

Design Aspects for Inverters with IGBT High Power Modules

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Abstract

With regard to the blocking ability and efficiency of the new 3.3 kV IGBT high voltage modules (IHV) with nominal currents of 800 and 1200 A, these IGBTs have advanced into operating ranges which up to now had been reserved to GTOs.

While GTOs must usually be operated with additional snubber circuits, which have to limit dv/dt and di/dt to acceptable values for the device, no handicaps exist for IGBT with regard to permitted peak values for the current rate-of-rise. The voltage rate-of-rise can easily be adjusted by the gate-resistor. The possible renunciation of snubbers offers the chance to cost, weight and volume reductions for inverters applying IGBTs. But at the same time low inductive power circuits, which are necessary to fully utilize the IGBT's voltage rating, acquire a new meaning.

Beside general questions like determination of stray inductances and the discussion of appropriate low inductive components, ideas will be given to the electrical engineer and mechanical designer, how the construction of an inverter phase - consisting of high power modules as well as DC-capacitor, heat-sink and busbar - could be arranged advantageously in a low inductive manner.

Introduction

When switching current-carrying semiconductors overvoltage spikes, which are caused by parasitic inductances distributed within the power circuit, arise across the devices. For a safe operation of the inverter it must be ensured, that the maximum permissible blocking voltage of the semiconductor will never be exceeded even under worst-case operating conditions. Otherwise a destruction of devices has to be assumed.

With inverters in GTO technology the voltage and current rate-of-rise has to be limited at the semiconductor: at turn-off to typical values of 500-1000 V/ μ s to prevent a re-triggering by dv/dt and at turn-on to a di/dt of 300-500 A/ μ s to prevent a local overheating because of a restricted current spreading in the device. Since these switching parameters cannot be controlled by the gate-unit usually passive snubber networks must be provided to maintain the aforementioned operating conditions.

Beside the limitation of the voltage rate-of-rise across the GTO the snubber also offers a desirable overvoltage protection, since it is limiting the turn-off voltage peak, too. A comparatively low inductive construction technology is therefore only necessary within the snubber circuit of the GTOs itself. Stray inductances within the main circuit may be helpful to reduce the turn-on current stress.

Numerous types of snubbers are known and proven in GTO and bipolar transistor circuits. All of them require considerable constructive and additional financial expenditures for the inverter. Unwanted snubber losses have to be removed which can particularly reach considerable values at higher switching frequencies. On the other hand snubber networks, which allow a regeneration of the absorbed energy, need additional costly circuitry. For dimensioning and calculation of different snubber types see [1].

No handicaps exist with regard to permitted values for the current and voltage rate-of-rise as long as the limits erected in the reversed biased safe operating area diagram (RBSOA) for IGBT and diode as well as the short circuit safe operating area diagram (SCSOA) are kept. [2] Since the IGBT is gate-controlled these values can easily be maintained by following the manufacturer's recommendation about gate driving conditions. Therefore, the use of snubbers is not longer required, which offers considerable cost, weight, and volume reductions for inverters using IGBTs.

The protection against dynamic overloads, the retention of the safe operating area of the IGBT, must be safeguarded by the gate conditions when using no snubber. The simplest possibility to reduce the peak turn-off overvoltages is done by the choice of a higher turn-off gate resistor. The IGBT will be driven slower by this measure. The dimensioning has to be done for the worst-case condition, the short circuit turn-off. Though at operating points of nominal or lower current higher losses and switching times have to be taken into account.

A more elegant measure is to intervene actively into the switching process and to control the dv/dt as well as the di/dt by the gate. By this the IGBT is driven in each operating point with the same dynamic behavior independently of current and voltage height. Disadvantageously the lower values for current and voltage rate-of-rise also lead to increased switching losses which can only partly compensated by shortening the other sections of the switching event.

The simplest measure for the avoidance of improper high dynamic overvoltages is the elimination of their reason: the distributed inductances throughout the inverter and its components.

The IGBT module with its additionally integrated freewheeling diode promises considerable simplifications in the construction of the inverter in opposite to the GTO disc type device. Beyond that the possibilities offered by the choice of appropriate further circuit components and by the mechanical design of the inverter should be used to achieve optimal results with a view to an as low inductive as possible construction.

This essay shall give ideas to this.

Test circuit and switching curves

Fig.1 shows the principle of a half-bridge, used as test circuit, and the resulting voltage and current waveforms when switching IGBT1. The stray inductance L_σ , shown as a concentrated circuit element, represents all distributed inductances within the commutation loop, shown as striped area. This loop contains the circuitry, which the load current leaves at turn-off and, on the other hand, that circuit components where the current is built up.

