Space Power Supplies

Figure 21
Power converter using a combination of a hybrid module and outboard discrete components for fast lead time and low cost. Unit shown is a 14 to 28 VDC converter with 90% efficiency at 40 watts.

Spacecraft and satellites have self contained electrical power systems derived from batteries, photovoltaic arrays, fuel cells or radio-isotope generators. This power may be unconditioned, or may be conditioned to a regulated bus level, from which several to several hundred converters must efficiently convert the power for end users.

The principal issue facing space power supply applications is that extremely high MTBF must be achieved with quantities that are relatively low, compared to other power supply applications. The low quantities hamper learning curve (experience) driven improvements. The methodology evolved for the design and construction of space power supplies has overcome the constraint of low quantities.

Several tried and true techniques have been established to resolve this issue.

One important method is the use of "heritage" designs. These are designs and processes that have successfully flown on other spacecraft. To the extent that the new application provides the same environment as the heritage environment, there is a lot of validity to this approach. The disadvantage of this approach is that it is much less useful as the time span between the new requirement and the heritage application widens. The idea of using heritage attains its greatest benefit within just a few years after the heritage application. If the use of heritage based on designs one or two decades old occurs, the benefit becomes a detriment.

Preferred parts lists solely based on heritage may lag the present day by twenty to thirty years. Many of the components may be commercially obsolete, leading to lower reliability. The equipment becomes heavier and larger, leading to other design compromises. The manufacturing processes to make the piece parts accumulate change over the years, invisible to the activities maintaining the preferred parts list.

Another important technique to improve reliability is the separate qualification of piece parts. This may be performed on discrete parts as well as hybrid and chip elements. The piece parts are qualified to environmental levels much higher than they will experience within the completed assembly, giving a factor of safety to the designer. Designs sometimes are less reliable than they might be because some aspect affecting reliability has been overlooked. This can be avoided by complete review and scrutiny. This oversight requirement can be satisfied by the submission of complete and comprehensive drawing packages. This is also necessary to assure control of the configuration.

To supplement or as an adjunct to any overall testing program, various analyses should be performed. These analyses verify that all piece parts are properly applied and that the customer's overall expectations for reliability will be achieved.

Also, as part of an overall quality system, all manufacturing and design processes should be documented. Where necessary, such as soldering, all operators should be trained and certified.

Space applications tend to have environments that are unique to each application, in contrast to aircraft, shipboard, vehicle and fixed uses. Radiation effects including total dose and SEU depend on the orbit as well as time on orbit. Deep space application have unique radiation requirements. Temperature cycles and extremes depend on the spacecraft's thermal control system as well as the location of the power supply.

Shock, vibration and pyrotechnic shocks also tend to be unique to the application.

Since space power supplies need to operate in a vacuum environment, all dissipative elements need predictable paths to the thermal sink. This is sometimes overlooked by neophytes.

Most spacecraft applications contain optical and other systems that are affected by out gassing of volatile materials. Therefore, all materials must be categorized and selected for low out gassing.

Packaging Design Choices

Figure 22
Eight output converter with BIT showing part hybrid/part discrete modular construction.

Space Power Supplies can be fabricated with all discrete piece parts, fully in hybrid microcircuit form or a mixture of both. The mixed construction can also consist of a number of self contained hybrid DC-DC Converter modules in a housing. In determining which approach is best, both technical requirements as well as cost and schedule must be considered. Normally, a full hybrid approach is more expensive and takes longer to develop than a part hybrid or full discrete design. However, this applies to units that are essentially custom. When requirements can be derived from standard or previously developed designs, the cost and schedule picture can dramatically change for the better.

Full hybrid power supplies using thick film substrates, chip and wire semiconductor die and surface mount components contained within hermetic enclosures allows the ultimate in packaging density. The elimination of individual piece part packages also improves overall reliability. Resistors are screened and fired directly on the ceramic substrates, and are tailored in size for their exact wattages.

The hermetic enclosure simplifies many environmental concerns and provides an excellent dormant storage life. The low mass of the chip components allows the full hybrid converters to withstand shock, vibration and acceleration that is considerably higher than tolerated by discrete units.

