

Evaluating SiC-MOSFETs and Si-IGBTs as Self-Protected Battery Disconnect Switch in MW-Capable Battery Applications

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Abstract

Currently, electrification of heavy-duty-transportation as well as installing MWh-scale battery-electric energy storage systems (BESS) to balance fluctuating energy sources is a growing market. To protect the battery in case of failure, DC-circuit breakers are needed, usually in form of fuses, contactors or even pyro-fuses. For low-power battery-applications, mechanical miniature switches (MEMS) can be used which appear insufficient if it comes to handling thousands of amps. In this paper, investigation is presented how IGBTs and SiC-MOSFETs could become the core component in such a safety application. Focus is on commercial vehicles, but the technology can be transferred to BESS as well.

1 High-power battery and disconnecting switch arrangement

Batteries as energy storage in both, stationary and mobile application, have grown into capacities that today easily reach hundreds of kWh in mobile applications and even MWh in utility-scale systems [1].

For the safety measures installed, this poses an additional challenge. A typical arrangement of battery cells - or battery-modules - features paralleled strings of series-connected cells. While the series-connection is necessary to increase the voltage, paralleling is needed to increase the capacity. A multitude of battery modules is arranged into what is considered "the battery".

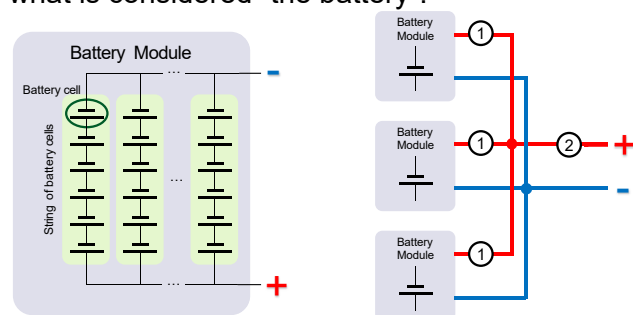


Fig. 1 High-voltage, high-power battery-setup, and potential positions for circuit breakers

Protection schemes can consider protection on each of the levels mentioned.

The most economic ones focus on disconnecting individual battery modules or the interruption of the main line connecting the battery to the application. The scheme described is seen in **Error! Reference source not found.** and the potential positions for circuit-breakers are marked as ① and ②.

Independent on the position, the circuit-breaker must provide bidirectional operation as it has to operate when charging and discharging the battery. Commonly, bidirectional semiconductor arrangements consist of individual paths for each direction and are built from anti-series connected switches. Two solutions are given in Fig. 2 and Fig. 3.

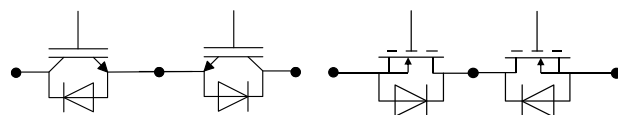


Fig. 2 IGBTs in common emitter configuration

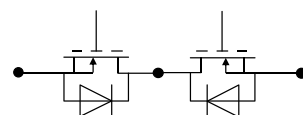


Fig. 3 SiC-MOSFETs in common drain configuration

Choosing common emitter allows controlling the switches for both directions from a single power supply as they share a common ground. From technical point of view, setting the switches up as common collector, respectively common drain, represents the same electrical solution.

2 Application requirements

To estimate the electrical requirements and judge the electrical performance, a generic in-city deliver-vehicle was assumed. For such vehicles, standardized, generic drive-cycles used for the estimation of fuel consumption can also be considered as a basis for their electric counterparts.

The two profiles *UN/ECE Elementary Urban Cycle Part 1 and 2* [2] were combined for this work. The resulting load-profile, the relevant technical data for the vehicle are summarized in Fig. 4



Fig. 4 UN/ECE Urban Cycle Part 1 and 2 combined

The formulas that were used to calculate the power demand along with parameters describing the vehicle are given in Table 1.

Contribution	Formular	Parameter / Values
Friction	$P_{\text{roll}} = m \cdot g \cdot \mu_r \cdot v$	$\mu_r = 0.008, m = 10.000\text{kg}$ $g = 9.81\text{m/s}^2$
Air Drag	$P_{\text{air}} = \frac{1}{2} \rho_{\text{air}} \cdot c_w \cdot A \cdot v^3$	$\rho_{\text{air}} = 1.2\text{kg/m}^3$ $c_w = 0.8$ $A = 4\text{m}^2$
Acceleration	$P_{\text{acc}} = F \cdot v = m \cdot a \cdot v = m \cdot \frac{dv}{dt} \cdot v$	$\frac{dv}{dt} = \frac{v_{n+1} - v_n}{\Delta t}$

Table 1 Formulas and parameters used in power demand estimation

The speed profile is given in 1s-steps and linear interpolation was done between each two steps. From the data presented, a current profile for this scenario was calculated with the result displayed in Fig. 5.



