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

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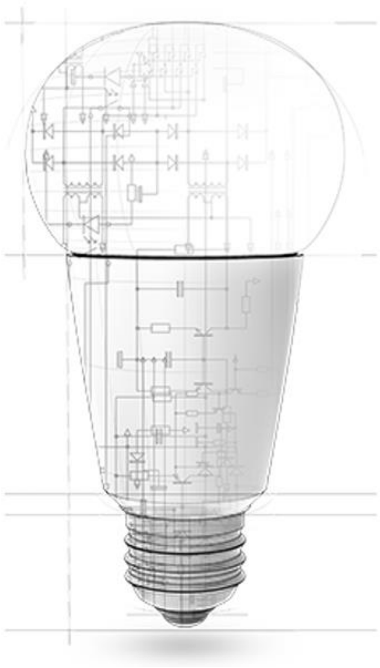
Agenda



- 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

www.premierwelding.co.uk

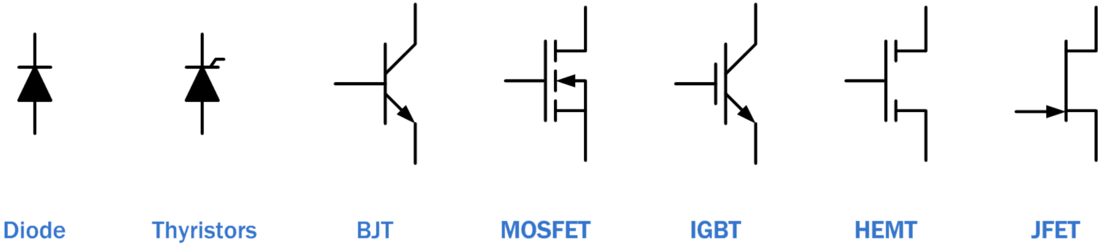
IGBT and High Voltage Rectifier Technologies

Power Semiconductors

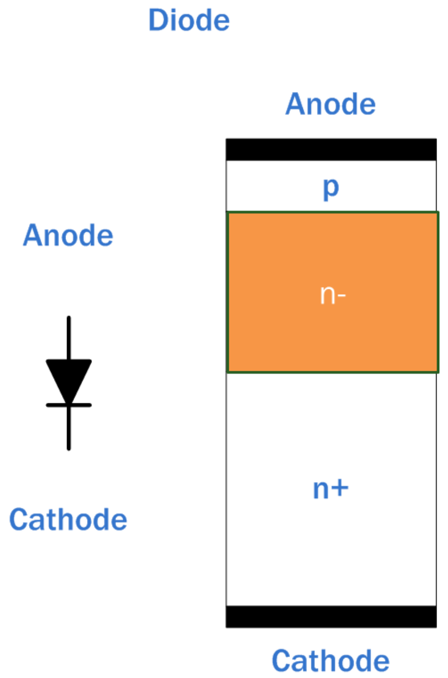
Power Semiconductors are used

to rectify, switch, control a voltage and/or current

Overview of most common devices:

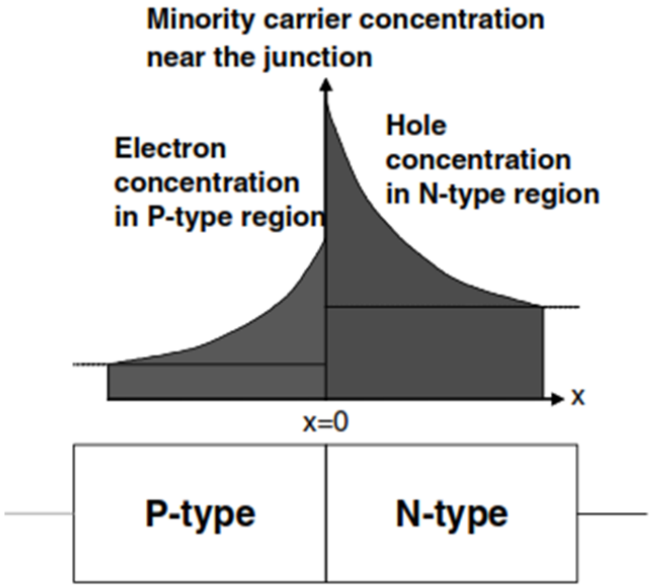


HV Rectifier Technology

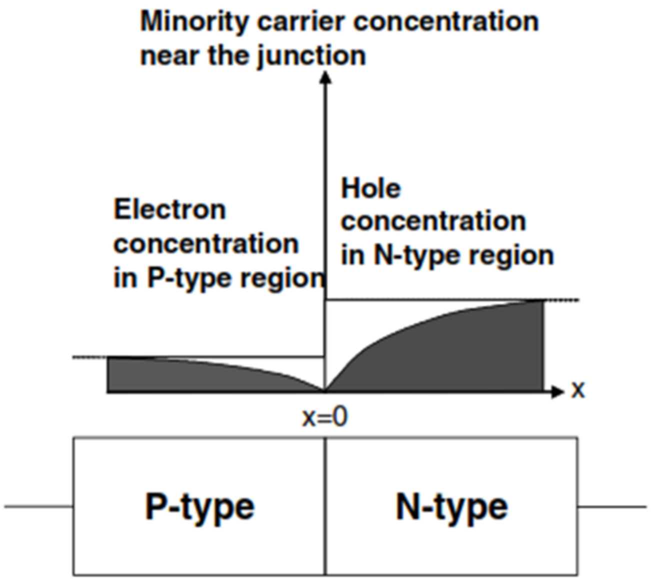


- A $p\text{–}n$ junction is needed for rectification
- Heavy doping is needed for good metal contacts for the p and the n
- Heavy doping results in low voltage rating, so a lightly doped n^{-} layer is required to give a high voltage rating
- This lightly doped region is known as the "drift region"

HV Rectifier – Conducting / Blocking



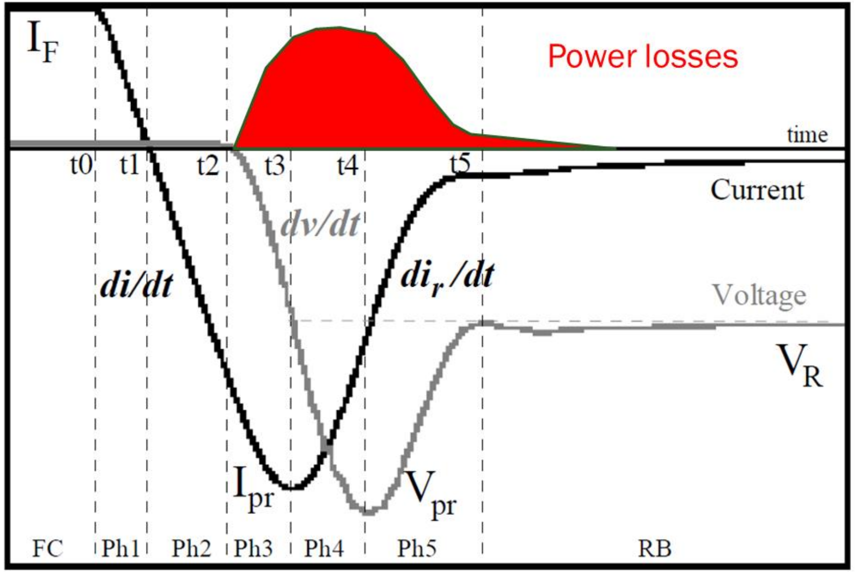
Diode conducting



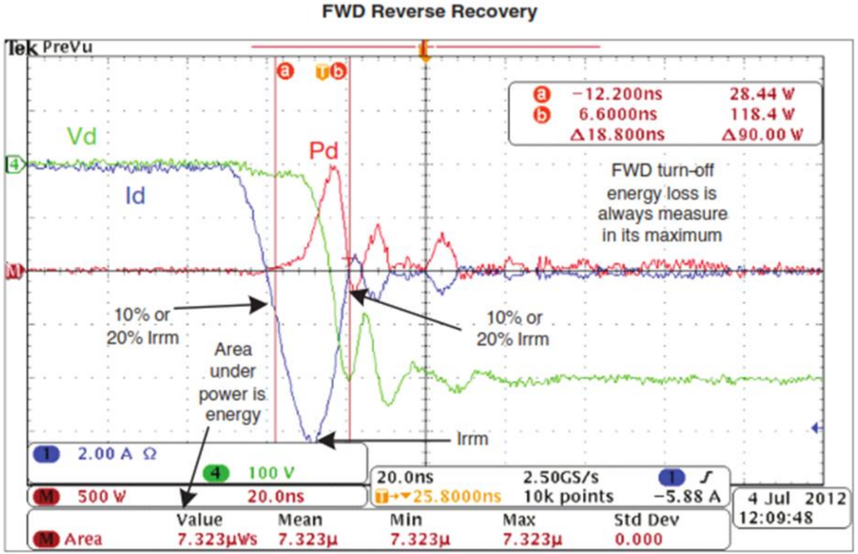
Diode blocking

HV Rectifier – Switching Characteristic

Typical reverse recovery behaviour

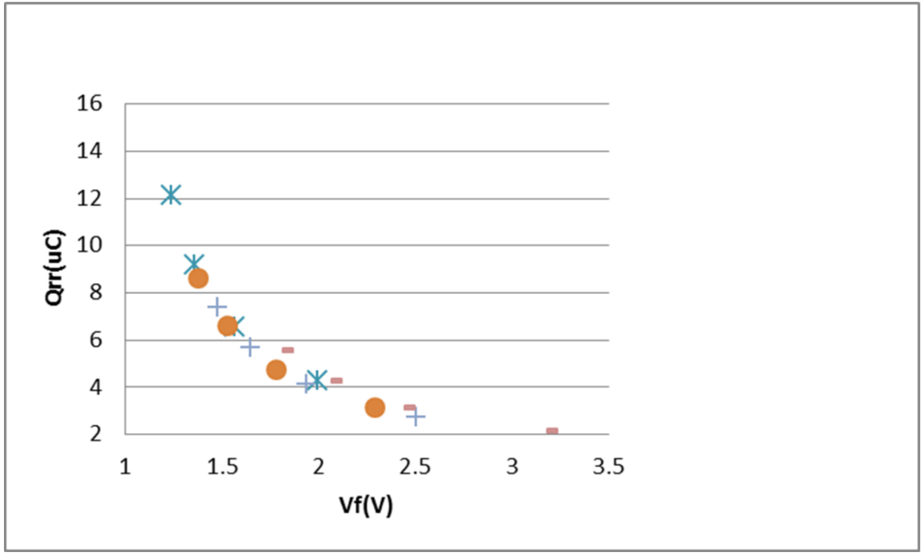


Measurement (slightly snappy)