Figure 23
Six output level 120 VDX input converter

One drawback for full hybrid construction is that full MIL-STD-981 magnetic component construction is not possible due to size constraints. This includes the aspects relating to terminal design and encapsulation. However, most of the MIL-STD-981 requirements can be retained.

Full hybrid construction is best suited for output powers up to 120 watts at the present. Above this level, thermal considerations of the major dissipators (semiconductor die and magnetic components) make it more practical to use separate packages at higher power levels.

Above the optimum power level for full hybrid construction, it is advantageous to mix hybrid construction with discrete parts. Discrete construction also encompasses surface mount piece parts and techniques.

In this mixed construction, the low power, complex circuits are contained within the hybrid. The higher power and bulkier components are packaged separately. This gives good volumetric efficiency and allows better thermal paths for the higher power dissipators.

Mixed hybrid and discrete construction is best suited for power levels from 50 watts to 1000 watts. This is the most compact construction that can offer full MIL-STD-981 magnetic components. In addition, the mixed construction allows mechanical provisions for EMI filtering, such as EMI plenums, making EMI filtering easier to implement than in full hybrids.

An advantageous variation of the part hybrid/part discrete approach is to combine a number of complete hybrid DC-DC Converters in an assembly, which can also include some small amount of discrete circuitry. This building block technique allows rapid development of complex units at a minimal cost.

Full discrete construction is suited best for high power applications as well as full custom applications that must be implemented with out dated preferred parts lists. In a high power situation, the size and weight savings produced by the low level hybrid microcircuits are not significant. Full discrete construction is applicable from several hundred watts to the kilowatt range.

One of the most important aspects of selecting a construction method is not technical, but depends on factors that are intangible. Inherent in the conservative structure surrounding many space requirements is the strong resistance to change.

Many recent programs are mandated to be "better, faster, cheaper," and attitudes toward using more modern packaging design are gravitating toward full hybrid and part hybrid designs as the power level permits.

Construction Techniques

In fabricating space power supplies, great reliance is placed on documenting detailed procedures for all manufacturing operations, as well as training and certification of all operators. Quality requirements such as NHB-5300 and MIL-Q-9858A mandate procedures for all manufacturing operations.

The purpose of the procedures is to allow review of the operation, consistency in its application and as a criteria for training.

For a typical hybrid manufacturer approximately 40 procedures may be required. For magnetic component manufacture, approximately 20 procedures may be required. For discrete assembly, approximately 30 procedures may be required. The hybrid procedures are written around MIL-H-38534, the magnetic procedures around MIL-STD-981 and the discrete assembly procedures are based on NHB-5300.

The operators performing these procedures are trained (in accordance with a training procedure), tested on their knowledge and ability to perform the procedure, then are certified for that procedure. Outside agencies have cognizance of the certification of procedures as well as instructors, which is renewed at periodic intervals.

The intent of generating all these procedures and methods is that nothing be left to chance or to interpretation. This overcomes part of the learning curve that would otherwise occur with a small unit quantity.

Piece Part Selection and Qualification

Figure 24
Single Output 120
to 28 VDC Converter

One of the distinguishing features of space power supplies is the care with which piece parts are selected.

Various preferred parts lists (PPL's) exist, many derived from MIL-STD-975. The advantage of using parts from these lists is that they represent mature parts with considerable heritage. The disadvantage of these lists is that the piece part and packaging technology is from ten to twenty years old. This produces units that are larger, heavier and less competitive than more current practice.

A phenomenon that must be unique to the space industry is often observed in designs based on PPL's. This is circuit design based on unique combinations of minimum types of so called standard parts. It's analogous to logic designs built entirely with NAND gates, or to linear circuits built entirely with NPN transistors.

The motivation for these types of designs is not only using parts on the PPL's, but also the monetary costs for minimum lot costs of the parts.

Very often, large excess amounts of space qualified piece parts have been purchased on earlier contracts, and the designers are mandated to use these parts until stock on hand is depleted. The resulting designs are very often non-competitive.

