DC Design Considerations

DC Device Ratings

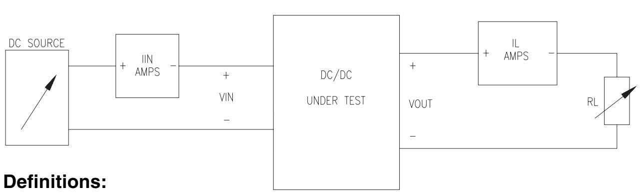
All electronics devices have a minimum and maximum DC input and output rating which is critical. Outside these ratings, operation of the device is unreliable. In DC DC converters, the important DC parameters usually consist of no output load and full output load conditions as extremes, with user generated or manufacturer supplied curves filling the points in between. DC/DC data sheets can be misleading if the device safe operating area (SOA) is not explicitly given. The SOA relates to the internal device limitations and thermal design limitations of a given device. It is bad practice to compare DC DC converters from short form catalogs where only absolute maximum ratings are given (i.e.: full output load and high input line operation at the specified maximums may not be simultaneously obtainable).

An important rating subgroup often not specified are fault mode DC parameters. Since most DC DC converters operate in a constant output voltage mode, a fault on the output (i.e. a short to common) is conveniently specified as a current or shown in a graph. The current limit curve with varying load impedance is usually sufficient to cover most if not all common load faults (i.e. shorted caps, solder bridges, screw drivers and the like).

DC Measurements

Converter DC measurements are relatively easy to make. Some typical measurements are efficiency (η) vs. line voltage (V in) and efficiency vs. load (IL) with constant V in. Using these two curves, data can be extrapolated for any input and output condition to give the device efficiency (η).

Efficiency relates directly to converter thermal performance. DC measurements can be made using simple (readily available in the lab) 3 ½ to 4 ½ digit integrating voltmeters. A typical test setup is shown in Figure 1. In this setup, both the source voltage and load current can be varied independently.



Definitions:
P IN = I IN X V IN
P OUT = I OUT X V OUT
EFFICIENCY = (P OUT/P IN) X 100%

Figure 1.

Basic DC/DC Measurement Test Jig and Definitions

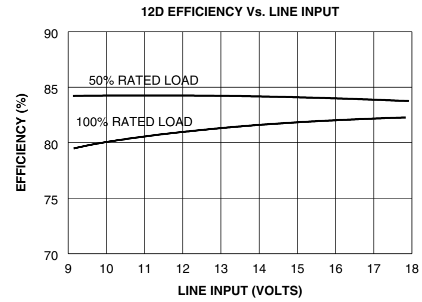


Figure 2.

Typical DC/DC Efficiency vs. Input Voltage Curve

The data can be reduced to device specific curves as shown in Figures 2 and 3. With data taken for several converter types, performance comparisons are easy to visualize.

Other useful DC measurements using the same basic test set up are: V out vs. load (load regulation), low input voltage behavior (to measure how the converter responds to brownouts), and output voltage drift with time and temperature.

Design for DC Regulation

To properly apply any power source, certain rules must be followed to achieve optimum performance. With respect to the DC regulation performance of the device, a knowledge of the system power layout is needed.

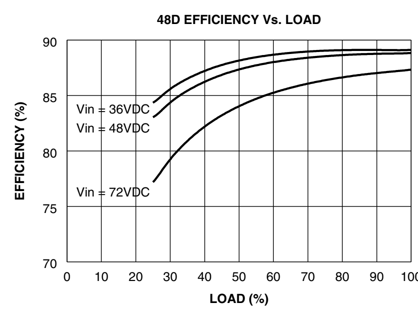


Figure 3.

Typical DC/DC Converter Efficiency vs. Output Load

For simple one load systems, the only consideration for the designer is maximum allowable line resistance (minimum conductor size) consistent with system regulations requirements (note: this is important for both the input and output conductors). When more than one load needs to be connected to the source (Figure 4), the user must determine the optimal way to do it. Figure 5 shows the wrong way to hook up the loads, the so called "daisy chain" approach. In this approach, remote sensing cannot be used effectively to regulate the system. At best, one load can be chosen and regulated. However, due to IR drops, each load experiences a slightly different potential. Couple these IR drops to a dynamic load situation (as opposed to static load requirements) such as TTL, and the system has to absorb whatever noise the source generates (see section on noise).

