IGBT Double Pulse Test
IGBT Double Pulse Test

- Basic principle of double pulse test
- Safe operation of IGBT
- What can be done with double pulse test
- Impact of Rg, Cge on IGBT switching
IGBT Measurements
Turn-on & Turn-off

Test Setup

Diagram showing test setup with various components labeled.
Basic Wave Forms

- Gate-Emitter Voltage $V_{ge}$
- Load Current $I_L$
- Collector Current $I_C$
- Collector-Emitter Voltage $V_{ce}$
IGBT Measurements
Turn-on & Turn-off

- Sample Wave Forms
Test Setup
Two Types of Short-circuits

- Before short-circuit occurs, IGBT is OFF & blocks the DC-bus voltage.
- The short-circuit is created by the switch-on of the IGBT.

- Before the short-circuit occurs, IGBT is ON & in saturation region.
- The short-circuit is created by applying the DC-bus voltage on C-E of the IGBT.

\[ V_{CE} \text{ never reaches } V_{CE\text{sat}} \text{ value!} \]

\[ V_{CE} \text{ de-saturates from } V_{CE\text{sat}} \text{ value!} \]
Diode Measurements

**Test Setup**
**Diode Measurements**

**Recovery**

- **Basic Wave Forms**

  - $V_{go}$ at Auxiliary Switch
  - $I_L$
  - $I_{Diode}$
  - $V_{CC_0}$, $V_{Diode}$, $V_R$, $V_{CC}$

  - Variabel
  - 100μs
  - ca. 15μs
  - Free-wheeling current $I_f$
  - Diode recovery
  - Over voltage during turn-on of diode
Diode Measurements
Recovery

Sample Wave Form

<table>
<thead>
<tr>
<th>$d_iF/dt$</th>
<th>Erec</th>
<th>Qr</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% $I_F-50%I_{RM}$</td>
<td>10%$V_R-2%I_{RM}$</td>
<td>$I_F=0-2%I_{RM}$</td>
</tr>
</tbody>
</table>

$E_{rec}:10%V_R$
Double Pulse Test

• **IGBT characterization**
  • Comparable test conditions as datasheet
  • Results close to Infineon datasheet expected.

• **Customer’s application setup**
  • Helpful for further design
  • Different test conditions, and different results expected
  • Both IGBT in the (2-level) leg to be tested – different commutation loop & different behavior
IGBT Double Pulse Test

- Basic principle of double pulse test
- Safe operation of IGBT
  - IGBT RBSOA
  - Diode SOA
  - Short circuit
  - Vge limit
  - Others – Not tested by double pulse test
- What can be done with double pulse test
- Impact of Rg, Cge on IGBT switching
IGBT Safe Operation – IGBT RBSOA

- **Pulse current (ICRM IRBSOA)**

  | Periodischer Kollektor Spitzenstrom | \( t_\text{p} = 1 \text{ ms} \) | ICRM | 900 | A |

  - \( I_{\text{CRM}} \) is defined as repetitive turn on pulse current, related to IGBT thermal
  - \( I_{\text{CRM}} \) may be exceeded during turn on due to reverse recovery.
  - \( I_{\text{RBSOA}} \) is defined as maximum turn off current

1ms is just test condition, real pulse width is depend on thermal
IGBT Safe Operation – IGBT RBSOA

- Blocking voltage (VCES)

| Collector-Emitter-Internal voltage | \( T_{j} = 25^\circ C \) | \( V_{CES} \) | 1700 | V |

\( V_{CES} \) specified at \( T_{j}=25^\circ C \). Higher \( T_{j} \), higher blocking voltage

Due to stray inductance inside module

\[ \Delta V = \frac{di}{dt} \cdot L_{\delta} \]

\( V_{CES} \) is easiest to be exceeded during turn off, due to external and internal stray inductance

\( V_{CES} \) can not be violated at any condition, otherwise IGBT would break through.
IGBT Double Pulse Test

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IGBT Safe Operation – Diode SOA

- **Blocking voltage (VRRM)**

  Periodische Spitzensperrspannung repetitive peak reverse voltage  
  $T_{j} = 25^\circ C$  
  $V_{RRM}$  
  1700  
  V

  Similar definition of $V_{CES}$ at $T_j 25^\circ C$

- **Pulse current (ICRM)**

  Periodischer Spitzenstrom repetitive peak forward current  
  $t_p = 1$ ms  
  $I_{FRM}$  
  900  
  A

  Similar definition of $I_{CRM}$, two time of $I_F$. 
IGBT Safe Operation – Diode SOA

Diode SOA

High voltage module specify the SOA of diode. Not only peak current and voltage is limited, peak power also is restricted. The instantaneous peak power should never exceed the limit for the max. power given in the SOA diagram.