Competitive space power supplies will inevitably use some quantity of what are termed "non-standard" parts. This may include parts that are military standard but not on the PPL, or parts that are custom, such as magnetics. For a full hybrid design, all chip components may be considered non-standard.

The typical procedure for using a non-standard part begins with the generation of a source or specification control drawing. This document not only specifies all the electrical and mechanical parameters of the part, but also defines the qualification and quality conformance requirements. When generated for chip components, these drawings may be called detailed device specifications. Qualification is the initial testing that qualifies the part to meet the requirements of the drawing, and usually includes environmental testing as well as electrical testing. Quality Conformance Inspection testing (also known as QCI) qualifies the particular lot of parts, and is usually done at periodic intervals. QCI normally has a smaller subset of tests than qualification testing, so is less expensive. QCI is also known as group A, B, C, D and E testing. Depending on the type of parts, the "group" testing may be just group A and B, or A through E. In the QCI process, one or more units are destroyed, adding additional expense. There are various strategies for reducing QCI cost, which require the informed direction and approval of the customer.

The qualification process for chip components is called element evaluation, and is performed in accordance with MIL-H-38534. This is also used for quality conformance inspection.

Magnetic components for space power supplies are almost invariably non-standard. The usual governing specification for magnetic components is MIL-STD-981, which builds on MIL-T-27 and related specifications. Like many other detailed parts specifications, MIL-STD-981 allows qualification (not QCI) by similarity, provided the "similar" part meets certain tests of "closeness" with the previously qualified parts. This permits cost savings in many instances.

After the piece parts have been documented, qualified and built, the parts may be subjected to a further screening known as Destructive Physical Analysis (DPA). DPA is a process wherein representative parts from a lot are dissected to verify construction meets detailed requirements. If the samples from the lot pass the DPA, the entire lot is accepted. If they fail, the entire lot is rejected or otherwise dispositioned. Many piece part specifications have specific DPA requirements. However, it is not unusual to impose other specifications, such as MIL-STD-1580, which have other DPA requirements. Sometimes, the specific requirements differ and a part that meets its detail requirement will not meet an overall DPA specification. Resolving these specification conflicts is a usual recurrence.

The economic and schedule result in requiring QCI and DPA's on discrete components often results in a full hybrid construction being less expensive and more readily available than discrete construction since element evaluation is a quicker process than QCI on many discrete items.

Documentation

Space Power Supplies require extensive documentation efforts for two general reasons. The first may be considered in the nature of design disclosure. This allows the customer to thoroughly review the design and construction prior to hardware fabrication, as well as to review results of testing prior to actual use. The second is to document all aspects of the unit to allow configuration control and to assure that the unit was built exactly as intended.

A comprehensive documentation program may be streamlined by drawing heavily on existing documentation. It is important to distinguish between customer review of existing documentation and customer review and approval of existing documentation. The former has modest cost impact as no drawings or procedures will be changed. The latter has greater possibility of cost impact since changes are usually inherent in the approval.

Drawing packages are generated to DoD-STD-1000 guidelines. There are three levels of drawing packages in this document, Level 1, 2 or 3. Level 1 is an engineering drawing package, and is intended for the purposes of design disclosure. This level of drawing may be inadequate for this purpose when depicting space power supplies.

Levels 2 and 3 are suitable for use to document configuration control, as differentiated from design dis-closure packages. Level 3 is the most comprehensive, and theoretically gives sufficient information for re-procurement if necessary.

The types of drawings contained in a Level 2 or Level 3 package follow a hierarchy, starting with the outline/installation drawing, next the top assembly drawing, then the lower level assemblies. This is followed by detailed fabrication drawings. When components are purchased, the drawing package includes source and spec. control drawings. These are supplemented by schematics, block diagrams, manufacturing procedures, etc. Very often, due to schedule requirements, there will be more than one configuration supplied. In that even, "as built" drawings are provided, depicting specific configurations.

Many of the parts will be covered by specification control drawings or source control drawings. The former type is used when the requirements are not highly critical and source qualification is not deemed mandatory. The latter restricts procurement of the part from approved sources. Source control drawings usually list requirements which must be satisfied to qualify a part.

