

Advanced Features in Sophisticated Inverter Design Supporting MW-Applications

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Abstract

Handling power in a megawatt regime is a common, yet challenging task. Projects like off-shore wind farms, remote solar arrays or the German *Energiewende* require robust, reliable and efficient power electronics. Considering off-the shelf components, this is difficult to implement. Though standardized components to handle this power level are available, protection and control methods need to be implemented according to the application's requirements. A holistic approach combining power electronic components, measurement equipment, sophisticated microcontrollers and protection methods especially focusing on a junction temperature determination is desired, not eliminating the degree of freedom to adapt the system to individual requirements. The present paper deals with the subject of designing a flexible, modular, self-protecting power stage to support this approach and demonstrates how these goals are achieved in the MIPAQ™ Pro intelligent power module.

1. Introduction

When increasing power from the kW to the MW regime, the challenge is to create modular power units which enable simple design-in into the customer's application, insight into the actual operating conditions and protection. For this task, a feature set for an intelligent power module (IPM) was defined and realized in the MIPAQ™ Pro.

In a nutshell, the MIPAQ™ Pro is Infineon's answer to high-power IPM requirements. It provides a portfolio of half-bridges with a number of current ratings in a uniform package concept, state-of-the-art power density and an outstanding feature set. The latter is described in this article.

2. Modularity and Scalability

Flexibility requires simplified handling and mounting of the power stage, demanding something small and lightweight. One-man-mountable units as building blocks for the MW customer application are preferred. Furthermore, it must be possible to scale up the power levels by parallelization with minimized electrical interconnection efforts for the customer.

Fig. 1 depicts the MIPAQ™ Pro for a 2400A nominal chip current with liquid cooling system. The dimensions of this high-power IPM are 350x215x120 mm³ (l, w, h) and the weight is less than 10kg making manual handling and mounting a simple task for one person.

The base circuit is a half-bridge allowing a large number of configurations in the customer's application like boost/buck converter, classical H-bridges or sixpack 2-level and break chopper configurations. All logic and control ports are directed to the front side only which allows simple connecting, even when already mounted in the customer's application.

Since the plugs are horizontally oriented and within the MIPAQ™ Pro's frame, no additional space needs to be reserved for the plugs and their handling, allowing a low overall construction height in the customer's application.

The internal design as well as clearance and creepage distances allows to derive a portfolio of 1200/1800/2400A nominal chip current in half-bridge configuration, 1200V and 1700V IGBTs and liquid and air cooling systems. The package is designed for an AC RMS current of 1000/1500/2000A, respectively. This large range of variants enables the customer to use the same mechanical and electrical concept to cover a variety of power levels.

Furthermore, as much as 4 MIPAQ™ Pro can be easily paralleled in the application. For this purpose, the MIPAQ™ Pro provides a master/slave mode of operation. Thus, the final application no longer needs an additional paralleling board: it is sufficient to connect the master MIPAQ™ Pro and leave the paralleling itself as well as the consolidation of all feedback to the MIPAQ™ Pro in the master position.

In order to support a simple design-in, the MIPAQ™ Pro package concept includes an optional adapter box which allows translating the electrical customer interface to optical or for generating electrical compatibility with existing customer applications. The adapter box can be integrated in and fixed to the MIPAQ™ Pro frame concept without consuming additional space as demonstrated in Fig. 1.



Fig. 1. MIPAQ™ Pro as liquid cooling version with an adaptor box mounted providing an optical interface

3. Reliability

As industrial applications are capital goods, availability, reliability and lifetime are of major importance. In order to address these topics, well-proven technologies are used on the power side.

As chip technology, IGBT4 is employed. The thermal interface to the cold plate is taken care of by Infineon Technologies' Thermal Interface Material (TIM) [1]. This helps to achieve a long lifetime of the power section and prevents a degradation of the thermal interface layer and subsequent thermal run-away and death of the silicon chips.

The logic connections to the power part utilize Infineon's PressFIT technology, which forms a cold welded connection and provides superior electrical properties and reliability.