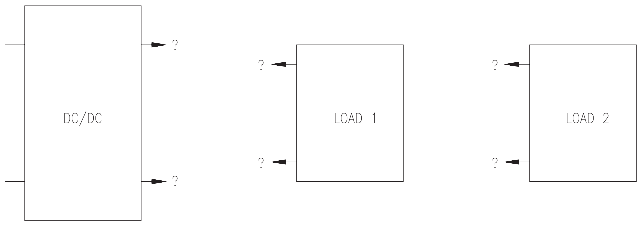


Figure 4.

The Multiple Load Problem: How to Connect Multiple Loads to One Power Source.

If all loads are equally dynamic and equally important to regulate, a much better load connection scheme is shown in Figure 6. Star distribution is easy to implement in most systems but it does require separate conductors for each load. The advantages of star distribution are that circulating currents in each load conductor are eliminated by proper sizing of each conductor, remote sensing can be effectively used and load variations made negligible.

In most real systems, sensitive circuits must be mixed with noisy circuits such as op amps and relays. The optimum distribution system can be a combination of star and daisy chain.

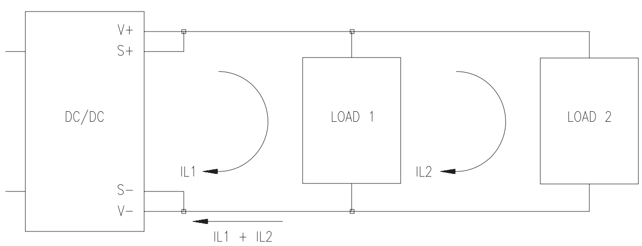


Figure 5.

Daisy Chain Distribution Showing Degradation Due to Wiring Resistance.

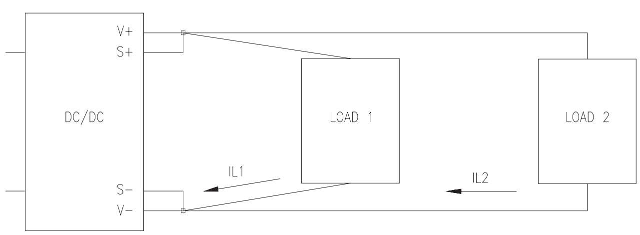


Figure 6.

Star Grounding Technique Showing Improved Regulation for Multiple Loads.

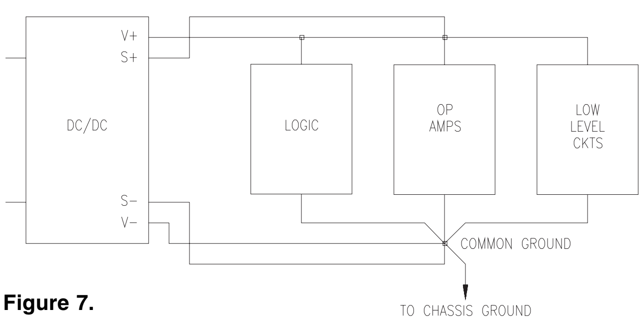


Figure 7.

Combination Daisy Chain and Star Grounding, Having the Advantages of Both Methods.

Figure 7 shows a system containing logic, op amps and sensitive low level circuits as loads. This distribution system maintains the op amps at near constant voltage (by virtue of remote sensing). Due to the static nature of the low level circuits, this branch tracks very well. The logic loads, which are usually noise makers themselves, are also immune to large levels of noise. These are connected to the power source with suitably sized conductors to produce the minimum IR drop to the loads. This will help regulation and reduce load induced noise.

When more than one supply is used, attention must be paid to the system grounding. Most problems with multiple analog/digital systems are due to circulating ground currents (i.e. analog currents circulating in digital ground lines and vice versa). Tying the analog and digital grounds together at only one point (such as the chassis ground) is the preferred method of preventing ground loop noise.

These methods for DC system design also provide a solid foundation for AC system design and design for low noise as presented in the next section.

