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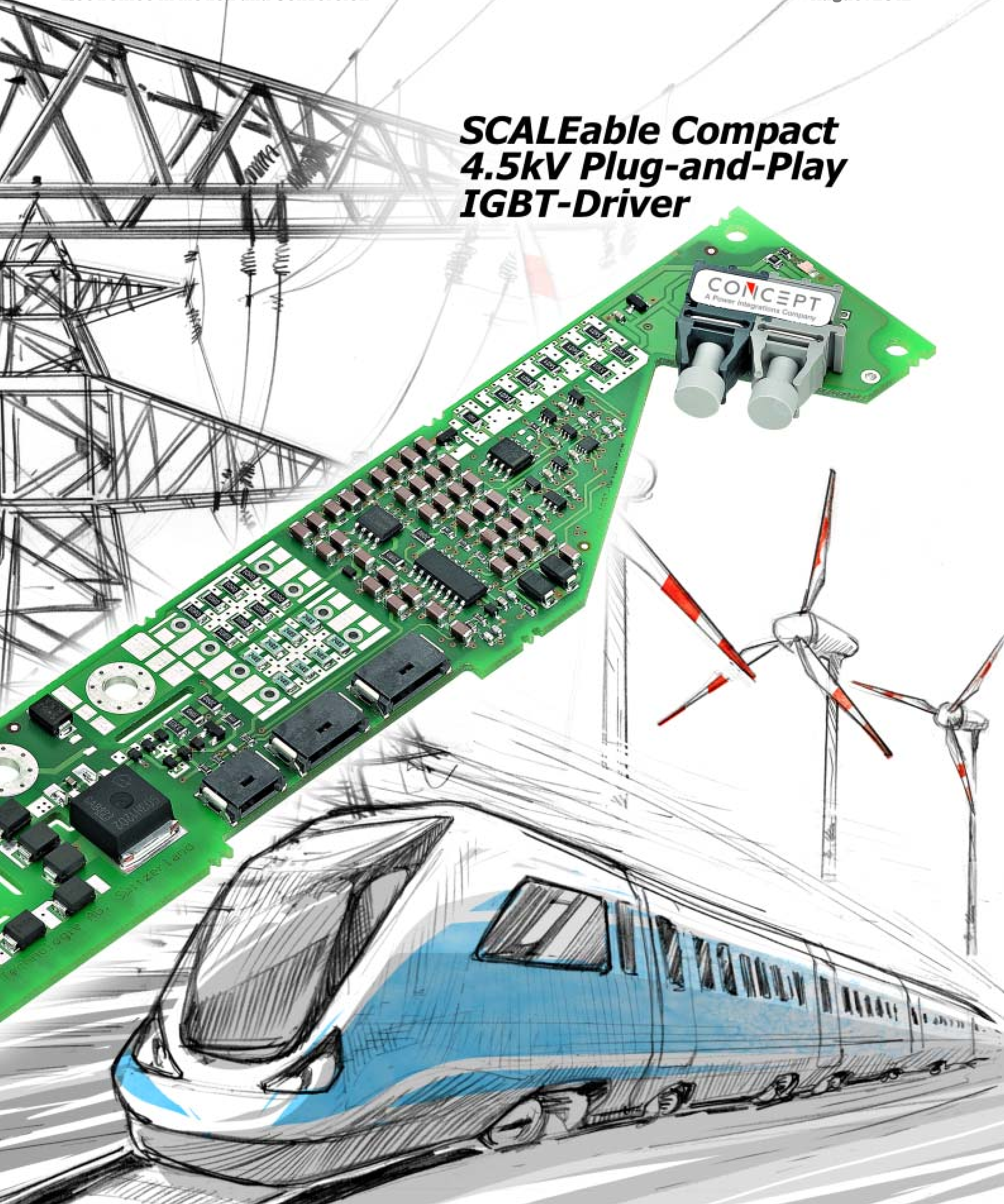
SCALEable Compact 4.5kV Plug-and-Play IGBT-Driver



Driving IGBTs in Parallel is Plug-and-Play

A new compact family of IGBT drivers provides better silicon usage and reduces the overall cost of high-power systems

By Olivier Garcia, CT-Concept Technologie AG

High-voltage/high-current drivers are a vital element of power electrical systems. In power converter applications such as traction, HVDC, medium-voltage drives or renewables, the performance of the drivers plays a key part in the overall performance and efficiency of the complete system. A new development in IGBT drivers enables multiple IGBTs to be connected in parallel safely with no setting-up or fine-tuning required.

