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Thick Film Hybrid DC-DC Converters are standard 'Brick' for Satellite Power Systems

By

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Abstract:

Thick film hybrid DC-DC converters offer unique size, weight, performance, and cost benefits for space design applications. Availability of different power levels, output voltage/current ratings, built-in functional features, and form factor configurations make them the ideal building block modules emulating the 'brick' style of the commercial counterparts. New generation hybrid bricks offer design solutions with substantial cost saving and reduced design lead time with extensive design analyses and qualification documentations.

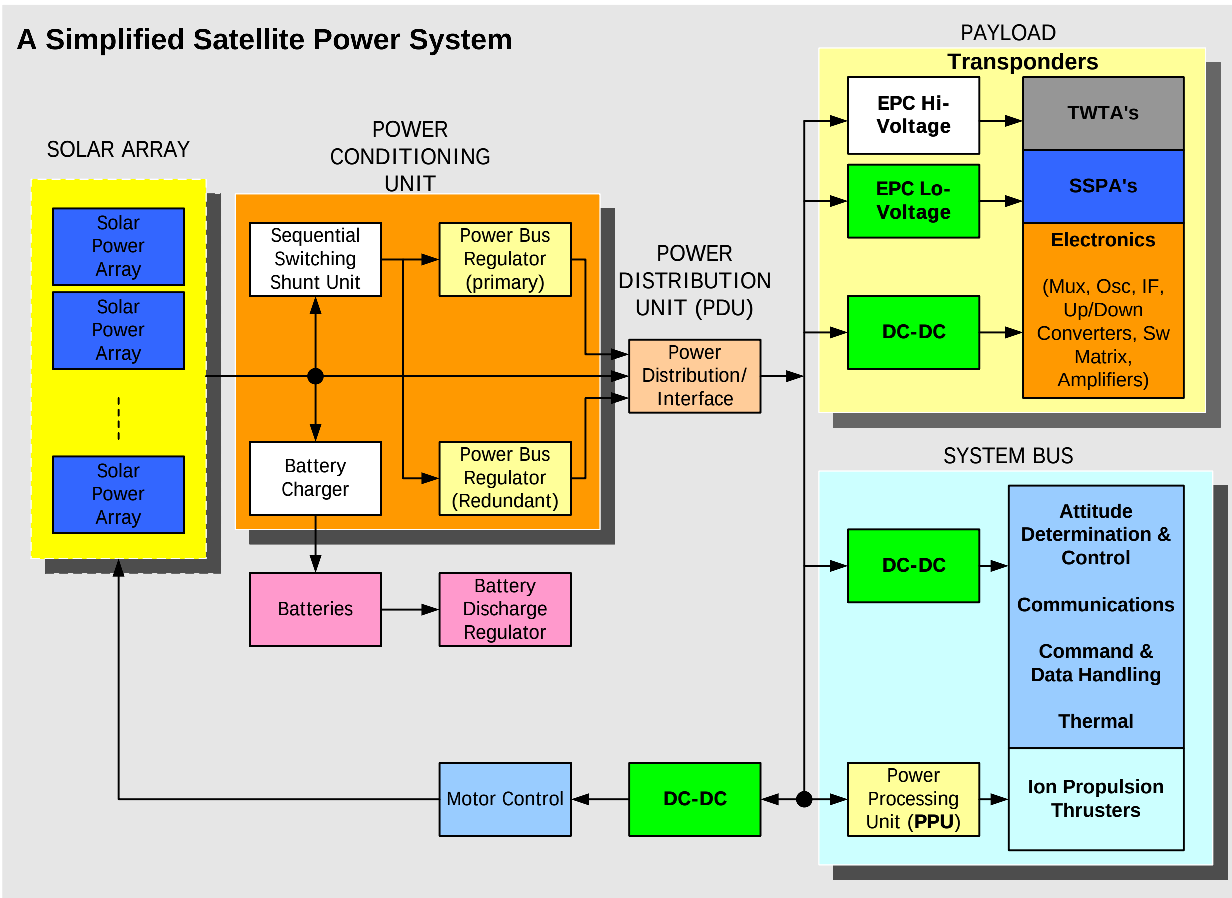
Introduction

Hybrid DC-DC converters have become the assembly of choice over the surface mount technology (SMT) for low power devices in the range of up to 120W. While requirements for many converters can only be met with custom design and in-house design solutions, the demand for standard off the shelf DC-DC converters continues to rise. Hybrid DC-DC converters offer a considerably smaller size and lighter weight than any of today's SMT assembly technologies. The reliability of a hybrid assembly remains a challenge but the assembly process has made dramatic improvement since the mid 80's when many users abandoned the hybrid technology and adopted the SMT for new designs. Thanks to the industry's standard specification MIL-PRF-38534 (Ref. 1) and many lessons learned over time, hybrid devices manufactured today are worthy of space missions of up to 18 years with the highest level of confidence. Hybrid DC-DC converters have made inroads into the space applications in recent years as the satellite designers look for ways to minimize size and mass. As hybrid DC-DC manufactures have a better understanding of the satellite functional interface requirements, more functional features are incorporated into the new hybrid converters. Additionally, the new generation hybrid bricks, IR's S, M3G and LS series offer a full compliment of design analyses and qualification test reports. This makes hybrid DC-DC converters even more desirable to the designers as they substantially reduce non-recurring costs not only in non-recurring engineering effort but also in documentation and qualification and offer reduced lead time. It is expected that the use of the new standard hybrid converters will continue to rise as the converter designs continue to gain heritage.

Satellite Power System Requirements

Electrical energy is one of the vital elements in keeping a satellite operational in orbit. Refer to Figure 1 for a simplified satellite power system. Solar panels convert solar energy to electrical energy. From there the electrical energy is processed, stored, regulated, and distributed to electronic loads, which consists mainly of analog and digital semiconductors, RF, optical, sensor, laser, and electromechanical devices. The converters labeled 'DC-DC' in Figure 1 typically receive power from a spacecraft power bus, which for most systems is well regulated. The range of the bus voltage is 20 to 120V DC. While the trend is moving toward higher bus voltages, the voltage level is mission and satellite design dependent.