In practice, source control drawings are frequently preferred over specification control drawings when the specifier is aware of undefinable parameters that are important or that only one acceptable source exists. Another reason for source control drawings may be that the specifier knows the recommended source has unique test equipment or capabilities not available elsewhere.

Schematics and block diagrams are used as tools for design reviews and later analysis. With space power supplies, if any repairs or modification is required, only the original source should be entrusted with this work, so schematics and block diagrams are not needed as submittals for customer maintenance.

Block diagrams and schematics are also useful in conjunction with theories of operation, which describe how a unit operates.

Plans, procedures and reports are another important area for documentation. These documents control the testing of space power supplies.

Test plans are an important part of any test program. It is not correct to assume that specifications covering environmental or EMI testing are in themselves sufficient for conducting tests. What is missing is the mechanical configurations, electrical connections, ambient conditions and pass/fail criteria. These elements must be reviewed by the test activity as well as the customer prior to conducting the tests. The test plan is the vehicle that describes the missing information prior to test execution.

When the test plan is approved by the customer, a test procedure is generated, covering the actual testing. This embodies the elements of the test plan. The test procedure describes the testing in greater detail, listing the equipment or facilities to be used as well as the sequence of testing.

Following the actual testing, a test report is generated. This describes the test results, and is often accompanied by photographs. If any anomalies have occurred during testing, this is noted in the report.

Analysis

Although many aspects of the space power supply's design are best characterized by testing, some areas also demand substantiation by analysis, which establishes the design margins.

In the development of a space power supply, the most frequently required analyses are circuit (SPICE), electrical stress, thermal, derating, worse case, MTBF, FMECA, EMI, environmental and radiation effects.

There is a hierarchy to these analyses, and just like in college courses, many have prerequisites.

The fundamental analysis is the circuit analysis, which usually employs a form of SPICE Modeling. The SPICE Model establishes the operating points and provides a sound analytical framework for later work. For a power supply, the SPICE Model gives data on the stability of the closed loop.

Using the SPICE Model to confirm operating points over a range of conditions, the worse case electrical stress for each part can be computed. Many parts have several parameters which must be assessed. For example, for a capacitor, working voltage as well as ripple current must be determined. For a resistor, it is power rating as well as maximum current or voltage. For diodes, it may be reverse voltage, reverse current, forward current and AC effects. The electrical stress information for all of the parts feeds into the thermal, derating and worse case analyses.

For the thermal analysis, the power dissipation for each part is computed. The goal of the thermal analysis is to determine how hot each component gets and verify that the computed temperatures meet design requirements. Since space power supplies are required to operate in vacuum conditions, heat removal is limited to conductive cooling and radiation. Practically, radiation is not significant.

One of the most useful tools for thermal analysis is the finite element analysis technique. This is represented by programs such as ALGOR FEA. The method of analysis proceeds in the following sequence. All heat paths are characterized. The physical construction is broken up into infinitesimal elements and the heat flow is computed by matrix manipulation. The resulting output of these programs is a node listing which can be portrayed as isothermic lines. This allows the hot spot temperatures to be readily seen.

If a component exceeds its required temperature, the thermal design can be iterated and the analysis re-run.

The thermal analysis and electrical stress analysis feed into the derating analysis. Overall specifications, such as MIL-STD-975 and related specifications, impose derating limits for piece part application, many being temperature dependent. The derating analysis is usually in tabular form, comparing each piece part's rating with its stress level. Often a customer will only explicitly need the derating analysis, however, the SPICE Model, electrical stress and thermal analysis are all required for a meaningful input.

A worse case analysis may take the SPICE Model and vary the tolerances of the various components in a random way. This is also called Monte Carlo analysis. Or, the drift of component tolerances may be assessed for an End of Life analysis. This type of analysis predicts how the power supply will operate at the end of a long duration, for example a 30 year Space Station application.

