Voltage, Current and Temperature Measurement Concepts
Enabling Intelligent Gate Drives

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Motivation

Intelligent Gate Drive

- Digital control unit (FPGA, CPLD, DSP) with computing power close to the power semiconductor
  - Programmable output characteristics [Hemmer2009]
  - Advanced control \( (di_C/dt, du_{CE}/dt) \) [Kuhn2008]
  - Extended and adjustable protection functionality (short-circuit, over-current, overvoltage-limiting, health monitoring, ...)
  - Extensive communication possibilities (digital transmission bus with control unit)

Need for measurements

- Integratable in gate driver, external circuits and IGBT; typ. without galvanic isolation

- Current measurement concepts
  - Collector current: \( i_C \)
  - Collector current slope: \( di_C/dt \)

- Voltage measurement concepts
  - Collector-Emitter voltage: \( u_{CE} \)
  - Collector-Emitter on-state voltage: \( u_{CE,\text{on}} \)
  - Collector-Emitter voltage slope: \( du_{CE}/dt \)

- Temperature measurement concepts
  - Junction temperature: \( T_j \)
Current measurement: $i_C$

Shunt resistor

\[ u_S(t) \approx R_S \cdot i_C(t) + L_S \cdot di_C(t)/dt \]

\[ u_{S,f}(t) = R_S \cdot i_C(t) \quad \text{(for } R_f, C_f = L_S / R_S) \]

(+)  
- Simple, cheap, passive (low noise & low disturbance)
- Possibility of integration in IGBT module (Infineon MIPAQ™, Semikron Semitrans®) or busbar (well dissipated losses)
- DC & AC measurement $u_{S,f}(t) \sim i_C(t)$ (high bandwidth due to compensation of $L_S$)

(-)  
- Losses: $P_L \approx R_S \cdot i_C^2$
  - Low losses = low amplitude resolution
  - Temperature drift
- Parasitic (commutation) inductance $L_S$
  - Accurate compensation needed
Current measurement: $i_C$

Current sense IGBT (split-cells: $n_S / n_{tot}$)

$u_S(t) = R_S \cdot i_S(t)$

$\approx R_S \cdot i_C(t) \cdot n_S / n_{tot}$

(typ.: $n_S / n_{tot} = 1/100 ... 1/1000$)

(-)
- High accuracy = low resolution
  - Small $R_S$ is needed for right scaling
- Cost, rarity
  - Only few types available
  - Often no alternatives

(+) Simple, passive
  (low noise & low disturbance)
- Integrated in IGBT module
  (Fuji Electric, Mitsubishi Electric)
- High bandwidth
- AC & DC measurement: $u_S(t) \sim i_C(t)$
- Low losses

Mitsubishi Electric IGBT module with integrated current sense IGBT and corresponding terminals

Mitsubishi Electric IGBT module with integrated current sense IGBT and corresponding terminals
Current measurement: $i_C$

Rogowski coil (passive integration)

$$u_r(t) = M_r \cdot di_C(t)/dt$$

Amplitude characteristic of $u_r / i_C$ | $u_f / u_r$ | $u_f / i_C$

- Simple, cheap, passive (low noise & low disturbance)
- High upper bandwidth (typ. $f_u > 50$ MHz)
- Integration in PCB / IPEM possible
- High freq. AC measurement: $u_r(t) \sim i_C(t)$
- Low losses
- Isolated, no saturation effects
- No additional commutation inductance

(-)

- No DC current measurement (high lower bandwidth $f_c$)
- Typ. too low amplitude resolution
- Signal integration needed
Current measurement: $i_C$

Rogowski coil (active integration)

\[ u_i(t) \approx M_r / (R_i \cdot C_i) \cdot i_C(t) \quad \text{for} \quad f_i \cdot C_i > f_c \]

- Active (noise)
- Parasitic effects of operational amplifier
  - Bias current, offset voltage ($R_d$ avoids DC-drift)
  - Limited gain-bandwidth-product
  - Limited lower bandwidth $f_c$, no DC

Amplitude characteristic of $u_r / i_C \mid u_i / u_r \mid u_i / i_C$

- Simple, cheap
- High upper bandwidth (typ. $f_u > 50$ MHz)
- Small lower bandwidth (typ. $f_c < 50$ Hz)
- Integration in PCB / IPEM possible
- Low to high freq. AC measurement: $u_i(t) \sim i_C(t)$
- Low losses
- Isolated, no saturation effects
- No additional commutation inductance
Current measurement: $i_C$

Integration of Rogowski coil to
- IPEM
- PCB

[Xiao2003]
Prototype of IPEM embedded Rogowski coil sensor

[Bortis2008]
PCB integrated Rogowski coils around single screwed terminals

[Bortis2008]
PCB integrated Rogowski coil around multiple screwed terminals
**Current measurement: \( i_C \)**