Fig. 5 Current profile acc. to the EPA-Drive-cycle

While the current for driving the vehicle remains below 300 A, regenerating the kinetic energy completely during breaking would require close to 600 A. As this correlates to a very hard breaking experience, a symmetric 400 A-arrangement is considered sufficient.

A dedicated 1200 V IGBT with a rated value of 200 A continuous current is considered for the circuit breaker. With a forward voltage of 1.2 V at 200 A and 125 °C die-temperature, and a diode in series that features a forward voltage of ~1 V for the same conditions, the bidirectional switch seen in Fig. 2 competes against a SiC-MOSFET-solution.

Given that the IGBT/Diode-combination features 2.2 V forward voltage, 400 A in two parallel paths leads to static losses of 880 W, representing an equivalent resistance of 5.5 mΩ.

With two MOSFET-channels in series during static operation, a sufficient number of MOSFETs to achieve $R_{\text{DSon}}=2.75\text{ m}\Omega$ needs to be paralleled for each of the switches in the bidirectional scheme.

The lowest R_{DSon} -values in 1200 V SiC-MOSFETS today are in the regime of 20 mΩ at chip temperatures of 25 °C. Assuming an increase to 30 mΩ at higher temperatures, the bidirectional switch in **Error! Reference source not found.** needs to consist of at least 10+10=20 SiC-MOSFET-dies.

It is in the nature of a circuit breaker, that no dynamic losses need to be considered.

The losses in the silicon-based solutions correlate to the linear relation $P_v = I \cdot (V_{\text{CE}} + V_F)$, while the SiC-solution features losses according to $P_v = 2 \cdot I^2 \cdot R_{\text{DSon}}$. As a result, the MOSFET-solution shows lower overall losses despite having the same losses at rated current of 400 A.

Based on the current-profile, the losses during operation can be calculated with the comparison of the power-loss profiles depicted in Fig. 6.

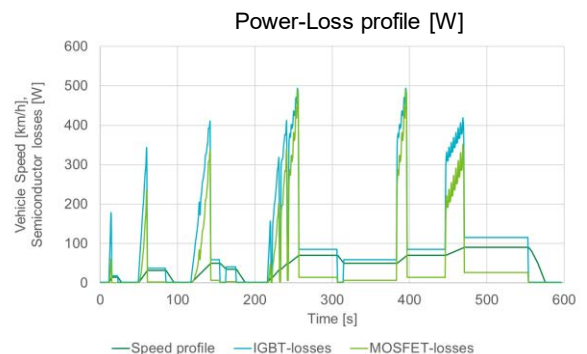


Fig. 6 Losses in IGBT and SiC-MOSFET compared

Checking the impact on the driving range, the energy lost in the circuit breaker needs to be considered.

These can easily be calculated for both solutions, the result is depicted in Fig. 7.

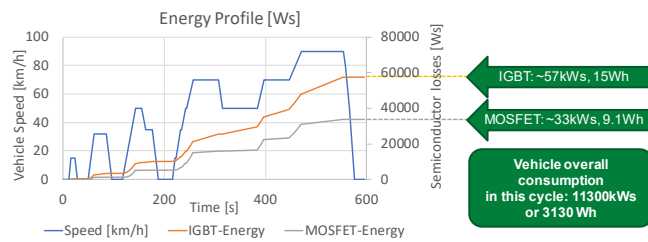


Fig 7. Energy lost in the battery disconnect switch for two different technologies

The advantage gained by SiC-MOSFETs within the 10-minute cycle is about 6 Wh. Assuming 48 of these cycles per day within 8 hours driving, the gain sums up to 288 Wh, representing a neglectable addition of about 0.9 km of range per day while driving 243 km.

Given that such a protection device is expected to qualify as highly reliable, the drawbacks of having 20 dies in the system instead of only 8 is obvious. Space-savings also do not occur and the higher cost for the raw materials make the SiC-based solution even less attractive.

For the remainder of the feasibility study, the focus therefore is set to an IGBT-based approach.

