The importance of fully-integrated CMOS: Cost-Effective Integrated DC-DC Converters

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Overview

• **Introduction**
  • DC-DC converters in CMOS
    – Passives
    – Active devices
    – Control

• **Inductive**
  – Converter Topologies
  – Converter Components
  – Control Systems

• **Capacitive**
  – Low Power
  – High Power
  – Exotic Cheap Technologies -> Organic DC-DC Converter
Introduction: Why & What?

- Bridge the Voltage Gap
  - Battery Voltage vs Supply Voltage
  - POL Converter close to load

- Enables
  - Multiple Voltage Domains
  - Voltage Scaling (AVS &DVS)

Need for DC-DC converters as basic building blocks
How DC-DC: SoC vs SiP

- **PowerSiP**
  - Bondwire interconnect to passives
  - # components vs footprint
  - Larger passives
  - Cost does not scale fully with production volume due to PCB and component cost
How DC-DC: SoC vs SiP

• PowerSoC
  – Very low supply impedance
  – Full decentralized power conversion (powergrid on chip)
  – Many voltage domains
  – Scalable
  – Small footprint
  – Cost scales with production volume
A Trend: (r)evolution

• Integration Paradigm
  – In RF-CMOS it brought us portable, low cost and versatile applications
  
  \[\rightarrow \text{A true technology revolution}\]

• Monolithic Integration of power electronics?
  – Even more compact utilities
  – Less energy losses
  – Longer Battery Lifetime (EEF)

\[\rightarrow \text{POWER-CMOS will complete the evolution that started with RF-CMOS}\]
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DC-DC in CMOS: Passives

• Inductors
  – Integration awareness of inductors
  – Bond wire inductor
  – Metal track inductor
Passives in CMOS

Inductors on-chip:

- Skin-effect
- Substrate losses

Round conductors & far from substrate/metal
Passives in CMOS

**Bondwire inductors:**
- Can be combined with C underneath (slots!)
- Low series resistance: ca. 50m$\Omega$/nH @ 100MHz
- Far from substrate
- Good for single-phase & high voltage
- Cannot be scaled well: no multiphase
Passives in CMOS

Metal-track inductors:
- Cannot be combined with C underneath
- High series resistance: ca. 250mΩ/nH @ 1GHz
- Close to substrate
- Good for multiphase & low voltage

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DC-DC in CMOS: Passives

• Capacitors
Passives in CMOS

• Capacitors
  – MIM Capacitors
    • Low Density
    • High Quality
    • Voltage Independent Cap

  – MOS Capacitors
    • High Density
    • Improving with Scaling
    • Voltage Dependent Capacitance
      – Non Linear

  – MOM Capacitors
    • Low Density
    • High Quality
    • High voltage
Passives in CMOS

- Capacitance Density
  - Type dependant
    - MOS-cap: ~10nF/mm²
    - MIM-Cap: ~2nF/mm²
    - MOM-Cap: ~0.5nF/mm²
  - Layout dependant
    - MIM-cap:
      - Poor Modeled
      - Little Layout freedom
    - MOS-cap
      - Poor Modeled
      - Lots of Layout freedom
      - Trade off
        Cap Density <> Resr
DC-DC in CMOS

• Actives
Actives in CMOS

• Only CMOS switches
  – CMOS is good in switching at high frequencies
  – This is necessary since small amount of passives
  – Close Integration with control
  – Adapted waffle layout for low parasitics

• But
  – Small breakdown voltage
    • Standard devices
      – 1-1.2V
      – Fast
    • IO devices
      – 2.5V-3.3V
      – Fast but not as fast as Standard Performance Devices

• Solution:
  – Use Switch Stacking
  or
  Voltage Domain Stacking
Actives in CMOS

• **Switch Stacking**
  - Put multiple switches in series to deal with higher voltages
    - Compensate for increase of $R_{\text{switch}}$
      -> Increase $W$
  - Hard for complex topologies and large # of switches in topology
  - Works perfect for Buck or Boost
    Cfr. Implementations

• **Voltage Domain Stacking**
  - Introduce multiple voltage domains
  - Make sure each switch in single domain
  - Take care of Start Up and transient behavior

\[
\text{Vin} = 2\times \text{Vbreakdown}
\]
Control

• Monolithic Integration enables
  – High Speed Control
  – Compact integrated solution
  – Extreme Multiphase

