Sensor Applications in Power Modules

Today, operation parameter monitoring is an integral part of power modules. Temperature sensors are more or less standard in power modules, and even current sensors are becoming an increasingly popular feature. In fact, unlike external solutions, integrated sensors are cost-effective solutions that offer users added protective functions plus volume reduction. **Arendt Wintrich, Application Manager, SEMIKRON Elektronik, Nuremberg, Germany**

Integrated sensors inside an IPM protect a power module like SKiiP over a wide range of operating conditions. With a well adapted evaluation circuit it offers high quality information for process control as a synergy effect. This saves space, costs and development time. The combination of the available sensor signals allows closing application specific protection gaps by an external observer.

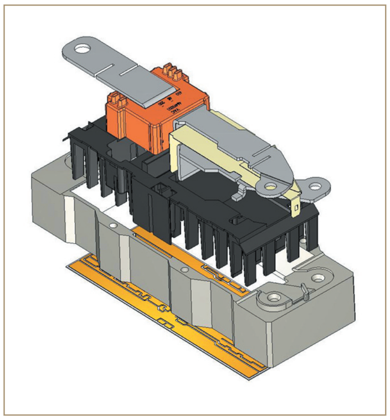


Figure 1: SKiiP power module with integrated current sensor at the AC terminal

Current sensors

If a power module is equipped with current sensors, the signal is used mainly for output current control (e.g. in drive applications) and also as an important secondary effect for device protection. Motor control requirements determine the current sensor characteristics. In many cases, failure including temperature drift has to be below 1-2%. The requirements for temperature (–40 to 125°C) and low current consumption are set by the power module itself. The device protection sets the limits for over-current capability (short circuit up to five times the nominal current) and the upper cut-off frequency (>100kHz).

Current shunts are a precise and cost-effective solution for low and medium-power devices. The current limit is approximately 30 to 40A. One disadvantage is the additional power losses; the other is the missing isolation and interferences in the IGBT gate signal if the shunt is used to measure the emitter current.

For high-performance and high-power semiconductor modules electrically isolated sensors are used. Pure Hall-effect sensors without compensation current show a lower performance in terms of tolerance and temperature stability. The sensors can be used in customer specific modules where the requirements are clearly defined. Sensors with a high degree of linearity and a low temperature drift operate with compensation current. This current neutralises the magnetic field of the measurement current inside the sensor core. The control signal for the compensation current amplifier is provided by Hall-effect, magnetic field or magneto resistive probes.

For intelligent power modules (IPM) like the SEMIKRON SKiiP-system, sensors with maximum accuracy are most suitable due to the high performance requirements of the final application. This sensor is integrated directly into the module case around the main terminal to save space in the final application (Figure 1). The evaluation circuit for signal monitoring and transformation is part of the driver circuit. A purpose designed ASIC guarantees a high integration rate and a high degree of reliability which is difficult to achieve by an external solution.

Inside an IPM the current monitoring circuit has direct access to the driver circuit. It can detect an external short circuit in a minimum time and can turn-off the power semiconductor within 2 to 3µs. In the future, this will become increasingly important for new IGBT generations where the permissible short circuit time is 6µs, compared with 10µs in the past.

A current sensor at the AC terminal of a voltage source inverter circuit cannot detect a short circuit inside of an inverter bridge. Here, the slope resistance of the semiconductor in on-state is used for protection purposes by means of $V_{CE(sat)}$ monitoring. The method is sufficient for short circuit protection but is not suitable for current measurements.

Temperature sensors

For device protection, several types of temperature sensors are available. These can have a negative (NTC) or positive (PTC) temperature coefficient. NTC sensors are used most frequently for standard industrial modules. SEMIKRON uses its own silicon chip sensor SKCS with PTC characteristic with a high linear characteristic and a low tolerance. In combination with a well adapted monitoring circuit, an IPM such as SKiiP provides an analogue output signal for temperature measurement and protection with a failure rate of less than 5°C.

The sensor position inside of a module largely affects its suitability for temperature protection. In fact, the sensor position is more crucial than the sensor tolerance in this respect. This is especially true if a hardware trip level is set by a driver or controller circuit.

