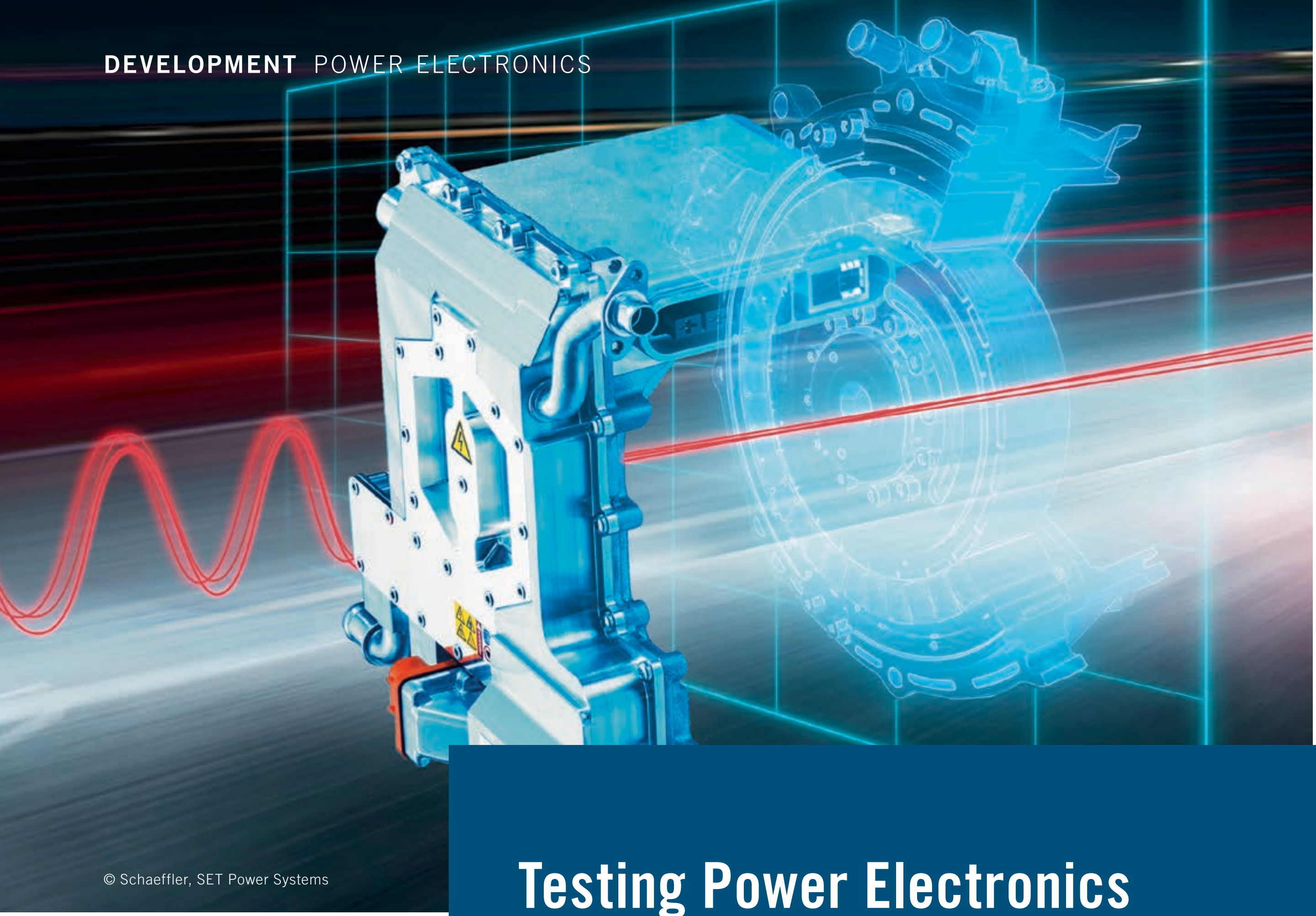

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Testing Power Electronics without an E-Motor

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Electrical powertrains are often part of safety-critical vehicle functionality. This requires comprehensive testing and verification, which is clearly demonstrated by the example of the drive inverter. This component comprises not just a level of signal complexity, but also power electronics, both of which must be taken into account by the test methodology. Due to shorter development times and increasing scope of functionality the challenge is still to maintain or even increase test quality and test depth despite this, without increasing test effort. A solution can be found in testing without e-motors, as is easily possible without e-motor. In this article, Schaeffler describes different test scenarios and areas of application for e-motor emulation using the example of e-motor emulators supplied by SET Power Systems.

