
Power Devices for GW VSC-HVDC Application
Development trend and status with StakPak
Power Device Trend for VSC-HVDC Application

- Brief Overview
- Power device development guideline
- StakPak: Design & Benefit
- IGCT: Potential Benefit
- Future Trend
- Summary
Overview of VSC-HVDC (simplified)
System vs device

<table>
<thead>
<tr>
<th>Name</th>
<th>HVDC Light</th>
<th>HVDC Plus</th>
<th>HVDC MaxSine</th>
<th>HVDC Flex</th>
</tr>
</thead>
<tbody>
<tr>
<td>OEM Rating Ref</td>
<td>ABB 1000 MW 16 links</td>
<td>Siemens 1000 MW 3 links</td>
<td>Alstom 25 MW Demo(+2)</td>
<td>CN OEMs 1000 MW 2+2…</td>
</tr>
</tbody>
</table>

Stack

Device

| Device | rating: 500-2100 A, 2500-4500 V |

→ Transmitted power up, device rating challenged
Overview of Power Semiconductors for VSC-HVDC
Typically 3300 & 4500V, potential 3000A+
## Basic Characteristic of power device

**3300V & 4500V, 1200-2000A**

<table>
<thead>
<tr>
<th>StakPak</th>
<th>HiPak</th>
<th>HiPak</th>
<th>IEGT</th>
<th>IGCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>4500V,2000A</td>
<td>5SNA 1200G450300</td>
<td>5SNA 1500E330305</td>
<td>ST2100GXH22A + diode</td>
<td>“5SHY 80Y4500”</td>
</tr>
<tr>
<td>VCES, V</td>
<td>4500</td>
<td>4500</td>
<td>3300</td>
<td>4500</td>
</tr>
<tr>
<td>Ic / 0.5I_{TGQM}, A</td>
<td>2000</td>
<td>1200</td>
<td>1500</td>
<td>2100</td>
</tr>
<tr>
<td>Max turn-off I, A</td>
<td>4000</td>
<td>2400</td>
<td>3000</td>
<td>5500</td>
</tr>
<tr>
<td>I_{FSM}</td>
<td>16-32 kA</td>
<td>9 kA</td>
<td>13.5 kA</td>
<td>-</td>
</tr>
<tr>
<td>V_{CEsat} / V_F,125C, V</td>
<td>3.33</td>
<td>3.53</td>
<td>2.68</td>
<td>4.7</td>
</tr>
<tr>
<td>Total switch losses/pulse, J</td>
<td>24.44</td>
<td>13.08</td>
<td>7.2</td>
<td>25</td>
</tr>
<tr>
<td>Conduction losses (3ms-pulse), J</td>
<td>20.0</td>
<td>12.7</td>
<td>12.0</td>
<td>29.6</td>
</tr>
<tr>
<td>Total loss (3ms pulse), J</td>
<td>44.4</td>
<td>25.8</td>
<td>19.2</td>
<td>54.6</td>
</tr>
<tr>
<td>Total losses (3300V →100%), J</td>
<td>127%</td>
<td>123%</td>
<td>100%</td>
<td>149%?</td>
</tr>
<tr>
<td>R_{th} (Junction to case), K/kW</td>
<td>4.5</td>
<td>9.5</td>
<td>8.5</td>
<td>5.25</td>
</tr>
<tr>
<td>Chip tech</td>
<td>SPT+</td>
<td>SPT+/trench</td>
<td>SPT+/trench</td>
<td>IEGT</td>
</tr>
<tr>
<td>Integrated GU?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>SC current limiting</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Case rupture (explosion rating)</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>SCFM</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes/No</td>
</tr>
</tbody>
</table>

- Losses increases with Vce square!
# Power Device: System needs and device options

