New High Power Semiconductors: High Voltage IGBTs and GCTs

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Abstract:

Ultra high power, high voltage, power electronics is on the verge of a new era. Two new power semiconductor technologies, the high voltage IGBT and the GCT (Gate Commutated Thyristor) are improving the performance, simplifying the design and increasing the reliability of applications ranging from 100's of KVA to many MVA. This paper will discuss the characteristics and application considerations of these revolutionary new technologies.

1. Introduction

In recent years, the performance of industrial power electronics for line voltages up to 600VAC has advanced rapidly. Initially, improvements were made possible by the development of high current isolated base darlington transistor modules. More recently, stunning improvements in IGBT technology has driven performance to new levels while substantially reducing cost. Over the same period, ultra high power, high voltage, applications advanced relatively slowly following fairly predictable improvements in GTO and high voltage thyristor technology. This paper presents two promising new power device technologies, the high voltage IGBT, and the GCT (Gate Commutated Thyristor) that have been developed for these applications. Both devices seek to replace the venerable GTO by offering snubberless turn-off capability and higher operating frequencies. The performance and application considerations that determine which technology is best for a given application will be presented.

2. Applications

The following discussion will focus on power semiconductor devices for applications operating at output power levels in excess of 100kVA. Generally speaking these applications are more specialized and considerably less common than lower power applications. Some of the most well known applications include: Propulsion inverters for mass transit and locomotives, high power industrial drives for steel and paper mills, and utility power conditioning, including static VAR compensation and flexible AC transmission. In these applications, limited power device capabilities often force the use of circuit topologies such as cycloconverters and current source inverters that have limited performance. Many of these applications could benefit in terms of efficiency and control accuracy through the use of a voltage source topology. In applications operating from AC line voltages of 600VAC and less, IGBTs with blocking voltage ratings of up to 1400V have provided an efficient low cost means of constructing high performance voltage source inverters. In higher voltage applications GTOs (Gate Turn-Off thyristors) have been used but their limited switching frequency of 300Hz or so, offers little advantage when compared to other circuit topologies. Clearly, a higher performance, high power semiconductor device is needed. Today, newly commercialized high voltage IGBTs with blocking voltages to 3300V and GCTs with blocking voltages to 6000V have been developed to address these requirements.
The HVIGBT (High Voltage IGBT) module is a logical extension of the technology used in conventional IGBTs. Several technical challenges had to be overcome in order for these devices to attain the desired characteristics. First, an IGBT chip with high blocking voltage, reasonably low on state voltage, and sufficiently wide safe operating area had to be developed. In lower voltage devices, a buffer layer structure (a.k.a. PT-Punch Through) similar to a PIN diode (figure 1a) was found to be optimally effective for this purpose. The buffer layer in these devices was formed as part of the epitaxial silicon wafer. Adapting this structure to a high voltage device requires a very thick epitaxial layer which presents serious cost and yield problems. One way around this problem is to use an NPT (Non Punch-Through) structure (figure 1b) for the device. The NPT structure does not have a buffer layer and is relatively easy to adapt to higher blocking voltage. Unfortunately, this approach requires a very thick n+ drift layer to prevent excessive leakage current at elevated temperatures. The thick high resistivity n- layer causes a significant increase in on state voltage \( V_{CE(sat)} \). In spite of this drawback, at least one manufacturer has adopted this approach. A better solution, developed by Powerex/Mitsubishi, is to use a specially processed FZ (Float Zone) silicon wafer with a diffused buffer layer. The much thinner n+ drift layer of this structure yields a substantially lower \( V_{CE(sat)} \) compared to the NPT approach. In addition, by utilizing proton beam irradiation to optimize the carrier lifetime in the buffer layer, a significant reduction in turn off switching losses was obtained. A comparison of NPT versus PT 3300V, 1200A devices is shown in figure 2.