2.1 Technical details arising from the use-case

Target of this work is substituting the combination of a classical fuse and a mechanical contactor with a solid-state switch.

Bidirectional switches made from semiconductors are state-of-the-art and currently used in inverter-arrangements like the Vienna rectifier or Matrix converters.

In contrast to being operated in inverter-mode, using a solid-state switch as a fuse comes with the challenge that interrupting an inductive current becomes the main task.

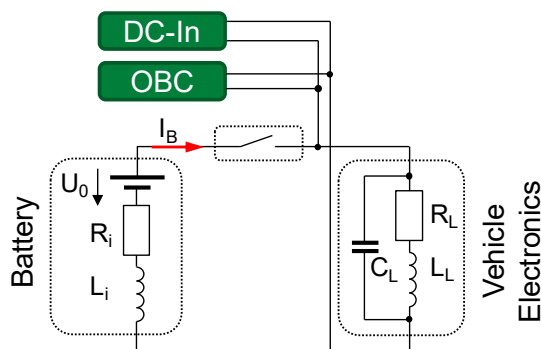


Fig. 8 Simplified schematic of a battery-powered vehicle

From Fig. 8, the basic challenges to consider can be derived:

- Connecting the vehicle's electronics to the battery may lead to high inrush-currents when charging the sum of capacitors C_L during start-up.
- Interrupting an overcurrent can occur during any mode of operation – driving, charging or regenerating energy during braking. As two current directions are demanded, there is no inherent freewheeling path.
- Batteries feature extraordinarily low internal resistances R_i . In combination with the inductances involved, high current change rates di/dt have to be anticipated.
- Losses in the solid-state switch are higher than in mechanical contacts and heat needs to be dissipated, demanding additional effort for thermal management.

At the same time, a semiconductor-based solution also offers advantages in comparison to mechanical switches and classical fuses:

- Turn-off becomes a matter of control, rather than excess-energy to trigger a fuse. Instead of tolerating a system-induced short-circuit current rating, a much smaller limit can be set to turn off an overcurrent.
- The semiconductor can act as pre-charge-unit to have a controlled voltage build-up in the vehicle.
- Sensors can be integrated and monitoring a variety of parameters can be done via software.
- Elimination of mechanical parts
- Overcurrent turn-off will not lead to a controlled destruction; the device remains resettable and reusable, eliminating replacement and maintenance.

2.2 Overvoltage protection schemes

Fuses and contactors can burn the energy stored in the inductance into heat by allowing controlled arcing. In semiconductors, due to the law of inductance, energy stored leads to a potentially destructive overvoltage that needs to be handled safely.

As the disconnecting event can take place with two current directions, a simple freewheeling diode is not an option. However, adding a freewheeling diode for one direction and use a crowbar for the reverse direction can be considered.

The crowbar consists of a thyristor and a break-over diode that in case of exceeding the voltage limit provides the gate-current for turn-on.

The correlating schematic is given in Fig. 9.

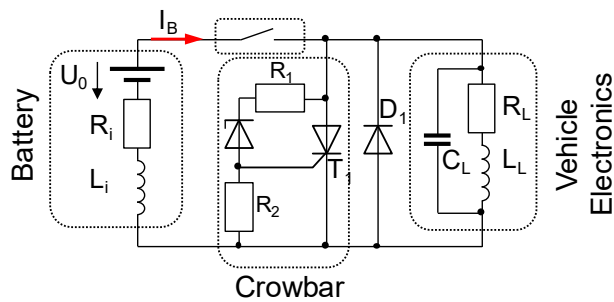


Fig. 9 Crowbar and freewheeling diode as overvoltage protection

To reduce the number of components in the setup, an approach based on transient voltage suppressors (TVS) can also be considered. Here, Zener-diodes limit the voltage across the switch to tolerable limits, transferring the energy into heat. TVS-Diodes with bidirectional function that offer both, sufficient blocking voltage as well as energy dissipation capacity are common components. The schematic using this approach is depicted in Fig. 10.

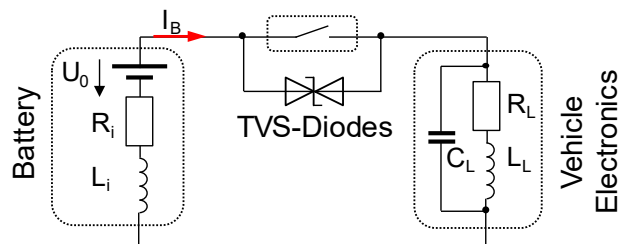


Fig. 10 Overvoltage Protection using TVS-Diodes

3 Prototype built for electrical testing

To not limit the options in an experimental setup, only the Si-IGBT-based bidirectional switch as given in Fig. 2 was implemented in an available package as seen in Fig. 11.