Pushing physical limit of semiconductors

<table>
<thead>
<tr>
<th>System needs</th>
<th>Device options</th>
</tr>
</thead>
<tbody>
<tr>
<td>High reliability &amp; availability</td>
<td>Incorporate feedback, controllability</td>
</tr>
<tr>
<td>Higher current</td>
<td>BiGT, Enhanced trench, bigger, IGCT, Tvj</td>
</tr>
<tr>
<td>Higher voltage</td>
<td>4500V, 6500V (but losses)</td>
</tr>
<tr>
<td>Higher surge current</td>
<td>BiGT, more diode, IGCT</td>
</tr>
<tr>
<td>Lower losses</td>
<td>Enhanced trench, technology curve</td>
</tr>
<tr>
<td>Higher energy density</td>
<td>BiGT, Enhanced Trench, chip size, IGCT</td>
</tr>
<tr>
<td>Case rupture (explosion rating)</td>
<td>PressPack/StakPak,</td>
</tr>
<tr>
<td>Design simplicity &amp; modularity</td>
<td>Modular type device</td>
</tr>
<tr>
<td>Series connection (DC-Breaker…)</td>
<td>PressPack device</td>
</tr>
</tbody>
</table>
Reliability consideration -1
Reliability is key to uninterrupted operation

- Robust chip design: large/high SOA and controllability
- Robust module design: low parts count & standardization
- Manufacturing: quality designed in, economy of scale, TQM
- Gate driver: must be matched for safe operation
- Application: low Ls, safety margin for worst conditions
- Vdc: design with 100 FIT (FIT rate exponential to Vdc)…
- Field feedback: essential for matured application
Guideline to Device Current and Voltage
Trade-off: voltage vs losses, current vs di/dt

**Voltage class**: less series connection but total losses up
- 7.5kV in IGBT, 10kV in IGCT demonstrated (junction termination challenge)
- Nominal Vce-sat up with Vce, switching losses up with V^2 (3300V → 6500V)
- 6500V feasible but 4500V optimal (price of passive component up with Vce)

**Current**
- Current density (A/cm²): new generation, e.g. enhanced trench
- Rth: improved cooling increase current capability, e.g. Presspack
- Bigger module: more chips in parallel limited by current sharing (asymmetric Ls),
- Over-voltage: caused by di/dt*Ls (unless Ls proportionally reduced)
- 4000 A limit?

IFSM: higher diode ratio e.g. StakPak & BiGT
IGCT product range – loss optimization

Moving along technology curve for optimized application

- Low on-state voltage, for breakers: 5SHY 35L4522.
- Low frequency: 5SHY 55L4500.
- Medium frequency: 5SHY 35L4520
- Low switching losses: 5SHY 40L4511 (proton-irradiated)

Energy saving potential: >1 MW/GW

November, 2016
Assembly Tolerant & Fail-Safe Operation

Efficient assembly & safe operation

Converter cell design and assembly

- **Assembly**: construction tolerance should not impact on fragile chip
- **Modularity**: facilitate whole power range with same device platform
- **Series** connection: PressPack favoured
- **Maintenance**: fast & easy access for replacement, low part counts

Fail-safe operation

- **SCFM**: device should fail into stable shorted state & last till breaker activated
- **Case rupture** (explosion rating): remain mechanically intact during fault, contain damage
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StakPak 5SNA 2000K451300 – Design
VCE = 4500 V, IC = 2000 A

SPT+ technology:
- Low-loss, rugged SPT+, large SOA
- High controllability
- Smooth switching SPT+ chip-set for good EMC

Press-pack module design
- High tolerance to uneven mounting pressure
- Explosion resistant package
- Direct bonding to Mo-basedplate → low Rth
- SCFM Fail-safe → for series connection
StakPak™ – ABB Proprietary IGBT module technology

- StakPak sub-module
- StakPak press-pack
- Semiconductor wafer
- Sub-module Cross Section
- IGBT Chip
StakPak Innovative Clamping
Easy and Controlled Clamping