The second major challenge was achieving the required 6000VRMS base plate isolation without a significant degradation of thermal performance. By adopting DBC substrate patterns with rounded corners and increased edge margins it was found that the 0.635mm thick aluminum nitride ceramic used in conventional modules could support the required voltage. In order to insure the reliability of this high voltage insulation, it was necessary to carefully examine corona inception and extinction. Voids in the solder and bubbles in the gel were identified as sources of partial discharge (corona). To improve these areas the gel potting and soldering processes were moved to a low pressure atmosphere. The result, is voidless solder and bubble free gel. By using this process the

### Table 1: HVIGBT Modules

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Voltage</th>
<th>Circuit</th>
<th>Voltage</th>
<th>Current (A)</th>
<th>Voltage</th>
<th>Current (A)</th>
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<tr>
<td>Dual</td>
<td>1700V</td>
<td>CM600DY-34H</td>
<td>2500V</td>
<td>CM400DY-50H</td>
<td>3300V</td>
<td>CM400DY-66H</td>
</tr>
<tr>
<td>Single</td>
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<td>CM800HA-34H</td>
<td>CM1200HA-34H</td>
<td>2500V</td>
<td>CM800HA-50H</td>
<td>CM1200HA-50H</td>
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<tr>
<td></td>
<td>3300V</td>
<td>CM1200HA-50H</td>
<td>CM1200HB-50H</td>
<td>CM800HB-50H*</td>
<td>CM1200HA-66H</td>
<td>CM1200HB-66H*</td>
</tr>
<tr>
<td>Chopper</td>
<td>1700V</td>
<td>CM600E2Y-34H</td>
<td>CM1200HB-66H*</td>
<td>2500V</td>
<td>CM800HA-66H</td>
<td>CM1200HB-66H*</td>
</tr>
<tr>
<td></td>
<td>3300V</td>
<td>CM1200HB-66H*</td>
<td>CM1200HB-66H*</td>
<td>CM1200HA-66H</td>
<td>CM1200HB-66H*</td>
<td>CM1200HB-66H*</td>
</tr>
</tbody>
</table>

![Figure 1: IGBT Chip Structure](image)

![Figure 2: HVIGBT On-State Voltage](image)
HVIGBT module’s isolation is able to meet the IEC 1287 partial discharge standard and has corona inception and extinction voltages of more than 3000V at 10pC.

A family of HVIGBT modules has been developed using these new technologies. The new family of devices is shown in table 1. A photograph of a HVIGBT module is shown in figure 3. In general, the new high voltage IGBTs have the same application advantages that have made IGBT modules the device of choice in lower voltage industrial applications. The gate drive requirements are essentially the same except that greater isolation in the power supplies and control signals is needed. The HVIGBT has a robust switching SOA that allows snubberless switching. Like lower voltage devices, the HVIGBT module includes a reverse connected fast/soft recovery free wheel diode.

4. The GCT

Even with the development of HVIGBTs, it is usually recognized that thyristor (latching) devices often have a better trade-off between on state losses and blocking voltage. This improved trade-off can be especially important in very high voltage applications. A comparison of this characteristic is shown in figure 4. Unfortunately, as we will see later, this improved trade-off inevitably comes with a sacrifice of dynamic control.

The GCT (Gate Commutated Thyristor) is a new thyristor device that is similar to a GTO. The goal of the GCT is to reduce the cost and complexity of the gate drive and snubbers required in GTO applications. The idea behind the GCT is to commutate the entire cathode current to the gate at turn off. By doing this a smooth transition from SCR (latching operation) to transistor operation can be achieved. In conventional GTOs, the unstable transition at turn off necessitates the use of large dv/dt snubbers. The key to the GCT is its gate driver and package design. In order to obtain snubberless turn-off capability, the driver must
abruptly divert the entire cathode current to the gate. The speed at which the main current transfers to the gate (dI_GQ/dt) has been shown to be directly related to the peak snubberless turn off capability of the GCT. To achieve high dI_GQ/dt a special ring gate package and low inductance gate driver were developed. A photograph of the Powerex/Mitsubishi GU-C40 gate driver and a FGC4000BX-90DS, 4000A, 4500V GCT is shown in figure 5. An exclusive, proprietary, circuit design allows the GU-C40 to deliver a dI_GQ/dt in excess of 7000A/µs. When used with the FGC4000BX-90DS GCT snubberless turn-off of 6000A has been demonstrated. Figure 6 shows a 4000A snubberless turn-off waveform. The low inductance package and driver also achieves a more uniform turn-on which allows a greater di/dt and a corresponding size reduction of the required di/dt limiting inductor.

