

# On-chip DCDC switched mode converters

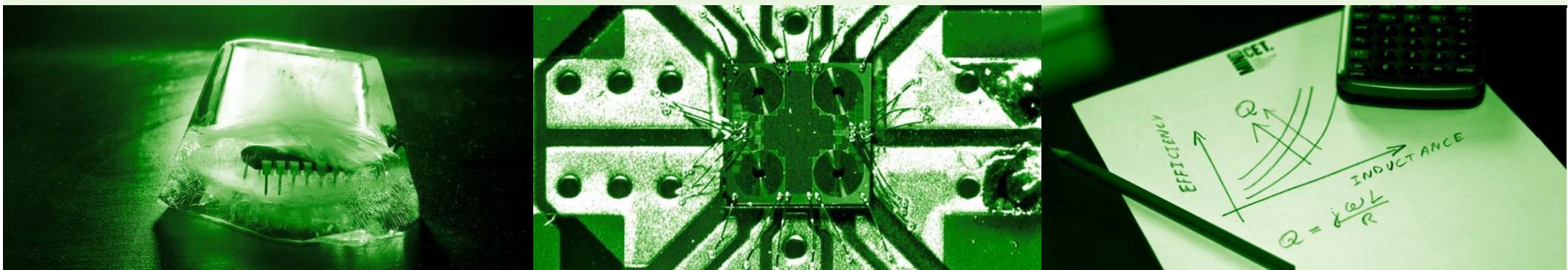


The Power of Efficiency.

The Power of Integration.

The Power of Competence.

Feb 2012



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# Contents



- **Introduction**
- **DC-DC Conversion**
- **Converter Components**
- **Control Strategies & Systems**
- **Implementation Examples**
- **Conclusions**

# Introduction

## Focus & Mission



### Mission

The leading center of **competence** in highly-**efficient** and highly-**integrated** Power Management IC and discrete design.

### Founded

Oct 2011, spin-off from KU Leuven, ESAT-MICAS.

### Size and experience

5 experienced mixed-signal electronic engineers (4 PhDs), combined > 50 years of design experience + additional resources available.

# Introduction

## The founders



### Mike Wens

2000-2004: Industrieel ingenieur KDG (Thesis DC-DC Dr. M. Van Paemel)

2004-2006: Burgerlijk Elektrotechnisch Ingenieur KUL (Thesis DC-DC Prof. M. Steyaert)

2006-2010: PhD "Fully-Integrated Inductive DC-DC Converters" (Prof. M. Steyaert)

2010-2011: IWT OZM type-1 mandate



### Jef Thoné

1996-1999: Graduaat Automechanica (Thesis µC Dr. D. Weyns)

1999-2002: Industrieel ingenieur KDG (Thesis µC (TI) G. Van Landeghem)

2002-2006: Project Manager - Analog designer Melexis Tessenderlo

2006-2011: PhD "Telemetry for Capsule Endoscopy" (Prof. R. Puers)



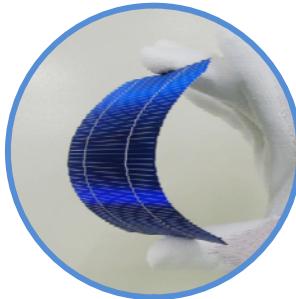
# Introduction

Match source to load for maximal efficiency.



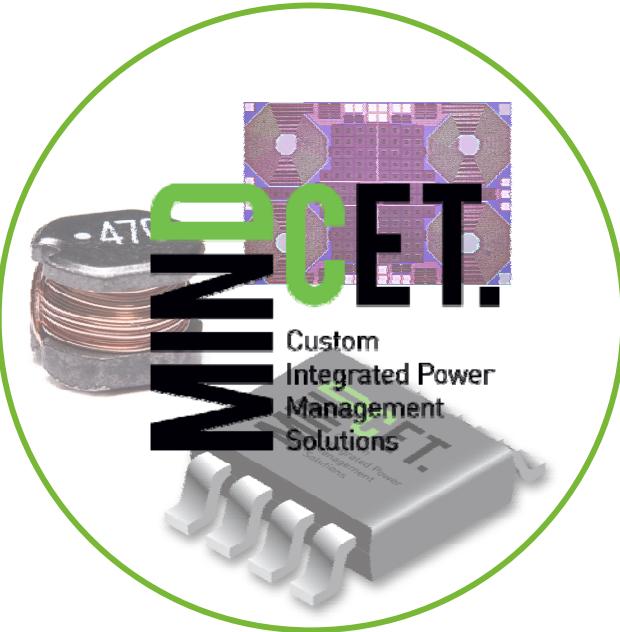
**Source →**

Battery, solar cell, fuel cell, ...



**Power Management**

Discrete, fully & highly integrated



**→ Load**

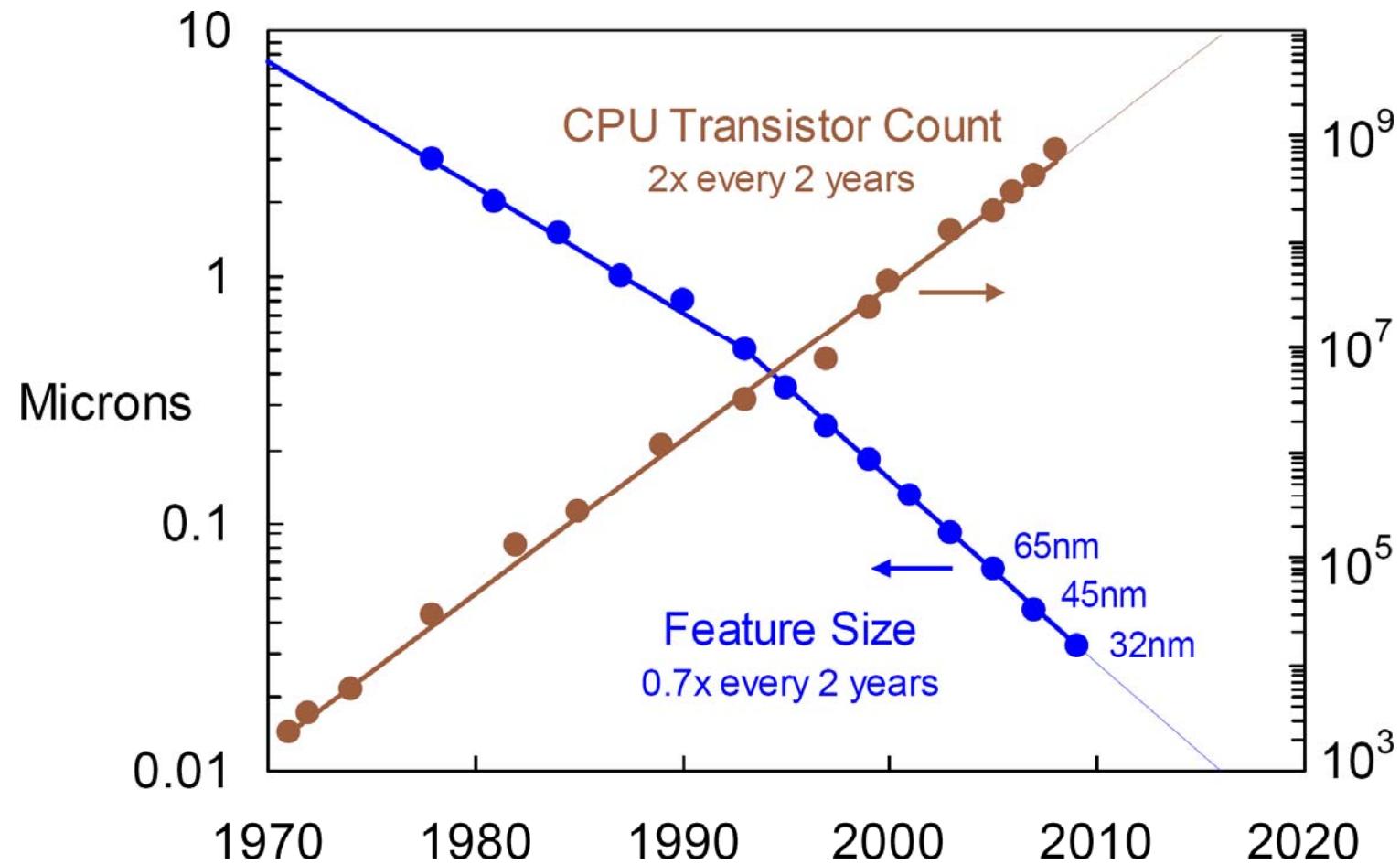
Implants, LED lighting, mobile,...



