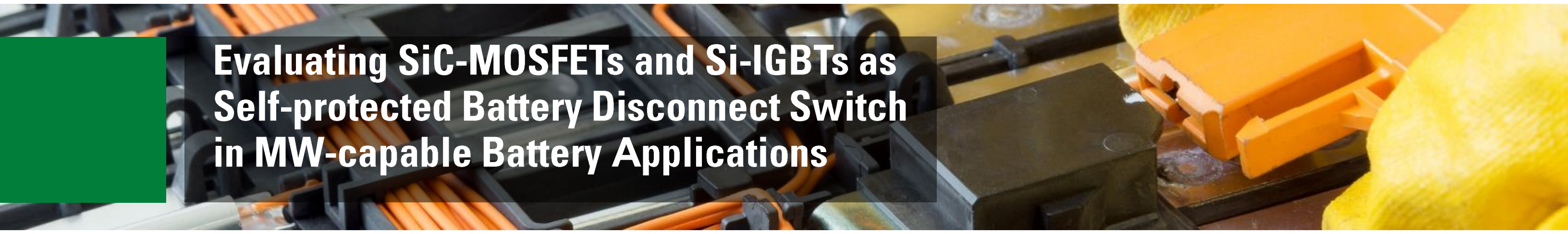


Evaluating SiC-MOSFETs and Si-IGBTs as Self-protected Battery Disconnect Switch in MW-capable Battery Applications

Objectives

This white paper gives insights into how to tackle the challenge of designing solid state solutions to replace mechanical battery disconnect switches. As several technologies in power semiconductors are available, a choice needs to be made. As battery disconnect switches work in DC-mode but differ from the operation in an inverter setup, a solution must be found to handle overvoltages during the turn-off event. In the absence of an inherent freewheeling path, combined with an undefined inductive load, higher energies need to be considered.

Applications

Applications include battery energy storage systems (BESS) and mobile battery solutions such as in electric heavy-duty vehicles. It also scales down to electric passenger cars, material handling in forklifts, e-bikes, and electric scooters.

Target Audience

The overview given in this work is aimed at developers of battery-powered systems challenged with the design of solid-state disconnect devices.

Contact Information

For more information on this topic, contact the Littelfuse Power Semiconductor team of product and applications experts:

- PowerSemiSupport@Littelfuse.com

Table of Contents

List of Figures

List of Tables

Introduction

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 the form of fuses, contactors, or pyro-fuses. For low-power battery-applications, mechanical miniature switches (MEMS) can be used, which appear insufficient when it comes to handling thousands of amps. This paper presents investigation into ways in which IGBTs and SiC-MOSFETs could become the core component in such a safety application. Although the focus is on commercial vehicles, this 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 applications, 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."

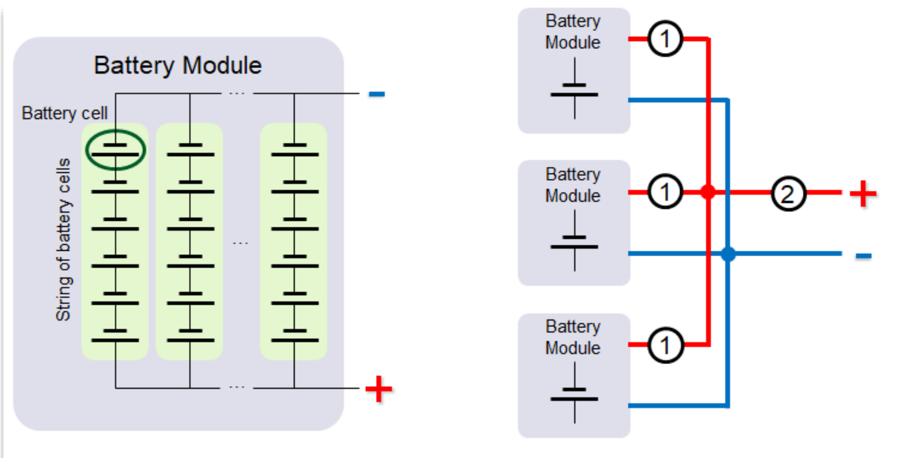
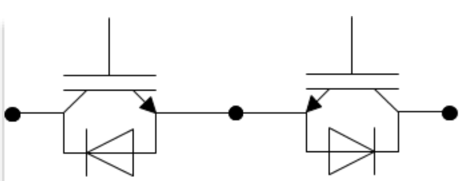


