INTRODUCTION
Electronic Switches

- **Thyristor**
  Can be turned *on* by gate signal but can only be turned *off* by reversal of the anode current

- **Gate Turn-Off Thyristor (GTO)**
  Can be turned *on* and *off* by the gate signal but requires large capacitor (snubber) across device to limit dv/dt

- **Transistor (transitional resistor)**
  Can be turned *on* and *off* by the gate (or base) signal but has high conduction losses (it's an amplifier, not a switch)

- **Integrated Gate Commutated Thyristor (IGCT)**
  Can be turned *on* and *off* by the gate signal, has low conduction loss and requires no dv/dt snubber
### Available Self-Commutated Semiconductor Devices

#### THYRISTORS
- GTO (Gate Turn-Off Thyristor)
- MCT (MOS-Controlled Thyristor)
- FCTh (Field-Controlled Thyristor)
- SITh (Static Induction Thyristor)
- MTO (MOS Turn-Off Thyristor)
- EST (Emitter-Switched Thyristor)
- IGTT (Insulated Gate Turn-off Thyristor)
- IGT (Insulated Gate Thyristor)
- IGCT (Integrated Gate-Commutated Thyristor)

#### TRANSISTORS
- BIPOLAR TRANSISTOR
- DARLINGTON TRANSISTOR
- MOSFET
- FCT (Field Controlled Transistor)
- SIT (Static Induction Transistor)
- IEGT (Injection Enhanced (insulated) Gate Transistor)
- IGBT (Insulated Gate Bipolar Transistor)
High Power Turn-off Devices

- **Power Semiconductors**
  - **Turn-off Devices**
    - Transistors
      - Darlington
      - IGBTs
    - Thyristors
      - GTO
      - IGCT
  - Thyristors
    - Line commutated
    - Fast
    - Bi-directional
    - Pulse
  - Diodes
    - Fast
    - Line commutated
    - Avalanche
Power Semiconductors …

are switches….

….for converting electrical energy
Turn-on Switches (Thyristors)

Thyristors (PCTs)

- thyristors produce voltage distortion in phase control mode

- will ultimately be replaced by ToDs, except...

  in AC configuration for:
  - transfer switches
  - tap changers
  - line interrupters
World Energy Consumption ...

... drives the need for high power electronics

Source: Mitsubishi Electric
Energy trend

By 2020:

- Energy consumption will double
- Electricity generation will double
- Electrification of end-consumption will quintuple

Today, only 15% of electricity flows via electronics

Medium Voltage conversion has only been economically possible in the last 10 years

Power conversion at MV levels set to grow faster than LV (20% p.a.)
SELF- COMMUTATED INVERTERS
Basic Topologies

IGCT Inverter

IGBT Inverter
Turn-on waveforms for IGCTs and IGBTs

$$E_{on - circuit} = (t_2 - t_0) \bullet V_{dc} \bullet (I_{load} + I_{rr})/2 ....(1)$$

$$E_{on - device} \approx I_{load} \bullet \int_{t_2}^{t_3} V_{switch}(t) \cdot dt ..............(2)$$
DEVICES
IGBTs
IGBTs – key features

- Transistors with insulated gate
- Allow $dv/dt$ and $di/dt$ control via gate signal (losses)
- High on-state voltage (transistor)
- High turn-on losses (no snubber)
- Low gate power requirements (voltage control)
- No passives required (independant $dv/dt$ and $di/dt$ control)
HiPak™ High Power IGBT Modules

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
<th>Type</th>
<th>Part Number</th>
<th>Vce 125°C</th>
<th>Vf 125°C</th>
<th>Eoff 125°C</th>
<th>Eon 125°C</th>
<th>Vdc</th>
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<tbody>
<tr>
<td>2500V</td>
<td>1200A</td>
<td>Single</td>
<td>5SNA 1200E250100</td>
<td>3.1V</td>
<td>1.8V</td>
<td>1.25J</td>
<td>1.15J</td>
<td>1250V</td>
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<tr>
<td>3300V</td>
<td>1200A</td>
<td>Single</td>
<td>5SNA 1200E330100</td>
<td>3.8V</td>
<td>2.35V</td>
<td>1.95J</td>
<td>1.89J</td>
<td>1800V</td>
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<td>3300V</td>
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<td>1800V</td>
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<tr>
<td>6500V</td>
<td>600A</td>
<td>Single</td>
<td>5SNA 0600G650100*</td>
<td>4.7V</td>
<td>4.0V</td>
<td>3.5J</td>
<td>4.0J</td>
<td>3600V</td>
</tr>
</tbody>
</table>