**BRIDGING THE VOLTAGE GAP**

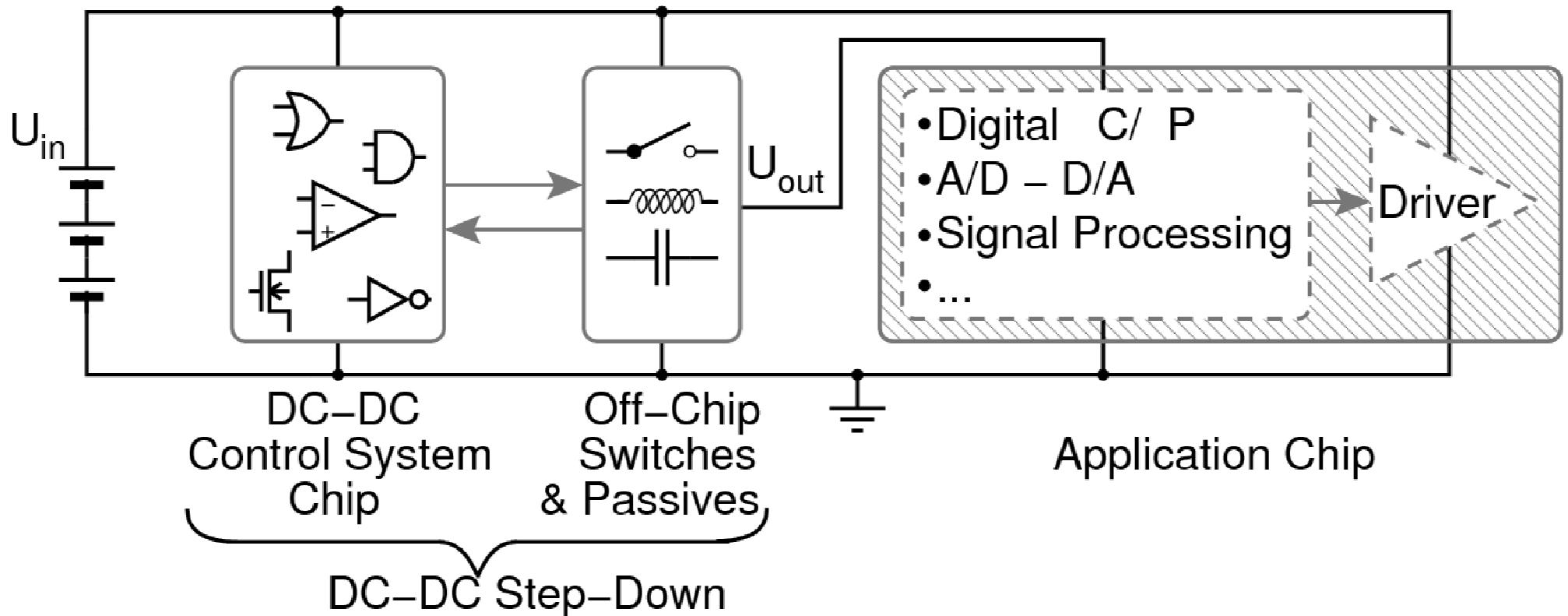
# Introduction

## CMOS Scaling



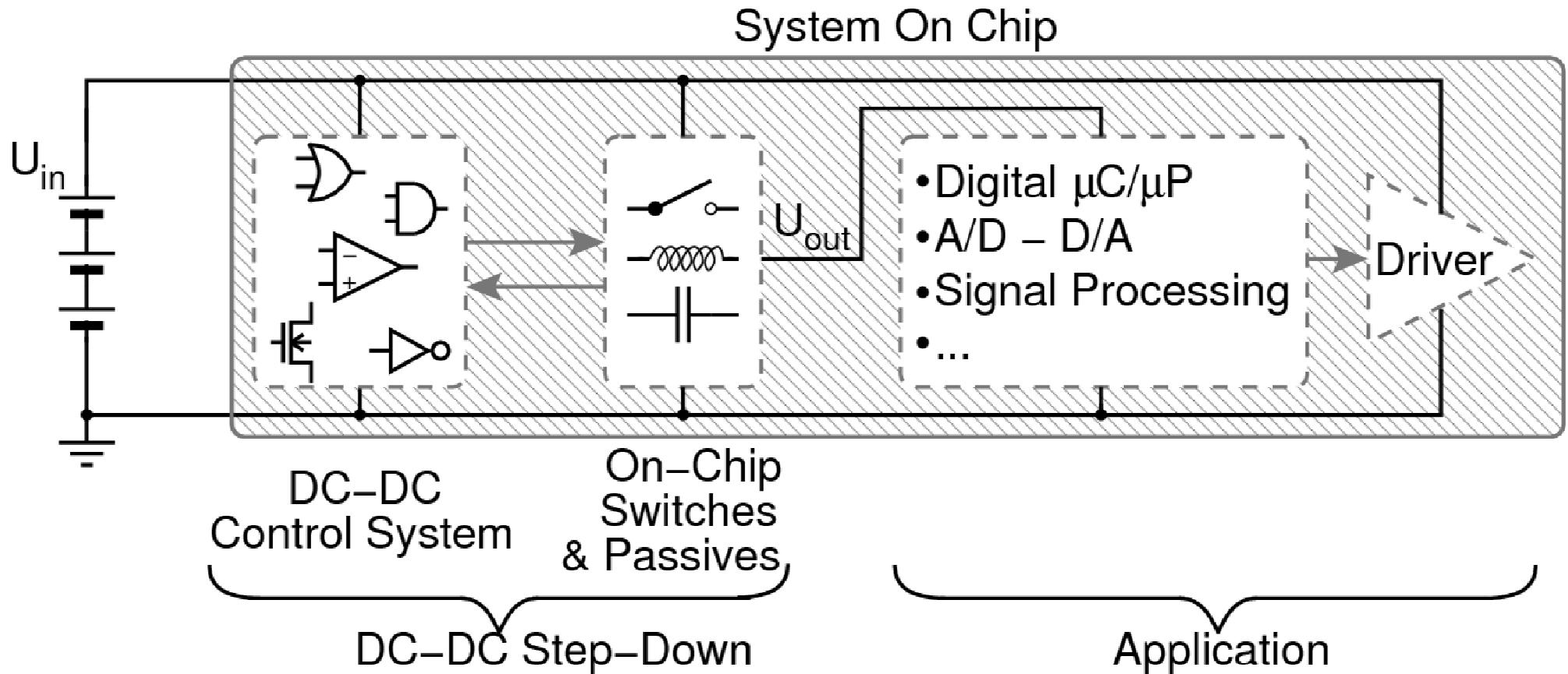
# Introduction

## Bridging the voltage gap: OFF-CHIP



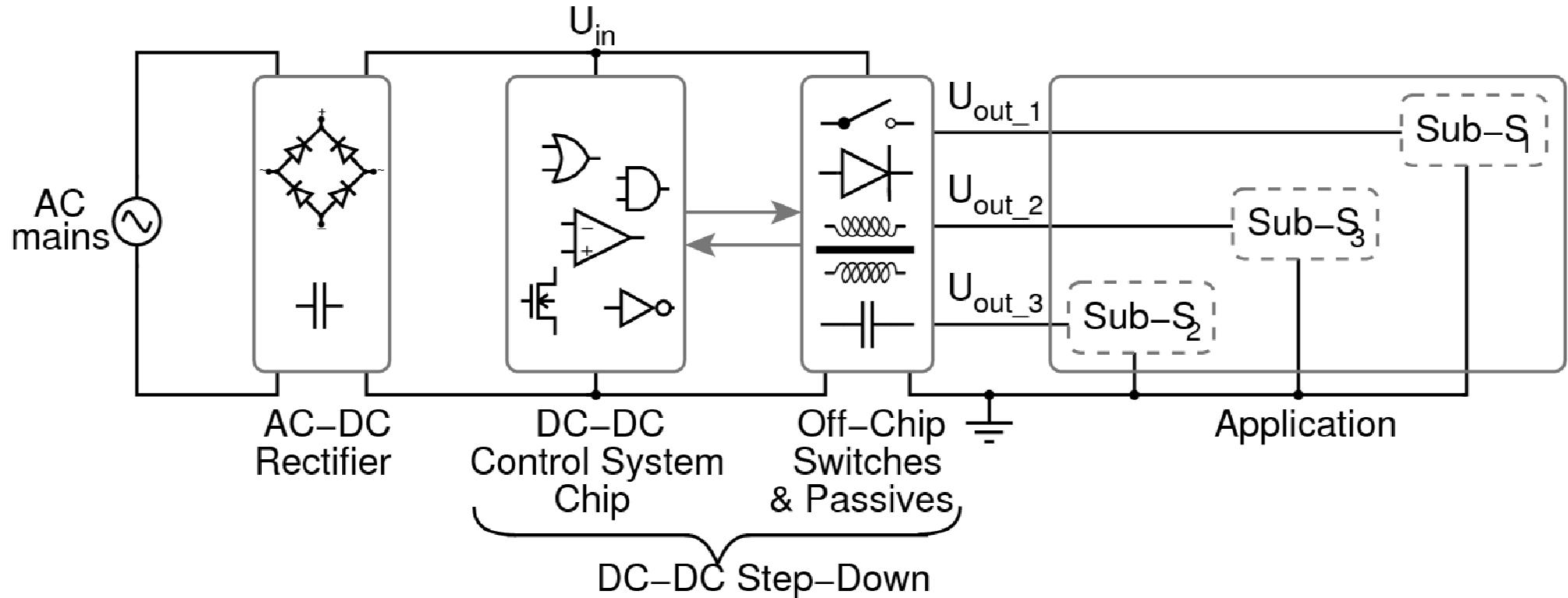
# Introduction

## Bridging the voltage gap: ON-CHIP



# Introduction

## Bridging the voltage gap: AC-DC = Runaway Train?



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# Contents



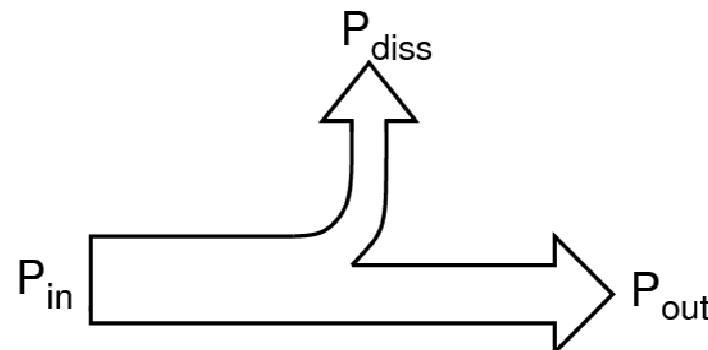
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- **Converter Components**
- **Control Strategies & Systems**
- **Implementation Examples**
- **Conclusions**

# DC-DC conversion

## Principle



$$\eta = \frac{I_{out}U_{out}}{I_{in}U_{in}} = \frac{P_{in} - P_{diss}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{diss}} = \frac{P_{out}}{P_{in}}$$

