Requirements of the Power Industry

- The Ideal Switch
  - high currents (turn-off, rms, average, peak, surge)
  - high voltages (peak repetitive, surge, dc-continuous)
  - fast switching (short on/off delays, short rise/fall times, short turn-on/off times)
  - low losses (conduction, switching)
  - high frequency (fast switching, low switching losses)
  - high reliability (low random failures, high power and temperature cycling, high blocking stability, low parts count)
  - compact constructions (low parts count, low losses)
Thyristors : High Power Devices

- High Power device design:
  - Transistor Structure (rugged turn off capabilities)
  - Thyristor Structure (low conduction losses)
- Devices developed along these lines

<table>
<thead>
<tr>
<th>Thyristors</th>
<th>Transistors</th>
</tr>
</thead>
<tbody>
<tr>
<td>• GTO (Gate turn-off thyristors)</td>
<td>• Bipolar Transistors</td>
</tr>
<tr>
<td>• MCT (MOS-controlled thyristors)</td>
<td>• Darlington transistor)</td>
</tr>
<tr>
<td>• FCT (Field-controlled thyristors)</td>
<td>• MOSFETs’</td>
</tr>
<tr>
<td>• MTO (MOS-turn off thyristor)</td>
<td>• IGBT (Integrated gate Bipolar transistor)</td>
</tr>
<tr>
<td>• EST (Emitter switched thyristors)</td>
<td></td>
</tr>
<tr>
<td>• IGTT (Insulated gate turn off thyristors)</td>
<td></td>
</tr>
<tr>
<td>• GCT (Gate Commutated Thyristors)</td>
<td></td>
</tr>
<tr>
<td>• IGCT (Integrated Gate commutated Thyristors)</td>
<td></td>
</tr>
</tbody>
</table>
Thyristor Structure and Equivalent Circuit

Thyristor structure: a) circuit symbol, b) device cross-section and c) equivalent circuit.
Thyristor I-V Characteristics

GCT's

- Dominance of thyristor structures:
  - Inherent ability to conduct larger currents with minimal losses
- Contenders for High Power Applications:
  - GTO's (Thyristor): Cumbersome snubbers required
  - IGBT's (Transistor): Inherently high losses
- GCT’s:
  - Semiconductor based on GTO structure
  - Gate Circuit has low inductance that enables cathode emitter to shut off "instantaneously"
Power switching devices - ratings

http://machines.ece.uiuc.edu/images/PE_persen_UIUC_v2.PDF
4.5kV, 3kA, IGCT (Integrated Gate Commutated Thyristor). The GCT (1) and the Gate Unit (2) form a single part. The PCB (3) connects the GCT and the drive.
## IGCT Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>State</th>
<th>Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Conduction:</td>
<td>thyristor</td>
</tr>
<tr>
<td>2</td>
<td>Turn-off:</td>
<td>pnp transistor</td>
</tr>
<tr>
<td>3</td>
<td>Blocking:</td>
<td>pnp transistor</td>
</tr>
<tr>
<td>4</td>
<td>Turn-on:</td>
<td>npn transistor</td>
</tr>
</tbody>
</table>
IGCT Block Diagram

Gate Unit

Supply (20V ac)

Command Signal (light)

X

1

RC-IGCT

RC-GCT

Anode

Gate

Cathode

Internal Supply (without galvanic isolation to power circuit)

Turn-On Circuit

Turn-Off Circuit

Logic Monitoring

Rx

-20V

5SHX 06F6004

ABB
IGCT Structure

Integrated Gate Commutated Thyristor

Conducting IGCT

Blocking IGCT
Conducting IGCT

- Operates as a thyristor
- Low on-state voltage

\[ V_{on} = 20 \text{ V} \]
\[ I_{32A} \]
Blocking IGCT

- Unity gain operation of the pnp transistor
- Operates as open base transistor
- Cathode junction is reverse biased
- Low gate inductance
- High current capability
IGCT I-V Characteristics

\[ I_G = 0 \quad \text{KA} \]
\[ \text{in 2 \mu s} \]
\[ 10 \text{ for 100ns} \]

\[ \sum_{\text{SW losses}} \]
Cont.
Semiconductor Technology

- Standard transistor
- Blocking voltage = Area under the curve
- Blocking voltage $\alpha$ silicon thickness
- Conduction loss $\alpha$ silicon thickness
- Switching loss $\alpha$ silicon thickness

\[
\text{Field (V/cm)}
\]

\[
\text{Thickness (\text{\mu m})}
\]

area under $D$ is $V$
Buffer layer transistor

- PIN structure
- Blocking voltage = Area under the curve
- Reduced silicon thickness
- Lower conduction and switching loss

