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Thermal Measurements of Power Converters – How and Why?

This document describes thermal measurements of power converters. It describes what to measure and how to measure. It contains also recommendations for datasheets and explanations of some temperature related terms in datasheets.

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The European Power Supply Manufacturers Association was established in 1995, to represent the European power supply industry.

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Abbreviations

The following abbreviations are used in this document:

DUT	Device under Test (normally a component in the power converter)
EMC	Electromagnetic Compatibility
IR	Infrared
PCB	Printed Circuit Board
PS	Power Supply

Abstract

This document describes thermal measurements of power converters. It describes what to measure and how to measure. It contains also recommendations for datasheets and explanations of some temperature related terms in datasheets.

Introduction

Depending on the measurement setup, the results from thermal measurements may differ quite a lot. One of the main differences is whether the measurements is done with restricted airflow (the air is forced to pass between two boards) or unrestricted airflow (with the walls far away from the board). For on-board DC to DC converters there are also other issues:

- should the converter be mounted on a board
- how shall it be mounted (soldered or socketed)
- what size of board
- what copper thickness
- how many layers
- what type of power planes (PCB pattern)

There are many parameters that are likely to differ from one measurement setup to another, so it will always be wise to be sceptical about any published data, even if it is measured in a correct way. It may not be relevant to the way the user will use the converter. Specifying temperature limit(s) for defined components or points on the PCB may assist the user in designing the application. This information is often contained in charts showing maximum allowed temperature for a certain combination of load, input voltage and wind speed (for air-cooled converters).

There are several main cooling methods for an on-board DC to DC converter:

- It may be designed to dissipate heat through the pins attached to the board, and the board itself becomes the heat sink for the converter.

- The hotspot components may have additional (small) heat sinks increasing the effect of the cooling air. Normally a large part of the heat is still transferred to the board through the pins.

- It may be attached to a 'baseplate' which is intended to be attached to a larger heat sink (e.g. a chassis), often referred to “cold wall”. This cooling method can be divided into two subcategories:

- When the majority of the heat is transferred to the cold wall.
- When a substantial amount of the heat still is transferred to the air.

For each of these methods the most relevant test setup would be quite different.

A power converter may also be intended to be mounted in a rack or as a stand-alone unit.

This will make it very tricky to find the one and only way to make thermal measurements of power converters.

Therefore this document will be divided into parts for each cooling method. It will also discuss different methods of measuring temperature and also different types of wind tunnels.

What to measure

It is important that the thermal measurements cover the most critical components, which not necessarily is the hottest component, e.g. schottky diodes may suffer from high leakage currents at elevated temperatures, typically above 100 ^{O}C, which may cause thermal avalanche. Other examples of temperature sensitive components are wet aluminium electrolytic capacitors and optocouplers. It is also important to point out that in some cases, the board may be the weakest link. Magnetic devices are also troublesome to measure, especially devices with gapped cores (flyback transformers, chokes), as the gap may cause local hot spots due to fringing effect.

Different methods of measuring temperature

The two main ways of measuring temperatures are by thermocouple or by optical methods, whether IR camera or thermometer.

Thermocouples

Thermocouples are considered to be accurate within ± 1 °C but there are many traps to fall into.

- They may pick up electrical noise
- They are relative, meaning that they need to be calibrated to a “cold junction”.
- Attachment to the DUT can be complicated.
- The wires of the thermocouple or disc type thermocouples may make the device to be measured considerably colder
- The wires of the thermocouples may obstruct or disturb the airstream.

Thermocouples come in several different types. Type K (Ni-Cr alloy/Ni-Al alloy); N (Ni-Cr-Si alloy/Ni-Si alloy) and T (Copper/Constantan) seem to be applicable for the temperature ranges to be measured. However type K is magnetic, and thermal characteristics vary considerably between examples.

Attaching thermocouples

When using thermocouples, it is important to attach the thermocouple tightly to the DUT (device under test). It is not adequate to use clips or the like to attach the thermocouple as this will not provide enough contact to the DUT, and the clip itself will cool the DUT.

