Application Guidelines for DC-DC Power Modules

This application note provides guidelines for proper use of DC-DC power modules in systems, including EMI filtering, inrush current control, stability considerations, thermal management, current-share, and practical evaluation.

EMI Filtering

The acceptable level of electromagnetic interference (EMI) generated by an electronic device is controlled by regulatory statute. In general, telecommunication systems must meet electromagnetic compatibility (EMC) requirements for radiated and conducted EMI per FCC part 15J (47 CFR part 15B) in USA and/or EN55022 (equivalent to CISPR 22) in Europe and rest of the world. To ensure that either standard, with minor exceptions, can be used to certify electronic equipment, FCC part 15 and CISPR 22 have been made to be harmonious.

All standard board-mount DC-DC power modules operate in high frequency switching mode involving fast dv/dt and di/dt, thus generate conducted and radiated EMI. Due to space constraints and ever increasing power density dictated by the system power requirements, they have very limited on-board filtering. For a system to pass EMC regulations, it's often necessary to add additional filtering components around the DC-DC power module.

There are two types of EMI noises generated from the operation of a power module: radiated noise and conducted noise. The radiated noise is sensitive to dv/dt and di/dt. The module's mechanical packaging also has impact on the strength of the radiation. Reducing dv/dt and di/dt often means sacrificing power module efficiency which is not a practical means under the demand of ever increasing higher power density. While the power module manufacturers shall pay great attention in their designs to minimize such radiation, system designs should suppress radiated EMI through proper bypassing, shielding, and grounding. The conducted EMI can be separated into differential-mode (DM) noise and common-mode (CM) noises. The differential mode noises appear between the positive and the negative leads at both input and output terminals; while the common-mode noises appear between the converter input/output terminals and the system ground. EMI filter is primarily for suppressing conducted EMI, though it also helps to reduce radiated EMI by containing the radiated EMI sources in a local area.

Figure 1 shows a typical EMI filter structure containing both DM and CM filtering. Components for DM EMI are drawn in orange and components for CM EMI are in green.

C_in2 represents electrolytic capacitors at the input of the power module and is primarily for holding the energy to keep the stiffness of the input voltage source, thus the proper stability and large signal behaviors of the power module. Further discussions on

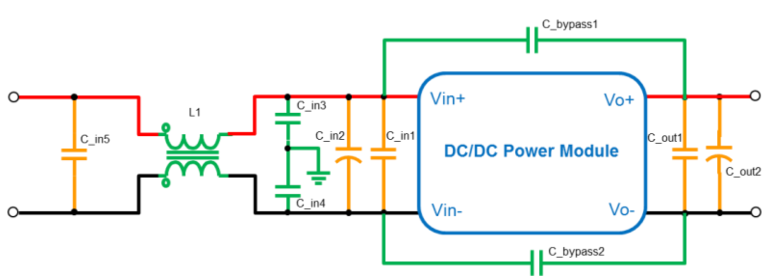

Figure 1 *Typical EMI filter structure for DC/DC power modules*

stability can be found in section “Stability Considerations”.

C_out2 represents electrolytic capacitors at the output of the power module. It is often used if the down-stream loads care about the stiffness of their input source, yet not necessarily required for the proper operation of the power module itself.

The rest capacitors shown in Figure 1 are for EMI filtering and fast load transients, and they should be a combination of ceramic and tantalum types. These capacitors have low ESR (equivalent series resistance) and low ESL (equivalent series inductance) for good filtering results. The reason of suggesting a combination of ceramic and other types of capacitors is because the extremely low ERS of the ceramic capacitors, when no other type of relatively higher ERS capacitors present, could cause instability of some power modules.

C_in3, C_in4, C_bypass1, and C_bypass2 are common-mode decoupling capacitors often in the range of 1-10nF with voltage rating sufficient to meet the system isolation voltage requirement. C_in3 and C_in4 are also common-mode decoupling capacitors when the connection to system ground is available.

L1 is a common-mode inductor. The common-mode inductance and the common-mode capacitors together provide the containment of the common-mode noise. The common-mode inductance of L1 is usually below 1mH considering its current rating and physical size. The leakage inductance of L1 serves as the inductance for differential-mode filtering.

The single-stage filter in Figure 1 is generally good for power modules below 150W. For power level above 150W, the two-stage filter structure shown in Figure 2 is recommended.

