Green PE
WP3: ADVANCED POWER ELECTRONICS FOR E-MOBILITY
TECHNICAL REPORT

Interreg
Baltic Sea Region

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1. Introduction

One of the main goals of the Green Power Electronics (Green PE) project was to demonstrate potentials, feasibility and relevance of advanced power electronics (PE) in the application fields of renewable energies, e-mobility and smart houses.

This technical report presents the activities and results that demonstrate new solutions for applications of advanced power electronics within the e-mobility sector.

Two pilot demonstrator products have been designed, fabricated and tested:

- Pilot demonstrator B1: A SiC-based battery conditioner in Denmark
- Pilot demonstrator B2: A SiC-based inverter for racing cars in Latvia

These products address different applications of PE in e-mobility, in terms of functional and technical parameters.

Context, purpose and target group

E-mobility assumes environmentally clean and energy efficient transport that uses electrically powered vehicles. According to the recent European White Paper on transport, the major goal of transition to E-mobility is reduction of the conventionally-fuelled urban transport by halve in 2030 and ruling it out of cities by 2050. This requires radically new vehicle electronics with power train integrating components based on wide bandgap (WBG) semiconductors, such as Silicon Carbide (SiC) and Gallium Nitride (GaN). Therefore, the focus of the pilot has been on implementation of these devices in the e-mobility applications.

The major objectives of the technical implementation of the pilot included the demonstration of advantages of the advanced power electronics (PE) components based on wide bandgap semiconductors, within the e-mobility applications. It also presents the potentials for positive impact of the advanced PE on the e-mobility sector in Baltic Sea Region (BSR). This technical report also provides the technical data for the dissemination actions within the Green PE project.

The pilots' target group includes industrial companies, especially SMEs, research centres and technology transfer organisations working within the areas of power electronics manufacturing and applications. This technical report will contribute to increase the capacity of SMEs and stakeholders to take competent decisions concerning uptake and implementation of the advanced PE components.

Main research objectives and results

The main research objectives included:

- Selection and evaluation of PE products, for which utilization of the advanced components would be specifically beneficial.
- Specification, design and fabrication of the demonstration units for the selected products.
- Tests of the demonstrator units and measurements of their major technical parameters.

Two types products of PE products have been selected due to their key importance in the e-mobility applications. They include a battery conditioner with capability of being used in a broad range of e-mobility applications (pilot demonstrator B1) and a motor drive designed for electrically driven racing cars (pilot demonstrator B2).

The first and highly positive result of the pilot is that the development and prototyping of products based on new SiC components can be done within relatively short period of time (around one year). This is especially important for SMEs which have very scarce resources to run product development programs.

Computer simulations and tests of the demonstrator units clearly showed that the modification of both products with the SiC components resulted in improvement of a range of important product characteristics, including an increase in the switching frequency and energy efficiency, improved PWM control, a more compact design and an increased power density.

The implementation of the pilot has also demonstrated that the world market for advanced PE components is very dynamic, and therefore, the product development programs at SMEs should always consider possible impact of appearance of even more advanced components.

2. Pilot B1: A SiC-based battery conditioner in Denmark

2.1. Technical resume

The pilot demonstrator has been aimed at developing and manufacturing a demonstrator unit for a grid-connected battery conditioner with capability of utilization in a broad range of mobile applications. The bidirectional feature of the unit allows for both charging and discharging high voltage Li-Ion and LiFePO batteries with minimized energy losses. This enables energy efficient conditioning of the batteries during daily charging, battery stack manufacturing, and – potentially – also for future grid support in smart grid installations.

To provide a high conversion efficiency, the unit is designed so that it does not include galvanic isolation and uses SiC power modules configured as a 2-level switching, 4-quadrant active rectifier, with the batteries connected across the DC-link. An electronic circuit for control of grid and battery inrush currents during connection and disconnection is included.

United SiC's UJ3C and UF3C silicon carbide FETs were used. They are based on a unique cascode configuration and high performance G3 SiC fast JFETs co-packaged with a cascode optimized MOSFET, which are the only standard gate drive SiC devices on the market today. The high switching speed, the fast body diode, high temperature operation, low RDS(ON) and ruggedness of SiC FETs (cascodes) make them an excellent solution for all switching circuit topologies.

Two generations of these modules have been tested, and already the first generation has demonstrated that the switching frequency can be increased, without sacrificing efficiency, which leads to a more compact design, thus increasing the power density of the unit. Also, the SiC devices showed significantly more symmetric switching times, compared to silicon IGBTs. For the SiC devices, the ratio of turn-on/turn-off delays is roughly 1:1, whereas for Si based IGBT's this can go as high as 1:3. This provided smaller dead time in the PWM control signals. As a result, the distortions originating from the dead time non-linearities were reduced significantly.