4. Insight into Operating Conditions

One main feature of the MIPAQ™ Pro is the ability to provide the customer with a deep insight into the power semiconductor's operating conditions. For enabling this feature, sophisticated digital supervisory electronics has been implemented, which is based on an industrial microcontroller. An overview on the implementation is given in Fig. 2.

Insight into the operating conditions is first of all provided by direct measurement of current, DC-link voltage and NTC temperature of the power semiconductor section. Sophistication comes in by utilization of the microcontroller capabilities, which digitizes the sensor signals and allows adjusting the transfer functions.

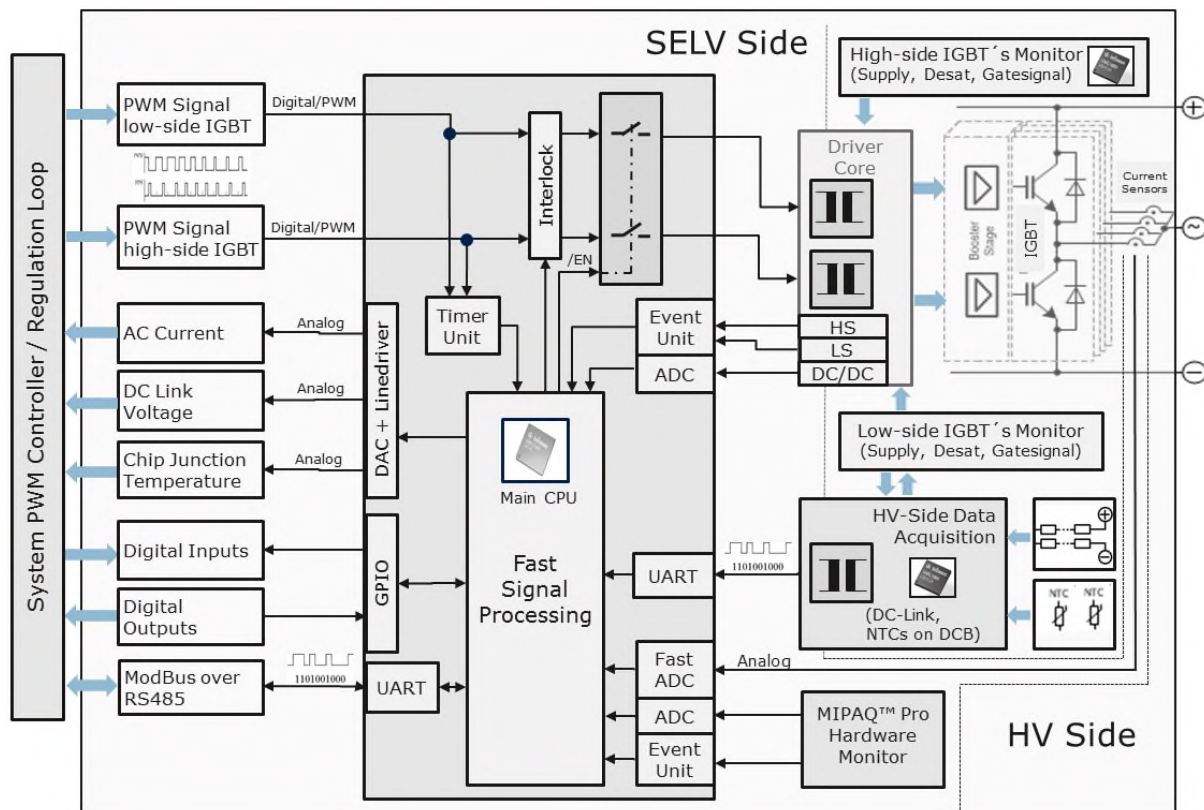


Fig. 2. Simplified MIPAQ™ Pro block diagram

Furthermore, the MIPAQ™ Pro performs an in-situ IGBT and diode junction temperature calculation based on the measured operating conditions. For this purpose, the MIPAQ™ Pro measures current, voltage and NTC temperature and calculates the corresponding dynamic and static losses in IGBT and diode accurately and synchronously to the switching operation. The resulting dissipated power is then folded with the time-dependent thermal behavior of the power section, described by the Z_{th} matrix including cross-coupling between IGBT and diode.

