High Performance Power Converters for Saturn-Bound Cassini Spacecraft

Krauthamer, Stan, and Radhe Das, Joe White, Dave Rogers, Donald Nieraeth, and Chris Stell, Power Electronics Group, Jet Propulsion Laboratory, (California Institute of Technology, Pasadena, California, 91109

The complexity of Class A Saturn-bound Cassini spacecraft power system stems mainly from the unusual constraints and design requirements that are imposed on the design of its power converters. The factors influencing the design include: Radioisotope Thermal Generator (RTG) as the electrical power source and its electrical characteristics, output power requirements, environmental considerations such as high radiation level, broad temperature excursion, electromagnetic compatibility, conducted susceptibility and radiated and conducted emissions, pulse-load operation, fault protection, mass, volume and efficiency.

The power converter units (PCUs) designed for the Cassini spacecraft system were subject to several unique (unusual) design constraints in addition to the standard requirements placed On any space mission of long duration. This paper describes these design constraints, discusses the problems that arise from them, and presents some performance data (Ref. 1 and 2)

The major design requirements are summarized in the following list:

- Synchronization
- Input/output isolation
- Stringent low frequency radiated EMI limits
- Conducted EMI
- MIL-STD high frequency EMI limits
- Input and output common-mode emissions
- Low-noise outputs
- Single event upset effects
- Stringent pulse load regulation for MIL-STD-1553B Bus
- Transient cross-regulation
- 100-krad (Si) tolerance
- Efficiency > 80%
- Multiple outputs (3 to 9)
- 12-year minimum life in space
- Stringent input impedance limit
- Power hold-up
- Commonality considerations
- input voltage design range: 2?-35 volts
- Output power range.: 1-36 watts
- No-load operation
- Overvoltage protection
- Power status monitoring
- Component restrictions

Critical Design Requirements

While all the requirements listed above had to be taken into account in the design, one particular subset of requirements posed special difficulties because of their inherently contradictory nature. These requirements were the input impedance limitation, transient load response, and transient cross-regulation. This section discusses some of the implications of these requirements.

The spacecraft specification calls for an input impedance limit (looking into the converter) of

$$Z_{in} = \frac{V_{BUS}}{I_{dc}} \sqrt{\frac{1+(f/4000)^2}{1+(f/600)^2}}$$

where Idc is the input current, f is frequency, and V_{BUS} represents the nominal bus voltage. in order to meet this requirement, the conducted EMI specification, and provide sufficient converter stability margin, a filter with an uncommonly large inductance and an uncommonly small capacitance is required. This seriously impacts load voltage transient behavior, particularly in view of the stringent load transient requirements. It would in general be preferable to have a relatively large capacitance to help support the transient load. The input filter for a 10 W converter is shown in Fig. 1,

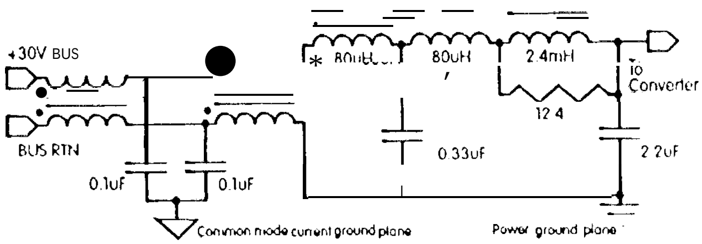

Figure 1. input Filter Schematic Circuit Diagram

The transient load for MIL-STD-1553B Bus Interface Unit (BIU) occurs on the 5 Vdc output and has a magnitude of 0.9A. Transient loads as high as 2,7A (3 BIUs) are required in some PCUs. This transient occurs at loads, from approximately 10% load to 100% load at 10% load steps. The design requirement is to keep the 5 Vdc output entirely within a ± 2% regulation band (100 mv) during the transient,