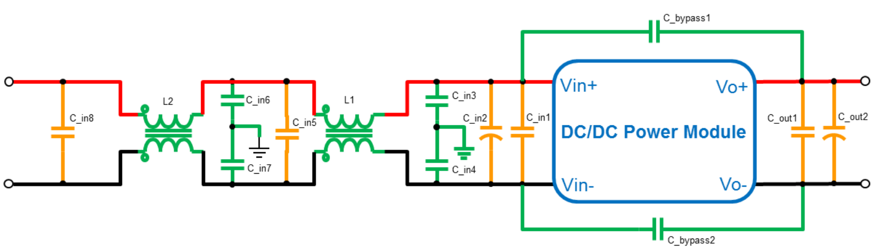

Figure 2 *Two-stage EMI filter structure*

The layout (component placement and trace routing) of EMI filter is critical for obtaining the best filtering result. The system designers shall keep the following guidance in mind when doing system board layout:

- ✧ Run the positive and negative power paths (both input and output of the power module) as close as possible and better in parallel in a multiple layer PCB, minimizing the loop area because any loop area will either pick up noise and turning them into conducted noise or radiate out noise to pollute other part of the system.
- ✧ Remote sense lines should run together with their corresponding power path and the loop formed by the sense+ and sense- lines should be minimized.
- ✧ A copper plan should be placed under the power module and coupled to the input and output terminals of the power module through ceramic capacitors of proper voltage rating. This helps to contain the radiated noise from the fast dv/dt and di/dt inside the power module. This copper plan should be buried in an internal layer of the system board to prevent possible violation of isolation spacing distances between input and output.
- ✧ Avoid the coupling of a noisy trace and a quiet trace. This suggests place the filter components and the power module in a straight flow.

- Use short paths and minimize loops for capacitor branches in the filter to avoid the trace impedance defeating the purpose of low impedance of the high frequency capacitors. Therefore C_in1 and C_out1 in Figure 1 should be placed as close to the power module as possible.

Stability

For a DC-DC power module to function properly in a system, the system design should provide a sufficiently low impedance power source to feed the power module, and the output impedance of the power module should be sufficiently low as well for good transient response. These requirements are usually assured by placing extra capacitors across the input terminals and the output terminals of the power module.

Input Source Related Stability

C_in2 should be low ESR electrolytic capacitor(s) that provide sufficiently lower impedance than the input impedance of the power module to keep the power source (line) impedance from interacting with the power module input impedance, therefore, secure the stability of the power module operation.

The recommended capacitance of C_in2 for the 36-75V input voltage range is 33-100uF per 100W output power. For 18-36V or 18-75V input ranges, the capacitance of this C_in2 shall be significantly higher to limit both the power loss in this capacitor and the allowed voltage swing during start-up and load transients.

Load Impedance Related Stability

In many applications, additional capacitors are used at the output of DC-DC power modules, often in the range of several hundred to tens of thousands micro-farad (μF). Such external output capacitors help to reduce the switching ripple at the output, and reduce the voltage variation during load or input transients.

When large amount of ceramic capacitors are used at the output of a power module, it could cause the power module to become unstable due to the very low ESR of these capacitors. This is a complicated matter as it is related to small signal analysis of converter designs, the system board designs, and the characteristics and locations of the capacitors used. The current mode control scheme adopted in most of NetPower's designs makes power modules' stability insensitive to the ESR of the load capacitors. For a robust system design when using large amount of load capacitance, a combination of ceramic capacitors and capacitors with moderate ESR such as tantalum, polymer, electrolytic capacitors often provide satisfactory results.

Inrush Current Control

Due to the presence of the capacitors at the input of the power module, especially the bulk capacitor C_in2, the inrush current at the power on, especially when hot-swap plugging in a circuit card, could cause significant transient on the input dc bus. Such transients can cause shut down of adjacent circuitry, trigger over current protection of the input source, or even blow the input fuse. Therefore, a proper inrush current control mechanism shall be implemented to limit the current amplitude during power on.

A typical inrush current control circuit is shown in Figure 3, in which a MOSFET Q is in series with the input line. When the input voltage is applied, the rising of the gate voltage of this series MOSFET is governed by the passive network at its gate (resistors R1 and R2, capacitor C1 and zener diode ZD). As the MOSFET goes through its linear conduction mode to reach its full conduction state, it limits the current charging the input capacitors (represented by Cin in Figure 3).