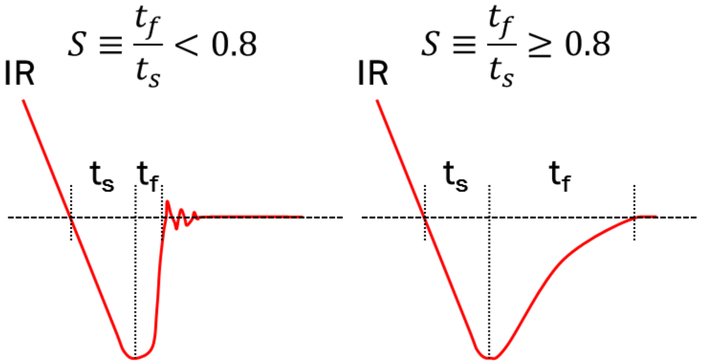


HV Rectifier – Switching Characteristic

Trade-Off-curve

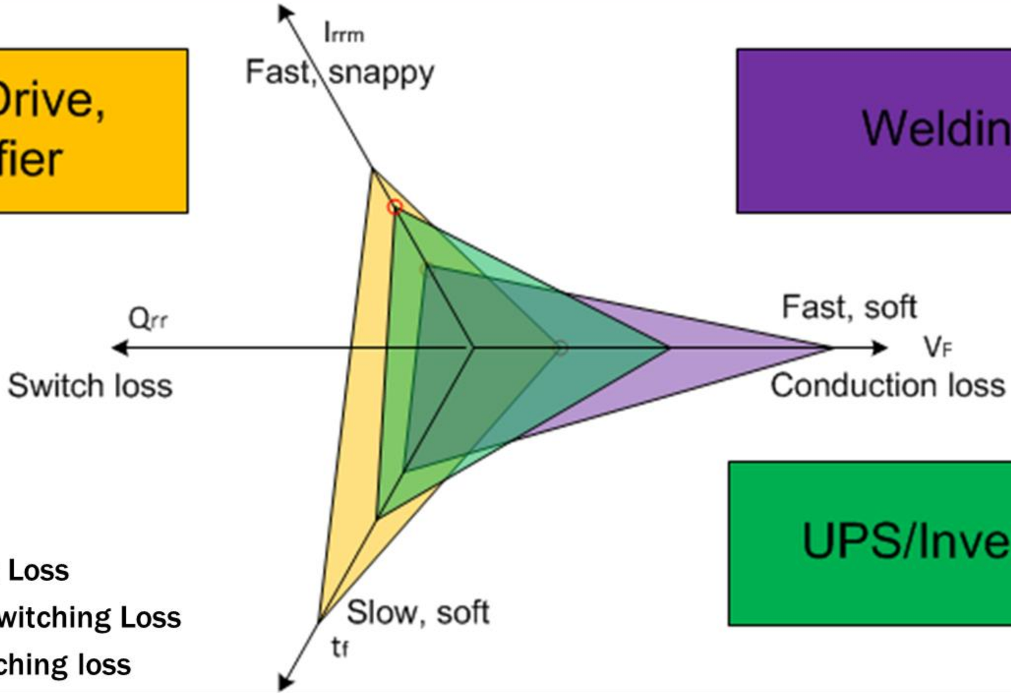


Softness Definition



HV Rectifier Applications

Motor Drive, Rectifier



Welding

UPS/Inverter

Effect of parameters:

Forward Voltage V_F: Conduction Loss

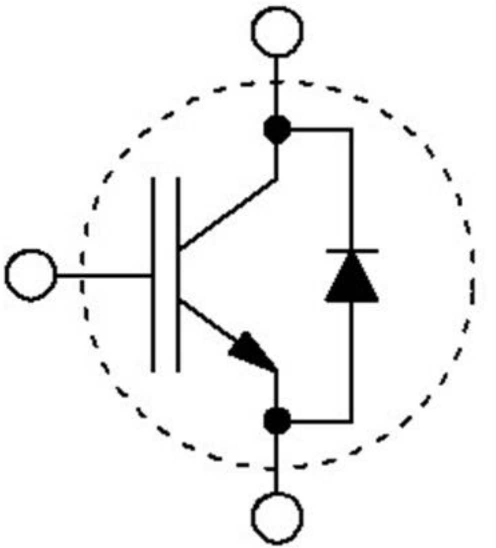
Reverse recovery Charge Qrr: Switching Loss

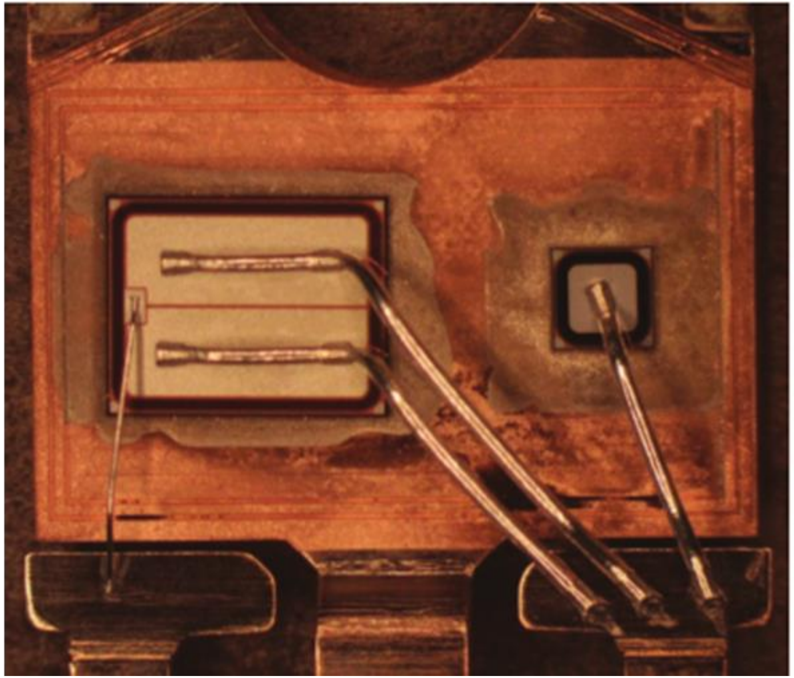
Reverse Recovery Time t_{rr}: Switching loss

Peak reverse Current I_{rrm}: Diode switching loss

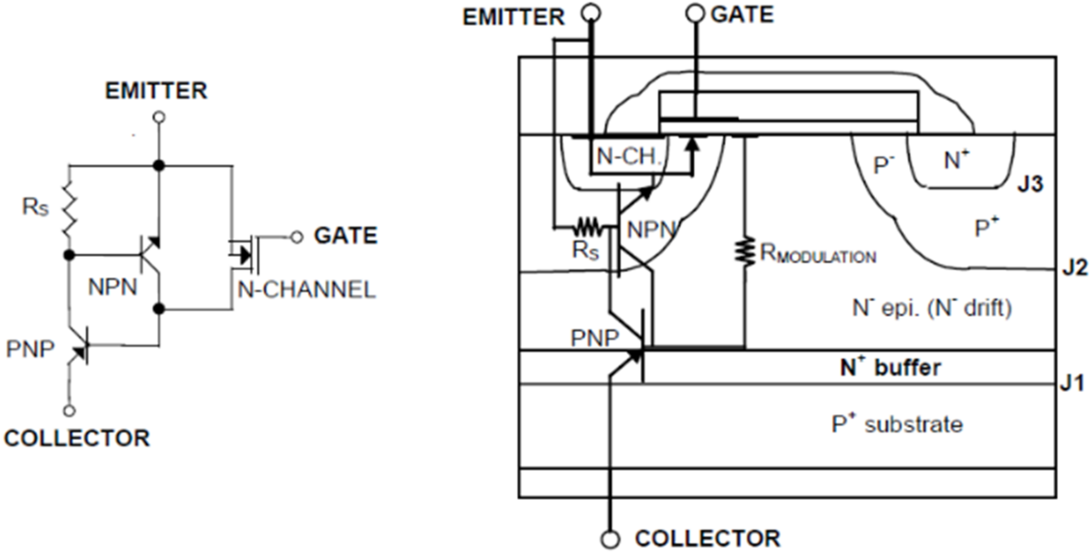
Softness S: EMI

IGBT Technology





IGBT Technology



Equivalent Circuit for the IGBT

and a Cross Section of the IGBT Structure (PT and N-Channel)

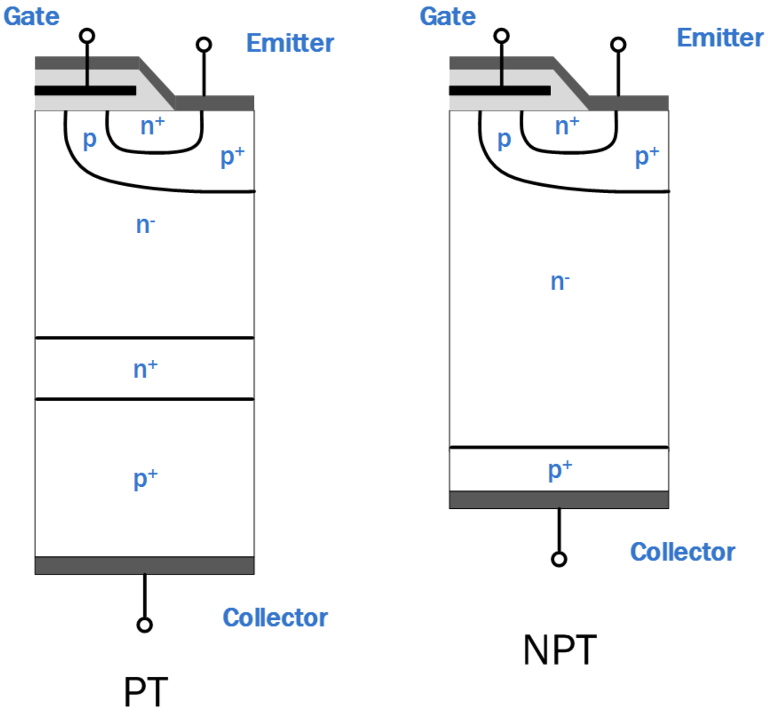
IGBT Technology

Punch through (PT) IGBTs

- based on heavily-doped p^+ substrates used for Epi growth
- large turn-off energy (Temp.dep.)
- negative TCO on Vce_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 Vce_sat (pos. TCO)
- Higher robustness (di/dt, Short Circuit)