It should be noted that in theory any GTO can be operated at unity turn-off gain and achieve snubberless turn-off capability. The present GCT however, is a highly optimized device. By taking the hard drive conditions as a given the designers were able to achieve substantial reductions in turn-off losses and on state voltage.

5. Application Considerations

The HVIGBT and GCT have both been shown to have advantages over GTOs in high power voltage source inverter applications. Which technology is best? If state of the art examples of each technology are compared, it is possible to make a case for either of them. The deciding factor appears to be the requirements of the end application.

A. Power Circuit Topology

![Figure 7: Voltage Source Inverter Phase Leg Comparison](image)
Figure 7 shows one arm of a single level voltage source inverter constructed using GTOs, GCTs, and HVIGBTs. At first glance, there does not appear to be much difference between the GTO and GCT circuit. However, in actual applications the difference is significant. The GCT uses a voltage clamp circuit instead of an RCD snubber because it is not necessary to limit the dv/dt at turn off. The clamp circuit is typically smaller and considerably lower loss than the GTO’s dv/dt snubbers. In addition, the GCT has higher turn-on di/dt capability. This makes it possible to significantly reduce the size of the di/dt snubber reactor and its associated losses. These circuit changes combined with the GCT’s inherently lower turn-off losses permit a significant increase in operating frequency. While GTOs are typically limited to switching frequencies of a few hundred Hertz in most applications, the GCT can be operated at frequencies greater than 1kHz.

Clearly, the HVIGBT topology is simplest of all. The reason is that unlike the GTO and GCT, the IGBT can control the turn on di/dt. This eliminates the need for a di/dt snubber. If low inductance laminated buswork is used, it is possible to operate the HVIGBT without any additional snubbers or clamping circuits. However, using the power device to control the di/dt results in substantially higher turn-on losses. These losses could be reduced by adding a di/dt snubber. In this case, the IGBT and GCT power circuits would be virtually identical.

B. Gate Drive

Figure 8 shows a comparison of the typical gate drive current required for the GCT and HVIGBT. Table 2 shows typical gate drive characteristics. The GCT requires an initial high current pulse to bring the entire device area into full conduction. For the 4000A GCT, this current pulse is typically 200A for about 5µs. In order to achieve the data sheet turn-on di/dt rating of 1000A/µs this pulse must be applied at a rate of at least 100A/µs. At first, this may sound difficult, but it is relatively easy compared to turn off. During steady on state operation, a continuous current of at least the device’s main current must be applied to assure that the device’s entire area stays fully on. For the 4000A GCT, a continuous current of about 10A is required in the on state. At turn-off a reverse current pulse equal to the device’s main current must be applied. For full rated snubberless turn-off capability, the

