IGBT Technologies and Applications Overview: How and When to Use an IGBT

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Agenda

• Introduction
• Semiconductor Technology Overview
• Applications Overview:
  – Welding
  – Induction Heating
  – Half Bridge in Solar and UPS Applications
  – Emerging/Advanced Topologies
• Losses distribution
• IGBT Gate-Drive
• Conclusions
Introduction

Source: Yole Développement, 2015 report
Requirements of Applications

• Many factors drive the selection of right IGBT for the application
  – Robustness (SOA, UIS, Short Circuit, Transient conditions...)
  – Thermal capability (Tjmax, Delta T)
  – Switching frequency
  – Diode performance

• Package
  – R_th
  – Isolation (creepage/distance)

• Efficiency
  – Each application/topology has a unique split of Power loss contributors, depending on device parameters.

• Cost
IGBT and High Voltage Rectifier Technologies
Power Semiconductors are used to rectify, switch, control a voltage and/or current.

Overview of most common devices:

- Diode
- Thyristors
- BJT
- MOSFET
- IGBT
- HEMT
- JFET
• A $p$–$n$ junction is needed for rectification

• Heavy doping is needed for good metal contacts for the $p$ and the $n$

• Heavy doping results in low voltage rating, so a lightly doped $n^-$ layer is required to give a high voltage rating

• This lightly doped region is known as the “drift region”
HV Rectifier – Conducting / Blocking

Diode conducting

Diode blocking
HV Rectifier – Switching Characteristic

Typical reverse recovery behaviour

Measurement (slightly snappy)
HV Rectifier – Switching Characteristic

Trade-Off-curve

Softness Definition

\[ S \equiv \frac{t_f}{t_s} < 0.8 \]

\[ S \equiv \frac{t_f}{t_s} \geq 0.8 \]
Effect of parameters:
Forward Voltage $V_F$: Conduction Loss
Reverse recovery Charge $Q_{rr}$: Switching Loss
Reverse Recovery Time $t_{rr}$: Switching loss
Peak reverse Current $I_{rrm}$: Diode switching loss
Softness $S$: EMI
IGBT Technology
IGBT Technology

Equivalent Circuit for the IGBT
and a Cross Section of the IGBT Structure (PT and N-Channel)
### IGBT Technology

**Punch through (PT) IGBTs**
- based on heavily-doped $p^+$ substrates used for Epi growth
- large turn-off energy (Temp.dep.)
- negative TCO on $V_{ce\_sat}$.

**Non punch through (NPT) IGBTs**
- based on $n$- substrate with a lightly doped $p$ layer implanted.
- thick substrate is used to sustain high breakdown voltage -> higher cost
- Lower switching losses
- Higher $V_{ce\_sat}$ (pos. TCO)
- Higher robustness (di/dt, Short Circuit)
Field Stop IGBT Planar

The FS technology combines the features of NPT and PT IGBTs structures:

- Implanted backside $p^+$ of NPT on Float-zone material. Include $n$ buffer of a PT
- Low pos. TCO
- Better Vce_sat/Eoff Trade-off-curve
- Low Eoff (short and low Tail-Current, nearly no Temp-dependency)
- SC-rating possible
Trench gates
(NPT-Trench, FS-Trench available)

- Higher cell-density
- Better $V_{ce\_sat}/E_{off}$ Trade-off-curve
- Less sensible on parasitic NPN
What about reverse conducting?

- A simple change in structure generates a PN-junction
- Called RC-IGBT (Reverse Conducting) or SA-IGBT (Shorted Anode)
- No standard Symbol
- IGBT + monolithic diode = 1 Die
- Cost benefit / Compact
- Shared Rth
- Compromise in IGBT and Diode characteristic
IGBT Technology

The IGBT Triangle

On-state Voltage Drop \[\leftrightarrow\] Turn-off Loss \[\leftrightarrow\] Ruggedness

Power Efficiency

Reliable Operation

Technology evolution \[\rightarrow\] moving towards the trade-off chart origin
Technology optimization \[\rightarrow\] application specific tuning
Application Overview

Welding
The majority of welding machine include inverters. Accuracy in P / I control -> better welding process. Higher Power-density / compactness / weight. With PFC more power out of a single-phase.
Application Overview - Welding

