Design and Manufacturing of Application Specific High Power Converters

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Abstract
During the past decade, power electronic R&D focus has had to shift remarkably: from technology during the 80’s to total system cost in the 90’s. Simplicity of design, modularity and reduced parts-count has thus had to become the main targets, and snubberless operation a major issue.

Due to its transistor characteristics, the IGBT is a champion in this new design philosophy. Thyristor type devices like the GTO, MCT and SiTh offered low on-state loss at high blocking voltage but, entering the field from low end of the voltage spectrum, the IGBT could beat all of them. Today, IGBTs are even operated at kV and kA levels.

Nevertheless, high on-state loss at high blocking voltage and high packaging complexity tend to hinder the IGBT at high current. With large wafers and low losses, bipolar devices are much more feasible for such types of power. Spinning off from the GTO, the IGCT has demonstrated its ease of wafer production, well proven packaging, reliability and snubberless turn-off at the same time.

This presentation summarises the IGCT’s development. Device characteristics but also topology, design aspects and system characteristics are brought into the focus. A high degree of modularity, design simplicity and parts-count reduction is observed. Building blocks are analysed and further potential investigated. Examples from various application areas are presented including Medium Voltage Drives, DVRs, UPSs and very high power series connection. IGCTs thus present themselves as the big brother of the IGBT, ready to serve the user in the high power domaine like the IGBT does at lower power.

Introduction
Innovation is the path to the future. It is driven by technology push and market pull.

Technology push originates from bright new ideas which sometimes may condense quantum leaps. But it also originates from the large number of comparatively small steps which result from the steady focus on continuous improvement.

Market pull today is felt mainly as the demand for cost reduction. Cost is the number one consideration, and it ranks also as second and third! But quality and lead-time are not really behind it: in fact, they go without saying! Every profession today is confronted with this trend – even those who enjoyed a stable environment for decades.

What does this mean for power electronics? What answers have been found? What is the future?
Every design something special

After the application of mercury vapor arc rectifiers, silicon diodes and thyristors really meant a step into a new era characterized by comparably small designs well suited for stationary and rolling stock. Power electronic converters then became available for a wide range of applications and in particular, traction drives benefited from new opportunities. Long development and qualification did not count so much at that time, since the benefit in most cases was high enough to finance the expenses, and enough specialists were available for the highly interdisciplinary task of design and manufacturing of such systems.

With the introduction of the bipolar transistor and the GTO to power electronics in the 80’s the situation really did not change much. Then, a wider power range could be addressed and forced commutated turn-off opened a new degree of freedom to improve system characteristics. But still the design and manufacturing of power converters remained a highly interdisciplinary task calling for power electronic specialists.

Power electronics and, in particular high power electronics, stayed in a niche protected against a flood of aggressive marketing. And although device researchers were eager to find the “ideal switch” [1-9], nothing really happened until some years ago. – So, where did the change come from?

Design and manufacturing breakthrough

The breakthrough came as the IGBT was maturing. In the beginning, the IGBT’s appeal was driven by such ideas as 1) “MOS-control” equated to “easy drive”, 2) “snubberless operation” equated to “easy design” and “easy control” and 3) “parallelizing of chips and devices” equated to “modular design”, “easy power scaling” and “cost effectiveness”. All these basic ideas led to a reduction of design complexity, taking out the need for very high interdisciplinary know-how and thus opening designs for a wide range of application.

Today, IGBT converters are wide spread throughout power electronics. They are found in small power high volume applications as well as in medium and high power.

Design has become modular. Single devices still are used for high volume production but in the “classical” fields of power electronics, converters and drives, modules with a number of devices linked together to represent a function are now sold by component producers. Furthermore, drive and protection functions have been merged into the modules and such power electronic building blocks have received a great deal of attention from the market.

Application specialists therefore no longer have to deal with the details of device selection, drive, low inductance snubber design etc. They can just take from the shelf what they need. There is no doubt: modularization did a great job for the application of power electronics and the IGBT has been the key to open the door.