• But impedes
  – Current Measurement
  – Digital Control
    • 100MHz-1GHz switching frequency
    • DSP does not comply with this
### Intermezzo: Efficiency Enhancement Factor (EEF)

#### DC-DC₁

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{out}$</td>
<td>1 W</td>
</tr>
<tr>
<td>$k_{lin}$</td>
<td>$k_{SW}$</td>
</tr>
<tr>
<td>$\eta_{lin}$</td>
<td>80 %</td>
</tr>
<tr>
<td>$\eta_{SW}$</td>
<td>85 %</td>
</tr>
<tr>
<td>$\Delta \eta$</td>
<td>$\eta_{SW} - \eta_{lin}$ = 5 %</td>
</tr>
</tbody>
</table>

\[
P_{in\_lin} = 1.25 \text{ W} \quad P_{in\_SW} = 1.18 \text{ W}
\]

\[
\Delta P_{in} = P_{in\_lin} - P_{in\_SW} = 0.07 \text{ W}
\]

\[
EEF = \left. \frac{\Delta P_{in}}{P_{in\_lin}} \right|_{k_{lin}=k_{SW}} = 5.6 \%
\]

#### DC-DC₂

<table>
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<tr>
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<td>$P_{out}$</td>
<td>1 W</td>
</tr>
<tr>
<td>$k_{lin}$</td>
<td>$k_{SW}$</td>
</tr>
<tr>
<td>$\eta_{lin}$</td>
<td>50 %</td>
</tr>
<tr>
<td>$\eta_{SW}$</td>
<td>55 %</td>
</tr>
<tr>
<td>$\Delta \eta$</td>
<td>$\eta_{SW} - \eta_{lin}$ = 5 %</td>
</tr>
</tbody>
</table>

\[
P_{in\_lin} = 2 \text{ W} \quad P_{in\_SW} = 1.82 \text{ W}
\]

\[
\Delta P_{in} = P_{in\_lin} - P_{in\_SW} = 0.18 \text{ W}
\]

\[
EEF = \left. \frac{\Delta P_{in}}{P_{in\_lin}} \right|_{k_{lin}=k_{SW}} = 9 \%
\]

\[
EEF = 1 - \left. \frac{\eta_{lin}}{\eta_{SW}} \right|_{k_{lin}=k_{SW}}
\]
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Inductive Converters: Control

**PWM vs PFM:**

**Graphical representation:**
- Two graphs showing waveforms labeled as $U_{tri}$ and $U_{err}$.
- $\Phi_1$ vs $t$ on two separate scales.
- Equations:
  \[ f_{SW_{-}PFM} = f_{SW_{-}PWM} \]
  \[ \Delta U_{out_{-}PFM} = \Delta U_{out_{-}PWM} \]

**Key points:**
- Efficiency comparison $\eta_{SW_{-}PFM}$ vs $\eta_{SW_{-}PWM}$.
- Output power range $P_{out_{\min}}$ to $P_{out_{\max}}$. 

**Discussion:**
- Comparison of Pulse Width Modulation (PWM) and Pulse Frequency Modulation (PFM) control strategies in inductive converters.
- Graphs illustrate the waveforms and their corresponding parameters, highlighting the differences and similarities in their operation.
- Formulas provide a quantitative basis for understanding the performance differences.

**Key terms:**
- PWM: Pulse Width Modulation
- PFM: Pulse Frequency Modulation
- $U_{tri}$: Triangular wave
- $U_{err}$: Error signal
- $\Phi_1$: Magnetic flux
- $t_{on}$, $t_{off}$: On-time and Off-time intervals
- $f$: Frequency
- $\Delta U$: Voltage change
- $\eta$: Efficiency
Inductive Converters: Control

Constant On/Off-Time (COOT):

- Higher eff. vs PWM
- No current sensing
- Mostly digital
- Fast transient response
- Fixed voltage ratio
- Load regulation dependant on the ripple
Inductive Converters: Control

Semi-Constant On/Off-Time (SCOOT):

Low Load

DC–DC$_1$  DC–DC$_2$  DC–DC$_3$  DC–DC$_4$

High Load
Inductive Converters

PWM example:

