Designing with a Distributied Power Architecture

INTERPOINT® PRODUCTS APPLICATION NOTE

Although the concepts stated are universal, this application note was written specifically for Interpoint products.

One of the quiet design revolutions of the 1980s was the rapid growth of distributed power architecture in a wide variety of complex electronic systems. Distributed power architectures replace multiple central power sources with a single bulk supply that is converted to the end-use voltages by dc-dc converters located at the point of need. The growth of this design technique is demonstrated by the size of the dc-dc converter market

The first large-scale use of distributed power was in the avionics industry, where it provides smaller size, lighter weight, better operation with battery power and more efficient sub-system isolation and redundancy. As avionic designers replaced hydraulic systems with increasingly complex electronics, requirements for different voltage and power levels increased rapidly.

Distributed power networks let engineers power all the sub-systems from a single 28-volt bus and a central battery bank rather than running redundant wiring for each voltage level throughout the airframe. In addition to saving weight and space, this architecture made it easier to design and upgrade separate sub-systems without making wholesale changes to overall system wiring. The use of converters also made it easier to control the quality of power. dc-dc converters can provide very close regulation of output voltages in spite of fluctuations in input voltage and load, an important feature for many sensitive sub-systems.

Another important advantage that distributed power brought to high reliability programs is isolation. Since switching dc-dc converters use transformers in the conversion process, they provide electrical isolation, making it easy to build in redundancy and to protect whole systems from effects of isolated failures. Even though power ICs can perform some of the conversion and regulation tasks, because they cannot provide the same isolation levels, distributed power architectures are likely to depend on dc-dc converters for the foreseeable future.

Distributed power is everywhere in avionic programs. Interpoint, for example, one of the first companies to specialize in converters for high reliability programs, provides dc-dc converters for virtually every airliner made by Boeing, McDonnell Douglas and Airbus Industries, the space shuttle, Stealth bomber, F-14, F-16, F-18 and Mirage fighters, as well as helicopter and missile systems. The design advantages of distributed power have helped it spread to industrial controls, automotive applications, computer systems, medical electronics, telecommunications and every application that uses complex systems with a requirement for multiple power and voltage levels, light weight, or battery back-up.

Today, the shift toward distributed power is also being fueled by fundamental changes in the kinds of components going into electronic systems. For the last decade, levels of IC integration have increased at exponential rates, with CMOS emerging as the most common technology for the new VLSI systems. With CMOS devices throughout a system, many boards require 5 volts as well as 12 or 15 volts. This means that one more central power supply is required, and it must supply more power to a greater percentage of a system's boards.

CMOS presents electrical characteristics that complicate the design of central power systems. CMOS circuits use power during switching by charging and discharging parasitic capacitances, causing step function load changes. By placing the power supply at the point of need rather than in a low-voltage centralized power supply, potential problems from distribution path inductances and back-panel and connector pin impedances are minimized. These issues have become even more important with the development of advanced semiconductor devices which require even lower voltages and higher performance from the power network.