Gluing or soldering the thermocouple is the recommended attaching method. Using tape is tricky and not recommended. It is important that the amount of attachment material is small compared to the DUT. Even more important is that the thermocouple is in good thermal contact with the DUT; little of the glue or solder should be between the DUT surface and the thermocouple.

It is also important that the wires are thin, especially if the thermocouple is attached to a small component, even more so if this component has thin and/or few terminals (pins).

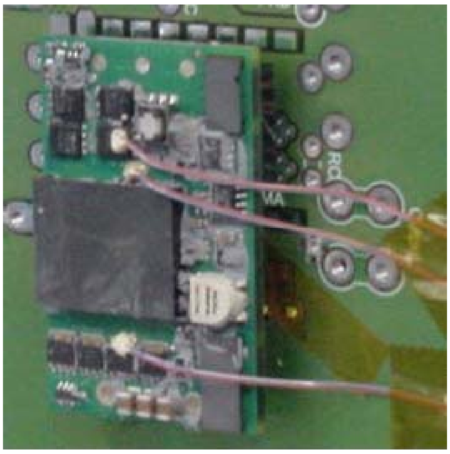

Figure 1 A board mounted power converter with attached thermocouples

The thermocouples shall be attached to electrically “quiet” points, preferably terminals or nodes where the voltage is (AC-) ground. Switching nodes shall be avoided. The wires from the thermocouples shall be kept away from switching nodes and magnetic components (especially gapped magnetics) as they may pick up noise. It is important for all electrical methods when measuring simultaneously on two or more points to use equipment with proper isolation so that the points not will be short circuit to each other.

Thermistors

Thermistors, which are available in small packages, may also be used to measure component temperatures. They should be connected with very fine wires to minimise the wires thermal effect on the component under test. What is said about attaching thermocouples above is basically true also for thermistors.

Optical methods

IR cameras are often used to get a quick view to locate the hotspots. Due to different emissivity of different components the accuracy will be poor. It is not possible to measure directly on metal surfaces. They have to be painted in some way, and this will affect the temperature of the DUT. IR thermometers have the same problem. Another problem is how to measure shadowed components. Also the top surface of the device may not have well specified thermal impedance to the junction.

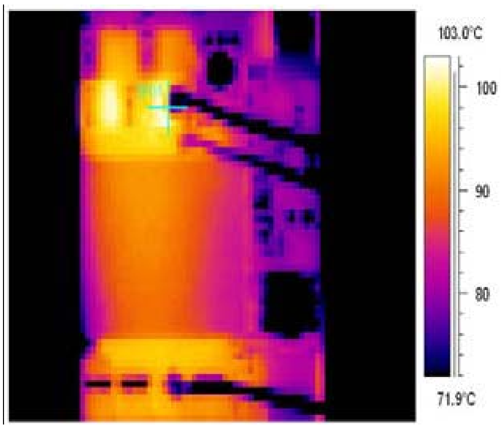

Figure 2 A thermal image of a board mounted power converter

It is not recommended that IR thermometers or cameras are used for final temperature measurements.

Temperature measurement methods of magnetic devices

Temperature measurements of magnetic devices are tricky, and one shall be aware of there are many pitfalls. Both high magnetic and electrical fields are apparent and both may disturb the measurement device. The measurement device (sensor) may disturb the performance of the magnetic device so that it does not behave normally. Therefore it is important to choose the proper method for each type of magnetic device. A wirewound device should probably be measured in another way than a flat magnetic device with PCB windings. Therefore it is difficult to recommend one method. Below is however some methods described.

The temperatures of windings can be determined either by the thermocouple method or by the resistance method described below. The temperatures of parts other than windings (e.g. the core) can be determined by the thermocouple method. Any other suitable method of temperature measurement which does not noticeably influence the thermal balance and which achieves a sufficient accuracy may also be used. The choice of and position of temperature sensors shall be made so that they have minimum effect on the temperature of the part under test.