One particular caution is to manage the timing of inrush control and the turn-on of the power module. If the inrush MOSFET Q is still in its linear conduction mode while the power module is turning on, Cin could easily be discharged to below the under voltage protection point of the power module and the power modules shuts down. This is an often encountered phenomena of hiccup start up until Q is turned fully on.

If the power module on/off control pin doesn't have an active control circuit, for example, tied to Vin(-) for negative control logic modules, the inrush process has to be designed fast enough to avoid the above

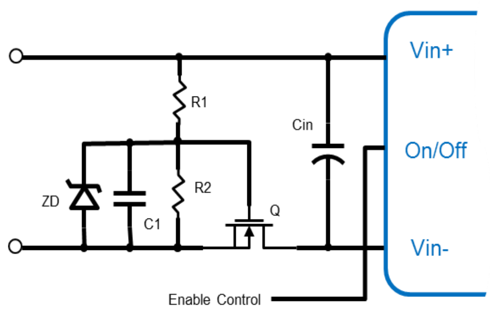

Figure 3 *Typical Inrush Current Control Circuit*

mentioned unwanted shutdown, yet slow enough to limit the inrush current to the acceptable level. When the On/Off pin is controlled by a system enable control signal, the system controller should be set to provide this enable signal after the inrush process is complete.

ICs designed for hot-swap are available from power management IC vendors such as Texas Instruments and Linear Technology. These IC's provide more freedom in controlling the inrush current and they have a "power good" signal that can be used to turn on the power module upon the completion of the inrush process avoiding the premature start up as discussed above.

Thermal Management

The thermal management of DC-DC power modules is one of the most important application issues as more and more applications demand high power and high current in smaller packages and require the modules to operate under increasingly stringent environment.

The key factors affecting the thermal performance of a given DC-DC power module are:

- ✧ Airflow and Orientation
- ✧ Ambient Temperature
- ✧ Heat transfer path

Available airflow and its orientation with reference to the power module have great impact on the module's thermal performance. It is recommended that customers place the converter at a location where it receives the maximum available airflow and in the preferred transverse orientation.

Most applications demand the converter to be able to operate at an elevated ambient temperature. Some extreme applications, such as outdoor equipment, require the power modules to run under 85˚C or even higher ambient temperature. The thermal derating curves in the product datasheets provide a guideline for such applications. NetPower's derating curves are generated using de-facto industry standard of 125 °C power semiconductor junction temperature. Although the derating curves are supposed to be very important for system designs, the performance of a power module in a system often cannot be well represented by these curves, and evaluation at the system level is necessary. The detailed evaluation considerations are illustrated in "Thermal Evaluation" under "Practical Evaluation Techniques" section.

The baseplate option available on most NetPower modules provides customers the flexibility in their designs to deal with extreme environments. A baseplate by itself will improve the thermal performance. The higher the airflow speed, the more improvement a baseplate will bring. Typically, under a condition of 200LFM airflow and 50C ambient temperature, a baseplate can boost the output power by 15% or so. Additional heatsink can be added to some baseplates for enhanced thermal performance.

Current-Share

Load current share is a feature needed either for boosting the total available current to power the load or for redundancy in high reliability designs. Current share can be achieved with either built-in current share feature or an external circuitry. The built-in current share can also be distinguished by active current share or passive (droop) current share.

With an external current share circuitry, the output trim function is used to adjust each power module's output voltage slightly up or down based on the imbalance of the currents in the power modules operating in parallel. For details of such technique, please reference to the application guide of ICs designed for this purpose. Major power management IC manufacturers offer such ICs. This section focus on built-in current share features.

Droop Current Share:

The principle of droop current share is simple: if the output characteristic of a power module exhibits a droop nature, i.e., the output voltage droops down when the output current rises. With the droop characteristic, the power modules in parallel will automatically share the load current. Not all applications can accept a varying voltage, yet the bus converters supplying the intermediate bus voltage in the popular IBA (Intermediate Bus Architecture) can. Some of NetPower's products offer the droop feature as an option listed under Electrical Options in its part numbering system. When using a power module with the droop feature, special attention needs to be given to the system board layout to balance the resistance of the copper traces connecting from the output of each power module to the load for good current share results. In Figure 4, R1 – R8 represent the trace resistance of each branch. For the best results of current share, the system board layout should try to satisfy the following as much as possible: R1+R3=R2+R4 and R5+R7=R6+R8. The resistance balance condition on the secondary side is more important for the current share accuracy.