- Independent suspension for each chip with individual spring-contact
- Contact force for the chip is defined by the spring and not influenced by uneven mounting force
- Surplus external force is absorbed by the rugged module frame
- Tolerant against inhomogeneous mounting force – the choice for large stacks
- $F_m = 60-75$ kN

Internal construction of the sub-module reveals the unique ABB design:
Press-Pin with Spring contacts for each Chip position

clamping operation:

$F_1 < F_2 < F_3$

$F = c \cdot \Delta x$
StakPak - Gate drive

- Standard gate IGBT driver can be used
- RG-on = 1.8 Ohm, RG-off = 8.2 Ohm, CGE = 330 nF
- Active clamp available
- Standard gate driver interface
- Gate driver with small jitter needed for series connection
IGBT StakPak – Modular Design

$n$ standard submodules + Glass fibre reinforced frame =

Possible current ratings
700A – 3000A
StakPak line-up
Product Matrix

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Voltage $V_{CES}$ [V]</th>
<th>Current $I_C$ [A]</th>
<th>IGBT / Diode current ratio</th>
<th>Submodules [n]</th>
<th>SCFM rated</th>
</tr>
</thead>
<tbody>
<tr>
<td>5SNA 3000K452300*</td>
<td>4500</td>
<td>3000</td>
<td>1:1</td>
<td>6</td>
<td>no</td>
</tr>
<tr>
<td>5SNA 2000K452300*</td>
<td>4500</td>
<td>2000</td>
<td>1:1</td>
<td>4</td>
<td>no</td>
</tr>
<tr>
<td>5SNA 2000K451300</td>
<td>4500</td>
<td>2000</td>
<td>1:1</td>
<td>4</td>
<td>yes</td>
</tr>
<tr>
<td>5SNA 2000K450300</td>
<td>4500</td>
<td>2000</td>
<td>1:2</td>
<td>6</td>
<td>yes</td>
</tr>
<tr>
<td>5SNA 1300K450300</td>
<td>4500</td>
<td>1300</td>
<td>1:2</td>
<td>4</td>
<td>yes</td>
</tr>
<tr>
<td>5SNR 20H2501</td>
<td>2500</td>
<td>2000</td>
<td>1:1</td>
<td>6</td>
<td>yes</td>
</tr>
<tr>
<td>5SNR 13H2501</td>
<td>2500</td>
<td>1300</td>
<td>1:1</td>
<td>4</td>
<td>yes</td>
</tr>
<tr>
<td>5SNR 10H2501</td>
<td>2500</td>
<td>1000</td>
<td>1:1</td>
<td>3</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- The standard 1:1 IGBT to Diode current ratio suits most applications
- For special applications which require high diode performance, ABB offers a 1:2 IGBT to Diode current ratio
Phase current simulation (2 level) (250Hz, RMS) 3000K452300 (4500V / 3000A, Tj100° C)
StakPak 5SNA 3000K452300 (4500V, 3000A)

50 Hz 6000A transient over-current: $dT = 10^\circ$ C per switch, $dT = 10^\circ$ C for 3 ms (150Hz), $dT = -10^\circ$ C for 3 ms off

→ turn-off of 6000A (2Ic) transient over-current realistic if designed $T_j = 100^\circ$C
Project references
HVDC Light technology

Awarded 1200 MW HVDC Light Project by Scottish Hydro Electric
Example: Same IGBT Chip Technology for HVDC «Light» Off-Shore Windpark DolWin in the North See

165 km / ±320 kV / 800 MW

ABB IGBT StakPak operating in more than 10 HVDC Light projects worldwide
IV Characteristic of StakPak
10 kA reached w/o desaturation -5SNA 2000K450300
Turning off behavior of StakPak Safe 10 kA turn-off with snubber -5SNA 2000K451300