Figure 1 is a simplified block diagram of a typical electronic system in two versions-one using centralized power supplies and a second using distributed power. In each system, the logic is distributed between six boards, each with a requirement for a specific power level and one or more different voltage levels.
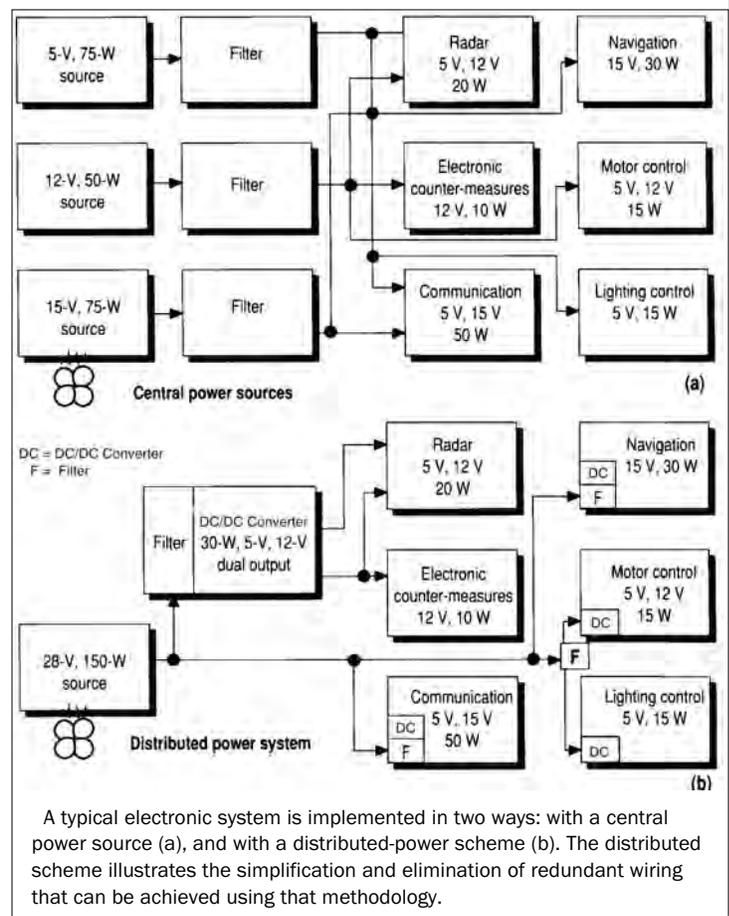

A typical electronic system is implemented in two ways: with a central power source (a), and with a distributed-power scheme (b). The distributed scheme illustrates the simplification and elimination of redundant wiring that can be achieved using that methodology.

FIGURE 1: CENTRALIZED POWER VS. DISTRIBUTED POWER

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To use centralized power systems, the designer provides central supplies at 5, 12 and 15 volts, a central filtering and thermal management system, and interconnect wiring to the boards. For the distributed power version of the same system, one central 28 volt nominal bulk supply is provided, and dc-dc converters supply the power levels needed at the appropriate voltages. When a board needs multiple voltages, dual or triple outputs are used. In the distributed system, most of the converters are placed on the single board for which they are supplying power. However, it is also possible to use a single converter with enough power to serve several boards. These higher level distributed power supplies may be board-mountable, but at higher wattage levels (above 200 watts) are more likely to be cage-mounted. The general principles of distributed power design are straightforward, but two significant problems inevitably must be solved when power supplies are moved from a central location to the point of use.

The first of these is noise: when several switching power supplies are placed in the system, conducted and reflected ripple from the converters themselves needs to be measured and controlled. The second is heat: when power supplies are compressed into small cases and mounted on logic boards, the designer must also ensure that heat generated during the conversion process is dissipated.

CONTROLLING NOISE
All switching dc-dc converters first transform a dc input voltage to an ac voltage and then convert the ac voltage back to the To use To use centralized power systems, the designer provides central supplies centralized power systems, the designer provides central supplies at 5, 12 and 15 volts, a central filtering and thermal management system, and interconnect wiring to the boards. For the distributed power version of the same system, one central 28-volt nominal bulk supply is provided, and DC/DC converters supply the power levels needed at the appropriate voltages. When a board needs multiple voltages, dual or triple outputs are used. In the distributed system, most of the converters are placed on the single board for which they are supplying power. However, it is also possible to use a single converter with enough power to serve several boards. These higher level distributed power supplies may be board-mountable, but at higher wattage levels (above 200 watts) are more likely to be cage-mounted. The general principles of distributed power design are straightforward, but two significant problems inevitably must be solved when power supplies are moved from a central location to the point of use.