Figure 1 – A Simplified Satellite Power System



Electronics for both the payload and bus system typically require 3.3 to 28 volts DC though the voltage requirements are declining toward 1V and less for digital loads. Key requirements for the converters include reliability, power efficiency, output voltage regulation, output ripple/noise, short circuit protection, output over-voltage protection, synchronization, on/off command, on/off status telemetry, and input-output isolation. For higher current applications, typically 10A and greater, remote sensing capability to compensate for the voltage drop in the output lines is often required. For RF sections of the satellite, converters with low noise performance are imperative. In all cases, the converters must be designed to meet some level of electromagnetic conducted emission (CE) and conducted susceptibility (CS) requirements, which are system dependent although MIL-STD-461 (Ref. 2) is the industry's standard for most US military programs. The new generation hybrid DC-DC converters are designed to accommodate most of these requirements. The discussion of this article excludes the EPCs for SSPA applications and is limited to DC-DC converters that provide regulated power to the electronics in the payload and system bus of a satellite.

Radiation Requirements

Converters are generally required to operate continuously in the radiation environment without damage or without performance degradation with accumulative total ionizing dose (TID) in the range of 2-3 Krads to 100 Krads or more. TID level is mission dependent. Also required is the converter's ability to survive and recover from single event phenomena (SEE), e.g., single event upset (SEU), single event latchup (SEL) and single event burnout (SEB). The typical SEE energy level is LET (linear energy transfer) of 37 to 83 MeV-cm^2/mg. SEE level is mission dependent. Other radiation requirements may include performance under neutron, proton, and high dose rate radiation. However, these requirements are unique to strategic weapon applications. Table 1 lists the typical requirements of a space DC-DC converter.

Table 1 – Typical Requirements of Space-Borne DC-DC Converter

Parameter	Typical Requirement
Electrical	
Input Voltage	28V unregulated; 50V, 70V and 100V regulated
Input Inrush Current	Required at the system level, but frequently flowed down
Output	Single, dual or triple
Output 1 (main)	+1.0 to +15V
Output 2	+5 to +15V, 5 to15% of total output power
Output 3	-5 to -15V, 5 to 15% of total output power
Output Power	A few watts to 40 watts
Input-Output Isolation	Required
Output Ripple	20 to 50 mVp-p typical, 1-5mVp-p for some RF applications
Efficiency	50-70% for 5-15W, and 70-90% for 15-40W
EMI	CS and CE modified versions of MIL-STD-461C/D/E
Overvoltage Protection	Yes, shut down, limit 10-20% above Vnom (generally required for redundant applications)
Turn-on Overshoot	<5% Vnom, output rises monotonically
Turn-on Delay Time	0.5 to 10mS
Bus Current Telemetry	At the system level
Step Load Response	<2-5%,<200-500µS, half-load/full-load
Output Telemetry	Yes
Temp Telemetry	Required on some programs
Remote Sense	Required for main output
Synchronization	Yes

