Function, Technology and Features of IGCTs and High Voltage IGBTs

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Outline

1. Introduction

2. Structure, Function and Characteristics of IGBTs

3. Structure, Function and Characteristics of IGCTs

4. Latest IGCT Technology Developments
   • IGCT Series Connection
   • 10kV IGCTs

5. Conclusions
Power Semiconductors

- SCR
- IGCT 10kV (ABB)
- IGCT 6.5kV (ABB)
- GTO
- 6500V/600A (Eupec)
- 12000V/1500A (Mitsubishi)
- 7500V/1650A (Eupec)
- 6500V/2650A (ABB)
- 5500V/2300A (ABB)
- 6000V/6000A GTO (Mitsubishi)
- 6000V/6000A IGCT (Mitsubishi)
- 4800V/5000A (Westcode)
- 4500V/4000A (ABB, Mitsubishi)

Power MOSFET
- 200V/500A (Semikron)
- 3300V/1200A Module (Eupec)
- 2500V/1800A Press-Pack (Fuji)
- 1700V/2400A Module (Eupec)
## PowerSemiconductors for MV Converters

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<td>Press-Pack</td>
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<td>3300V; 1200A 4500V</td>
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<td>TOSHIBA</td>
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<td>ABB</td>
<td>4500V; 1500A</td>
<td>6.75</td>
<td>IPM</td>
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<td>IGCT</td>
<td>ABB</td>
<td>4500V; 3500A 5500V; 2300A</td>
<td>15.75</td>
<td>Press-Pack Press-Pack</td>
</tr>
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<td>MITSUBISHI</td>
<td>4500V; 4000A 6000V; 6000A</td>
<td>18 36</td>
<td>Press-Pack Press-Pack</td>
</tr>
</tbody>
</table>
Characteristics of Conventional GTOs

Advantages:
1. High on-state current density
2. High blocking voltage and switch power
3. High off-state dv/dt withstand capability
4. Integration of inverse diode on the same silicon wafer
5. Small part count in the reliable press-pack case
Turn-off Waveforms of GTOs

Characteristics

- Typical Turn-off Gain: $I_T/I_{RG} = 3 - 5$
- $dv/dt = (500-1000) \text{ V/µs}$
Turn-off Behaviour of GTOs

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Characteristics of Conventional GTOs

Disadvantages:
1. Inhomogeneous turn-off transient
2. Limitation of $dv/dt$ to about 500-1000V/µs
3. Bulky and expensive snubber circuits
4. Complex gate drive
5. High gate drive power
Structure of a NPT - IGBT Chip
Conduction State of a NPT - IGBT

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Structure of an IGBT Module

- Silicon Chip 220 µm
- Solder 80 µm
- Aluminium oxide - Isolation 380 µm
- Upper & lower copper layer 300 µm
- Solder 80 µm
- Baseplate (Copper) 3 mm
- Thermal compound 50 µm
- Heatsink
Hard Turn on Transient of an IGBT Module

(FZ1200R33KF1 (3300V; 1200A), \( V_{dc}=2250\text{V} \), \( I_o=1050\text{A} \), \( T_j=25^\circ\text{C} \))
Hard Turn off Transient of an IGBT Module

(FZ1200R33KF1 (3300V; 1200A), \( V_{dc} = 2250V \), \( I_o = 1050A \), \( T_j = 25^\circ C \))
Characteristics of High Power IGBT Modules

Protection:
• Limitation of short circuit current by IGBT (e.g. $V_{GE}=15V; I_C=3*I_r$)
• Turn off transient within 10µs
• Short Circuit Safe Operating Area: $V_{dcreg}=2500V; I_{Creg}=3.5*I_r$

Failure:
• Heavy destruction of IGBT by overcurrent
• Mostly open circuit after destruction
Characteristics of High Power IGBT Modules

Reliability:
• Aluminum wires and bonds are critical parts at power cycling tests
• Increase of thermal resistance by migration of thermal contact grease and inhomogeneous thermal contacts
Characteristics of IGBT Gate Units

- Very low gate drive power (e.g. 3-5 W)
- Control of $dv/dt$ and $di/dt$
- Active overvoltage protection – active clamping (e.g. for series connection)
- Active short circuit protection
Characteristics of IGBT Modules