As a result, the customer controller can simply read out the calculated IGBT and diode junction temperatures T_{vj} , which belong to the main dimensioning factors of every power semiconductor. The direct availability of the junction temperatures allows the customer on the one hand an accurate verification of the dimensioning of the system and on the other hand a supervision of the performance during operation in the application while allowing an optimum time to market.

As indicated in Fig. 3, the MIPAQ™ Pro provides direct feedback to the system controller for current, voltage and temperature, as well as error information by electrical signals. Furthermore, digital feedback on all other parameters described is provided via a Modbus interface.

5. Smart Protection

Based on the insight into the operating conditions, the MIPAQ™ Pro monitors and ensures operation within the specified limits of each monitored parameter, e.g. current, voltage and especially the calculated IGBT and diode junction temperatures.

For this purpose, warning limits and shutdown limits have been defined for each parameter observed and are stored in the microcontroller as parameter sets. Before reaching the operation limits, the MIPAQ™ Pro issues a warning signal to the customer's application, indicating a situation close to the specification limits and enabling the superordinated control to return to the safe operating area. Should even the shutdown limit be exceeded, the MIPAQ™ Pro shuts down operation, it blocks the PWM signals, and thereby avoids destruction. This feature is especially useful during the design-in phase when the inverter's operation limits are still being explored. During operation in the field on offshore wind farms where service is extraordinary costly, a shutdown prior to destruction is mandatory.