Parameter	Typical Requirement
Undervoltage Lockout (UVLO)	Yes
Soft Start	Yes
On/Off Command	Yes, bi-level or pulse command
On/Off Status Telemetry	Yes
Output Voltage Adjustment	Yes
De-rating	NASA PPL-21/ MIL-STD-1547/ MIL-STD-975/ESA PSS-01-301
Mechanical/Environment	
Operating Temp	-34 to +71C qualification, program dependent, often has a wider temperature range for qualification level than acceptance requirement of flight hardware
Storage Temp	-40 to +85C, typical, program dependent
Random Vibration	Dependent of launch platform
Pyrotechnic Shock	Dependent of launch platform
Acceleration	Dependent of launch platform
Humidity	60-95% RH
Explosive Atmosphere	Shall not cause ignition
Size	Key design requirement
Mass	Key design requirement
Qualification	MIL-PRF-38534, Class K
Package Construction	Hermetically sealed thick film hybrid
Radiation	
Total Ionizing Dose (TID)	25 to100Krads, may be with shielding
Single Event Effect (SEE)	37 - 83 MeV-cm^2/mg, shall not sustain permanent damage from cosmic ray or performance degradation from SEE: no SEU, no SEB, no SEGR, no SEL, no SET
Neutron	If required, shall be designed to withstand, without permanent performance degradation after exposure to neutron equivalent influence of $\leq 5x10^{12}$ n/cm^2
Dose Rate Upset/Recovery	Classified, x to y rad(si)/sec., recover autonomously
Dose Rate Survival	If required, shall not sustain permanent damage or permanent performance degradation after exposure to dose rate of X $\leq$ rad(si)/sec. The pulse has FWHM (full-width-half-maximum) of 18-100 nS.
Dose Rate Operate Thru	If required, must operate thru after exposure to X $\leq$

Parameter	Typical Requirement
	rad(si)/sec.
Electromagnetic Pulse (EMP)	If required, is designed to prevent EMP, hardening techniques are required.
System-Generated EMP (SGEMP) Burnout	If required, is designed to prevent SGEMP burnout, hardening techniques are required.
Enhanced Low Dose Rate Effects (ELDRS)	5 to 10 mrads/second, becoming a standard

Electrical Design Considerations

Efficiency is one of the key performance requirements for a converter. Equally important is the ability of a converter to function without performance degradation in the radiation environments for its design life and its ability to operate through the SEE events. Selection of a design topology is a critical first step in the design process. The output power level usually dictates the selection of a design topology. Flyback is most appropriate for low power designs in the range of a few and up to 10 watts. Single switch forward converter is usually deployed for power requirements up to 40W or more. Other topologies, dual switch forward, half-bridge, and full-bridge are used but usually for higher power designs

Robust performance and reliability of a design is the ultimate design objective. To meet this objective, existing circuits with known performance are frequently deployed for new designs. Component selection presents another significant factor in meeting the reliability and performance objective. Only components with known radiation performance are selected for all designs typically with better than 2 to 1 design margins. Additionally, all components are normally de-rated per the guidelines of the industry's MIL-STD-1547 (Ref. 3) and NASA PPL-21 (Ref 4). The obsolete MIL-STD-975 (NASA Standard Electrical, Electronic, and Electromechanical (EEE) Parts List) is also referenced for some programs though it is supersed

It is a common practice at IR that a typical DC-DC converter design begins with circuit simulations. Computer design simulation saves time and reduces the length of the design cycle, thus shortening time to market. Accurate design simulations simplify design tasks and mitigate design risks.

Most designs for space applications must be validated not only by actual testing but also by design analysis. Components stress analysis, thermal analysis, reliability prediction, mechanical analysis, failure modes and effects, and worst case and aging analysis are often a large part of the design requirements. The analyses are expected to be completed and approved prior to design finalization and manufacturing of flight models. This is a standard procedure within the flow of new product development at IR.