Everything o.k. now?

When chips are big enough to easily cover a function and packaging is simplified so that it does not represent a significant fraction of the cost, then the user has to pay what he really gets. Is it fair to say that this is the case with low and medium power IGBT modules rating up to say 300A / 1200V? There we have EconoPack and LoPack [10] modules for high volume application and SKiiPPACK [11] for the wide range of fairly low volume markets. Design engineers then can concentrate on system design and only troubleshooting is left for power electronic specialists.

But when power is too high for a small number of chips, then paralleling of chips and packaging become a major issue. Soldering a large number of chips into a multi-MW package, connecting them by
bond wires and then insulating everything with gel is still difficult, costly and all but reliable. The many papers published on high voltage IGBT chip design and packaging tell this story and high voltage IGBT developments always seem to find many more problems than initially anticipated.

In fact, this issue has been known for a long time. It is the strength of the press pack that it can reliably handle large silicon wafers and thereby drastically reduce the parts count in high current device manufacturing. And it is the strength of the ceramic housing that it can keep an inert atmosphere, say nitrogen, to generate reliable and lasting insulation for high voltage on the wafer and between the conducting parts inside the housing. High voltage IGBTs, therefore, are now being packed into press packs by some manufacturers and MOS-technologists were looking for ways to produce large, say 3 – 4 inch wafers, only a few years ago [12].

Packing a large number of chips into a press pack is a real challenge for production and wafer defect density is still too high to allow the production of large chips: the discussion on repair techniques has been virtually stopped for some time. High power MOS-devices therefore have not yet reached maturity and simplicity which may encourage MOS researchers to lean back and take a rest!

**Bipolar technology for high current and high voltage**

Compared to MOS, the strength of bipolar wafer technology clearly lies in simplicity of processes, increased wafer dimensions and higher tolerance to silicon defects. As a consequence, GTO wafer diameters and hence current ratings have increased step-by-step to reaching 6kA / 6kV at 6” diameter [13]. Wafer processing, press pack technology and high temperature cycling withstand capability due to floating silicon designs have been strong arguments for GTOs in high voltage / high current applications.

But, finally, cost comes as the major issue. For a long time it was not easy to see where high voltage IGBTs would end up. Discussions still are ongoing but after some years of commercial production a clearer picture is emerging from the market. It is bipolar technology which comes off much better than expected, a fact that should encourage us to reconsider “good old technology know-how” and to look for ways of solving the real problems rather than creating new ones.

**From GTO to IGCT**

Reduction of snubber capacitance has always been a main target of GTO development. Improvements in the homogeneity of wafer processing did help [14], some increase of gate turn-off dI/dt was tested and with small devices even snubberless operation was achieved [15]. Nevertheless GTO operation had to be understood more deeply (Fig. 1) to prepare for the breakthrough [16] (Fig. 2). And means to

**Fig. 1:** 3kA 4.5kV GTO turn-off. A 3µF snubber has been installed.
apply such a high
\( \frac{\text{d}I}{\text{d}t} \) to the gate of
the device (Fig. 3, 4)
had to be devised to
really make the con-
cept feasible.

Compromises in
wafer design which
had been found em-
pirically for high
GTO turn-off capa-
bility at the same
time became unnec-
essary. As a conse-
quence, buffer layer
technology was in-
troduced (Fig. 5),
wafer thickness re-
duced and carrier
profiling applied by
transparent anode
design and electron
and proton irradiation. As observed before with IGBTs, on-state losses were thereby drastically re-
duced for the same turn-off losses (Fig. 6) or vice versa. Wafer thickness of the turn-off device then
came close to the optimum necessary for freewheel diodes. Integration of these diodes on the same
wafer with the turn-off device became a natural step (Fig. 7) and due to linear scaling of the devices
obtained, it became easy to create a full family (Fig. 8). In this way the Integrated Gate Commutated
Thyristor (IGCT) was born – a device exhibiting a set of new features, but still based on all the old
“goodies” of the GTO.