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There are many different schemes used to make the dc to ac transformation, but they all generate unwanted signals that can be conducted or transmitted throughout a system. The magnitude of these signals is determined by the frequency of the ac voltage, internal and external filtering, and at high frequencies (above about 1 MHz) the converter's mounting and connection scheme. They are also affected by the nature of the switching topology that generates them. In general, pulse-width modulated converters that keep a constant switching frequency create noise in a predictable bandwidth that can facilitate attenuation. Resonant or zero-switching converters can create less intrinsic noise, but their load-dependent variable switching frequencies tend to generate noise over wide frequency excursions, making them difficult to control. For any kind of converter, however, it is important to measure and control the three most significant types of noise: input differential noise, input common mode noise, and output noise. The following section briefly defines each type, suggests measurement techniques, and identifies attenuation strategies.

It is also important to note before discussing filter design that effective filtering may require detailed technical information about the converter. Converter manufacturers are happy to provide the data needed, and often they can supply filters as standard products which are designed to work with their own converters.

INPUT DIFFERENTIAL NOISE
Input differential mode noise is noise current that flows because of a voltage difference between the two input conductors. The input noise of a converter can be modeled as shown in Figure 2. The converter switching transistor or transistors are simulated by a switch F_S which turns on and off at the switching frequency of the converter. The load is simulated by a variable resistor R~L that changes with the load. L and C make up an input filter built into the converter. Nearly all converters will have an input capacitor, and most will have at least a small series inductance as well.
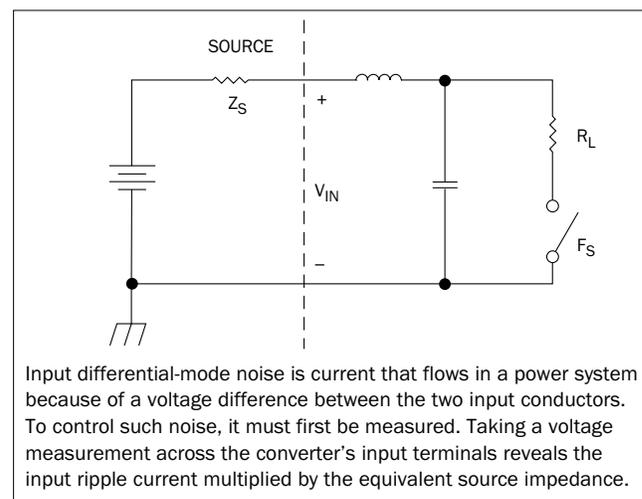

Input differential-mode noise is current that flows in a power system because of a voltage difference between the two input conductors. To control such noise, it must first be measured. Taking a voltage measurement across the converter's input terminals reveals the input ripple current multiplied by the equivalent source impedance.

FIGURE 2: SIMPLIFIED INPUT DIFFERENTIAL MODE NOISE MEASUREMENT

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In the test setup of Figure 2, a voltage measurement is made across the input terminals of the converter with a voltage probe. The quantity measured is the input ripple current times the equivalent source impedance. If the source supply and the test setup never changed, the noise from different converters could be directly compared. But to measure the actual ripple current, the source impedance must be known, and source impedances depend on poorly controlled parameters of the components in the output of the source supply. At frequencies above a megahertz even placement of wires on the bench will make a significant difference in the measured results. If an ideal, zero impedance source could be used, the measured noise voltage would always be zero, no matter how high the noise current.