Assembly Construction of a Thick Film Hybrid DC-DC Converter

Thick film hybrid assemblies have served the electronic industry since the 1960's. Their benefits are quite apparent upon examination of its construction. Refer to Figure 2 below for a typical construction of a thick film hybrid.

Figure 2 – Basic Elements of a Typical Thick Film Hybrid Assembly

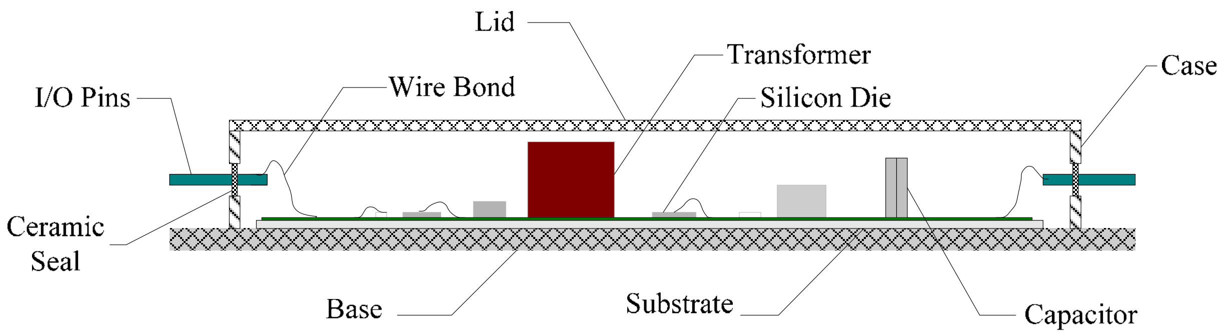
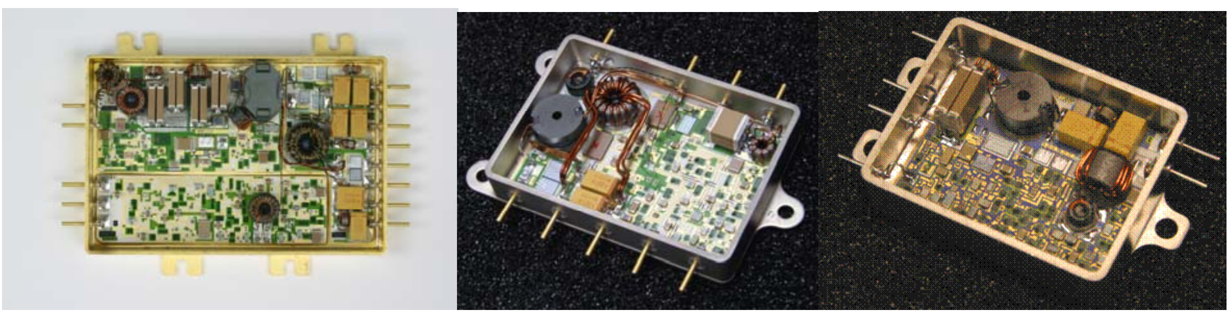


Figure 3 – Actual Thick Film Hybrid ‘brick’ DC-DC Converters



A thick film hybrid assembly is a hermetically sealed device. The rectangular or square tubular case is typically Kovar or cold rolled steel. It is welded to a base of a similar material or a material of a comparable TCE (temperature coefficient of expansion) to insure minimal bonded stress. Similarly, the lid with like material or like TCE is welded to the case to form an air-tight, hermetically sealed construction.

An assembly of a thick film hybrid usually begins with an attachment of electrical components (semiconductor die, capacitors, diodes, etc.) by way of solder reflow or epoxy to a bare substrate with screen printed resistors. The substrate is usually Alumima (Al_2O_3). Beryllium oxide (BeO). is also frequently used. DBC (direct bonded copper) is used for high current applications. Transformers and other magnetic parts are usually attached to a substrate or the base of the assembly with an epoxy with space qualified out-gassing characteristics. The substrate assembly is then solder reflowed or bonded with an epoxy to the base. The assembly is completed with attachment of lead frames from the substrate to the I/O pins. The hybrid converter is electrically tested and inspected to insure proper functionality and acceptable workmanship before a lid seal and additional reliability screening as required.

