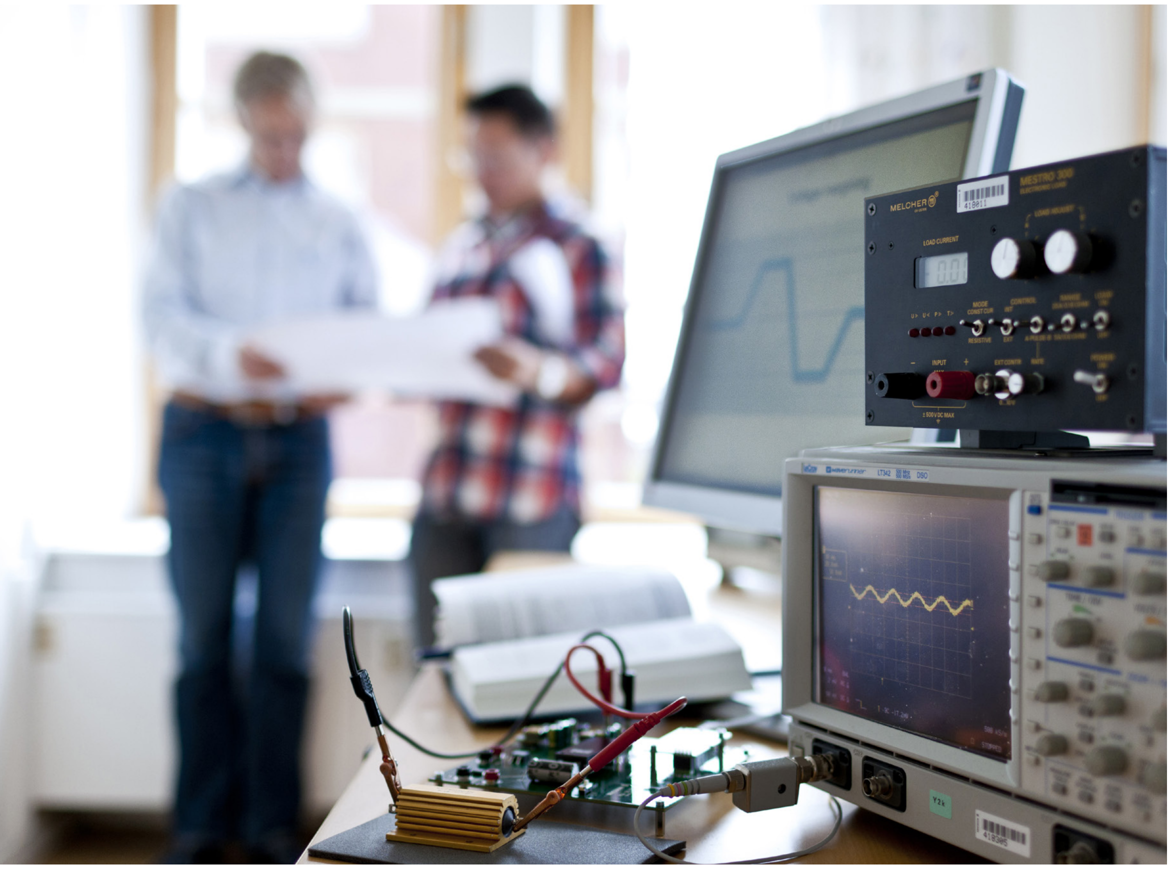
Thermal Characterization of Flex Power Modules



Design Note 019

Flex Power Modules

Abstract

The latest power modules feature extremely compact form factors and high efficiency operation. The high packaging density is accomplished by using materials with excellent thermal properties in conjunction with extensive attention to the details of thermal design.
From the user's point of view, the objective is to extract as much power from these modules as possible while maintaining highly reliable operation. In order to accomplish this, the user must understand how the Flex power modules are specified from a thermal point of view. The user must also be aware of the testing and analysis techniques required in order to successfully integrate the power module into his or her unique system. This design note provides information on Flex's thermal testing and specification methodology as well as tips and techniques that the end user may utilize when designing the power module into their system. The design note is general in nature in that it will address all of the recent Flex power module product families. It is intended for use in conjunction with the information contained in the power module datasheets. When installed within the end-use equipment, the power module's operating temperature and failure rate will be influenced by many factors, including:

