Benefits of System-oriented IGBT Module Design for High Power Inverters

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Abstract

Although today IGBT modules with blocking voltages up to 6500 V are available there are many applications that require the design of inverters with ratings close to or even beyond 1 MVA with 1200 V or 1700 V devices. The requirement to connect to the low voltage grid, system requirements for high switching frequency or voltage limits for associated system components may restrict the use of higher voltage inverters. On the other hand using lower voltage devices may result in lower cost because these devices are manufactured in larger quantities. Typical applications for such inverters are industrial variable speed drives, UPS-systems, heavy duty commercial vehicles as well as grid connection of microturbines or renewable energy systems like windmills or large solar farms. Designing power electronic circuits to switch currents in the range of several 1000 A within fractions of a microsecond is a demanding task for every engineer and requires a sound knowledge how to transform the implications of Maxwells laws into blueprints for busbars. Paralleling of smaller units helps to minimize stray inductances but unfortunately creating the new task of ensuring proper current sharing. Beside these technical challenges the power electronic designer is more and more faced with cost targets difficult to meet. In the beginning of power electronics, with the power semiconductor devices being the biggest item in the quantity survey, it was wise to address this just by trying squeeze as much current out of it as possible. Today with power semiconductors getting less expensive and other components raising in cost it may be advantageous to optimize in a different way.

Introduction

For the design of high power semiconductor module device focused considerations as well as system oriented aspects have to be taken into account. Some typical aspects to cover from the device point of view are internal current sharing between the paralleled dies, minimizing internal inductances and considering thermomechanical issues to provide sufficient useful lifetime regardless of the inherent CTE-mismatches of the different materials used. Typical system aspects to take care for during module design are to enable easy and efficient heatsinking, to provide means for a low inductance DC-link connection and to consider that gate drive circuits need to be placed close to the control terminals. Further it is always an important issue in the high power range to allow easy parallel connection since changing to a bigger module isn’t an option any more.
The following sections will show how the size of the PrimePACK™ baseplate, prefer the half bridge module approach and the increased junction operating temperature provide advantages for system design regarding choice of heatsink and minimizing DC-link inductance. Later switching waveforms for a single module as well as for paralleled modules will be presented. Results on static and dynamic current sharing will be discussed separating device, driving and power circuit layout impact. In the last section short circuit switching waveforms confirming the advantages of the suggested approach for inverter design will be presented.

Thermal design considerations

For inverters in the high power range the two most important design decisions are the choice of heatsink arrangement and the choice if single ore dual modules are to be used. Both topics are closely related to each other and will be discussed for the following two examples:

- Three-phase inverter with 800..1000 A nominal module current (at $T_c > 80$ °C)
- Phase-leg with a module nominal current in the range of 2400..3000 A

Technologies for heatsinks

Some of the applications listed above may benefit from using water-cooled heatsinks. Using watercooling may be especially advantageous when other parts of the equipment rely on water cooling like induction heating equipment or lasers, when availability of clean cooling air is limited, when final removal of waste heat is only possible by aircondition or when space available is very restricted. There are only few cases where water cooling currently is applied beside these exceptions. Due to that background the discussion on thermal considerations in this paper will be limited to aircooled heatsinks. For aircooled heatsinks there is a wide range of technologies available which are listed here in the order of increasing performance:

- Extruded heatsinks
- Extruded heatsinks overcoming the fin length to fin spacing limitation by new manufacturing technologies, e.g. by fitting separately extruded baseplate and fins together
- Folded fin heatsinks
- Heatsinks using material different from aluminium
- Heatsinks with heatpipes

Due to the fact that the cost increase for the more advanced technologies may be significant, inverters in the power range under consideration typically are designed using heatsinks of one of the first three categories. If a design does not seem viable using one of these technologies it is usually more economical to increase the current rating of the modules than to use more advanced heatsinks.

Contrary to the approach usually preferred by electrical engineers for choosing the heatsink the following process of selecting a heatsink will not start with the module but with the enclosure and the requirements imposed by the end user of the inverter. Power electronic equipment in the power range under consideration is usually installed in control cubicles having a height of 1,80 m to 2,20 m and being placed in front of a wall. Aircooled heatsinks are usually mounted at the backside of these cabinets. An alternate approach uses racks where several heatsinks placed above each other are cooled by a horizontal airflow entering the cabinet at the front and leaving it at the backside. In both cases the most important dimension for the end user is the width of the cabinets. To limit overall equipment size it is therefore advantageous to use a heatsink as long and deep as possible but with limited width. Due to limits on the fin length to fin spacing ratio caused by the restrictions of the extrusion process it is not possible to manufacture heatsinks having fins longer than 100 mm at an appropriate spacing by extruding. Heatsink suppliers have overcome this limitation by new technologies like extruding baseplate and fins separately or the folded fin heatsink. Folded fin heatsinks consist of a baseplate and fins made from sheet metal connected together by brazing. Applying these technologies is more efficient than to rely on heatspreading within the baseplate of an extruded heatsink laterally.