* High voltage version

AISiC base-plate & AlN substrate
StakPak™ - stackable press-packs (collector side)

StakPak-H4: 2.5 kV/1300 to 3000 A

StakPak-H6: 2.5 kV/ 2000A to 3000 A

StakPak-L2: 4.5 kV/600 to 1000 A

StakPak-J6: 4.5 kV/2000 to 3000 A
IGBT Press-packs

Conventional IGBT press-pack:
*requires tight mechanical tolerances*

StakPak™ IGBT press-pack with individual springs:
*suitable for long stacks with compounded tolerances*
StakPak™ HVDC Valve

Long stacks would require very tight mechanical tolerances to ensure identical force on each chip in each housing:

- on assembly
- over time
- with temperature cycling
- with shock and vibration
IGBT Trends
IGBT Trends

- Higher voltages
- Higher *Safe Operating Area* (SOA)
- Softer (controlled) switching
Soft switching: 3.3kV SPT* IGBT/Diode chip-set

IGBT Turn-off
- \(V_{cc} = 1800\text{V}\)
- \(I_c = 50\text{A}\)
- \(R_{Goff} = 33\text{ohm}\)
- \(L_s = 2.4\mu\text{H}\)
- \(T_j = 125\text{°C}\)

Diode Turn-off
- \(V_R = 1800\text{V}\)
- \(I_F = 100\text{A}\)
- \(R_{Gon} = 33\text{ohm}\)
- \(L_s = 2.4\mu\text{H}\)
- \(T_j = 125\text{°C}\)

* Soft Punch Through
Soft switching: 8 kV IGBT PT vs SPT

The diagram shows the current and voltage over time for conventional PT device and SPT. The high di/dt giving rise to EMI issues is indicated on the diagram.
3.3kV Diode RBSOA Performance

3.3kV/100A Diode RBSOA during Reverse Recovery
\( V_R = 2500V, \ I_F = 200A, \ di/dt=1000A/\mu s, \ L_s = 2.4\mu H, \ T_j = 125^\circ C \)

Peak Power = 0.8 MW/cm²
No clamp, no snubber
4.5kV IGBT RBSOA Performance

4.5kV/40A IGBT RBSOA during Turn-off
\[ V_{cc} = 3600\text{V}, \, I_c = 120\text{A}, \, R_G = 0\text{ohm}, \, L_s = 12\mu\text{H}, \, T_j = 125^\circ\text{C} \]

**Dynamic Avalanche**

**SSCM**

\[ I_c = 3 \times I_{\text{nominal}} \]

**Peak Power** = 0.5 MW/cm²

No Clamp, No Snubbers
6.5kV IGBT RBSOA Performance

6.5kV/2x25A IGBT RBSOA during Turn-off
\( V_{cc} = 4500V, I_c = 100A, R_G = 0\, \text{ohm}, L_s = 20\mu H, T_j = 125^\circ C \)

Peak Power = 0.25 MW/cm²
No Clamp, No Snubbers
6.5kV IGBT Short Circuit Performance

6.5kV/25A IGBT SCOSA during Short Circuit
\( V_{cc} = 4500V, I_{cpeak} = 290A, V_{GE} = 18V, L_s = 2.4 \mu H, T_j = 25^\circ C \)

Peak Power = 1.35 MW/cm²
No Clamp, No Snubbers
3.3kV IGBT Module RBSOA Performance

3.3kV/1200A IGBT module during Turn-off (24 IGBTs)
$V_{cc} = 2600V$, $I_c = 5000A$, $R_G = 1.5\,\text{ohm}$, $L_s = 280\,\text{nH}$, $T_j = 125^\circ\text{C}$

No clamp, no snubbers
IGCTs
IGCTs – key features

- Thyristor with integrated gate unit
- Low on-state voltage
  (thyristor)
- Negligible turn-on losses
  (turn-on snubber)
- No explosive failures
  (fault current limitation by circuit)
Principle of IGCT Operation

Conducting Thyristor

[Diagram showing the conductivity of a thyristor with anode, cathode, and gate connections.]