- Ambient temperature
- Airflow velocity
- Direction of airflow
- Size of the printed circuit board (PWB)
- Number and thickness of the conductivelayers within the PWB
- Layout of the PWB
- Other component power dissipation on the PWB
- "Shadowing" of airflow by other components
- Turbulence of the airflow

Obviously, it is not possible for Flex to predict all of these variables for each specific application and publish corresponding test data. Instead, the most basic and important variables are accounted for and reasonable assumptions made for others. With these ground rules, typical thermal performance data may be published in the datasheets. This design note will document the assumptions and testing techniques used by Flex when we publish the power module data. These data will provide "ballpark" estimates of the thermal performance within a typical system.

After selecting a power module by using the ballpark thermal design, the user is urged to verify the actual thermal performance in their system and obtain more accurate measurements of the power module operating temperature. This design note will explain this process and give an example of using the module datasheet along with system evaluation to achieve a reliable thermal design.

The Derating Curve

The power delivery capability of DC/DC converters is limited by their maximum operating temperature. The output power or current at which this upper temperature limit is reached will vary with the thermal operating conditions in the user's application – most notably the ambient air or PWB temperature and the airflow velocity in the vicinity of the converter. While these parameters are not usually known with a high degree of precision until after a system prototype is operational, it is often possible to determine a ballpark value for them based upon experience with past systems. These initial estimates are then used when selecting a power converter for use in a particular system environment. Manufacturers of DC/DC converters support this selection process by publishing thermal performance data in the datasheets for their power converters. The most commonly used format for this data is called a derating curve.

A derating curve shows how the maximum output capability of a converter varies as a function of its ambient operating temperature. The output capability is expressed in either power (watts) or current (amps) depending upon the type of converter and its typically application. The ambient operating temperature can be specified in several ways:

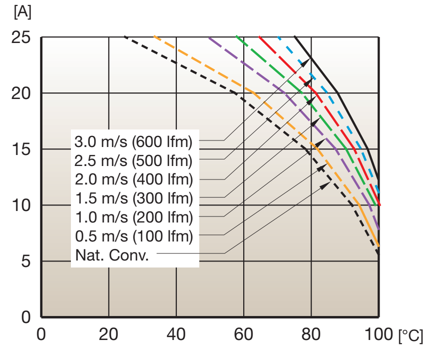
- Ambient air temperature adjacent to the converter (elevated above room temperature)
- PWB temperature adjacent to the converter
- "Hot spot" temperature at a specific location on the converter

The choice of how to express the operating temperature is decided upon by the manufacturer based upon the thermal design of the converter, the manufacturer's specification philosophy and the expected end-use applications. A typical derating curve will have output power or current on the vertical axis and operating temperature on the horizontal axis. For derating curves based on ambient air temperature, the output capability of the converter will vary as a function of the airflow velocity since more heat can be removed at higher velocities. Derating curves based on ambient air temperature therefore typically contain multiple curves, each one supporting a particular value of airflow velocity.

A typical derating curve is shown in Figure 1. This curve is taken from the datasheet for the Flex PKB4619 power module. This converter supplies an output voltage of 2.5 V at up to 25 A of output current. The derating curve for this converter is based upon ambient air temperature in the vicinity of the power module. Curves are provided for airflow velocities of from 0.2 m/s, a typical natural convection environment, up to 3 m/s which is a practical upper limit of airflow velocity based on fan limitations and acoustic noise.