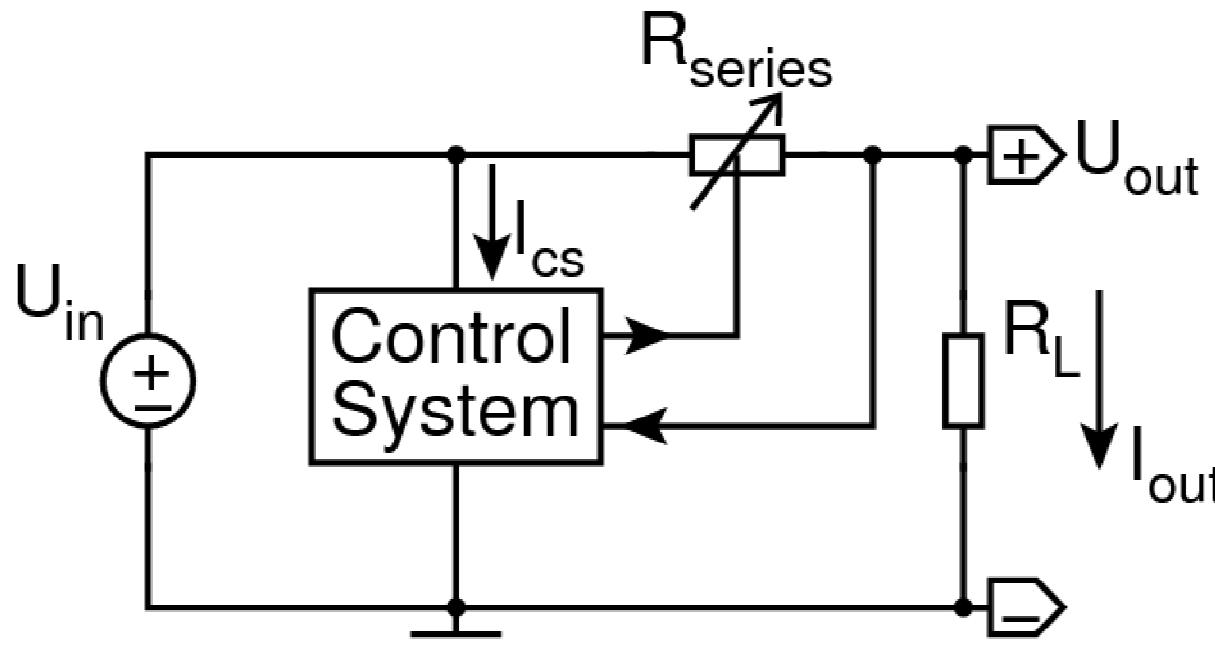


$$k = \frac{U_{out}}{U_{in}}$$

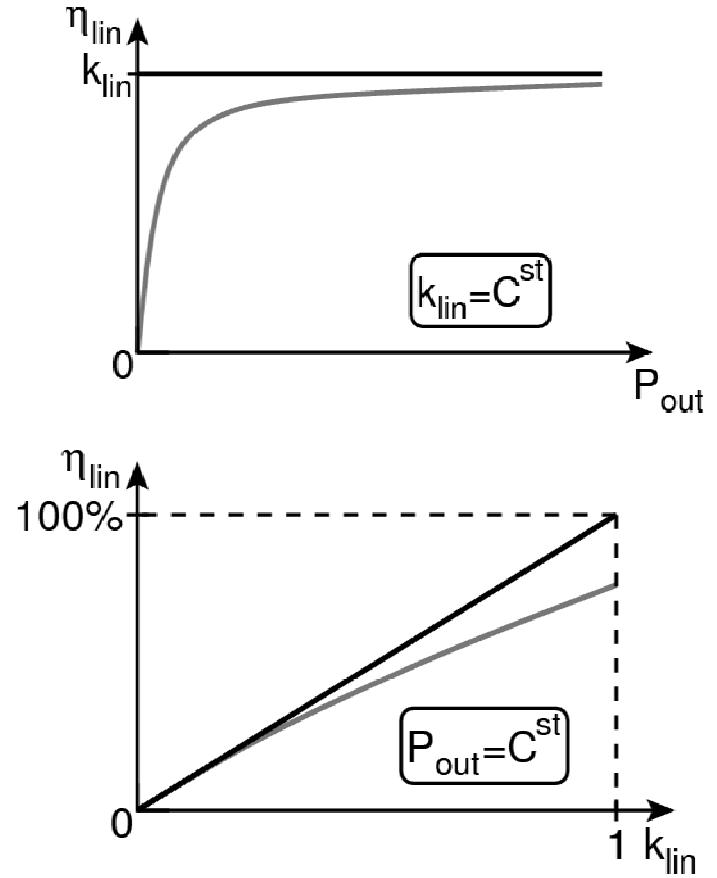
# DC-DC conversion

Linear voltage converters

## Series converter



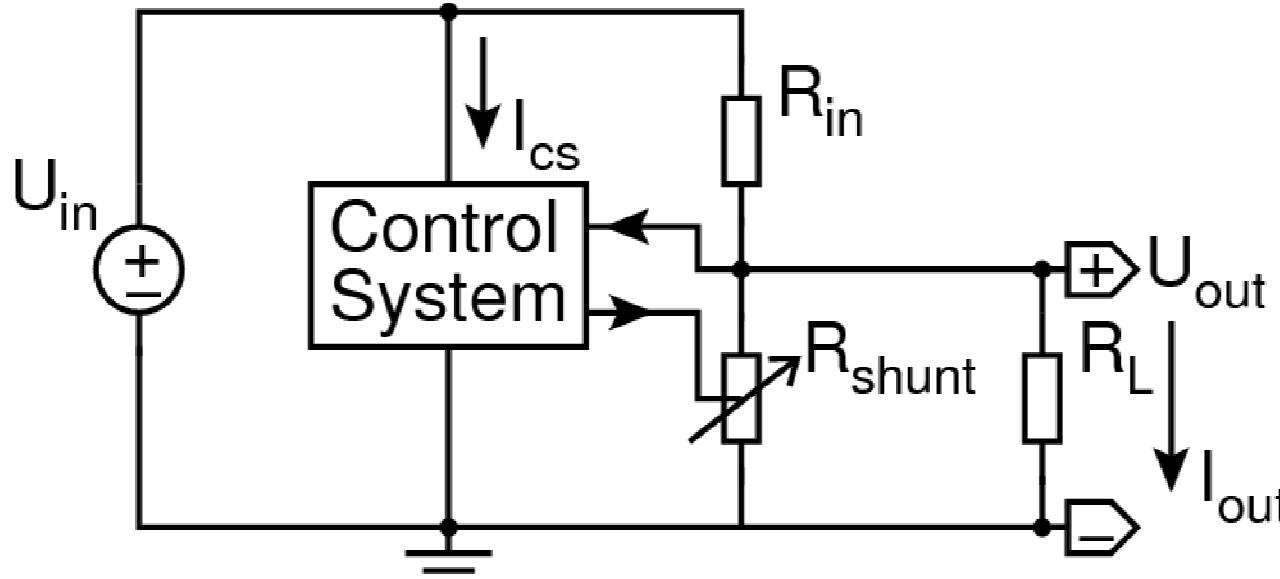
→ Dissipate excess power



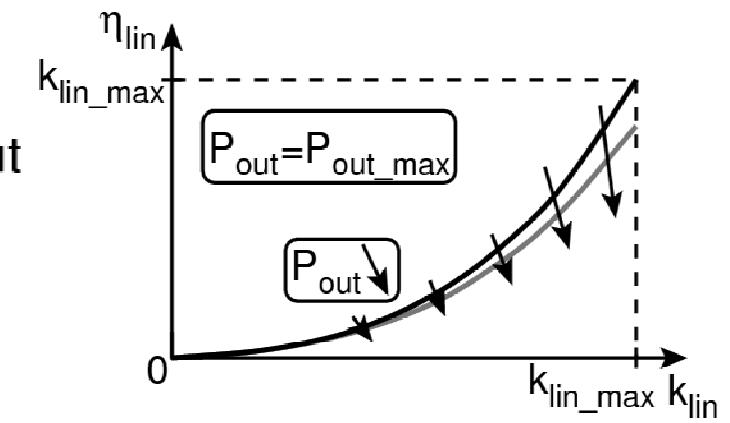
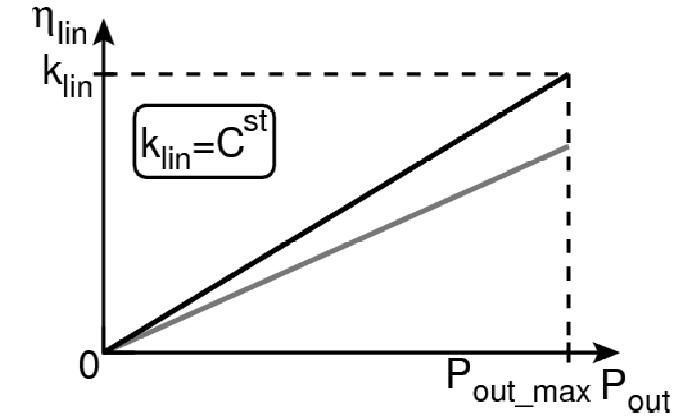
# DC-DC conversion

