EVS24
Stavanger, Norway, May 13-16, 2009

Power Electronics Based on SiC and Si/SiC Hybrid Modules

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Abstract

Silicon Carbide (SiC) is considered as being the future semiconductor material for future electronic devices in military and commercial applications. This is due to specific features which provide decisive benefits for their deployment. Highlights are better efficiency, reduced space claim and the chance to significantly increase the level of the cooling temperature. In addition to the higher compactness these specifics might offer the chance to integrate SiC based power electronic systems in regular vehicle cooling systems.

The paper presents an overview on some recent power electronics developments of L-3 Communications Magnet-Motor GmbH (MM) using Si/SiC hybrid and SiC based modules. Focus is on AC propulsion power electronics for supplying MM's permanent magnet motors and generators. This work was executed as part of a project for the German Agency for Defence Technology and Procurement (BWB).

The first device is a power electronics component equipped with Si/SiC hybrid modules which consist of conventional Si IGBT power switches combined with SiC recovery diodes. Its big benefit is the reduced losses at voltage levels considerably higher than for conventional modules. The paper provides an overview on this type and the test results in its combination with an MM permanent magnet motor up to 1000 - 1200 VDC. A different approach of MM is represented by a laboratory prototype equipped with SiC cascode elements. Main focus was on the realization and testing of the cooling strategy that allows input temperature up to 115°C including a decoupled area with intrinsic lower level temperature for the conventional electronic elements inside the device. The electronic design and mechanical arrangement of the device is presented including some test results.

Keywords: SiC propulsion power electronics, high temperature cooling

1 Introduction

L-3 Communications Magnet-Motor GmbH (MM) is a well known supplier of highly compact electric propulsion and energy supply systems in particular for vehicles. This covers prototypes and small series equipment for military vehicles of weight level up to 28 tons as well as for commercial vehicles and passenger cars. An overview of MM's military applications was presented at the AECV 2007 conference [1]. The MM systems include electric motors and generators, power electronics and control and diagnosis elements. A new field of MM products is the Integrated Starter Generators ISG for on-board and external electric power supply that are the basis for Mild Hybrid applications. The systems offer best performance at low weight and volume for best integration into vehicles. Integration also means harmonization of control and cooling interfaces. The latter requirement means the connection of the cooling circuits of the vehicle and the electric systems to a common one on the same temperature level in order to avoid double efforts. This approach is hard to fulfil with today's power electronic components that are equipped with Si based IGBT modules and diodes. This technology is being developed for increasing operating current ability but there are technological constraints and physical limits that prevent significant improvements in terms of increased junction temperature of the chips, higher switching frequencies and higher voltage levels with improved efficiency. Silicon Carbide SiC is considered as being the appropriate way out of these constraints due to some important improvements such as:

- Higher current density → improved compactness
- Increased operating temperature → higher cooling temperature level
- Higher break through voltage → increased voltage level
- Lower static and dynamic losses → improved efficiency.

In view of these features MM has been engaged for years in the development of SiC based propulsion power and DC-to-DC modules. After having successfully proved the principal feasibility of active SiC switches in a basic test arrangement MM has been working in a project on motor/generator inverters for two different approaches. The first one focussing on a motor inverter using Si-based IGBT's and SiC freewheel diodes for increasing the power density of the component and to lower the switching losses. The second one covering an inverter for an electric fan drive using active SiC cascode switches enabling coolant inlet temperature of 115°C. These activities were funded by the German Federal Agency for Defence Technology and Procurement (BWB) within the period of 2004 to 2008.

MM is a well experienced supplier of prototypes of electric drives and energy supply systems for military and commercial vehicles. Typical examples are the South African CVED 8x8 vehicle, which is a full electric hybrid application in the 28 tons class, see Fig. 1 below.

Fig. 1: CVED 8x8 vehicle with electric hybrid propulsion system of MM

The growing demand for more electric power on-board the vehicle and for external supply purposes has led us to the new product line of Integrated Starter Generators ISG systems. This covers in-line generators which are integrated between the combustion engine and the conventional transmission. There are two types realized by MM providing electric power ratings of up to 65 kW @ 2500-4300 rpm (G36) and 75 kW 1900-3000 rpm (G37). For a photograph of the G36 in a demonstration arrangement see Fig.2 below. Both ISG machines are designed to SAE3 flanges and can be adapted to larger SAE2 ones by adapter rings.