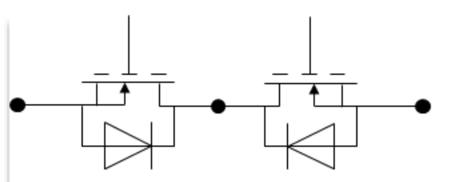
Figure 1. High-voltage, high-power battery-setup, and potential positions for circuit breakers

Protection schemes can consider protection on each of the levels mentioned. The most economical 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 Figure 1 and the potential positions for circuit-breakers are marked as ① and ②.

Independent of 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 Figure 2(a) and Figure 2(b).



(a) IGBTs in common emitter configuration



(b) SiC-MOSFETs in common drain configuration

Figure 2. Bidirectional semiconductor arrangements

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

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 and the relevant technical data for the vehicle are summarized in Figure 3.

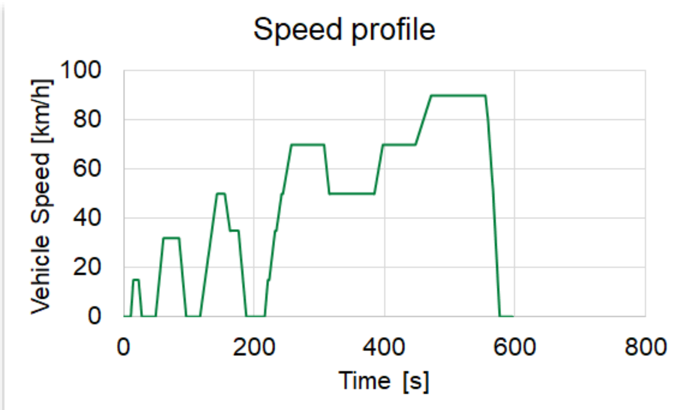


Figure 3. UN/ECE urban cycle part 1 and part 2 combined

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

Table 1. Formulas and parameters used in power demand estimation

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

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 Figure 4.

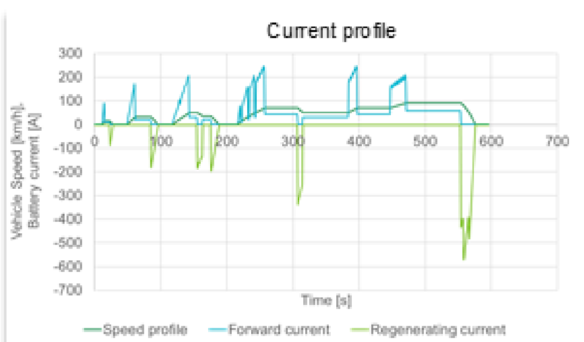


Figure 4. Current profile according to the EPA-Drive-cycle

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 an extremely 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 Figure 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_{DSon}=2.75 mΩ 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 mW at chip temperatures of 25°C. Assuming an increase to 30 mW at higher temperatures, the bidirectional switch in Figure 2(b) 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 $P_v=I\cdot(V_{CE}+V_F)$, while the SiC-solution features losses according to $P_v=2\cdot I^2\cdot R_{DSon}$. 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 Figure 5.

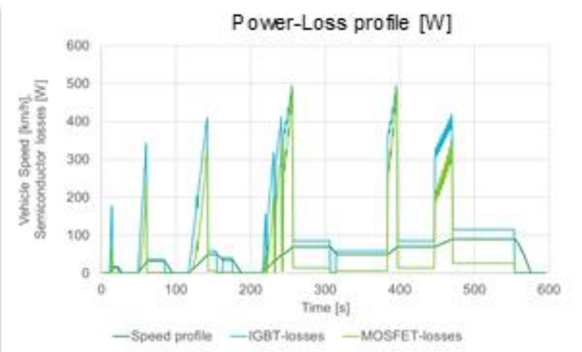


Figure 5. Losses in IGBT and SiC-MOSFET compared

Checking the impact on the driving range, the energy lost in the circuit breaker needs to be considered. This can easily be calculated for both solutions; the result is depicted in Figure 6.