IGBT turn off \( V_{cc} = 3000 \) V, \( I_{ce} = 10000 \) A, \( C_s = 5 \) \( \mu \)F, \( 5 \) Ohm, 
\( L_s = 200 \) nH, \( T_j = 85 \) °C, \( V_{ge} = 18 \) V
Converter topologies
DC breaker operation

- $I_c = 15 \text{ kA}, V_{cc} = 3000 \text{ V}$
- $C_s = 7.5 \mu\text{F}$ - value depends on inductance in a main circuit to limit the Turn off overvoltage

![IGBT turn off: $V_{cc} = 3000 \text{ V}, 15000 \text{ A}, C_s = 7.5 \mu\text{F}, RT$](image)
Test of series connected StakPak 4500V/2000A
Uniform IGBT turn-off of 12kV

Voltage development to 3kV on each StakPak

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November, 2016
Application example of StakPak
Hybrid DC breaker tested to 80 kV, turn-off 16 kA (5ms)
StakPak – Summary

Most powerful device for VSC-HVDC & DC-Breaker

- StakPak is the most powerful IGBT module available (3000A, turn-off 10kA, IFSM 24kA)
- Fail into shorted stated, long term stability possible
- Flexible current rating with surge current options
- Uniform chip pressure via individual spring
- Enable easy & controlled clamping system for long stack
- Efficient cooling offering high rated power
- Explosion proof
- Tailor-made for T&D applications (safe, reliable, redundancy, uninterrupted)
- Some 14+2 HVDC projects in safe operation
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What is an IGCT?

- An IGCT is...
  - An Integrated Gate-Commutated Thyristor
  - Based on GTO and IGBT technology and requires no turn-off snubber
  - Conducts like a thyristor but turns off like an IGBT
    - turn-off loss of an IGBT
    - conduction loss of a thyristor
    - turn-on loss of a mechanical switch!
  - Introduced in 1997
  - Three manufacturing locations world-wide:
    - Japan (Mitsubishi)
    - Switzerland & Czech Republic(ABB)
    - ZhuZhou (CSR-TEC)
IGCT
Integration of Gate unit and power semiconductor

- IGCT operation requires low inductive coupling of gate unit and power semiconductor
- Integration of
  - power semiconductor
  - Low inductive device package
  - Gate unit
## Product range - IGCT

### Asymmetric

<table>
<thead>
<tr>
<th>Part number</th>
<th>VDRM (V)</th>
<th>VDC (V)</th>
<th>ITGQM (A)**</th>
<th>ITAVM (A)</th>
<th>Package (mm)</th>
<th>MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>5SHY 35L4520</td>
<td>4500</td>
<td>2800</td>
<td>4000</td>
<td>1700</td>
<td>85/26</td>
<td>8</td>
</tr>
<tr>
<td>5SHY 35L4521</td>
<td>4500</td>
<td>2800</td>
<td>4000</td>
<td>1700</td>
<td>85/26</td>
<td>8</td>
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<td>5SHY 35L4522</td>
<td>4500</td>
<td>2800</td>
<td>4000</td>
<td>2100</td>
<td>85/26</td>
<td>10</td>
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<tr>
<td>5SHY 40L4511</td>
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<td>2800</td>
<td>3600</td>
<td>1430</td>
<td>85/26</td>
<td>7</td>
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<tr>
<td>5SHY 55L4500</td>
<td>4500</td>
<td>2800</td>
<td>5000</td>
<td>1870</td>
<td>85/26</td>
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<td>5SHY 50L5500</td>
<td>5500</td>
<td>3300</td>
<td>3600</td>
<td>1290</td>
<td>85/26</td>
<td>6</td>
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<tr>
<td>5SHY 42L6500</td>
<td>6500</td>
<td>4000</td>
<td>3800</td>
<td>1290</td>
<td>85/26</td>
<td>6</td>
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<tr>
<td><strong>5SHY 30L9500</strong> *</td>
<td>9500</td>
<td>5000</td>
<td>3000</td>
<td>1700</td>
<td>85/26</td>
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</tbody>
</table>