It was very important to check out the performance improvements related to the new SiC modules released in Q2 2018. Computer modelling has given about 50 % reduction in both switching and conduction losses by changing from the 1st to 2nd generation of 1200V SiC modules. In practice, somewhat smaller improvement values (due to EMI issues, voltage ringing, etc.) had been expected, and in the prototype/demonstrator version, 25 % to 30 % reduction in total losses was achieved. Compared to the Si- based solutions, this is of an order magnitude better, as the typical losses when using Si components would be more than double that has been achieved with SiC in this design.

2.2. Technical aspects

A full technical description of the battery conditioner and the product test results are presented in a further document (Appendix 1). Here the major aspects are addressed.

An off-the-shelf grid inverter from GridCo GCO-15 Grid Inverter, 15kW was used in its standard configuration only slightly modified to contain the DC/DC converter power stage and control PCB. Two fully working prototypes have been fabricated.

It has been proven, that with the use of wideband power switches, combined with a high switching frequency, a highly efficient, power dense and easily produced DC/DC converter can be realized. Due to the high efficiency, the addition of an extra conversion step has only a small impact on the overall system efficiency.

The modified grid inverter is unchanged in its physical dimensions, however some mechanical changes in brackets, standoffs and internal cabling have been necessary.

The DC/DC converter serves as an interface between the fixed DC-link voltage to almost any voltage up to 750VDC and expands significant the feasible user applications of the original grid inverter.

At the time that the converter assembly took place, a substitute of the initially planned SiC JFET from United Silicon had to be fund. This caused the maximum current capability to be lowered from the originally target of 30A to 20-25A DC.

Despite from that, efficiency and power values of reasonable levels were achieved.

2.2.1. DC/DC converter design and related results

The DC/DC converter serves as a voltage expansion interface, between the grid inverters fixed DC-link voltage to virtually any voltage from 0 up to 750VDC.

The converter is realized by means of a double boost/buck converter operating at high frequency (96kHz) to reduce the size and cost of the magnetics components. It is therefore essential for achieving a high inverter efficiency to use wideband switching devices with low RDSon and small internal capacitances to obtain low conduction and switching losses.

The power transistors are decided to be in the well-known package T0247 for easy mechanical implementation on a heat sink that fits into the existing cooling concept in the GridCo inverter (forced air ventilated cabinet, intake from bottom).

The major aspects that have been innovative for Converdan and are an important outcome of this pilot demonstrator include:

- Gate Drive with high Common-Mode Transient Immunity (CMTI), low delay time and signal distortion
- Low inductance, high current PCB layout
- Temperature management with high dielectric withstand and low thermal resistance to fit in existing cabinet
- Operating wideband switching devices from United Silicon Carbide (G3 SiC JFETs with a cascode optimized MOSFET)

2.2.2. Control PCB and firmware and related results

The control of the DC/DC converter is maintained with a standard DSP control PCB CVD item number 520045 PCBA GCO-CTRL.

A model of the DC/DC converter has been built in PLECS. The control algorithms and state machines has been simulated to avoid unexpected discoveries late in the project plan. Focus has been on soft start, current regulation and supervisor trip functions.

To save firmware developing time, the DC/DC converter FW is based on the reuse of the GridCo HW driver layer and function code. However, reuse has been to some extent a source of unforeseen malfunction. Regulation and state machine are new outcomes of this pilot demonstrator.

Figure 1: DC/DC board with the SiC MOFETS
Source: Converdan A/S

2.2.3. Test results

A summary of the test results is presented in the extended Converdan technical report (Appendix 1 of this document).

Conclusions

1) The product designed, fabricated and tested within pilot project B1 has demonstrated relevance, advantages and feasibility of utilization of wide-band-gap semiconductor devices in e-mobility applications.
2) It has been proven that modification of the existing inverter designs by using SiC components results in improvements of a range of important product characteristics, including an increase in the switching frequency and energy efficiency, improved PWM control, a more compact design and an increased power density. It is shown that the total energy losses could be reduced by more than 25 % with a new generation of advanced SiC components. And this reduction is about an order of magnitude larger as compared to the typical losses in the product design based on Si components.
3) The important outcome of this demonstrator-project resides within the technical details and experience of utilization of advanced SiC components in battery conditioners. This provides a technical basis for dissemination materials and activities directed towards the target groups of the Green PE project.