This derating curve conveys a lot of useful information. For example, it shows that in a natural convection environment (0.2 m/s airflow velocity) the converter can supply its full 25 A output current up to an ambient temperature of about 25°C, which is a typical room temperature. Consequently natural convection cooling would not be adequate for this converter if it were to be used internal to a system with elevated ambient temperatures without decreasing the output current. In an application with 1.5 m/s airflow and an ambient air temperature of 70°C, the maximum output current would be about 22 A. The curve can also be used to determine the required airflow velocity. For example, for the converter to supply 20 A of current at an operating environment of 80°C, the required airflow velocity would be about 1.8 m/s.

As shown above, the derating curve is a very powerful tool for the power system designer in terms of selecting a converter for a particular application. Be aware, however, that published derating curves contain assumptions and test methodologies that can vary from supplier to supplier and that there is no industry-wide standardization with regard to their format or the generation of the underlying data. The following section defines the approach used by Flex to generate derating curves for its power modules.



Available load current vs. ambient air temperature and airflow at V_I = 53 V. DC/DC converter mounted vertically with airflow blowing from output pins to input pins.

Figure 1 - Typical Derating Curve - PKB4619.

Flex Thermal Test Methodology

A DC/DC converter's temperature as a function of ambient air temperature and airflow velocity must be measured to obtain the raw data to use in generating the derating curve. It is important that these measurements be reproducible and taken under well-defined conditions. Flex accomplishes these goals by using a wind tunnel for the thermal characterization of its power modules. The wind tunnel is configured so that it simulates the airflow conditions that the power module might encounter in a typical system application. A horizontal wind tunnel with the converter under test mounted vertically is used to model the packaging configuration of many popular rack systems. Figure 2 shows a top view of the wind tunnel cross-section.

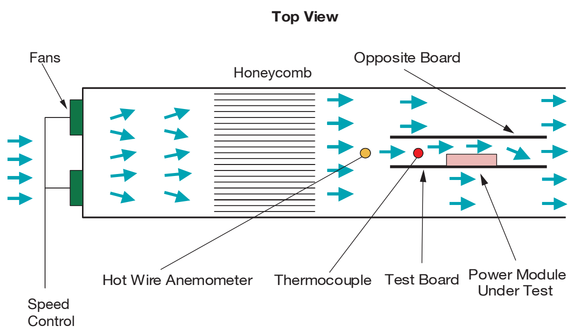


Figure 2 - Wind Tunnel Configuration.

The module under test is soldered to a 254 mm (10 in) by 254 mm (10 in) square vertically oriented PWB test board. The number and thickness of the copper layers in the board varies based upon the power level of the module type being tested, as shown in Figure 3. Another board is placed parallel to the test board. This second board simulates the adjacent card or PWB that would typically be encountered when the converter is used in a multiple board rack mounted system.

Product Height (mm)	Board Spacing (mm)
< 8.5	15
8.5 to 12.5	20
> 12.5	25

Power at 3.3 V	No. of 35 µm Layers
< 75 W	8
>= 75 W	16

Determination of Number of Board Layers.

Model Types	Board spacing	Board Layers
PKR, PKU, PMC	15 mm	8
PKB, PKG, PKM-E, PKV, PME, PMF, PMB	20 mm	8
PKJ-E, PMH, PMJ	20 mm	16
PMB	25 mm	8
PKJ, PKJ-B, PKL, PKM, PKM-C	25 mm	16

It is important to use this second board as it will influence the airflow direction and turbulence in the vicinity of the power module. The spacing between the two boards is a function of module height as defined in Figure 3. The Flex test setup allows for continuously variable airflow velocity from zero to over 3 m/s, encompassing the range of most practical forced convection cooled systems. The airflow velocity is varied by means of four DC fans mounted at the inlet side of the wind tunnel. The airflow can be adjusted by changing the DC voltage to the fan motors. A honeycomb is used to smooth out the turbulent fan output and convert the airflow into a laminar stream. At the output of the honeycomb, and 3 inches in front of the module being tested, a hot wire anemometer is mounted. This device is used to accurately measure the airflow velocity as it impinges into the area between the two boards. Flex usually conducts the thermal tests with airflow velocities of 0.2 (to simulate free convection), 0.5, 1.0, 1.5, 2, 2.5 and 3 m/s.