More severe with small current at low temperature due to snap off and oscillation.
IGBT Double Pulse Test

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- What can be done with double pulse test
- Impact of Rg, Cge on IGBT switching
IGBT Safe Operation – short circuit

**Short circuit current (ISC)**

<table>
<thead>
<tr>
<th>Kurzschlussverhalten SC data</th>
<th>$V_{GE} \leq 15,V$, $V_{CC} = 1000,V$</th>
<th>$V_{CE_{max}} = V_{CES} - L_{sCE} \cdot \frac{di}{dt}$</th>
<th>$t_p \leq 10,\mu s$, $T_{j} = 125^\circ C$</th>
<th>$I_{SC}$</th>
<th>1800</th>
<th>A</th>
</tr>
</thead>
</table>

SC1: Short before Switch On

SC2: Short after Switch On

The short circuit current value is a typical value. In applications, SC1 and SC2 can only be safely turned off when desaturated, the short circuit time should not exceed 10us.
IGBT Safe Operation – short circuit

- **Short circuit condition:**
  - $V_{GE}$: gate voltage (15V)
  - $V_{CC}$: DC bus voltage
  - $T_{vj}$: short circuit start temperature

It is important to clamp gate voltage during short circuit.
IGBT Double Pulse Test

- Basic principle of double pulse test
- Safe operation of IGBT
  - IGBT RBSOA
  - Diode SOA
  - Short circuit
  - Vge limit
  - Others – Not tested by double pulse test
- What can be done with double pulse test
- Impact of Rg, Cge on IGBT switching
IGBT Safe Operation – Vge limit

Gate-emitter voltage (Vge)

<table>
<thead>
<tr>
<th>Gate-Emitter-Spitzenspannung</th>
<th>VGES</th>
<th>+/-20</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>gate-emitter peak voltage</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Gate Clamping:

- Limitation of increase of gate voltage due to positive feedback over $C_{GC}$
- An issue with long durations regarding gate oxide break down
- Limitation of short circuit currents

**Methode 1**
Gate-Supply Clamping

**Methode 2**
Gate-Emitter Clamping
IGBT Double Pulse Test

- Basic principle of double pulse test
- Safe operation of IGBT
  - IGBT RBSOA
  - Diode SOA
  - Short circuit
  - Vge limit
  - Others – Not tested by double pulse test
- What can be done with double pulse test
- Impact of Rg, Cge on IGBT switching
IGBT Safe Operation – Others, not tested by two-pulse test

- Maximum junction temperature
  - IGBT & Diode loss estimation
  - Thermal impedance

- Reliability
  - DC stability

- Thermal cycling & power cycling

- Min switching time

---

<table>
<thead>
<tr>
<th>Maximum junction temperature</th>
<th>Wechselrichter, Brems-Chopper / Inverter, Brake-Chopper</th>
<th>$T_{\text{vJ}}$</th>
<th>175</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature under switching conditions</td>
<td>Wechselrichter, Brems-Chopper / Inverter, Brake-Chopper</td>
<td>$T_{\text{vJ}}$</td>
<td>-40</td>
<td>150</td>
</tr>
</tbody>
</table>

| Kollektor-Emitter-Gleichsperrspannung DC stability | $T_{\text{vJ}} = 25^\circ\text{C}, 100$ fit | $V_{\text{CE D}}$ | 2100 | V |

| Minimum turn-on time | $t_{\text{Fon min}}$ | 10,0 | μs |
IGBT Double Pulse Test

- Basic principle of double pulse test
- Safe operation of IGBT
- What can be done with double pulse test
  - Check switching waveforms – oscillation?
  - Measurement of loss, switching time, stray inductance
  - Verify IGBT RBSOA, diode SOA
  - Verify short-circuit protection
  - IGBT Paralleling
  - Optimize Driver design
- Impact of Rg, Cge on IGBT switching
Both too small $R_g$ and too large $R_g$ can lead to oscillations.
IGBT Double Pulse Test

- **Basic principle of double pulse test**

- **Safe operation of IGBT**

- **What can be done with double pulse test**

  - Check switching waveforms – oscillation?
  - Measurement of loss, switching time, stray inductance
  - Verify IGBT RBSOA, diode SOA
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  - Optimize Driver design