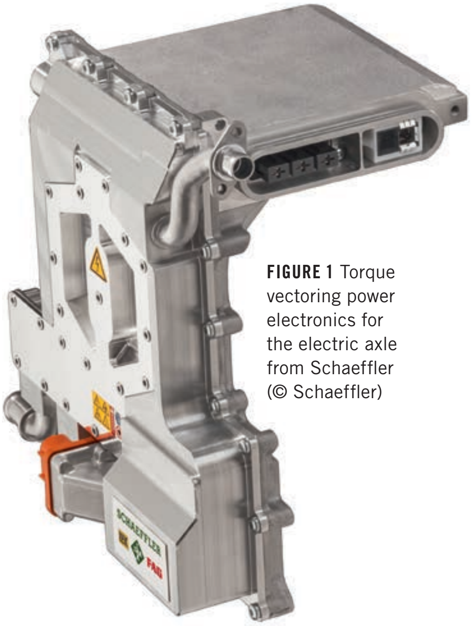


FIGURE 1 Torque vectoring power electronics for the electric axle from Schaeffler (© Schaeffler)

A WIDE RANGE OF ELECTRIC DRIVE TOPOLOGIES

Schaeffler has conceived a portfolio of e-mobility products based on decades of experience in drivetrains: Electric axles, hybrid modules and electric wheel hub drives. A modular system has been developed that ranges from electronics, software to mechanics. The product portfolio covers all relevant functional scope in fine steps from 48 V up to high voltage systems (e-axle, hybrid module, e-wheel drive).

Schaeffler exploits all possibilities and cooperates with the best partner available in specific areas to support them in the development and series production of electrical drive systems, whereby Schaeffler assumes system responsibility. A holistic view and deep levels of integration results in considerable added value. Depending on the system topology, there is a range of requirements on the safety level (Automotive Safety Integration Level - ASIL) of the components, which also influences the test methodology.

NEW TEST METHODS

Schaeffler reacts to the continuously growing complexity of mechatronic systems with simultaneously shorter development times by applying a consistent standardisation concept over all projects. This is equally valid for hardware (HW), software (SW) and the tool chain. Due to the heavy dependence and tight integration of development and test procedures, the system's degree of complexity is increased and hence as a consequence the test complexity:

- Complex mechatronic products can no longer be tested on a dynamometer test bed (problem of integration, separation of individual modules for test, inadequate fault representation).
- Depending on the project, the component test is tested either at the supplier's site, or at the manufacturer's site or both. The system specification requirements are only tested after the system integration test.
- "Fail safe" and "Fail operational": Systems must not only be capable of assuming a "safe state", but in a fault scenario, they must remain "functionally operational" (electrical braking and as preparation for autonomous driving).

The ISO 26262 norm, first introduced in 2011, reliably describes for the first time the functional safety of vehicles and dealing with hazards that can originate form E/E systems on a vehicle level. Its approach: Constructive and verifying measures on different system levels are intended to lead to the most fault-free and robust functioning of the E/E system possible. This approach is not new and draws on decades of proven methods from the aviation industry (refer to ATZelektronik 4|2015). The standard provides recommendations and requirements on the most suitable methods or measures as a function of the ASIL rating.

POWER-HIL EMULATES MOTOR AND LOAD

Schaeffer has invested in a Power Hardware-in-the-Loop system (P-HiL), **FIGURE 1**, in the area Electrical Drive Systems to develop automotive power electronics, **FIGURE 2**. This extends the testing possibilities of the currently existing HiL system and dynamometer test beds for drive electronics, **TABLE 1**.

The test methodology "Power HiL" for the testing of drive inverters is still relatively new but offers many advantages over conventional approaches.