### Reverse conducting

<table>
<thead>
<tr>
<th>Part number</th>
<th>VDRM (V)</th>
<th>VDC (V)</th>
<th>ITGQM (A)**</th>
<th>ITAVM (A)</th>
<th>Package (mm)</th>
<th>MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>5SHX 26L4520</td>
<td>4500</td>
<td>2800</td>
<td>2200</td>
<td>1010</td>
<td>85/26</td>
<td>5</td>
</tr>
<tr>
<td>Diode part</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>390</td>
<td></td>
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<tr>
<td>5SHX 19L6020</td>
<td>5500</td>
<td>3300</td>
<td>1800</td>
<td>840</td>
<td>85/26</td>
<td>4</td>
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<tr>
<td>Diode part</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>340</td>
<td></td>
</tr>
<tr>
<td>…F, H…</td>
<td>4500-5500</td>
<td>2800-3300</td>
<td>520-1100</td>
<td></td>
<td>85/26</td>
<td></td>
</tr>
<tr>
<td><strong>5SHX 80Y4500</strong> *</td>
<td>4500</td>
<td>2800</td>
<td>8000</td>
<td>3400</td>
<td>150/26</td>
<td>16</td>
</tr>
</tbody>
</table>

* under development, ** max turn-off current
IGCT for Wind Converter Application Comparison Results (300Hz) - PLECS Simulation

<table>
<thead>
<tr>
<th>Converter</th>
<th>Sw. Losses (kW)</th>
<th>Cond. Losses (kW)</th>
<th>$P_{\text{Clamp}}$ (kW)</th>
<th>$P_{\text{input}}$ (kW)</th>
<th>Losses (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Level IGCT</td>
<td>13.3</td>
<td>20</td>
<td>10</td>
<td>8530</td>
<td>0.5</td>
</tr>
<tr>
<td>3 Level IGBT (2 in</td>
<td></td>
<td>)</td>
<td>17</td>
<td>36</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ABB PRODUCT</th>
<th>Tj (Outer position) (°C)</th>
<th>Tj (Inner position) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCT 5SHY 55L4500</td>
<td>112</td>
<td>85</td>
</tr>
<tr>
<td>IGBT 5SNA 1200G450350</td>
<td>110</td>
<td>93</td>
</tr>
</tbody>
</table>

- **Semiconductor losses alone reduced by 23%**
- **Energy saving per 10 MW power rating**
  \[2 \times (0.65 - 0.5)/100 \times 10'000'000 = 30 \text{ kW}\]
  \[\times 5 \text{ USD} = 150 \text{ kUSD}\]
- **Energy saving 3 MW/GW**
IGCT Application Benefits

- Integrated gate unit → higher level integration
- Low parts count → very high reliability & low FIT
- Low on-state losses → inverter efficiency >99.6%
- High rated current → no paralleling needed (2x “HiPak”)
- Very high power & density (2-side cooling) → compact design
- High load cycling capability → long term reliability
- High current turn-off capability (8kA) → high power
- Classic stable SCFM → ideal for HVDC application
- Competitive MW/USD → Cost effective solution
- > 50 kpcs in field → FIT rate comparable to HVDC Thyristors
- Potential for VSC-HVDC application
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Technology Drivers for Higher Power (the boundaries)

**Area Increase**
- Larger Devices
- Extra Paralleling

**Integration**
- Termination/Active HV, RC, RB

**New Technologies**

**Loss Reduction**
- Carrier Enhancement
- Thickness Reduction (Blocking)

**Increasing Device Power**

**SOA Increase**
- Latch-up / Filament Protection
- Controllability, Softness & Scale

**Improved Thermal**
- High Temp. Operation
- Lower Package $R_{th}$

**Traditional Focus**
- $V_{max} I_{max}$

**Density**

**New Tech.**

$\Delta T/R_{th}$

$V.I$ Losses

$I$ Area

$I$ Integration
IGBT Technologies

Next 10 Year Technologies

Cell Design

IGBT Technology

Bulk Design

Planar

Enh.