It is recommended to quickly turn off the magnetic device (e.g. by turning of the converter it is a part of) and take temperature readings immediately to verify that the readings when the device was working are correct.

Temperature rise of a winding

The value of the temperature rise of a winding is calculated from the formula:

For a copper winding: $\Delta t = [(R_2 - R_1)/R_1](234.5 + t_1) - (t_2 - t_1)$

For an aluminum winding: $\Delta t = [(R_2 - R_1)/R_1](225 + t_1) - (t_2 - t_1)$

Where:

- Δt is the temperature rise, in K
- R_1 is the resistance of the winding at the beginning of the test, in Ω
- R_2 is the resistance of the winding at the end of the test, in Ω
- t_1 is the room temperature at the beginning of the test, in ºC (or K)
- t_2 is the winding temperature at the end of the test, in ºC (or K)

It is important to ensure that the windings are at room temperature at the beginning of the test otherwise the test may be misleading.

It is recommended that the resistance of windings at the end of the test be determined by taking resistance measurements as soon as possible after switching off, and then at short intervals so that a curve of resistance against time can be plotted for ascertaining the resistance at the instant of switching off. One shall also be aware of that this method only measures the average temperature over the winding and not the hot spot temperature.

Wind tunnels

A Typical Wind Tunnel

A typical wind tunnel, Figures 3 and 4, consists of a mechanical and electrical system, a control program and measuring equipment.

The Mechanical System

The mechanical system consists of a variable speed fan, flow straightener, contraction part and a test section. The test section consists of the device under test (DUT) which is usually mounted on a test board with an adjacent board to simulate a card rack environment. Smoke is sometimes used in wind tunnels to show airflow.

The test board is designed to model realistic heat absorption and spreading. The size of the test board and amount of copper has an effect on the test result. Both longitudinal and transversal airflow studies can be carried out when the test board is rotated. Rotation of the board and airflow direction typically changes heat dissipation.

The space between the board and the adjacent board is important. Smaller board spacing seems to help the module to run cooler under both natural convection and forced convection conditions. The phenomenon is caused by different mechanisms. Under natural convection conditions, this is due to so-called “chimney effect”. Once spacing is greater than the boundary layer thickness, further increase of spacing makes no difference. Under forced convection, single-point air velocity measurement does not define the total volumetric airflow. When the board spacing becomes smaller, the test unit (module and boards) presents more flow resistance, resulting in less airflow and a lower measured velocity between the test boards.

The Electrical System

The electrical system includes power supply, load controls, wind velocity anemometer and temperature gauges. Adjustable airflow, adjustable input/output current and voltage mean a wide range of conditions can be studied. Some wind tunnels also have a heating element.

Local ambient temperature may be measured using thermistors, which are available in small packages and should be connected with very fine wires to minimise errors from heat conduction through the wires.

Data logger (data acquisition unit) and a PC are used for data acquisition and control. The recorded data should include component, ambient and atmospheric temperatures, module input and output voltages and currents, air velocities and other wind tunnel parameters.

The traditional two-orientation (longitudinal and transverse) testing is not sufficient to provide a complete representation of the module's thermal performance. It is also necessary to collect data at various input voltage and output current levels for a given flow and ambient temperature condition.

The airflow can be measured by anemometer and volumetric calculation. Hot-wire anemometers used to measure airflow directly in front of the module ensure the highest airflow accuracy. The airflow type can be turbulent and laminar. Laminar is the more conservative approach.

Open or closed loop wind tunnels

The advantage with the closed loop wind tunnel is the isolation of the airflow. There is no disturbance from the outside. The air has the same temperature and can be heated by a heating element. The problem with the setup is that it can easily overheat; it is hard to move the test board, cables and sensor cables from the outside.