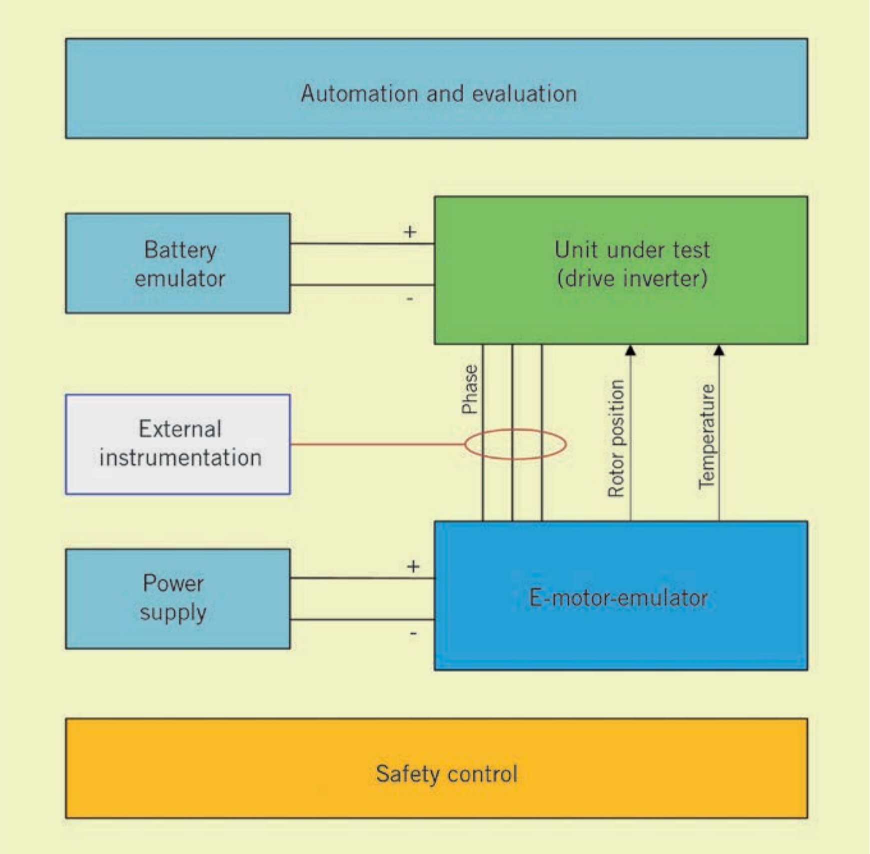


FIGURE 2 Block diagram showing the components of a Power HiL system from SET Power Systems (© SET Power Systems)

Test context	Tool	Test objective
Inverter software with virtual power hardware	Signal level HiL	Function of the inverter software
Complete power electronics with virtual e-motor	Power-HiL (E-motor emulator)	Function of the inverter (original state)
Electric drive with virtual vehicle	Dynamometer	Function of the powertrain

TABLE 1 Testing possibilities of the currently existing HiL system and dynamometer test beds for drive electronics (© SET Power Systems)

It is worth particularly worth noting that when using this technology, the object being tested does not need to be manipulated – a very important prerequisite for meaningful tests. Typical HiL layouts on a low power signal level make many compromises here. In contrast, the unit under test can be tested in an unchanged state on a dynamometer test bed with regards to its performance data and also concerning a demonstration of the correct functioning of the signal electronics with the power path. However, a disadvantage of this test method is the inadequate fault stimulation possibilities. It requires a huge effort, and is often not even possible, to inject faults in such test beds. Above all, such stimulation is only poorly reproducible and could even destroy the test bed. Fault scenarios on the e-motor that can occur in later operation are thus not satisfactorily emulated. If stimulated faults lead to uncontrolled phase currents, this can lead to losing the unit under test.

An e-motor emulator (power HiL) connects both “worlds”: The electrical power flows (in a protected system) in real terms; the mechanical world is simulated in realtime. Depending on the application, SET Power System offers e-motor emulators with a range of different power and voltage classes to demonstrate the verification requirements of ISO 26262, **FIGURE 3**.