The ambient air temperature is measured by a thermocouple just ahead of the converter being tested. This temperature will be within a few degrees of the ambient room temperature. The converter under test is instrumented with an array of thermocouples attached to significant locations as defined by the Flex engineering team. These readings will define the maximum available output power or current as a function of the airflow velocity. The PWB temperature is also measured, as this is sometimes used to evaluate system thermal operating conditions.

The thermal test results will depend upon the module orientation – that is, the side of the module that is oriented toward the cooling airflow. Before detailed measurements are made, the module is tested in each of the four orientations to determine which is the best from a thermal point of view. This orientation is then used for the remainder of the testing. This best orientation is also documented in the converter's datasheet so that the user can mount the device in the most advantageous orientation in the system application. The difference in thermal performance with orientation is most noticeable with open-frame type of converter package designs. The detailed thermal evaluation is done using the nominal input voltage for the particular module being evaluated (i.e. – 53 V for modules with the standard telecom input voltage range). Four output power or current settings are normally used, such as 25%, 50%, 75% and 100% of the full load rating.
A typical test session would start with the power module running at 25% load and 3.0 m/s airflow velocity. The temperatures being monitored would be allowed to stabilize, which can take several minutes. All of the thermocouple readings would be logged during and after the stabilization process. Then the airflow would be reduced to 2.5 m/s and the process repeated. This procedure would be continued for each of the 28 combinations of airflow velocity and load current. If the maximum design temperature limit of some point being monitored in the converter is exceeded, that portion of the test is terminated. Due to the stabilization time required, the testing can become quite time consuming.

As an example, we will show how the derating curve shown in Figure 1 was generated. The PKB4619 is a 2.5 V 25 A output isolated DC/DC converter with a nominal input voltage of 53 V. The limiting thermal condition for this converter is a maximum converter PWB temperature of 110°C. We will show how two of the points on the 2 m/s airflow curve were determined.
One of the test conditions for this module is an output current of 10 amps. When the test setup stabilizes with the module running at 10 A and a 2 m/s airflow, the ambient air temperature measures 27.1°C and the PWB temperature measures 36.8°C. That is, there is a 9.7°C temperature rise from ambient air to the PWB temperature. Thus, the critical 110°C PWB temperature would be reached with an ambient air temperature of 110 – 9.7 = 100°C. This data point is highlighted in Figure 1.

Another point on the 2 m/s curve is obtained at an output current of 25 A. Under these conditions, the ambient air temperature measures 26.2°C and the PWB temperature measures 71.7°C, giving a temperature rise of 45.5°C. In this case, the critical 110°C PWB temperature would be reached with an ambient air temperature of 110 – 45.5 = 64°C. This data point is also highlighted in Figure 1. In a similar fashion, additional data points can be determined to complete the generation of the 2 m/s curve and also the curves for the other airflow velocities.

Initial Thermal Assessment from Datasheet Information

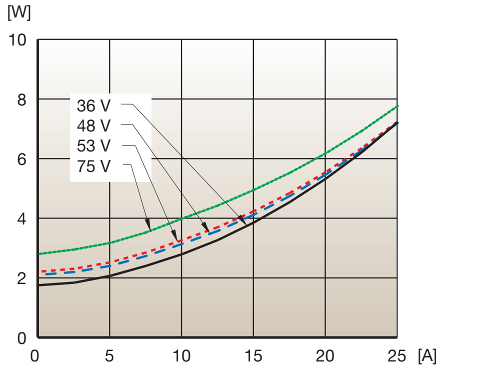
The datasheet for all Flex power modules contains a derating curve that will be the most useful tool for the initial evaluation of the thermal suitability of the module for a particular system application. As shown in the preceding section, the derating curve can provide several types of valuable information and is recommended as the best general method for preliminary thermal assessment. In this section we will discuss some of the limitations of the derating curve and also an alternate approach that can be useful in some situations.