Size of heatsink

Doing thermal design for high power inverters is not as easy as for lower power ratings. Whereas for low power heatsinks the thermal resistance is usually given for a specific package mounted on that heatsink, large heatsinks are characterized by applying a uniform power density to the mounting surface. In a real application not the whole area will be covered with components, the distribution of power dissipation will not be the same for all operating conditions and even below one module the heatflow will not be uniform. Of course today there are powerful thermal simulation tools available allowing to analyze a given setup in details. However, with such tools available it is often overlooked that the task of an engineer is usually not to analyze a given setup but to search for an optimal solution. At least for initial steps using analytical methods and available experimental data provides more benefits. As an example the thermal resistance of differently sized heatsinks for the same module will be calculated as the sum of value R_{thhsa} given in the data provided by a heatsink supplier [1] and the spreading resistance R_c calculated according to [2]. Fig. 1 shows the result for a fictive module with a baseplate size of 150x150 mm² mounted on heatsinks ranging from 150x200 mm² to 400x 300 mm² at cooling air speed of 11 m/s.

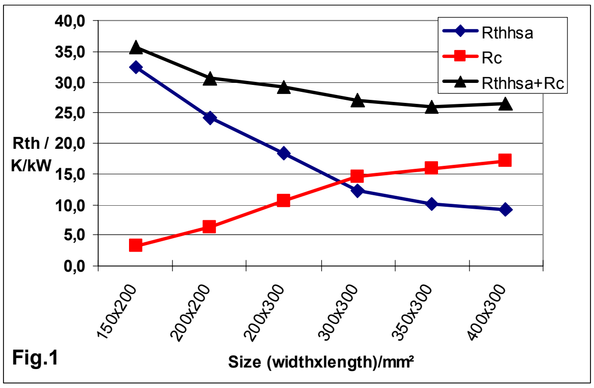


Fig.1

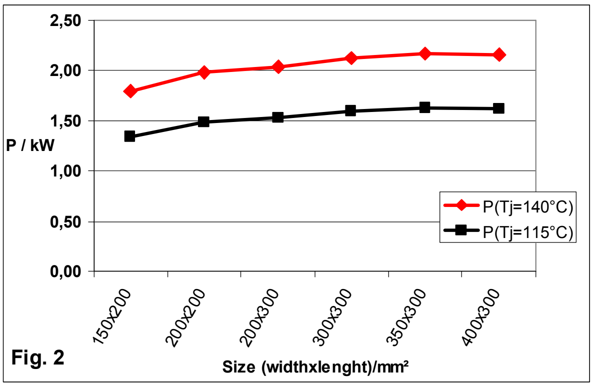


Fig. 2

Fig. 1: Thermal resistance of a 150x150 mm² module on different heatsinks
Fig. 2: Power dissipation of a 150x150 mm² module at different junction temperatures

Two conclusions can be derived from that figure:

- The benefit gained in R_{thhsa} by increasing heatsink size is compensated to a large extend by spreading resistance R_c caused by lateral heat conduction in the baseplate.
- As a result increasing heatsink size far beyond module baseplate size will only provide marginal improvement in total R_{th} of the heatsink.

Other options to improve heat dissipation

But what options are available to increase power dissipation if neither changing to a higher performance heatsink technology nor an increase in heatsink size is feasible? For a given thermal resistance the only way to increase power dissipation is to increase heatsink temperature. Whereas most IGBT power modules up now to no have been limited to an operating junction temperature T_{vjop} of 125°C recent advances in semiconductor and module technology now allow an increase of T_{vjop} to 150°C [14]. What benefit this can provide for the choice of a heatsink is depicted in Fig. 2. For this example it is assumed that the module introduced above is operated in continuous operation with a junction temperature 10 K below the maximum operating junction temperature to provide some headroom for overload conditions. For the module and the interface to the heatsink a thermal resistance of 20 K/kW in total is assumed. Calculations are based on 40°C ambient temperature.

The increase in junction temperature provides more gain in power dissipation capability than increasing the heatsink four times, a surprising result. For a smaller size module the comparison would be less impressive but still significant.
Unfortunately some restrictions have to be considered when operation at increased junction temperature is intended as described above:

- The temperature swing for power cycling will increase
- The large area solder connection from DBC to baseplate is subjected to higher temperature swing, thermal cycling specifications have to be considered
- Due to increased heatsink temperature ambient operating temperature for other components close by will increase
- Losses will increase slightly, for typical operating conditions an increase by 0.3% per K can be expected

In spite of this operation at elevated heatsink temperature is an attractive option for many applications.