Controlled power switching at high power levels can be implemented using thyristors, bipolar transistors, power MOSFETs and IGBTs. Up to the mid 1980s thyristors were the dominant technology and still are at extreme power levels of hundreds of MW. Today IGBTs with voltage classes up to 6.5 kV now dominate the power ranges. The technical advantages of IGBTs - high dielectric strength, relatively high current density, ease of driving and good short circuit protection - have made these power semiconductors standard components for almost every power stage rated at 10 kW or more.

The IGBT is a complex device but can simply be explained as a bipolar output transistor driven by a MOSFET input. At higher current levels the conduction losses are much lower than for an equivalent power MOSFET, and without the need for the high base drive current of a bipolar transistor. However, because of the high voltages and currents involved, driving high-power IGBTs is not a simple matter.

An IGBT is turned on with a positive voltage of typically 15 V with respect to the emitter potential applied to its gate. To guarantee turn off it is necessary to bias the gate to approximately -7 V to -15 V with respect to the emitter to overcome the reverse transfer capacitance (also known as the Miller capacitance) which can couple part of the collector voltage to the gate in bridge applications.

Whereas it is relatively easy to drive an IGBT whose emitter is connected to the ground, in a bridge circuit, which is basic to most IGBT applications, the mid-point of the bridge and thus the emitter potential of the high-side switch jumps back and forth between the positive and negative potentials of the supply voltage at speeds of 5 to 25 kV/µs. This results in large potential differences between the upper driver of the half-bridge and the control electronics. The gate driver must operate reliably in the presence of these surges and optimize the conduction and switching losses of the IGBT modules in both normal switching operation and under overload conditions.

Requirements for drivers

The most important requirements to be fulfilled by drivers for high voltage IGBTs can be summarized as follows:

- Galvanic isolation between IGBT and control electronics (signal path and power supply)
- Ability to turn IGBTs on and off inside the IGBT SOA (safe operating area) with minimal switching losses
- Ability to switch the IGBT at the optimal switching frequency (driver output power can be tailored to the target IGBT module)
- Overvoltage protection (reduction of the turn-off overvoltage)
- Monitoring functions such as IGBT short-circuit protection and supply under-voltage detection

Overvoltage protection is the one element central to the design of an IGBT driver.

Turn-off over voltages

The rated blocking voltage of a semiconductor switch must never be exceeded. This requirement must be fulfilled under all working conditions including turn-off transients from over-current or short-circuit conditions. Due to the stray inductances in the layout of the power stage and the high values of the current changes di/dt, overvoltages in the range of hundreds to thousands of volts can be produced. In extreme cases these voltage spikes can reach values higher than the maximum permissible collector-emitter voltage $V_{CE(max)}$. Figure 1 below is the basic active clamping circuit [1] that can guard

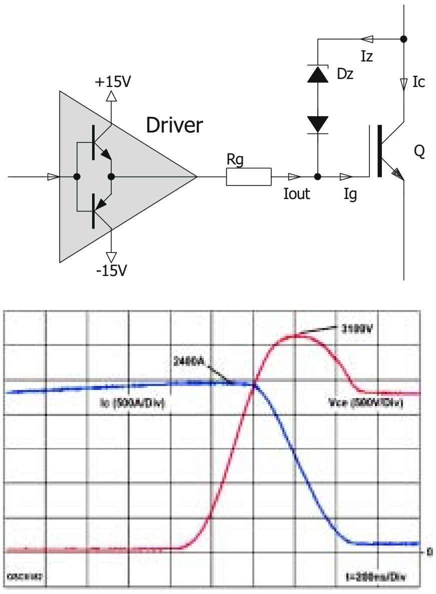


Figure 1 Basic active clamping circuit (top) and its optimized behavior (bottom)

against turn-off voltages exceeding $V_{CE(max)}$.

The transient voltage suppressor diodes Dz between collector and gate cause the IGBT to partially turn on when the collector voltage reaches a pre-defined level. This prevents any further increase of the collector voltage.