A case study in which different sensor positions were investigated was carried out.

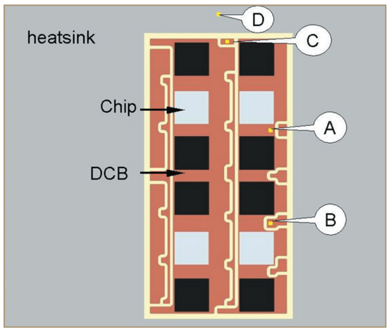


Figure 2: Case study about different temperature sensor positions inside a power module; Model and temperature simulation

A model of a power module is shown in Figure 2. This module has no copper base plate and is mounted on an air cooled aluminium heatsink. The thermal coupling of the sensor varies from A) direct connection to the power semiconductors at the same copper layer, to B) and C) insulated at different positions within the module to D) beside the module on the heatsink. Each sensor has a different thermal resistance junction (j) to sensor (r) $R_{th(j-r)}$ owing to the different thermal coupling.

A trip level for over-temperature protection can be set under quasi-static conditions for each of these sensors. If, for example, Tj = 140°C must not be exceeded, the trip level for 'over-temperature turn-off' of the investigated system would vary from 120°C (sensor A), 110°C (sensor B), 100°C (sensor C) to 70°C (sensor D). The better the coupling between source and sensor, the lower the influence of the cooling system. This is a big advantage of an integrated solution.

Nevertheless, for other cooling conditions (heatsink material and root thickness, cooling medium, thickness of thermal grease…) the trip levels have to be set to new levels. This makes it difficult for the manufacturer of an IPM to set the over-temperature trip level to an appropriate value for any given application. For this reason, the sensor signal should be monitored externally by a superior controller and the temperature protection level should be matched to the cooling system, if required.

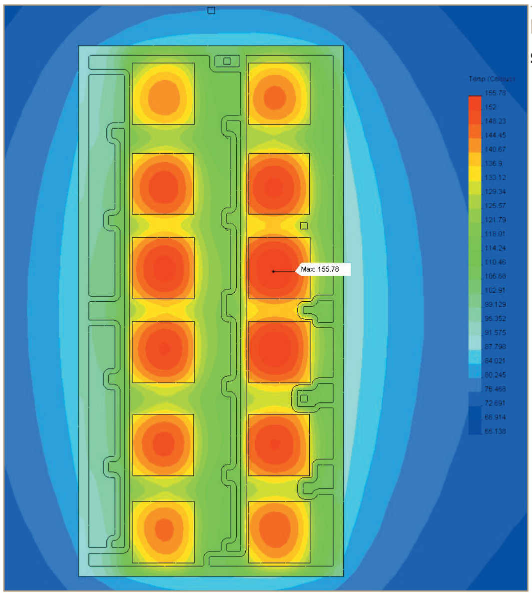


Figure 3: Temperature simulation

To show the influence of the cooling system, the thickness of the thermal grease layer was increased from 50 to 100µm. Sensor A has the best thermal coupling to the power semiconductors and therefore the lowest influence on $R_{th(j-r)}$ can be seen. The value is increased only by 3%. Sensor B and C get a 7-8% higher R_{th} value. The cooling system has the highest influence on the $R_{th(j-r)}$ of Sensor D. The value is increased by more than 25%.

Another question is whether a temperature sensor is capable of protecting the power semiconductor in case of short time overload. Each sensor has a position-specific delay in reaction time to a rising junction temperature. The behaviour is described by the thermal impedance $Z_{th(j-r)}$. It behaves differently to what one would expect (see Figure 3). A comparison of $Z_{th(j-r)}$ and the thermal impedance junction to heatsink $Z_{th(j-s)}$ (directly below the chip) shows that the system junction-sink has reached steady state conditions after one second and the system junction-sensor needs up to 100s. The reason for this is the heat spread inside the heatsink.