Another difficulty is pulse load cross-regulation, i.e., disturbances caused on the secondary outputs due to the transient loading on the main (5 Vdc) output. For efficiency reasons, the auxiliary outputs are magamp regulated. When the 5 Vdc output is pulsed, the converter's duty cycle must increase immediately in order to maintain the 5 V output, This results in a large and rapid increase or decrease in the volt-seconds applied to the magamp. To counteract this increase, the magamp control circuit must respond as quickly as possible,

The use of magamps leads to difficulties in stabilizing the converters. Because the converter is current-mode controlled and the total output power of the auxiliary outputs is near or exceeds that of the main output under nominal conditions, the magamp input impedance can cause severe distortion of the converter's loop gain, especially under light load conditions. The interaction is most severe near the magamp's filter resonance when the input impedance is minimum. To stabilize the input impedance (as well as improve transient cross regulation) we added a second feedback loop (Fig. 2) that senses the volt-seconds applied to the filter. This is not a feed-folward loop as the sense point lies after the magamp modulator.

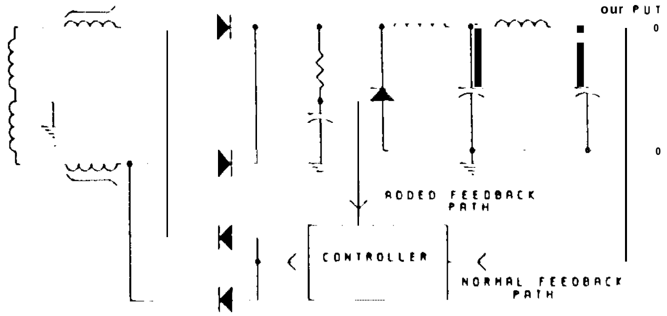

Figure 2. Magamp Feedback loop

The Cassini science instruments require very quiet power supplies. For example, ripple plus spikes must be below 5 mv p-p for proper instrument performance, In addition, common-mode (CM) noise has proven to be an insidious problem in past missions. in a scientific spacecraft such as Cassini, it is not desirable to shunt the CM currents to the chassis using feed-through capacitors and baluns. The currents injected into the chassis are a secondary source of EMI, Structure current is known from past experience to be one of the primary causes of interference with various scientific experiments particularly those involving plasma wave science.

Common-mode noise is caused by parasitic capacitive coupling between primary and secondary transformer windings It has been long recognized that a primary/secondary electrostatic shield is an effective method for reducing CM noise. however, it has not been appreciated, to our knowledge, that secondary to secondary parasitic capacitance causes circulating "common-mode" noise current between secondary outputs. These currents which never appear in measurements of input line CM noise (which is the only requirement levied by the spacecraft) can be a source of upset to the attached instrument,

The method we have implemented does not require shunting CM currents to the spacecraft structure, does not require an EMI enclosure to be effective, and suppresses both input and output CM currents regardless of the number of outputs. The filtering scheme is shown in Figure 1. It is simply a two-stage CM filter. Another advantage of a two-stage filter is that the choke design is somewhat easier since the shunt capacitance, while important, is not as critical as it would be in a single-stage CM filter. In our design the second filter stage provides an additional 40 dB of CM noise rejection. This scheme provides little protection against CM currents injected into the supply other than that provided by the series impedance of the CM chokes. Suppression of incoming CM requires introducing a shunt path to the chassis.

Common-mode requirements are specified only for the input. Output CM noise is troublesome in the many sensitive instruments aboard Cassini. As a result of analysis and test, a design requirement was established in order to keep the output CM current below 6 microampere. This was done to insure proper operation of sensitive instruments.

The instrument designer has levied requirements on the PCU designer. Some of these requirements are as follows: power-on-reset (POR) signal, undervoltage lockout, overvoltage protection (+5 Vdc output) and maximum allocated printed circuit board (PCB) area for the PCU.

It was important for cost and schedule considerations to reuse as much of the design as possible for each converter. PWM circuits, housekeeping power supplies, drive circuits, synchronizing circuits and output regulators of identical design were used in all converters,

The requirement to use class S components restrict the choice of PWMS, FETs, and magnetic materials, and magnetic core geometries.