Basic active clamping works well for systems with lower technical requirements. Rg(off) must be dimensioned for overload conditions such as turn-off of at double the rated current, short-circuit and a temporarily increased DC-link voltage. In normal operation this results in increased switching losses and turn-off delays. So this simple method is unsuitable for high-power modules and repetitive operation.

An improved active clamping circuit [2] is shown in Figure 2.

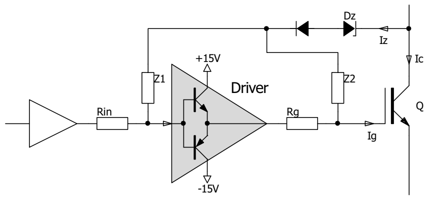


Figure 2: Principle of an IGBT driver with Advanced Active Clamping

Here, the base of the chain of clamping diodes is, as before, connected to the gate of the IGBT, but is additionally connected to the input of a booster stage. The driver voltage is consequently raised as soon as a current flows through the clamping element. The driver stage now no longer draws any current from the clamping element, and the current flowing through the clamping element is now available exclusively for charging the gate. The VCE turn-off overvoltage and the power loss in the clamping diodes can thus be dramatically reduced. This circuit was used successfully in the first generation of SCALE plug-and-play drivers produced by CT-Concept Technologie AG, a specialized manufacturer of high-power drivers based in Switzerland and recently acquired by Power Integrations of San Jose, CA.

Figure 3 shows Advanced Active Clamping (AAC) implemented in practice in a SCALE-2® driver core produced by CONCEPT.

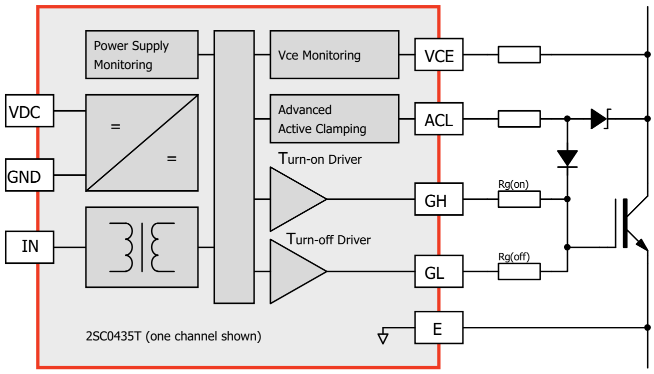


Figure 3: SCALE-2® Integration of Advanced Active Clamping illustrated by the 2SC0435T driver core

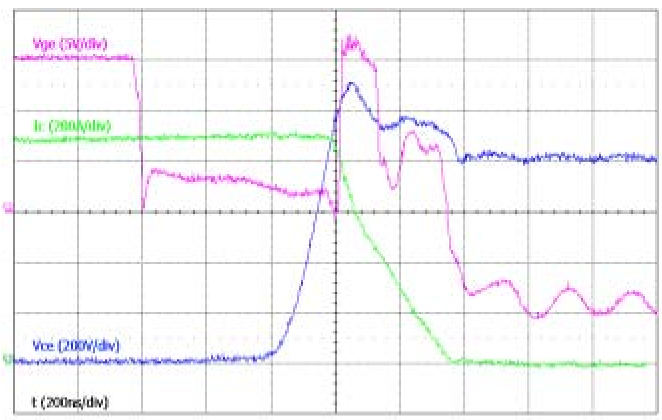


Figure 4: Switching behaviour of a FF450R12IE4 IGBT with the 2SP0320T. V_{dc} = 800V and I_c = 900A, L_{stray} = 68nH

The base of the clamping elements is connected not only to the gate of the IGBT, but also to the ACL input of the SCALE-2® driver ASIC. The gate driver ASIC, implemented in fast analog CMOS technology, continuously raises the output resistance of the turn-off driver stage as the current to the ACL input increases. When the current reaches several 100 mA, the output stage reaches high impedance, so that the driver no longer absorbs any current from the clamping element.

Figure 4 shows the turn-off behavior of the 2SP0320T plug-and-play driver with an IGBT module FF450R12IE4 using SCALE-2® technology with Advanced Active Clamping.