Active Current Share

The power modules with built-in active current share feature have a designated parallel or current-share pin either on the primary side or on the secondary side. When these modules are operating in parallel, these current-share pins shall be tied together. This pin is noise sensitive and the following

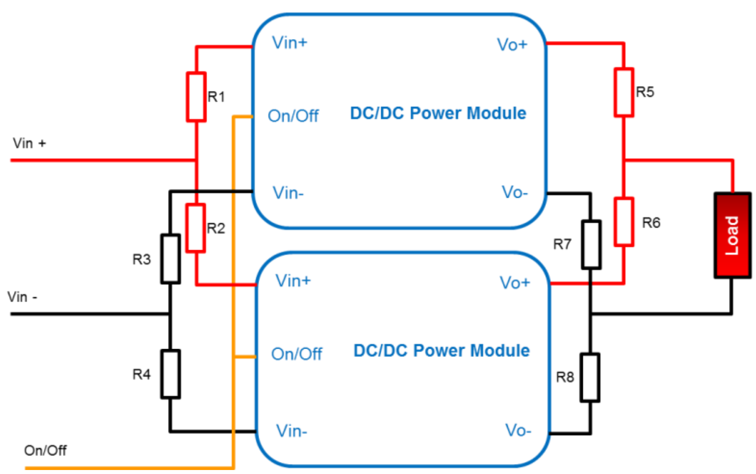

Figure 4 *Power modules with droop current-share operating in parallel*

guidelines shall be followed in system board design.

- ✧ A ground plane shall be placed under the converters in parallel to make sure that the current-share signals of these converters have the same referencing point.
- ✧ Minimize the loop formed by the current share signal traces and the above mentioned ground plane.
- ✧ Minimize the distance among the converters in parallel.
- ✧ Try to use symmetrical input and output current paths.
- ✧ The output remote sense leads of all converters in parallel shall be connected to the point where the voltage regulation is required.
- ✧ Try to arrange the positions of the power converters or the airflow paths so that all converters in parallel receive similar airflow and running under similar thermal environment.

Practical Evaluation Techniques

Evaluating DC-DC power modules for a specific application is a complex and error-prone process, and requires a thorough understanding of the power module and the application environment.

Efficiency Measurement

Conversion efficiency is a key parameter that is used in evaluating power modules. It's essential to achieve high efficiency so heat generated inside a module is low. Measuring the efficiency correctly is challenging. Since a 1% discrepancy in efficiency measurement means a significant change in terms of the losses, the accuracy of the measurement becomes critical for any meaningful result. Figure 5 shows a setup for measuring the efficiency of power modules.

To obtain the correct measurement, it is recommended to solder the converters into the evaluation board. The following cautions shall be taken for a good efficiency measurement:

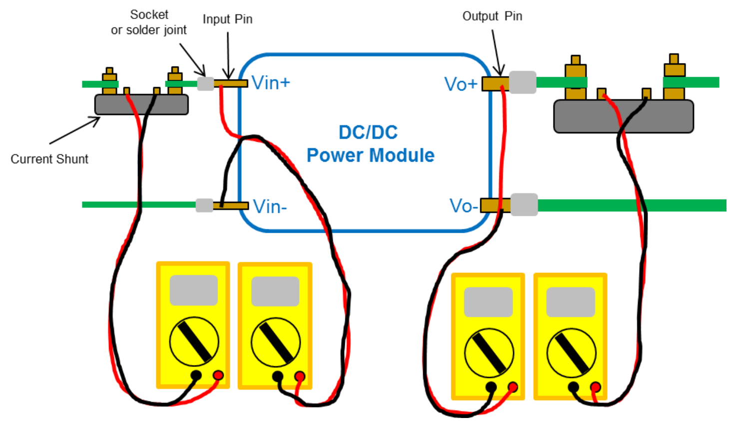

Figure 5 *Efficiency measurement setup*

- ✧ If the power converter is plugged into sockets, the contact resistance between the pins and the sockets especially at the output terminals varies with many factors, and can cause significant power losses. Therefore, when using sockets, the output voltage readings shall be taken at the pins right above the sockets, not on the system or evaluation board.
- ✧ The multi-meters shall have at least 5-digit accuracy. Since all variables determining the efficiency are dc values, it's important that the meters' reading is not sensitive to the ac ripples that inevitably present in a switched-mode power supply.
- ✧ The input and output currents shall be measured with high-accuracy shunts. Such a shunt has a small and well-defined resistance to convert a current into a voltage signal normally in the range of mV. However, the measurement of such low amplitude signal is susceptible to switching noises, especially the common-mode noise. Filter capacitors may be used to achieve valid readings

The typical efficiencies published by NetPower as well as most other power module manufacturers are measured at room temperature while the converter is in cold state. For the purpose of comparing the measurements with the published efficiency, the measurement shall be taken quickly once the converter is powered up. In general, the efficiency drops while the component temperature rises. One should use the "hold" button of the multi-meters to hold all four numbers within a few seconds apart.

