Series connection of IGBTs

Effective factors for voltage sharing:

<table>
<thead>
<tr>
<th>Static</th>
<th>Dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>device characteristics</td>
<td>$\Delta I_{CES}$, $\Delta T_j$</td>
</tr>
<tr>
<td>driver</td>
<td>$\Delta T_j$, $\Delta V_{ge,th}$, $\Delta t_{on}$, $\Delta t_{off}$, $\Delta Q_{rr}$</td>
</tr>
</tbody>
</table>

Recommendations:

- use devices of one production lot (smallest parameter deviations guaranteed)
- symmetrical design of gate driver (minimize deviations of delays)
- symmetrical cooling conditions (identical heat-sink temperature and flow rate below the series connected devices)
- use parallel resistors with $I_R \approx 5.10 \times I_{CES_{max}}$ to enforce static voltage sharing
- use RC snubber to equalize voltage rate of rise
Series connection of IGBTs

Snubber circuit:

Alternative: use of 3- or multi-level circuit configurations
## Common line voltages

<table>
<thead>
<tr>
<th>Line voltage</th>
<th>IGBT voltage class</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 VDC (max. appr. 900 VDC)</td>
<td>1200V</td>
</tr>
<tr>
<td>750 VDC (max. appr. 1100 VDC)</td>
<td>1700 V</td>
</tr>
<tr>
<td>up to 1300 VDC controlled</td>
<td>2500 V</td>
</tr>
<tr>
<td>1500 VDC (max. appr. 2100 VDC)</td>
<td>3,3 kV (or 2x 1700 V in series/3-level)</td>
</tr>
<tr>
<td>up to 2500 VDC controlled</td>
<td>4,5 kV</td>
</tr>
<tr>
<td>3000 VDC (max. ca. 4500 VDC)</td>
<td>6,5 kV (or 2x 3,3 kV in series/3-level)</td>
</tr>
<tr>
<td>2,3 kVAC (≈3,3 kVDC)</td>
<td>“ “</td>
</tr>
<tr>
<td>4,16 kVAC (≈5,9 kVDC)</td>
<td>6,5 kV in series/3-level</td>
</tr>
<tr>
<td>6,6 kVAC (≈9,4 kVDC)</td>
<td>6,5 kV in multi-level configuration</td>
</tr>
</tbody>
</table>
### Insulation requirements

**Insulation requirements according to IEC1287:**

<table>
<thead>
<tr>
<th>Module</th>
<th>Viso Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7 kV</td>
<td>4 kV</td>
</tr>
<tr>
<td>3.3 kV</td>
<td>6 kV</td>
</tr>
<tr>
<td>6.5 kV</td>
<td>10.2 kV</td>
</tr>
</tbody>
</table>

\[ U_P = 2 \times \frac{U_m}{\sqrt{2}} + 1000 \text{ V} \]

2 series connected modules double the blocking, but not the insulation capability! This means: an additional insulation between module and heatsink is required!

**Solution:**
1. 3-level-circuit → grounding of the mid-point possible
2. **B5** modules → 3.3 kV blocking voltage with increased (10.2 kV) insulation
Circuit configurations

direkte Serienschaltung
direct series connection

Dreipunktumrichter
3-level configuration
Advantages & disadvantages of multi-level- vs. series-connection

Voltage sharing across the semiconductors:
+ statically no problem, because forced by divided DC link capacitor
+ dynamically no problem, because IGBTs don’t switch synchronously

+ no RC-snubber for voltage sharing necessary

+ clearly improved sinusoidal current shape due to higher output frequency at similar switching frequency per IGBT

+ no modules with increased insulation or extra module to heat-sink insulation needed, because mid-point can be grounded

- SC turn-off has to take place in correct sequence (outer IGBTs first) (additional expenses for driver and control)

additional components needed for
- divided DC-link capacitor
- additional mid-point diodes
Output power:
appr. 3 MW with 6.5kV / 600A-devices

3-level-circuit

Mittelpunktsdioden
„NPC“ neutral point clamped

devided DC-link capacitor

Output power:
appr. 3 MW with 6.5kV / 600A-devices
Design of a 3-level-inverter

- Multilayer bus-bar
- Connection for clamping capacitor
- Clamping diode
- IGBT module
- IGBT-gate-unit
- Heat-sink (forced air cooling)
- Line-capacitor
Comparison of phase voltages 2 / 3-level-inverter
Output voltage of a 3-level-inverter

200A/div
200V/div

\( y_{uv} \)

\( i_u \)

2ms/div
alternative 3-level-configuration

... and 4-level? ....
4-level-configuration
4-level-configuration NPC
Output voltage of a 4-level-inverter ... and 5-level? ....
5-level-inverter  8-level-inverter