Full Bridge

Half Bridge

2 Switch forward

Leg:
Collector Current
Gate Voltage
Collector Voltage
Application Overview - Welding

- $E_{on}$ is very low due to ZCS (Zero Current switching) Diode contribution to $E_{on}$ is negligible
- $E_{off}$ is the dominant portion of IGBT losses.
- Conduction loss caused by $V_{CE_{sat}}$ is secondary because of low duty cycle.
- Reverse recovery loss is the main part of the diode losses.
- $V_F$ is low, short FW-phase

$E_{on} = 0.1 \text{ mJ}$

$E_{off} = 1 \text{ mJ}$

$E_{diode} = 0.25 \text{ mJ}$
Losses Distribution in a full-bridge welding machine 5 kW. Nominal AC 230 V Input. Output current Full load (250 A)
Application Overview
Inductive Heating
Principle Inductive Heating

Equivalent of an Induction Cooking system

Scheme of an Induction Cooking
Application Overview – Induction Heating

Resonant Half Bridge

Quasi Resonant
Application Overview – Induction Heating

Light load

Frequency increases at lighter load or pan lifting. Despite near ZVS, $E_{ge}$ increases due to dramatically increased

$$I_c = C_r \times \frac{dV_{ce}}{dt}$$

Pulse skipping is an alternative control method to keep out of this zone

High load

Frequency decreases at heavier load. IGBT maintains nearly ZVS but diode is conducting higher current. Low resistive pan causes the same effect for the diode
IGBT losses are dominated by conduction loss. IGBTs with marginally high $V_{CE_{sat}}$ but drastically lower $E_{off}$ can be shown to yield reasonable performance.

- Similar losses pattern in both RHB and QR systems.
- Diode can be co-packed or monolithic. $V_F$ is not critical since diode only conducts for a short period.
- IGBTs with higher UIS rating.
Application Overview

Halfbridge
• High side IGBT always commutates with low side FWD and vice versa.
• IGBT turn-off generates over- or undervoltage (dep. on load-current direction)
• IGBT turn-on induces FWD turn-off -> reverse recovery current -> IGBT Eon.
Application Overview – Half Bridge

- HB can produce only two output voltage levels
- High \(dv/dt\) produces higher EMI
- Just 2 levels generate high output-ripple
- A connection to the neutral point would offer a 3rd level
• I-type and T-type NPC Topologies are most popular
• T-Type is natural extension – operation similar to HB
• Additional devices needed (T_2, T_3, D_+, D_ for I-, T_2, T_3 for T-type)
• Two additional control signals are required
• Extensions possible for higher level Topology (for I-type)
• 600V devices instead of 1200V increases Efficiency
Application Overview – Three level Topologies

Inverter Mode – Bang Cycle

$V_{o}>0$, $I_{o}>0$
$T_1$, $T_2$ ON;
$D_1$, $D_2$, $T_3$, $T_4$ OFF
$T_1$ high frequency;
$T_2$ line frequency.

Inverter Mode – Hang Cycle

$V_{o}>0$, $I_{o}>0$
$T_2$ ON;
$T_1$, $T_3$, $T_4$ OFF
$T_3$ high frequency;
$T_2$ line frequency.

Rectifier Mode – Bang Cycle

$V_{o}>0$, $I_{o}<0$
$D_1$, $D_2$ ON;
$D_3$, $T_3$, $T_4$ OFF

Rectifier Mode – Hang Cycle

$V_{o}>0$, $I_{o}<0$
$D_3$ ON;
$T_3$, $T_4$ OFF
$T_3$ high frequency;
Application Overview – Three level Topologies

Inverter Mode – Bang Cycle

Inverter Mode – Hang Cycle

Rectifier Mode – Bang Cycle

Rectifier Mode Mode – Hang Cycle

$V_i > 0$, $I_p > 0$
$T_1$, $T_3$ ON;
$T_2$, $T_4$ OFF
$T_3$ high frequency;
$T_2$ line frequency.