Performance Benefits

The design and construction of a hybrid offers many benefits both in electrical and mechanical performance. The individual semiconductor die in all cases are in their smallest form. This allows a hybrid assembly to be as small as possible. The smallest form factors also yield the lowest possible mass. Additionally, the silicon die have very low profiles which present a minimal concern for most vibration and shock environments. On the other hand, passive components such as capacitors, especially stacked capacitors, and magnetic parts generally have high profile. Care must be taken to insure their adherence adequacy to the substrate or the assembly floor to which they are attached when operating under extreme environments. These high profile components are generally secured with a space qualified epoxy to provide a strong bond to withstand the required shock and vibration during launch.

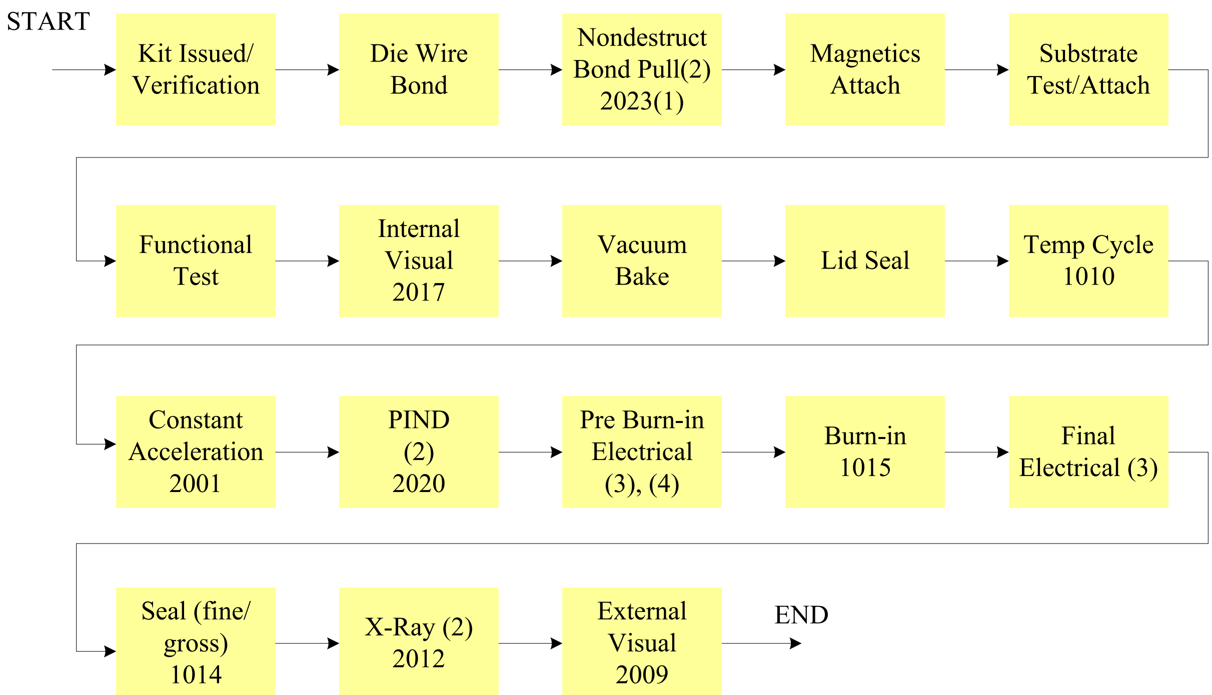
An enclosed and sealed package of a hybrid offers a moisture free environment which promotes long term reliability. It also provides an effective shield against most radiated electromagnetic interference (EMI) signals from the external sources that could upset or interfere with the performance of the electrical circuits within the package. It also circumvents any internally generated EMI from radiating and negatively affecting the other electrical circuits or equipment nearby. Their inherent short electrical connections minimize parasitic impedances, which yield clean waveforms and minimize snubber components. Thermally, the assembly design offers a very short thermal path from the junctions of semiconductor die to the base which minimizes thermal resistances resulting in minimal junction to base temperature rise. All these benefits make the hybrid designs the assembly of choice for space applications where performance, size, mass, and reliability are imperative.

Manufacturing Flow, Reliability Screening and Qualification

Figure 4 depicts the typical manufacturing and screening steps of a hybrid assembly. MIL-PRF-38534 is the manufacturing standard specification for microcircuits that are applicable to hybrid DC-DC converters. There are five screening classes, D, E, G, H, and K in accordance with MIL-PRF-38534. Class K is considered the most demanding. It is designed to provide the highest reliability level. Class D is at the lowest end of the screening spectrum. Class H and K are the most common levels required by most applications, space and non-space. Qualification conformance inspection (QCI), group A, B, C, and D are additional tests and inspections to which samples of a lot of devices built are subjected. It is designed to validate and to insure the highest level of reliability of a hybrid design as required by MIL-PRF-38534. Summary of QCI requirements are shown in Table 2.