When using the derating curve in the datasheet, be aware that its underlying data was obtained as described earlier in this design note. Several variables were defined as a part of the test metho-dology such as PWB board size, board to board spacing, thickness of the PWB, and the orientation of the power module with respect to the airflow direction. If your system application varies significantly from these assumptions, you should consider being somewhat conservative in the module selection or expected output current or power. The degree of conservatism can be based on your past experience with the type of system environment being considered.

Some users of power converters have thermal design tools or mo-dels that they use to predict the thermal performance of their system's components, including the power conversion elements. If the thermal modeling tools have been fairly accurate when used with past systems, this can be a good way to proceed and may provide more accurate results than are obtained by using the generalized derating curve. Flex supports this type of analysis for many of its pro-ducts by publishing additional thermal design information in their datasheets. This information can take the form of curves showing typical power dissipation as a function of operating conditions and curves defining the thermal resistance from the power module to the ambient air or the user's PWB. These data can then be inserted into the user's thermal modeling software along with parameters for other components and sub-assemblies.

For example, Figure 4 shows two additional thermal design curves that are part of the datasheet for the PKB4619 power module. The power dissipation curve defines the typical power dissipated at all combinations of input operating voltage and output current. This can provide a very useful input for a thermal modeling tool. Be aware, however, that this curve is predicated upon a converter PWB temperature of +25°C. The thermal resistance curve defines the thermal resistance from the power module PWB to the ambient air in °C/W as a function of airflow velocity. As expected, it shows that the thermal resistance decreases (more efficient cooling) as the airflow velocity increases. Thermal data such as shown in Figure 4 can also be used for the purpose of making manual calculations of expected temperature rise in a given operating environment. The temperature rise calculation result can then be used to estimate the maximum allowable ambient temperature. As an example, we will determine the expected temperature rise and maximum operating ambient temperature fora PKB4619 power module operating at 20 A output current with 1.5 m/s airflow velocity. The input voltage will be in the nominal 48 to 53 V range.

From Figure 4a, the power dissipation at 20 A is 5.9 W
From Figure 4b, the thermal resistance at 1.5 m/s is 4.5°C/W

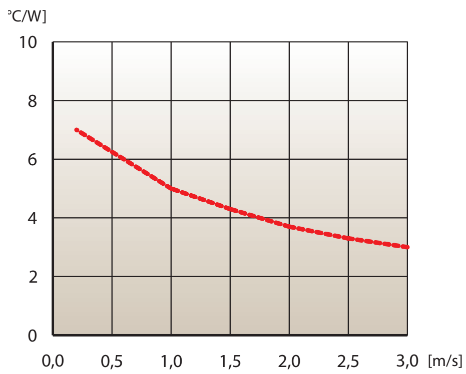


Dissipated power vs. load current input voltage at T_{PWB} = +25°C

Figure 4a - Test Conditions by Module Type.

Temperature rise (ambient air to module PWB) =
5.9 W x 4.5°C/W = 26.5°C
The module is specified to have a maximum PWB temperature of 110°C.
The maximum operating ambient is then:
110°C – 26.5°C = 83.5°C

It is instructive to compare this result with the derating curve in Figure 1. Using the derating curve at 20 A and 1.5 m/s, we obtain a maximum ambient operating temperature of approx-imately 78°C. Why is there a 5 degree difference? The answer lies in the assumptions used in the power dissipation curve in Figure 4a. This curve is generated at a converter PWB tempera-ture of +25°C.