AC Design Considerations

Identification and Measurement of Noise Sources

A block diagram of a converter operating in a simple system is shown in Figure 8. The converter has a dynamic load that is switching at a frequency of FL. This produces a fluctuating current at the input and output of the converter due solely to the load. The converter is driven by a power supply isolated from the AC line. The converter itself is switching at a rate of FS. This produces a fluctuating current at its input due to the internal switching which is added to the load induced ripple current.

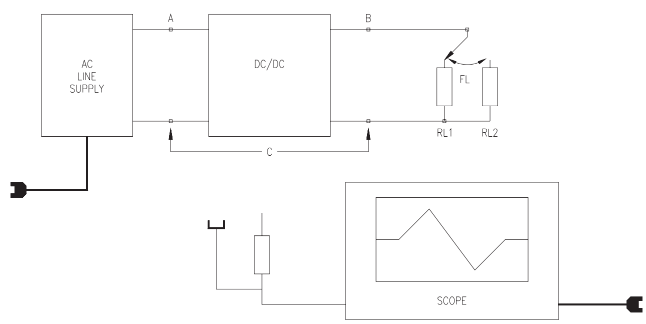


Figure 8.

DC/DC Test Setup and Three Possible Measurement Nodes. Which Measurements at What Nodes Give Meaningful Results?

If a scope were connected to points A, B and C in the figure, certain wave forms would be observed at distinct frequencies related to FS and FL. How valid would these measurements be? Do they actually characterize the converter or are they so dependent on the circuitry around the converter that meaningful comparisons between converters are not valid? In the next sections the four major noise measurements that can be made on any converter and the method used to make these measurements will be defined.

Input Noise

The input of a converter can be modeled (simplified) as a switch, variable resistor and the input filtering (if any) built into the converter (Figure 9). The switch is actuated at either FS or 2FS depending on the converter topology (single ended or push pull) and the variable resistor can be changed to model the load variation. This simple model helps make the input circuit and its interaction with the source understandable. The source can be an ideal voltage source.

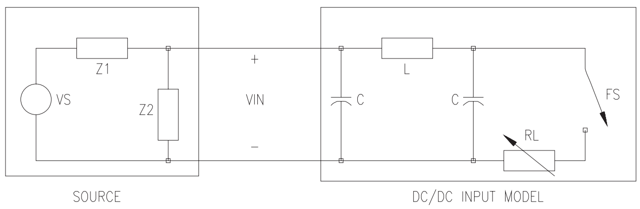


Figure 9.
Simplified DC/DC Input Circuit Model Showing the Non-Ideal Source and the DC/DC Input Filter Circuits. The Chopper is Modeled by a Switch and a Variable R for Simulated Load Variation.

What is needed is a measurement circuit that will qualify the noise development by this circuit in a meaningful way and without interaction with the source. A voltage measurement can be made if a scope is connected across the input terminals on the converter.

This measurement could be used to correlate data about different converters. However, what it is really measuring is the ripple current produced by the converter multiplied by the equivalent source impedance of the source in parallel with whatever impedance the converter presents to its terminals. As long as the power supplies aren't changed, all measurements will correlate. Unless the circuit impedance levels are known, the gathered data is not useful in predicting how the converter will operate in the final production circuit.

The key words in the last paragraph are "ripple current". What is really measured is "ripple current" and it's interaction with circuit impedance level.

A better way is to shunt the converter and source with an RC network of known impedance level (making sure that the impedance level is flat for all the significant harmonics of the input ripple current). The amount of current ripple that the converter generates is then measured. This circuit is shown in Figure 10. The values for R and C are chosen to provide 0.25 ohms over the frequency range of interest. An impedance of 0.25 ohms was chosen because it is typical of a capacitor impedance that might be placed on the PCB in the final user circuit. The current can now be measured with a wideband (20 MHz) current probe.

At this point it is appropriate to point out that, depending on the noise waveform produced by the converter, vastly different measurements can be made with different scope bandwidths. An industry standard bandwidth is 20 MHz (-3dB single pole rolloff).