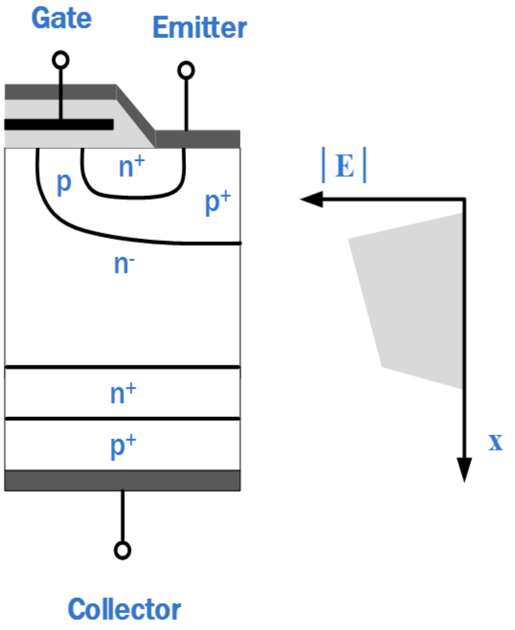


IGBT Technology

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



Public Information

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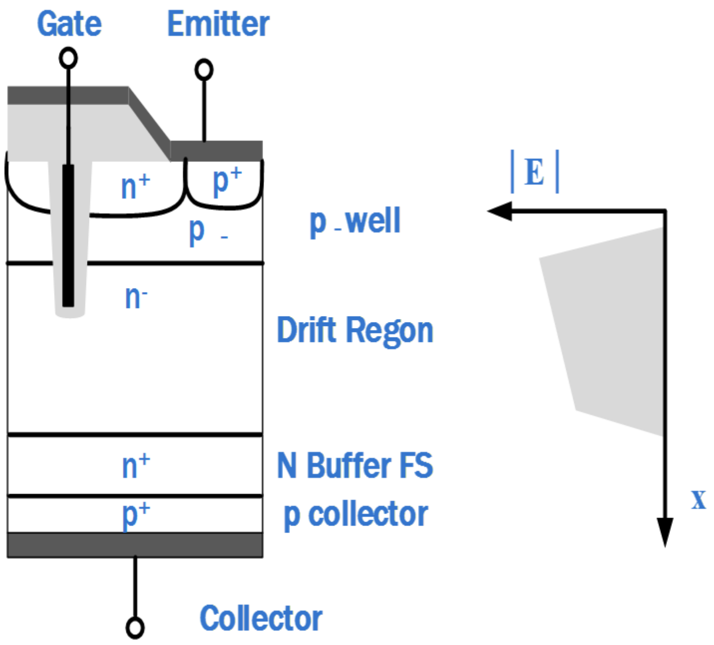
IGBT Technology

Trench gates

(NPT-Trench, FS-Trench available)

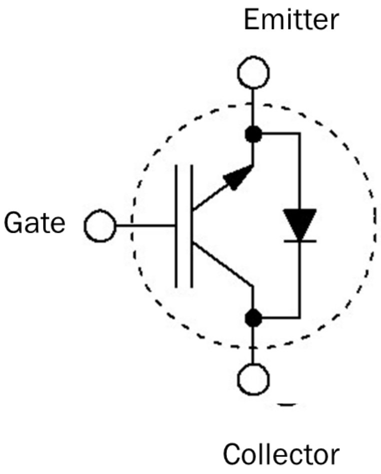
- Higher cell-density
- Better Vce_sat/Eoff Trade-off-curve
- Less sensible on parasitic NPN

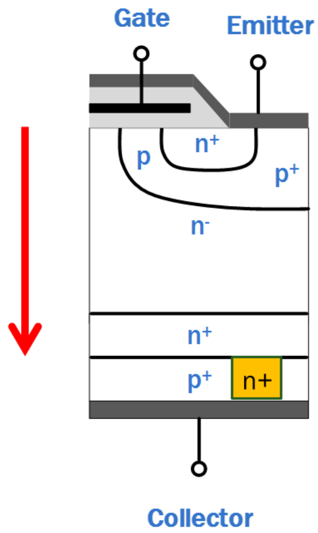


IGBT Technology

What about reverse conducting?

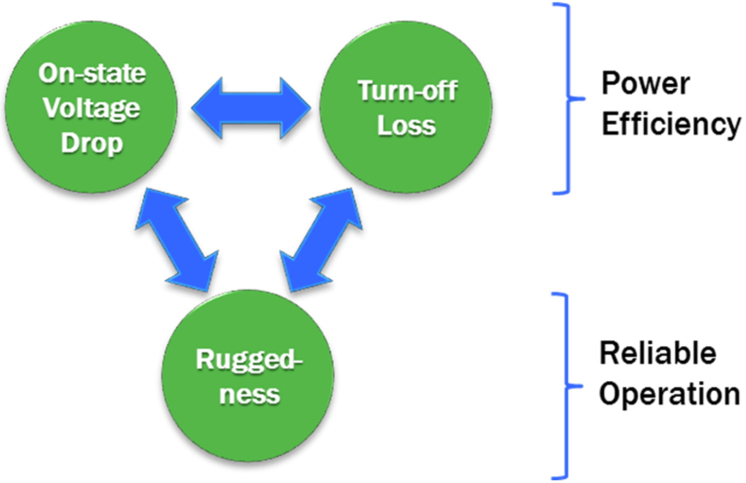
- A simple change in structure generates a PN-junction
- Called RC-IGBT (Reverse Conducting) or SA-IGBT (Shorted Anode)
- No standard Symbol
- IGBT + monolithic diode = 1 Die
- Cost benefit / Compact
- Shared Rth
- Compromise in IGBT and Diode characteristic



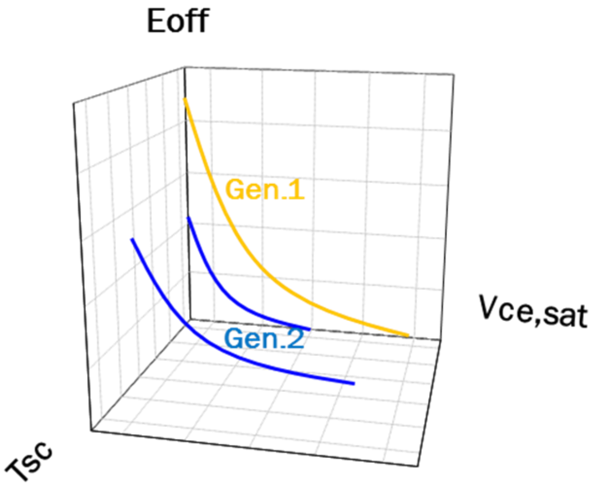


IGBT Technology

The IGBT Triangle



Trade off relationships



Technology evolution → moving towards the trade-off chart origin

Technology optimization → application specific tuning

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Application Overview

Welding

Application Overview - Welding

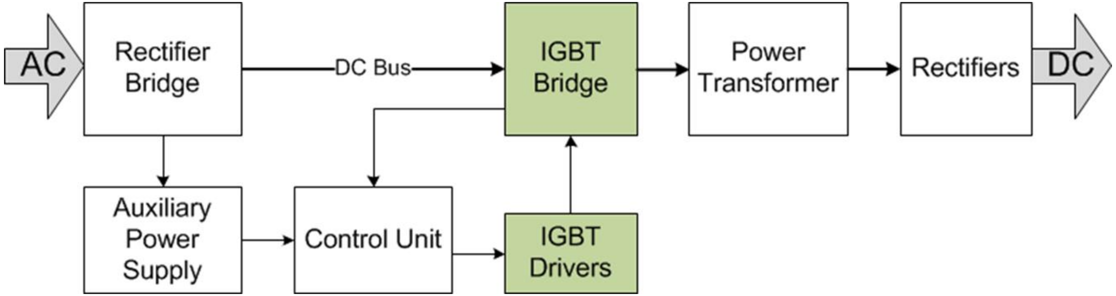
The majority of welding machine include inverters .

Accuracy in P / I control -> better welding process.