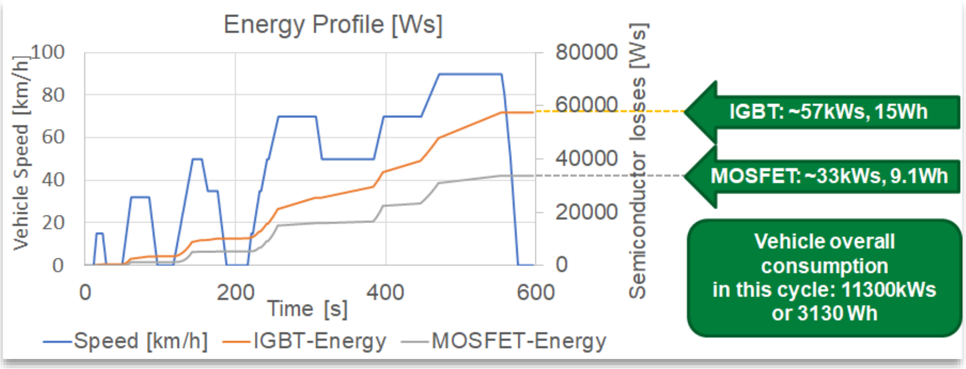


Figure 6. Energy lost in the battery disconnect switch for two different technologies

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 negligible 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

The 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.

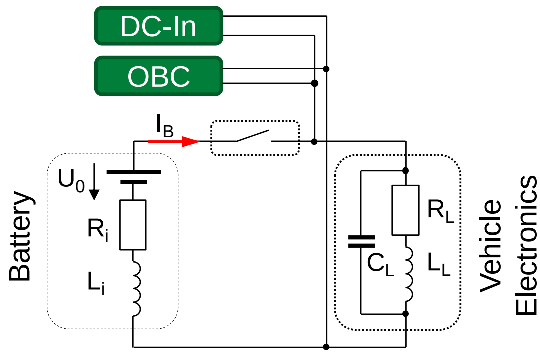


Figure 7. Simplified schematic of a battery-powered vehicle

From Figure 7, 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 breaking. As two current directions are required, 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.
- Mechanical parts can be eliminated.
- 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, stored energy 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 using a crowbar for the reverse direction can be considered.

The crowbar consists of a thyristor and a break-over diode that provides the gate-current for turn-on in case the voltage limit is exceeded. The correlating schematic is given in Figure 8.

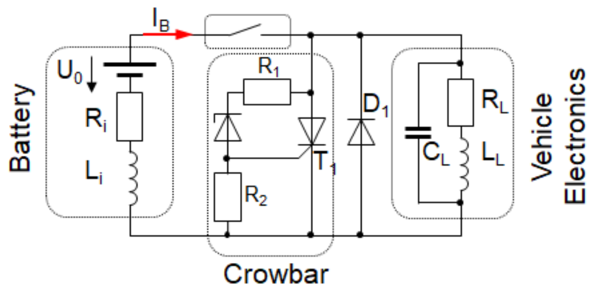


Figure 8. Crowbar and freewheeling diode as overvoltage protection

To reduce the number of components in the setup, an approach based on transient voltage suppressor (TVS) diodes 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 Figure 9.