Linear voltage converters

## Shunt converter



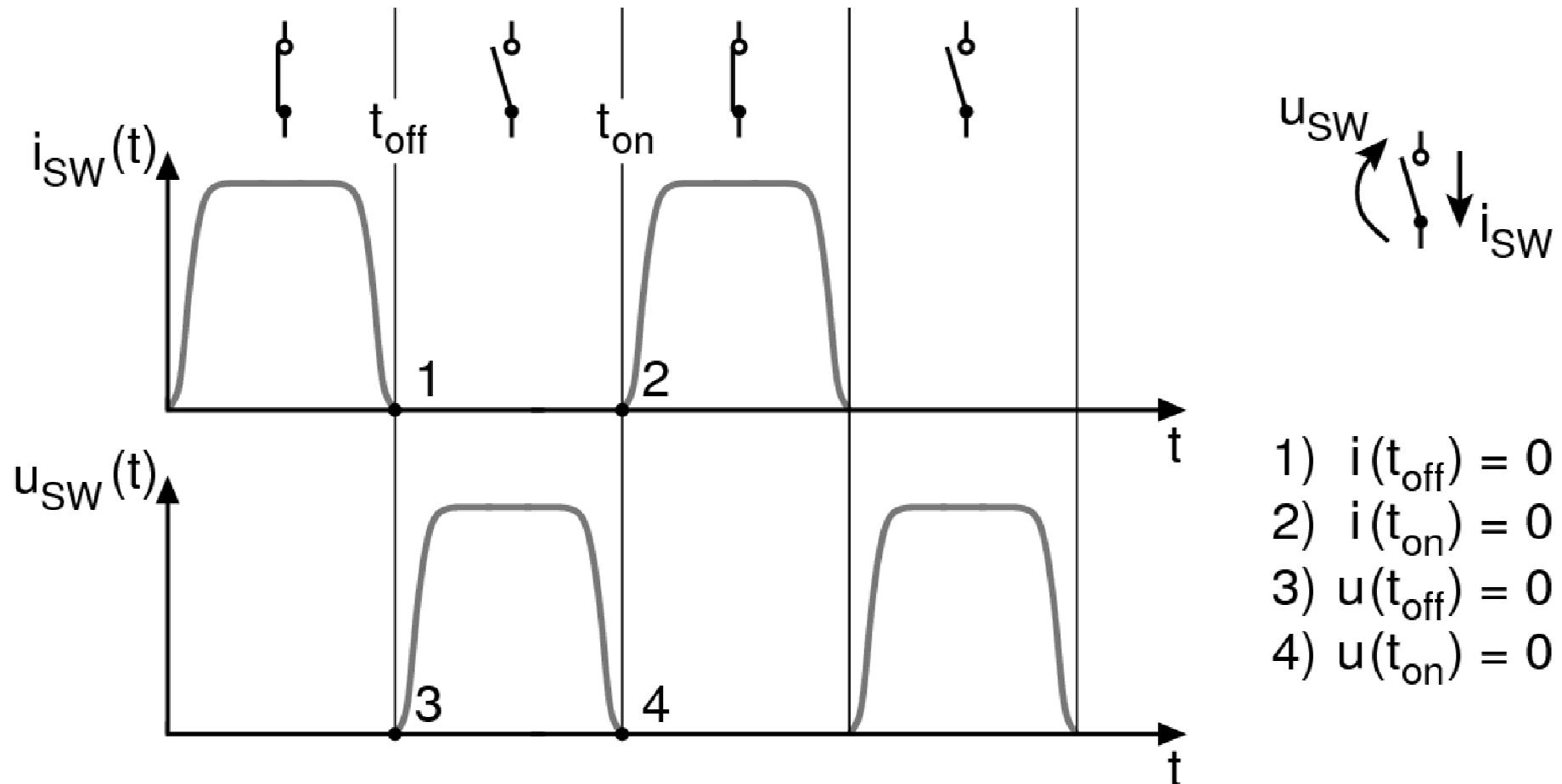
→ Dissipate excess power



# DC-DC conversion

Switched-mode voltage converters

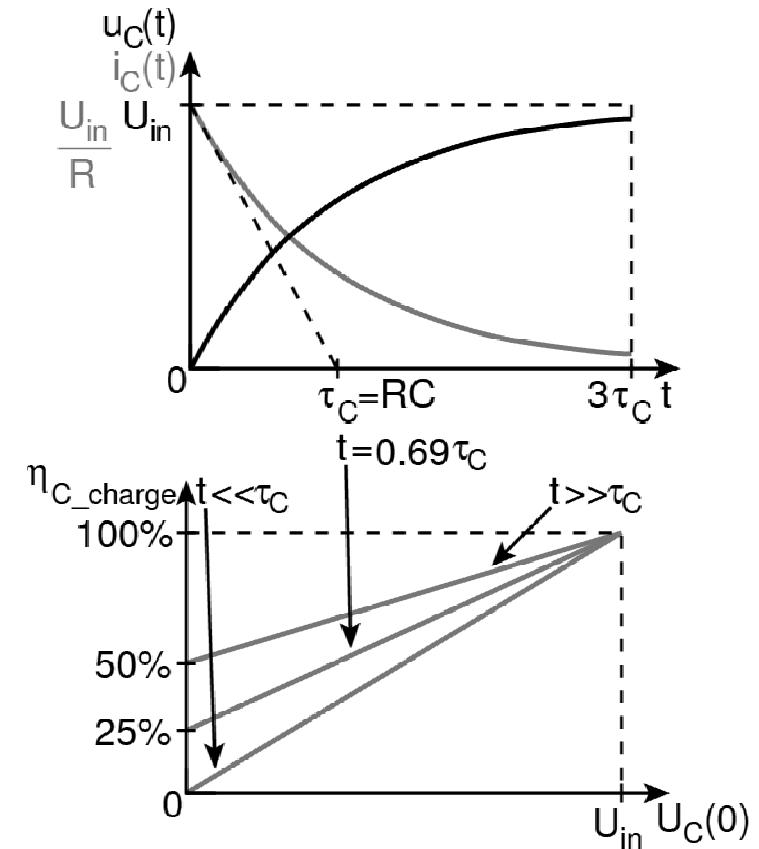
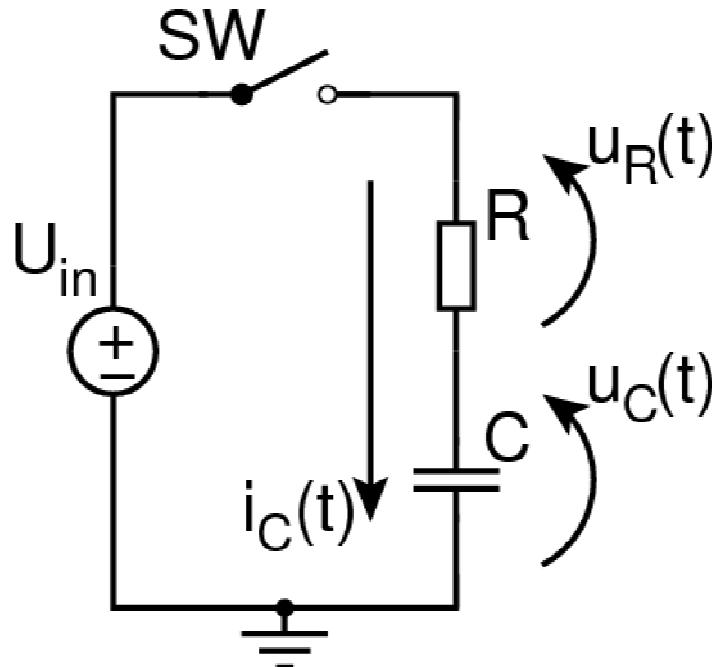
## Principle



# DC-DC conversion

Switched-mode voltage converters