For qualification of a radiation performance rated device, converters must be processed and qualified in accordance with a radiation hardness assurance (RHA) program which must be qualified by DSCC (Defense Supply Center Columbus). Refer to MIL-PRF-38534, reference 1 for comprehensive and the official requirements of these screening classes and complete QCI and RHA qualification requirements.

Figure 4 – Manufacturing and Screening Flow



Notes:
1. Test method, IAW MIL-STD-883 (Ref. 5)
2. For Class K device only
3. In accordance with applicable device specification
4. Optional for Class H

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Table 3 – Summary of MIL-PRF-38534 QCI Requirements

Group A	Group B	Group C	Group D
Static tests at 25°C	Physical dimensions	External visual	(Package related)
Static tests at max rated temp	PIND (1)	PIND	Thermal shock
Static tests at min rated temp	Resistance to solvents	Temp cycle (1)	Stablization bake
Dynamic tests at 25°C	Internal visual/mech	Temp cycle or thermal shock (2)	Lead integrity
Dynamic tests at max rated temp	Bond strength	Mech shock or const accel	Seal (fine/gross)
Dynamic tests at min rated temp	Die shear strength	Seal (fine/gross)	
Func tests at 25°C	Solderability	PIND	
Func tests at max/min rated temp	Seal (fine/gross) (1)	Visual examination	
Switching tests at 25°C	ESD	End-point electrical	
Switching tests at max rated temp		Steady state life test	
Switching tests at min rated temp		End-point electrical	
		Internal water vapor content	
		Internal visual/mech	
		Wire bond strength	
		Element shear	

Notes:
1. For Class K device only
2. For Class H and not required for Class K

Hybrid 'Brick' DC-DC Converters

The standard hybrid bricks can be generally grouped in two major categories by radiation performance. The two radiation levels are referred to as 'radiation tolerant' and 'radiation hardened'. Radiation tolerant hybrid bricks are designed for a mission life up to 3-4 years, which usually means the bricks have low radiation TID rating in the range of 5 to 25Krads. SEE performance is also lower usually in the range of 37-40MeV-cm2/mg. Designs of these bricks may or may not include radiation rated components. Many bricks designed for military and aerospace applications are characterized under radiation and upgraded for use in the low radiation environments. They may be suitable for low earth orbit (LEO), medium earth orbit (MEO), deep space probes, scientific experiments or other similar applications. For applications with longer mission life, usually up to 18 years, in geo-synchronous orbit (GEO) the radiation hardened hybrid bricks with radiation rating of 50 to 100 Krads or higher are the appropriate devices. All IR space rated devices meet the radiation requirements by design. Some of the bricks have immunity capability against displacement damage due to neutron environments. Some will survive the high dose rate environments.

A generous selection of standard off the shelf class H and class K hybrid DC-DC converters exists for space applications in the market today. Some hybrid bricks are built, screened and qualified to DSCC RHA requirements though IR does not have a DSCC qualified RHA plan at this time. They are available from less than 5W to more than 40W of output power. The common output configurations are single, dual and triple output. Standard popular output voltages range from 1.5V to 15V with a form factor of approximately 1.0"x 1.0" and less than 0.5" in height and up to 3.0"x 2.0"x 0.5"H. Input/output pins are available in various configurations, some with pins perpendicular to the mounting base, some with the pins exiting from the sides of the case in parallel with the mounting base. Some newer designs include functional features such remote on/off command, remote sensing, synchronization, under voltage lockout, output voltage adjustment, and integrated EMI filter. Samples of these hybrid ‘brick’ converters are shown in Figure 5. Newer IR radiation hardened hybrid DC-DC converters come with extensive documentations and design analyses including radiation qualification test reports. This has been the major selling point for these hybrid bricks as the customers reap the benefits of not having to fund the design analyses and qualification of the converters. IR’s standard off the shelf converters are shown in Table 4.