Output Ripple and Noise Measurement

Output ripple is referring to the voltage swing caused by charging and discharging the output capacitors at the switching frequency; while noise is about the ringing at much higher frequencies caused by the turning on and off of the power switches. To separate the ripple and the noise, the output ripple voltage measurements are conducted by limiting the oscilloscope bandwidth to 20-25MHz, while the output noise measurements are taken with full bandwidth of the oscilloscope. Figure 6 is an example of measured output ripple of a 36-75V input power module.

The ripple and noise measurement results are sensitive to the measurement setup since extra noise pickup, common-mode noise, and ground-loop noise can easily get into the measurements. To obtain a correct measurement, special attention should be paid to these below issues:

- Ground connection: sometimes poor grounding can cause a lot of noise. A complex grounding loop can be formed by the grounding connections of the power source, the module, the load and the oscilloscope, and also the parasitic capacitive coupling inside the power module. Often, single-point grounding is not easy to obtain at high frequencies. The best way to avoid this problem is to

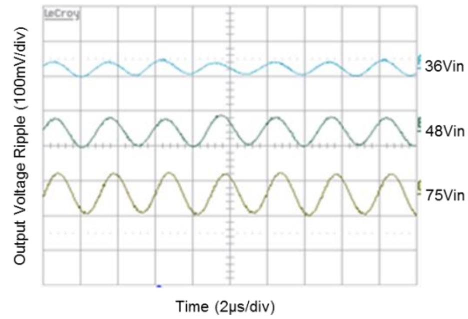

Figure 6 *Output ripple measurement*

use differential probes. An isolation transformer can also be used to isolate power source to the power converter and the oscilloscope. Resistive load shall be used since it doesn't have any ground connection.
- A loose connection between power module pins and the sockets or between oscilloscope probes and the test points may cause the measured ripple much higher or lower than it really is. Whenever possible, a soldered connection should be used.
- A ceramic cap should always be connected at or close to the points where the probe is attached. The probe (probes) should be arranged to minimize extra noise pickup.
- The scope bandwidth is another factor affecting the readings. The published ripple waveforms by almost all manufacturers are obtained with 20-25MHz bandwidth. For measuring noise, the oscilloscope should be set to full bandwidth to catch the very high frequency components at the input/output terminals.
- It's highly recommended to measure output ripple voltage with a setup similar to actual application and with filter attached. The filter can reduce the common-mode noise and ground interaction in the measurement. The output voltage ripple is a differential signal by definition, but common-mode noise and ground interaction can distort the measurement. If good grounding and

filtering is not possible, it's recommended to connect an input terminal (usually Vin-) to an output terminal (usually Vo-) together through a short wire or a capacitor.

- ✧ Use a BNC connector if possible because oscilloscope probe leads can easily pick up radiated noise to yield misleading readings. If wire connection is used for connecting the BNC to the test point, make sure the two wires are twisted and as short as possible.
- ✧ Output ripple voltages could also vary significantly with the input voltage change. Customers should check the ripple at low, nominal, and high line conditions.

Output Voltage Startup Waveform

Today's complex electronic systems often require their IC's to follow a given sequence during power-up. To accommodate the tolerance of the IC threshold voltages, power modules need to provide a monotonic and fast-rising output voltage during a startup process. Please note that load capacitance and load current have significant impact on this waveform. Two extreme corner conditions should be checked: minimum load with minimum output capacitance and maximum load with maximum output capacitance.

Figure 7 is an example of the output voltage of a power module with monotonic start up characteristic.

