed down their fabrication lines, and some of the remaining ones' inventory is shipped from die banks from long-shuttered fabrication facilities. The analog supplier base is the thinnest. Learning to migrate functionality to modern IC technologies, while preserving or increasing radiation hardness, is critical to hardened systems of the future.

POWER CONVERTER MEETING PRESENT MARKET TRENDS

Based on a program initiated in the late 1990's by the Innovative Science & Technology Office of the Ballistic Missile Defense Organization (BMDO/TOI), Pratt & Whitney - Space Propulsion is developing a new DC-to-DC power converter for space and military applications. The development approach is to leverage commercial technologies to achieve enhanced radiation hardness, improved reliability, long-term availability, and product affordability.

The main objective of this effort is to produce an advanced DC-to-DC power converter responding to all market trends, with direct use on satellite platform-payload equipment and military systems. The overall objectives of this program are: (i) identify a power technology platform able to accommodate market needs, (ii) select silicon radhard technologies with the highest tolerance to radiation environments, (iii) radharden power converter controllers, and (iv) conduct radiation testing to validate controllers' radiation resistance. With respect to the power converter radiation hardness there are two objectives: (i) meet survivability requirements for strategic applications with the present development, and (ii) achieve operation-through at strategic survivability levels in the next phase of the development.

Power Technology Platform

The selected power technology platform is the Vicor's second generation zero-current-switching and zero-voltage-switching quasi-resonant power architecture. Selection was based on the following technology attributes: very low parts count, non-hybrid construction, and superior electrical features. Operating at frequencies in excess of 1 MHz, Vicor converters offer state-of-the-art performance in terms of power density, efficiency, noise, miniaturization, reliability, and redundancy. Standard features such as wide range trimming and programming, current limiting, remote sensing, output inhibit and latching OVP/OTP, which are imbedded in the converter controllers, yield unmatched protection, versatility, and reliability. Presently military non-radhard power converters are fully developed and qualified. These converters exceed the input voltage operating requirements of MIL-STD-704D/E for 28Vdc, DOD-STD-1399A for 155Vdc, and MIL-STD-704D/E for 270Vdc. All units are manufactured under a quality system that meets or exceeds MIL-I-45208 in ISO 9001 registered facilities, using fully automated assembly lines to ensure a consistent high level of quality.

The high degree of silicon integration for the converter control functions in two Application Specific Integrated Circuits (ASICs) results in a major parts count reduction. Parts count varies from 8 to 30 based on converter power level. Low parts count increases reliability, significantly reduces the design and qualification cycle for new products, and provides significant recurring cost savings. The calculated failure rate of the Vicor power converter is less than 25 fits. Hermetically sealed encapsulation enables the converters to meet MIL-STD-810, MIL-S-901, and MIL-STD-202 environmental requirements for humidity, fungus, salt, fog, explosive atmosphere, acceleration, vibration, and shock. Vicor converters have a high degree of flexibility to accommodate major parametric modifications by changing only a few passive components. This feature is attributed to a high level of integration of the Vicor topology control functions in just two ASIC controllers, which serve any converter independent of the voltage or power levels. Thus, prototypes for new designs can be turned around in a matter of weeks. In addition, because all Vicor converters of a certain power/package class are essentially mechanically and thermally alike, the qualification cycle of the new products is significantly reduced. These combined features translate into substantial development risk mitigation, a shorter time-to-market and important (recurring and non-recurring) cost savings over current offerings.

Silicon Technology Selection

Radiation hardening of the Vicor converters is achievable by replacing only three active part types with radiation tolerant equivalents: the power MOSFETs, the Primary ASIC controller, and the Secondary ASIC controller. Radhard power MOSFETs are off-the shelf components manufactured by International Rectifier and Fairchild Semiconductors. The non-radhard versions of the ASIC controllers designed and fabricated using a high-voltage bipolar silicon technology are being translated into a radhard version. The present development (commenced in 1998) uses the Intersil RSG process which is compatible with the operating supply voltages in the Vicor module “brain” boards. By design high levels of tolerance to other radiation effects can be achieved: (i) no single effect effects under heavy ions with Linear Energy Transfer (LET)), (ii) survives high dose, and (iii) operation after high neutron fluences. The redesigned power converters are expected to meet survivability requirements for strategic applications; however, the design does not provide for dose rate photocurrent compensation and is not expected to operate properly in this regime.