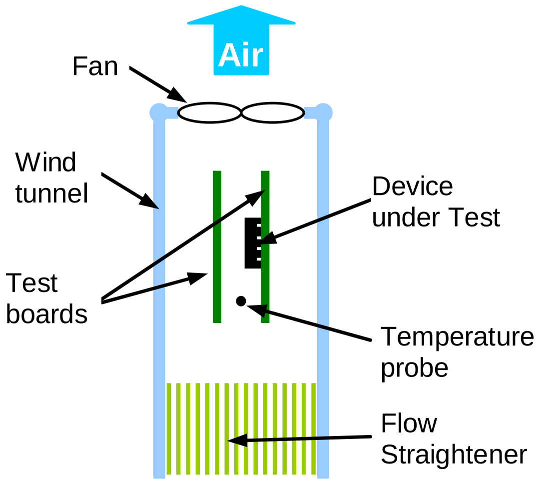

Figure 3 Open loop wind tunnel

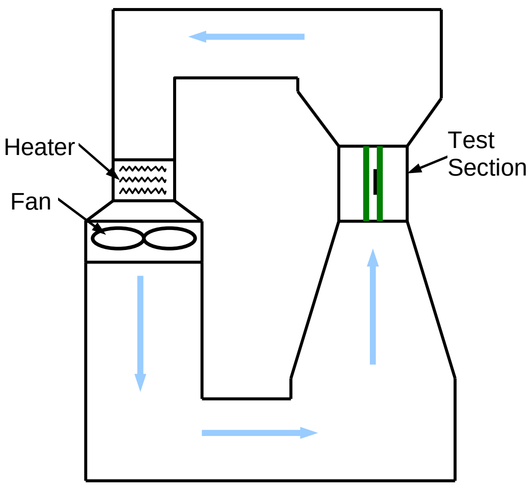

Figure 4 Closed loop wind tunnel

Advantages of the Closed Circuit Tunnel compared with the Open Circuit Tunnel:

- Power requirement for a given speed is lower.
- Particulate matter can be contained within the circuit.
- Noise is significantly lower
- Laboratory air movement (air vents, doors, windows, etc.) does not affect wind tunnel flow.
- Air entering the test section is free of laboratory dust.
- Fan blades are not as vulnerable to damage from model failure.

Disadvantages of the Closed Circuit Tunnel compared with the Open Circuit Tunnel:

- Cost is generally three times greater.
- Footprint is much larger and requires more overall space.
- Temperature can become an issue during prolonged runs

Thermal testing of power converters

It should be pointed out, that in all thermal measurements, the most critical component may vary with conditions, and it may be that for some components no load is worst case, while for others full load or short circuit is worst. Also the supply voltage will affect which component is closest to it its limit. As a result, it is necessary to thermocouple many components in both the control circuit and power train, to assure that devices are operated with proper derating.

On-board converters intended to dissipate heat through the pins.

For most on-board converters, some heat sinking occurs through the pins. As a result, the use of sockets to connect units during thermal testing is not recommended. Depending on the design of the sockets, thermal transfer may be significantly degraded. The impedance of the socket connection also creates losses which generate heat, further degrading the thermal performance compared to the real, soldered-in application.

Converters designed primarily for heat sinking through the pins are commonly lower power units. Their construction and terminal design are normally optimized to facilitate this cooling technique. Often, they may have higher pin counts to increase conduction. The terminals may be designed with thermally conductive materials, or with larger surface area. Some products in this category have also traditionally been encapsulated, to allow better heat distribution across the internal devices.

These products are usually targeted towards applications with low airflow environments (e.g. natural convection cooled), and high ambient temperature outdoor applications. They can also find use in forced convection applications, especially when the thermal environment is challenging, or airflow to the power supply is shadowed by other components upstream of the airflow.

The thermal performance of these products will be particularly sensitive to attributes of the test board where they are mounted, since it provides the primary heat path. Considerations for the test board include:

- Board material e.g. FR4, ceramic
- Copper weight
- Copper pattern
- Size of board
- Temperature of the test board
- Number of power planes
- Location of power planes in the stack-up (inner or outer layers)

- Use of thermal vias (especially for SMT power converters)

The thermal testing of these units is usually performed in a wind tunnel configuration as described above to provide a controlled environment, but often without any forced air (natural convection only). The wind tunnel simulates the chimney effect seen in frames with vertically mounted cards.