![Diagram](image-url)
Transparent emitter

- Small anode gain
  - Thin Anode Emitter
    - Allows electrons to recombine at metal interface without generating holes
- Silicon thickness can be reduced by 1/3
  - Allows for optimum thickness to incorporate free wheeling diode
- Low turn off losses
Reverse Conduction

- Requires free wheeling diode
  - Limits rate of current change
- Integrated into wafer
  - GTO’s too thick before to integrate FWD
Gate unit

- Optically controlled
  - Fiber optic data link module
- Unity gain turn off
- Low initial turn on gain
- Relatively smaller in area (to GTO)
  - Transparent emitter
- Lower tail current
  - Reduced stored charge (because of buffer layer)
- $\frac{di}{dt}$ control at the input (to match with free wheeling diode)
- Low inductive coupling to gate module
- Low voltage gate source
- Low turn on/off times (higher switching rate)
Gate Unit Power Consumption

- Power supplied to gate
  - Thermal dissipation in the gate circuit (includes gate-cathode region)
    - Depends on switching frequency and duty cycle.
    - Part of the power is transferred to the load during turn-off.
Gate unit power consumption

- Graph showing power consumption vs. switching frequency for different duty cycles:
  - duty cycle: 0.1, 0.5, 1

- Graph showing power consumption vs. $I_{TGQ}$ for different switching frequencies:
  - $f_s = 1000$ Hz
  - $f_s = 500$ Hz
  - $f_s = 50$ Hz
AC Input

- Rectifier and Voltage regulator integrated in the gate-drive circuit board
  - Simplification of control interface
  - Reduction in system cost
- Allows direct connection to an isolation transformer with AC square wave output-voltage range 0f 24-40V
Cont.

- Optical Status Feedback
  - Regulated internal supply voltage
  - State of gate-cathode output
  - Optical signal transmission of both command and feedback.
Low noise housing

- Non magnetic materials for GCT housing
  - Reduction in acoustic noise (because of high current and di/dt noise problem in multi-megawatt converters.)
IGCT/GTO gate switching

\[ f_{IGCT} \approx 10 \times f_{GTO} \]
## Optical Gate Control Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{on,CS}$</td>
<td>Optical input power</td>
<td>$&gt; -20$ dBm</td>
<td>Valid for 1mm plastic optical fibre (POF)</td>
</tr>
<tr>
<td>$P_{off,CS}$</td>
<td>Optical noise power</td>
<td>$&lt; -45$ dBm</td>
<td></td>
</tr>
<tr>
<td>$t_{GLITCH}$</td>
<td>Pulse width threshold</td>
<td>$\leq 500$ ns</td>
<td>Max. pulse width without response</td>
</tr>
<tr>
<td>CS</td>
<td>Receiver for command signal</td>
<td>Agilent, Type HFBR-2528</td>
<td>Note 2</td>
</tr>
</tbody>
</table>
Optical Data Link (HFBR-0508)

- Fiber-Optic Transmitter and Receiver
  - DC-10MBd with low PW distortion
  - 50m with POF, 500m with HCS

- Transmitter: 650nm
  - LED
  - Couples into 200 μm dia. HCS fiber & 1mm dia. POF
Cont.

- Receiver
  - Silicon PIN photodiode
  - Digitizing IC
    - Logic compatible output
    - Corrects for PW distortion for the first bit

HFBR-2528 Receiver Block Diagram.
Applications

- Power Electronic Building Blocks
  - Universal blocks for high power applications
  - 27 MW
  - 99.6% efficiency
  - Used in wide variety of industrial equipment
    - Transportation
    - Energy Management
    - Marine Propulsion
Cont.