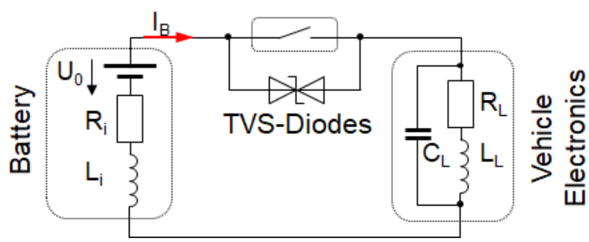


Figure 9. Overvoltage protection using TVS-diodes

3. Feasibility Study, Built for Electrical Testing

To avoid limiting the options in an experimental setup, only the Si-IGBT-based bidirectional switch as given in Figure 2 was implemented in an available E3 package, as seen in Figure 10.

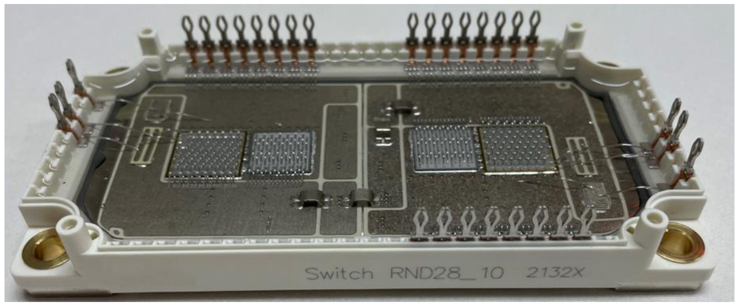


Figure 10. 200 A, 1200 V bidirectional switch arrangement in an E3 Power Module

Having the switch as a unit allows for the examination of various protection schemes in the lab. To evaluate the electrical performance, this setup 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 power module 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 absolutely 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 at 2 kA. A measurement result of this turn-off is contained in Figure 11.

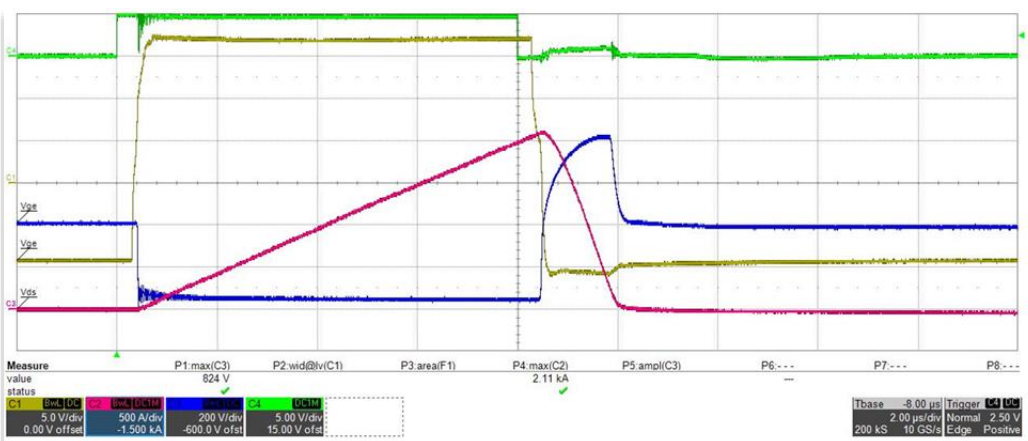


Figure 11. Turn-off, 400 V / 2000 A

Despite the extremely 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 V applied is summarized in Figure 12.

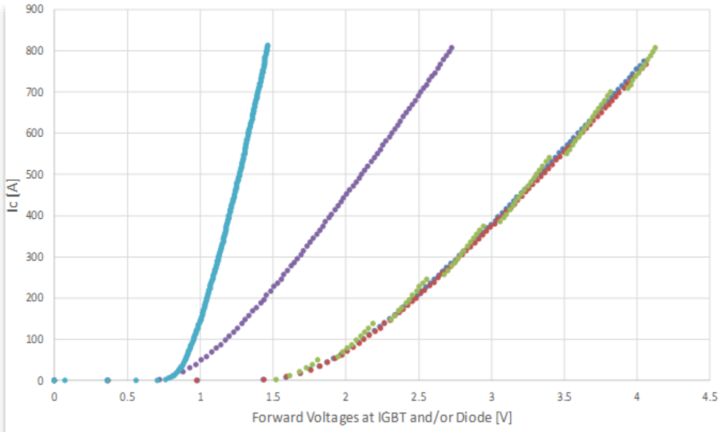


Figure 12. Forward characteristic of the switch under test

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 Figure 13. With a temperature swing of ΔT_{vj} = 85 K for the IGBT and ~80 K for the diode, the device performs as predicted.