More accurate test results can be obtained by the test setup of Figure 3. Here, the noise current of the converter is measured directly with a current probe so the source impedance Z_s will make little difference in the current measured. The effects of Z_s are further reduced by the bypass capacitor C_B which should be a high quality unit with small series inductance and resistance over the frequency band of interest (usually the switching frequency and above). The connection wires from CB to the converter should be as short as possible to minimize parasitic inductance and radiated noise. If the converter's internal filtering is not sufficient to attenuate the differential noise to the levels needed in the system, additional LC sections may be added on the input. The capacitors should be quality tantalums with low equivalent series resistance (ESR) and equivalent series inductance (ESL) over the frequency band being filtered. Pot cores are typically used for the inductors.
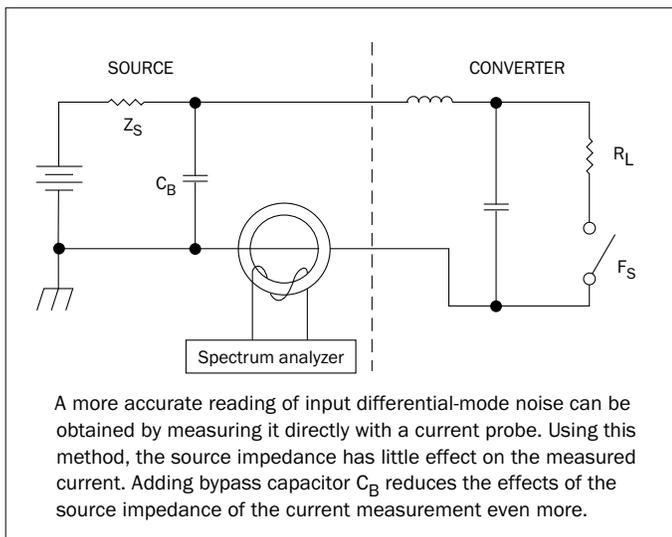
For the filter to work correctly, the Thevenin equivalent impedance on the converter side of the filter must be lower than the input impedance of the converter. This is important because all switching power supplies are constant power, negative input impedance devices. As their input voltage goes up, the input current must go down to keep the input power approximately constant. Since the input impedance of the converter is negative and the output impedance of the added filter will be positive, it is possible for them to cancel-to zero at some frequencies and become unstable. Consequently, accurate information from the manufacturer about the input impedance of the converter is crucial when designing the filter

INPUT COMMON MODE NOISE

Figure 4 shows how to measure input common mode noise. In a dc-dc converter, switching transistors are typically mounted in close thermal contact with the chassis. To maximize heat transfer the electrical insulation between the collector or drain of the switching transistor is made as thin as practical. This creates a parasitic capacitance from the drain or collector of the transistor to the chassis. When the switch opens or closes, noise current will flow from the switch through the parasitic capacitance, through R_L and C, and then through the ground connection back to the chassis. This noise current is small because the parasitic capacitance is small (typically < 10 pF), but an LC filter in the converter is ineffective against it because the current flows around it instead of through it.
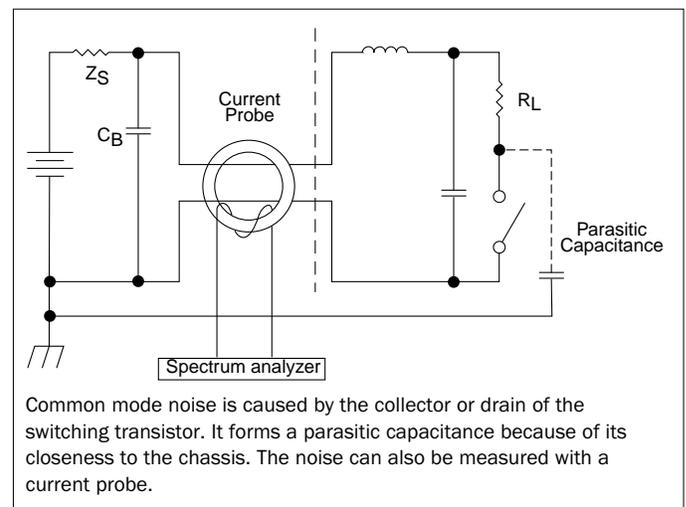

Common mode noise is caused by the collector or drain of the switching transistor. It forms a parasitic capacitance because of its closeness to the chassis. The noise can also be measured with a current probe.

FIGURE 4: MEASURING COMMON MODE NOISE

A more accurate reading of input differential-mode noise can be obtained by measuring it directly with a current probe. Using this method, the source impedance has little effect on the measured current. Adding bypass capacitor C_B reduces the effects of the source impedance of the current measurement even more.