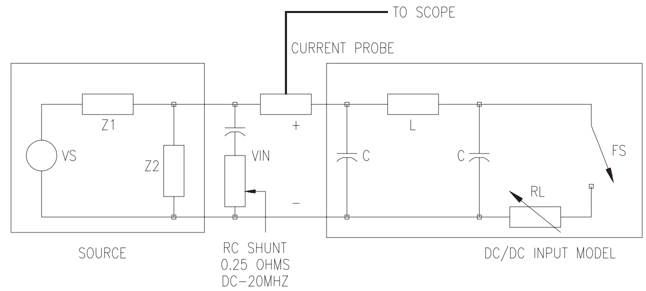


Figure 10.
Reflected Input Ripple Test Setup Showing the RC Current Shunt and The AC Current Probe Position.

One final note about input current ripple is that, depending on the converter design, the maximum reflected ripple may not be at full load. Sometimes even no load can produce the worst case P-P ripple so it is important to check this measurement at many different load levels.

Output Noise

The output noise of a converter can be measured by placing a scope on node B of Figure 8. Depending on circuit wiring and the ground clip length on the scope probe, this may or may not produce a useable measurement.

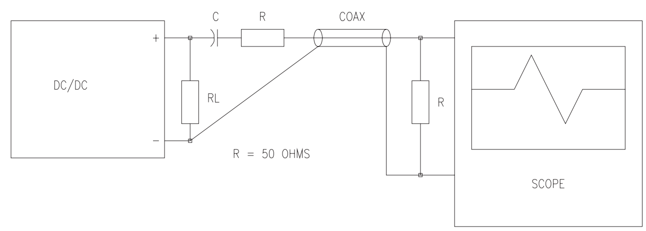


Figure 11.
A Wideband/Low Distortion Output Noise Measurement Circuit.

A study of a typical noise spike seen on an oscilloscope indicates that the spike may contain significant amounts of energy to well above 100 MHz in bandwidth. This is the justification needed to develop a wideband 20 MHz low distortion measurement circuit for the output noise measurements. The use of properly terminated transmission lines is necessary to take a low distortion wideband measurement. In Figure 11, such a system is diagramed. The circuit consists of a DC blocking capacitor (which also sets the low frequency roll off bandwidth), a series 50 ohm resistor, a length of 50 ohm coax to the scope and a 50 ohm termination directly at the scope input terminals. With such a setup, nanosecond risetimes can be sent over several feet of coax from the converter to the measurement scope with the only waveform distortion due to how well (or poorly) the interconnections are made. Bad interconnections result in impedance mismatches.

The measurement as read on the scope is divided by 2 due to the two 50 ohm resistors. Therefore, the measured noise is ½ the actual converter P-P noise.

Frequently, the measurement bench is "hot" meaning that the noise levels displayed will vary when the bench, scope,

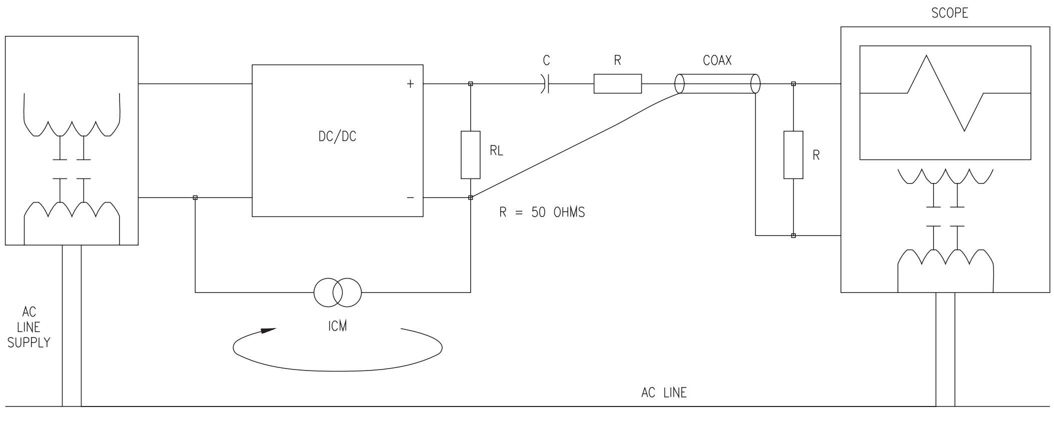


Figure 12.
Output Noise Measurement with Common Mode Current

wires or other instruments are touched. This "hot" indication is a telling sign that the measurement is false.