Advantages

1. Full insulation of base plate (simple cooling)
2. Simple mounting
3. Low cost plastic package

Disadvantages

1. Undefined failure mode (mostly open terminals)
2. Possibility of explosion
3. Poor power cycling capability
4. Single sided cooling
Physical Arrangement of an IGBT Press Pack
Characteristics of IGBT Press Packs

Advantages

1. Short circuit in failure mode enables redundant converter design (e.g. \( (n+1) \), \( (n+2) \))
2. No explosion
3. Double sided cooling

Disadvantages

1. No insulation of heat sink
2. Higher packaging costs
Physical Arrangement of IGCTs

91mm 4.5kV IGCT for water cooling

51 mm 4.5kV IGCT for air cooling
Comparison of PT and NPT Structure

Electric Field and Doping Level of 4,5 kV PT- und NPT-GTOs
IGCT Turn-off Waveforms

- **Anode-Voltage** $V_d$ (kV)
- **Anode-Current** $I_a$ (kA)
- **Gate Voltage** $V_g$ (V)

- $V_{dm}$
- $I_{tgq}$

Thyristor vs. Transistor

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Characteristics of IGCTs

Protection:

• Active turn-off transient for $I_{\text{short}}(t)<I_{\text{Amax}}$ (e.g. at external short circuit)

• Internal shoot through:
  • IGCTs safely short circuit the dc-link
  • $di/dt$-clamp limits maximum peak current
Characteristics of an IGCT- Gate Drive in Comparison to a GTO Gate Drive

- Storage time: \( t_{s-IGCT} = \frac{1}{15} t_{s-GTO} \)
- Despite of increase of \( I_{gqrn} \):
  \( Q_{g-IGCT} = 0.4 \times Q_{g-GTO} \)
- Transparent anode: On-state gate current of IGCT is reduced by 50%
- IGCT gate drive power is reduced by 50%
- Uncritical minimum switching times do not require control on IGCT gate drive
Characteristics of IGCTs

Reliability:
- Low part count and press-pack case enable high reliability
- Qualification tests and field experience:
  - FIT (Failure in one billion hours) < 2300
  - for a 3MVA inverter
Turn-off Transient of an IGCT Inverse Diode

(4500V; 1560A - RCIGCT; $V_{DC}=2800V$, $I_F=1300A$; $V_{DM}=4335A$; $\frac{di}{dt}=400A/\mu s$)
Motivation of Research

- **General Development Trend** →
  
  Increasing importance of PWM-VSIs

  - Replacement of Cycloconverter and LCI
  
  - Increasing use in energy systems (e.g. Windparks, HVDC, STATCOMs, Active Filters, High Power UPS)
  
  → Increase of converter voltage and power

- **Converter voltage of** $V_{\text{out,RMS}} = 6 \text{ kV} – 10 \text{ kV}$ →
  
  - Series Connection of IGCTs
    
    (e.g. $n=3$ devices per switch position in 3L-NPC VSI)
  
  - Increase of device voltage at useful silicon utilization
    
    (e.g. 10kV IGCT / diode: $V_{\text{out,RMS}} = 6 \text{ kV} – 7.2 \text{ kV}$ in 3L-NPC VSI)
Voltage definitions

- \( V_{DC \, MAX} \) (≈ 15 seconds @ \( T_{Jmax} \))
- \( V_{DC \, NOM} \) (continuous @ \( T_{Jmax} \))

Approximations:
- \( \approx 100 \, \mu s \)
- \( \approx 10 \, ms \)
## Device Voltage Ratings in 3-Level Inverter ($N = 1$)

<table>
<thead>
<tr>
<th>Nominal RMS Line Voltage</th>
<th>Nominal DC Half-Link Voltage</th>
<th>Maximum DC Half Link Voltage</th>
<th>Maximum Repetitive Blocking Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{RMS}$ (kV)</td>
<td>$V_{DC,NOM}$ (kV)</td>
<td>$V_{DC,MAX}$ (kV)</td>
<td>$V_{DRM}$ (kV)</td>
</tr>
<tr>
<td>2.3</td>
<td>1.9</td>
<td>2.2</td>
<td>3.3</td>
</tr>
<tr>
<td>3.3</td>
<td>2.7</td>
<td>3.1</td>
<td>4.5</td>
</tr>
<tr>
<td>4.16</td>
<td>3.4</td>
<td>3.9</td>
<td>5.5</td>
</tr>
<tr>
<td>6</td>
<td>4.9</td>
<td>5.6</td>
<td>8</td>
</tr>
<tr>
<td>6.6</td>
<td>5.4</td>
<td>6.2</td>
<td>9</td>
</tr>
<tr>
<td>6.9</td>
<td>5.6</td>
<td>6.5</td>
<td>9.5</td>
</tr>
<tr>
<td>7.2</td>
<td>5.9</td>
<td>6.8</td>
<td>10</td>
</tr>
</tbody>
</table>
### Number N of Series Connected Devices in 3L NPC VSI