## Capacitive converters: Charging capacitors

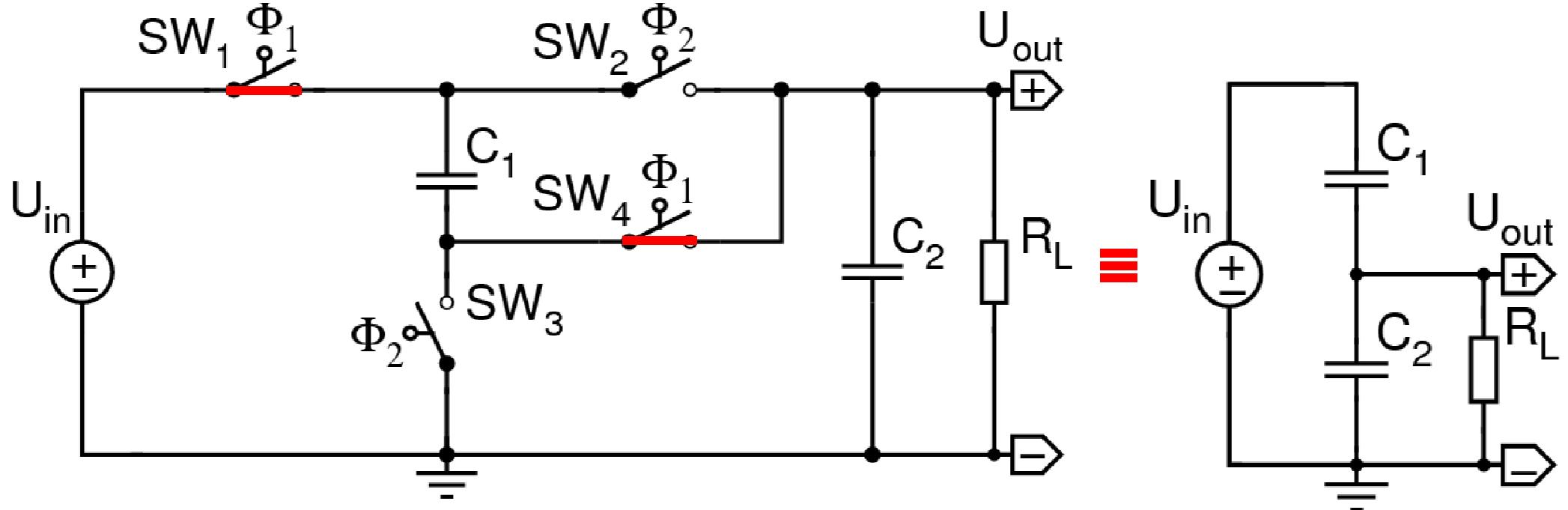


→ Losses independant of  $R$

# DC-DC conversion

Switched-mode voltage converters

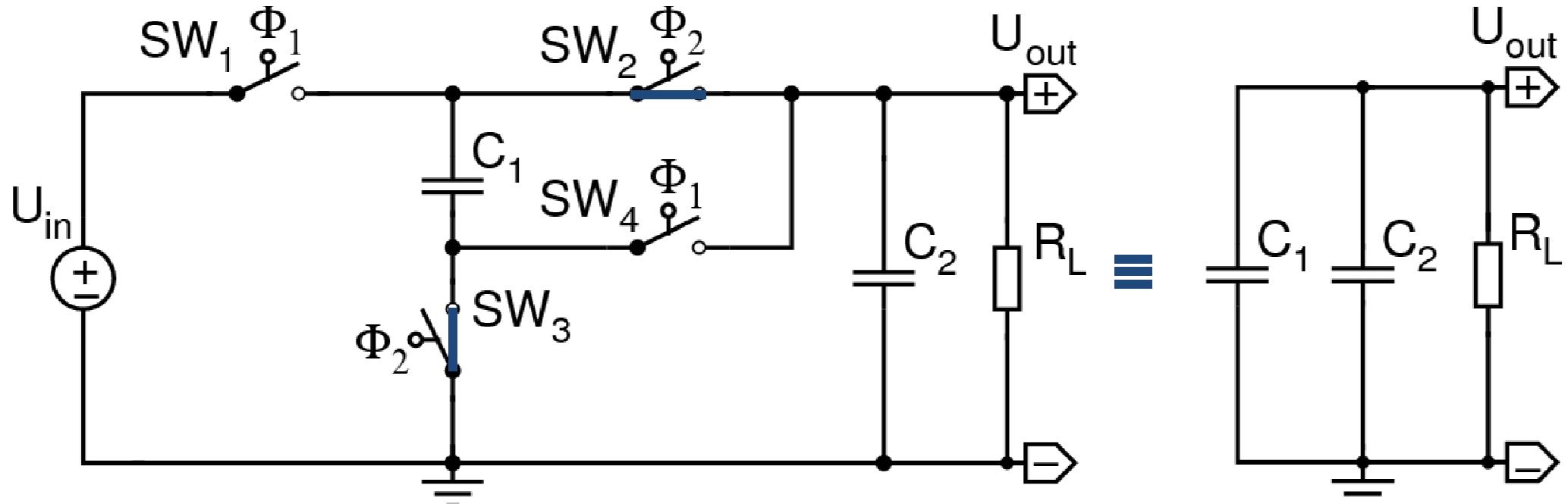
## Capacitive Step-Down Converters 1/2: Charge Phase