**Steps towards a modular technology**

With such a new device one step towards new converters is achieved. But, just replacing GTOs by
IGCTs would still keep complex circuitry, difficult design and bulky realisation. Snuberless operation
is the key to circuit simplification with IGBTs. So, what about IGCTs?
“Snubberless” high power circuitry

In Fig. 9, the classical Undeland circuit is shown: during turn-off of the positive rail GTO $G_1$, snubber capacitor $C_1$ is active; during that of the negative rail GTO $G_2$, a series connection of $C_1$ and $C_2$ is active. $C_2$ then is chosen several times larger than $C_1$, and consequently it can act as a DC-link clamp as well. Parasitic inductance in the main DC capacitor bank thereby becomes less important, making design for high voltages (large bus-bar distances) and high currents (large bus cross-sections) a lot easier.
Without the necessity for a turn-off snubber $C_1$ and $C_2$ are omitted, and the circuit simplifies (Fig. 10).

![Fig. 10: Same as Fig. 9, but snubber capacitor removed.](image)

Now, high $dI/dt$ transients generated by the switching devices act on the parasitic inductance of $R_S$, $D_d$ and the DC-bus. With currents ranging to several kA high switching transients $dI/dt > 5kA/µs$ are observed. Such transients would generate more than 5000V on a typical parasitic inductance of 1µH. A circuit according to Fig. 10 therefore can not be realised for such high current.

In Fig. 11 a clamp capacitor is introduced again. $C_d$ here will have to clamp fast transients through $D_d$ only. As a consequence, $C_d$ is much smaller than $C_2$ in the Undeland circuit, typically it comes close to the value of a GTO’s snubber capacitor ($C_1$ in Fig. 9). The parasitic capacitance of the DC-bus therefore does not effect the turn-off transient of the GCTs and the freewheel diodes.

Due to small silicon wafer thickness and transparent anode design, IGCTs turn-on faster than GTOs. With 91mm wafer diameter ($f_{T戈M} = 3…4kA$) the $dI/dt$ limit is pushed from the GTO’s $500A/µs$ to more than $3kA/µs$ [17]. But high voltage diodes, due to comparably large storage charges, still recommend a limitation in the range of $dI/dt = 0.5 \ldots 2kA/µs$. The external inductor $L_S$ with freewheel circuit $D_d$, $R_S$, thus has to be kept in the circuit.

$L_S$, $R_S$, $D_d$ and $C_d$ in fact form a multi-purpose clamp: under normal operation $D_d$ and $C_d$ limit transient voltages on the switching devices, $L_S$ limits $dI/dt$ at diode reverse recovery, and $D_d$, $R_S$ form the freewheel path for the energy stored in inductor $L_S$. Additionally $L_S$ will limit the fault current under shoot-through. Without additional components, a GCT phase leg thereby is fully protected even under worst case conditions. The design of such a converter already has become quite modular and straightforward (Fig. 12).

High current inductors, high voltage capacitors and high voltage power resistors can represent a considerable volume. In Fig. 11 these devices are active only during switching transients and fault condi-
tions. One single multi-purpose clamp therefore may serve a number of phases (Fig. 13). In NPC topology, only two such clamps are required to serve all 3 phases with a total of 12 GCTs (Fig. 14).

**Modular design**

Already in the circuit diagram more steps towards increased modularity can be recognised: gate driver plus reverse conducting GCT to IGCT, IGCT plus cooler to integrated power block (Fig. 15) and 4 power blocks plus two zero diodes to a phase stack (Fig. 16). Three of these stacks plus one clamp \((D_d, C_d)\) then form the heart of the converter (Fig. 17). Also, terminal layout and interconnection are less critical since parasitic inductances in those loops are already clamped.