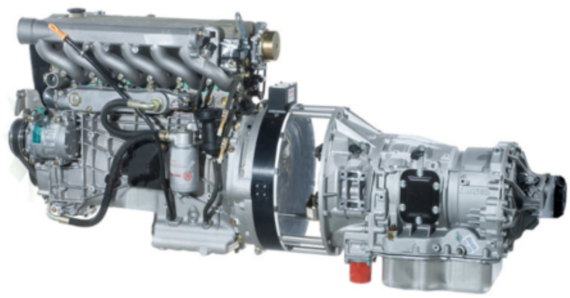

Fig. 2: G36: 65 kW @ 3500-4300rpm

Other ISG system elements are power electronics elements for processing and supplying the different output options. This includes 24 VDC and 12 VDC and AC 1-phase and 3-phase supply at 120/210 VAC and 220/400 VAC.

Fig. 3 shows the MM power electronics type S31 which is a typical MM standard propulsion power electronics equipped with conventional Si-based IGBT technology.

Fig. 3: MM Si-based power electronics S31

The S31 type provides characteristic features as follows:

- Output: 3 phase 130 kW (cont.)
- 550 A / 450 A peak (10 s / 30 s)
- Input: 800 VDC (max)
- Volume: 10.4 dm^3
- Mass: 15.2 kg
- Cooling: water/glycol, 70°C, 12.4 ltrs/min

An overview of MM's electric and electronics devices is presented in another contribution to the AECV 2007 conference, [2]. Detailed information including relevant data sheets can be taken from MM's web-site [3].

The focus of the activities which are described in this paper is the implementation of SiC technology in order to achieve (i) increased DC voltage without increased switching frequency losses in conventional Si technology, (ii) higher power density and (iii) higher level of cooling and ambient temperatures. This includes collecting more experiences on the new SiC modules and solving the challenges of temperatures inside the inverter beyond 100°C.

2 Design, realization and system integration of a Si/SiC hybrid based power inverter S42/0

As a basis for this new inverter type called S42/0 MM selected the existing propulsion power electronics type S31 which is shown in Fig. 3. It is originally equipped with conventional Si IGBT modules in SEMIX4 case and operates at DC link voltage of 750 VDC. We used the chance to get SiC Schottky free wheel diodes integrated into the SEMIX3 Trench IGBT modules, i.e. adapted from SEMIX4 to smaller SEMIX3 modules. Supplier was SiCED of Germany.

The expectation was:

- to significantly reduce the losses at high switching frequencies and
- to increase the level of the DC link voltage up to 1200 VDC.

2.1 Overall design of the Si/SiC hybrid inverter S42/0

The internal arrangement of the inverter is shown in Fig. 4.

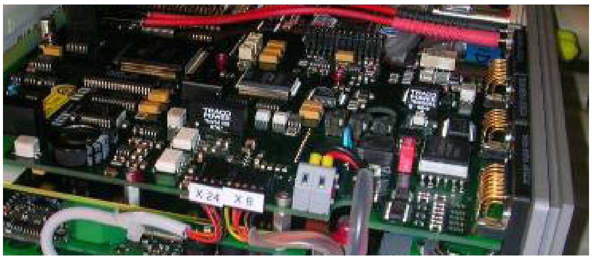

Fig. 4: Internal arrangement Si/SiC based inverter

The IGBT Si/SiC hybrid modules are directly attached to the coolant plate at the bottom part of the device. The IGBT drivers that have been adapted to the higher DC link of 1200 VDC are located directly above the modules. The control cards are arranged in the upper section of the inverter. The cooled plate is equipped with cooling fins to ensure internal air/water heat exchange for such elements which need air cooling.

The high current distribution is realized with multi layers that are electrically insulated by multi film insulation material according to the higher DC level. The inverter has been defined to be insulation tested at a peak voltage of 3.4 kVAC for 1 min according to DIN ED 1987-3-7-2000, the standard ISO 6469-3-11-2001 did not yet apply.

2.2 Laboratory tests at passive load, comparison of Si standard module versus Si/SiC hybrid module

The first campaign of measurements to the inverter was dedicated for evaluating the basic switching characteristics and for respective comparisons between the standard Si and Si/SiC hybrid module. This covered e.g. measurements of phase peak current related to operating/switching frequency and the interdependence of inner module temperature on phase current and operating/ switching frequency at passive load. The results are given in the diagrams in Fig. 5a (Si module) and 5b (Si/SiC hybrid module). Measurements were executed at DC link voltage 1200 VDC and coolant flow of 14 ltrs/min for both modules mounted at the same cooling plate.