Table 4 – IR’s Standard off the Shelf Hybrid ‘Brick’ Space Rated DC-DC Converters

Series		Po	TID	SEE	Neutron	Dose Rate**	Size	Wt.
		W	Krads (Si)	Mev-cm2/mg	neutrons/cm2	Rads(Si)/sec	(L"xW"xH")	(g)
Rad-Tolerant	AMA	5	25	60	1.00E+12	4.00E+04	1.13x1.13x0.33	32
	AMF	12	25	60	1.00E+12	4.00E+04	1.60x1.38x0.33	36
	AMR	30	25	60	3.00E+12	4.00E+04	2.14x1.53x0.33	68
	M3L*	25	25	37	3.00E+12	1.00E+10	2.30x1.50x0.425	85
	M3H*	40	25	37	3.00E+12	1.00E+10	3.00x2.00x0.445	125
Rad-Hard	ARH	30	100	83	3.00E+12	1.00E+11	2.70x1.675x0.50	120
	ART	30	100	83	3.00E+12	1.00E+11	2.70x1.675x0.50	120
	S	10	100	83	N/A	N/A	1.71x1.31x0.425	50
	LS*	30	100	83	N/A	N/A	2.30x1.50x0.425	85
	M3G*	40	200	83	8.00E+12	4.00E+10	3.00x2.00x0.475	100
	ARM	30	1000	83	3.00E+12	1.00E+11	2.70x1.675x0.50	120

* includes MIL-STD-461 compliant filter
**Survival

Figure 5 – Sample Case Styles of Standard Space Rated Hybrid Bricks

AMA/AMF/AMR Series S Series M3L/LS/M3H Series

M3G Series

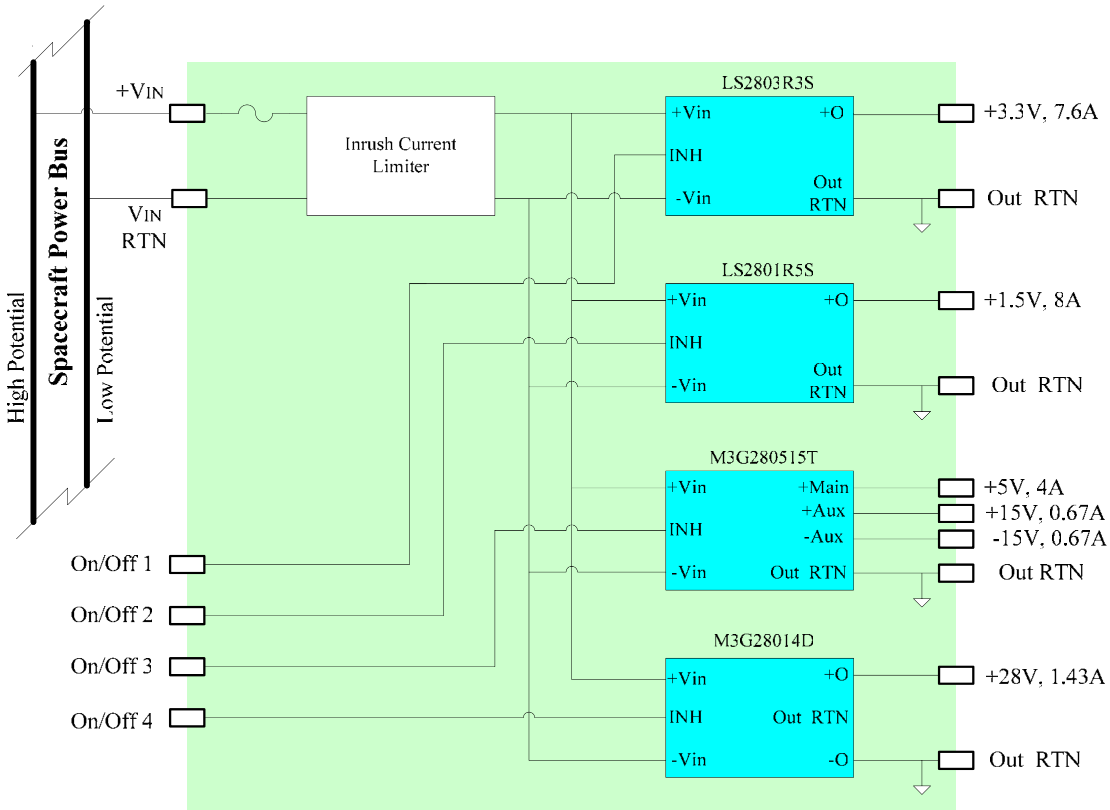
ARH/ART/ARM Series

Note: Drawings are not scaled.