Solid tantalum and ceramic capacitors are used extensively in all PCUs. "They exhibit low variation in capacitance and ESR down to -30° C. However, the application of solid tantalum capacitors requires detailed knowledge and understanding of MIL-C-39003/10 and MIL-HDB-978-B documents, Surge current rating and parallel operation are critical characteristics to consider. Wet slug tantalum capacitors which have limited application have unstable capacitance and ESR characteristics at low temperature, As a result, they have long been the bane of designs that must operate over large temperature ranges while maintaining fast response to transient loads and low ripple voltage levels

Design Approach

Both push-pull and forward converter topologies were examined, Based on trade-off analyses, both topologies were used. A forward converter using synchronous rectification was designed and built. An efficiency gain of approximately 5% over the Schottky diode implementation was achieved (Ref. 3). This topology, however, was not extensively used because of PC board area constraints, Fig. 3 shows block diagram of a generic Cassini spacecraft power converter,

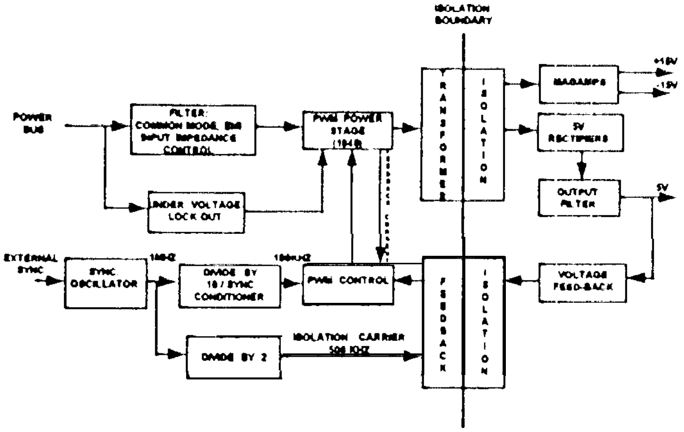

Figure 3. Block Diagram of a Generic Cassini Spacecraft Power Converter

Thermal Requirements

The power converters and electronic assemblies for deep space missions are designed for a thermal environment quite different from that encountered in the usual airborne or ground equipment, All the heat generated inside the spacecraft must be radiated from the surface of the individual shear plates, The effectiveness of the heat removal will depend on the emissivity of the plate, the surface area and the absolute temperature, The maximum shear plate temperature for the qualification of the design is at 75° C and the maximum worst case allowable junction temperature for any semiconductor is 110° C.

Mechanical Considerations

By industry comparison, the Cassini power converters are large for their meager power output capability, The baseline 10W converter occupies approximately 226 sq. cm. with a max. height of 1.8 cm. This relatively large size attributed to a considerable amount of ancillary and core circuitry required to meet typical functional requirements and stringent core electrical requirements. For instance, strict CM noise requirements led to the use of dual inductor CM filters on every input and every output. Input impedance requirements lead to the use of a multi-stage input filter. Precision POR, undervoltage lockout, over-voltage protection and external synchronization circuitry drove the component count up further. Ultimately, the packaging technique employed had to be space efficient if all the components were going to fit. Surface mounting components are used to minimize the PC board area.

The PCUs are fabricated on multi-layered polyimide PCBs using mostly surface mount devices, The magnetics, which are exclusively toroidal in geometry, are potted in rectangular cups that have copper leads emanating from the base on one or more edges. This arrangement provides an inspectable surface mountable device with short lead lengths, which reduces the radiated emissions. To further reduce emissions, the converters are placed in an EMI enclosure. The heat generated by any device on PCU is rejected via the device package through the leads and/or a thermally conductive bond to the PCB. There are three solid copper layers within the PCB which serve the dual purpose of electrical ground planes and waste heat conduction paths. Multiple mounting bosses around the perimeter of the PCB provide mechanical rigidity and a conduction path to remove heat from the PCB. The mounting bosses are attached to an aluminum honeycomb plate which connects to an outboard radiating surface referred to as the shear plate. Electronics units arc grouped together in bays which share a common shear plate. The units are stacked in parallel enabling the component side of one unit to radiate its waste heat to the honeycomb plate of the adjacent unit.