<table>
<thead>
<tr>
<th>Nominal RMS Line Voltage</th>
<th>N of 4.5 kV IGCTs / Diodes</th>
<th>N of 5.5 kV IGCTs / Diodes</th>
<th>N of 10 kV IGCTs / Diodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{RMS} (kV)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3.3</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4.16</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>6.6</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>6.9</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>7.2</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
IGCT - Series Connection

Reasons for Voltage Unbalance of Series Connected Devices

Static
• Deviating leakage currents

Dynamic
• Delay between Gate Signals
• Deviating switching behavior (e.g.)
  • Different tail or reverse recovery charges
  • Different switching times (dv/dt’s, di/dt’s)

Consider
• The IGCT has a latching thyristor structure!
  ⇒ Control of dv/dt or clamping of switch voltage by gate control in active region is not possible – in contrast to the IGBT or MOSFET!
  ⇒ External balancing 2-Pole required!
Balancing Circuit

- Dynamic voltage balancing: **RC-Snubber**
- Static voltage balancing: **balancing resistor**

Design Tradeoffs:
- low losses $\rightarrow C_{\text{Snub}} \downarrow$
- good balancing $\rightarrow C_{\text{Snub}} \uparrow$, selected IGCTs
Design Criteria

- avoid $V_{\text{max}} > 4.5\text{kV}$ (immediate device destruction)
- average blocking voltage lower than $2.8\text{kV}$ (FIT)

Values given for 4.5kV IGCTs
IGCT - Series Connection (RC - Snubber)

Test Setup
- Buck Converter
  - $V_{DC}=6$ kV, $I_{out}=4$ kA
- $n=2$
  - 91mm 4.5kV IGCTs
  - 68mm 4.5kV diodes
- Snubber
  - $R_{snub}=1$ Ω
  - $C_{snub}=500$ nF
  - $R_p=25$ kΩ
IGCT Series Connection - Turn-off Transient

\[
V_{DC} = 4.6\text{kV}; \quad I_{out} = 2\text{kA}; \quad n = 2; \quad T_j = 115^\circ\text{C}; \quad C_{\text{snub}} = 500\text{nF}; \quad R_{\text{snub}} = 1\Omega
\]
Losses

\[ V_{DC} = 4.5 \text{ kV}, \quad I_{out} = 2 \text{ kA} \]

- \( E_{\text{off,IGCT}} \)
  - snubberless: 8 J
  - with snubber: 6.4 J

- \( E_{\text{on,IGCT}} \)
  - snubberless: 0.5 J
  - with snubber: 1.6 J

- \( E_{\text{off,Snubber}} \)
  - with snubber: 0.65 J

- \( E_{\text{on,Snubber}} \)
  - with snubber: 0.63 J

- \( E_{\text{total}} \)
  - with snubber: 8.5 J
  - with snubber: 9.28 J

- \( V_{DC} = 4.5 \text{ kV} \)
- \( I_{out} = 2 \text{ kA} \)
## Technical Data Phase Leg / 3~ Inverter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value / Type</th>
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<tr>
<td>nominal dc input voltage</td>
<td>$V_{DC} = 13.2 \text{kV} \ (\pm 10%)$</td>
</tr>
<tr>
<td>rms output current</td>
<td>$I_{out} = 1.5 \text{kA}$</td>
</tr>
<tr>
<td>nominal peak output current</td>
<td>$I_{out, \text{peak}} = 2.5 \text{kA}$</td>
</tr>
<tr>
<td>output power</td>
<td>$S_{out} = 8 \text{MVA} / 24 \text{MVA}$</td>
</tr>
<tr>
<td>carrier frequency</td>
<td>$f_s = 700 \text{Hz}$</td>
</tr>
<tr>
<td>IGCT 5SHY35L4503</td>
<td>(4.5kV 91mm)</td>
</tr>
<tr>
<td>diode (4.5kV 68mm)</td>
<td>D65S45 (4.5kV 68mm)</td>
</tr>
</tbody>
</table>
IGCT Series Connection - Output Waveforms