# DC-DC conversion

Switched-mode voltage converters

## Capacitive Step-Down Converters 1/2: Discharge Phase

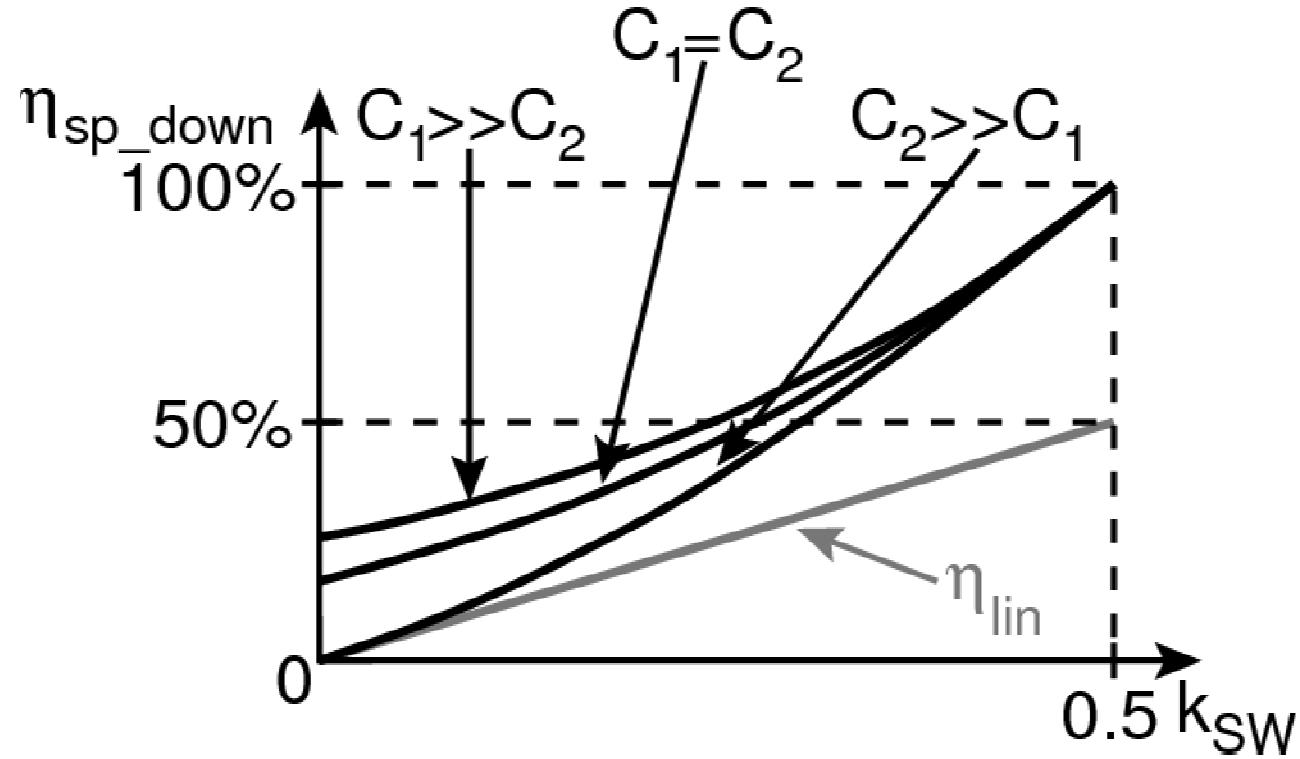


→ Works well for constant voltage conversion ratio

# DC-DC conversion

Switched-mode voltage converters

## Capacitive Step-Down Converters 1/2

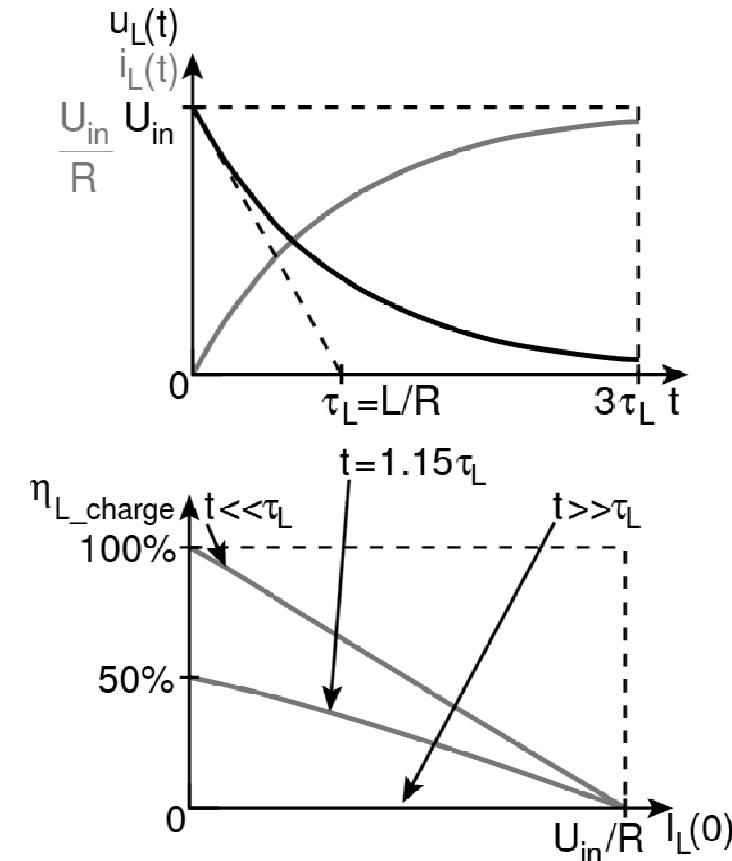
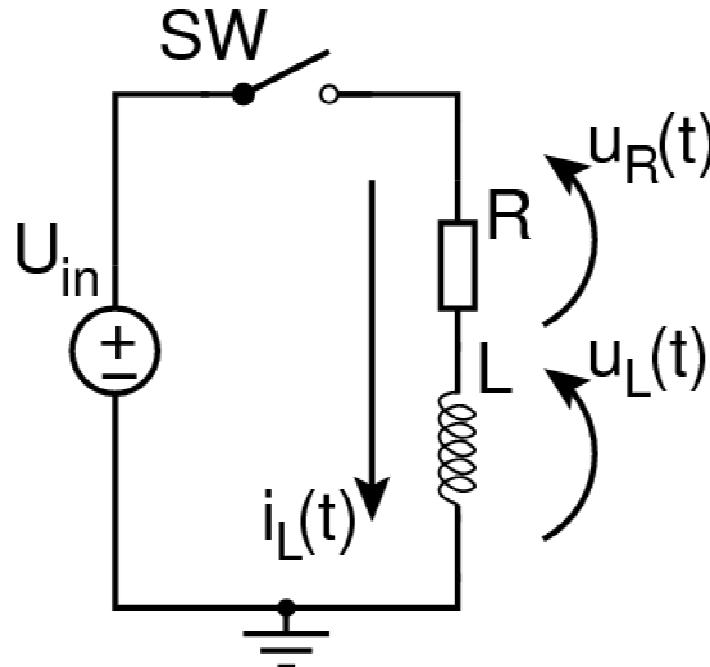


→ Works well for constant voltage conversion ratio

# DC-DC conversion

Switched-mode voltage converters

## Inductive converters: Charging Inductors

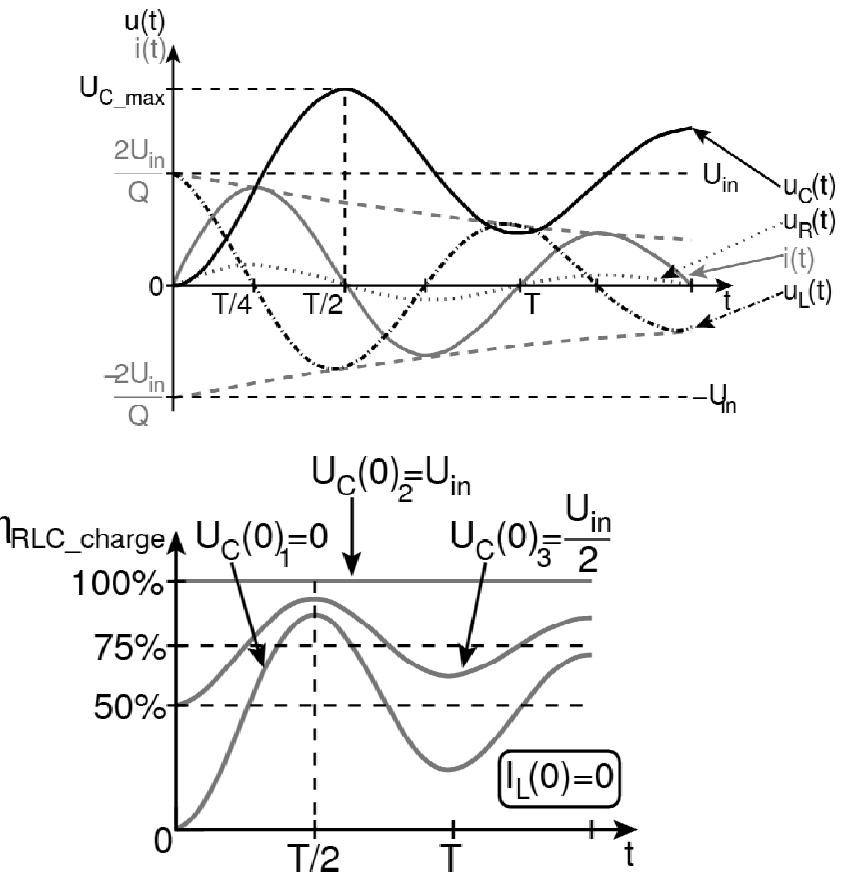
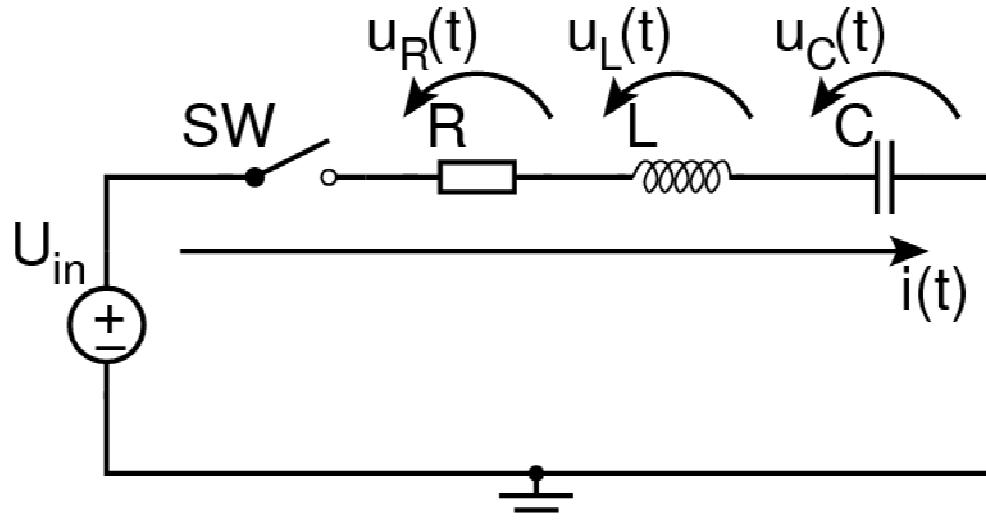