Figure 12 illustrates how the bench can be hot even when low distortion measurement techniques are used. Some parasitics have been added to the circuit model including scope capacity to the AC power line, DC source capacity to the AC power line, the capacitance across the DC/DC isolation barrier and a bidirectional AC current generator across the DC/DC isolation barrier labelled I_{cm} for common mode current. Immediately a current path can be seen from the DC source through the converter through the scope and back to the DC source. This is the reason for the "hot" bench. Along with I_{cm}, there exists a major ground loop. The cause of I_{cm} will be discussed later on, but first a look at how to break the ground loop. A battery used to power the DC DC converter would break the loop at the DC source. However, batteries are difficult to obtain in most labs and they constantly need recharging. Besides, what happens to I_{cm} when the loop through the AC line is broken? To answer this first look at I_{cm} and where it comes from.

DC DC converters work by chopping the DC input with high speed transistor switches. A DC DC converter operating from a 72 volt input may have internal voltage swings of 150 volts or more. With these large voltage swings, charging and discharging of internal capacitances occurs every cycle. This causes a current to flow in the lowest impedance path it can find: first through the scope and DC supply destroying the output noise measurement and then, in the case of the battery source, through the input to output capacitances of the DC DC converter (assuming that the battery would have very low capacitance to ground).

The output noise measurement setup can continue to measure just the output noise (and not the common mode current effects) by shunting the common mode current in a 'tight loop' right at the DC DC converter itself.

20 pf from input to output common of a DC DC converter can make quite a difference in the measured output noise and in how 'hot' the test bench appears.

In summary, output noise must be measured with good RF wiring techniques such as those presented in Figure 12. The resulting measurements must not be affected by placement of the user's hands in relation to the scopes, DC source or the converter itself if meaningful measurements are to be made.

Common Mode Noise

In the last section, common mode current was discussed, as well as its origin and how to reduce its effects on output noise measurements. This approach is fine but what you really need is a way to measure this common mode noise current in a way that is repeatable and to use a 'standard' current shunt at the DC DC converter to achieve high accuracy output noise measurements.

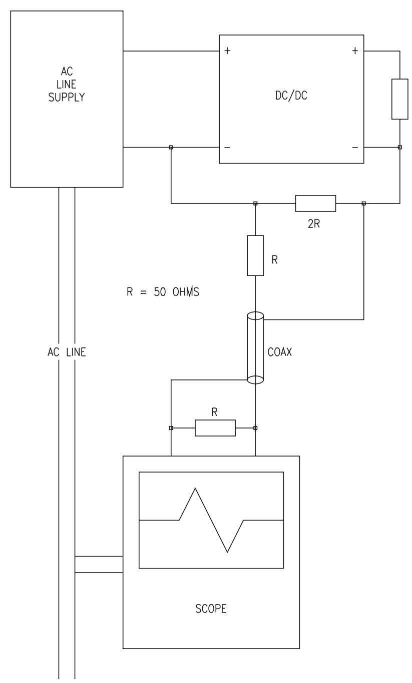


Figure 13.

Common Mode Current Noise Test Circuit. This circuit shows high immunity to the test circuit/test equipment environment.

The noise in question is high frequency spike noise with a lot of high frequency content (again not all converter topologies produce spike noise. This is a generality). The test circuit will produce high quality noise measurements on almost any waveshape.

The high frequency 50 ohm terminated transmission line measurement method must be used. Figure 13 shows one such measurement method. The scope and series 50 ohm resistors add up to 100 ohms in parallel with the 100 ohm resistor across the device grounds to give a net 50 ohms across the device. The scope measures a voltage impressed across 50 ohms and this can be converted to a current by:

$$I_{cm} = V \times 2 / 50 \; \textit{(volts P-P / ohms)}$$

Typical measurements range from 100's of microamps to 10 or 20 mA P-P depending on the converter's construction. The measured current could be artificially lowered by the manufacturer by capacitively shunting the current inside the converter. Because they are related, the I_{cm} and input to output capacitance specifications should be used together when comparing different makes of converters.

One final note on common mode current. When the scope is disconnected from the common mode current circuit, the network should still be terminated with the 50 ohms from the scope to present a constant 50 ohm termination across the DC DC converter grounds.