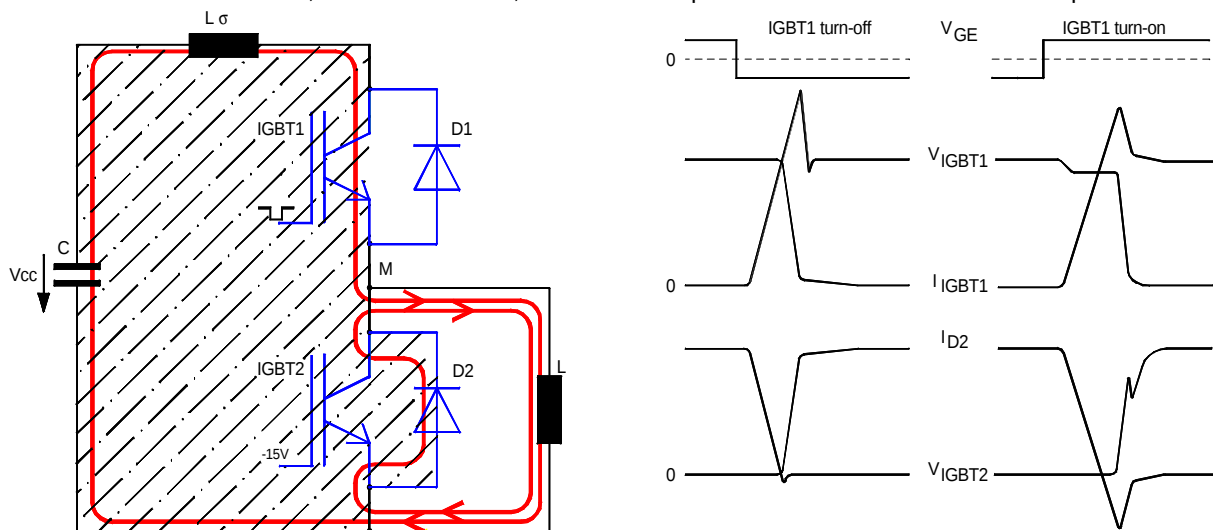


Fig.1: Half-bridge circuit with current and voltage waveforms when switching IGBT1

When turning off the upper IGBT1, its current, whose magnitude is maintained by the inductive load, commutates into the diode D2 of the lower module for free-wheeling. IGBT1 takes over voltage up to the value of V_{cc} and then, during the following fall time, the current is reduced through IGBT1 and at the same time is built up in diode D2.

The current rate-of-rise di/dt , dependent on current and voltage as well as temperature, is typically in the range of 3-6 kA/μs; values of up to 10 kA/μs can be reached under short circuit conditions. Due to the falling current a voltage drop of $-L_\sigma * di_{off}/dt$ occurs across the stray inductance L_σ . It is overlayed to the DC link voltage V_{cc} and seen as a voltage spike across the turning-off IGBT1. Permissible limits for turn-off current and overvoltage can be deduced from the RBSOA diagram of the IGBT.

If IGBT1 is turned on again, the load current commutates back from the branch of the diode D2 and is taken over again by IGBT1. Due to the rising current in this path a voltage drop of $L_\sigma * di_{on}/dt$ occurs over the stray inductance.

This reduces the DC link voltage as long as diode D2 is still conducting. No voltage is taken over, until the peak of the reverse recovery current is exceeded.

If this point is reached, it depends strongly on the recovery behavior of the diode, with which rate-of-rise the current goes through zero and with which rate-of-rise diode and anti-parallel IGBT must take over blocking voltage. High stray inductances and / or a snappy diode behavior may lead to considerable overvoltage spikes at this point.

A RBSOA diagram similar to the IGBT one was defined for the diode. It allows to be checked whether diode reverse recovery current and blocking voltage stay within the limits of the safe operating area under worst-case conditions. The diodes used in the IHV modules show a soft recovery behavior, which ensure a limited rate-of-rise of the reverse current and only lead to low overvoltages over the full temperature range.

Determination of stray inductances

As known the inductance of an electrical arrangement is defined by the volume which is penetrated by the magnetic field. From this it can be derived, that the spatial extension of the striped area in fig.1 is a measure for the over all stray inductance of the circuit. It must be the aim of the developer and design engineer to select appropriate, low inductive components and to arrange and connect the parts in such a way that a spatial optimization, i.e. the lowest possible volume, is reached.