To reach the same performance goals would be impossible in a deep-junction process. Even meeting a dose rate goal three orders of magnitude less would require the addition of extensive photocompensation, adding to circuit size (device count). The need for burnout limiting resistors renders it impractical to meet the desired operational level, because the device photocurrents become so large that voltage headroom collapses. One of the rad hard ASICs is already at the maximum size the packaging technology can accommodate (driven by SEU design); further circuit bloat is not tolerable.

By contrast, the form factor of the ASIC die fabricated in a submicron SOS process can readily match or beat the original commercial devices’. The reduced device photovolume results in simple circuit designs (no photocompensation required except on the most sensitive nodes). Thin silicon produces resistors with higher sheet resistivities, but higher doping - thus less modulation under both dose rate (downward) and neutron (upward).

The high density opens the door to design techniques unavailable to the designers in the older bipolar technologies - self-correcting analog circuitry (du jour in contemporary mixed signal circuits) can shrug off long-term drift from aging, stress and radiation; digital accumulators and DACs can replace sensitive integrator servo loops; redundant analog circuits for SET suppression is not a big deal, when 100 transistors can fit in the space of one of their predecessors.

The residual hurdle for application of low voltage CMOS technology in high voltage environments is surmountable by either of two means. The fully insulating substrate makes it possible to simply stack devices, with some elaboration of control circuitry, to stand off the working voltages. This is something that is already done in EEPROM programming circuits in this technology. The second alternative is the use of higher-voltage DMOS structures. DMOS-style transistors exceeding 40V breakdown have been obtained by simple layout manipulation (unmodified SOS process), and this exceeds the natural breakdown of the “high voltage” process MOS devices and bipolar devices. This enables simple internal preregulation for core circuitry, and high voltage output drive capability.

Because the SOS process is a commercial technology recently introduced, and primarily supported by commercial RF / photonics IC volume production (1M units / quarter), its life expectancy is sound.

Nuclear Analysis and Hardening

A generic set of piece-part design-to-requirements has been designed to support the ASICs hardening goals; however these levels were established on a generic "strategic" needs basis. SAIC is reviewing the environment specs of several critical strategic space systems to determine a full complement of design requirements to ensure compatibility with strategic use. Examples are packaging issues, where and how the shielding within the system will effect dose enhancement, X-ray effects such as structure/cable electromagnetic pulse (EMP) incident on external pins, and natural electron/fission beta charging of dielectric components. These will be included in the hardening process to ensure that the final product is completely compatible with the hardening requirements of future host satellites. Based on these more complete requirements, SAIC will develop the objectives and methodology for the radiation test series to ensure that a complete set of data is obtained to demonstrate power subsystem hardness in the system context.

CONCLUSION

The distributed architecture concept achieves low cost through flexibility and reduced development (design and qualification) effort. The cost of the PPU components is one of the dominant factors of the overall PPU cost. The low parts count and components’ costs are of importance for future military and commercial applications. The high flexibility of the power converter under development to accommodate parametric changes with minor modification allows for major reductions of the costs and time-to-market. Repeated manufacturing processes used for converters’ fabrication lead to increase reliability and cost reduction.

ACKNOWLEDGMENTS

The authors wish to express their gratitude for the encouragement and resources provided by BMDO/TOI. In particular, Dr. Leonard Caveny, former director of BMDO/TOI, deserves credit for recognizing the value of these projects. In addition, the authors wish to gratefully acknowledge the extraordinary performance the NASA GRC team in solving the many technical challenges in the EXPRESS power processor, which led to a successful ground demonstration. The sponsorship of Air Force Phillips Lab for a low power PPU is also importantly acknowledged.

REFERENCES

1. J.K. Koester, C.E. Lazarovici, J.M. Sankovic, G.A. Herbert, V.A. Petrosov, A. Romashko, V. Petrusevich, "The EXPRESS/T-160E Space Flight Test Program", IEPC 97-183, 25th International Electric Propulsion Conference, Cleveland, Ohio, August 1997.
2. C.E. Lazarovici, R.S. Lin, E.J. Britt, "Distributed Power Architecture for Electric Propulsion Applications", 1999 01-1383, SAE Aerospace Power Systems Conference, Mesa, Arizona, April 6-8, 1999.
3. C.E. Lazarovici, "Ultra-compact, High-Power Density Power Processing for Small Hall Effect Thrusters", F04611-98-C-0051 SBIR Final Report, February 2000, AFRL/PR Technical Library.
4. C. McLean, J. McVey, C.E. Lazarovici, E.J. Britt, "Innovative Low-Power Hall Effect Thruster", AIAA 00-3247, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, Alabama, 17-19 July, 2000.