- **Impact of Rg, Cge on IGBT switching**
Definition of Eon and Eoff_IEC60747-9

Eon definition

- $10\% I_C$ to $2\% V_{CE}$

Eoff definition

- $10\% V_{CE}$ to $2\% I_C$
### Definition of Eon and Eoff

<table>
<thead>
<tr>
<th></th>
<th>Eon</th>
<th>Eoff</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC60747-9</td>
<td>10%Ic-2%Vce</td>
<td>10%Vce-2%Ic</td>
<td></td>
</tr>
<tr>
<td>IEC60747-9 Ed2 2005-06-10</td>
<td>10% Vge-2%Vce</td>
<td>90%Vge-2%Ic</td>
<td></td>
</tr>
<tr>
<td>Infineon Module</td>
<td>10%Ic-2%Vce</td>
<td>10%Vce-2%Ic</td>
<td>Incl. 0-10% Ic at full Vce</td>
</tr>
<tr>
<td>Infineon Discrete</td>
<td>10%Vge-3%Vce</td>
<td>90%Vge-1%Ic</td>
<td></td>
</tr>
<tr>
<td>IR Discrete</td>
<td>10%Ic-5%Vce</td>
<td>10%Vce-5%Ic</td>
<td></td>
</tr>
<tr>
<td>Fairchild Discrete</td>
<td>10%Vge-0%Vce</td>
<td>90%Vge-0%Ic</td>
<td></td>
</tr>
<tr>
<td>Tyco Module</td>
<td>10%Vge-3%Vce</td>
<td>90%Vge-1%Ic</td>
<td></td>
</tr>
</tbody>
</table>

- IGBT module datasheets give two/three Eon & Eoff values at $T_j = 25^\circ C$ & $T_j = 125^\circ C/150^\circ C$, respectively, all for $I_{C,nom}$ & around $\frac{1}{2} V_{ces}$, $VGE = \pm 15V$.
- Eon & Eoff, especially Eon increases with increase of RG
- Eon & Eoff increase with the rising of $Tj$
Definition of $t_{\text{don}}$, $t_r$, $t_{\text{doff}}$ and $t_f$

<table>
<thead>
<tr>
<th></th>
<th>$t_{\text{don}}$</th>
<th>$t_r$</th>
<th>$t_{\text{doff}}$</th>
<th>$t_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10% $V_{\text{ge}}$-10%$I_c$</td>
<td>10%$I_c$-90%$I_c$</td>
<td>90%$V_{\text{ge}}$-90%$I_c$</td>
<td>90%$I_c$-10%$I_c$</td>
</tr>
</tbody>
</table>

**IGBT Turn on**

**IGBT Turn off**
Stray Inductance System Stray Inductance

Sample Wave Form

\[ L_\sigma = dV_{CE} \cdot \frac{dt}{di} \]

Note: connect to power terminal when measuring external busbar stray inductance.
Diode switching measurement

- IGBT module datasheets give two/three Erec values under Tj = 25°C & Tj = 125°C/150°C, all under IF,nom & ½ VCES, VGE = -15V
- Erec decreases with the increase of RG
- Erec increases with the rising of Tj
Dead Time Estimation

\[ t_{DT} = \left( t_{doff}(max) + t_f(max) - t_{don}(min) \right) + \left( t_{PHL_{max}} - t_{PLH_{min}} \right) \times 1.2 \]

- **IGBT**
  - \( T_j, I_c, \text{ and } R_g \) has small impact on \( T_{don} \)
  - Min \( T_{don} \) typically at small \( I_c \), small \( R_g \)

- **Driver**
  - **Margin**
  - \( T_j, I_c, R_g, \text{ and } V_{ge} \) has significant impact on \( T_{doff} \)
  - Max \( T_{doff} \) at: small current \( I_c \)
    - High temperature \( T_j \)
    - Variation of \( V_{th} \) should be considered
    - Big \( R_g \)
    - Unipolar \( V_{ge} \)

- \( T_f \) can be neglected because it is typically very small

- Propagation delay time of driver must be considered to calculate \( t_{DT} \)
Dead Time Estimation

Block diagram of test to simulate variation of vth and driver with bipolar output

Varification of Dead Time, both high temperature and low temperature should be tested
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  - IGBT Paralleling
  - Optimize Driver design
- Impact of Rg, Cge on IGBT switching
For 3\textsuperscript{rd} and 4\textsuperscript{th} IGBT, \(R_{\text{goff}}\) has little impact on \(E_{\text{off}}\), \(dv/dt\), and \(di/dt\)

- \(di/dt\) is only controllable if the gate voltage doesn’t drop below the Miller Plateau level before \(I_C\) starts to decrease
- \(dv/dt\) and \(di/dt\) are controllable by the gate resistor when \(R_{\text{goff}}\) is very large
- A larger resistor will result in a smaller \(dv/dt\) and \(di/dt\)
Verify IGBT RBSOA