The following diagram shows, which influence the use of various line types has both in the inside construction of the components and at the connections among the parts. The advantages of a stripline or coaxial cable can clearly be recognized. Striving for loop inductances in the range below 100 nH, the use of separate round wires should be avoided even for shortest connections.

A calculation of the resulting inductance of a construction is usually not possible due to the complex, geometric layout of the complete system. Besides an estimation based on experience and / or available data sheet values the inductance is commonly measured by the current rate-of-rise in combination with the overvoltage peak at turn-off or by the voltage drop across the IGBT when switching under short circuit conditions.

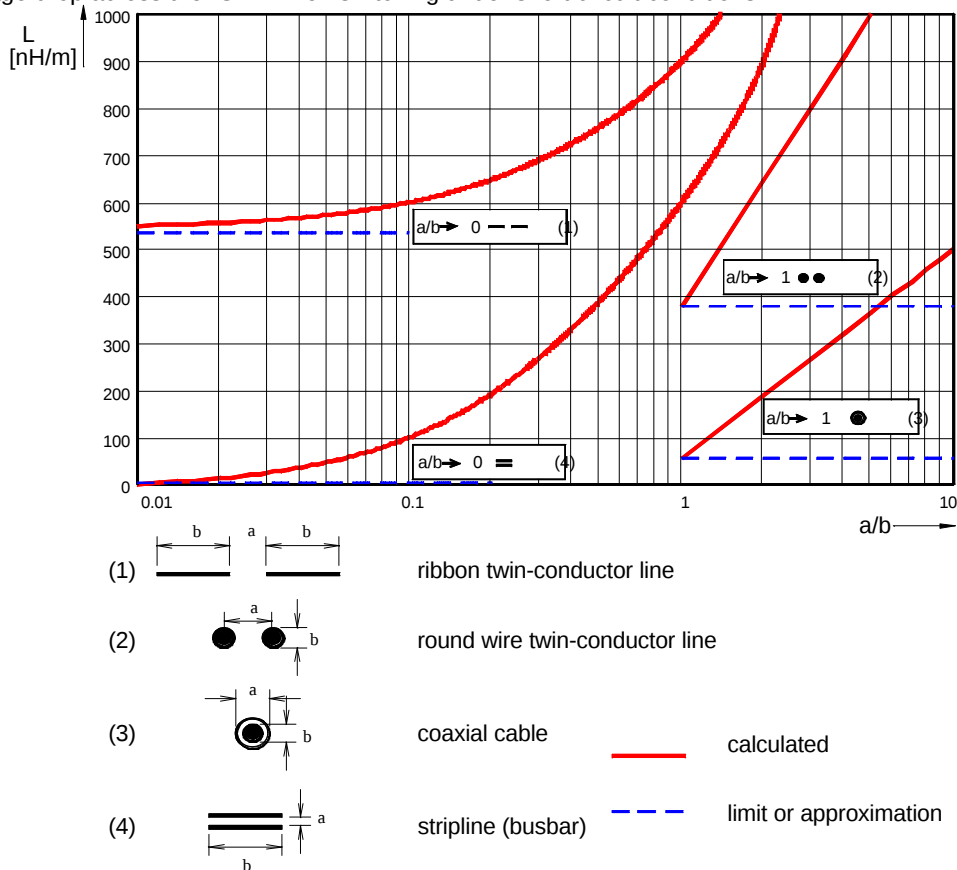


Fig.2: Inductance referred to length of different line types

Another possibility which is particularly of advantage if the piece of equipment still has not yet been taken into operation is shown in fig.3. The aim is to determine the stray inductance through measuring the resonant frequency