Trench

SOA

NPT

SPT/FS

Silicon Thickness Limit (little more to gain)

Higher Temp

Integration BIGT

2nd Gen. Enh. Trench

Ratings

1990

2015

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November, 2016
Slide 36
Enhanced Trench (EHT) for IGBT

- ABB EHT ready 2016 (1700 - 3300V)
- Current density up 20% (3300 - 4500V)
- StakPak 4500V 3000A → 3600A
Integration: Bimode Insulated Gate Transistor (BIGT)
Integrates an IGBT & RC-IGBT in one structure to eliminate snap-back effect

- Increased IGBT and diode area, MOS control needed for full potential
  HiPak: 3300V/2000A shown, Surge current up by 2x
  StakPak: 4500V/3000A demonstrated for DC-Breaker (CIGRE 2014)
ABB in High Power Semiconductors
Application DC Breakers based on a BIGT Chip and StakPak package

The BIGT (Bimode Insulated Gate Transistor) enables lower losses in both directions and a comfortable maximum breaking current up to 16kA at operating times within 5ms.

The New Module Standard (LinPak)

- Dual Module Concept optimized for low Ls Applications
- High power density, low over-voltage, low switching losses
- 100mm x 140mm typical 3.3kV / 500A
- Ideal for modular parallel connection

<table>
<thead>
<tr>
<th>Module</th>
<th>Current Rating</th>
<th>Stray Inductance</th>
<th>Stray Inductance x Current</th>
<th>Module Over-voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>LinPak</td>
<td>900A</td>
<td>10nH</td>
<td>9µH</td>
<td>15.6%</td>
</tr>
<tr>
<td>PrimePack</td>
<td>1400A</td>
<td>10nH</td>
<td>14µH</td>
<td>24.3%</td>
</tr>
<tr>
<td>HiPak</td>
<td>3600A</td>
<td>8nH (x2)</td>
<td>57.6µH</td>
<td>100 %</td>
</tr>
</tbody>
</table>
6” RC-IGCT to turn off 8000 A
Most powerful semiconductor

- First prototypes of 150 mm (6”) RC-IGCT (RC = reverse conducting)
- Product development pending application
- Voltage: 4.5 & 6.5kV
- Target spec available: VDRM=4500V, ITGQM=8000A/9000A
- \(\Rightarrow\) loss reduction by >20%, compact & reliability (simplicity)
High Power IGBTs and Modules

**HiPak**
- 6.5kV
- 600A
- 900A
- 750A
- 1200A
- 1800A

**StakPak**
- 2000 → 3000 → 3600 → 4000A?

**LinPak**

**Trench BIGT / Enhanced Planar (SPT+)/ Trench**

**HiPak 2**
- Current Rating
  - 3.3kV
    - 2400A
    - 1800A
    - 1200A
  - 4.5kV
    - 1800A
    - 1500A
    - 900A
  - 6.5kV
    - 1500A
    - 1200A
    - 750A
    - 1200A
    - 900A
    - 600A
The MAIN THREE High Power MW Devices: POWER
Summary

- Power device pushes physical limit for multi-GW VSC-HVDC application
- 4500V appears a good voltage, up to 3000 A shown, Ic to 4000 A possible with StakPak, but challenge for Ls (< 100nH)
- Enhance reliability, via lower “piece count”, to ensure service availability
- Optimise along technology curve for reduced losses
- Improves chip technology curve via Enhanced trench $\rightarrow$ +20% Ic
- Increase effective chip area via BiGT $\rightarrow$ +20% Ic
- Increase of current by 30% via combined improvements feasible
- LinPak low Ls Module platform offers compact & low over-voltage design
- IGCT represents alternative for high power (low losses) application