Comparing different choices for module and mounting

Now, for the inverter 62mm-Modules (two single switch modules in parallel), IHM Dual modules and EconoPACK+™ will be considered. Placing the phase-legs on the heatsink side by side doesn't allow reducing the width to values lower than 400 mm. Smaller width is only possible if the phase legs are arranged one above each other. But in this configuration the phase legs are thermally stacked. The uppermost phase-leg will be subjected to the worst cooling conditions and will limit the available output current.
For the high current phase leg all the designs described above can be used by paralleling the three phase legs. An additional option is to use two single switch IHM modules with 140x190 mm baseplate [15]. This leads to a compact design but upper and lower switch are thermally stacked. If the total stray inductance is calculated for this setup the resulting value of 20 nH is significantly higher than of the setups consisting of multiple paralleled halfbridges e.g. six segments of EconoPACK+™ in parallel resulting in only 3.3 nH.

As described above all available options to design high power IGBT inverters suffer from some severe drawbacks if optimum system integration is considered. A small width of heatsink without drawbacks in thermal design is only possible if the module itself has a narrow but long footprint. Of course also in this case there will be some thermal stacking but for chips paralleled inside a module positive temperature coefficient of V_{CEsat} and V_F will ensure proper distribution of losses. Integrating halfbrigdes into one module provides low internal stray inductance. Increasing operating junction temperature avoids need for driving heatsink performance beyond reasonable limits. These considerations led to design of the PrimePACK™-module already presented in [9], [13].

Driver and the influence on dynamic IGBT module performances

Regardless of considered inverter power the suitable driver selection when IGBT modules with operation junction temperature of 125°C applied might be done quite easy. Ambient temperature around driver in this case is usually below 85°C. The availability of various IGBT drivers as an IC or PCB with driving current up to ±30A and output power till 15W per channel or more additionally, ensuring many isolating voltage classes is very good. The appropriate driver choice becomes more challenging when an engineer intends to use the newest IGBT modules introduced by Infineon Technologies AG with operating temperature of 150°C. Despite of many advantages the technology provides to the system design the increased junction temperature may increase the operating ambient temperature for surroundings e.g. for IGBT driver. In this case the appropriate driver selection must be done with modified criteria and the technology must be split up accordingly to the inverter power and dedicated module to be driven:

- Small power inverters employs IGBT modules which usually driven by drivers IC
- Modules used in medium power inverters are usually driven with similar to small power inverters drivers IC but usually with more powerful SMPS and additional amplifiers which results with increased driving power
- High power systems in most cases require specialized PCB drivers with highest output power

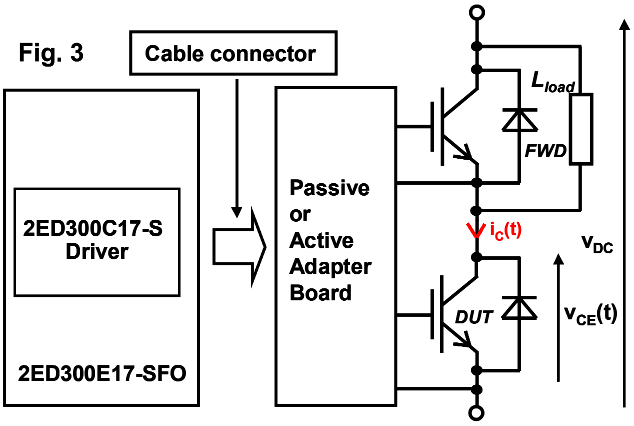
In order to minimize inverter volume and its cost in small and medium power systems the driver is mostly placed as close to the controlled IGBT gate as possible. Due to this IC location the increased ambient operating temperature has to be taken care of. With drivers based on Coreless Transformer technology like the single channel driver EiceDRIVER™ 1ED020I12-S [3] or the dual channel (half-bridge configuration) 2ED020I12-FI [4] [5] IGBT driver restrictions from LED degradation known form optocoupler based drivers are overcome.

Due to different driving requirements for IGBT modules in high power applications the usage of listed above IC drivers without fundamental changes is rather not possible and becomes more unrealistic when parallel module operation is needed. Usage of the powerful PCB driver as a universal solution for driving one module and many in parallel under these circumstances seems to be a proper choice.