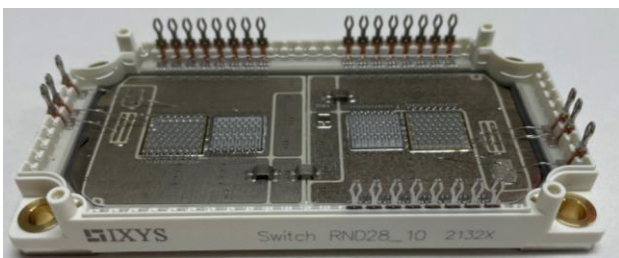


Fig. 11 200 A, 1200 V bidirectional switch arrangement in an E3 Power Module

Having the switch as a unit allows examining various protection schemes in the lab.

To evaluate the electrical performance, this prototype can be considered a per-unit-device.

Paralleling further dice to achieve the necessary current carrying capabilities to properly support the application is unavoidable.

3.1 Current handling capability testing

The IGBT embedded in the prototype is a newly developed 1200 V device with a cell-design optimized for very high desaturation currents. Being designed for fast reaction in protection schemes, focus was on low static losses. Dynamic losses were of literally no concern and sacrificed to focus optimization regarding forward voltage and current density.

With an active area of approximately 140 mm², the chip is developed to safely turn off at least 1600 A. In a classical double-pulse test, the chip successfully turned off 2 kA. A measurement of this turn-off is contained in Fig. 12.

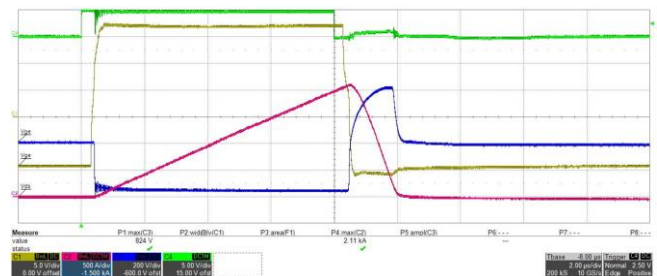


Fig. 12 Turn-off, 400 V / 2000 A

Despite the very high current density, there is no desaturation visible and the voltage across the IGBT remains low during the whole procedure. This is an important feature as such high currents in the presence of a desaturation voltage would lead to very high losses in the die. Without desaturation, the instantaneous losses remain low as well, substantiating that the device is a viable choice for the targeted application.

3.2 Static thermal behavior

In contrast to a contactor/fuse-combination, solid-state solutions inherently induce higher losses. The static thermal situation for the bidirectional switch was evaluated using infrared imaging with the device mounted on a heat sink with forced-air cooling. At currents of 200 A, the forward voltage of the IGBT remains below 1.5 V and the diode contributes about 1.1 V.

The forward voltage characteristic of the setup with a rated gate-emitter-voltage of $V_{GE} = 15\text{ V}$ applied is summarized in Fig. 13.

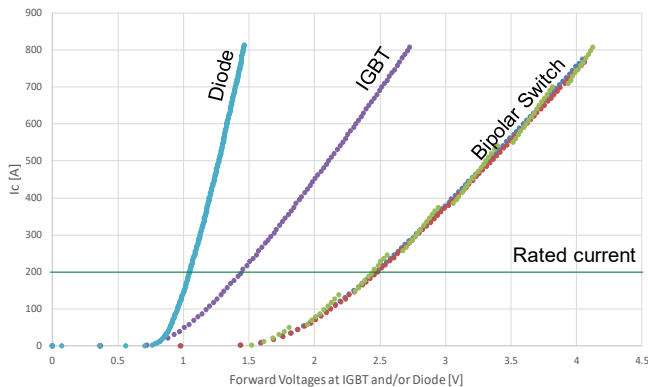


Fig. 13 Forward characteristic of the prototype switch

With about 220 W of losses in the diode and 280 W in the IGBT, the thermal situation at rated current can be observed to develop as seen in Fig. 14.

With a temperature swing of $\Delta T_{vj} = 85\text{ K}$ for the IGBT and $\sim 80\text{ K}$ for the diode, the device performs as predicted.