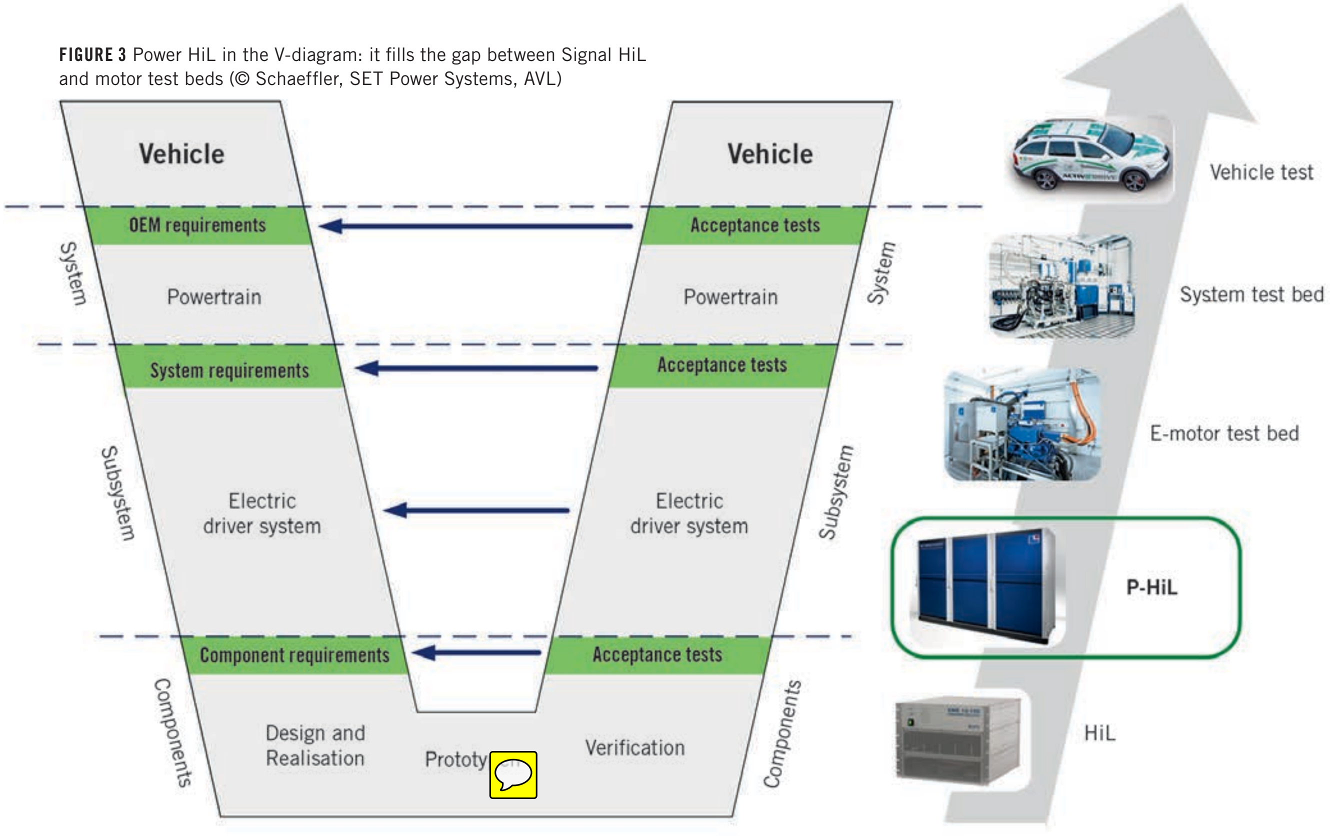
RESULTS FROM PRACTICAL TESTING

During the development of a torque vectoring power electronics for the Schaeffler e-axle, new test requirements arose out of the safety critical application (torque vectoring, ASIL level D). For the first time, the developers used the advantages of an e-motor emulator to verify the inverter. Two typical test scenarios from real practical tests will be used to illustrate this:

ASC AS SAFE STATE

When running permanently excited synchronous machines, impermissibly high voltages can occur at the inverter in a fault scenario. For example, this is the case if when in high-speed operation under field weakening the active control of the inverter fails. To protect the inverter, the motor alternating current lines can be short-circuited via the high or low side IGBTs of the B6 bridge. According to the motor characteristics, a defined short-circuit current occurs.

FIGURE 3 Power HiL in the V-diagram: it fills the gap between Signal HiL and motor test beds (© Schaeffler, SET Power Systems, AVL)