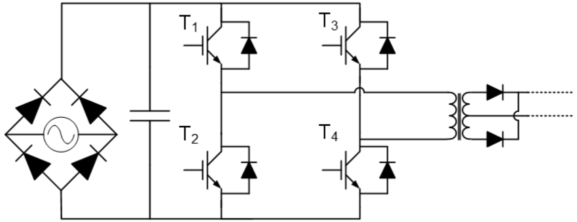
Higher Power-density / compactness / weight

With PFC more power out of a single-phase

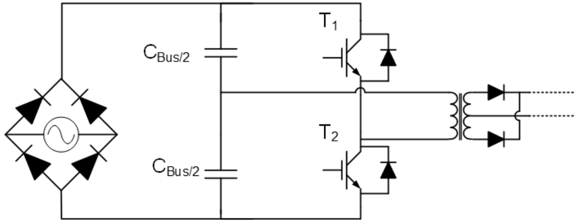
www.lorch.eu



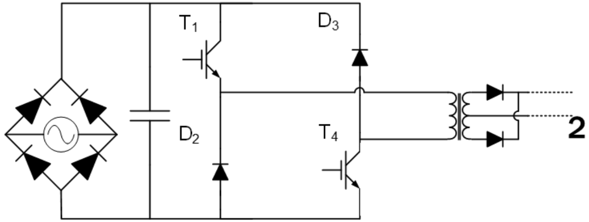
Application Overview - Welding



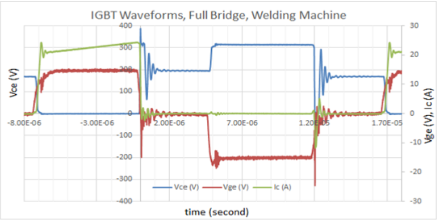
Full Bridge

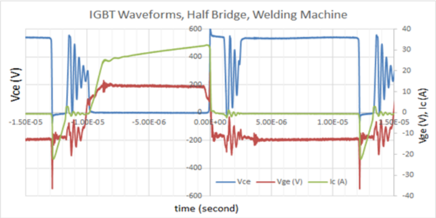


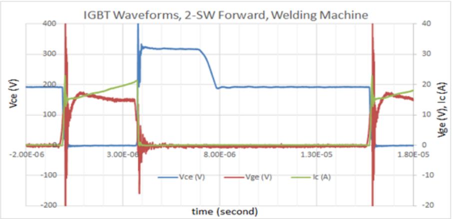
Half Bridge



2 Switch forward

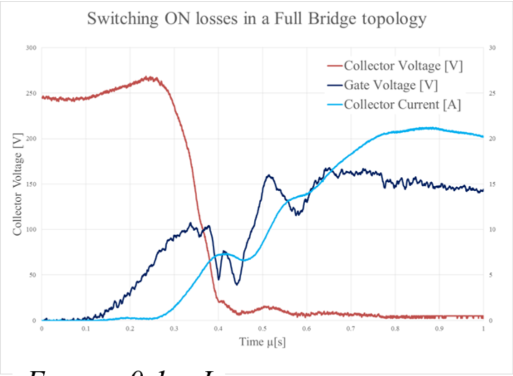




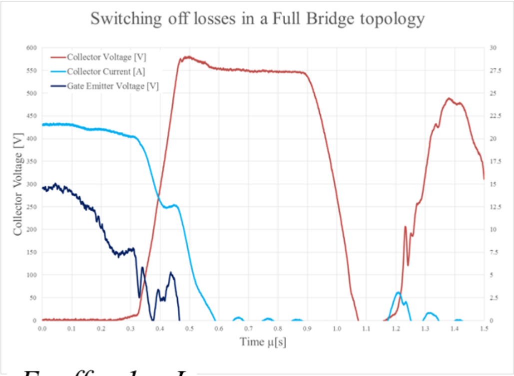


Leg:
Collector Current
Gate Voltage
Collector voltage

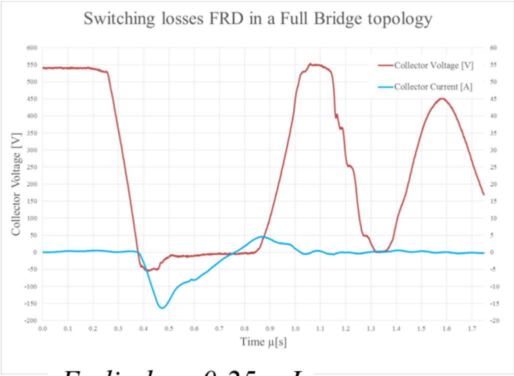
Application Overview - Welding



E_on = 0.1 mJ



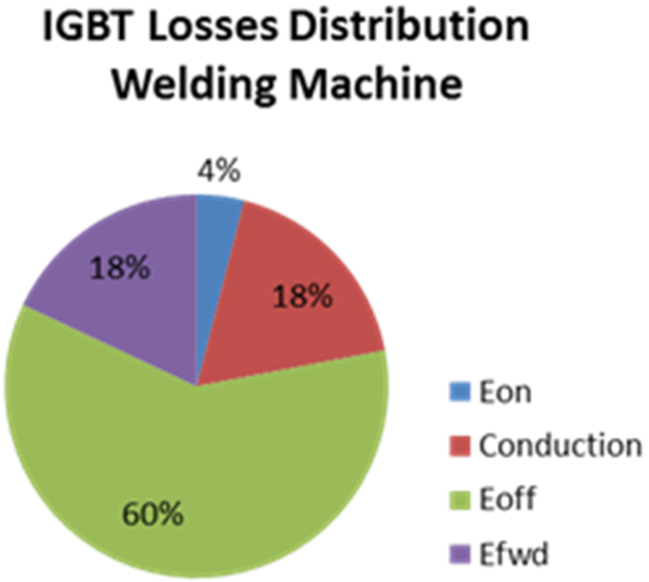
E_off = 1 mJ



E_diode = 0.25 mJ

- E_{on} is very low due to ZCS (Zero Current switching) Diode contribution to Eon 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

Application Overview - Welding



Losses Distribution in a full-bridge welding machine 5 kW.
Nominal AC 230 V Input.
Output current Full load (250 A)

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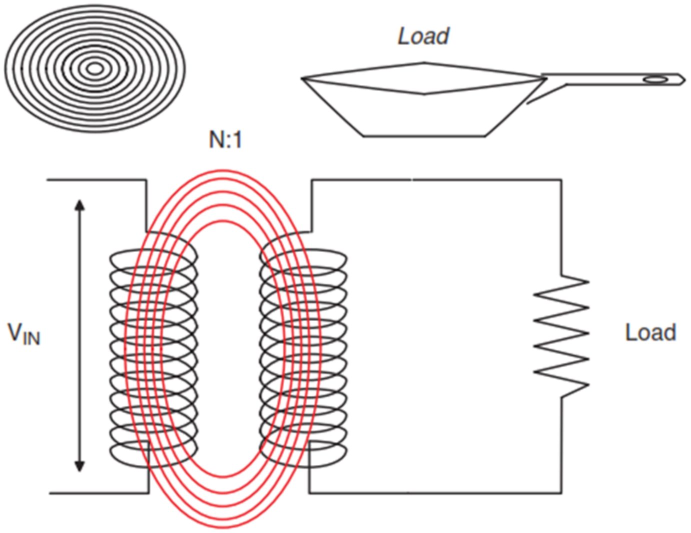
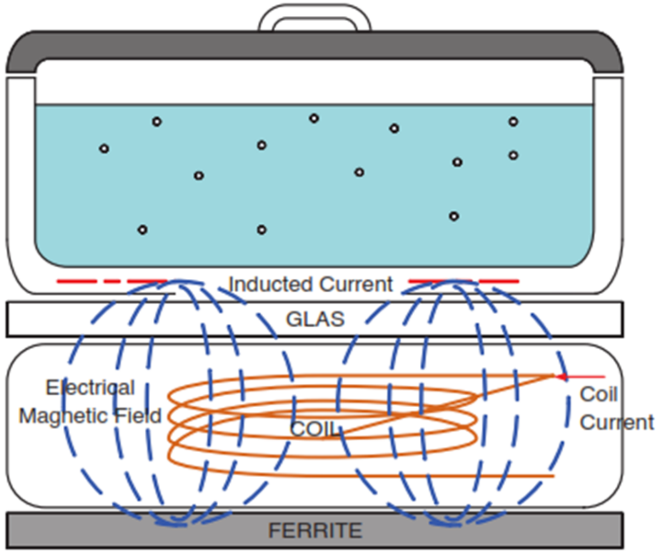
Application Overview

Inductive Heating

Principle Inductive Heating

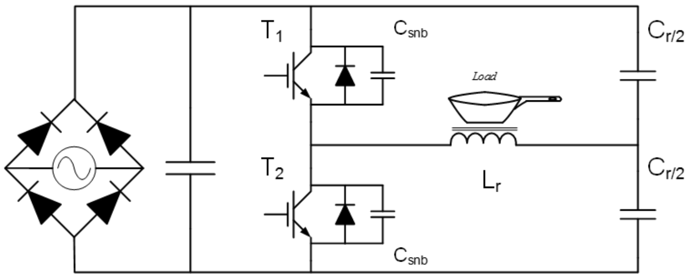


Equivalent of an Induction Cooking system

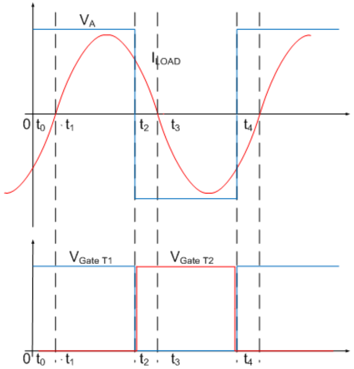


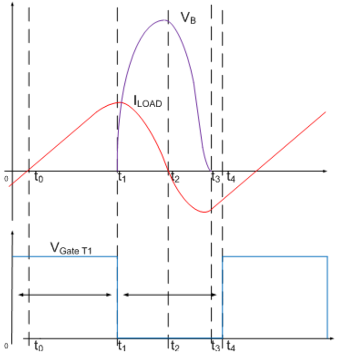
Scheme of an Induction Cooking

Application Overview – Induction Heating

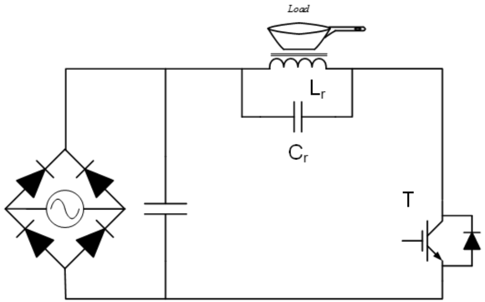


Resonant Half Bridge

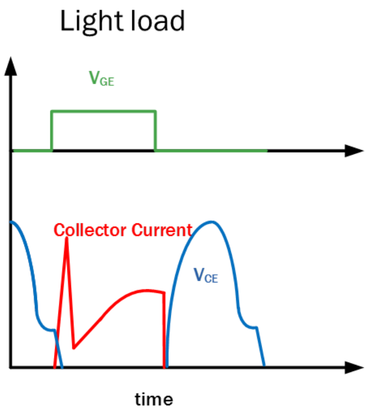




Quasi Resonant



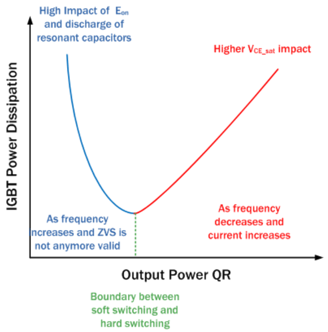
Application Overview – Induction Heating