Blocking Transistor

[Diagram showing the blocking state of a transistor with anode, cathode, and gate connections.]
IGCT turn-off

Anode voltage $V_d$ vs time $t$ (µs)

- $V_{dm}$: anode voltage
- $I_{tgq}$: anode current
- $V_g$: gate voltage

The thyristor starts to block at $V_g$.

Transistor follows the thyristor behavior.

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General turn-on waveforms for IGCTs and IGBTs

\[ E_{\text{on-circuit}} \]

\[ V_{\text{switch or L}} = V_{\text{DC}} \]

\[ I_{\text{load}} \]

\[ I_{\text{FWD}} \]

\[ \frac{\text{di}}{\text{dt}}_{\text{on}} \]

\[ t_0 \]

\[ t_{\text{on}} \]

\[ t_1 \]

\[ t_2 \]

\[ t_3 \]

\[ I_{\text{pk}} \]

\[ I_{\text{switch}} \]

\[ I_{\text{RR}} \]

\[ V_{\text{switch}} = f(t) \]
1500 A IGBT turning on 1000 A from 3000 V

$E_{ON} = 7.4 \text{ WS}$

$E_{ON\_circuit} = 4.1 \text{ WS}$

$I_C [250 \text{ A/div}]$

$V_{CE} [500 \text{ V/div}]$

$833 \text{ A/\mu s}$

$time [2 \mu s/div]$
4000 A IGCT turning on 1000 A from 3000 V

\[ E_{on\_circuit} = (t_2 - t_0) \cdot V_{dc} \cdot \left( I_{load} + I_{rr} \right) / 2 \ldots (1) \]

\[ = 1.5 \mu s \cdot 3000V \cdot 1900 A / 2 = 4.3 \text{Ws} \]
Adjustment of $dv/dt$ by lifetime control

![Graph showing adjustment of $dv/dt$ by lifetime control](image-url)

- $I_A$, $V_{AK}$, [A, V]
- $V_{AK}$: Green line for medium lifetime, Blue line for low lifetime, Red line for high lifetime
- $I_A$: Line for high lifetime

$t$ [μs] from 6 to 14
Low inductance housing
4 kA/4.5 kV IGCTs

- IGCT
- Power supply connection
- Visible LED indicators
- All copper housing
- IGCT
- Status Feedback
- Command Signal
- Optical fibre connectors
- GCT

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30 MW IGCT Power Management

15 + 15 MW 3-Level Back-to-Back Converter
for three-phase to single-phase conversion

Converter efficiency = 99.2%
4 kA/4.5 kV IGCT at 25 kHz in burst mode

- Anode voltage and current (V, A)
- $V_{DC \text{ start}} = 3.5 \text{ kV}$
- $V_{DM \text{ peak}} = 4.5 \text{ kV}$
- $I_{TGQ \text{ peak}} = 4 \text{ kA}$
- $T_J \text{ start} = 25 \degree \text{C}$
- $\alpha = 0.5$
IGCT Outlook
IGDT
Structure of IGDT – Integrated Gate Dual Transistor

Dual Gate Turn-off Thyristor
91 mm 4.5 kV IGDT turn-off

Dual-gate IGCT @ 85°C - gates triggered simultaneously

\[ V_{DC} = 2.8 \text{ kV} \]
\[ I_{TQG} = 3.3 \text{ kA} \]
\[ V_{DRM} = 4.5 \text{ kV} \]
\[ V_{TM} = 2.1 \text{ V @ 4 kA/125°C} \]
IGDT Series connection: leakage current reduction