FIGURE 3: DIRECT INPUT DIFFERENTIAL MODE NOISE MEASUREMENT

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The common mode noise can be filtered with a balun as shown in Figure 5. A balun is an inductor with two windings, both with the same number of turns. The balun presents a high inductance to the common mode current, but virtually none to the differential mode current. Note that the dots on the balun are both on the input side of the converter. This means that the differential current (including the load current) flows into the dot in the top winding and out of the dot on the bottom winding. Since the currents are equal but opposite and the turns in both windings are the same, the net flux in the core caused by the differential current is zero, even though the load current can be very high. As a result a high permeability ungapped core can be used for the balun, and it can have a relatively high common mode inductance with only a few turns. The much smaller common mode noise current flows primarily through the bottom winding and through both windings in the same direction. Thus the balun represents a high impedance to common mode noise currents.

A balun can be used to filter common mode noise. It presents a high inductance to the common mode current and virtually none to the differential-mode current. Because the much smaller common mode noise current flows primarily through the bottom winding and through both windings in the same directions, the balun presents a high impedance to common mode noise currents.
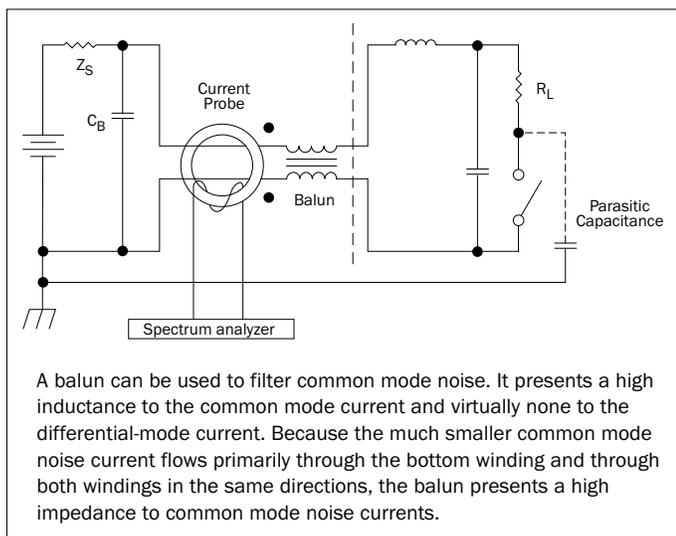
FIGURE 5: FILTERING COMMON MODE NOISE

OUTPUT NOISE

Output ripple voltage measurements are difficult to make even under the best conditions. Depending on the technique used, results may vary widely.

As with input noise current, there are two components of output voltage ripple: differential and common mode. Common mode output noise is usually dominated by current conducted through stray capacitances to the dc power line. It is of little interest in most system designs, but it does cause problems when measuring output ripple. The common mode component may have a bandwidth of several tens of megahertz, an area where most oscilloscopes have poor common mode rejection. As a result, common mode noise may appear as differential noise. Consequently, when measuring output differential noise, it is best to connect input and output commons

to case, and to use the case as a single point ground for all test equipment to minimize common mode interference.

The output differential noise is the noise voltage that appears between the two output terminals. The method used at Interpoint to measure differential output ripple is shown in Figure 6. The measurement must be carried out at the output pins of the converter to reduce the pickup of radiated noise. The 50-ohm series resistor and the 50-ohm terminating resistor are for impedance matching to the 50-ohm coaxial cable. Lead lengths, including the ground lead must be as short as possible to reduce the pickup of radiated noise. An optional parallel capacitance of 2700 pF at the scope will reduce the bandwidth to approximately 2 megahertz to permit viewing of the fundamental frequency component of the ripple.