The ACS1000 Drives family is created from such building blocks. Classical blocks are added: 12 pulse input rectifier, common mode reactor in the DC-link and a sine filter on the three phase output (Fig. 18). Due to this modularity, a wide family has been created in a short period of time including air cooled converters as shown in Fig. 17 and water cooled high power types (Fig. 19).
Series connection

The first IGCT applications used series connection [18] (Fig. 20). Precise timing of switching events was more important than snubberless turn-off. With well designed fibre optics and standard logic circuits, gate drive delay tolerances where cut to ±100ns and GCTs (called “hard driven GTOs” at that time) contributed no more than a further ±50ns. With a standard 3µF snubber, 3kA turn-off rating were achieved with excellent voltage sharing. A follow up system now in commissioning in Karlsfeld (Fig. 21) with the same snubber capacitor rated for 4kA turn-off, and voltage sharing is further improved (Fig. 22, 23, 3kA operation shown).

![Fig. 20: Circuit diagram of U-Module.](image)

![Fig. 21: Karlsfeld 66MVA converter.](image)

![Fig. 22: Turn-on of 5 GCTs in U-Module (7.5kV / 3kA).](image)

![Fig. 23: 5 GCT turn-off in U-Module (12kV / 3kA).](image)

Easy replacement of IGCTs

Modularity helps with design and with the right interfaces, it greatly simplifies servicing also. This is why the cooler has not been integrated in the IGCT. Bonding both together would reduce thermal resistance a little and hence allow more power but with IGCT and cooler separate, installation and replacement of IGCTs is straightforward and easy: dry and fast, no water handling, no dust problems. Figs. 24 – 26 are taken with the Bremen module and, in fact, installation of IGCTs is as simple as shown in these photos in all IGCT converters.

More designs and applications

Power quality applications may further demonstrate the flexibility of IGCT design. Even short voltage dips may cause trouble in, say, a modern silicon foundry. Here power must be injected into the line for a short period of time to compensate the dip. A dynamic voltage restorer fed from a DC-capacitor
bank has been designed for such purposes (Fig. 27): when a voltage dip is detected on the mains, the converter goes to 1050Hz switching mode, injecting power in series with the mains via transformer T1 under high dynamic control. In steady state, however, the converter is parked in a zero mode, short circuiting the transformer’s windings by connecting it to its negative DC-bus rail. In this way, switching losses only are generated during injection of power and steady state loss is kept very low. Forced air cooling is thus more than adequate for 900A phase current (Fig. 28).

Where voltage dips are more pronounced and the mains may even fall into open circuit condition for some time, then a full UPS (uninterruptable power supply) is required. The load, then, has to be separated from the mains and at the same time, power must be supplied by a converter (see block diagram in Fig. 29). A 4.5MVA system has been designed and commissioned comprising a 12 pulse converter with switching frequency $f_s = 1050\text{Hz}$ and a fast solid state 22kV 3-phase AC-breaker. Each phase module for 22kV AC is realised in a compact module (Fig. 30) comprising 9 bidirectional IGCT modules (Fig. 31). Each breaker’s IGCT module consists of two reverse conducting IGCTs in cathode-to-cathode configuration to block 5.5kV in both directions, a central logic board and a power supply for start up and steady state operation.
Summary and conclusion

Through “hard-drive”, bipolar *thyristor* type devices acquired snubberless turn-off characteristics. This feature, in fact, turned out to be the key to circuit simplification and converter design modularization.

Omitting snubberless turn-on - the second main advantage of IGBT design - is not, it transpires, an inconvenience: a multi-purpose clamp limiting transients close to the semiconductor devices, protecting against severe “collateral” damage under catastrophic failure and efficiently relieving the semiconductor of turn-on losses [19], more than compensates for this.

Traditional press pack design has thus been turned back into a strength: power building blocks are formed from compact high power devices, gate drivers on standard printed circuit boards and coolers. All support modular converter design, easy handling and highest reliability.

With traditional housing types and linear scaling of GCTs and diodes, a family of high power devices has been created within a short period of time. Cost effective IGCT converters from a few hundred kVA to more than 100MVA have already been realised. Development cost is drastically reduced by modular design. As a consequence, applications in high power systems can be addressed as efficiently as those in high volume markets.
REFERENCES