For each power semiconductor a maximum value for static power dissipation Ptot is specified. For an overload jump from 50% P_{tot} to 200% P_{tot}, as in the example, the semiconductor would overheat after a certain period. Sensor A would reach its trip level of 120°C after 0.19s, providing reliable device protection and keeping the junction temperature at around 150°C. The junction temperature of devices protected by Sensor B and C would be in a critical range of between 160 and 170°C; in these cases, the sensors would need 0.3 to 0.4s to reach trip level. Depending on the device properties, this could mean that the data sheet limit is exceeded. Sensor D has a reaction time of more than 1s and is therefore not able to protect the device.

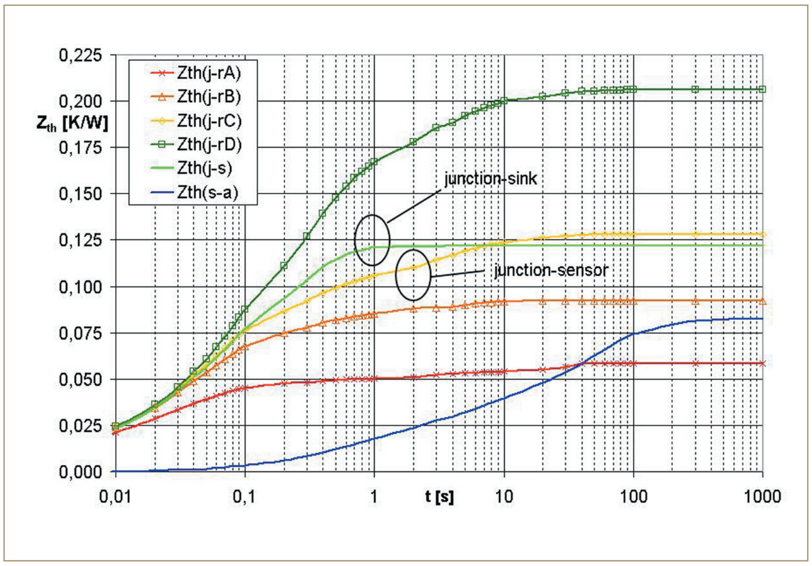
For conditions with a very high overload and a low start temperature, a temperature sensor is not able to provide any suitable protection.

An overview of the advantages and

Sensor A	Sensor B	Sensor C	Sensor D
Excellent thermal coupling to power semiconductors	Acceptable thermal coupling to diodes and IGBT	Acceptable thermal coupling to IGBT, insufficient to diodes	Low thermal coupling
Fast reaction time	Medium reaction time	Medium reaction time, higher than B	
Low influence of external cooling system $R_{th(j-r)}$	Influence of external cooling system on $R_{th(j-r)}$	Influence of external cooling system on $R_{th(j-r)}$ higher than B	High influence of external cooling system on $R_{th(j-r)}$
No insulation, additional measures at driver side necessary	Basic insulation, additional measures for safe insulation necessary	Basic insulation, additional measures for safe insulation necessary	Safe insulation

Table 1: Comparison of different temperature sensor positions with regard to suitability for power semiconductor protection

Figure 4: **Thermal impedances junction (j) to different sensor positions (rX) and to heatsink**



disadvantages of the different temperature sensor positions is given in Table 1. Due to its insulation, a sensor at position B is the preferred solution today. Future driver concepts with protection circuits and signal transforming at the driver secondary side could mean that sensor position A may be the better solution.

Integral protection

In case of a short overload, there is a gap in device protection. The current sensor trip values are set to high values to allow a short overload; for example for motor start. A longer operation at this current level will cause the device to overheat. In most cases the reaction time of the temperature protection components is too long to detect this.

A possible way of closing this gap is to use current and temperature signal for a software turn-off. The inverter controller calculates the junction temperature on the basis of the sensor temperature and the electrical operation conditions. The junction temperature can be calculated at the time t_p using the following equation:

$$T_j(t_p) = T_r + P_0 * R_{th(j-r)} + (P_{over} - P_0) \cdot Z_{th(j-r)}(t_p)$$

P_0 is the power dissipation at t = 0s and P_{over} is the power dissipation during overload. Here, the thermal impedance $Z_{th(j-r)}$ as described in the data sheet and the analogue temperature signal T_r are necessary.