- In no case shall over voltages exceed the maximum breakdown voltage of the IGBT.
- To control the IGBT it is necessary that the gate voltage hasn’t dropped below the Miller Plateau level.
Verify Diode SOA

developer: 600A / 6500V module

measured: $i_R(t)$ and $v_R(t)$
calculated: $p_{\text{peak}}(t) = i_R(t) \cdot v_R(t)$
Verify Diode SOA

- Erec, Irr, dv/dt, and di/dt will be decreased with increasing Rg
- Erec, Irr, dv/dt, and di/dt will be decreased with increasing Cg
- Higher Tj lead to decreased dv/dt and di/dt
- Diode tends to snap off with small current

No Cge, t/div=1us
Ron=Roff=1.8 Ω
Ic= 1/10 Inom

Soft recovery behavior
Verify Diode SOA – diode snap off

Can lead to high voltage with small current at low temperature
IGBT Double Pulse Test

- Basic principle of double pulse test
- Safe operation of IGBT

What can be done with double pulse test

- Check switching waveforms – oscillation?
- Measurement of loss, switching time, stray inductance
- Verify IGBT RBSOA, diode SOA
- **Verify short-circuit protection**
- IGBT Paralleling
- Optimize Driver design

- Impact of Rg, Cge on IGBT switching
IGBT short circuit protection – turn off voltage overshoot

Soft turnoff SC1 – reduce voltage overshoot
IGBT short circuit protection – gate clamping

- Without clamping
- With TVS clamping between GE
- With clamping to Vcc
IGBT short circuit protection – short circuit II

Turn off SC-II only when desaturated.
IGBT Double Pulse Test

- Basic principle of double pulse test
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- What can be done with double pulse test
  - Check switching waveforms – oscillation?
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  - Verify IGBT RBSOA, diode SOA
  - Verify short-circuit protection
  - IGBT Paralleling
  - Optimize Driver design
- Impact of Rg, Cge on IGBT switching
IGBT parallel

C1: the left IGBT
C2: $I_{DC}$ totally
C3: $V_{CE}$
C4: $V_{GE}$

The difference between paralleled IGBT becomes smaller and smaller
IGBT Double Pulse Test

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  - Verify IGBT RBSOA, diode SOA
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- Impact of Rg, Cge on IGBT switching
Optimize Driver Design

Driver comparison

6cm Gate cable

50cm Gate cable
IGBT Double Pulse Test

- Basic principle of double pulse test
- Safe operation of IGBT
- What can be done with double pulse test
- Impact of Rg, Cge on IGBT switching
Control turn on di/dt (diode reverse recover) and dv/dt (Eon) independently

<table>
<thead>
<tr>
<th>Range</th>
<th>Determined by</th>
<th>Condition</th>
<th>Influenced by</th>
<th>Influence on</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$V_{GE} &lt; V_{GEth}$</td>
<td>$C_{iss} = \text{const}$</td>
<td>$R_G, C_{GE} \parallel C_G$</td>
<td>$t_{don}$</td>
</tr>
<tr>
<td>2</td>
<td>$V_{GEth} &lt; V_{GE} &lt; V_{GEM}$</td>
<td>$C_{iss} = \text{const}$</td>
<td>$R_G, C_{GE} \parallel C_G$</td>
<td>$\frac{di}{dt}$</td>
</tr>
<tr>
<td>3</td>
<td>$V_{GE} = V_{GEM}$</td>
<td>$V_{GE} = \text{const}$</td>
<td>$R_G, C_{GC}$  ( (C_{GC} \gg C_G) )</td>
<td>$\frac{dv}{dt}$</td>
</tr>
</tbody>
</table>
Control turn on di/dt (diode reverse recover) and dv/dt (Eon) independently

\[ R_G = 8.2 \, \Omega, \quad C_G = 0, \quad I_C/\text{dt} = 5 \, \text{kA}/\mu\text{s}, \quad dV_{CE}/\text{dt} = 0.6 \, \text{kV}/\mu\text{s}, \quad E_{\text{on}} = 6.4 \, \text{J} \]

\[ R_G = 3.3 \, \Omega, \quad C_G = 100 \, \text{nF}, \quad I_C/\text{dt} = 4.5 \, \text{kA}/\mu\text{s}, \quad dV_{CE}/\text{dt} = 1 \, \text{kV}/\mu\text{s}, \quad E_{\text{on}} = 4.1 \, \text{J} \]

\[ R_G = 1.0 \, \Omega, \quad C_G = 330 \, \text{nF}, \quad I_C/\text{dt} = 5.1 \, \text{kA}/\mu\text{s}, \quad dV_{CE}/\text{dt} = 2.8 \, \text{kV}/\mu\text{s}, \quad E_{\text{on}} = 2.8 \, \text{J} \]
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