- High degree of integration
  - Gate drive is not application specific
  - Highest powers and lowest packaging cost at MV levels (press-pack semiconductors)

30 MW IGCT Power Management System
Parts Required

2-Level Inverter Component + Chips* vs. Inverter Rating
2.8 kV dc-link/600 Hz pwm

\[ \text{No of Components} \times \text{Chips} \]

- IGBT
- GTO
- GCT

* excluding Gate Unit

3-Phase Inverter Rating (MW)
Relative MVA costs for Press-Pack (hockey puck) designs comparing GTO, IGCT and IGBT in the same topology
Reliability

- For Press-Pack (hockey puck) designs comparing GTO, IGCT and IGBT in the same topology
  - IGCT has lowest FIT rate

<table>
<thead>
<tr>
<th>8 MVA Inverter Type</th>
<th>No of Chips per Switch (FIT)</th>
<th>Switch No of Chips per Diode</th>
<th>FW Diode (FIT)</th>
<th>Gate Driver (FIT)</th>
<th>N° Parallel Devices</th>
<th>Equivalent Discrete NPC Diode per Position (FIT)</th>
<th>Equivalent Clamp per Position (FIT)</th>
<th>Inverter Total (12 Positions)</th>
<th>FIT Ratio to IGCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCT</td>
<td>1</td>
<td>50</td>
<td>1</td>
<td>20</td>
<td>200</td>
<td>1</td>
<td>10</td>
<td>50</td>
<td>3'960</td>
</tr>
<tr>
<td>GTO</td>
<td>1</td>
<td>100</td>
<td>1</td>
<td>20</td>
<td>200</td>
<td>1</td>
<td>10</td>
<td>200</td>
<td>6'240</td>
</tr>
<tr>
<td>IGBT</td>
<td>24</td>
<td>120</td>
<td>12</td>
<td>60</td>
<td>150</td>
<td>2</td>
<td>10</td>
<td>50</td>
<td>9'120</td>
</tr>
<tr>
<td>POWER OUTPUT</td>
<td>3300W/6600V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Efficiencies</td>
<td>98% - 99%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Output Current Total</td>
<td>0 - 50 Hz</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harmonic Distortion (THD)</td>
<td>≤113%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage source</td>
<td>3-level neutral point clamped</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inverter</td>
<td>Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulation</td>
<td>Pulse Width Modulated (PWM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Semiconductor</td>
<td>Technology</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>GE Innovation Series MV-SP Drives</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Adaptive torque based motor control</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Previously made w/ GTO's now with IGCT's</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Benefits of IGCT use over GTO switch

- Low inductive coupling permits faster rates of change of gate current w/ low voltage gate source
Cont.

- Sustained higher switching improves performance and reduces harmonic distortion of current and voltage waveforms
  - Increases motor life expectancy
- High power factor
Cont.

- Inverter is a three level design
Cont.

- Harmonic Distortion
  - IGCT vs. old cycloconverter technology
  - IGCT means no expensive power filter to reduce THD

Comparison of input current wave form for the MV-SP versus the non-circulating input current cycloconverter technology.
Cont.

- Power Factor
  - pf is 1.0
    - Current and voltage are exactly in phase
  - Constant through speed range of motor
  - No external VAR compensation equipment required
IGBT vs IGCT

1MVA 2 Pulse Inverter Ratings

\( P_{\text{out}}: \)
\[ 1200\text{kVA} \]

\( V_{\text{out}}: \)
\[ 1200V_{\text{r.m.s.}} \]

\( I_{\text{out}}: \)
\[ 578A_{\text{r.m.s.}} \]

\( \text{PWM}: \)
\[ 750\text{Hz} \]

\( \text{Cooling}: \)
\[ \text{air} \]

\( \text{Ambient temperature}: \)
\[ 45^\circ\text{C} \]

\( \text{Type of cooling}: \)
\[ \text{forced air of 6m/s} \]

\( \text{Heat sink}: \)
\[ \text{extruded aluminium section} \]

\( \text{Load}: \)
\[ \text{motor of a p.f. of 0.9} \]

\( \text{Motor frequency}: \)
\[ 50\text{Hz} \]
Cont.