$$L_s = \frac{1}{(2\pi f_r)^2 * C}$$

f_r of the circuit formed by DC link capacitor C and L_σ by

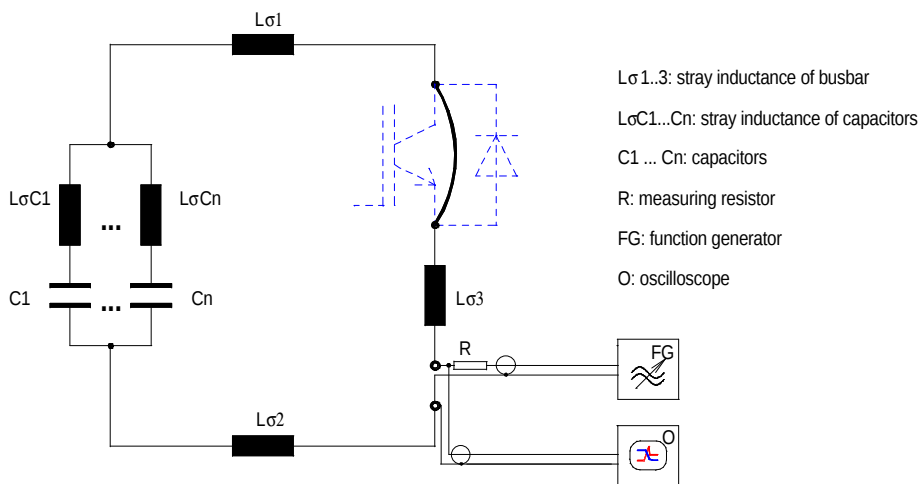


Fig.3: Arrangement for the determination of stray inductances

The stray inductances distributed across the single sections of the busbar as well as within the capacitors are represented in form of discrete components. One of the IGBT is shorted by a metal sheet. Across the other one, which is not mounted, a current with variable frequency is fed into the circuit by a frequency generator, using a resistor of $R \gg \sqrt{L_s / C}$. The voltage across the contacts is observed and the resonant point determined by tuning the voltage to its minimum. Since this can be difficult, additionally the phase angle between current and voltage can be tuned to 0. Considering the inner inductances of the two IGBTs, which are not effective in the circuit, the over-all stray inductance of the inverter can be determined from the known resonance frequency.

Components of the inverter

IGBT

Unlike the inside construction of a disc type device the module consists of a variety of single IGBT and diode chips. These are paralleled internally by bond wires. The connection to the external collector and emitter main terminals are done by parallel rails. The form of the power terminals permit the user to continue the internal low inductive construction to the outside with almost no transition. The external busbar has just to be screwed directly on the flat contact plates.

Fig.4 shows a IHV module with 3.3 kV blocking voltage and 1200 A nominal current. The module is specified with a value of 12 nH for the internal stray inductance.

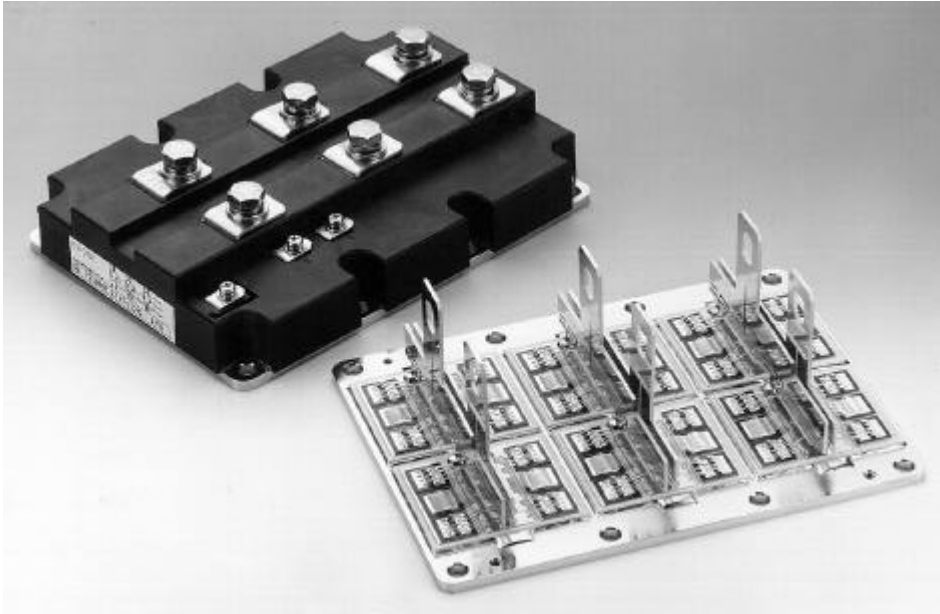


Fig.4: Internal construction of an eupec module
 The complete range of the IGV module family is shown in the following illustration. These designs developed by eupec have set a standard which has found worldwide distribution in the meantime.