Advanced Active Clamping provides, in addition to the advantages of simple Active Clamping solutions, the following benefits:

- Simple scalability in the voltage class
- Low thermal load of the clamping elements enabling repetitive operation
- Very low value gate resistors possible
- Steep limiting characteristic
- Suitable for all modern high-power IGBT modules
- Minimum switching losses
- Self-adapting system, acts only when needed
- Simply and safely configurable
- Competitive system costs

The system is self-adapting in that once the active clamping behavior has been set, the AAC feedback loop automatically distinguishes between normal switching, where low losses are the primary focus, and short-circuit turn off, where the main emphasis is placed on keeping control of transient overvoltages maintaining a limited current change rate di/dt.

SCALE-2® provides an effective solution for overvoltage protection. The other important requirements for high-voltage IGBT drivers will be considered with reference to SCALE-2® [3].

Short-circuit detection

Short-circuit detection is usually realized in IGBT drivers by monitoring the saturation voltage VCE(sat). The circuit checks if during the first 10µs after turn-on the collector emitter voltage has dropped below a pre-defined level depending on the IGBT type. If the collector voltage does not fall below that level, a short-circuit condition is assumed and the driver will turn off. Figure 5 shows two simple circuits used in SCALE products that provide a collector sense.

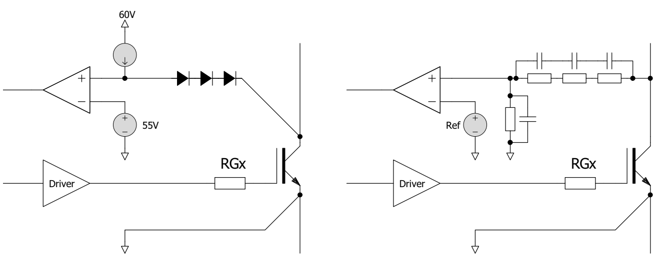


Figure 5: Two collector voltage sense circuits used in high voltage IGBT drivers

The circuit on the left is appropriate for a 3300 V IGBT driver. The current source provides a current of a few mA into the collector of the IGBT. The comparator checks if the collector voltage lies above or below the trip level of 55 V. Higher voltage IGBTs require trip levels of up to 500 V. For these, the circuit on the right would be used. This solution uses a high-voltage divider to scale down the collector-emitter voltage.

The SCALE-2® technology uses a new VCE monitoring circuit that replaces the high-voltage sensing through diodes (see Fig. 3) by a simple resistor chain. Its main advantage is precise, direct voltage measurement allowing any abnormal increase in IGBT saturation voltage to be detected. Direct VCE sensing is no longer influenced by parasitic capacitances of the high-voltage diodes and their pronounced temperature dependence. The dynamic VCE monitoring circuit enables a better fit to the VCE curve of the IGBTs.

The SCALE-2® drivers provide a tightly regulated +15 V gate voltage in IGBT on-state. This feature is particularly advantageous in short-circuit conditions. The high dv/dt values occurring in this failure mode inject considerable amounts of charge into the gate node (Miller feedback). This feedback causes the gate voltage to rise during a short-circuit, resulting in excessively high levels of short-circuit current. This is a dangerous situation for the IGBT module. SCALE-2® drivers use a Schottky diode clamp to limit the gate voltage to safe values (see Fig. 9). The stable 15 V supply absorbs the Miller feedback charge and safe operation of the IGBT is maintained.

Power and speed

The SCALE-2® ASIC chipset, used for example in the SCALE-2® driver cores 2SC0108T and 2SC0435T, introduces a delay of less than 100 ns in the turn-on and turn-off signal paths. This delay time is delivered at a superior repeatability of +/-10 ns including jitter and ageing. A comparison with other technologies such as optocouplers shows that the propagation delay time is typically as high as 500 ns with a mismatch of several 100 ns. Uneven ageing of separate drive channels is a common problem for fiber optics and optocoupler systems. In contrast, SCALE-2® drivers maintain symmetrical switching of the driver channels. The clear user advantage is constant IGBT losses over the lifetime of an inverter, especially in case of parallel connected IGBT modules.

Parallel connection of IGBT modules

In many high-power applications, the required current levels can only be achieved by connecting two or more IGBT modules in parallel. With these configurations, tight control and monitoring of the IGBT modules is essential as any out-of-control failure could have disastrous consequences. The power delivered by each module must balance the other and switching must be synchronized to avoid dangerously high commutation currents.