Load Induced Converter Noise

The last significant noise source is the converter's interaction with a time varying or dynamic load. In Figure 8, a dynamic load was shown as a switch alternately switching between two resistors. This simple model is sufficient to help understand load induced noise. The amount of load noise produced depends on the load characteristic such as repetition rate, rise time, amount of current change between steps and type of load change (continuous or step).

Depending on the frequency of the load change (this is the main frequency component of the load change such as rise time for a step load, not the repetition rate of the step), an interaction occurs with the converter output impedance to produce a voltage response.

Figure 14 shows a typical linear regulator output impedance vs. frequency curve as might be seen in high regulation low power DC DC converters.

If a 100 KHz 10 mA P-P sine wave load were attached to this converter as a dynamic load, the output impedance at this frequency is about 2 ohms. This will interact with the 10 mA load current to give an additional 20 mV P-P of noise at the converter output. The rising output impedance vs. frequency characteristic is common to all forms of constant voltage regulators; only the shapes change. The change is due to the fact that the regulator loop gain falls with frequency until no loop gain remains (closed loop unity gain frequency) as is required to close the loop in a stable manner.

The output impedance of a regulator can be measured with the circuit of Figure 15. Load current changes can affect all of the previously mentioned noise measurements. The only way to fully characterize a converter is to use the input and output conditions that will be present in your final system when making measurements. Unfortunately the manufacturer cannot foresee all possible input/output/load interactions, so sufficient measurement data must be provided (noise levels, for example) with given conditions so that the converter user can always refer back to the converter data sheet. Specifications without given measurement conditions are misleading at best.

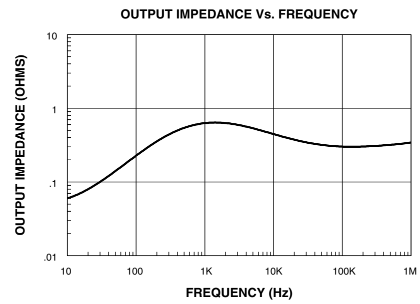


Figure 14.
Typical DC DC Converter Output Impedance vs. Frequency. The increase in output impedance with frequency is caused by a reduction in loop gain as required to make the overall circuit stable.

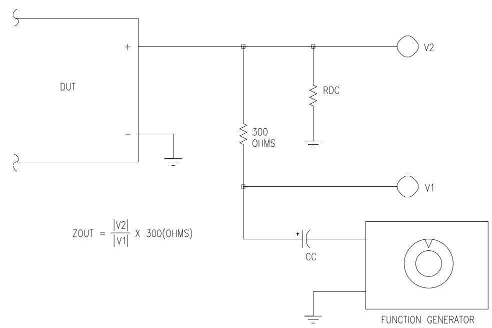


Figure 15.

Small Signal Output Impedance Test Circuit. Scale the 300 ohm Resistor as required so that 300 ohms>RDC. A frequency sweep of 10 Hz to 1 MHz is easily obtained with most common lab function generators.

Reduction of Converter/System Noise

Although converter manufacturers attempt to provide the lowest noise/lowest cost converter possible, sometimes the converter interaction with the final circuit produces too much noise for the system to tolerate even when good AC design techniques are followed. If the final circuit is too noisy, a series of steps can be followed to understand the source of the noise and solve the problem. This is always better than adding a 0.1 µf disk capacitor here and there to treat the symptoms of a system noise problem. All this usually does is "change" the noise so that it is harder to spot later.

The 6 Steps To Lower System Noise

1. Know where all the currents are flowing, both AC and DC. Ground loops are the single most common problem in system design.
2. Isolate the noise into one of the four sources of conducted noise as outlined in the last section.
3. Understand the converter interaction with the circuit and decouple the circuit from the converter.
4. Go back to the converter data sheet and test measurement circuits and correlate the circuit noise with basic converter noise.
5. Understanding is the key. If a theory fails, reformulate it until it stands up. Usually things don't work because one doesn't understand or immediately see where all the AC and DC currents are flowing.

6. Before any noise abatement steps are taken around the converter, such as adding more capacitance or adding LC filtering, consult the manufacturer. Converters are moderately complex analog feedback loops and adding impedances at various input and output ports may upset the feedback loop. This is true of both linear and switching technology power supplies. The manufacturer can often prevent the unwary user from turning the supply into a power oscillator, but only when they are consulted first.