Because the power supply manufacturer needs to select a standard test configuration, it can not accurately reflect every end application. Consequently, it is critical to perform system level thermal testing of the on-board power supply.

On-board converters where the hotspot components have additional heat sinks

Some on-board products are optimized more for convection cooling applications with forced air. For these products, the cooling is primarily shared between conduction (through the pins) and convection.

In these products, local heat sinks may be attached directly to components or certain areas of the PCB. They may have fins for improved surface area, or take the form of a heat spreading plate.

Because there is still a conduction aspect to the cooling, the considerations from the previous section still apply. The converters are tested in a wind tunnel environment, which allows the airflow to be precisely controlled as the products are characterized. The devices with a heat sink are still monitored with thermocouples at a suitable point to accurately assess junction temperature.

Converters featuring small pin-fin heat sinks on single components will be susceptible to airflow disturbances or blockages, so the devices may need to be checked in the end application. Those products which rely on a larger plate will be less sensitive, as they are exposed to a wider area of the airstream.

Converters intended to be mounted in sealed boxes or thermally coupled to the chassis

Standard wind tunnel measurements of thermal properties of power converters are not suitable for sealed-box applications. The sealed-box cooling conditions are different since both ambient temperature (inside the sealed box) and the baseplate temperature are important. In addition, thermal radiation from the module can be a significant part of the heat transfer. The thermal measurements should be performed at temperatures close to the actual operating conditions.

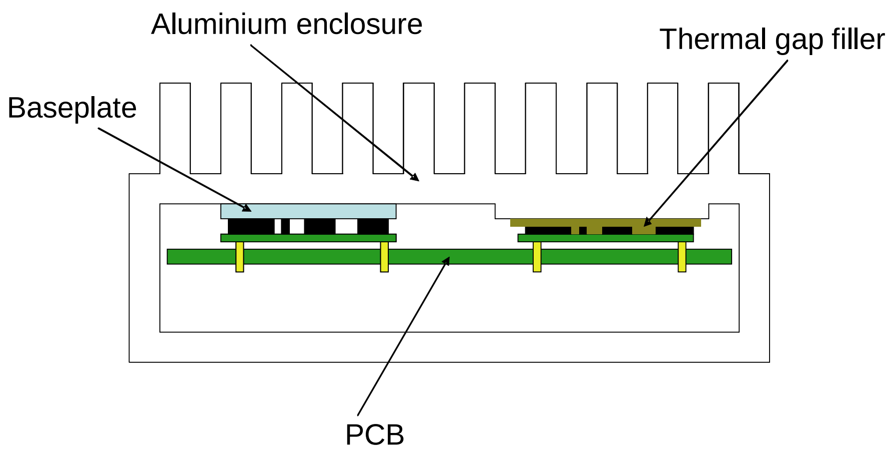

Figure 5 Typical sealed box application

The setup below is suggested for thermal verification. It is important that the device under test is adequately attached to the cold wall (in a similar way as it intended to be in its application). The hood and the cold wall should preferably be individually temperature controlled both adding and removing heat, in order to control the air temperature inside the box.

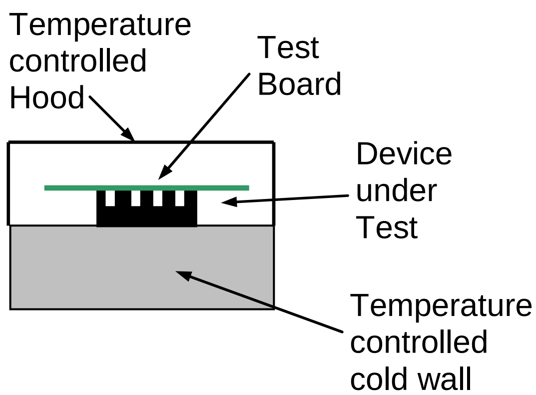

Figure 6 Test setup for sealed box applications

Rack-mounted converters with a chassis

The cooling situation of rack mounted power supplies, e.g. DIN rail power supplies depends very much on the assembly in the rack or cabinet.