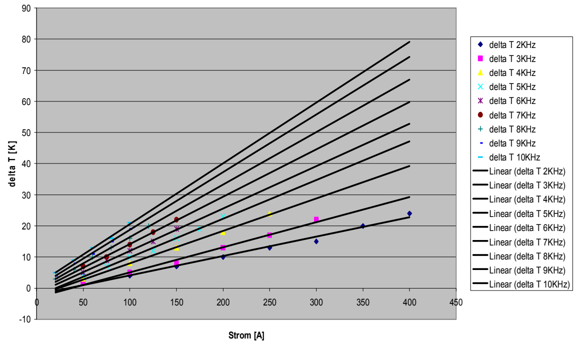

Fig. 5a: Standard Si module: DeltaT (module-coolant) in K versus current (Strom) in A with operation frequency as a parameter

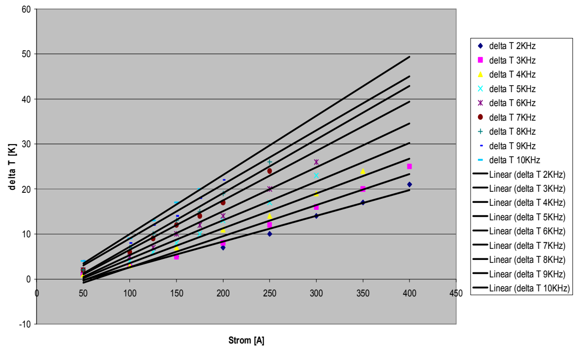

Fig. 5b: Si/SiC hybrid module: DeltaT (module-coolant) in K versus current (Strom) in A with operation frequency as a parameter

The results provide a clear view to the advantage of the Si/SiC hybrid module: At higher operating frequencies the temperature increase of the hybrid module is significant lower - up to 50% - compared to the standard Si module. Based on the linear relation of switching losses to temperature increase this means that the switching losses of the Si/SiC hybrid module are going down to approximately half of the Si standard module. The Si/SiC technology enabled to achieve a current plus of approximately 100 A at a discrete frequency.

2.3 System integration of inverter S42/0 with electric propulsion motor

For appropriate system testing of the Si/SiC hybrid inverter the MM test motor type M69 had to be adapted to the increased voltage level. Insulation of coils and inner electric connections has been improved to withstand the required peak testing voltage of 3.4 kVAC.

The test stand set-up consists of two MM machines type M69 that operate in back-to-back operation, i.e. connected via a mechanical shaft. The right machine is connected with the Si/SiC based power electronics S42/0 and operates in motor mode, the left one works in generator mode and is supplied by a S42/0 equipped with standard Si modules. Mechanical power transfer is from the right to the left side, electrical power transfer is in the opposite direction. The DC power input covers the losses.

Fig. 6 provides the block diagram of the test stand set-up.

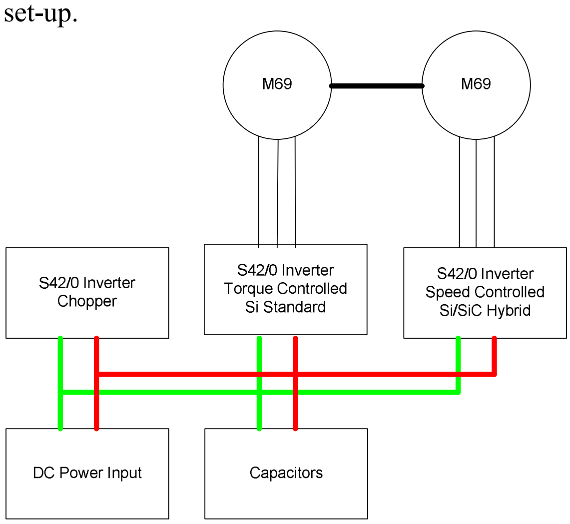

Fig. 6: Block diagram of test set-up of two MM motors M69 and three S42 inverters (Si and Si/SiC based)

Fig. 7 below shows the hardware equipment of the inverters in the test stand environment with the electric machines.