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>GTO</th>
<th>GCT</th>
<th>HVIGBT</th>
</tr>
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<tr>
<td>Turn-On Peak current (A)</td>
<td>25</td>
<td>200</td>
<td>15</td>
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<tr>
<td>Duration (µs)</td>
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<tr>
<td>On-State Current (A)</td>
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<td>Total Power (W)</td>
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<table>
<thead>
<tr>
<th>Characteristic</th>
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<th>FGC4000BX-90DS</th>
<th>Manufacturer “A”</th>
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<tbody>
<tr>
<td>Required Continuous On-Current</td>
<td>Based on maximum ( I_{GT} ) at 10C</td>
<td>10A</td>
<td>3.3A</td>
</tr>
<tr>
<td>( I_{GT} ) (A)</td>
<td>( T_{j}=25^\circ C )</td>
<td>1.2</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>( T_{j}=115^\circ C )</td>
<td>0.15</td>
<td>0.02</td>
</tr>
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</table>
driver must be able to supply a 4000A pulse applied at a rate of 6000A/\mu s. This requires a large number of paralleled low voltage MOSFETs and a bank of electrolytic capacitors. The Powerex/Mitsubishi GU-C40 gate driver’s output MOSFET has an effective $R_{DS(on)}$ of less than 300\,\mu \Omega and its output capacitor is 40,000\,\mu F. The MOSFETs and capacitors are arranged on a multi-layer PCB to form a low inductance parallel plate structure with an effective inductance to the GCT gate of around 3nH.

The HVIGBT’s gate drive is basically the same as lower voltage IGBTs. The gate of the HVIGBT is similar to a capacitor. To turn the device on and off, the capacitor must be charged and discharged. Like lower voltage IGBTs, the recommended turn-on voltage is 15V. In the off state a reverse bias of -10V to -15V should be applied to maintain good noise immunity. The recommended series gate resistance ($R_G$) for the CM1200HB-66H, 1200A, 3300V HVIGBT module is 1.6\,\Omega. With a gate voltage swing of 30V the maximum drive current is about 19A.

Clearly, HVIGBT gate drive is simpler and requires less power than GCT gate drive. One of the most significant contributions to the higher power requirements of the GCT gate drive is the need for continuous current in the on state. This current can be reduced if the GCT is designed with a lower gate trigger current. This approach has been adopted by at least one manufacturer. The problem that arises with this approach is that off-state noise immunity is degraded. Table 3 shows that the low trigger current device may be turned on with as little at 20mA at elevated junction temperature.

### C. Losses

Table 4 Summarizes the key loss characteristics of the HVIGBT and GCT. This comparison is not a particularly good one because these devices are not of the same rating. As expected, the GCT has a clear advantage in conduction losses while the IGBT has a clear advantage in turn-off losses. Turn-on losses can not be compared because the normal circuit topology for these devices is different (see A above). If a di/dt limiting turn-on snubber were used with both devices the turn-on losses would be about the same.

### D. Reliability

By itself, the GCT’s simpler monolithic design is likely to be more reliable than the relatively complex multi-chip HVIGBT module. In addition, the GCT’s pressure contact (a.k.a. “hockey puck”) design has well known advantages in terms of thermal cycle capability. On the other hand, the HVIGBT has a simpler, lower power gate drive, and does not require the array of external clamp and snubber devices that are needed with the GCT. Furthermore, the HVIGBT module does not require the precision mechanical clamping assembly that is needed with large hockey puck devices. Clearly, reliability will be driven by the requirements of the end application and the system design. In any case, both devices have been shown to have reliability advantages over the GTO’s that they are intended to replace.

### 6. Conclusion

Figure 9 shows today’s concept of the appropriate application range for HVIGBTs and GCTs. The GCT’s GTO like structure is expected to be relatively easy to adapt to higher voltages and currents.
Six thousand volt GCTs with snubberless turn-off capability in excess of 4000A have been demonstrated and will soon be commercially available. In addition, the GCT’s small turn off delay and fail short characteristics make it desirable for series connected applications. In particular, ultra high power electric utility applications are now being considered. The HVIGBT appears to be best suited for the lower end of high power applications. In these applications, the HVIGBT offers increased performance and greatly simplifies design and assembly. Research on both the HVIGBT and GCT continues. Future breakthroughs from both the device and system perspective are likely to alter the form of figure 10.

7. References

1. Satoh, et. al., "6kV/4kA Gate Commutated Turn-off Thyristor with Operation DC Voltage at 3.6kV", ISPSD 1998
5. Satoh et. al., "A New High Power Device GCT (Gate Commutated Turn-off) Thyristor", EPE 1997