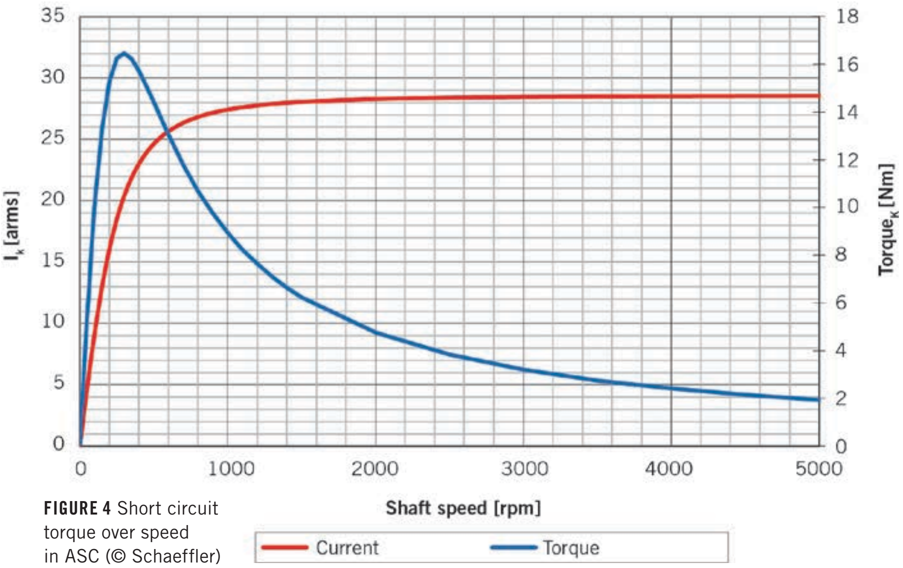


FIGURE 4 Short circuit torque over speed in ASC (© Schaeffler)

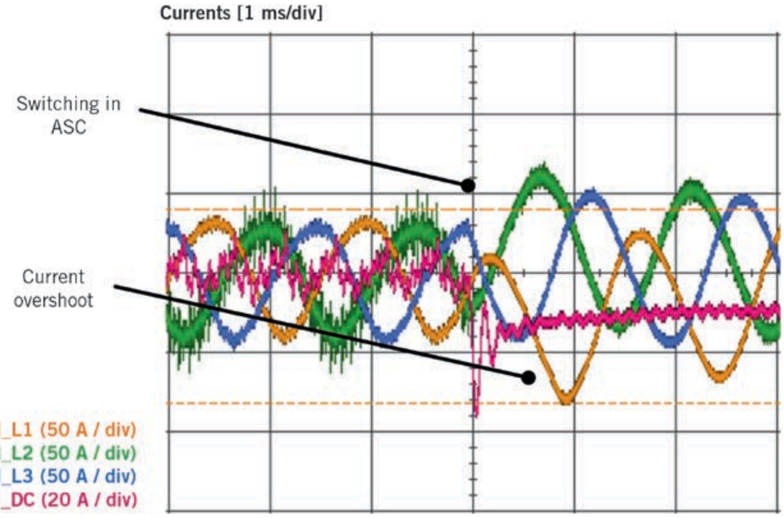


FIGURE 5 Dynamic transition to ASC operation (© Schaeffler)

The measurable voltage on the terminals is practically zero, thus causing the flow of the electrical motor to move almost completely into the reactive power state. The system finds itself in a safe state called "active short circuit".

However, this operating state causes an undesired torque as a function of speed. **FIGURE 4** shows the torque and speed traces from an e-motor test. If the motor is driven further form the outer system (for example when towing the vehicle), the permanent currents in the motor and electronics during an ASC scenario must be considered when designing the layout of an electrical drive system.

P HiL is able to emulate steady state ASC operation at any speed for any amount of time. Speed ramps were run over several minutes in permanent short circuit conditions in order to observe the thermal behaviour of the power electronics. On a normal test bed, the mechanical dimensions would set limits due to the thermal loading.

In dynamic operation, the switch between normal and ASC mode plays an important role. The problem in these situations are the transient compensation processes that occur during the mode switch. **FIGURE 5** shows the dangerously high initial current peaks measured on the Power HiL. These oscillate aperiodically to a steady state short circuit current that is dependent on the speed of the e-motor. Excessive start-up currents can destroy the semiconductor elements or even irreversibly demagnetise the permanent magnets in the motor. Protection in the drive inverter ensures however that the permissible limits are not exceeded during these transitional periods.

Further typical protection systems are the recognition of overvoltage, excessive temperature and overspeed; diverse monitors checking for resolver signals, cable breaks and short-circuit recognition. On a Power HiL, these complex protective functions can be easily and reproducibly verified. By testing on the original unit under test, it can be verified whether these protective circuits are reliably triggered. This is done for all possible operating points and within the specified tolerance; on the one hand to guarantee protection, and on the other to prevent undesirable triggering still with a high degree of availability.

The Power HiL has proved itself here as an ideal test tool. In tests accompanying development, dynamic conditions, saturation and cross-coupling in short-circuit operation; robustness, fault threshold, reaction and trigger times for the drive inverter can be tested under full power in the laboratory.