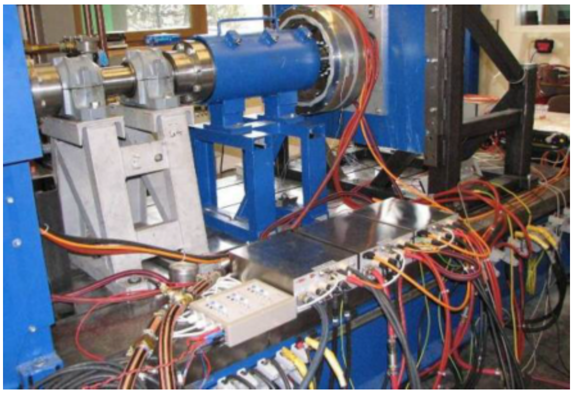

Fig. 7: Test stand set-up of two MM motors M69 and three S42 inverters (Si and Si/SiC based)

The test runs included power transfer up to approx. 120 kW at voltage level up to 1000 VDC (limit given by the specification of the test stand). The hybrid module has higher power conversion that is due to its motor operation. This is shown in the measuring record of Fig. 8 in comparison to the Si based module that runs in generator mode.

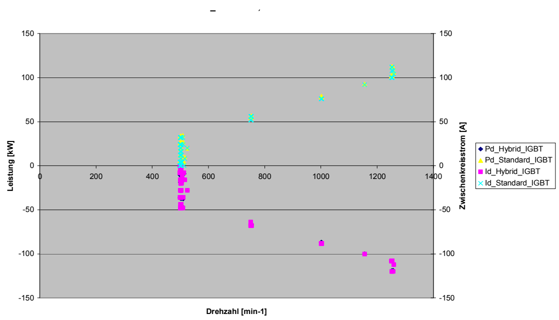

Fig. 8: Power (Leistung) and DC current (Zwischen-kreisstrom) versus speed (Drehzahl) of hybrid versus standard module

The most significant result of the tests is the considerably reduced temperature difference of the hybrid module compared to the standard one. Fig. 9 presents the relevant results of the hybrid and the standard module at 1000 VDC and operating frequency of 4 kHz.

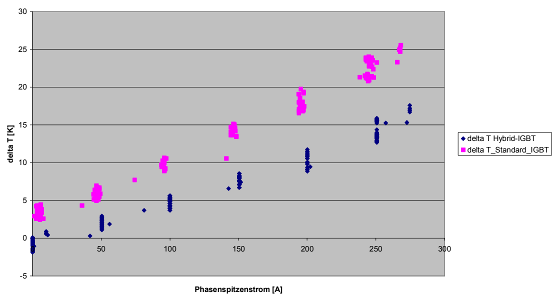

Fig. 9: DeltaT versus phase peak current of hybrid versus standard module

The temperature difference is directly proportional to the produced losses, so the results clearly confirm approximately 60% the losses of the Si/SiC module compared to the standard Si module.

3 Design and realization of the system integration of a SiC based inverter (type name S41) with liquid cooling 115°C

The list of requirements of this inverter includes the realization of a full SiC equipped inverter operating at a maximum inlet temperature level of the liquid coolant of up to 115°C.

The most important tasks covered:

- Define and integrate the SiC switches into the system environment of an inverter
- Realize and manage the high temperature cooling level of the SiC modules and lower level required by the standard Si elements used for controls and drivers.

3.1 Inverter design

Work on the inverter design started in 2004/2005 and so MM was tasked to make a down-select of the SiC components which were available that time. Nevertheless MM was able to switch over to improved elements that became available in the later course of the development.

3.1.1 Electronic architecture and modification of control

MM executed pre-studies that were focused on learning the basic features of SiC elements. Measurements covered the switching and conducting characteristics of single SiC cascode elements as well as some basic tests in an arrangement of some switches.

The JFET SiC has "normally-on" operation. In order to achieve the "normally-off" switching behaviour of an N-MOSFET or IGBT module the JFET element has been combined with a low voltage Si-MOSFET to a cascode switch. This configuration is shown in the block diagram in Fig. 10 below.

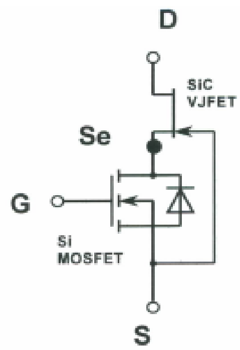

Fig. 10: Block diagram SiC cascode arrangement

Fig. 11 presents the results of loss measurements to the SiC cascode elements in an H-bridge arrangement. Candidate for this measurement campaign was the SiC cascode type 1000 V of a continuous drain current 3.5 A supplied by SiCED GmbH.