The following situations influence proper cooling:

- Direction of mounting
- Restriction of airflow by other components above or underneath the power supply (PS)
- Heat dissipation from the PS which can add unacceptable heat to any device mounted nearby. Also equipment mounted directly beside the Power supply will hinder the proper cooling of the power supply.

The data sheet should clarify all these parameters especially the minimum clearances A, B, C and D should be specified.

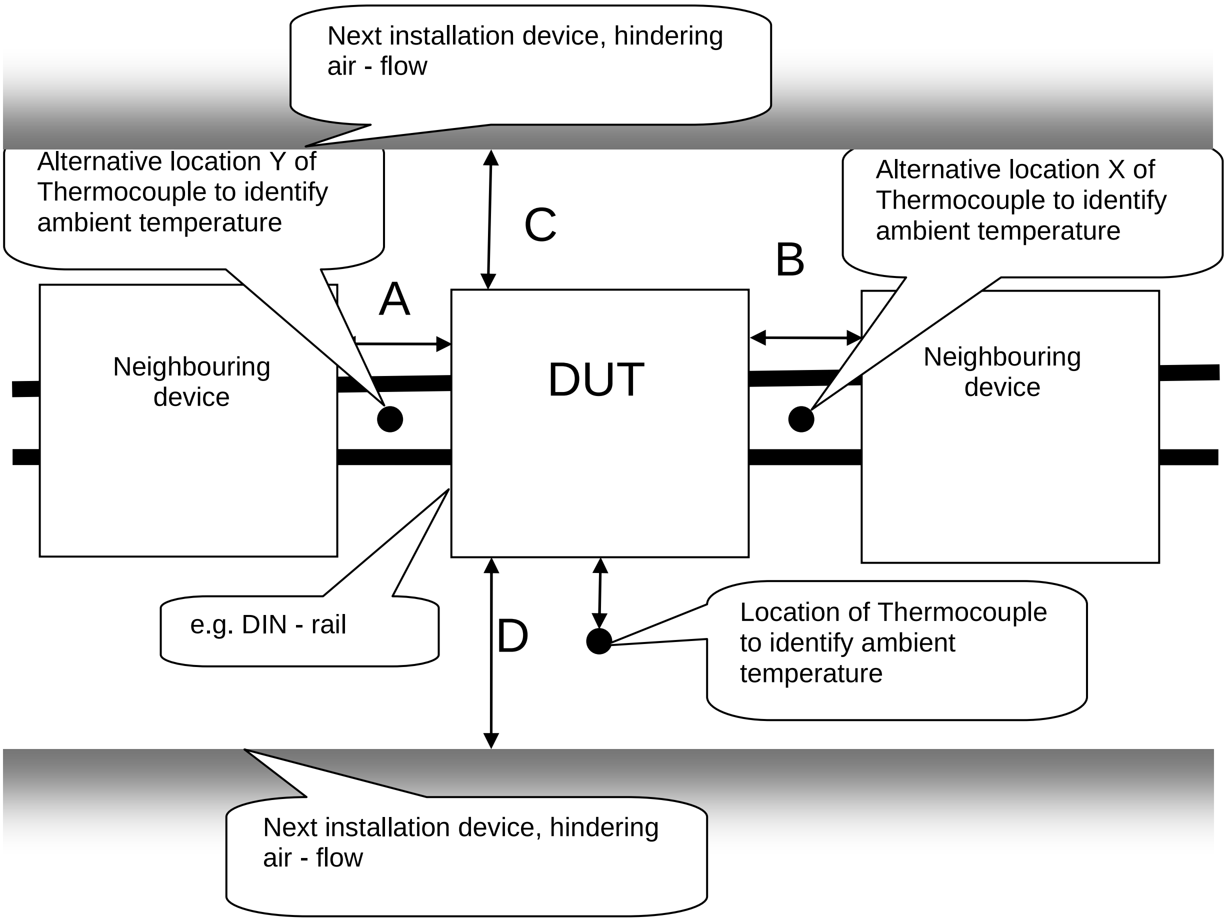

Figure 7 Test setup for rack-mounted converters

The minimum distances A, B, C and D are evaluated in a simulated heat test. Since it is important to simulate the cooling expected in the equipment rack, care should be taken not to introduce additional cooling. The following method was found to be appropriate:

The DUT should be mounted in the “upper case” with the spacings as shown above and must be fitted with thermocouples on the most critical components. For thermocouples please refer to section “Attaching thermocouples” above.

It is recommended that this equipment is put in a heat chamber at the specified maximum ambient temperature. After switching off the fan of the heat chamber, record the temperature of the components when temperatures have stabilised.