- **IGBT inverter design**
  - Designed with minimum inductance
  - Requires compact and lateral design based on a single wide-area heat sink

- **IGCT inverter design**
  - Inverter bridge does not require low-inductance construction
    - No need for extremely compact construction
Cont.

- Power Loss Comparison
  - IGBT dissipates 48% more power than IGCT

<table>
<thead>
<tr>
<th></th>
<th>IGBT</th>
<th>Diode</th>
<th>Switch</th>
<th>IGCT</th>
<th>Diode</th>
<th>Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power loss:</td>
<td>1023W</td>
<td>359W</td>
<td>1382W</td>
<td>502W</td>
<td>435W</td>
<td>937W</td>
</tr>
</tbody>
</table>
- **Thermal Budget**
  - IGBT total power loss is too high for 1 heat sink
  - Solution: Distribute to more heat sinks => complications

<table>
<thead>
<tr>
<th>Number of IGBT modules mounted on one heat sink</th>
<th>6 modules</th>
<th>3 modules</th>
<th>2 modules</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal resistance of heat sink required</td>
<td>&lt;0.0075</td>
<td>&lt;0.015</td>
<td>&lt;0.023</td>
<td>(K/W)</td>
</tr>
<tr>
<td>Size of heat sink</td>
<td>84 x 750 x 800</td>
<td>84 x 750 x 800</td>
<td>84 x 500*500</td>
<td>(mm)</td>
</tr>
<tr>
<td>Thermal resistance of heat sink</td>
<td>0.01125</td>
<td>&lt;0.01125</td>
<td>&lt;0.020</td>
<td>(K/W)</td>
</tr>
<tr>
<td>Number of heat sinks required</td>
<td>not possible</td>
<td>2 heat sinks</td>
<td>3 heat sinks</td>
<td>6/800</td>
</tr>
</tbody>
</table>
- IGCT power loss is less than IGBT and more manageable heat sinks
- Still not ideal and can be improved with water cooled

<table>
<thead>
<tr>
<th>Number of IGCTs mounted between two half-sinks</th>
<th>6 modules</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal resistance required for a half-sink</td>
<td>&lt; 0.120</td>
<td>(K/W)</td>
</tr>
<tr>
<td>Size of heat sink</td>
<td>84 x 200 x 200</td>
<td>(mm)</td>
</tr>
<tr>
<td>Thermal resistance of a half-sink</td>
<td>0.100</td>
<td>(K/W)</td>
</tr>
<tr>
<td>Number of half-sinks</td>
<td>12 elements</td>
<td></td>
</tr>
</tbody>
</table>
Cont.

- 3-Level inverters
  - IGBT cannot handle the voltage
  - IGCT can handle up to 6600V in this case

- Lifetime
  - IGBT: 10,000 cycles
  - IGCT: 100,000 cycles

3600 V (max)
Cont.

- IGCT is more economical for both 2 and 3 level inverters
  - Saves costs in heat sink design although it adds cost due to \( \text{di/dt limiting reactor} \) and an overvoltage clamp but is still cheaper than IGBT

- Can handle higher off-state voltages
  - 3300 V DC in 2 level
  - 6000 V DC in 3 level
Trends & Future

- Current operation of 250 kW/cm²
  - Twice this rating has been achieved and should be available in coming years
- Increase in junction temp. ratings
- Larger on state currents up to 6 kA will become common
- Voltage up to 10 kV are under consideration for numerous MV applications
Conclusion

- Excellent component characteristics
- **High rated voltage**
- Low turn-on and commutation losses
- Good utilization of the silicon area
- Even current distribution in the silicon
- Linear relationship between the active wafer area and current rating
- Central $\text{di/dt limiter with integrated clamp}$
  - Improves minimum on/off time (100 $\mu$s to 10 $\mu$s)
  - Allows higher frequency
- Moderate expenditure for cooling
Series connection easily achieved
Absolute safety even under worst case conditions
Simple drive circuit
Directly coupled gate signal (on / off)
Requires \( \frac{di}{dt} \) limiting reactor and a clamp
No \( \frac{dv}{dt} \) snubber required
Less power consumption
- Only few components: all standard
- Modular mechanical construction
- Monolithic integration up to the highest ratings
- Simple to service
- High overall efficiency
- Highest possible reliability
- Small size and low weight