The property of tightly controlled delay paths provided by SCALE-2® is efficiently used to drive 130 x 140 mm and 130 x 190 mm high-voltage IGBT modules synchronously in the master-slave topology made possible with the following high-voltage driver families from CONCEPT:

- 1SP0635: 1.2 kV - 3.3 kV IGBT modules with 6 kV isolation voltage
- 1SP0340: 4.5 kV IGBT modules with 6 kV isolation voltage
- 1SP0335: 3.3 kV - 6.5 kV IGBT modules with 10.2 kV isolation voltage

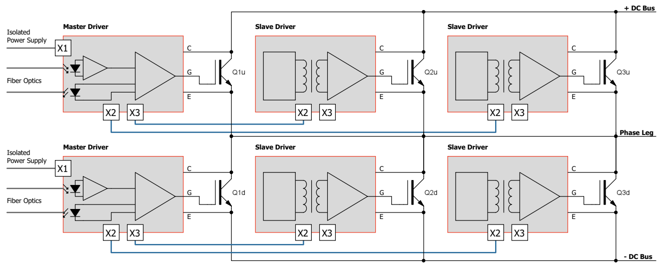


Figure 6: Principle of parallel connection of 1SP0335 drivers with one master and two slaves in a half-bridge configuration (example)

The new family of SCALE-2® drivers from CONCEPT [4] provides a master-slave configuration for IGBT paralleling with plug-and-play ease of implementation. Users need only mount the drivers onto the corresponding IGBT module. The system can then be put into immediate operation with no further development or matching effort. Figure 6 shows the principle of master-slave configuration [5].

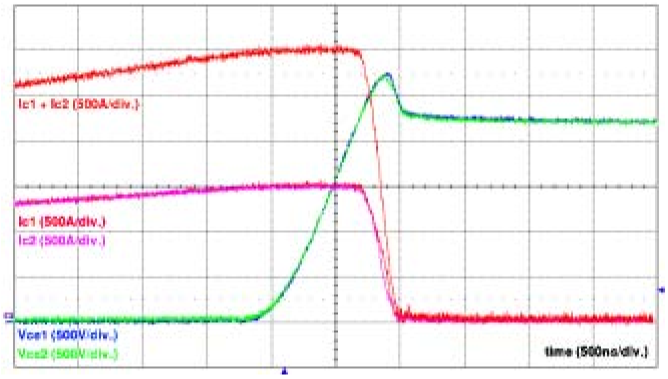


Figure 7: Turn-off of two parallel-operating IGBTs with 1SP0635

The master is equipped with a fiber-optic interface and global fault management. The slaves are connected to the master by a bus cable which distributes the common command signal and the secondary-side supply voltages.

Because of the extremely low jitter and low variance of propagation delay of the SCALE-2® chipset, all IGBTs operate at virtually the same gate-driving voltage as illustrated in Figure 7. The architecture provides unlimited and easy scalability for a wide range of applications and power levels.

Figure 8: 1SP0340V2M0 master driver mounted on a IGBT module

The master-slave architecture provides the following additional advantages in parallel IGBT configurations:

- Dynamic Advanced Active Clamping temporarily allows extremely high DC-link voltages. This is a particular advantage for traction, windmill and solar converters.
- Dynamic short-circuit detection to protect the IGBTs fully from any kind of short-circuit while fully utilizing the collector current capability of both low conduction-loss optimized and fast-switching IGBTs.
- Centralized monitoring of gate-emitter voltages of all individual drivers by the master to ensure correct parallel operation.

The slave modules can only be used in conjunction with the master drivers when parallel connection of IGBT modules is required. Up to three slaves can be connected with one master.

The slave module in Figure 10 illustrates the exceptional level of integration achieved with the overall component count yielding a very high MTBF.

Power supply and electrical isolation

The drivers of the 1SP0335 and 1SP0340 families are modular in the sense that the driver card and power supply (DC-DC converter) are two separate units. The power supply unit is designed as a separate module attached close to the IGBT (see Fig. 11) and is available in different versions up to a specified operating voltage of 12 kV.