→ Losses dependant of  $R$

# DC-DC conversion

Switched-mode voltage converters

## Inductive converters: Charging Capacitors & Inductors

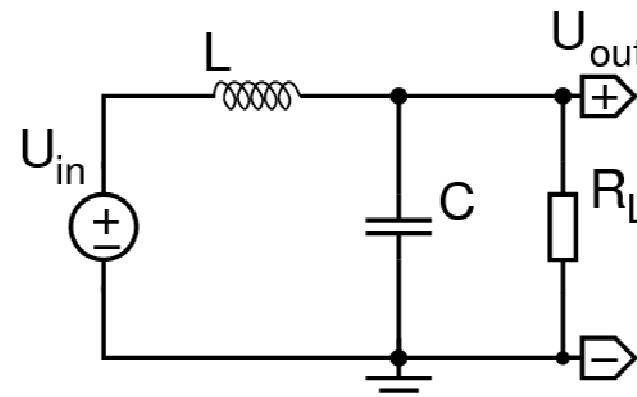
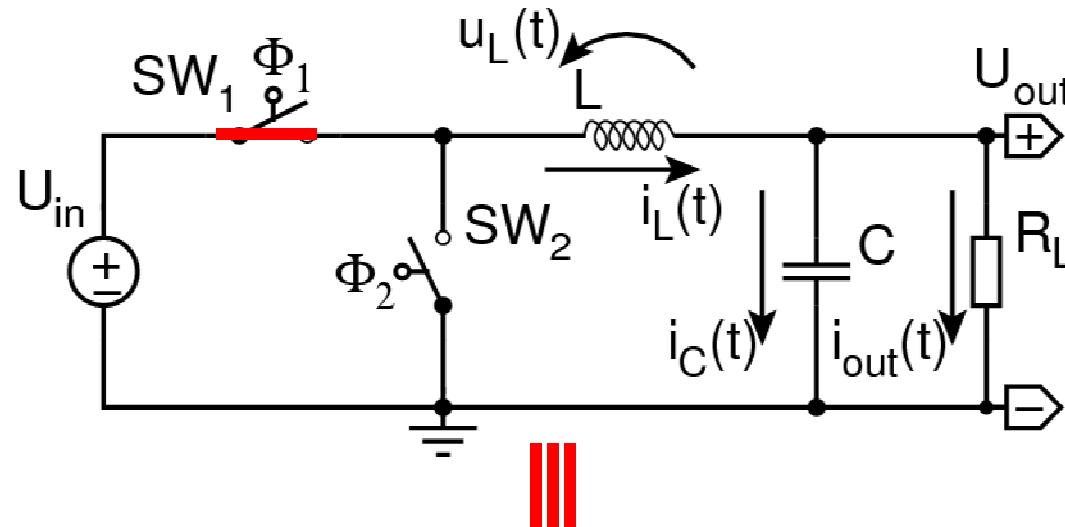


→ Losses dependant of R

# DC-DC conversion

Switched-mode voltage converters

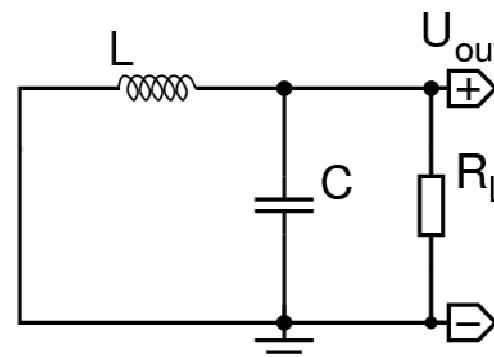
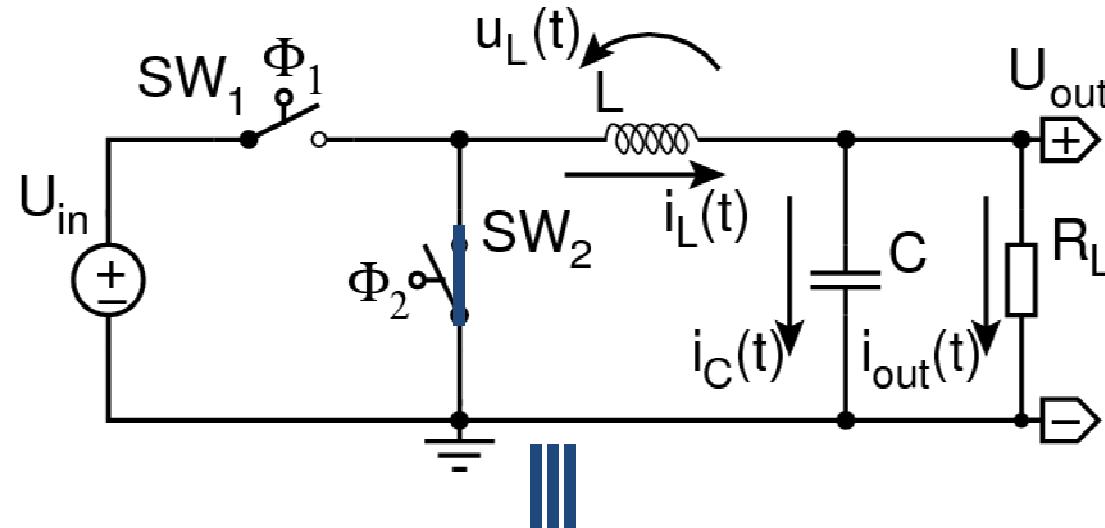
## Inductive Step-Down converter: **Charge Phase**



# DC-DC conversion

Switched-mode voltage converters

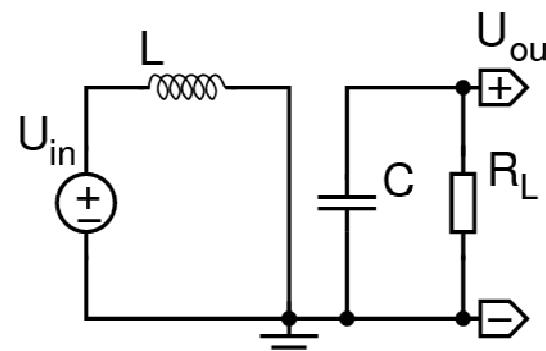
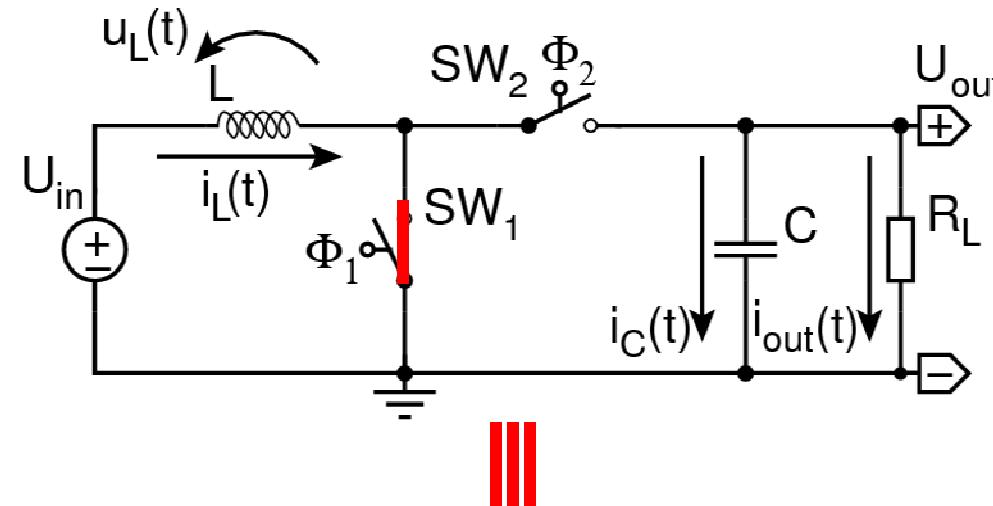
## Inductive Step-Down converter: Discharge Phase