3. A SiC-based inverter for racing cars in Latvia

3.1. Technical resume

The pilot demonstrates that adoption of wide band gap semiconductors in electric motor drive inverter improves the overall system efficiency as compared to a traditional silicon-based power electronics solution. The efficiency gains are particularly important in high performance vehicle applications where the system output is pushed to the limits. A purpose built all-electric racing car which produces in excess of 1 MW output power was chosen as a demonstration platform (*Figure 2*).

Figure 2: All-electric racing car eO PP100. *Source: Drive eO*

The electric drive train package of this racing car comprises of a total number of seven permanent magnet synchronous three-phase electric machines which provide traction to all four wheels. An inverter (input operating voltage ≤800 V_{dc}, peak output phase current ≤450 A_{rms}) is used for each electric machine. A field-oriented control algorithm is implemented. The motor drive units are all connected on a common controller area network.

A single inverter unit from this racing car was used as basis for an experimental study. Its original Si-based power electronics module was replaced with a SiC hybrid module available as an engineering sample from the supplier Semikron. The appropriate hardware and software modifications were implemented to operate the new module.

Back-to-back comparison was performed on an electric motor dynamometer at steady state conditions (motor angular speed 2000 rpm, inverter output phase current 200 A_{rms}, inverter switch temperature change dT/dt = 0, motor stator temperature change dT/dt = 0). An increase in inverter efficiency from 92% to 96% was measured due to much lower switching losses in case of the SiC hybrid module. The observations were backed up by a double pulse test on the power modules which showed virtually no reverse recovery for the SiC diodes.

These gains allow downsizing the energy storage system and the inverter liquid cooling system on the racing car, both of which enhance the outright vehicle performance and its competitiveness.

The efficiency gains offered by SiC-based power electronics are in fact highly relevant to any mobile vehicle application as they provide means for increasing the vehicle range and reducing the battery charge time for a set drive cycle.

3.2. Technical aspects

3.2.1. Test hardware

Three phase electric motor inverter eO A0850 (input voltage ≤800 V_{DC}, output current ≤450 A_{rms}), principal components (*Figure 3*):

(1) power module;
(2) power module liquid cold plate (50:50 water and glycol mix circulation);
(3) power module gate driver printed circuit board;
(4) microcontroller ARM ® Cortex ® Infineon XMC4700 printed circuit board;
(5) DC capacitor bank 480 µF;
(6) current sensors ±600 A.

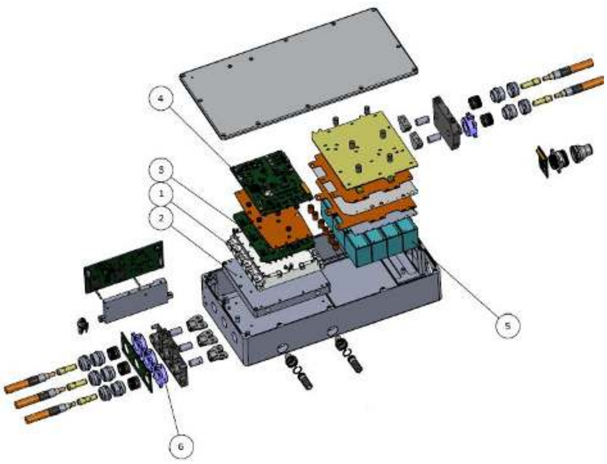

Figure 3: Principal components of eO A0850 inverter. Source: Drive eO

Two different power modules (*Figure 4*) were installed in the inverter and compared:

(a) module with Si diodes, Semikron part number SKiM459GD12E4;
(b) hybrid module with SiC diodes, Semikron part number SKiM459GD12F4V4.

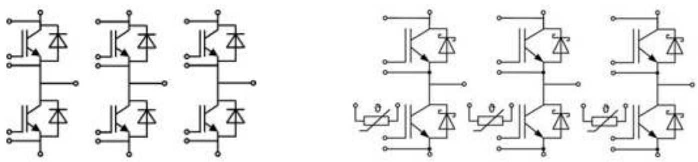

Figure 4: Power modules with Si diodes (left) and SiC diodes (right). Source: Semikron

Experimental measurements were performed using a Tektronix MSO3000 series oscilloscope and an electric motor dynamometric test bench (*Figure 5*) fitted with:

(1) electromagnetic brake;
(2) permanent magnet synchronous electric motor YASA-400 (nominal output power 80 kW, peak output power 160 kW at 700 V_{dc});
(3) test inverter;
(4) liquid cooling system;
(5) power analyser HIOKI-3194;
(6) analogue signal converter L-Card E-502 and data logging software PowerGraph.