Due to the relatively large IGBT driving power necessary in this type of applications and amount of heat returned by heatsink the probability of operating the driver with ambient temperatures even above 85°C is very likely. Unfortunately, there are no drivers on the market matching to the exacting temperature and power requirements. One possible method to take advantage of elevated module junction temperature and make use of existing driver technology without overheating phenomena risk is moving the driver into cooler inverter area. Naturally this means that the basic driver functions are split up in two. A kind of adapter board as an interface between driver core and driven IGBT module must be applied. Based on EiceDRIVER™ 2ED300C17-S [6] driver board form Infineon a system with two kinds of adapter board basically ensuring the same functionality in this paper is proposed and discussed in detail:

- passive adapter board – gate current is provided by the driver core
- active adapter board – gate current partially generated in driver core but mostly supplied by the adapter board, this solution allows on providing additional useful functionalities

In both cases the 2ED300C17-S provides all other driving functions like proper gate-emitter voltage, galvanic isolation, logic and short circuit protection. The basic system configuration consisting of a driver and an adapter board is shown on Fig. 3. Both parts are connected by an appropriate cable. Great effort was contributed to optimise and compare Active Voltage Clamping and especially to evaluate the limitation of overvoltages when the IGBT turns-off high currents. In order to describe a universal system approach suitable for driving as well a single module and as paralleled modules single IGBT dynamic performances will be discussed first. All presented measurements here were done with standardized laboratory setup and new developed PrimePACK™ module – FF1000R17IE4 [8].



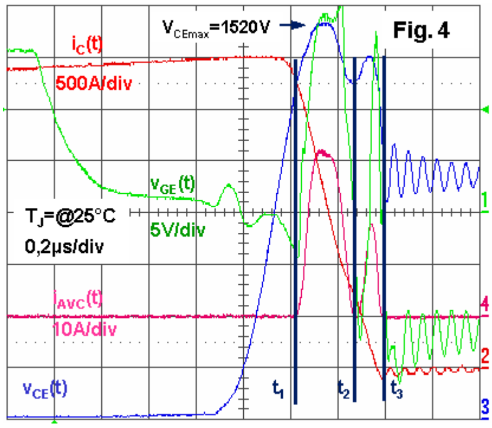


Fig. 3: Block diagram showing the driver idea

Fig. 4. Waveforms of FF1000R17IE4 during turn-off, V_{DC}=900 V, I_C=3 kA, E_{off}=1150 mJ, V_{CEmax}=1520 V, R_{Goff}=1.8 Ω, L_Q=66 nH, T_J=25 °C

Passive adapter board

One channel of the operational circuit diagram of the Passive Adapter Board is shown in Fig. 5a. The PCB containing this circuit for two IGBTs in half-bridge configuration is shown in Fig. 5b.

The components and their functions on this board are:

- Desaturation diodes used for collector-emitter saturation voltage monitoring
- Active Clamping diode chain, protecting IGBT from temporary V_{CE} overvoltages during turn-off
- Gate-emitter clamping diodes – protecting gate and limiting collector current during short circuit
- External gate resistors

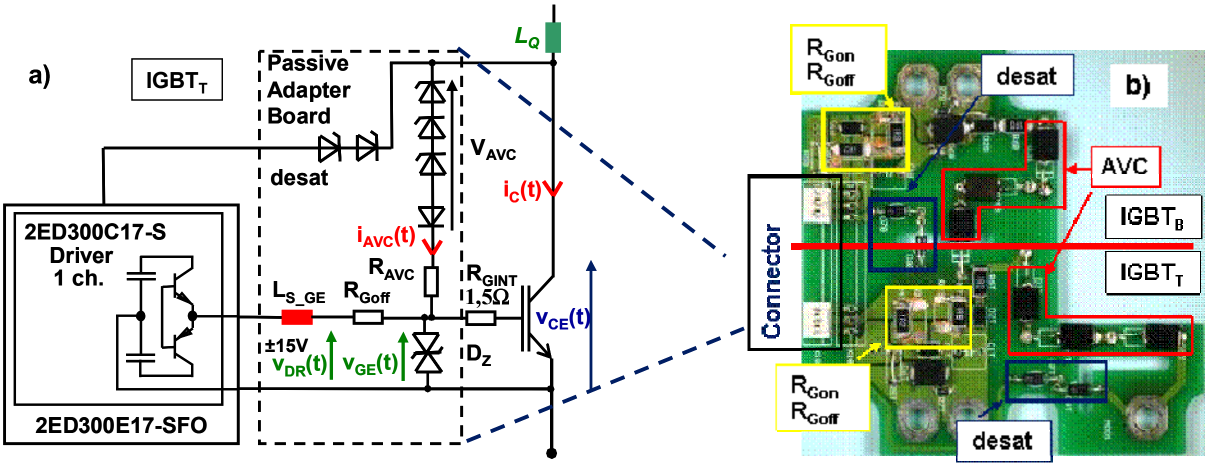


Fig. 5. Operational circuit and PCB of the Passive Adapter Board

Since no active components are placed on the adaptor, the total gate current has to be supplied from the driver via the cable. With increased gate inductance the gate current during the rise of collector current is higher. As a consequence significant impact of the parameter in this connection on the switching performance can be expected [7] [9].