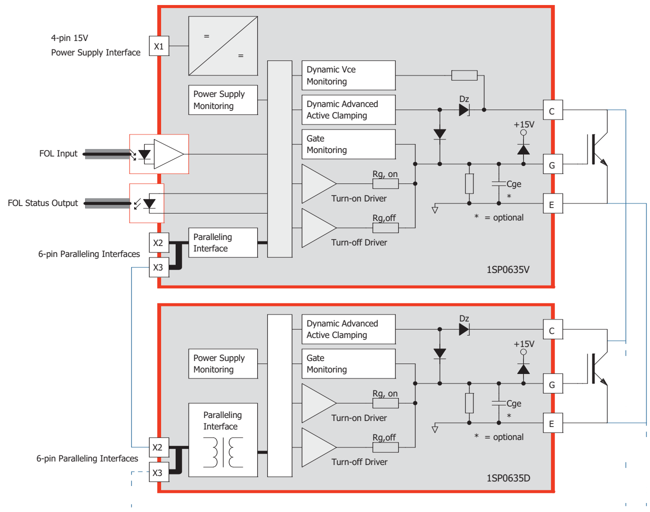


Figure 9: Master slave architecture of SCALE-2® plug-and-play driver 1SP0635

With this modular concept, any driver unit developed to match a specific IGBT module can be used for any required insulation specifications. Only the separate power supply unit must be chosen or adjusted to a specific application. On the basis of this concept, the drivers for IGBTs in the voltage range from 3.3 kV to 6.5 kV can be implemented in 2-level, 3-level and multi-level inverter topologies.

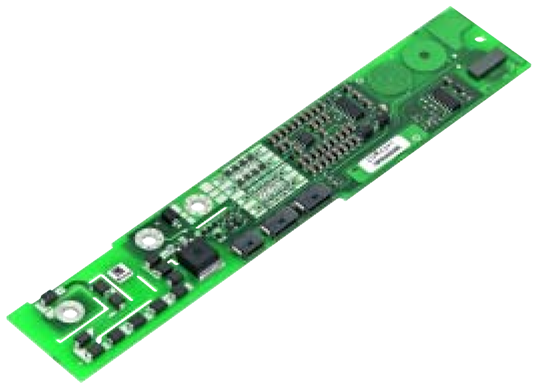


Figure 10: 1SP0340D2S0 slave module

The 1SP0340, the latest member of the high-voltage SCALE-2® driver family, provides a new level of performance and economy driving 4.5 kV IGBTs in a 6 kV isolation package. With performance and functionality optimized at 4.5 kV operation, the 1SP0340 is constructed in a smaller footprint and using fewer components than previously required. Yet the module provides all the advanced features of SCALE-2® - Direct parallel connection, dynamic advanced active clamping, gate-voltage Miller clamping and dynamic desaturation protection.

Plug-and-play design and implementation

All the components required for the optimal and safe driving of the relevant IGBT module such as smallest gate resistors designed to minimize switching losses, gate clamping, etc. are included on the driver. It includes components for setting the monitoring turn-off trip level and the response time. Its plug-and-play capability means that it is ready to operate immediately after mounting. The user needs invest no effort in designing or adjusting the driver to a specific application.

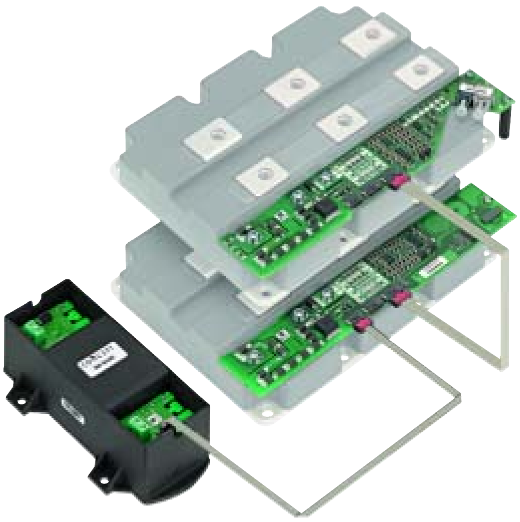


Figure 11: 1SP0340 (right) with power supply ISO5125I (left)

These features enable system designs with higher DC voltages and less derating in parallel operation of IGBT modules, leading to better usage of the silicon and thus lower overall system cost.

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