A Sample System Design Solution

The standard hybrid bricks are ideal building blocks for many space applications. They offer size, weight, and cost benefits. Refer to Figure 5 for a sample system design solution. The modular design provides designers flexibility in assembly layouts. The modules may be placed near the loads to provide optimum electrical performance. The sample solution uses the LS family with low output voltage capability for digital loads and M3G series for analog application for a total of 6 outputs and 117W total output power. Both the LS and M3G include a ‘soft start’ design feature. It allows the output to rise in a control fashion hence the peak input inrush current is minimized. However, the inrush current module in the design example may not be required if the input bus voltage is well controlled. Both the LS and M3G series are capable of performing continuously in the radiation environments typically of geosynchronous orbit with a minimum total ionizing dose (TID) of 100Krads and single events (SEB, SEGR and SEL) with LET of 83 MeV-cm^2/mg.

Figure 5 – A Sample Power Converter System with 6 Outputs and 117W Rating



Note:
1. Shaded blocks are IR's building block 'brick' converters. Customer is to design the inrush current limiting circuit as needed by the system requirements.

Trends

As more radiation hardened digital devices such as FPGAs, memories, DSPs, ASICs, etc. become available the distributed power architecture (DPA), a two stage power design is gaining popularity in space power system designs. The hybrid bricks are ideal for such design applications. The front end power conversion will be a high efficiency down converter converting a spacecraft power bus to an intermediate voltage of 5V to 8V DC. The intermediate voltage is then converted down to the lower regulated voltages of 3.3V to 1V as required by the digital loads. The voltage regulation is accomplished by a synchronous buck regulator, one regulator per output. A typical system design will require 2 or more outputs. The synchronous buck regulators are non-isolated topology that has been used since the early 1960's. They offer excellent static and dynamic performances when located near the digital loads. The new generation of the brick designs will include the down converter and the POLs.

Future Challenges

Size, reliability, cost and efficiency have been the main drivers for most satellite designs. These design drivers are expected to continue. Challenges for next generation hybrid bricks are then to reduce module sizes through components integration and to boost efficiency by incorporating new and better performing devices. Advances in space qualified ICs and MOSFET devices will be needed for the improvements to be feasible. Radiation hardened PWM ICs, synchronous rectifier driver ICs and synchronous buck regulator ICs with higher frequency performance must also be available. Lower gate charge and lower on-resistance radiation hardened MOSFETs are essential in efficiency improvements. Since not all system designs require the exact same functional features and power levels, miniaturization and modularization of the system elements i.e., power conversion and functionality, should reduce size and cost as the users would only use and pay for the required elements and the required power output. Modularization should also offer lower individual module costs as modules at higher quantities may be built, processed and tested in a larger batch resulting in lower manufacturing costs.

Conclusions

Standardization of hybrid 'brick' DC-DC converters for space applications has been a challenge because each satellite manufacture has its own standard requirements. Some inroads have been made with thick film hybrid 'bricks' converters. New generation standard off the shelf hybrid bricks have become more attractive and are gaining popularity as they offer extensive design documentation and qualification at very little or no recurring costs. Integration of various circuits in a form of monolithic integrated circuits or ASIC must take place to further reduce size of the hybrid bricks. Performance characteristics of radiation-hardened MOSFETs must advance to further improve efficiency in power conversion. Finally, modularization may provide notable size reduction and reduced program costs as designers would use and procure only hybrid bricks as needed.

Acknowledgement

I would like to thanks the following colleagues for their valuable input and graphic supports: Russ Hansen and Nazik Maloyan.

References

1. MIL-PRF-38534E, "Hybrid Microcircuits, General Specification for", Department of Defense.

2. MIL-STD-461C, "Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference", Department of Defense.

3. MIL-STD-1547B (USAF), "Electronic Parts, Materials, and Processes for Space and Launch Vehicles", Department of the Air Force.

4. "Goddard Space Flight Center Preferred Parts List PPL-21", The Parts Branch Office of Flight Assurance Goddard Space Flight Center.

5. MIL-STD-883E, "Test Method Standard Microcircuits", Department of Defense.

6. “Military Satellites Pose Engineering Challenges in DC-DC Converter Development”, Tiva Bussarakons, Defense Electronics, A Primedia Publication, May 2004.

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