Beside turn-on and turn-off in the normal operatig range IGBT turn-off at high currents must be also considered. When V_{CE} voltage reaches the level of 1300 V (t_1- t_2 time period on Fig. 4) than diodes in Active Voltage Clamping chain start conduct current called i_{AVC}. One part of the i_{AVC} goes to the IGBT gate – limited by R_{GINT} and the second part is conducted and limited by R_{Goff}. Since this current diversion can not be avoided the Active Clamping diodes have to operate at high currents to provide useful voltage limitation. This may cause high power dissipation and a poorly defined clamping voltage.

The situation when dI_C/dt has been limited in order to keep the V_{CEmax} voltage bellow maximum IGBT voltage capability is presented in Fig. 4.

It is very important to notice two facts:

- v_{GE} voltage shown on Fig. 4 is the voltage at the modules gate terminals, real gate voltage is different due to module internal gate resistors
- The dI_C/dt during turn-off can be successfully changed using relatively simple control strategy. Use of the advanced methods like described in [10] [11] is not necessary

Active adapter board

Functions of the active adapter boards are similar to passive version presented in previous paragraph. Additional amplifier called booster is implemented. This booster is used for the ordinary control signal from the driver as well as to implement a function called boosted active clamping. The one channel operational circuit and the PCB are shown in Fig. 6. With the active adapter board placed directly on the module switching performance of the IGBT gets independent from cable length. ´

With the signal from the clamping diodes being also supplied to the booster input, diverting a large amount of i_{AVC} to R_{Goff} is avoided. When V_{CE} reaches 1300V (Fig. 7) active clamping diodes (Fig. 6) start to conduct current. Great part of the current is shared between IGBT gate (limited by R_{GINT}) and driver output (limited by R_{Goff}) but small part creates positive voltage on the bipolar amplifier input - v_{boost}. The amplified voltage stays as long as V_{CE} is above the diode chain steady voltage (t_1-t_2 on Fig. 7) and finally reduces the i_{AVC} current peak. Current in the clamping diodes in that way is reduced and improved performance of clamping is achieved as can be seen in Fig. 11 and Fig. 12.

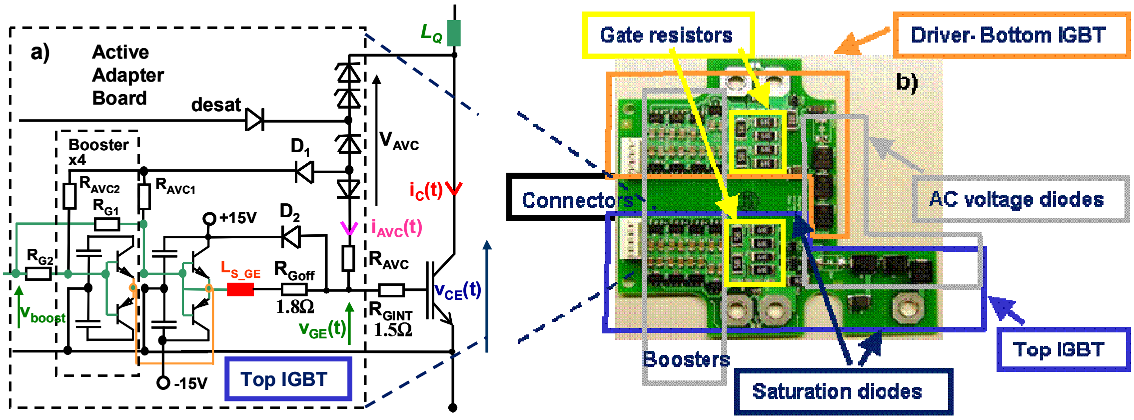
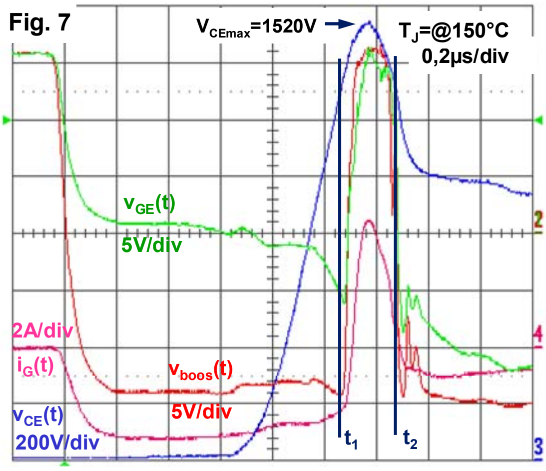