\( V_{DC} = 2800 \text{ V} \)

- Anode gate floating (no bias)
- Anode gate with 20V reverse biased

\[ I_D (mA) \]

\[ T_J (°C) \]

140°C
91 mm 4.5 kV IGDT - Leakage current control

$V_{GK} = -20V$, $T_J = 25^\circ C$

$I_D$ - anode leakage current [mA]

$I_{GA}$ Anode gate current [mA]
IGDT anode gate control of tail current

![Graph showing IGDT anode gate control of tail current](image-url)
Increased SOA
IGCT SOA improvement at 4.5 kV

**TODAY**
- 38 mm reverse conducting
- 250 kW/cm²

**TOMORROW**
- 91 mm asymmetric
- 1000 kW/cm²
- 400 kW/cm²
6.5 kA @ 2.8 kV_{DC} on 91 mm wafer

Snubberless turn-off
T_j = 125°C, V_D = 2.8kV

Developmental 4” 4.5 kV IGCT with improved GU and silicon design allowing 50% SOA improvement
1.3 kA @ 2.8 kV\textsubscript{DC} on 38 mm RC wafer

Developmental 2” 4.5 kV RC\_IGCT with improved GU and silicon design allowing 300% SOA improvement
10 kV IGCT
Engineering Sample of 68 mm 10 kV IGCT
Forward Blocking Characteristics at 25°C

Anode Current $I_{DR}$ [mA] vs. Blocking Voltage $V_{AK}$ [kV]

- magnified by factor 1000:
  - $1 \mu A / \text{div}$

(<17 $\mu A \text{ @ } 10 \text{ kV, 25°C})
Forward Blocking Characteristics at 125°C

(<14 mA @ 7 kV, 125°C)

(8-13 mA @ 6 kV, 125°C, $P_L=50W-80W$ (5%-10% of $P_{RP}$)
Turn-off Waveforms (SOA)

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

Switching characteristics:
\( E_{\text{off}} = 14.8 \text{ J}, V_{\text{AK, max}} = 8 \text{ kV}, t_{\text{off}} = 8 \mu\text{s}, t_f = 1 \mu\text{s}, t_{\text{tail}} = 5 \mu\text{s}, 250 \text{ kW/cm}^2 \)
Conclusions
SOA Limits of HV Devices are increasing

- Under RBSOA operational conditions
  - Devices withstands dynamic avalanche mode
  - IGBTs withstands “SSCM” mode
  - Devices achieve the ultimate square SOA behaviour
Switching-Self-Clamping-Mode “SSCM”

IGBT SOA turn-off waveforms including SSCM
- devices start to limit voltage during turn-off
- over-voltage safely reaches the static breakdown after turn-off

\[
di/dt = \frac{V_{SSCM} - V_{DC}}{L_S}
\]
For high power conversion, only two devices possible today:
- IGBT
- IGCT

Safe Operating Area is increasing from 250 kW/cm² to 1 MW/cm²

IGDT offers possibility of high voltage devices with low losses (future?)
Challenges
Challenges for HV Power ToDs

- High voltage devices present following challenges:
  - Dynamic Avalanche ruggedness (for reliable operation)
  - Short Circuit Failure Modes (IGBT) and fault interruption (IGCT)
  - Design Trade-off between Losses and SOA
  - Critical Punch-Through voltages (for controllable voltage, low EMI)
  - High DC link voltage (leakage stability, cosmic ray withstand)
  - Large inductance and overshoot voltages in HV power systems
  - High frequency (limited by losses, $T_J$)
Challenges for this decade

- 10 kV switches with 1 kHz snubberless operation
  (for the 6.9 kV\textsubscript{RMS} MV line for drives and power conditioners)

- Snubberless series operation
  (static and dynamic for MV lines > 6.9 kV\textsubscript{RMS})

- Power supply free operation
  (autogenous power supply for series connection)

- System cost-reduction
  (e.g. pay-back times \( \approx \) 1 year for MV Drives)

- Reduced thermal resistance and increased \( T_J \)

- Reduced losses?
ABB