**IGBT bonding inductance**

\[
\begin{align*}
\text{Auxiliary (kelvin) emitter terminal needed} & & \quad (-) \\
\text{Dependency on gate current} & & \quad (-) \\
\quad & \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{Resettable integrator circuit beneficial} \\
\text{Parasitic effects of operational amplifier & switch} & & \quad (-) \\
\quad & \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{Bias current, offset voltage (} R_d \text{ or } s_i \text{ to avoid DC-drift)} \\
\text{Parasitic inductance } L_E \text{ integrated in IGBT module} & & \quad (-) \\
\quad & \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{Dependency on tolerances of manufacturing process} \\
\quad & \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{for accurate measurements without calibration} \\
\text{Simple, cheap} & & \quad (+) \\
\text{High upper bandwidth (typ. } f_u > 50 \text{ MHz)} & & \quad (+) \\
\text{Small lower bandwidth (typ. } f_c < 50 \text{ Hz)} & & \quad (+) \\
\text{Parasitic inductance } L_E \text{ integrated in IGBT module} & & \quad (+) \\
\quad & \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{no sensing hardware needed} \\
\text{Low to high freq. AC measurement: } u_i(t) \sim i_C(t) & & \quad (+) \\
\text{Low losses} & & \quad (+) \\
\text{No additional commutation inductance} & & \quad (+) \\
\end{align*}
\]

\[
\begin{align*}
\text{Current measurement: } i_C & = \frac{s_i \cdot (L_e \cdot i_C(t) - L_e \cdot i_G(t))}{R_i \cdot C_i} \\
& \approx \frac{u_i(t)}{R_i \cdot C_i} - \frac{u_{Ee}(t)}{L_e} \cdot \frac{d}{dt} + \frac{L_e}{L_e} \cdot \frac{d}{dt} \cdot i_G(t) \frac{d}{dt}
\end{align*}
\]

\( s_i \) is used to minimize the influence of \( i_G \) (\( s_i \) closed during the gate current transients, i.e. before the switching transients of \( i_C \))
Giant Magnetoresistive (GMR) Sensor

High resistance

No Applied Field

Current Direction

Low resistance

Linear Range

Resistance

[Olson2003]

[Shah2004]

[Slatter2011]

Prototype of Sensitec’s GMR current sensor (CMS) $f_u \approx 4 \text{ MHz}$

(+)

- DC to AC current measurement
- Possibility of integration to IPEM
- Low losses

(-)

- Additional commutation inductance
- Limited upper bandwidth (cf. Rogowski coil)
  - Sensitec CMS series: $f_u = 4 \text{ MHz}$
- Active (noise)
- Evaluation & compensation circuit needed
Current derivative measurement: $\frac{di_C}{dt}$

**Bonding inductance**

$u_{Ee}(t) = -L_E \cdot \frac{di_C(t)}{dt} + L_e \cdot \frac{di_G(t)}{dt}$

- **(+)** Simple, cheap, no sensing hardware needed
- **(+)** Accurate (direct signal measurement)
- **(-)** Auxiliary (kelvin) emitter terminal needed
- **(-)** Dependency on manufacturing process

**Rogowski coil**

$u_r(t) = M_r \cdot \frac{di_C(t)}{dt}$

- **(+)** Simple, cheap
- **(+)** Accurate (direct signal measurement)
- **(-)** Rogowski coil needed
- **(-)** Dependency on stray field
Current derivative measurement: $d{{i}_{C}}/dt$

**Passive derivation of current signal $u_{in}$**

$u_{f}(t) = a \cdot du_{in}(t)/dt = b \cdot d{{i}_{C}}(t)/dt$ (for $f_{in} < f_{c}$)

**Active derivation of current signal $u_{in}$**

$u_{d}(t) = a \cdot du_{in}(t)/dt = b \cdot d{{i}_{C}}(t)/dt$

(+)
- Simple, cheap
- Passive (low noise)

(-)
- Indirect measurement (derivation)
- Low amplitude resolution
- High amplitude = low bandwidth

(+) Simple, cheap

(-) Indirect measurement (derivation)
- Active (noise)
- High amplitude = high noise

Y. Lobsiger | 2011/06/30 @ ECPE Workshop Munich
Compensated passive voltage divider

\[ u_{CE,L}(t) = \frac{R_L}{R_H + R_L} \cdot u_{CE}(t) \]

(for \( C_L = C_H \cdot \frac{R_H}{R_L} \))

Typ. no additional capacitor \( C_H \) needed as the parasitic capacitances of \( R_H \) and the PCB layout are high enough for compensation with \( C_L \)

- Minimal possible output capacitance
- High impedance

(+)
- Simple, cheap
- Passive (low noise)
- High bandwidth, adjustable gain

(-)
- Additional IGBT output capacitance
- Blocking voltage of \( R_H \) is about \( u_{CE,max} \)

[Wang2009]
Decoupling diode $D$

Voltages of $u_{CE}$ above $u_+ - u_{D,f}$ are clipped by diode $D$ that is then in blocking state

Compensation of $u_{D,f}$ is needed if the exact value of $u_{CE,on}$ is needed

Offset $u_D$ in measured voltage $u_{CE,lim}$

Dependency of $u_D$ on

- Temperature $T_D$
- Current $i_D$

High blocking voltage of diode $D$ needed (about $u_{CE,max}$)