Fig. 6. Operational and practical circuit of the Active Adapter Board



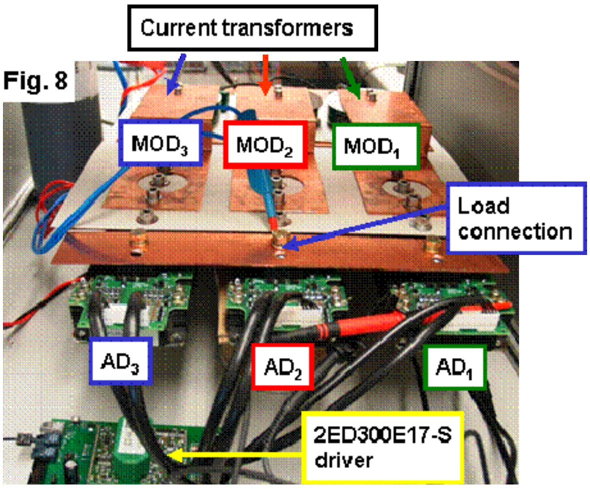


Fig. 7. Waveforms of FF1000R17IE4 during turn-off, V_{DC}=900 V, I_C=2.5 kA, E_{off}=940 mJ, V_{CEmax}=1520 V, R_{Goff}=1.8 Ω, L_Q=66 nH, T_J=150 °C

Fig. 8. Universal laboratory test setup for PrimePACK™ modules investigation

Experimental results

To prove the claimed advantages of the new module and to support engineers in designing inverters many switching tests for a single module as well as for three modules in parallel connection using presented adapter boards have been performed. The two systems with different adapter boards and the influence on IGBT dynamic performances for a single module will be presented at first. Based on the gained knowledge the series of measurement results with modules connected in parallel will be shown later.

Test setup

The test setup consists of a low inductive and symmetrical bus-bar arrangement with possibility of connecting three PrimePACK™ modules in parallel with bus capacitance of 6.3mF is shown in Fig. 8. Three identical current transformers are inserted to the DC-link connection to monitor individual currents of paralleled modules. All investigations were performed with double pulse test and inductive load. The single module was investigated on position MOD2.

Single module - the adapter boards comparison

Fig. 9 and Fig. 10 show that the cable length between driver and adapter board changes E_{on}, E_{rec} and P_{fwd_peak} at IGBT turn-on when Passive Adapter Board is used. Larger cable length lead to faster turn-on (Fig. 9). Increased distance from 10cm (L_{S_GE}=0.8 µH) to 50cm (L_{S_GE}=1.25 µH) reduce E_{ON} by 38%. But this speed up should not be regarded as an advantage because also diode recovery has to be considered as it is shown in Fig. 9 and Fig. 10.

The E_{rec} increases by 36% and P_{fwd_peak} increases by 55%. In this case the module is operated outside of the specified range and local diode overheating and device failure may be the consequence. To compensate for the unwanted speed up, the gate resistor value (R_{Gon}) must be increased form the datasheet value [8] of 1.2 Ω to 1.8 Ω. This change protects the module but increases turn-on propagation delay $t_{d\ on}$.

In case of active adapter board the distance between booster and auxiliary gate connectors stays always the same. This results with stable gate inductance (L_{S_GE}=0,63 µH) and stable dynamic transients. Nevertheless, obtained IGBT losses again are not like in datasheet. E_{on} increased by 34% compared to datasheet value (E_{on}=240 mJ) but E_{rec} stays nearly unchanged.
To achieve datasheet value for E_{on} the turn-on gate resistor R_{Gon} was decreased down to 0.6 Ω. It is necessary to point out that in situation when power is generated close to IGBT the changes on R_{Gon} value influence mostly E_{ON} losses, however recovery diode losses and diode recovery diode peak power are stable.