Reliability/Design Considerations

Power supplies, in general, must dissipate some amount of wasted energy as heat. This means that, for a given case volume, the supply with the highest efficiency will run with the lowest internal temperature rise. This raises the question, "At what ambient temperature can this supply be run?"

Ambient ratings in still air are basically meaningless because the power supply and its load will raise the ambient temperature of a small enclosure above the outside ambient temperature. Where should the ambient temperature be measured? At 1 millimeter away from the case? At one meter? And how does a user characterize a power supply at a high ambient temperature? Merely placing the supply in an oven and setting it to 70°C does not produce meaningful results if the oven is forcing air across the converter surface. Also, what effect does oven volume have on ambient?

While ambient temperature ratings are very useful in characterizing low power op amps, it is misleading to use with high power devices such as power supplies. A much better and more meaningful rating for a power converter would be to rate the converter at some case temperature either at the heatsink or at some other specified measurement point. This puts the responsibility of ambient temperature control on the user where it belongs; the power supply manufacturer has no control over how the power supply is used in the customer's system.

At CALEX, power converters are rated at a maximum operating case temperature and enough data is provided to calculate what the case temperature rise is over a non-moving air, room ambient temperature environment. This parameter is defined as case temperature rise/package watt dissipated and it is a measure of the thermal effectiveness of the case design. This parameter is very sensitive to case material composition (plastic, steel or copper etc.), and case volume. As an example of case temperature design, let's study a typical design:

Problem:

Find the case temperature rise above room ambient.

Given:

CALEX Model 24D15.200 converter

Max + Load Current = 100 mA = 1.5 watts

Max - Load Current = 160 mA = 2.4 watts

Total Power = 3.9 watts, 65% of Full Rated Power Used.

Input Voltage Range = 22.8 to 25.2 volts

Case Temperature Rise/ Package Watt = 10°C/watt Dissipated

Solution:

From the data shown in this catalog, efficiency of a 15 volt dual 6 watt converter operating at 65% of full power can be read from the curve as 66%. This allows the calculation of input power and current at the nominal input voltage of 24 volts as:

$$P_{input} = P_{out} / N = 3.90/0.66$$
$$= 5.9 \text{ watts}$$

$$\text{Input} = P_{input} / V_{input} = 5.92/24$$
$$= 0.25 \text{ amps}$$

The input current is constant for a constant load current, independent of input voltage for this non-pulse width modulated converter. Using the worst case input voltage of 25.2 volts the package dissipation (in watts) can be calculated as:

$$P_{input} = I_{in} \times V_{in}$$
$$= 0.25 \times 25.2 = 6.3 \text{ watts}$$

$$P_{dissipation} = P_{input} - P_{output}$$
$$= 6.3 - 3.9 = 2.4 \text{ watts}$$

From our case constant of 10°C/package watt, the expected case temperature rise is 24°C (2.4 × 10).

Given the case constants, this method is just like calculating semiconductor junction temperatures. This is a much more useful method of specifying power converters than simply listing an ambient temperature rating. High reliability in power converters is not magic. The reliability of a power converter or any piece of electronic equipment is inversely related to junction temperatures and the temperatures of resistors and capacitors that go into the making of the electronic device.

The Four Steps to Proper Thermal Design

Thermal design is a relatively easy job once the converter is specified properly. The basic steps are:

1. Calculate the converter power dissipation (or measure it if enough information is not given).
2. Calculate the case temperature rise at room ambient.
3. Calculate the amount of additional heatsink or forced air cooling required (if any) to keep the device within its package ratings.
4. Use direct measurement techniques to verify steps 1-3 above in the final system.

These are the easiest steps in the entire system design but they can make the difference between an unreliable, unsuccessful product or a reliable successful product. Unfortunately, all to often, these steps are left out of the design phase.

Conclusion

The proper use of switching DC DC converters is not any more difficult than using the latest high performance op amp or newest microprocessor. However, DC DC converter misuse can prove much more devastating to a system because of the power levels involved. The best way to optimize your system performance is to fully characterize the converter and intended load early in the design cycle so that no surprises show up in the final system.