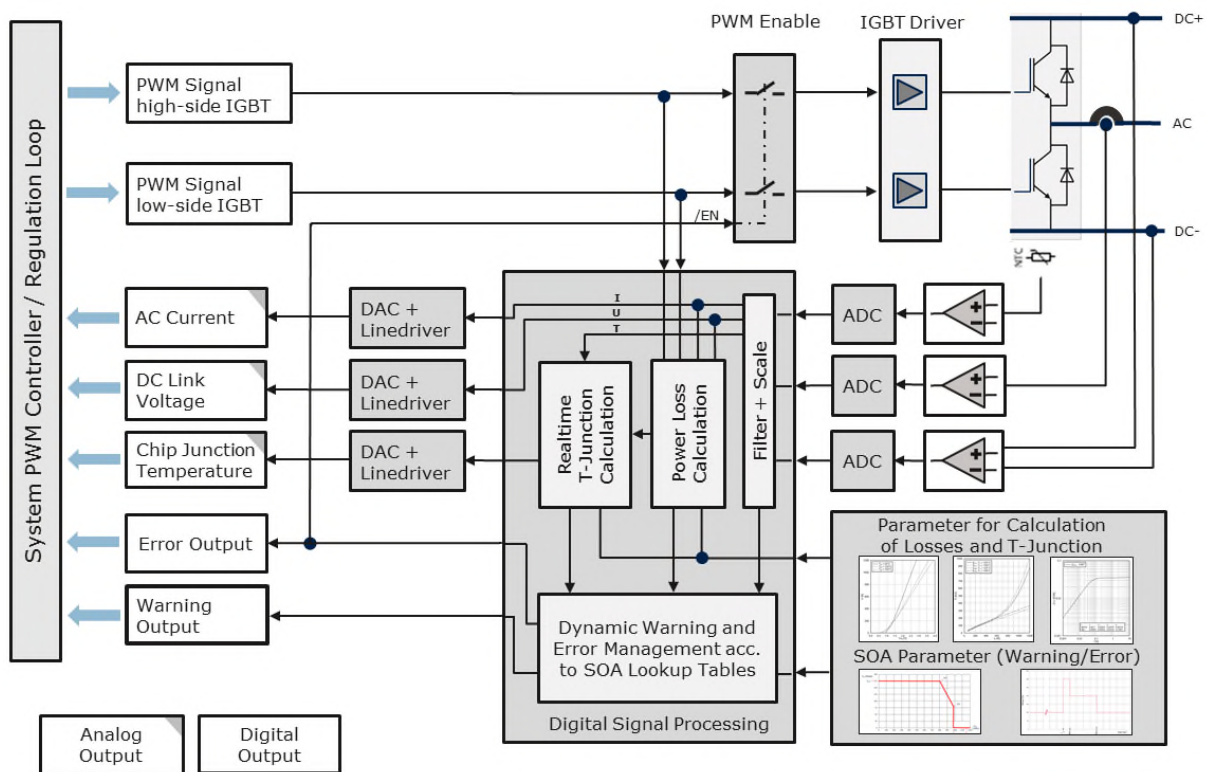


Fig. 3. Improved Warning and Error handling of a Power Stage using digital signal processing.

The warning and shutdown levels can be adjusted by the customer to keep the degree of freedom to adapt the system to individual requirements.

The overall warning and error handling is depicted in Fig. 3. Besides this general smart protection scheme, a number of additional protection measures were taken care of.

An advanced overvoltage protection was implemented with a low-tolerance static limit enabling high DC-link voltages and a dynamic feedback loop to the gate for a fast limitation of overvoltages and protection from overvoltage destruction during commutation at IGBT turn off. The working principle is shown in a measurement in Fig. 4 for the case of dynamic protection. The bias to the gate slows down the switching process, limiting the overvoltage to safe values. This type of protection is especially important for low junction temperatures and low currents, e.g. during start-up, where IGBT switching is naturally faster and where additional switching losses are acceptable. For operating conditions at the upper limits of

current and temperature, the advanced overvoltage protection is not active so that the maximum output power is not affected.

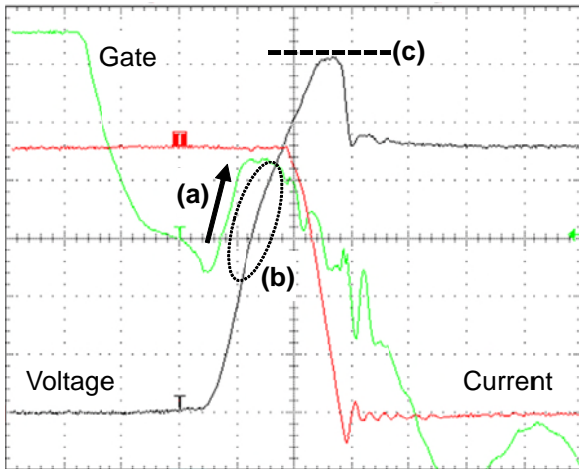


Fig. 4. Advanced overvoltage protection demonstrating (a) the feedback impact to the gate, (b) reduction of switching speed du/dt and (c) the limitation of the overvoltage peak.

Special care was put into the timing of the protection functions. The built-in current sensor provides a rise time of $<2.5 \mu\text{s}$ and the current sensing and evaluation chain is fast enough to shut down in overcurrent conditions. Additionally, IGBT desaturation monitoring is implemented for shutting down in short-circuit conditions and the MIPAQ™ Pro is capable of sustaining a short circuit duration of $10\mu\text{s}$. The shutdown of over- and short-circuit currents is done by a soft shutdown procedure taking care of overvoltage protection during these exceptional cases. Furthermore, the soft shutdown can be activated by the customer's controller for operation close to the DC-link voltage limit.