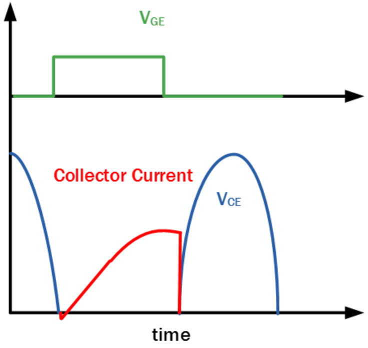


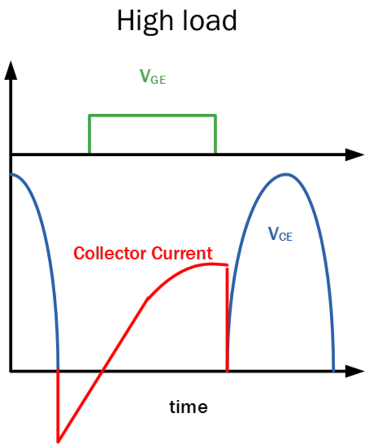
Frequency increases at lighter load or pan lifting. Despite near ZVS, E_{on} increases due to dramatically increased

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

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

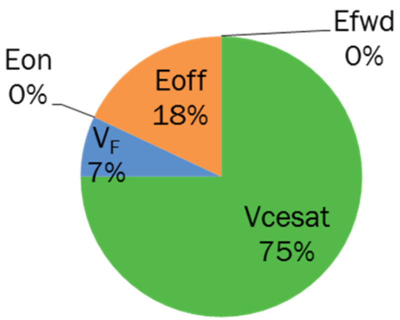




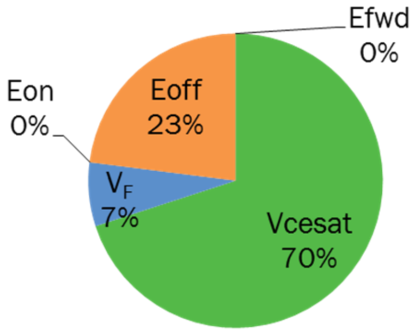


Frequency decreases at heavier load. IGBT maintains nearly ZVS but diode is conducting higher current. Low resistive pan causes the same effect for the diode

Application Overview – Induction Heating



IGBT Losses Distribution in a RHB



IGBT Losses Distribution in a QR

- 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

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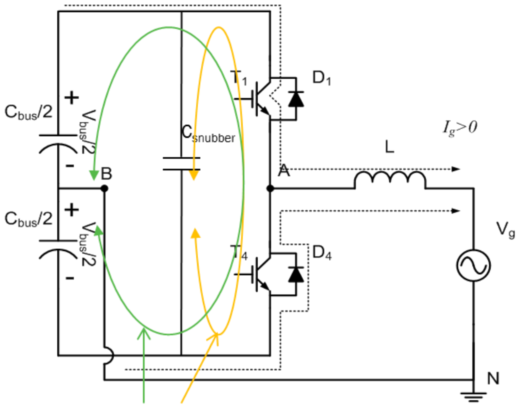
Application Overview

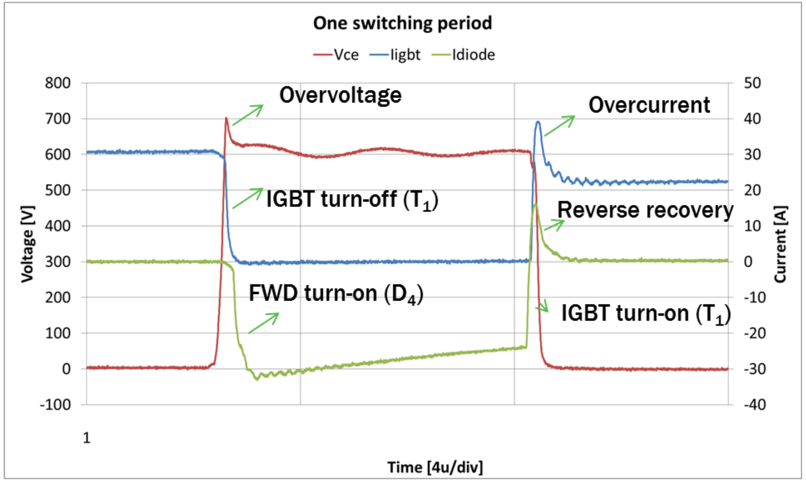
Halfbridge

Application Overview – Half Bridge

Half-bridge topology

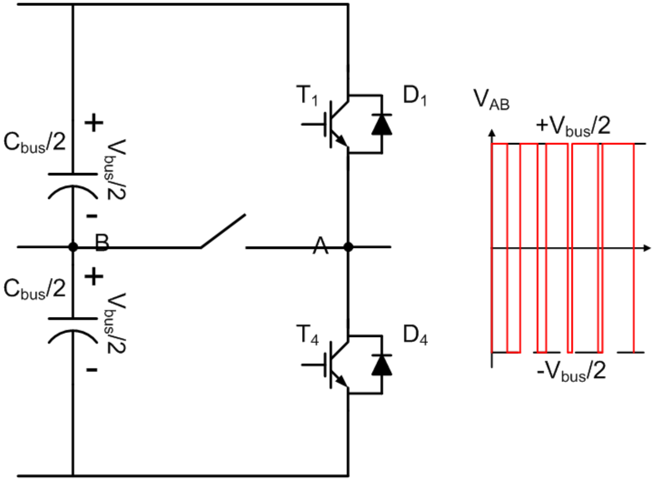


Commutation paths

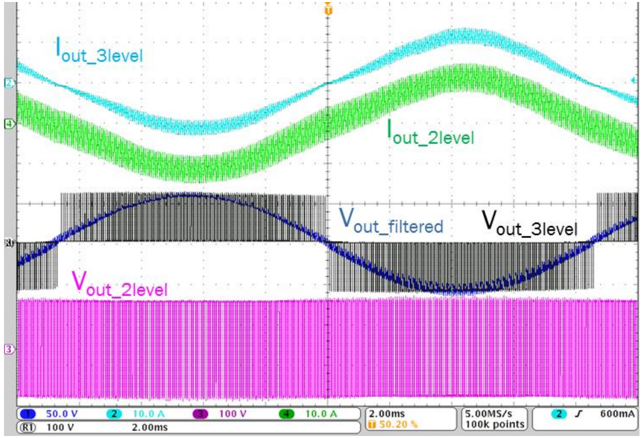


- High side IGBT always commutates with low side FWD and vice versa.
- IGBT turn-off generates over- or undervoltage (dep. on load-current direction)
- IGBT turn-on induces FWD turn-off -> reverse recovery current -> IGBT Eon.

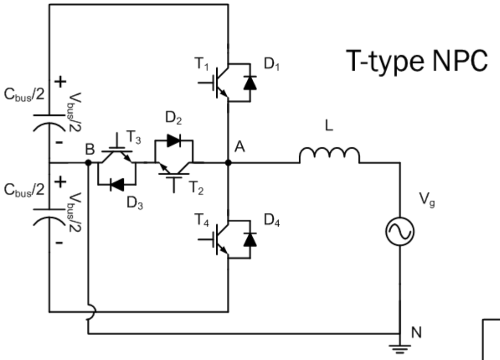
Application Overview – Half Bridge

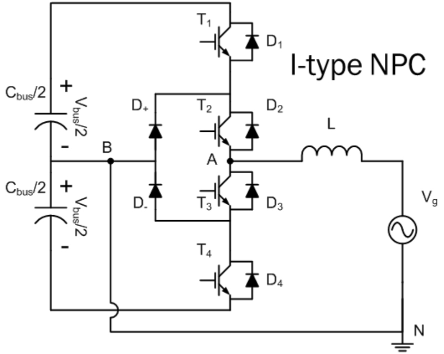


- HB can produce only two output voltage levels
- High dv/dt produces higher EMI
- Just 2 levels generate high output-ripple
- A connection to the neutral point would offer a 3rd level



Application Overview – Three level Topologies



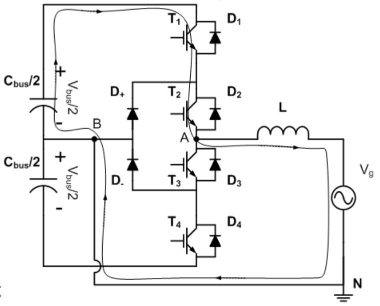


NPC: Neutral Point Clamped

- 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

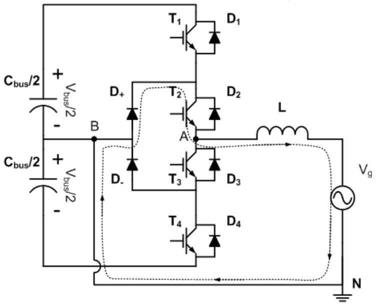
Application Overview – Three level Topologies

Inverter Mode – Bang Cycle



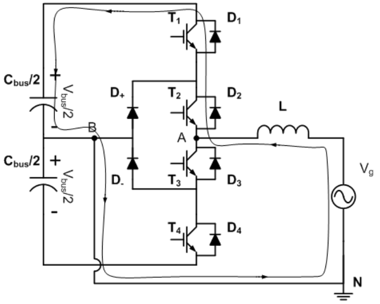
$V_g>0$, $I_g>0$
T_1 / T_2 ON;
D_+/D_-/T_3/T_4 OFF
T_1 high frequency;
T_2 line frequency.

Inverter Mode – Hang Cycle



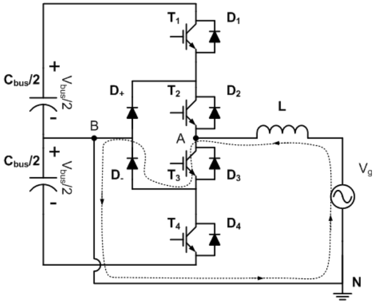
$V_g>0$, $I_g>0$
T_2/D_+ ON;
D_-/T_2/T_3/T_4 OFF
T_1 high frequency;
T_2 line frequency.