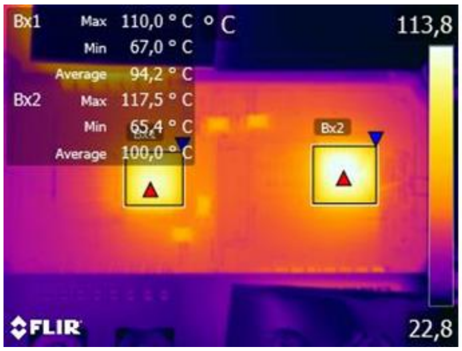


Figure 13. Temperature development during operation, forced-air cooling, 25°C ambient temperature

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 Figure 14 reveals that the single-die arrangement at up to 85°C junction temperature and 400 V_{dc} remains below 4 µA.

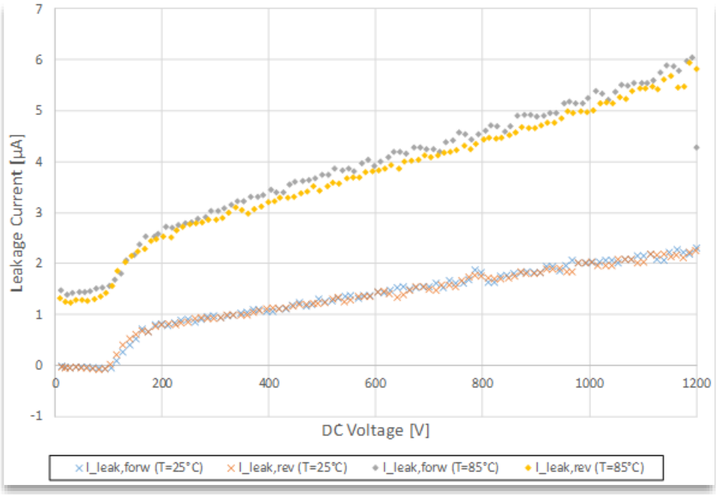


Figure 14. Leakage Current Measurement

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 note 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 test specimen 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 application 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 15 highlights a measured result, charging a 440 µF capacitance from 0 V to about 450 V in about 230 ms.

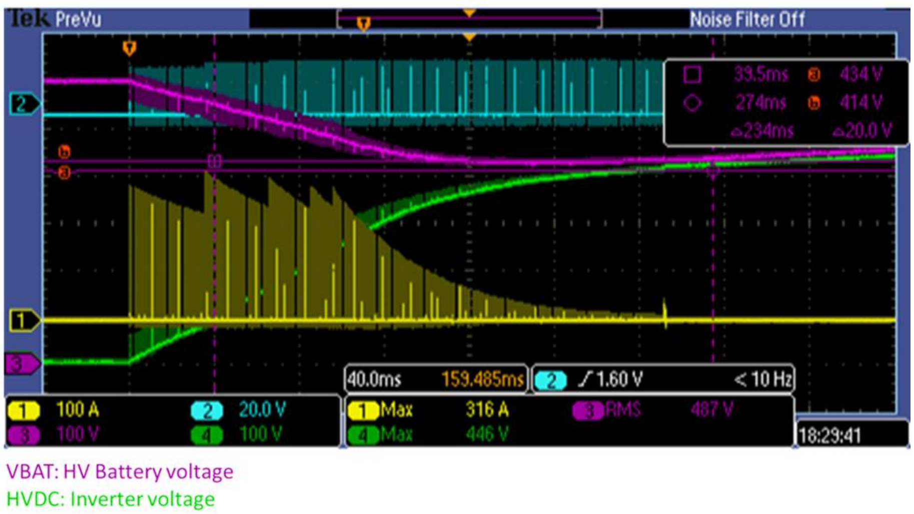


Figure 15. Charging process, applying a static pulse pattern to a DC-link capacitor

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 was no general specification regarding the application's impedance, tests were successfully done with up to 3 mF of capacitance and DC-voltages of up to 800 V.