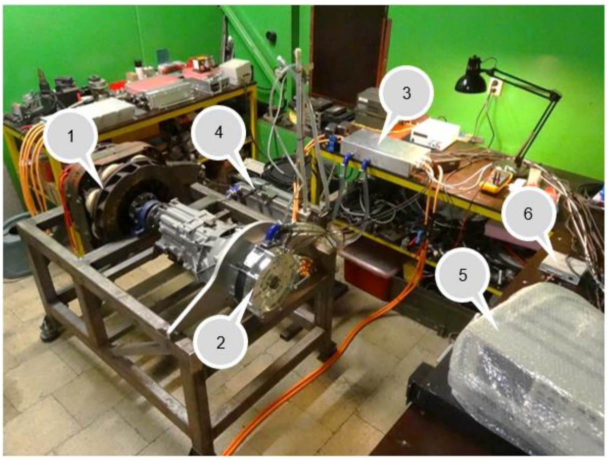

Figure 5: Dynamometric electric motor test bench. Source: Drive eO

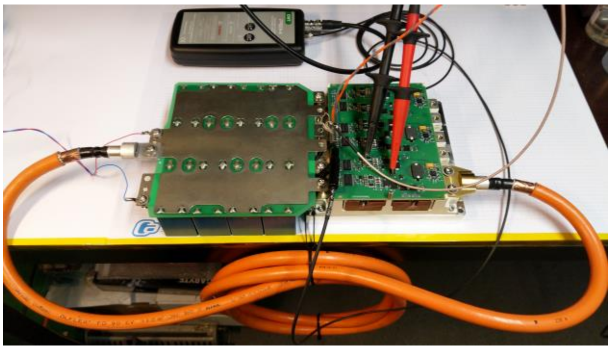

Figure 6: Double pulse test setup. Source: Drive eO

3.2.2. Test results

Measurements of switching time and energy dissipation of power modules were performed with a double pulse test connected to an inductive load in a test circuit (Figure 6) according to *Semikron AN 1403 "Determining switching losses of SEMIKRON IGBT modules"*.

The most significant difference in dynamic characteristics between the two power modules observed during testing was the *negligible reverse recovery* for SiC diodes as compared to Si diodes (*Figure 7*). It means that the overall switching efficiency in the future might be considerably improved if SiC diodes are used. Furthermore, the switching frequency can be increased if required for the motor control.

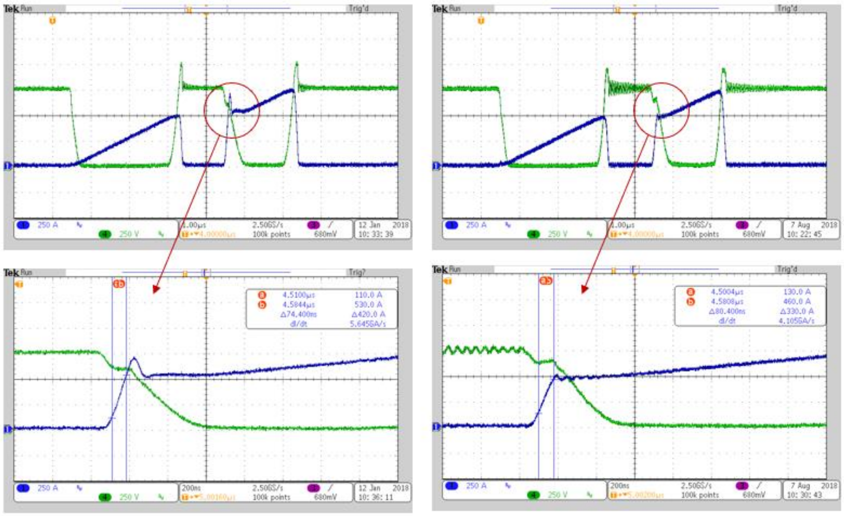

Figure 7: Double pulse test of Si module (left) and SiC module (right).
Source: Drive eO and Green PE project

The efficiency of the inverter was measured at electric motor angular speed 2000 RPM (using motor controller in speed control mode) and inverter output current 200 A_{rms} (set by the electromagnetic brake load).

Experimental measurements were taken at three points in the system (*Figure 8*):

(1) inverter DC input;
(2) inverter AC output;
(3) electric motor output shaft.