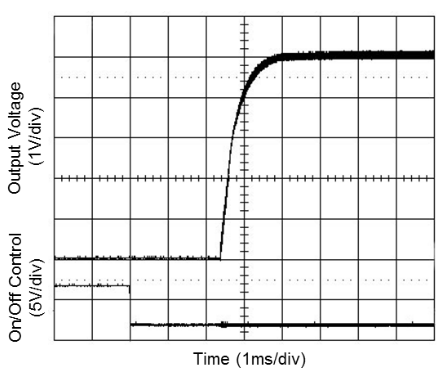

Figure 7 *Output voltage monotonic startup*

Pre-biased startup is another commonly concerned characteristic. In today's electronic systems, multiple voltages are required. Some sophisticated ICs require multiple voltages to power chip. There is often a required sequence for these different voltages to be established for these ICs to work properly. It's often the case that lower voltages are required to be established sooner than the higher voltages. When a lower voltage is established, it could go through some internal paths in an IC or circuits on the system board to pre-charge the output of a higher voltage rail. When the power module for the higher voltage rail starts, its output voltage should be monotonically rising other than dropping down before rising up.

Thermal Evaluation

Thermal performance of a power module determines how much current or power it can output reliably. In many applications power modules are required to operate at a challenging environment. To achieve good thermal performance, a module needs to have high efficiency to reduce its power loss and thus heat generated. The module must also have good heat distribution across the module, as well as a good mechanism to remove the heat out of the module.

A module's thermal performance is characterized by its thermal derating curves often found in datasheets. Thermal derating curves define how many amperes of current a power module can output under various airflow speeds / orientations and ambient temperatures. The derating curves are based on the data obtained in wind-tunnel tests conducted by power module manufacturers. Figure 8 depicts the wind-tunnel setup used at NetPower, in which a power module is soldered on a circuit board and a spacing board simulating a real system is placed with

1" board pitch. The measuring point of the ambient temperature is directly above the power module.

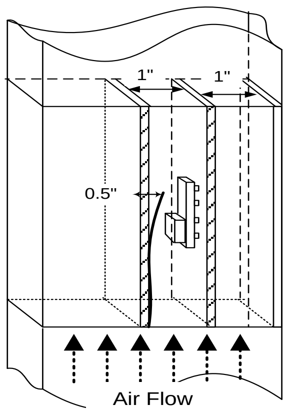

Figure 8 *Wind-tunnel setup*

Among power module manufacturers there are differences in temperature measurement method and location, airflow measurement method and location, construction of the test fixtures, spacing board design and pitch, etc. These differences have significant influence on the resulted derating curves. Because of these differences, the derating curves published by different suppliers cannot be directly compared to determine whether one module is better or worse than another module from a different vendor. It is strongly recommended to evaluate the module's thermal performance in actual systems, or in a condition closely simulating the actual application. In the datasheets, NetPower suggests a component on the power module for customers to monitor the temperature based on which to determine if the power module is operating within the specification. Figure 9 shows an example of thermal monitoring location recommended in NetPower's datasheet.

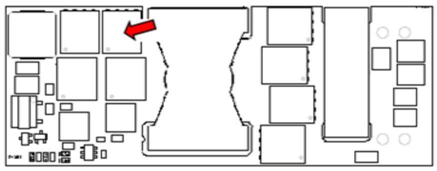

Figure 9 *Temperature monitoring point*

If a thermal coupler is used to measure the temperature on that component, the wire connecting the thermal coupler should be much smaller than the component itself to avoid unintended heat transfer through the wire. Also, the thermal coupler should not be attached to places with high voltage, such as the drain leads of primary power MOSFETs. If an infra-red temperature meter is used, the measurement area of the meter should be significantly smaller than the device's area for meaningful results. A better way to evaluate a power module is to obtain a thermal image of the whole module because such image gives the user much more information than a point on the derating curve. One example image of NetPower's modules is shown in Figure 10.

Even if the power module manufacturer has done everything correctly in generating the

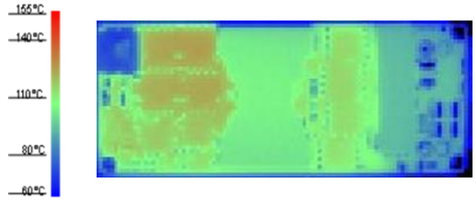

Figure 10 *Thermal image of a power module*

thermal derating curves, it's very likely that the application environment is different from the supplier's test environment. The user needs to evaluate the module's thermal performance in the system under different conditions. Performing thermal tests in an early stage is of great value and could save a lot of time and effort later. If the actual thermal environment and/or the maximum load current were unknowns, it would be beneficial to select the power module that has effective options for thermal performance enhancement, such as the ability to add a baseplate and/or heatsink.