Measurements of differential output ripple must be taken at the converter's output pins to reduce the effects of radiated noise. Lead lengths must be kept to a minimum for the same reason. By adding parallel capacitance at the oscilloscope input, bandwidth can be reduced enough so that the ripple's fundamental frequency component can be viewed.
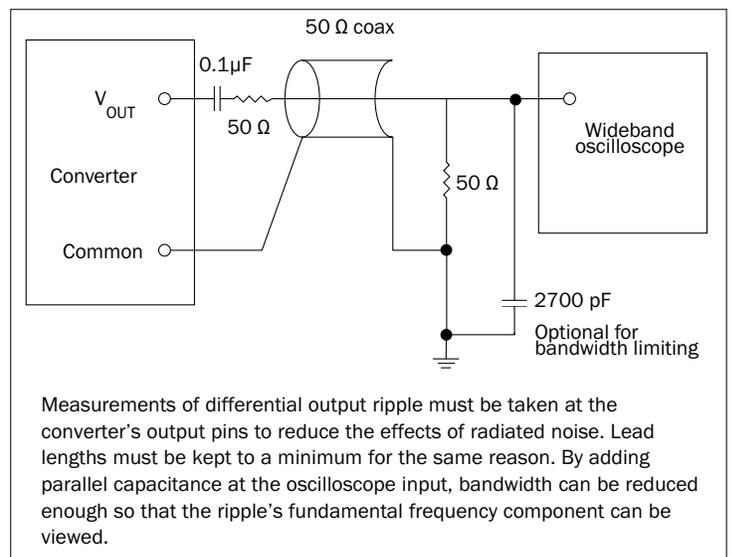
FIGURE 6: MEASURING DIFFERENTIAL OUTPUT RIPPLE

If the converter's internal output filtering is not sufficient to bring the noise levels within system requirements, additional LC sections may be added on the output. Like the input filter, the capacitors should be quality tantalums with low equivalent series resistance (ESR) and equivalent series inductance (ESL) over the frequency band being filtered. If only high frequencies are being filtered, a good ceramic capacitor may be adequate. Pot cores are also typically used for output inductors.

If the corner frequency of the added LC filter approaches the bandwidth of the converter's internal control loop (nearly always <100 kHz), stability problems may result. If there is any doubt, contact the manufacturer of the converter.

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Without filtering on the input, the noise spectrum for a typical 15-W dc-dc converter exceeds the limits of MIL-STD-461C.
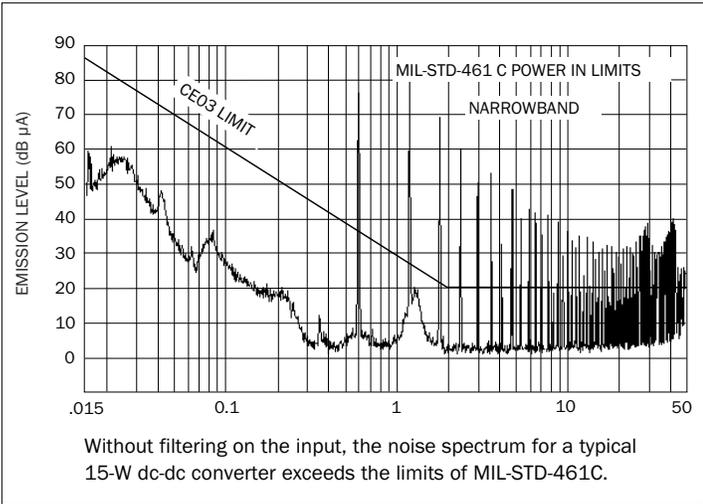
FIGURE 7: UNFILTERED DC-DC CONVERTER