The ambient temperature might be measured at the indicated location for input temperature of the power supply. Ambient temperature is measured at alternative location X and/or Y and taking the mean value if both temperatures X and Y are measured.

Due to the different causes of power loss, these measurements should be taken at a variety of input voltages and loads to ensure that the worst condition for each component are determined.

As a general rule: Components in the input circuitry like EMC Filters, rectifier or fuses have their worst case temperature at the point of lowest input voltage.

Components at DC - Bus like capacitors or transformers usually have their highest temperature at the maximum input voltage.

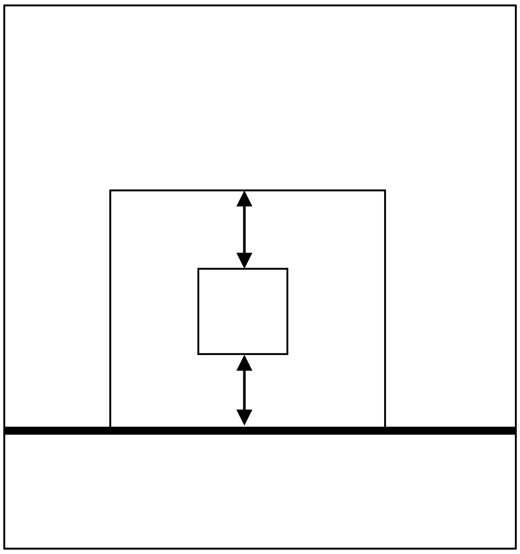

Figure 8 Front view of Test Arrangement

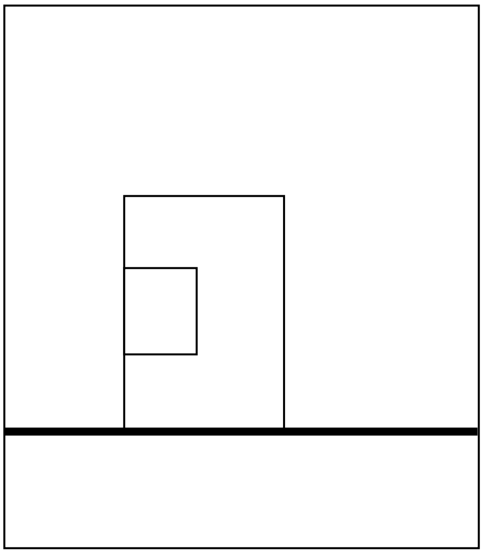

Figure 9 Side view of Test Arrangement

Temperature differences between nominal and maximum output power sometimes can be used to verify the maximum allowed temperature e.g. to IEC 60950 where in some cases different levels for “normal operation” and “abnormal operation” are stated.

Recommendations for datasheets

General

Temperature specifications in technical specifications and datasheets are causing a lot of confusion. This section is intended to clarify what is meant by different temperature specifications and includes recommendations for the thermal data to be included.