- Input voltage range: 1.6 V-2 V
- Output voltage range: 2.5 V-4 V
- Output power range: 25 mW-150 mW
- Maximum power efficiency @ $U_{out}$ = 3.3 V: 63%
- Maximum output ripple: 200 mV
- Maximum load variation: 9 MHz
- Switching frequency: 100 MHz

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Inductive Converters

COOT example 1:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage range</td>
<td>2 V-2.6 V</td>
</tr>
<tr>
<td>Output voltage range</td>
<td>1.1 V-1.5 V</td>
</tr>
<tr>
<td>Output power range</td>
<td>0 mW-180 mW</td>
</tr>
<tr>
<td>Switching frequency range</td>
<td>30 Hz-300 MHz</td>
</tr>
<tr>
<td>Power efficiency @ $U_{in} = 2.6$ V and $U_{out} = 1.2$ V</td>
<td>52 %</td>
</tr>
<tr>
<td>Efficiency Enhancement Factor</td>
<td>12 %</td>
</tr>
<tr>
<td>Maximum output ripple @ $P_{out} = 0$ mW</td>
<td>110 mV</td>
</tr>
<tr>
<td>Minimum output ripple @ $P_{out} = 180$ mW</td>
<td>60 mV</td>
</tr>
<tr>
<td>Load regulation $\delta u_{out}/\delta i_{out}$</td>
<td>$-0.51 \Omega$</td>
</tr>
<tr>
<td>Line regulation $\delta u_{out}/\delta u_{in}$</td>
<td>$-0.083$</td>
</tr>
</tbody>
</table>

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Inductive Converters

COOT example 2:

Input voltage range: 3 V - 4 V
Output voltage range: 1.5 V - 2.1 V
Output power range: 0 mW - 300 mW
Switching frequency range: 20 Hz - 140 MHz
Power efficiency @ $U_{in} = 3.6$ V and $U_{out} = 1.8$ V: 65%
Efficiency Enhancement Factor: 23%
Maximum output ripple @ $P_{out} = 0$ mW: 160 mV
Minimum output ripple @ $P_{out} = 300$ mW: 50 mV
Load regulation $\delta u_{out}/\delta i_{out}$: $-0.3 \Omega$
Line regulation $\delta u_{out}/\delta u_{in}$: 0.02

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Inductive Converters

SCOOT example:

- Output Power 800mW
- Efficiency Enhancement Factor +21%
- Power density 213mW/mm²

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Capacitive Converters

• Use nothing but
  – Solid state switches
  – Capacitors
    • Density and Quality increase by scaling

• 2-Phase operation
  – Topology corresponds with VCR
  – VCR:1/2 -> 1 cap || VCR:4/5 -> 3 caps
Capacitive Converters

- Up-Conversion
  - The voltage Doubler design
    - Multiphase – 16 phase
    - Analog Loop
    - Ripple < 0.5%
    - Efficiency up to 82%
Capacitive Converters

- **Down Conversion**
  - Point Of Load Converter
    - 3.9V-3.05V Input
    - 1.52-1.3V Output
    - 150mW Max Pout
    - 77% Efficiency
  - Multiphase Hysteretic Control

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Capacitive Converters

- High Voltage Up-Conversion
  - The 10-stage High Voltage Dickson
  - 300mW
  - 70V output – 12V Input
  - High Voltage Technology
  - Efficiency 86% per stage

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Published ECCE 2009 – San Jose
Capacitive Converters

- Organic DC-DC
  - No CMOS but cheap
  - ‘Plastic’-technology
  - Only PMOS
  - Cap-type Converter
    - 3-stage Dickson
  - 18V Input
  - 60V Output

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Overview
Conclusion

• POWER-CMOS is the logic evolution of RF-CMOS
  – Continue the development of high performing fully-integrated DC-DC converters to set a new milestone in integrated circuits

• Cost-effective Bulk CMOS is able to deliver attractive DC-DC converter specifications
  – Go multiphase
  – Go digital control

• Inductive converters: main issue is inductor quality (and ESR)
• Capacitive converters: quest for higher densities (attention to ESR)
• Use EEF as benchmark to validate performance compared to linear regulator
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- **More info**