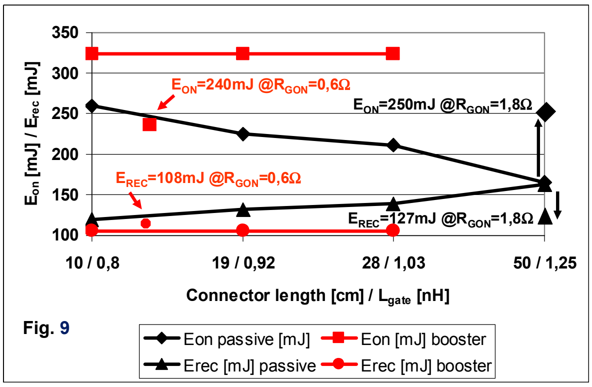


Fig. 9

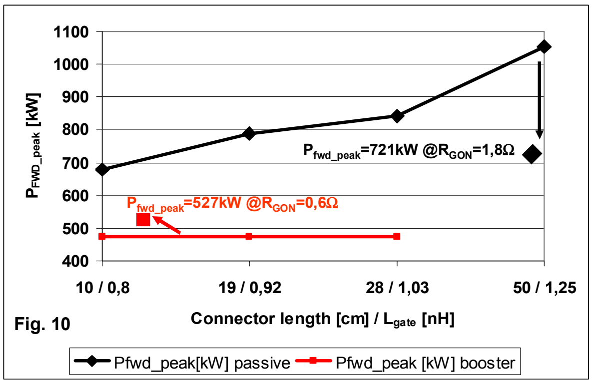


Fig. 10

Fig. 9. Comparison of energy losses (E_{ON}, E_{rec}) during turn-on transients versus connector length (recalculated to inductance) for passive and active adapter board when: R_{Gon}=1.2 Ω, I_{Con}=1 kA, T_J=25°C, V_{DC}=900 V
Fig. 10. Comparison of maximum FWD diode peak power during IGBT turn-on transients versus connector length (recalculated to inductance) for passive and active adapter board when: R_{Gon}=1.2 Ω, I_{Con}=1 kA, T_J=25°C, V_{DC}=900 V

Fig. 11 and Fig 12 show how using a booster on the adaptor board decouples maximum collector voltage V_{CEmax} and maximum current in the clamping diodes from the choice of R_{Goff}. It can be noticed that active version limits the i_{AVC} and provides better V_{CEmax} voltage limiting in contrast to passive version. Although measurement was performed for various R_{Goff} gate resistors. Values for practical use should not be lower than recommended by the module manufacturer [8].

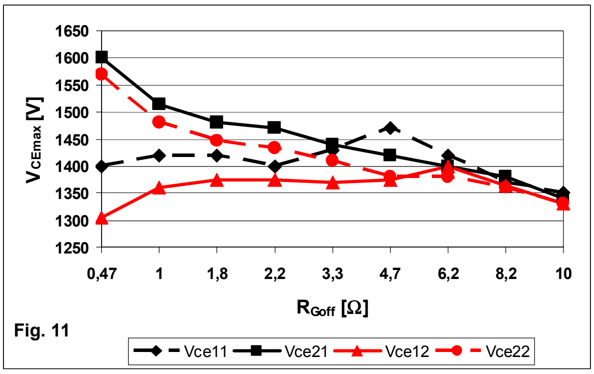


Fig. 11

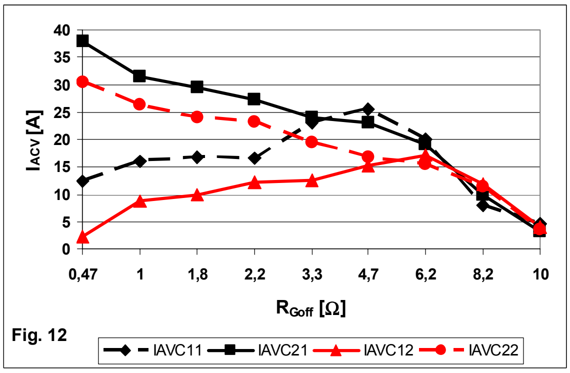


Fig. 12

Fig. 11. / Fig 12. Comparison of V_{CEmax} / I_{AVC} during turn-off transients versus gate resistor values R_{Goff} for Passive and Active Adapter Board when: T_J=25°C, V_{DC}=900 V and indexes: 11- I_C=1 kA passive board, 21 - I_C=2 kA passive board, 12 – I_C=1 kA active board, 22 – I_C=2 kA active board

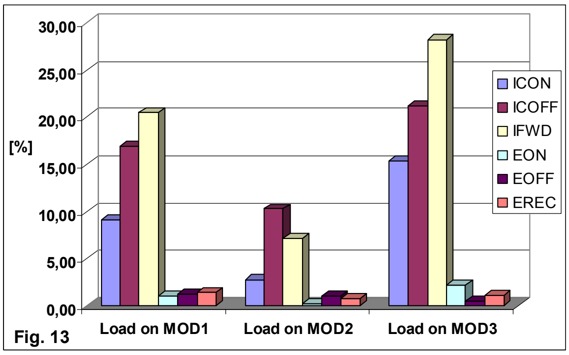
Modules in parallel - the optimal configuration

When modules are connected in parallel the dynamic and static collector current balancing is a key factor affecting modules utilisation at given load conditions [16]. As the problem is well known by engineers it is often intended to increase the output system power without paralleling of modules [7] [12]. Laboratory researches presented here do not focus on the influence of a deviation in module parameters but indicate how driver configuration can help to obtain better current balancing without using matched devices. Additionally the influence of load connection position under normal and short circuit operation are also indicated.