Structure of temperature specifications

Generally three different types of temperature ratings are specified in technical specifications and datasheets, namely:

- Absolute Temperature Rating (Limit)
- Thermal Derating (normally by curves in a chart)
- Normal Operating Range

These have different goals and therefore they will differ.

Absolute Temperature Rating

Absolute Temperature Rating is used as a limit for which short term temperature surges should not exceed. Normally there is no problem for the device to operate close to the absolute maximum rating, but there is a risk that using the device for longer periods close to and at this temperature the device will be damaged or its useful life will be substantially shortened. Normally, 100 hours at this temperature will not substantially shorten the products useful life (this is however dependent on each and every application). Thermal protection may be engaged at or below Absolute Maximum Rating. Absolute Maximum Rating may be given for certain point of the converter, the case or even ambient.

Thermal Derating

Thermal derating curves normally show that none of the components in the assembly is exceeding the derating temperature specified in the derating guidelines for each component. It should be noted that the derating curves in a technical specification or a datasheet are very dependent on the conditions they were measured which may or may not reflect the application. As long as the temperature is below these curves the useful life will not be substantially shortened.

At and close to these curves, some parameters may deviate from what is specified under “Normal Operting Range”. Typically two parameters may deviate, namely ripple and output voltage accuracy. Also different types of voltage and current thresholds may deviate from what is specified under normal operating range.

Normal Operating Range

Normal operating range is the temperature where the product performs in accordance to the technical specification (however, there may be some parameters that are specified in a narrower range or even at a specified temperature). The temperature range for normal operation is normally given for a reference point. This may be a specified component or a location on the PCB. In some cases the ambient air could act as reference, but as air speed and direction will affect the converter it is often difficult to use ambient as reference.

Overtemperature Protection Threshold

Normally one tries to design in such a way that the overtemperature protection does not trigger within the temperatures of thermal derating curves and especially not within normal operating range. The overtemperature protection shall however trigger before the product is permanently damaged. This is not always easy to achieve as the product may survive for a few minutes at a certain temperature but will be damaged if the temperature stays for hours or days. Typically the overtemperature threshold is set to be just above the absolute temperature rating, but, as the absolute temperature rating only says that the device will not take permanent damage, the overtemperature threshold may even be lower than the absolute temperature rating.

Typical data sheets content

Power modules should be specified with recommended operating conditions that ensure safety and reliability is not compromised. The safety reports of products with safety certification typically specify temperature limits and where the temperature is measured. Typically the allowable maximum temperature of an encapsulated module would be stated as a ‘body temperature.’ On an un-encapsulated module it would be specified at a specific location on the PCB or on one or more components. This provides designers with temperature limits for safety and reliability assessment of their end product. With only temperature limit data the end product designer is only able to measure what happens in his product to ensure ratings are not exceeded, but not to predict the allowable rating.

The allowable rating depends on maximum allowable module temperature which is a function of many variables discussed earlier including:

Location (e.g. is airflow shielded by other components? Are there nearby heat generating sources?), thermal conductivity between module and its mounting, orientation, airflow speed, air temperature, supply voltage, load current.

Prediction of the allowable rating of a power module at different temperatures may be achieved in a number of ways. One method used by power module designers is to characterize maximum allowable dissipation across the operating temperature range by providing charts that plot:

Maximum Power dissipation vs. temperature for several airspeeds, e.g. 0.2, 0.5, 1, 2 and 3 m/s (40, 100, 200,400, 600 lfm). This information is often given in charts showing maximum temperature versus load current.

These charts are presented for particular conditions of mounting, airflow pattern, orientation etc. The data sheet must also include a means of calculating dissipation at the required input voltage and load current. One option is to supply plots of Power dissipation vs. Output current for the extremes of allowable supply voltages.

The process to predict the allowable rating temperature is then:

Derive power dissipation at the required supply voltage and load current.

Determine the maximum allowable ambient temperature from the intercept of power dissipation with airspeed.

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