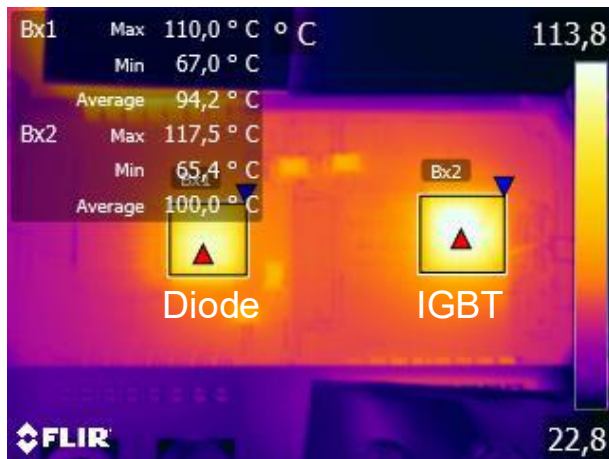


Fig. 14 Temperature development in the prototype, forced-air cooling, 25°C ambient temperature

3.3 Leakage current

To prevent losses in off-state, which could lead to uncontrolled thermal development, drain power from the vehicle's battery or pose a risk to people during maintenance, the application requires that the leakage currents remain below 50 μA .

Leakage current depends on temperature and was measured using a curve-tracer.

The result displayed in Fig. 15 reveals, that the single-die arrangement at up to 85°C junction temperature and 400 V_{dc} remains below 4 μA .

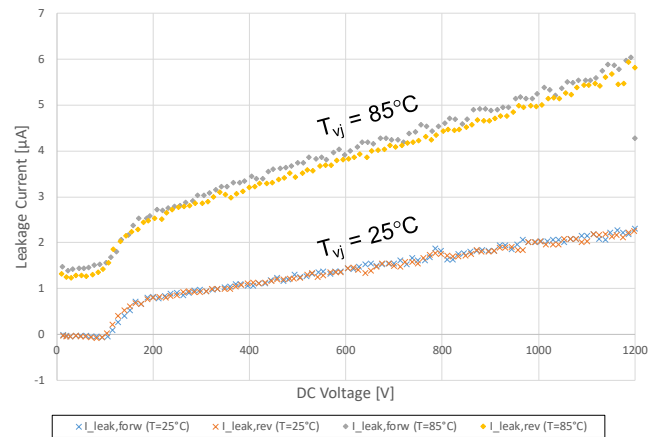


Fig. 15 Leakage current measurement

From this, it can be concluded that the approach remains feasible with up to 10 chips in parallel, opening the option to build a bidirectional switch with up to >16 kA turn-off capability and still remain within the 50 μA -requirement.

It is important to notice, that the leakage current during operation is of no concern and the temperature in non-operating conditions returns to ambient temperature quickly, further relaxing the leakage-current requirement.

4 Application related testing

The double-pulse test is designed to observe the semiconductor's behavior under conditions found in a typical inverter setup.

To get an insight into the capabilities in a battery-driven application, a further prototype including the TVS-diodes and equipped with two parallel semiconductor sets to turn off >3000 A was built.

This device is currently in use to determine the capabilities in overcurrent-handling as well as gathering experiences on the applicational setup and the parasitic parameters involved.

4.1 Pre-charging the DC-capacitors

Charging an application's DC-link efficiently without a resistive pre-charging unit and without DC-contactors to bridge a resistor is a welcome feature in battery-powered applications. Charging an initially discharged capacitor can be achieved as a software-feature, once a bidirectional battery-disconnect-switch is installed.

The device in this test was connected to a DC-source to test operating it in a pulsed mode to limit inrush-currents while charging the DC-capacitors quickly and reliably.

Figure 16 highlights a measured result, charging a 440 μF capacitance from 0 V to about 450 V in about 230 ms.

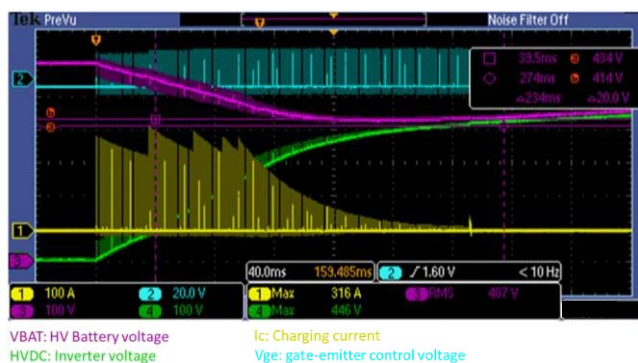


Fig. 16 Charging process, applying a static pulse pattern to a DC-link capacitor

The charging current was limited to a maximum of 316 A by the source's internal resistance and the remaining stray inductance of the setup.