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 undampened 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 Figure 16, giving a rough insight into the differences in reaction time that solid-state fuses can achieve. Depending on the control and the current sensor's speed, overcurrent exceedance can be detected in a matter of µs and turn-off can be initialized.

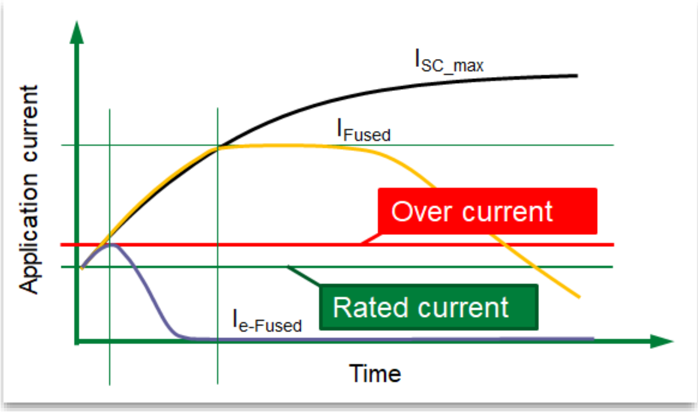


Figure 16. Quantitative Comparison of reaction speed, classical fuse vs. solid-state switch

Tests with the device to be studied started with an 800 V 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 Figure 17.

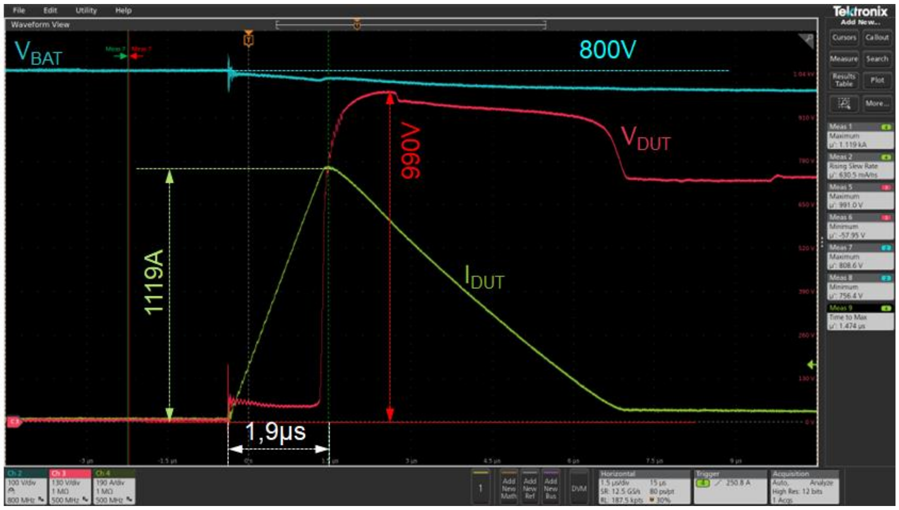


Figure 17. Overcurrent turn-off event

Several conclusions can be drawn from the measurement. As expected, the overcurrent of only 1119 A is far lower than an undampened 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 requires faster reaction within the controls, the energy involved gets smaller. With higher inductances, the current change rate gets reduced; however, the energies involved, according to $E=1/2L \cdot i^2$, 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 requires taking 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 completely different from inverter-operation. The overvoltage during turn-off particularly needs 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 present a favorable solution with benefits in material cost, reliability, and thermal management.

6. References

[1] Renewable Energy World, https://www.renewableenergyworld.com/solar/10-notable-battery-storage-projects-that-went-live-in-2021/#gref, visited July 2022

[2] EPA, United States Environmental Protection Agency Vehicle and Fuel Emissions Testing, Dynamometer Drive Schedules, https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules, visited July 2022