Rectifier Mode – Bang Cycle



$V_g>0$, $I_g<0$
D_1 / D_2 ON;
D_+/D_-/T_3/T_4 OFF

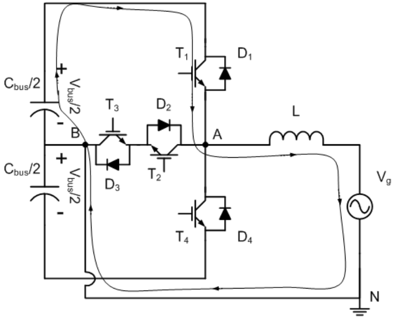
Rectifier Mode – Hang Cycle



$V_g>0$, $I_g<0$
D_-/T_3 ON;
D_-/T_2/D_1/T_4 OFF
T_3 high frequency;

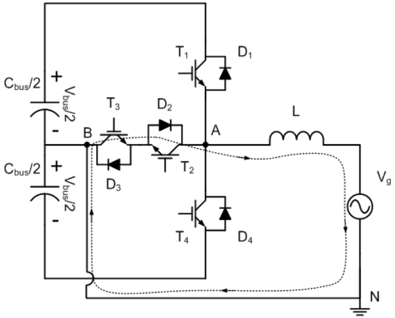
Application Overview – Three level Topologies

Inverter Mode – Bang Cycle



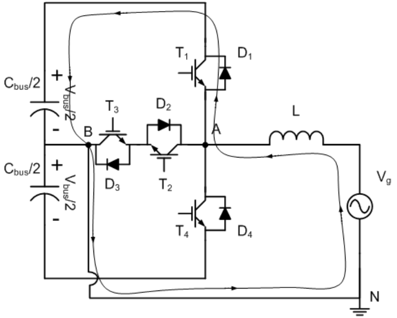
$V_g>0$, $I_g>0$
T_1 / T_3 ON;
T_2 / T_4 OFF
T_1 high frequency;
T_3 line frequency

Inverter Mode – Hang Cycle



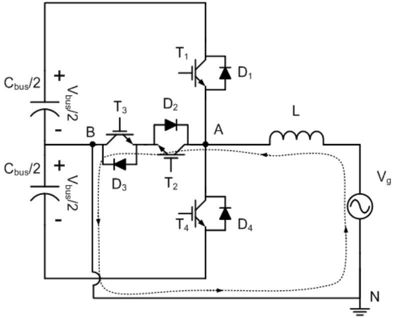
$V_g>0$, $I_g>0$
T_3 / D_2 ON;
T_1/T_2/T_4 OFF
T_1 high frequency;
T_3 line frequency.

Rectifier Mode – Bang Cycle



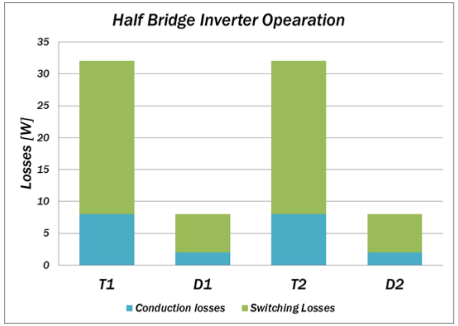
$V_g>0$, $I_g<0$
D_1 ON;
T_2/T_4 OFF
T_2 high frequency;

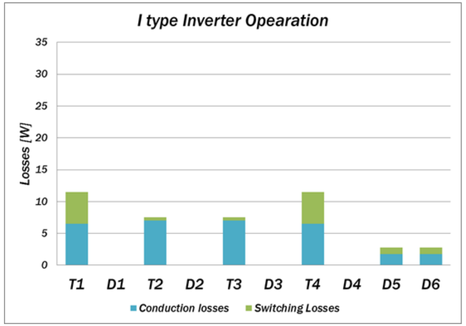
Rectifier Mode Mode – Hang Cycle

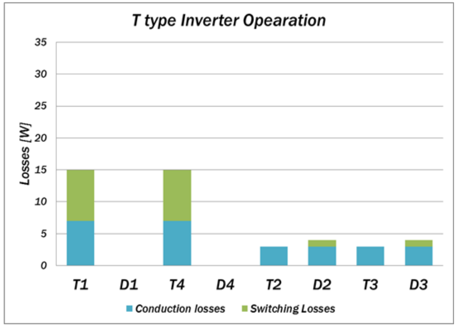


$V_g>0$, $I_g<0$
D_3/T_2 ON;
T_1 / T_4 OFF
T_2 high frequency;

Application Overview – Three level Topologies





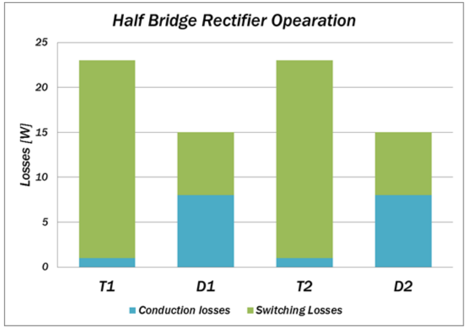


Composite Losses – **Inverter Mode**

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

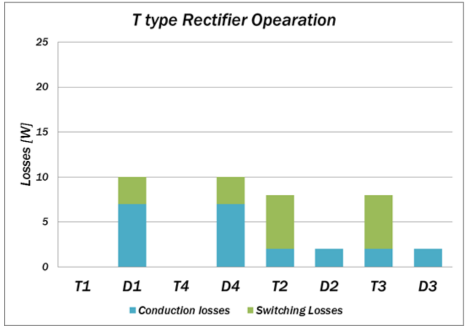
Application Overview – Three level Topologies

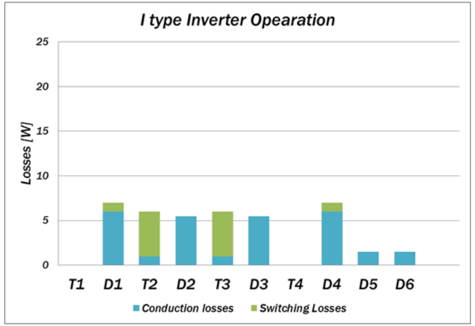


Composite Losses – **Rectifier Mode**

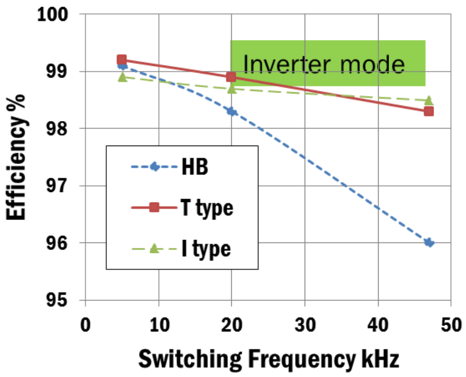
From Schweizer et al. ETH-Z (IECON 2010)

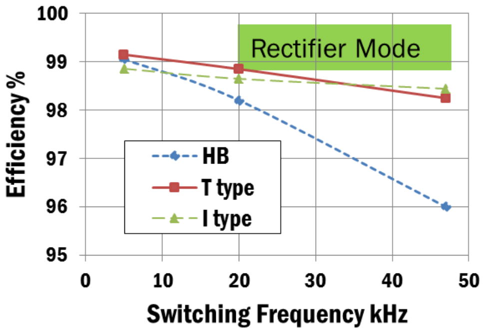
- 10 kW, V_{bus} = 650 V, V_{Output} = 325 V, I_{Output} = -20.5 A
- f_{sw} = 32 kHz
- HB: 81 W total
- T-type: 39 W total
- I-type: 39 W total





Application Overview – Three level Topologies

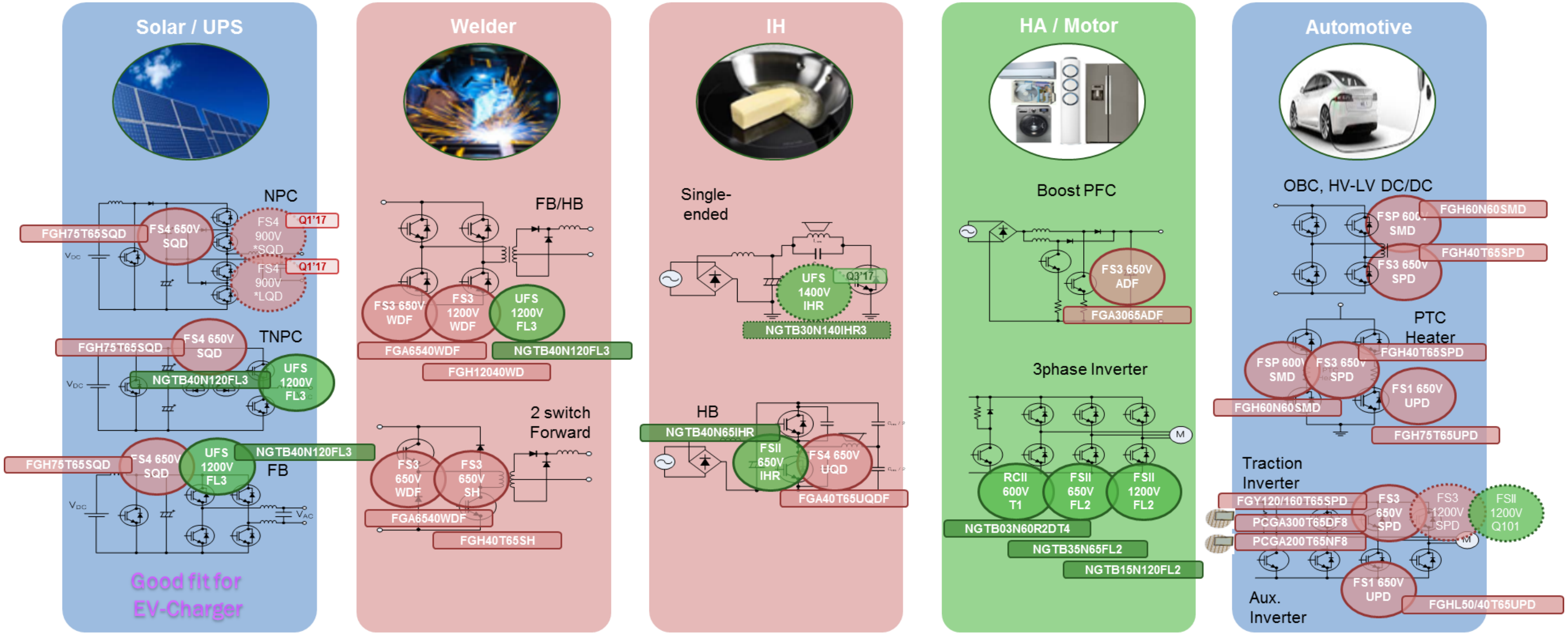




Frequency Dependence of Efficiency

- 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



SQD: FS4 high speed IGBT, **LQD**: FS4 low V_{CE_SAT} IGBT, **FL2**: FSII high speed IGBT, **FL3**: FSIII high speed IGBT, **WDF**: FS3 high speed IGBT for Welder, **SH**: FS3 high speed single IGBT, **IHR**: RC IGBT for IH
UQDF: FS4 IGBT for soft switching appl., **ADF**: FS3 high speed for Boost PFC, **RCII T1**: SCR RC IGBT, **UPD**: FS1 SCR IGBT, **SMD**: FS1 Gen.2 high speed, **SPD**: FS3 SCR IGBT