EXTERNAL FILTERS

Converter manufacturers frequently manufacture external filters for customers who require very low noise. Input filters are the most common, but output filters are also sometimes found. The manufacturer should insure that there are no stability problems when the filter is used with their converters. A quality manufacturer will also have specialized knowledge of high frequency RF layout techniques that most systems manufacturers lack. The improvement in noise performance can be considerable. For instance, Figure 7 shows the input noise spectrum from an Interpoint MHF+ 15-watt converter without added filtering.
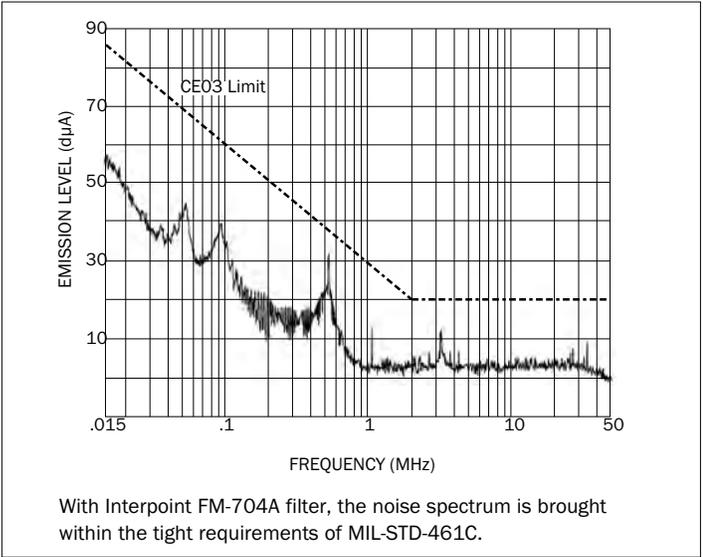

With Interpoint FM-704A filter, the noise spectrum is brought within the tight requirements of MIL-STD-461C.

FIGURE 8: FILTERED DC-DC CONVERTER

Figure 8 shows the same converter's input noise with an Interpoint FM-704A filter. The noise is reduced well below the stringent requirements of MIL-STD-461C (CE03), "Conducted Emission Requirements for the Control of Electromagnetic Interference". In addition to filtering, the FM-704A also limits input voltage transients and surges to a level safe for the converter.

MANAGING THERMAL DISSIPATION

Heat dissipation is the second problem that designers of distributed power systems must contend with. Since no dc-dc converter is 100% efficient, some of the input power converted is released as heat which must be removed to prevent excessive internal temperatures.

Most dc-dc converter designs place the heat producing elements in close thermal contact with a metal heat conducting surface on the component's case, usually the baseplate. The maximum baseplate operating temperatures universally found on product data sheets can be as low as 70°C for most commercial and industrial parts and up to 125°C for some military applications. It is important not to exceed rated values (except within the confines of output derating curves) because the internal temperature of power handling components will be considerably higher than the case temperature. When parts are subjected to over-temperature, operation may become degraded, reliability is impaired and component life is shortened.

For all converters, the user must provide a thermal path that can conduct internally generated heat to the outside. For converters larger than about 5 watts of output power, this thermal path usually includes a heat sink. The first step in designing a heat sink or thermal management system is to find the power dissipated in the converter (this is not the same as the power delivered to the load). This value is determined by subtracting the power delivered to the load from the total power supplied to the converter. All power that is not delivered to the load ends up as heat in the converter that must be removed. This value may be calculated as follows:

$$P_{diss} = (P_{out} / \text{efficiency}) - P_{out}$$

Manufacturers supply minimum efficiency values on the product data sheets, usually only for full load operation. More accurate calculations are possible with graphs showing efficiency vs output power. However, even when efficiency decreases as the load drops, the worst case (greatest) dissipation usually occurs at full load. Once Pdiss is known, designers can use component specifications from the manufacturer's data sheet and the following formulas to calculate heat sinking requirements for a given power output and ambient temperature, and the maximum safe power output for a given heat sink capacity and ambient temperature. (Note, however, that no heat dissipation guidelines can be accurate in all cases. The specific conditions of an application must always be considered.)

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For finding heat sink capacity O_{sa}:

$O_{sa} = (T_c - T_a) / P_{diss}$, where

$T_c = T_{op} - (T_{op} - T_{fp})(P_{diss} / P_{dmax})$ and

$P_{dmax} = (P_{outmax} / Eff) - P_{outmax}$

T_c is the unit's maximum case temperature. T_a is the maximum ambient temperature. P_{diss} is the power dissipated in the unit. T_{op} is the temperature at which the unit is rated for 0 watts (maximum derated operating temperature). T_{fp} is the maximum case temperature for full rated power. P_{dmax} is the maximum allowed power dissipation at or below T_{fp}. P_{outmax} is the maximum rated output power. Eff is the minimum efficiency at maximum output Power. P_{out} is the required output power.