$V_i > 0$, $I_p < 0$
$D_1$ ON;
$T_2$, $T_4$ OFF
$T_2$ high frequency;

$V_i > 0$, $I_p < 0$
$D_2$, $T_2$ ON;
$T_1$, $T_4$ OFF
$T_2$ high frequency;
Composite Losses – Inverter Mode

From Schweizer et al. ETH-Z (IECON 2010)

- 10 kW, $V_{bus} = 650$ V, $V_{Output} = 325$ V, $I_{Output} = 20.5$ A
- $f_{sw} = 32$ kHz
- HB: 81 W total
- T-type: 39 W total
- I-type: 40 W total
Composite Losses – Rectifier Mode

From Schweizer et al. ETH-Z (IECON 2010)

- 10 kW, $V_{bus} = 650$ V, $V_{Output} = 325$ V, $I_{Output} = -20.5$ A
- $f_{sw} = 32$ kHz
- HB: 81 W total
- T-type: 39 W total
- I-type: 39 W total
Application Overview – Three level Topologies

Frequency Dependence of Efficiency

- Applicability of topology depends on operating conditions
- T-type shines at lower frequencies
  - Reduced switching losses compared to HB
  - Low conduction losses (fewer series devices)
- I-type (NPC) better at high frequency
  - Even lower switching losses
- Semiconductor improvements can shift the transition point to right
- Higher dc link voltage can shift the transition point to lower frequency
Fitting Parts for Your Application

Solar / UPS

Welder

IH

HA / Motor

Automotive

Good fit for EV-Charger


Public Information

ON Semiconductor®
IGBT Gate-Drive
IGBT-Gate-Drive

Turn-ON:
• Controlled by Gate,
• carriers into base-region controlled by parasitic N-MOSFET.
• Fast Gate-Drive -> Fast start of Collector-Current

Turn-OFF:
• Beside interrupting Base-current no mechanism to move carriers out of Base-region
• Tail-current phenomen (no control)
Gate-Drive-Impedance

IGBT with Parasitic Capacitances

\[ C_{les} = C_{ge} + C_{gc} \text{ with } C_{ce} \text{ shorted} \]
\[ C_{oes} = C_{gc} + C_{ce} \]
\[ C_{res} = C_{gc} \]

Example:

\[ R_g < \frac{V_{th}}{C_{gc} \cdot \frac{dv}{dt}} \]

\[ R_g < \frac{7.5 \text{ V}}{84 \, \text{pF} \cdot \left( \frac{3500 \, \text{V}}{\mu\text{s}} \right)} \]
\[ R_g < 25.5 \, \Omega \]
Gate-Drive-Impedance

Active area <-> Saturated area

Transductance $g_{fs}$

Graph of the Output Characteristics of the IGBT at 25°C
Gate-Drive-Impedance

Output Source Current vs. Voltage

Output Sink Current vs. Voltage
Gate-Drive-Impedance

Drive Current with “Zero” Impedance (100 nF load, VCC=15V, VEE=-8V)

NCD570x sources/sinks 4.0A/6.2A at 9V  Comp. sources/sinks 1.1A/2.9A at 9V
Gate-Drive-Impedance

Competition – $E_{ON} = 7.44\, \text{mJ}$; NCD5700 + Opto – $E_{ON} = 6.8\, \text{mJ}$

Higher $R_g$ results in lower $I_g$ initially

$V_{ce}$ starts falling earlier + resulting in lower $E_{on}$

Miller plateau $I_g$ is higher

Total energy savings
Gate-Drive-Impedance

PCB tracks / Pins add parasitic Inductivities

Figure 6. Equivalent Gate Drive Circuit
Gate Drive Essentials

IGBT-Drive:
- Low impedance Drive – low Sw Losses
- Short distance / low inductive Layout
- 4-lead-package
- UVLO of IGBT-Driver >12V
- Single or Bipolar drive
- Miller-clamp
- Desat-detection (OCP/SCP)
- Soft-off (overvoltage)
Conclusions

• IGBT is a mature and proven technology with future potential
• HV-Diodes have Trade-offs and need to be adapted to the application
• Different Generations of IGBTs offer Pros and Cons
• Various Applications have different requirements
• 3-Level-Inverter offer performance Improvement
• Essentials on Gate-Drive of IGBTs
Thank You

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