IGBT Gate-Drive

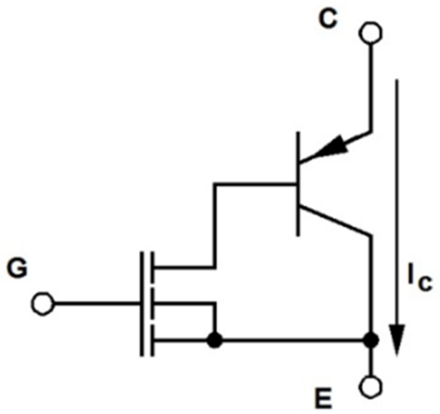
IGBT-Gate-Drive

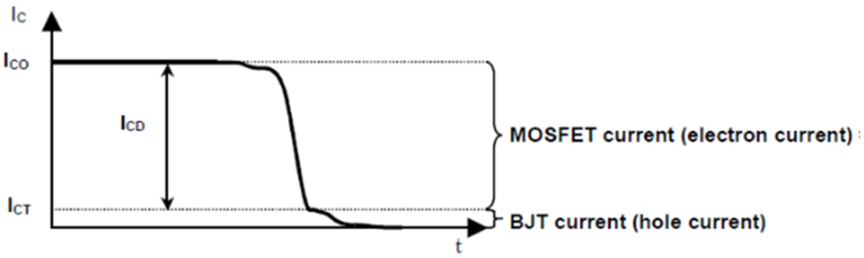
Turn-ON:

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

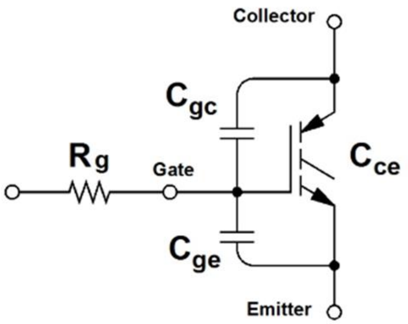
Turn-OFF:

- Beside interrupting Base-current no mechanism to move carriers out of Base-region
- Tail-current phenomen (no control)





Gate-Drive-Impedance

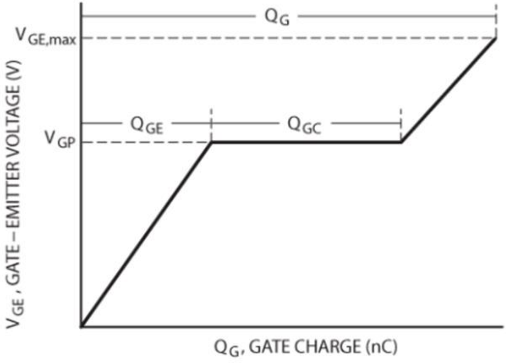


IGBT with Parasitic Capacitances

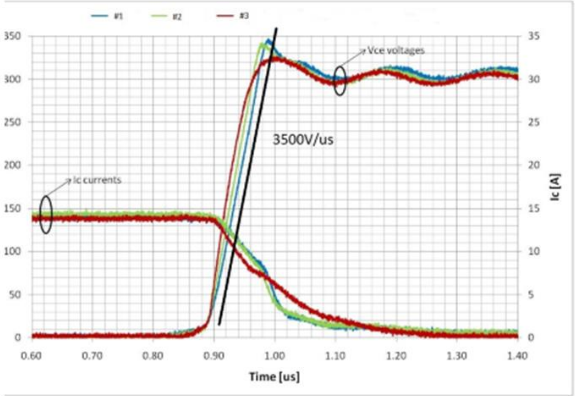
$C_{ies} = C_{ge} + C_{gc}$ with C_{ce} shorted

$C_{oes} = C_{gc} + C_{ce}$

$C_{res} = C_{gc}$



Theoretical Gate Charge Curve showing V_{GP}, Q_G, Q_{GE}, and Q_{GC}



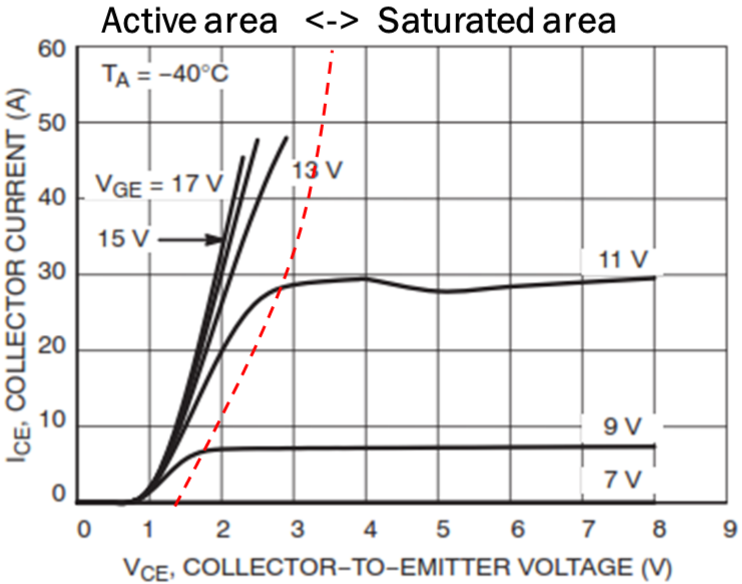
maximum total gate resistance is:

$$Rg < \frac{V_{th}}{Cgc \cdot \left(\frac{dv}{dt}\right)}$$

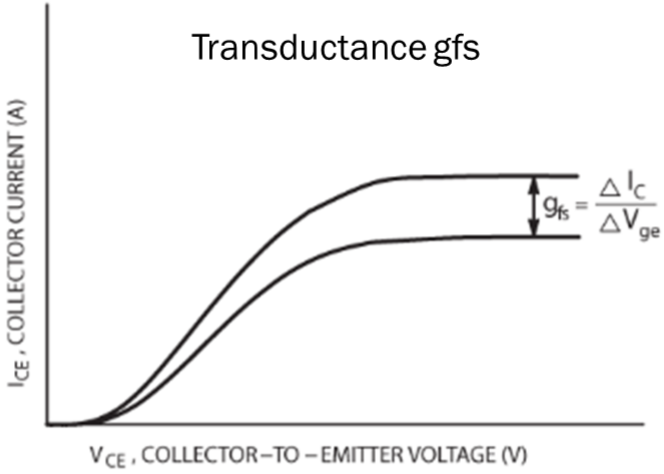
Example:

$$Rg < \frac{7.5\ V}{84\ pF \cdot \left(\frac{3500\ V}{\mu s}\right)} \qquad Rg < 25.5\ \Omega$$

Gate-Drive-Impedance



Graph of the Output Characteristics of the IGBT at 25°C



$g_{fs} = \frac{\Delta I_C}{\Delta V_{ge}}$

Illustration of the Measurement of IGBT g_{fs}

Gate-Drive-Impedance

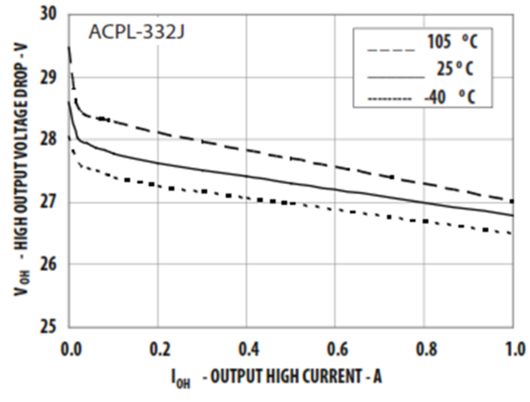
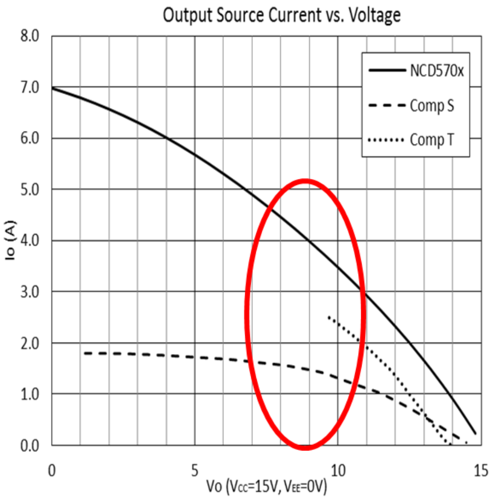
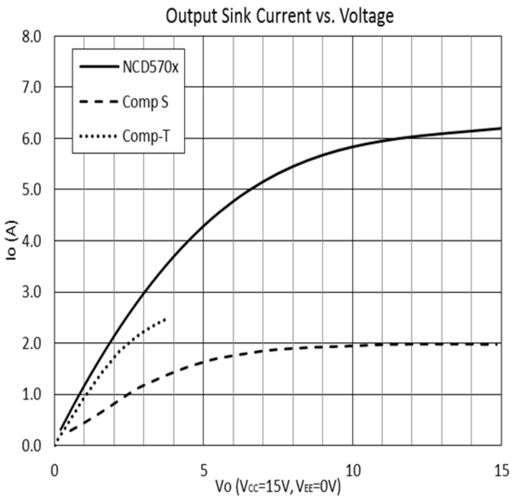