OPEN GATE AS SAFE STATE

A further protective function is the so-called "open gate". In order to protect the inverter and motor from overcurrents, all IGBTs (insulated gate bipolar transistor) are permanently shut down to prevent an energy flow from the battery via the inverter to the e-motor. The transition to the "open gate" state can have many different causes. If an IGBT fails, depending on the fault condition, it is no longer possible to switch into the ASC state described above, since otherwise an internal short-circuit of the bridge B6 would occur. If the failure of an IGBT is recognised, erroneous switching must be prevented. This is also valid for damaged isolation of the motor connections or if phase short circuits are diagnosed. A fault in the signal level can also require a transition into the "open gate" state. Fault conditions that lead to simultaneous switching of the upper and lower IGBTs are particularly critical. Such faults must be recognised quickly and reliably. Shut-

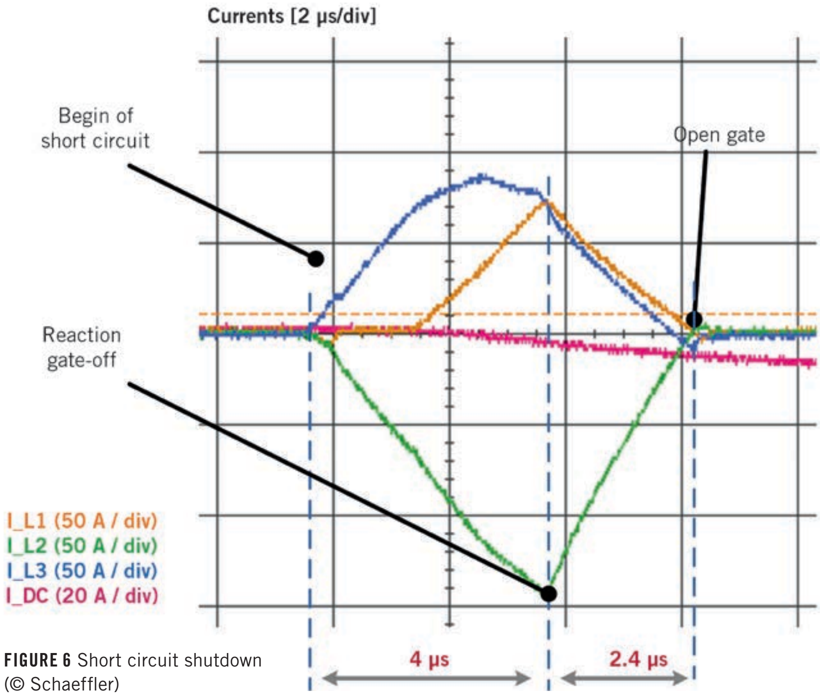


FIGURE 6 Short circuit shutdown (© Schaeffler)

ting down a IGBT gate in such a case ensures that the power electronics are not damaged.

FIGURE 6 shows an example of the current trace of the three phases during a phase short circuit and the triggering of the "open gate" state. Approximately 4µs after the fault occurs, the IGBTs are put into the "open gate" state. There is a hard shutdown of current from L2 (green) within a further 2 µs at 580A in order to move the system into the safe state.

The Power HiL system allows such wide-ranging monitoring and protective functions to be tested under real conditions at any operating point in the laboratory. The e-motor emulator recreates the static and dynamic behaviour of the e-motor on the electrical connection level. Additional instrumentation can capture and evaluate the reaction of the drive inverter more precisely. Proof of both product and functional safety issues can be efficiently and reproducibly substantiated in this way.

SUMMARY AND OUTLOOK

In order to guarantee the function and reliability of drive inverters, e-motor emulators as Power Hardware-in-the-Loop systems can contribute substantially today and will continue to establish themselves as a testing methodology in the future. An important but complex criterion remains the accuracy of such emulation compared to the behaviour of real motors. Automated verification procedures will be able to guarantee this in the future. For the daily routine of development and testing this means that future trends can be quickly tested in the laboratory. Electrical drive concepts can be tested under full power in the laboratory, without the necessity of having the future e-motor physically present. This permits the decoupling and parallelisation of many tasks in the development process of electrical drive systems, which leads to considerable time and cost advantages. Effectiveness and efficiency are thus not only guaranteed in the test process, but also in the development.

THANKS

Our particular thanks go to the student Daniel Fritz for his valuable contributions to this article. Mr Fritz studied electrical engineering at Karlsruher Institute for Technology (KIT) and is in close contact within the auspices of his final dissertation with the P-HiL system at LuK GmbH & Co. KG in Bühl (Germany).