Measurements were recorded when the system reached steady-state operation, i.e. inverter power module switch temperature change dT/dt = 0 and electric motor stator winding temperature change dT/dt = 0.

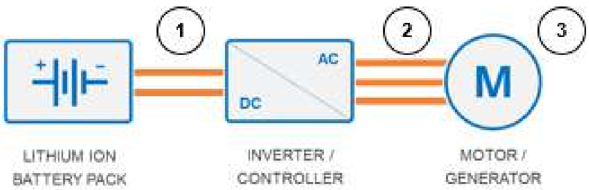

Figure 8: Points of experimental measurements in the system. Source: Green PE project

The results presented in *Table 1* show considerable gains in inverter performance when using SiC power module: efficiency increases from 92.2 % (Si) to 95.6 % (SiC) and power module switch temperature reduces from 48 °C (Si) to 44 °C (SiC).

An attempt was made to readily increase the switching frequency from 10 kHz to 15 kHz, however no meaningful change in system efficiency was observed. A comprehensive implementation and further study of high frequency operation was beyond the scope of this pilot demonstrator.

Table 1				
Parameter	Unit	Si 10kHz	SiC 10kHz	SiC 15kHz
(1) DC input				
DC bus voltage	[Vdc]	660	665	656
DC current	[Adc]	76.6	72.0	73.9
Input power	[kW]	48.6	47.5	48.2
(2) AC output				
Phase voltage	[Vrms]	175	174	176
Phase current	[Arms]	203	203	200
Output power	[kW]	45.0	45.6	45.0
(3) Motor output				
Mechanical torque	[Nm]	189	189	188
Angular speed	[rpm]	1986	1998	2009
Mechanical power	[kW]	39.5	40.3	39.6
Inverter efficiency (1-2)	[%]	92.2	95.6	95.0
Motor efficiency (2-3)	[%]	88.5	88.4	88.8
Total efficiency (1-3)	[%]	81.7	84.6	84.4
Steady state operating temperatures				
Inverter switch	[C]	48	44	44
Motor stator winding	[C]	57	57	57

Table 1: Measurement results Source: Drive eO, Green PE project

The efficiency gains demonstrated within this pilot demonstrator can be directly applied to optimize the electric powertrain at vehicle level, for example, reduce the size and power output capability of the energy storage system and/or heat exchanger unit of the motor controller liquid cooling system (*Figure 9*). These modifications would enhance the vehicle's outright performance through reduction in its inertial mass and aerodynamic resistance.

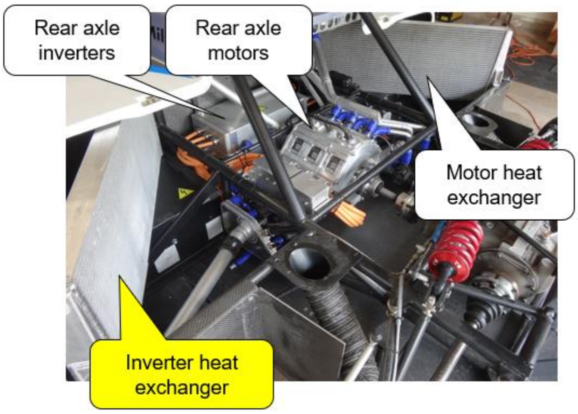

Figure 9: Rear axle drive train assembly of eO PP100 racing car. Source: Drive eO

APPENDIX 1

Converdan, 2019. Converdan Engineering technical report, 2019, HV DCDC Technical Note P180403-001.

Project Facts

- 17 project partners: research institutions, companies and technology transfer organisations
- Duration from 2016 to 2019
- Budget: EUR 3.1 mllion
- European Regional Development Fund
- Interreg Baltic Sea Region Programme
- Led by University of Southern Denmark

Project Partners

- University of Southern Denmark (Denmark)
- Applied Research Institute for Prospective Technologies (Lithuania)
- Christian Albrechts Universität Kiel (Germany)
- CLEAN (Denmark)
- Converdan A/S (Denmark)
- Kaunas Science and Technology Park (Lithuania)
- Kaunas University of Technology (Lithuania)
- Latvian Technological Center (Latvia)
- NATEK Power Systems AB (Sweden)
- Polish Chamber of Commerce for Electronics and Telecommunications (Poland)
- Renewable Energy Hamburg (Germany)
- RISE Research Institutes of Sweden AB (Sweden)
- Sustainable Smart Houses in Småland (Sweden)
- Ubik Solutions OÜ (Estonia)
- University of Latvia (Latvia)
- University of Tartu (Estonia)
- Warsaw University of Technology (Poland)

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