$V_{\text{DC}} = 14.2\, \text{kV}$; $I_{\text{out, rms}} = 1.5\, \text{kA}$;
$f_s = 700\, \text{Hz}$; $f_{\text{out}} = 50\, \text{Hz}$
IGCT Series Connection - Test Setup

- DC-Link Capacitors
- Load Inductor
- IGCT-Stack
- RC-Snubber
- 0.9m

Photo *Phase Leg*
Trade-off Curves of 5.5 kV and 10 kV IGCTs

- Similar losses of ideal series connection of 5.5 kV IGCTs and 10 kV IGCTs

- Additional snubber losses in real series connection (e.g.)
  - Static: $P_R (R_p=25 \, k\Omega)$
  - Dynamic: $E_{\text{snub},C} \approx 0.15 E_{\text{off,IGCT}}$
    - (4.5 kV IGCTs / N=2
      @ $V_{\text{DC}}=4500\,V$, $I_{\text{out}}=2\,kA$)

**Graph:**
- 10 kV design: $V_{\text{DC}}=5.16\,kV$
- Ideal series connection of two 5.5 kV IGCTs: $V_{\text{DC}}=5.16\,kV$
- Decreasing lifetime
- 5.5 kV design: $V_{\text{DC}}=2.58\,kV$

**Equations:**
- Static: $P_R (R_p=25 \, k\Omega)$
- Dynamic: $E_{\text{snub},C} \approx 0.15 E_{\text{off,IGCT}}$
  - (4.5 kV IGCTs / N=2
    @ $V_{\text{DC}}=4500\,V$, $I_{\text{out}}=2\,kA$)
Potential of 10 kV IGCTs and Diodes

Compared to an IGCT series connection (N=2)
10 kV IGCTs / diodes feature:
→ Comparable losses for $f_s = 200$ Hz-1 kHz
→ Reduction of part count
  - by 71% ($S \leq 5.5$ MVA)
  - by 41% ($S > 5.5$ MVA)
→ Increase of reliability
  - by 56% ($S \leq 5.5$ MVA)
  - by 12% ($S > 5.5$ MVA)
→ Simpler stack design
  • Avoidance of RC snubber
→ Simpler maintenance
  • Avoidance of semiconductor selection and RC snubber
Design of 10 kV IGCTs

- Manufacturing process in line with standard IGCT / GTO process
  → Double diffused p-base
  → Heavily doped cathode emitter
  → Buffer layer for field stopping
  → Low efficiency p – Anode

- Cosmic ray withstand capability: 2 FIT / cm²
  → n-base thickness: 1050 µm
  → Substrate doping level: 4.2 \(10^{12}\) cm\(^{-3}\)
  → Silicon resistivity: 1000 Ωcm
Engineering Sample of 68 mm 10 kV IGCT
Forward Blocking Characteristics at 25°C

magnified by factor 1000:
1 µA / div

(<17 µA @ 10 kV, 25°C)
Forward Blocking Characteristics at 125°C

Comparison T = 125°C

(<14 mA @ 7 kV, 125°C)  (8-13 mA @ 6 kV, 125°C, \( P_L = 50\text{W}-80\text{W} \) (5%-10% of \( P_{RP} \))

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On-state Characteristics

\[ V_T = V_{T0} + r_d \cdot I_A \]

- \( V_{T0} \) (Threshold voltage): 3.5V
- \( R_d \) (On-state resistance): 1m\( \Omega \)

(4.5V @ 1 kA, 125°C)
Turn-off Characteristics

Test circuit and stack design
($V_{DC} = 2.4kV-7kV$, $I_A = 100A-1kA$, $T_j = 25^\circ C-115^\circ C$, $L_{cl} = 13.6\mu H$, $C_{cl} = 1\mu F$, $R_{cl} = 2.3 \, \Omega$)
### Switching characteristics:

\[ V_{DC} = 5.7 \text{ kV}, \ I_A = 900 \text{ A}, T_j = 85^\circ \text{C}: \ E_{off} = 11 \text{ Ws}, \ t_f = 1 \mu\text{s}, \ t_{tail} = 6 \mu\text{s}, \ V_{AK,\text{max}} = 6.7 \text{ kV} \]
Turn-off Waveforms