Performance Characteristics

Since there are many PCUs with different requirements, performance of only the Remote Engineering Unit (REU) is presented. The block diagram of the Cassini REU power converter was shown in Fig, 3. It uses a push-pull current mode controlled PWM. The main regulated output is 5 volts. Other auxiliary outputs are magamp regulated. In other converters where current levels are low, linear regulators are used. Fig. 4 shows the converter efficiency over load and temperature at an input voltage of 28V. Because the spacecraft power system is peak power limited, the design maximizes efficiency at full load. The maximum efficiency is approximately 79°/0. Fig. 5 shows the converter's pulse load response, which is not symmetrical with respect to positive and negative going transients. For the positive load transient, response time is limited by the volt-seconds available for slewing the output inductor, Approximately 25 mv of the voltage drop shown is due to resistance of a common-mode choke that is outside the regulation loop, Fig. 6 shows a spectrum analyzer plot of the narrowband CM input noise current. Note that the actual noise only occurs at multiples of SO Khz. The regions in between are due to environmental noise and the noise floor of the analyzer, The emissions are 30 dB below specification. Table 1 summarizes the converter's regulation and ripple performance, On the 12 volt outputs, the fundamental ripple is below 1 mv, and the dominant noise is switching spikes, Fig. 7 shows mechanical layout of the converter.

