Switching Losses: Output Capacitance

Ideal Switching
Experimental Switching Waveforms

The Double Pulse Test

Fig. 7. Double pulse test circuit schematic.

Fig. 16. Turn-on $E_{on}$ at 25°C.
Converter Efficiency Vs. $f_s$

\[ P_{\text{loss}} = P_{\text{cond}} + P_{\text{fixed}} + W_{\text{on}} f_{\text{sw}} \]

Converter Optimization
Wide Bandgap Materials

Power MOSFET: Conclusions

- A majority-carrier device: fast switching speed
- Typical switching frequencies: tens and hundreds of kHz
- On-resistance increases rapidly with rated blocking voltage
- Easy to drive
- The device of choice for blocking voltages less than 500V
- 1000V devices are available, but are useful only at low power levels (100W)
- Part number is selected on the basis of on-resistance rather than current rating
Insulated Gate Bipolar Junction Transistor

- A four-layer device
- Similar in construction to MOSFET, except extra $p$ region
- On-state: minority carriers are injected into $n^-$ region, leading to conductivity modulation
- Compared with MOSFET: slower switching times, lower on-resistance, useful at higher voltages (up to 1700V)

The IGBT

Symbol

Equivalent circuit

Location of equivalent devices
Conclusions: IGBT

- Becoming the device of choice in 500 to 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:
  - 3300 V devices: HVIGBTs
  - 150 kHz switching frequencies in 600 V devices