As there is no general specification regarding the applications impedance, tests are ongoing with up to 3 mF of capacitance and DC-voltages of up to 800 V.

Current limitations are based on safety concerns when handling and discharging stored energies.

4.2 Overcurrent turn-off

The most critical event to be handled is a short circuit. However, a solid-state switch can be triggered before the undamped short circuit current reaches the level typically needed to trigger classical fuses. The correlating trigger signal can be gained from a suitably fast current sensor.

Quantitatively, the correlations are sketched in Fig. 17, roughly giving an insight into the differences in reaction time that solid-state fuses can achieve.

Depending on the control and the current sensor's speed, exceeding an overcurrent can be detected in a matter of μs and turning it off can be initialized.

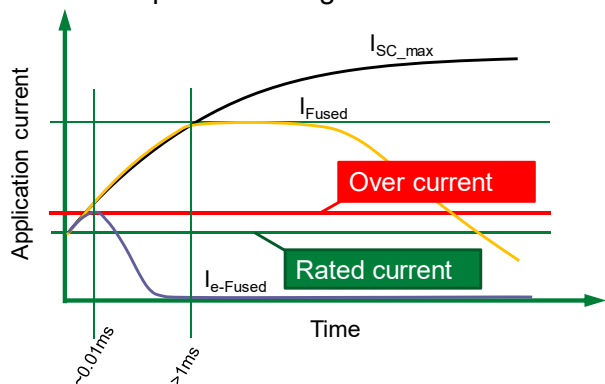


Fig. 17 Quantitative Comparison of reaction speed, classical fuse vs. solid-state switch

Tests with the prototype started with an 800V battery setup and the device was turned on to form a short circuit.

Results from the tests are contained in the scope-plot given in Fig. 18.

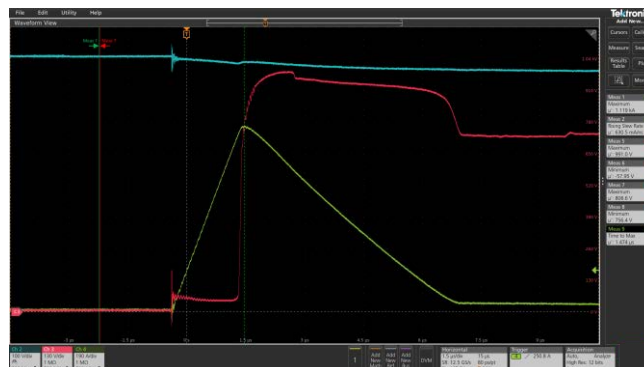


Fig. 18 Over current turn-off event

Several conclusions can be drawn from the measurement:

As expected, the overcurrent of only 1119 A is far lower than an undamped short-circuit current would have been.

The clamping arrangement integrated into the device reliably held the voltage at levels well below the switches' breakdown voltage and was able to handle the energy stored in the setup's inductance. The challenge to build a generic battery-disconnect switch remains the unknown inductance within the application.

While a low inductance increases the current change rate and thus demands faster reaction within the controls, the energy involved get smaller. With higher inductances, the current change rate gets reduced, however the energies involved, according to $E = 1/2 L \cdot i^2$, tend to grow. Also, the time the TVS-diodes have to withstand the current stress increase, making dimensioning of those parts more difficult, yet possible.

5 Summary

Searching for a suitable power semiconductor component to act as a solid-state replacement of fuses demands to take a closer look into the targeted application and the use-case that must be served. For DC-circuit-breakers in battery-based applications, the application conditions and requirements are totally different from inverter-operation and particularly the overvoltage during turn-off demands attention. The solution based on large-scale TVS-diodes to handle excess energy during turn-off has proven to work reliably.

With the lack of high switching frequencies and the cost-pressure in these applications, a solution based on SiC-MOSFETs does not reveal reasonable advantages.

Instead, dedicated IGBT-designs as demonstrated do pose a favorable solution with benefits in material cost, reliability and thermal management.

6 Reference

- [1] Internet source: Renewable Energy World
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