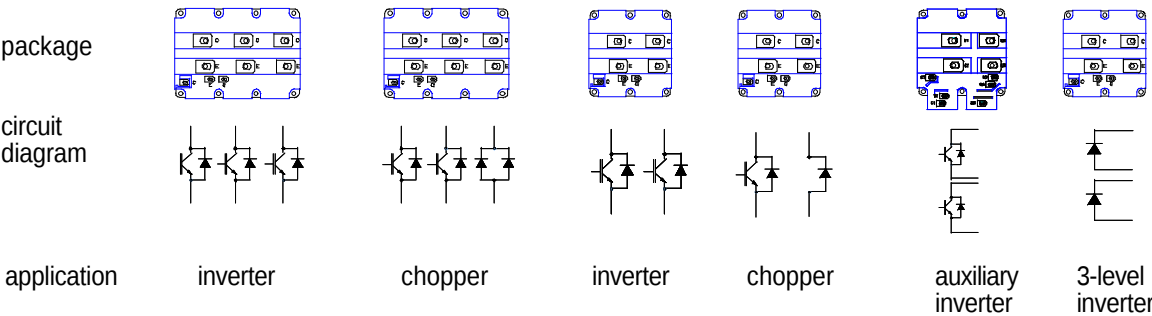


Fig.5: High power module family

Busbar

The reduction of the volume surrounded by the electrical circuit must be of highest priority in the construction. In consideration of high currents and the necessary isolation and with a simultaneously desired, simple connection technology the multilayer stripline is - as opposed to a coaxial cable - the most practicable solution for the inverter construction. Even extended busbars, as long as their layers are flat and narrow, contribute only a comparatively low share to the inductance of the electrical circuit. It remains the task of the designer, to optimize the busbar's transition areas between the single parts of the electrical circuit.

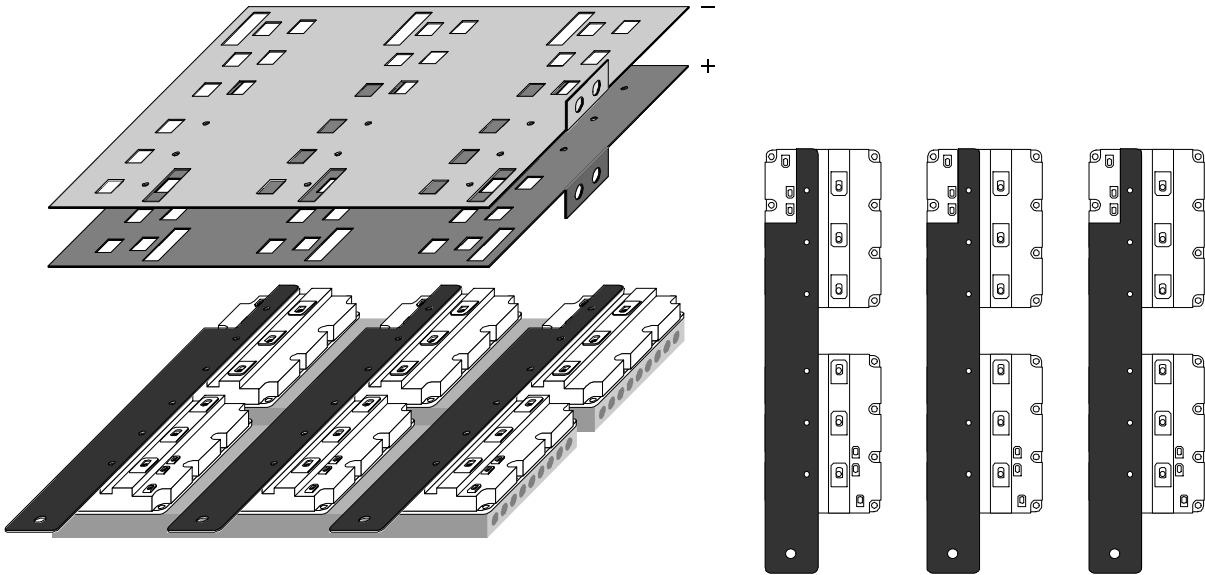


Fig.6: Example of a three-phase inverter busbar

The principle of such a busbar is shown in fig.6. It can be recognized how the IGBTs of the three inverter phases are connected with the busbar of the DC-link capacitors shown in fig.7 by two parallel metal layers. The single layers are mutually laminated by an isolating foil and can be stuck together to a complete busbar. At the rectangular windows the upper and lower foils are hermetically sealed to avoid problems with air and creeping distances in this area.