For finding maximum safe power output P_{out}:

$P_{out} = P_{dt} Eff / (1 - Eff)$, where

$P_{dt} = P_{dmax} (T_{op} - T_a) / (O_{sa} P_{dmax} + (T_{op} - T_{fp}))$

P_{dt} is the maximum safe power dissipation in the unit above T_{fp}.

Take, for example, the Interpoint MFW single output, 28 volt in/12 volt out dc-dc converter. It is rated for full power operation (up to 70 watts) at a case temperature of 85°C derated to zero power at 125°C. Its minimum efficiency is 81%.

To find the needed heat sink capacity for a maximum output load of 12 volts and 4 amps in a maximum ambient temperature of 50°C, we must

1. Find P_{diss} the power dissipated in the unit:

$P_{out} = (12 \text{ volts})(4 \text{ amps}) = 48 \text{ watts}$

$P_{diss} = (48/0.81) - 48 = 11 \text{ watts}$

maximum dissipated in unit

2. Find P_{dmax}, the maximum allowed power dissipation at or below 85°C.

$P_{dmax} = (70/0.81) - 70 = 16$

3. Find T_c, the maximum allowed case temperature:

$T_c = 125 - (125-85)(11/16) = 98°C$.

4. And find O_{sa}, the required heat sink coefficient:

$O_{sa} = (98 - 50)/11 = 4.4°C/watt$ or less

A heat sink of 4.4°C/watt thermal resistance or less will be required for the application.

To find the maximum safe output power for a heat sink capacity of 3°C per watt and maximum ambient temperature of 70°C, we again determine the minimum efficiency (81 %) from the data sheet and use the same value for P_{dmax} (16 watts).

Then we

1. Find the maximum safe power dissipated in the unit:

$P_{dt} = 16 (125 - 70)/(3(16) + (125-85)) = 10 \text{ watts}$

2. The maximum safe output power is:

$P_{out} = 10(0.81)/(I - 0.81) = 43 \text{ watts}$

Several options are available for actual heat sinking. In all cases, the heat sink must be brought into close contact with the heat source to facilitate maximum transfer. When the base plate is the source, U-channel or bathtub type sinks work best, although heat sinks may also be bolted directly to a mounting flange. Additionally, it is recommended that an electrically insulating material with good thermal conductive characteristics be employed between the converter and the heat sink. This material will fill surface irregularities, reducing baseplate to heat sink thermal resistance.

When the dc-dc converter will be exposed to free moving or forced air flow, it is possible to use convective heat sinking to transfer heat from the converter to the surrounding air. The method of removing heat preferred by Interpoint is conductive heat sinking, which works by transferring converter heat to a colder material through direct contact. As it does not rely on air movement past the device, applications requiring a sealed enclosure are possible as long as a continuous path of low thermal impedance ensures transfer of heat to the enclosure's surface. For thermal characteristics of specific heat sinks in still and moving air, the designer should always consult the heat sink manufacturer.

There are also alternatives to standard heat sink products which put the burden for determining thermal resistance on the designer. Users report that for smaller converters (less than 10 watts), large areas of circuit board metallization under the converter can serve to distribute heat away from the device. For larger converters, a plate of a good thermally conductive material under the converter can conduct heat away from the device. Ideally this plate would extend to the edge of the circuit card where heat could then be transmitted to the side wall of the enclosure.

CONCLUSION

Building distributed power networks with dc-dc converters offers weight, size, isolation, and power quality advantages to the designer of complex electronic systems. It also provides a more efficient overall methodology for designing and upgrading electronics with multiple voltage and power requirements than central power sources can offer. Problems of noise and thermal management always need to be solved by systems designers, no matter what kind of power network is used. The particular kinds of noise and heat issues that distributed power systems raise can be easily solved, even by designers not familiar with the methodology. And quality manufacturers of power products supporting distributed power offer complete applications support services that can help designers with design problems.

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