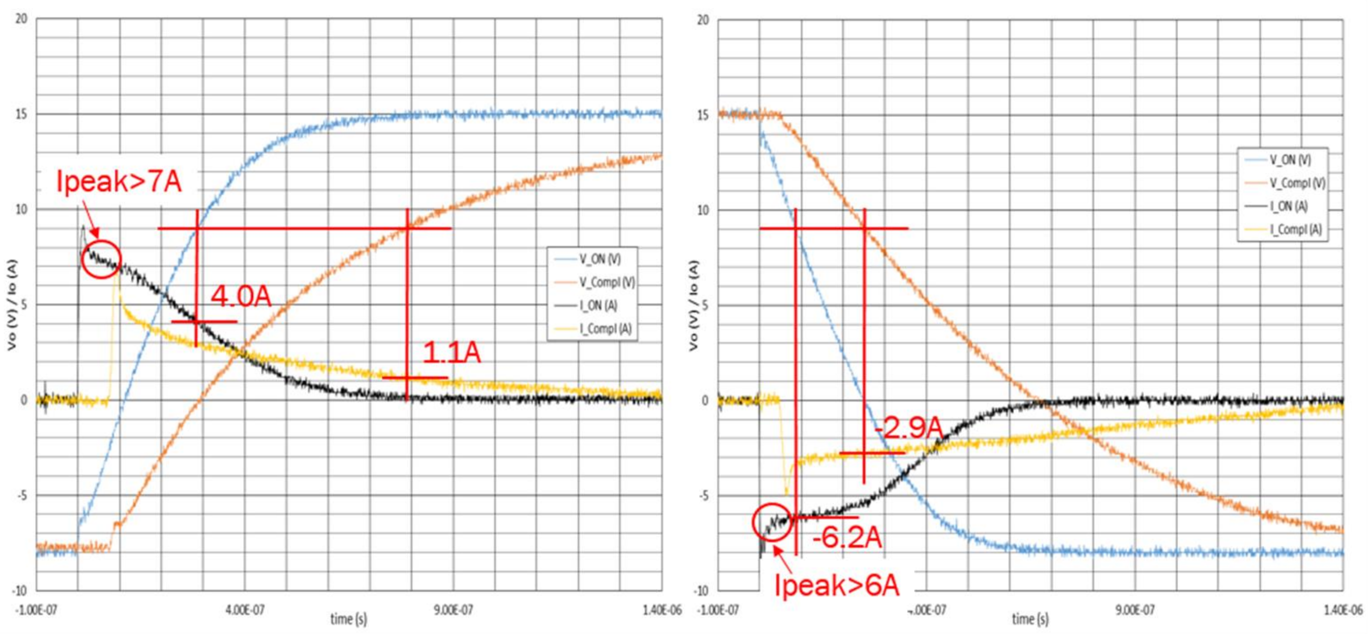
Figure 6. V_{OH} vs. I_{OH}





Gate-Drive-Impedance

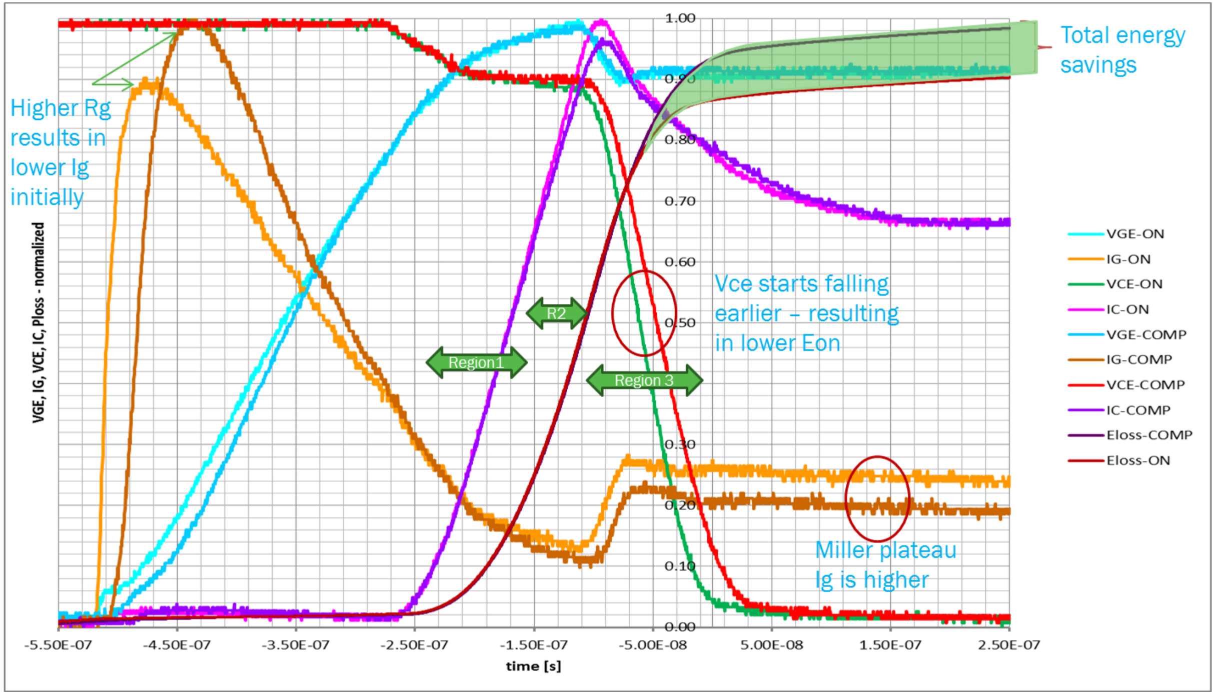
Drive Current with "Zero" Impedance (100 nF load, VCC=15V, VEE=-8V)



NCD570x sources/sinks 4.0A/6.2A at 9V   Comp. sources/sinks 1.1A/2.9A at 9V

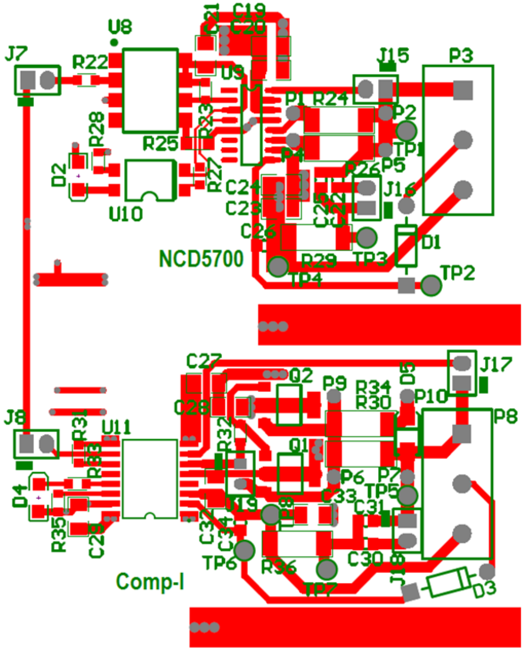
Gate-Drive-Impedance

Competition – E_{ON} = 7.44 mJ; NCD5700 + Opto – E_{ON} = 6.8 mJ



Gate-Drive-Impedance

PCB tracks / Pins add parasitic Inductivities



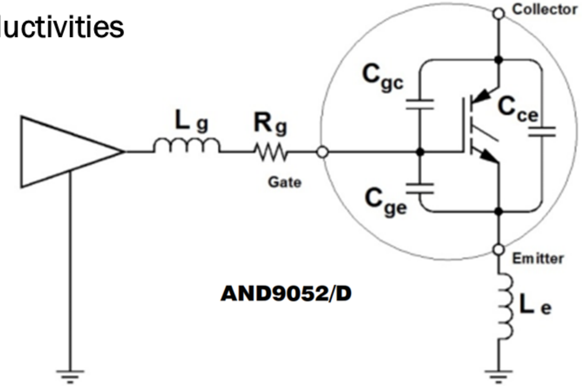
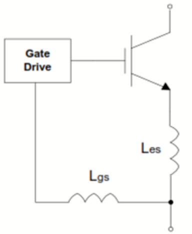
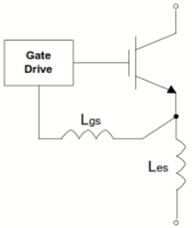
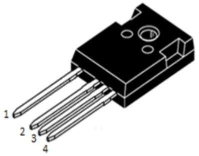


Figure 6. Equivalent Gate Drive Circuit



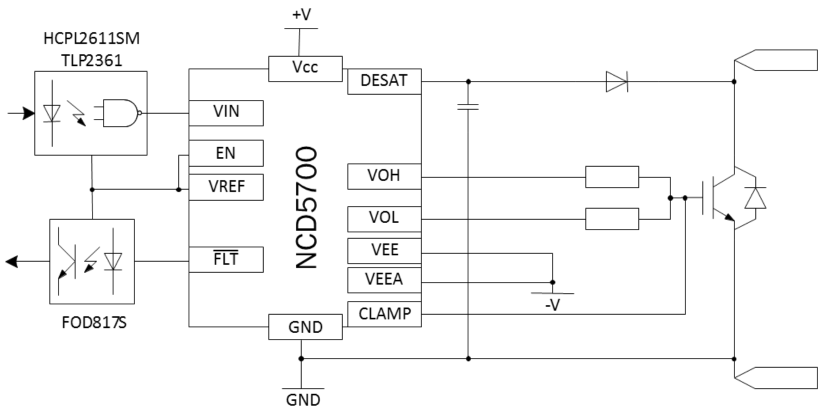




Gate Drive Essentials

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

For more information regarding these products or our complete portfolio of products, please contact your local sales person or authorized distributor.

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