Capacitor

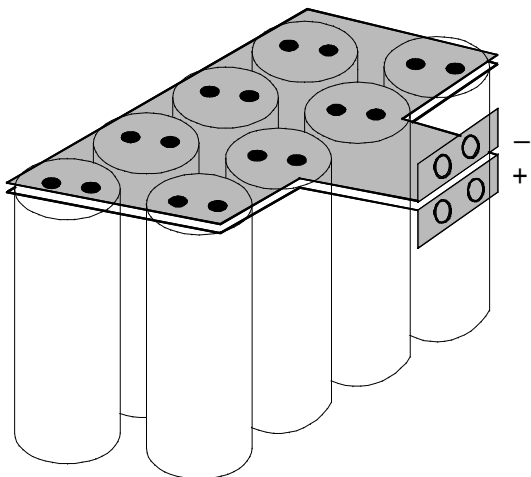


Fig.7: Capacitor bank with busbar

Dependent on the power range of the inverter as well as on the filter requirements capacitors with capacities in the area of approx. 1 mF up to 100 mF are used for the DC-link. With regard to supply voltages of 230 VAC to 1500 VDC different technologies like electrolytic, metallized paper, oil or gas-impregnated film capacitors can be used. Usually aspects like cost, volume and reliability are of prime importance to the user when deciding on the or the other type.

When using capacitors housed in cans the paralleling of several devices is carried out in form of a capacitor bank. The use of a busbar, like shown in fig.7, is of particular advantage for the reduction of wiring inductances.

The further development of the internal construction technique of dry capacitors finally results in devices which are optimally adapted to the risen requirements by minimization of the internal stray inductances. [3] Two measures have contributed to this: On the one hand the winding inductance could be reduced sharply by a coaxial construction. On the other hand, striplines are now used instead of conventional wires to connect windings and terminals.

With this technology, which is already practiced outside the capacitor, the inductance of the internal connection can be lowered considerably. A further reduction of the inductance is achieved by new flat, plastic feedthroughs which permit the external busbar to be fixed closely to the terminals. Devices with four terminals and the above mentioned measures lead to parasitic inductances in the range of only 35 to 50 nH per capacitor.

Construction variants

For the construction of inverters with high power modules, arrangements are recommended which allow, together with the components of DC-link, cooling and wiring, an optimized low inductive design. For the module types of FS... (six pulse bridge) and F4... (H-bridge) the connections within the phases are already done in the modules internally. For the most efficient modules, the FZ... (single switch) and FF... (dual module) they have to be realized by the user. For all module types an appropriate connection to the DC-link capacitor has to be done.

With the example of a phase leg existing of two IGBT single modules according to fig.1 the hereof combinable four basic arrangements with suitable busbars are represented. The complete converter, depending on the application e.g. a 3-phase inverter, a H-bridge or 4-quadrant converter, consists of a corresponding number of mechanically parallel arranged phases.

The shown arrangements in fig.9 are of exemplary nature since the construction is strongly influenced by installation dependent aspects. While the busbar close to the IGBT main terminals allows only few variants, the number and shape of the used capacitors (capacitor bank of cans or rectangular housings) can be decisive for the overall design of the busbar. The type (natural or forced air, water or heat-pipe) and efficiency of the cooling as well as the shape of the heat-sink can, in combination with the capacitor geometry, make the one or the other IGBT arrangement appear more or less favorable for the inverter construction.

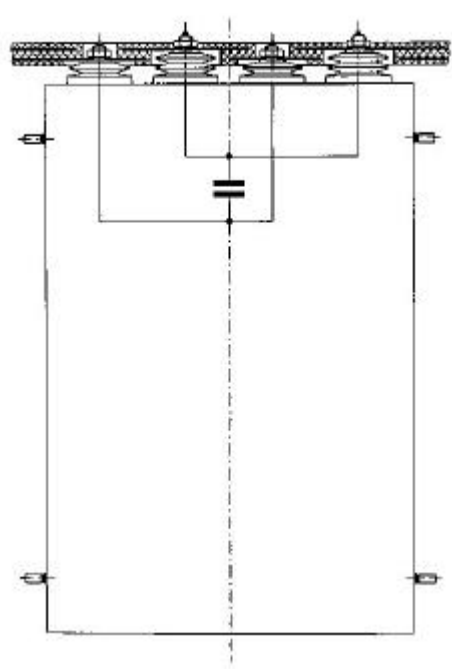


Fig.8: Optimal connection of a low inductive capacitor by a busbar [4]