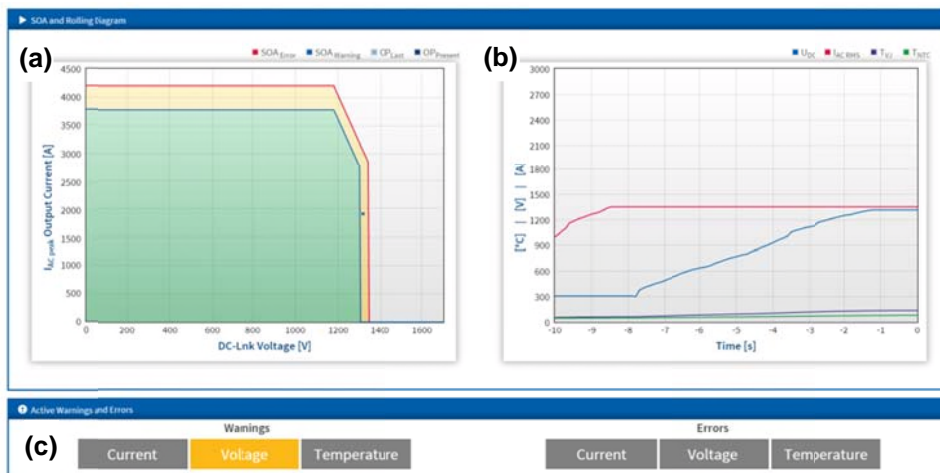


Fig. 5. Demonstration of read-outs from the MIPAQ™ Pro

The T_{vj} calculation supervision allows operation up to and including junction temperatures of the nominally chip rating of 150°C . For enabling this, the warning limit is slightly below and the shutdown limit is at this value. The T_{vj} calculation itself is performed once per ms, allowing a close observation and fast reaction to temperature rises during overload conditions, e.g. drive start-up or LVRT in wind applications.

A demonstration of the MIPAQ™ Pro read-outs for the example of a warning due to high voltage is shown in Fig. 5: (a) RBSOA diagram with warning- (blue) and shutdown limits (red). The dot shows the actual point of operation, which is chosen to be above the warning limit and below the shutdown limit. The graph in (b) depicts current, voltage and IGBT junction temperature as a function of time. The status bar (c) indicates the warning due to the fact that the voltage exceeded the warning limit.

6. Communication

The MIPAQ™ Pro communication concept is sketched in Fig. 6 demonstrating the example of two paralleled IPMs in a phase leg connected to the system controller. A service and diagnosis box is connected to the last slave IPM. The figure demonstrates that the system controller only needs to connect to the MIPAQ™ Pro acting as master, facilitating the design-in of paralleled MIPAQ™ Pro and eliminating the necessity for a paralleling board.