Thermal resistance vs. airspeed measured at the converter. Tested in windtunnel with airflow and test conditions as per the Thermal consideration section.

Figure 4b - Thermal Design Curves PKB4619.

In actuality, the module will have an elevated operating temperature as a function of its output current and environmental conditions as described previously. At elevated temperatures, the conversion efficiency of the module can degrade somewhat from its 25°C value, resulting in increased power dissipation.

This effect is quantified for the PKB4619 in Figures 5 and 6.

Figure 5 plots the conversion efficiency vs. airflow velocity for various levels of output current. The nominal specified efficiency for this converter is 88% as shown in the figure. Figure 6 is based upon the same data as used for Figure 5 but instead plots the converter efficiency vs. the PWB temperature of the converter. Note that at output currents of 10 and 15 A, the measured efficiency is actually better than the specified efficiency. At the higher current levels of 20 and 25 A, the increased operating temperature results in a degradation of efficiency as shown. As the airflow velocity is increased (lower operating temperature), the efficiency degradation is reduced. For the example used above, the actual efficiency at 20 A and 1.5 m/s from Figure 5 is approximately 86.9%.

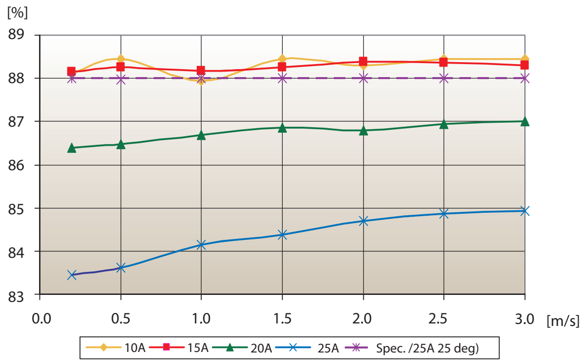


Figure 5 - Efficiency vs. Airflow Example.

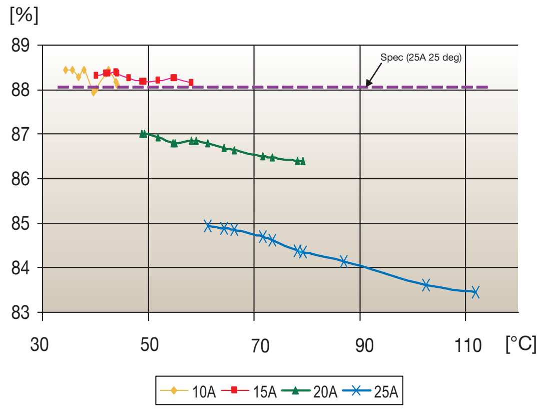


Figure 6 - Efficiency vs. PWB Temperature Example.

We can then calculate the power dissipation at 86.9% efficiency:

Output Power = 2.5 V x 20 A = 50 W

Input Power = 50 / 0.869 = 57.5 W

Power dissipation = 57.5 – 50 = 7.5 W

The temperature rise is:

7.5 W x 4.5°C/W = 33.7°C

And the maximum operating temperature is:

110°C - 33.7°C = 76.3°C

This result is in close agreement with the 78°C value obtained from the derating curve in Figure 1.

Since the intent of the initial design sizing is to be somewhat conservative, it is recommended that the derating curve be used when estimating maximum operating temperatures. The derating curve and the thermal resistance curve in Flex datasheets are both obtained by using the wind tunnel methodology as described earlier, and have the effects of efficiency changes as a function of operating temperature imbedded in them. In keeping with industry practice, the efficiency and power dissipation curves are predicated on a fixed temperature of 23 +/- 2°C.