MTBF (Mean Time Before Failure) analyses predict the failure rate of the space power supply. Using mostly experiential information and methods derived from MIL-HDB-217, and drawing on the temperature and electrical stress levels derived from earlier analyses, the failure rate may be computed. Computer programs to perform the computation are available. Simplified assessments using only the parts count are possible. However, they are not as precise as the actual stress method. Clearly, the electrical stress and thermal stress of the piece parts must be determined to accurately predict MTBF.

FMECA (Failure Modes Effects Criticality Analysis) is often required to be performed for a space power supply, as this allows more reliable units to be achieved. A knowledge of the functional operation as well as the failure rate of each piece part is needed to prepare a FMECA. Therefore, the MTBF and all subsidiary analyses are required for a FMECA.

EMI analyses are often required as an adjunct to testing. The benefit of an EMI analysis is that it may be performed before hardware is constructed, or may assess areas that may be difficult or costly to test. EMI analyses are often based on SPICE Models. Filter configurations may be readily modeled, as well as parasitic effects. This gives the designer a look ahead so that the design can anticipate and solve EMI problems before the (possible) long lead hardware is assembled.

Environmental analyses primarily consider the effects of mechanical inputs to the power supply, including vibration, shock and acceleration. These are most useful before actual hardware is built, although analysis may also help to fix inadequate mechanical designs. Finite element analysis techniques are mostly used, with the worst case elements modeled.

Radiation effects analyses consider the known effects of radiation on piece parts, such as the Vgs shift in power MOSFET's and the leakage current increases in semiconductors due to radiation induced defects. These analyses are based on the SPICE Model and the worse case analysis.

Testing

The purpose of a test program is risk mitigation. Unlike terrestrial power supply applications, environmental testing is performed in conjunction with analysis, not as an either/or situation. Testing alone may not reveal design margins or weak spots. Analysis alone may be flawed. Therefore, a balanced combination of analysis and testing is generally favored. The most significant tests are usually shock, vibration, thermal vacuum, EMI and radiation.

Most applications for space power supplies have a relatively benign shock and vibration environment on orbit, but a severe requirement during transportation and launch. Pyrotechnic shocks are normally the most challenging requirement for low mass units.

Thermal vacuum testing is another important area that cannot be confirmed without testing. Every heat dissipating component must have a reliable path of conductive heat removal. Many power supplies designed for non-space use neglect this necessity, and so fail when exposed to the hard vacuum environment of space.

EMI is another important area that varies widely from application to application. Because of the small capacity of most space electrical bus systems, there has been little standardization of bus specifications. This translates to a wide diversity of EMI requirements. Test plans, always important, assume an even greater importance in light of this diversity.

Radiation effects are normally tested on piece parts because of the great expense involved in testing complete units. The piece parts tested are those that are known from experience to be most susceptible to radiation. In addition, since relatively few facilities can perform tests such as SEU resistance, long lead times and high costs for testing are common.

Successful testing programs characterize the equipment with minimal cost and schedule impact. One of the best ways found to facilitate this is to precede a formal qualification test program with an informal pre-qual program.

A pre-qual program is designed to hit the hot spots, or technical high risk areas of the development task, at an early stage in the program and at a modest cost. An assessment is made of the highest technical risk areas, and only those areas are tested. Test plans, procedures and reports are kept informal, which holds down costs. Source inspection is not invoked, streamlining the schedule. A pre-qual program can be performed with a brassboard, prototype or pre-production unit, and does not require flight level hardware.

A pre-qual program has two benefits. If it precedes a formal qual program, it gives early assurance of a satisfactory design. If testing shows that changes are necessary, changes can be made on non flight hardware, avoiding the high costs and long lead times of flight hardware.

The second benefit exists when the next higher assembly beyond the power supply will be subjected to formal qualification tests. In that event, the pre-qual program will give reasonable justification for combining the formal qualification test of the power supply with the testing of the next higher assembly.

Conclusion

Space Power Supplies cannot be practically repaired after deployment. Over the years, a body of knowledge has developed that offers guidance for producing highly reliable supplies. In the transition to smaller, faster and less expensive power supplies, it is important to use good judgment to wisely achieve these goals without fatally compromising the mission reliability.