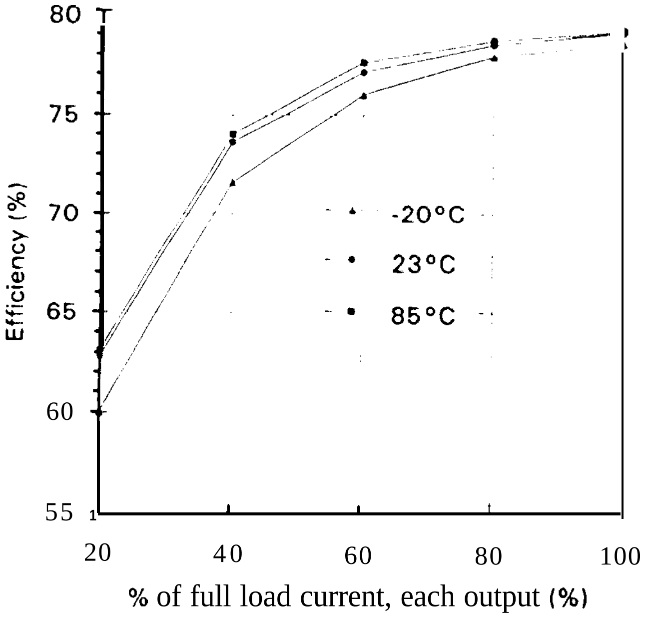

Figure 4. Efficiency vs. % of Full load Current @ Vin = 28V

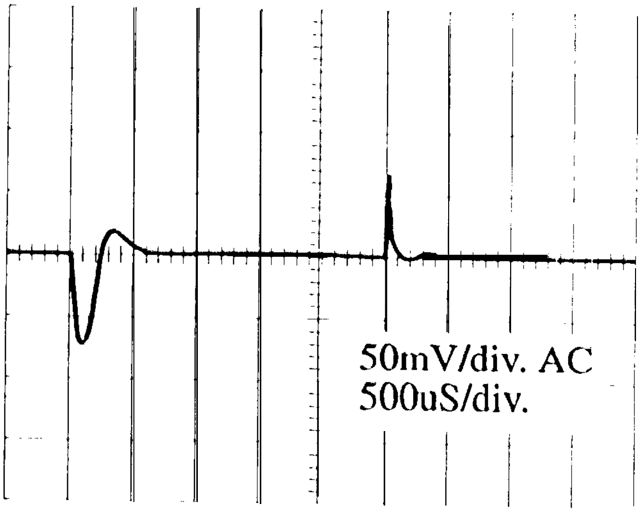

Figure S. +5Vdc Output Response to 0.09 to 1.1A lend transient @ Vin = 30V

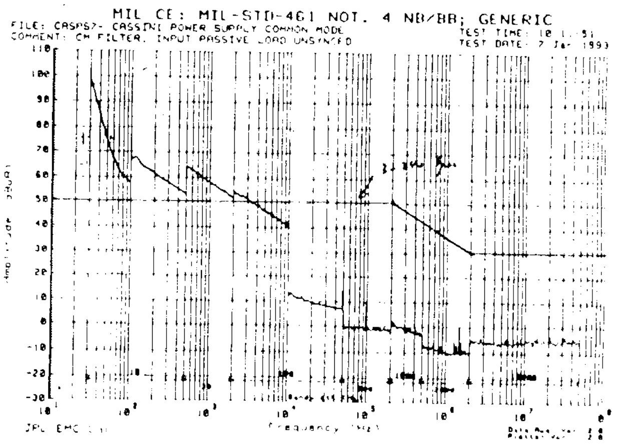

Figure 6. Narrow Band input Common-Mode Current Emissions

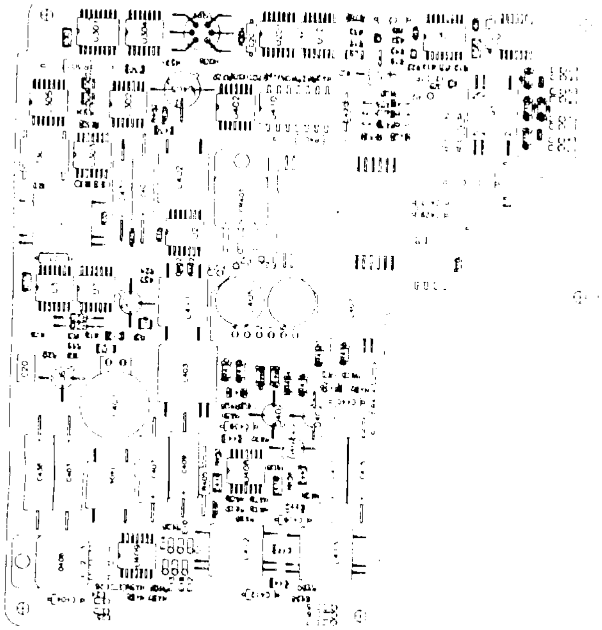

Figure 7. PCU Mechanical lay Out

Table 1. Worst Case Performance Under Stated Test Conditions

Test Conditions:
Vin 22.0, 30.0, 35.5 Vdc
Temp: -20°C, 25°C, + 85°C
+ 5V Load current 0.09 to 1.1Adc
+/-12V Load current 0.035 to 0.1Adc

Parameter:	Units:	Worst Case Value:
Input Ripple (dc loads)	mA p-p	7
Min. max. load Efficiency	%	79
+ 5 V DC Voltage Reg:	% change from 25°C Voltage	-0.14
+5V Ripple + Noise	mV p-p	12
+5V Transient Response: (Curr. step= 0.2 to 1. 1A) Undershoot Overshoot Settling Time	 mV mV ms	 160 150 0.75
+12V DC Voltage Reg:	% change from 25°C Voltage	-0.14
+12V Ripple + Noise	mV p-p	5

Conclusions

Test results and requirements correspond very well for the wide variety of PCUs. As indicated earlier, the PCUs are mechanically rigid and conduction paths are efficient in removing heat, Despite advanced techniques used, the designs are not optimal with regard to mass, volume and efficiency because of the many complex requirements imposed on the designer.

Acknowledgments

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