System Thermal Verification

Using the derating curves in the power module datasheets along with the other techniques described previously are essential steps in selecting a converter for a particular system application. If these steps are followed with some degree of conservatism, the probability of a successful system thermal design is high. However each system is unique and may have design parameters that differ from those contained in the assumptions used for generating the derating curves. Some typical areas of uncertainty include:

- Using the power module in a non-optimal orientation to the airflow
- Unknown airflow velocity at the power module
- Shadowing of the airflow by other components
- Degree of ambient air "preheating" from other components
- Influence from power dissipation of other components via conduction through the PWB
- Construction and thermal conductivity of the system PWB

In order to quantify the above variables and assure the designer that the system thermal design is sound, Flex strongly recommends that a system thermal verification be performed. This verification basically measures the local operating environment for each power module in its system configuration. The temperature of one or more locations on the power module is measured in the system environment along with the local airflow velocity and ambient temperature. This type of test should be conducted for two conditions – a "worst case" performance situation and a typical operating condition.

The worst case test should use maximum system current loads, completely populated systems, and the maximum expected room environmental temperature. This test will verify that the power module will supply the maximum required current under the most severe expected environment and still remain within its maximum ratings.

The typical operating test is useful for obtaining normal operating temperatures that will be experienced in most systems. These data can then be used as an input for predicting the reliability of the power module in this particular system. For systems with variable speed fans, this type of test is a powerful tool for making the design tradeoffs between fan speed, acoustic noise, fan power and system reliability.

The two most commonly used methods for measuring temperature are thermocouples and IR photography. When used in a system environment, IR photography tends to be cumbersome and inconvenient. If the converter of interest is in a multi-board rack, it is difficult to observe it with the camera without modification of the adjacent structures which determine the airflow to the converter. Defining the emissivity of each of the materials and components is also quite difficult to do accurately. For these reasons thermocouples tend to be the easiest and most accurate method for monitoring the operating temperatures at specific locations within the system.

At a minimum, one thermocouple should be attached to each power module at the location indicated on the datasheet as being the limiting operating temperature for the converter. Quite often this will be the PWB of the converter, a particular magnetic structure or the case of a semiconductor device. It is recommended that the thermocouple be attached to the power module with a thermally conductive but electrically non-conductive bonding adhesive. Use only a small amount of bonding agent to minimize its influence on the thermal paths. Another thermocouple should be used to measure the localized ambient air temperature at each power module. This thermocouple should be located perhaps 10 mm in front of (direction of arriving airflow) the module and at the same level as the top of the power module. Two other thermocouples should be used to monitor the inlet air temperature to the system and the system's exhaust air temperature. It is often useful to include other thermocouples at critical locations in the system, such as the system PWB board temperatures and temperatures of key electronic components.

A hotwire anemometer probe can be used to measure the airflow velocity at each power module. This step may not be required if all the measured temperatures are within the desired limits. It is a very useful tool, however, if the temperatures at one or more locations are higher than desired and the system airflow must be modified to reduce them. A multi-channel data logger is normally used to record and correlate the temperature and airflow measurements with the system operating conditions.

Conclusion

This design note has summarized the process used within Flex for obtaining and publishing thermal performance data for its power modules. We have also shown how to use this published data to formulate preliminary estimates as to the suitability of a module for a particular application and to predict its performance in the system environment. The importance of a final system level thermal verification test was also emphasized. In most cases the information published by Flex in conjunction with the thermal design methods discussed above should result in easily configured and reliable systems. If your system presents a unique thermal environment or you would like further clarification of thermal design issues, please contact Flex for additional technical assistance. Flex has an on-going program to provide the user with the most meaningful thermal design information, so it can also be helpful to check the Flex website occasionally for the latest datasheets, application notes and design notes for the products you are considering.

Formed in the late seventies, Flex Power Modules is a division of Flex that primarily designs and manufactures isolated DC/DC converters and non-isolated voltage regulators such as point-of-load units ranging in output power from 1 W to 700 W. The products are aimed at (but not limited to) the new generation of ICT (information and communication technology) equipment where systems' architects are designing boards for optimized control and reduced power consumption.

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