Figs 4.38 p.38 The IGBT
1.75kV - 2600 A V \frac{1}{3}
Now in place is PG 3T
Location of equivalent devices
for Power System
Equivalent circuit
Bipolar
flow of
von
No S.S.
Gate
To keep 50W
Symbol
Collector
Emitter
Conclusions: IGBT

- Becoming the device of choice in 500-1700V applications, at power levels of 1-1000kW
- Positive temperature coefficient at high current — easy to parallel and construct modules
- Forward voltage drop: diode in series with on-resistance, 2-4V typical
- Easy to drive — similar to MOSFET
- Slower than MOSFET, but faster than Darlington, GTO, SCR
- Typical switching frequencies: 3-30kHz
- IGBT technology is rapidly advancing — next generation: 2500V
ON to off Transition R load

\[
\frac{1}{2} \cdot V_{\text{off}} \cdot I_{\text{on}} = P_{\text{loss}}
\]

\[P_{\text{loss}} \times \Delta t = W_{\text{loss}}\]

Fig 3a: Ideal Voltage and Current Waveforms with Resistive Loading

\{ \text{other} \}

\[V_{\text{DS}}, I_D, \text{Ringing} \]
ON to off transition “L” load

\[ P_{loss} = \frac{1}{2} V_{off} I_{on} \]

\[ W_{loss} = P_{loss} \times nt \]

Blithley assumes \( I_L \) hangs till \( V_{DS} \) → Max

Fig 3b: Ideal Voltage and Current Waveforms with Inductive Loading
Current tailing in IGBTs

The kid was a tail-a-long one

Worst Feature: Problem 4.1

Wow

$\text{On} \ \text{of} \ \ 1-2 \ \text{kA}$

$V_{\text{on}} \ : \ 2-3 \ \text{V}$

$\text{On} \ \text{loss}$

$I_{\text{on}} \ \text{Voff}$

Too long

High $\text{loss}$

Very high

Energy per

$\text{on-off}$

Transition due to long

$E_{\text{on-fsw}} \ \text{off}$

$I = E_{\text{on-fsw}} \ \text{off}$

Fundamentals of Power Electronics

Chapter 4: Switch realization
Switching loss due to current-tailing in IGBT

Example: buck converter with IGBT

\[ P_{sw} = \frac{1}{T} \int_{sw} \! p_A(t) \, dt = (W_{on} + W_{off}) \, f_s \]

Fundamentals of Power Electronics

Chapter 4: Switch realization
Problem 4.7

Multiply \( v_{CE}(t) \), \( i_C(t) = p(t) \)

Estimate energy under \( p(t) \) waveform by graphical integration

**IGBT**

**Transition**

\[ p(t) \]

**Turn-on**

**Transition**

\[ \begin{align*}
1.0 & \rightarrow 0.75 \\
1.25 & \rightarrow 1.0 \\
1.5 & \rightarrow 1.25 \\
2 & \rightarrow 1.5
\end{align*} \]

**Straight line approximation**

Sum areas 1 - 4:

1. \( \frac{1}{2} (14000)(0.25 \cdot 10^{-6}) = 1.75 \text{ mJ} \)
2. \( \frac{1}{2} (19000+4000)(0.125 \cdot 10^{-6}) = 1.125 \text{ mJ} \)
3. \( \frac{1}{2} (4000+1000)(0.375 \cdot 10^{-6}) = 0.9375 \text{ mJ} \)
4. \( \frac{1}{2} (1000)(0.5 \cdot 10^{-6}) = 0.25 \text{ mJ} \)

Total \( 4.1 \text{ mJ} = E_{on} \)

**IGBT**

**Transition**

\[ p(t) \]

**Turn-off**

\[ \begin{align*}
0 & \rightarrow 0.5 \\
1.0 & \rightarrow 0.5 \\
1.5 & \rightarrow 1.0 \\
2.5 & \rightarrow 1.5
\end{align*} \]

\( \frac{1}{2} \) \( \begin{align*}
5 & (4000)(0.5 \mu s) = 1.0 \text{ mJ} \\
6 & (4000+2000)(0.5 \mu s) = 1.5 \text{ mJ} \\
7 & (2000)(1.5 \mu s) = 1.5 \text{ mJ}
\end{align*} \)

Total \( 4.0 \text{ mJ} = E_{off} \)

\( \frac{E_{on} + E_{off}}{E_{SW}} = 8.1 \text{ mJ} \)

(Any estimate near this value is OK)
**Buck DC losses Buck are F1D**

Buck converter model: conduction loss

\[ V = D(V_g - D_V) - P'_V_D \]

\[ V = V_g + V_D = D(V_g - V_{on} + V_D) \]

so \[ D = \frac{V + V_D}{V_g - V_{on} + V_D} = 0.505 \]

<table>
<thead>
<tr>
<th>Element</th>
<th>Power loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGBT</td>
<td>12.6 W</td>
</tr>
<tr>
<td>diode</td>
<td>7.4 W</td>
</tr>
<tr>
<td>total</td>
<td>20 W = P_{cond}</td>
</tr>
</tbody>
</table>

\[ \text{Converter efficiency} = \frac{P_{out}}{P_{in}} \]

\[ P_{in} = P_{out} + P_{loss} = P_{out} + P_{cond} + E_{sw, fsw} \]

\[ \eta = \frac{P_{out}}{P_{out} + P_{cond} + E_{sw, fsw}} = \frac{2000}{2000 + 20 + (8.1 \times 10^3)_{fsw}} \]

Plot on next page

From Eq. (4.23): \[ f_{crit} = \frac{20W}{8.1\mu J} = 2.5 \text{kHz} \]
Problem 4.7, part (c)
Efficiency vs. switching frequency

Efficiency

100.00%
90.00%
80.00%
70.00%
60.00%

1000
10000
100000
fsw

1KHz
10KHz
100KHz

36.9% heat loss
Current tailing in IGBTs

Causes $E_{sw \, \text{off-on}}$

Chapter 4: Switch realization

Fundamentals of Power Electronics