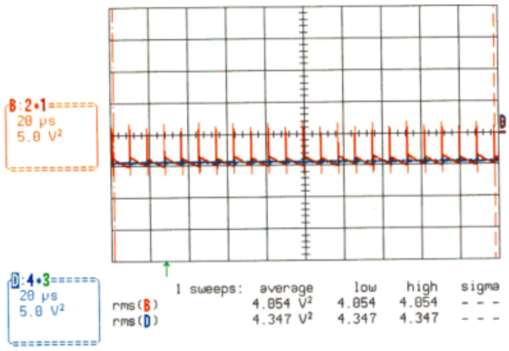

Fig. 11: Loss measurements to SiC cascode switches in H-bridge design (curve D: power input, curve B: power output)

Result of the measurements:

- Input power: P_{in} = 434 W
- Output power: P_{out}= 405 W
- Power losses: P_{loss} = 29 W.

As a consequence of the lessons learnt from the pre-studies and based on the availability of the modules MM started the electronic system architecture with the SiC Cascode switches IXYS ISPPAC i4-PAC provided by SiCED.

Key data of this JFET type are as follows:

- Cont. Drain Current: I_D = 4 A @ T_C = 25°C
- Pulsed Drain Current I_{OL} = 9A @ T_C = 25°C
- Max. Drain-Source Voltage V_{DS} > 1500 V
- Max. Gate-Source Voltage V_{GS} < 20 V
- Drain-Source Res. $R_{DC(on)}$ = 0.39…0.48 Ω
- Junction Temperature T_{jmax} = 150°C
- Thermal Resistance $R_{th\ j\text{-}c}$ = 2.2 K/W
- Packaging: ISOPLUS i4-pac.

In parallel to the running inverter activities JFET samples with improved higher current ability (19 A continuous) became available. The same mechanical interfaces enabled the introduction of the new type and the utilization of the experiences from the smaller type.

Key data of this improved JFET type:

- Arrangement: 3 chips in one module
- Continuous Drain Current:
  I_D = 19 A @ T_C = 25°C
  I_D = 15 A @ T_C = 85°C
  I_D = 11 A @ T_C = 125°C
- Drain-Source Res. $R_{DC(on)}$ = 0.25 Ω
- Junction Temperature T_{jmax} = 175°C
- Thermal Resistance $R_{th\ j\text{-}c}$ = (3x1.8) K/W
- Includes Si-MOSFET SPD25N06S2-40.

The power section of the inverter is arranged in 3-phase B6 design. Several additional features have been implemented in order to protect the SiC modules from over-temperature (by measurement closest to the module including calculation of the chip temperature), from over-current (by control of the drain-source voltage drop) and from over-voltage (by active clampling).

3.1.2 Cooling design and architecture

The major focus of this inverter was on the specific cooling method to be realized and managed inside the device. The conventional cooling design of MM inverters follows the concept of a central plate which is internally water cooled and which is the base plate for mounting all heat producing elements. Other elements that cannot be fixed on this cooled plate are cooled by internal air flow dissipating the thermal power to an internal air-water heat exchanger. In order to meet the high overall temperature requirement of T > 100°C of the new SiC inverter it was necessary to significantly modify the internal arrangement of the power electronics.

Two challenges exist for operating the inverter at such level of temperatures:

- Pressure resistant design of the coolant circuit
- Thermal separation of the SiC modules which can operate at T > 105°C from the lower level (T =< 80°C) conventional Si based modules used in control boards, drivers, voltage control devices, opto couplers etc).

The internal cooling of the inverter makes use of Peltier elements as electrical coolers. They transfer thermal energy from lower to higher temperature levels. The cooler part of the Peltier element is thermally connected to an internal air heat exchanger for dissipating the losses produced by the conventional Si elements at lower temperature levels. Fig. 12 shows a test set-up of the Peltier element used in the SiC inverter S41.

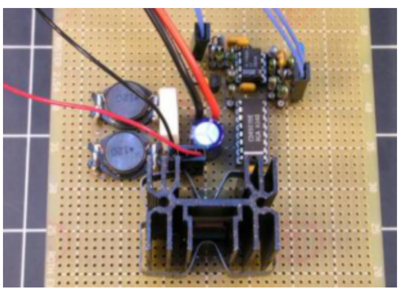

Fig. 12: Test set-up of Peltier element in inverter S41

The hot end of the Peltier elements that reaches temperatures up to 150°C is fixed at the cooling plate of the SiC elements for transfer of thermal energy into the coolant.