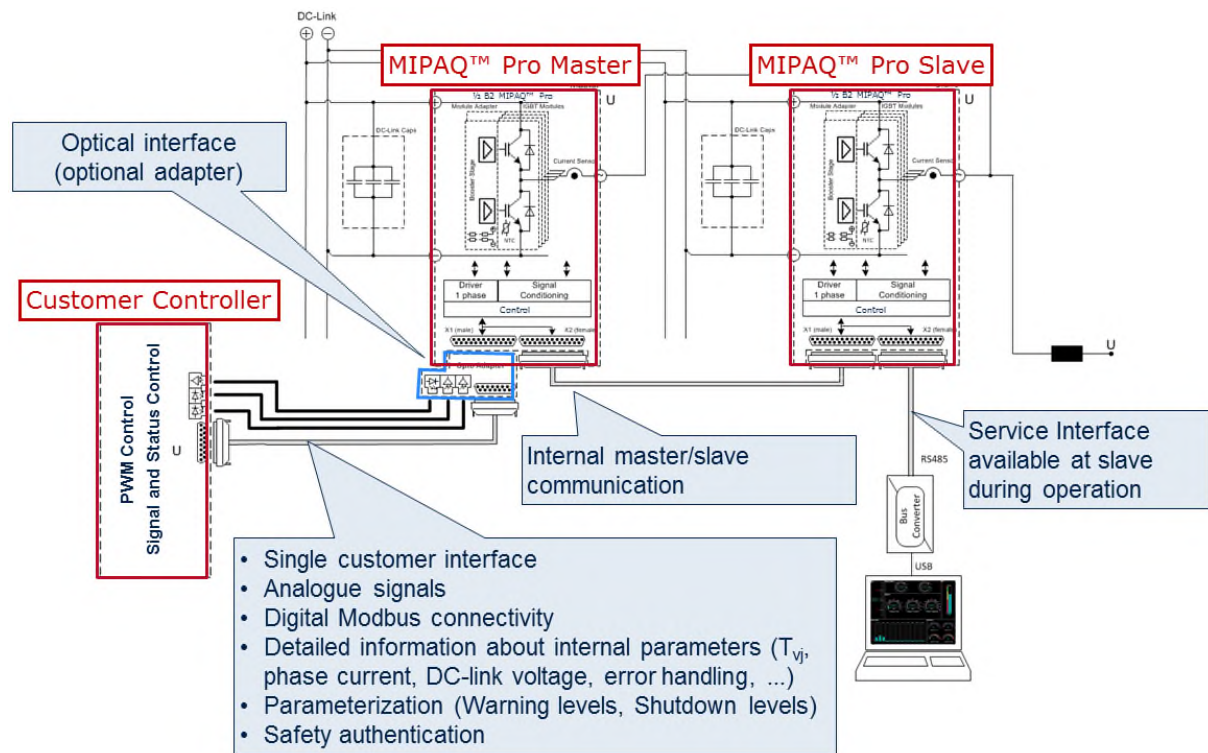


Fig. 6. Communication concept sketched for one phase in a parallelization of 2 MIPAQ™ Pro. The remaining available slave connector can be used to connect a diagnosis box.

As physical master interface to the customer's application, the MIPAQ™ Pro provides a male 25- pole sub-D connector. A 25- pole sub-D female connector is provided as slave interface for a paralleled MIPAQ™ Pro in a daisy chain.

The master connector includes the PWM inputs for high- and low-side power switches, electrical sensor feedback to the customer for voltage, current and temperature as well as electrical error signals for warning and shutdown events.

For access to the digital functions, the master connector additionally includes a RS485 interface with Modbus-RTU protocol. This Modbus interface allows extended digital access to sensor and status information, like average and peak values of AC current, DC-link voltage, NTC- and calculated IGBT junction temperature, more detailed warnings and error information.

For enabling a retroactive analysis of the cause for a shutdown or failure event, the MIPAQ™ Pro logs key operating conditions like current, voltage and IGBT junction temperature and counts exception cases in an included data logger. The data logging is performed on a μs scale for the last 10ms in a ring buffer and the recorded data is frozen upon a failure condition for read-out. Fig. 7 shows a visualization of the data logger content after read-out.

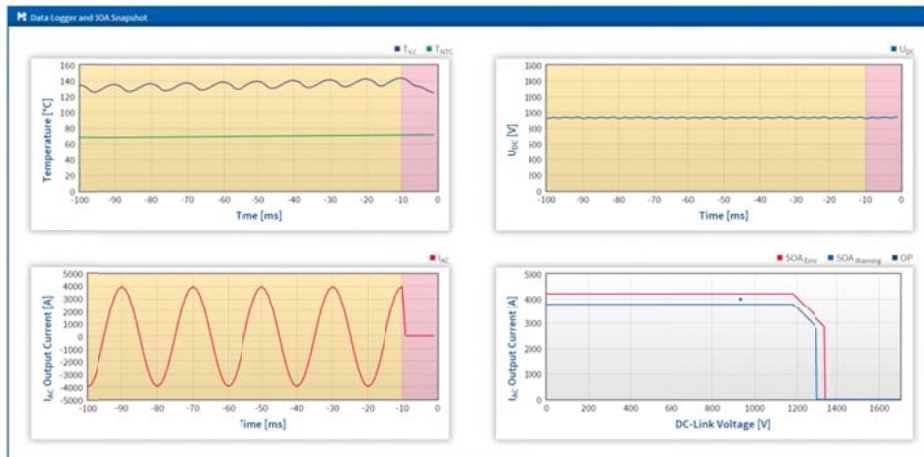


Fig. 7. Visualization of the data logger read-out after an overtemperature condition resulted in a shutdown.