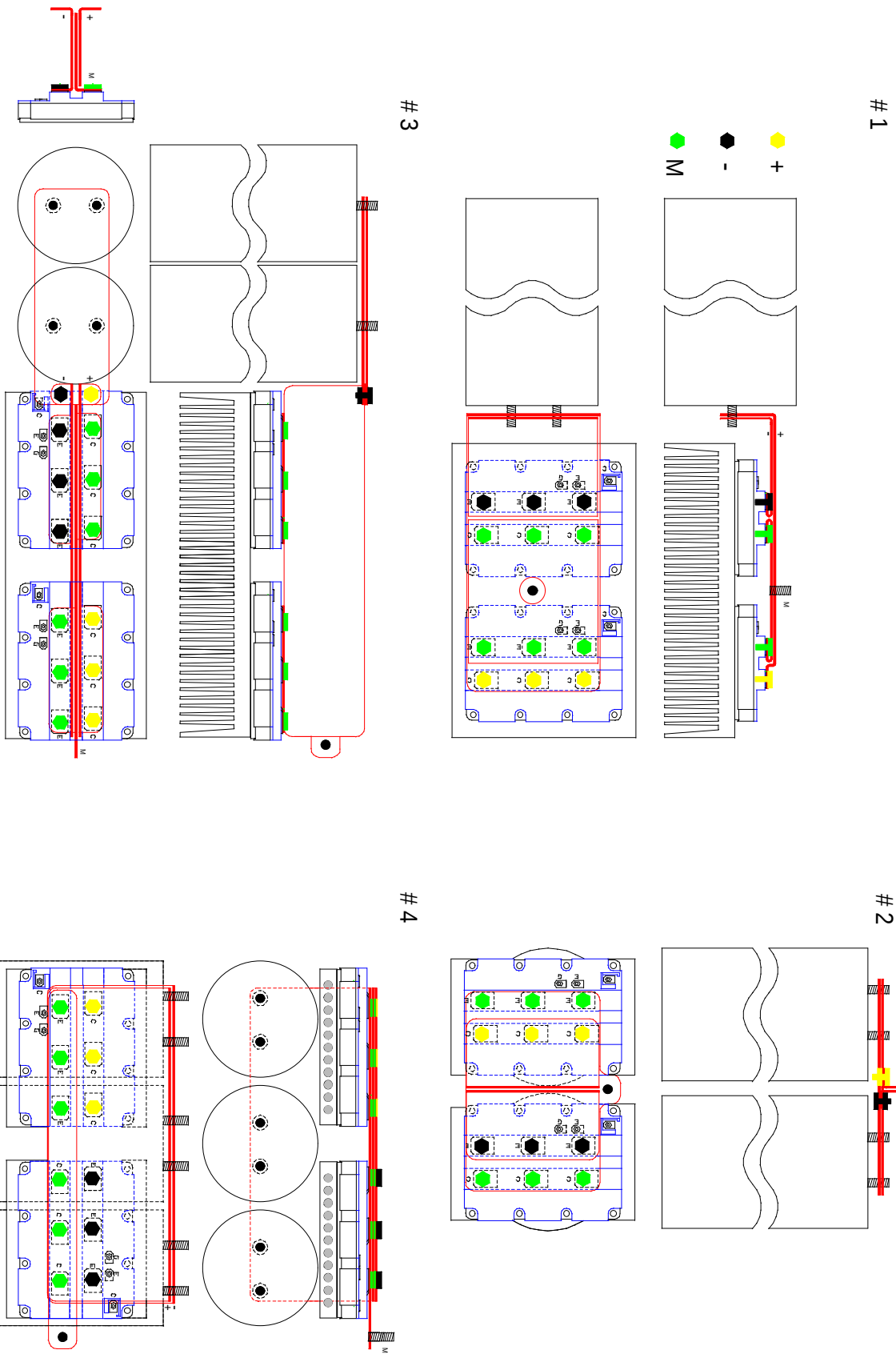


Fig.9: Arrangements #1 - #4 of single inverter phases

Arrangement #1

The IGBTs are arranged in a way that the emitter of the "upper" IGBT1 and the collector of the "lower" IGBT2 lie directly side by side. The midpoint "M" of the phase is realized by a simple, rectangular rail. This connection can, as shown in arrangement #2, be transferred to the side of the rail though; in this case there is no necessity for holes through the upper rail.

The connection of the DC-link is made by the "+" and "-" marked rails, which cover the IGBTs. For easy handling the three rails can be stuck together to one unit. To avoid problems with high current densities the covering rail also can be designed without screw holes as shown in fig.9.

Arrangement #2

In this version the DC-link capacitor is placed under the construction of heat sink and IGBTs. The position of the IGBTs to each other is identical to the first arrangement; the connections of midpoint and DC-link to collector and emitter terminal are mixed up respectively. Sticking together the plus-, minus- and midpoint rails is impossible here because of a missing access to the IGBT modules. This arrangement is advantageously, if the cooling is carried out by two separated water cooling rails. A corresponding construction may be conceivable also in air-cooling, but this will lead to additional expenses for air duct and gaskets.