Operating conditions:
\( V_{DC} = 2.5 \text{kV} - 5.7 \text{kV}, \ I_A = 800 \text{A} - 900 \text{A}, \ T_j = 85^\circ \text{C} \)

Switching characteristics:
\( V_{DC} = 5.7 \text{kV}, \ I_A = 900 \text{A}: \ E_{\text{off}} = 11 \text{Ws}, \ V_{AK,\text{max}} = 6.6 \text{kV}, \ t_f = 1 \mu\text{s}, \ t_{\text{tail}} = 6 \mu\text{s} \)
Turn-off Waveforms (SOAR)

Operating conditions:
\( V_{DC} = 7 \text{kV}, I_A = 1000 \text{A}, T_j = 85 \text{°C} \)

Switching characteristics:
\( E_{off} = 14.8 \text{ J}, V_{AK,max} = 8 \text{ kV}, t_{off} = 8 \mu\text{s}, t_f = 1 \mu\text{s}, t_{tail} = 5 \mu\text{s} \)

World Record!
## Specification of 68mm 10kV IGCTs

<table>
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<th>Electrical and thermal characteristics</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{DRM} )</td>
<td>( 10 \text{ kV} )</td>
</tr>
<tr>
<td>( V_{DC} )</td>
<td>( 6 \text{ kV} )</td>
</tr>
<tr>
<td>( V_{GR} )</td>
<td>( 22 \text{ V} )</td>
</tr>
<tr>
<td>( V_{TM} )</td>
<td>( 4.5 \text{ V} )</td>
</tr>
<tr>
<td>( I_{TGQ} )</td>
<td>( 1000 \text{ A} )</td>
</tr>
<tr>
<td>( E_{OFF} )</td>
<td>( 11 \text{ Ws} )</td>
</tr>
<tr>
<td>( R_{th \ J-C} )</td>
<td>( 13 \text{ K/kW} )</td>
</tr>
<tr>
<td>( T_{J Max} )</td>
<td>( 125^\circ \text{C} )</td>
</tr>
<tr>
<td>( I_{TSM} )</td>
<td>( 10 \text{ kA} )</td>
</tr>
</tbody>
</table>

- \( T_j = 0 - 125^\circ \text{C} \)
- for 100 FIT, 100% DC
- \( V_{DC} = 6 \text{ kV} \)
- \( I_A = 1000 \text{ A}, V_{DC} = 6 \text{ kV} \)
- \( r_d = 1 \text{ m}\Omega, V_{TO} = 3.5 \text{ V} \)
Conclusions

• IGBTs and IGCTs replace GTOs in MV Converters

• Advantages of IGBTs
  • IGBT MOS-controlled device
    → Low power GU
    → GU control of dv/dt and di/dt
    → Short circuit current limitation and active turn off
    → Active clamping
  • Simple mechanics
  • Simple scalability
Conclusions

Disadvantages of IGBTs

- Higher losses and poorer Si-utilization than IGCTs
- Limited power cycling capability of IGBT modules
- Costs (especially of IGBT press packs)

Development trends

- Reduction of losses and costs by new technologies and high volume production
Applications of HV - IGBTs

1. Traction Converters (LSC, MSC)
2. Energy Systems (e.g. HVDC, SVC)
3. Industrial Medium Voltage Drives
Conclusions

Advantages of IGCTs

• Maximum Silicon Utilization → Low costs / MVA
• Small Part Count + Press pack → High Reliability + Explosion Free Inverters
• Low On-state and Total Losses → High Efficiency and Power Density
• 4.5 kV / 5.5 kV IGCT product family → 300 kVA-10 MVA Inverters without Series or Parallel Connection
Conclusions

Disadvantages of IGCTs

• Shoot through protection →
  High mechanical stress for IM / SM

• Thyristor structure →
  No dv/dt or di/dt control → Clamp
  Larger gate drive power and size
Conclusions

• Development trends
  • IGCT: Mature device
  • Increase of device voltage (e.g. 10kV IGCT)
  • Increase of $T_{j\text{max}}$ (e.g. $T_{j\text{max}} = 175\,^\circ\text{C}$)
  • Low cost, efficient series connection
Applications of IGCTs

1. Industrial Medium Voltage Drives

2. Energy Systems
   - Railway Interties
   - Power Quality Products
     - e.g. Dynamic Voltage Restorer
   - Wind Energy Systems