Simple, cheap

Passive (low noise)

High bandwidth

$u_{CE,lim}(t) = u_{CE}(t) + u_{D,f}$ (for $u_{CE} < u_+ - u_{D,f}$)

$u_{CE,lim}(t) = u_+$ (for $u_{CE} >= u_+ - u_{D,f}$)
Voltage measurement: $u_{CE,\text{on}}$

**Limiting Z-diode**

- Low bandwidth ($Z$ and $D$ conducting before $v_{CE}$ drops below $v_Z + v_{D,f}$)
  - Charge recovery of diodes
  - Low-pass of $R$ and diode’s capacitances
  - High voltage rating for $R$ (about $u_{CE,max}$)

\[ u_{CE,\text{lim}}(t) = u_{CE}(t) \quad (\text{for } u_{CE} < u_Z + u_{D,f}) \]
\[ u_{CE,\text{lim}}(t) = u_Z + u_{D,f} \quad (\text{for } u_{CE} \geq u_Z + u_{D,f}) \]

- Voltages of $u_{CE}$ above $u_Z + u_{D,f}$ are clipped by Z-diode $Z$ and diode $D$

- Simple, cheap
- Passive (low noise)
- No offset voltage in $u_{CE,\text{lim}}$
- Low blocking voltages of $D$ & $Z$ needed

[Carsten1995]
Parallel switch S

- Direct connection when switch is closed \((s = 1)\) (low noise)
- No offset voltage in \(u_{CE,\text{lim}}\)

\[
u_{CE,\text{lim}}(t) = \min(u_{CE}(t), u_{\text{lim}})
\]

When \(s = 1\) then: \(u_{CE,\text{lim}} = u_{CE,\text{on}}\)

- Switch S needs same blocking voltage as IGBT (about \(u_{CE,\text{max}}\))
- Separate switching signal \(s\) needed
  - Derived passively by \(u_{CE}\) [Kaiser1987]
  - Provided by digital control unit
  - Limited bandwidth due to delayed switching of S
Passive derivation of voltage signal $u_{CE}$

$$u_f(t) \approx R_f \cdot C_f \cdot \frac{du_{CE}(t)}{dt}$$

(for $u_f \ll u_{CE}$ and $f < f_c$:

(i) $d u_{Cf}/dt \approx d u_{CE}/dt$
(ii) $i_{Cf} = C_f \cdot d u_{Cf}/dt$
(iii) $u_f = R_f \cdot i_{Cf}$

Amplitude characteristic

- Simple, cheap
- Passive (low noise)
- Low gain needed (allows high bandwidth)

- Additional IGBT output capacitance
- Voltage rating of $C_f$ is $u_{CE,max}$
- Good linearity of $C_f$ required

[Wang2009]
Temperature measurement: $T_j$

**NTC thermistor:** $R_t = f(T)$
- On-chip integration
  - Distance to IGBT cell
- Typ. resolution: $R_t / T \approx 10\,\text{kΩ} / 200\,\degree\text{C}$

**Sensing pn-diode:** $v_f = f(T, i_f)$
- On-chip integration
  - Arranged directly next to IGBT cell
- Typ. resolution $v_f / T \approx 1.7\,\text{mV} / \degree\text{C}$

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**Powerex IGBT module with integrated NTC thermistor**

[Ichikawa2009]

**Fuji Electric IGBT module with int. on-chip sensing diodes**

[Ichikawa2009]

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**Infineon Datasheet**

[Schmidt2009]

[Ichikawa2009]

[Maxim AN3500, 2005]
**Temperature measurement: $T_j$**

**Gate driving characteristic:**
- $T_j = f(v_{GE,th})$ - resolution: typ. 1 V /100 °C (depending on IGBT)
- $f(t_{d,\text{on}}, t_{d,\text{off}})$ - resolution: typ. < 2ns / °C (depending on IGBT & gate current)

**IGBT output characteristic: $T_j = f(i_C, v_{CE,\text{on}})$**
- Need for and dependency on $i_C$ & $v_{CE,\text{on}}$ measurements
- Evaluation by DSP / FPGA in interpolated 3D-table
- Not usable around the crossover-point between positive and negative temperature coefficient, that is typ.
  - above nominal current for PT IGBTs
  - well below nominal current for NPT IGBTs
Temperature measurement: $T_j$

**Internal gate resistor: $T_j = f(R_{G,int})$**
- Integrated in IGBT module
  - No additional sensor needed
  - Very small distance to IGBT junction
  - Connection to int. gate terminal needed
- Low temperature dependency of $R_{G,int}$
  - Positive temp. coefficient
  - Precise acquisition system needed

**Thermocouple (e.g. Pt100)**
- Glued on the IGBT chip
  - Glue with low thermal impedance needed
  - Location close to IGBT chip center
- Large time constant of thermocouple ($\approx 200 \text{ ms}$)
  - Switching transients of $T_j$ can not be measured
- High accuracy for $T_{j,\text{avg}}$ measurement
- Opening of IGBT module needed

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[Brekel2009]
Literature