Fig. 13, Fig. 14 and Fig .15 show the static and the dynamic current unbalance with different driving strategy and load connections (Fig. 8) at 1 kA current V_{DC}=900 V. The static current imbalance is calculated as a maximum deviation from mean value of paralleled modules. To separate deviations in switching speed from static current sharing, the dynamic losses are normalised to the actual current first. Hence deviations of this value (mJ/A) from mean are shown.

Modules used during investigation were taken from production without any parameter selection and their static voltages data are as follow:

- MOD1: V_{CEsat} @1kA = 2.21V; V_F @1kA = 2.03 V
- MOD2: V_{CEsat} @1kA = 2.19V; V_F @1kA = 2.06 V
- MOD3: V_{CEsat} @1kA = 2.27V; V_F @1kA = 2.04 V



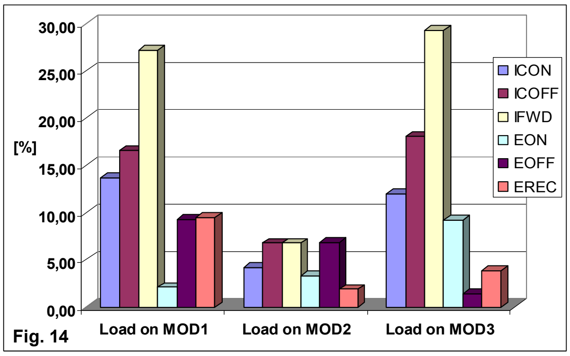
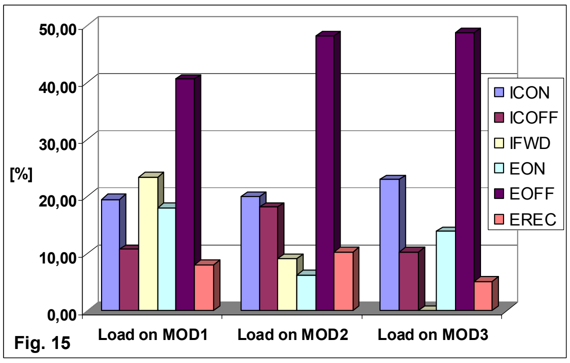


Fig. 13. IGBT and diode static current sharing and energy losses comparison for driver configuration: one driver and 3x Active Adapter Board

Fig 14. IGBT and diode static current sharing and energy losses comparison for driver configuration: one driver and 3x Passive Adapter Board



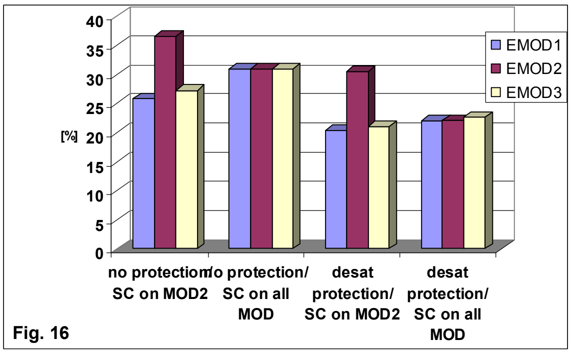


Fig 15. IGBT and diode static current sharing and energy losses comparison for driver configuration: 3x driver and 3x Active Adapter Board. Time delay between drivers is less than 12 ns

Fig 16. IGBT energy losses comparison for driver configuration: one driver and 3x Active Adapter Board with and without short circuit protection (10 µs, max. duration for short circuit)

If one driver is used the lowest static current imbalance for an IGBT and diode is obtained when load is connected to middle module (MOD2) (Fig. 13, Fig. 14), regardless of adapter board type used. Using three separate drivers causes three times higher deviations.

Dynamic losses are mostly related to the current switched for systems with one driver. In the system with three independent drivers an additional imbalance in dynamic losses ocurs. The different results might be explained as follow:

- One driver and active adapter boards leads to exactly the same driving signal for paralleled modules with no influence of cable lengths. Additionally, controlled modules are highly decoupled on the gate side. Static current is shared accordingly to symmetry setup and dynamic performances are not influenced by driving conditions
- One driver and passive adapter boards: static current sharing is influenced by dynamic imbalances. IGBTs are not decoupled from gate side.
- Three different drivers: every module is controlled independently. Small difference with gate signal timing and voltages results in uncorrelated static current and dynamic losses distribution

Current imbalance during short circuit has direct influence on energy distribution shown on Fig. 16 and depends on the setup symmetry only and the location of the short circuit.

Conclusion

Impact of driver setup and other external parameters on static and dynamic current distribution have been investigated. With a given set of module parameters the most predictable results in parallel connection are provided when one driver and three active adapter boards are applied. Regardless on connector lengths this approach makes the IGBT operation stable when single module is operated. The system might be used for operating one module and parallel without any changes. Further this approach provides additional benefits regarding collector voltage clamping and thermal management of the driver

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