There is thermal insulation between the two thermal sections. As a result the air temperature in the Si area was below 80°C.

The photograph in Fig. 13 shows the internal set-up of the inverter S41 in fold back view. The power elements are arranged on the copper cooling plate. The boards above the power part are the drivers and the control unit. The black part underneath the power part is the internal air cooler that is connected to the cooled plate via the Peltier elements.

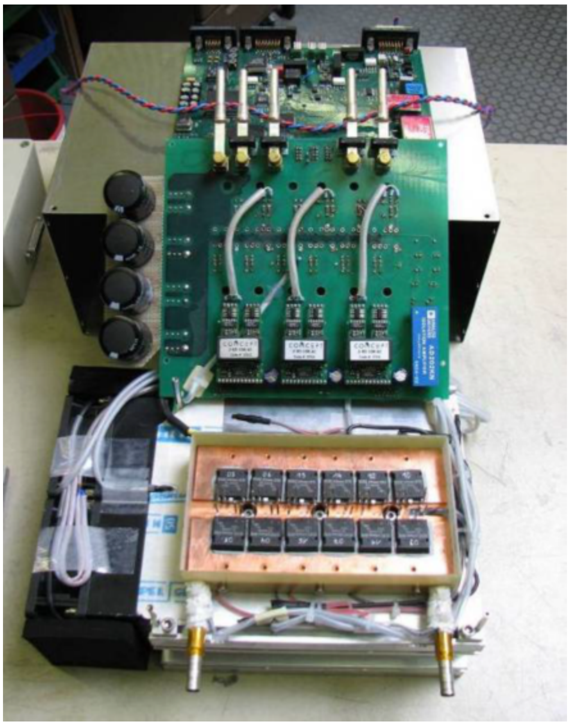

Fig. 13: Internal set-up of inverter S41

The tests covered measurements of the thermal stability of the S41 device at operation conditions of current loads up to 10 A_{eff} at water inlet temperatures up to 115°C.

The measurements have been conducted with an ohmic-inductive load and using a two stage cooling system, see the block diagram of the test set-up shown in Fig. 14.

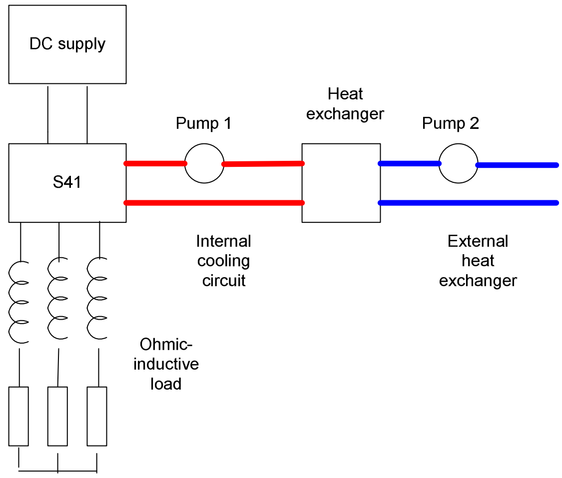

Fig. 14: Test set-up of inverter S41

The results achieved in the measurement campaign were quite promising, see the graphs in Fig. 15 below. It shows the temperature characteristics of the Si area for water inlet temperature levels 100°C and 115°C with the power part operating at DC link voltage 750 VDC and a continuous phase current of 10 A. Even at the highest coolant inlet temperature the area of Si based elements keeps at a maximum of approx. 80°C.

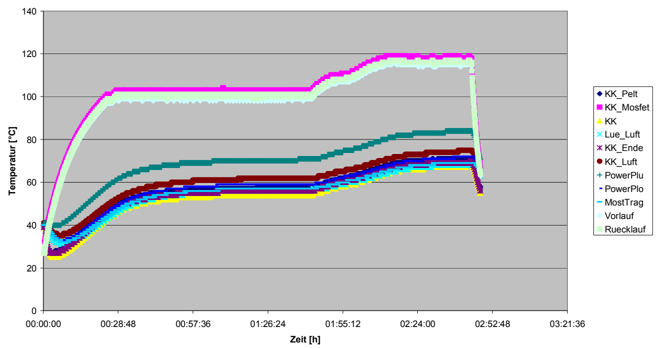

Fig. 15: Temperature shapes of inverter S41 at 750VDC and continuous phase current 10A

References

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