The slave connector can be used as service interface even during operation in order to gain access to the information on operating conditions and the data logger or in order to easily adjust warning and shutdown levels. In a paralleled connection, this option refers to the last slave connector in a paralleled leg which is always available.

7. Application Reflected Design

When defining standard components for a wide range of applications, one of the challenges is to reflect individual requirements from all of these applications with a sensitive balance between efforts for supporting one individual application and corresponding costs which are not utilized by the other applications. For the MIPAQ™ Pro, special care was taken in this discipline.

For wind applications, a common design-limiting end customer requirement is the low-voltage ride-through (LVRT) capability, which typically represents an overcurrent condition for the power conversion equipment in the 20...100ms range. In the MIPAQ™ Pro, this capability is taken care of by the design of the incorporated protection functions. As real-time junction temperature calculation and monitoring is performed at high sampling rate, smart protection against IGBT over-temperature is offered during LVRT.

In solar applications, especially high DC-link voltages can occur during no-load conditions. As a consequence, the overvoltage protection of the high-power IPM is not allowed to be triggered during the high-voltage no-load condition. The MIPAQ™ Pro's advanced overvoltage protection uses a novel approach to provide a robust dynamic overvoltage protection during operation while allowing a low-tolerance – and therefore large - static overvoltage protection level.

Large drives usually require operation modes, in which it must be possible for the equipment operator to shut down the driving torque in a safe way (Safe Torque Off, STO). This condition is described in the standard IEC 61800-5-2 and SIL levels according to IEC 61508 apply, involving redundant shutdown paths and additional sensing paths. These redundancies can require additional external power contactors, which represent a significant contribution to the overall system costs. For such applications, the MIPAQ™ Pro is prepared to support the

STO case by a separate voltage input via the logic connector. In that way, the customer's application can shut down the power supply for the IGBT driver core independently of canceling the PWM signals. At the same time, the digital supervisory electronic remains in operation and allows a confirmation of the shutdown. This concept is designed in accordance with the cited standards and conforms up to SIL level 2, thereby allowing a reduction of the system costs by removing the additional contactor in the load path.

A more commercial aspect addresses protection against copy-cats and securing the post-sale service business for the MIPAQ™ Pro's customer. For the first, special means are employed to prevent copying the MIPAQ™ Pro. The customer's post-sale business can be secured by an integrated security chip from Infineon's family OPTIGA™ Trust, which allows the customer's application to optionally apply state-of-the art authorization techniques. Thus, the customer has the option to verify on the one hand, that the application works with original MIPAQ™ Pro products only and on the other hand that it works with customer-supplied MIPAQ™ Pro only. In this way, an unauthorized exchange of genuine MIPAQ™ Pro can be prevented in the end user application by the customer according to his business model.

8. Summary

The MIPAQ™ Pro demonstrates how the customer's requirements can be realized when increasing power from the kW to the MW regime. For this purpose, an outstanding feature set was defined and implemented, addressing the need for modular power units, fast and simple design-in as well as insight into operating conditions and smart protection.

The approach to use fully tested and qualified high-power IPMs as building blocks for MW applications enables a short time to market for the customer.

Several aspects have been considered supporting a tremendously simplified design-in at the customer. The inverter power level is easily scalable by paralleling without additional cabling efforts in the customer's application due to the master/slave concept. The level of insight into the operating conditions especially focusing on the junction temperature calculation combined with monitoring and smart protection allows the customer to precisely verify the inverter dimensioning while giving feedback in overload situations and avoiding destruction. At the same time, the MIPAQ™ Pro allows to adapt the system to individual requirements by adjustable warning and shutdown levels or by optionally making use of the security functions.

Special support for wind, solar and large drive applications is offered by the design-in of corresponding functionalities into the MIPAQ™ Pro offering cost and effort benefits on system level.

9. References

[1] M. Schulz, S. T. Allen, W. Pohl, „The Crucial Influence of Thermal Interface Material in Power Electronic Design“, Semi-Therm 2013, San Jose (USA), 2013