Arrangement #3

To achieve an optimal access to the IGBT the busbar, advantageously a closely laminated package, can be placed vertically above the modules. For changing an IGBT only its mounting screws of the base plate and the terminals have to be removed, not, like in the arrangements #1, #2 and #4, further parts of the busbar or the motor connection. The IGBT gate-drive can be mounted particularly simple and close to the auxiliary terminals since these are freely accessible at both modules. Plus-, minus- and motor rail could be designed extensively and without additional holes.

The side view shows, how motor- and minus-connection are angle-bent at the base of the busbar package. Correspondingly for the right IGBT the plus rail is bent to the collector (in the drawing up) and the motor rail to the emitter (down).

Arrangement #4

Contrary to arrangement #3 one of the IGBTs is revolved for 180°. The midpoint M is connecting the lower power terminals as a narrow rail and gets laterally out of the busbar area. For obtaining an optimally low stray inductance not only plus and minus potential, but also plus and midpoint potential in the area of the left as well as minus and midpoint potential in the area of the right IGBT have to be brought closely together.

Because the electrical connection of the capacitors as well as the conveyance of the coolant is carried out from the same side, it is not possible to define a stand-alone "phase module" as done before. A solution for a inverter construction could be a flat busbar of the plus and minus potentials as already shown in fig.6.

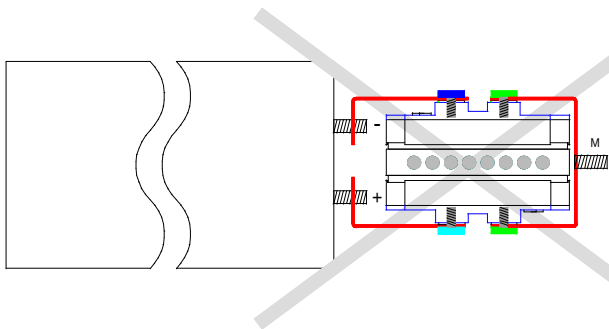


Fig.10: Inadmissible arrangement

An example for an inadmissible arrangement is shown in fig.10. In the arrangements #1-#4 the flat busbar opens up only at the capacitor and IGBT terminals. The volume enclosed by the busbar and therefore the contribution to the over-all inductance is rather low .

Here the commutation loop contains the complete construction of IGBTs and heat-sink, hence a considerable volume is included. A rough estimation of the contribution of the busbar to the total stray inductance of the circuit results in values in the range of several 100 nH.

Summary

With regard to their high blocking ability of up to 3.3 kV and with nominal currents of up to 1200 A, IGBTs have advanced into operating ranges which up to now had been reserved to GTOs.

For the protection of GTOs against re-triggering at turn-off and because of restricted current spreading at turn-on the dv/dt and di/dt at the device have to be limited. Therefore snubbers are usually used; a measure which increases weight and volume of the inverter, causes costs and problems at the removal of additional losses.

For the IGBT no handicaps exist with regard to permitted values for the current rate-of-rise. The voltage rate-of-rise at turn-off can easily be adjusted by the gate resistor. Consequently the use of snubbers is no longer required, which results in a considerable cost, weight and volume reduction for the inverter in IGBT-technique.

Stray inductances within the power circuit of GTO-inverters have a di/dt limiting effect and are therefore desirable to a limited extent. Their negative influence on the overvoltage across the device at turn-off is reduced by the - anyway needed - dv/dt limiting snubber circuit. Comparable stray inductances within the power circuit of the snubberless operated IGBT-inverters, in combination with the considerable higher di/dt values at turn-off, can lead to high overvoltage spikes. With regard to the RBSOA diagram these overvoltages may limit the maximum permissible DC-link voltage. Therefore, a low inductive circuit design is of extremely high significance.

In this paper, the inverter developer and designer has been presented with ideas of how to design single inverter phases by arranging high power modules and the additional components of DC-link, cooling and wiring advantageously in a low inductive manner.

Literature

[1] eupec: IGBT Modules; Technical Information

[2] M. Hierholzer et al.: Switching Characteristics and Limits of 3.3kV IGBT Modules
PCIM Hong Kong October 1997 Proceedings

[3] Vetter: High Performance Capacitors for Low-Inductance Circuits
English reprint from Siemens Components 28 (1990)

[4] H. Vetter: Dry Capacitors for Traction
PCIM Europe, No. 2/97

[5] S. van Acker: Laminated Busbars and Excor, Key Components for controlled Power Distribution
in high Power Applications; Power Conversion May 1996 Proceedings