# DC-DC conversion

Switched-mode voltage converters

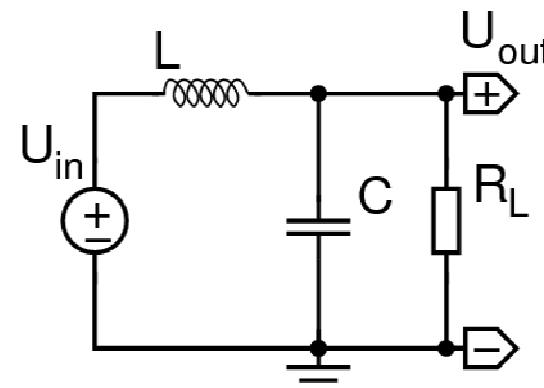
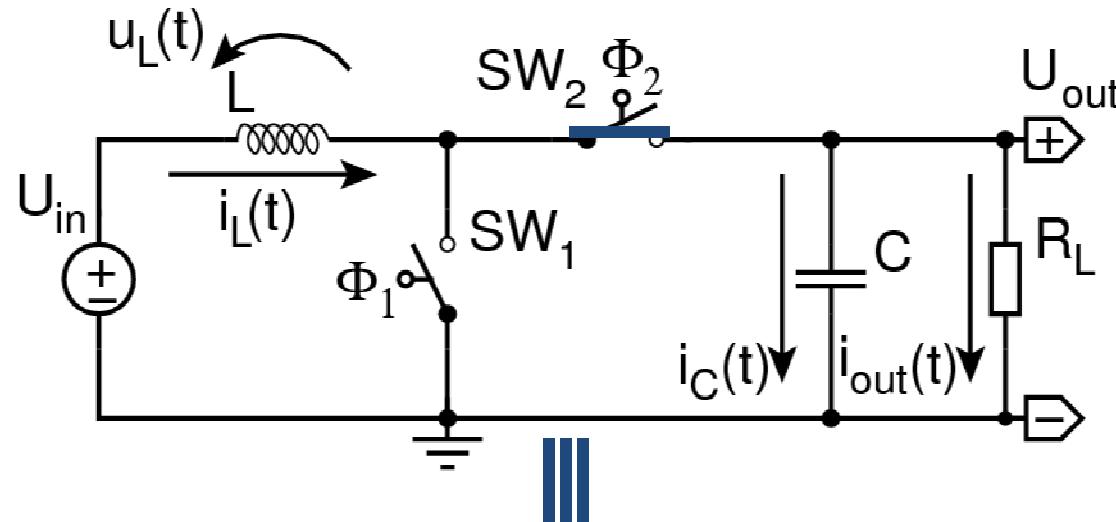
## Inductive Step-Up converter: Charge Phase



# DC-DC conversion

Switched-mode voltage converters

## Inductive Step-Up converter: Discharge Phase

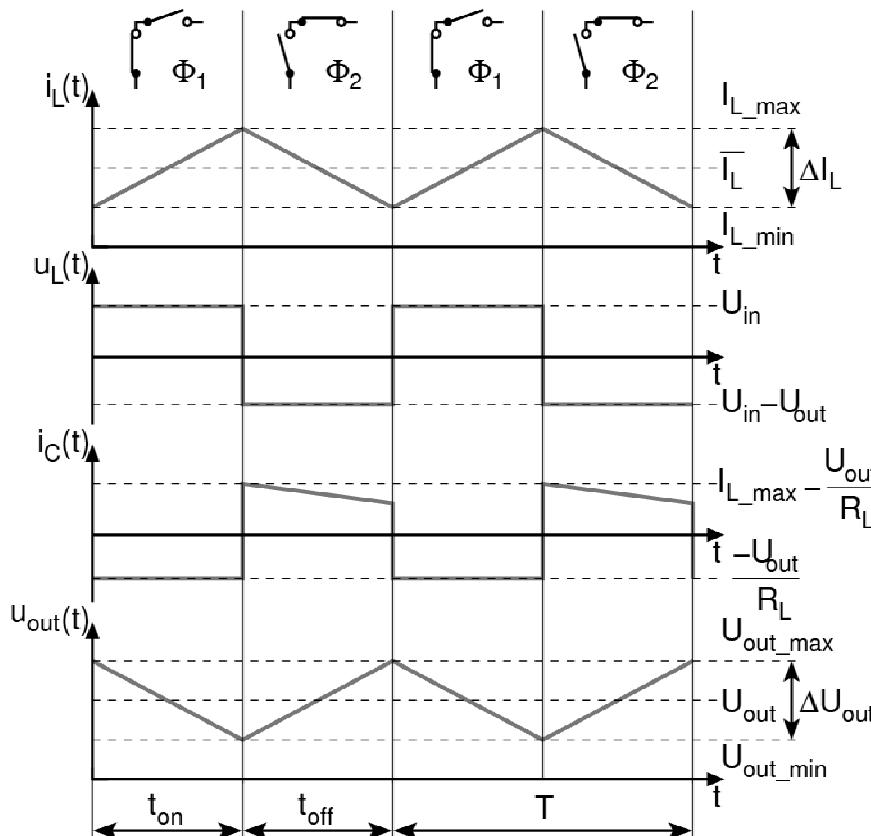


# DC-DC conversion

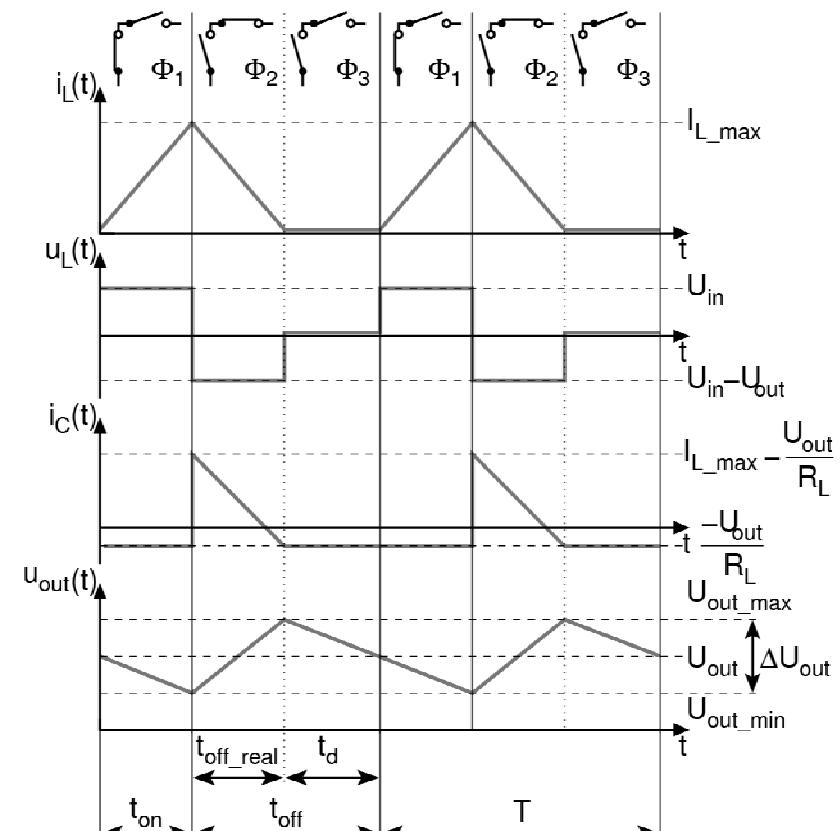
Switched-mode voltage converters

## Inductive converters: Continuous vs Discontinuous mode

### Continuous



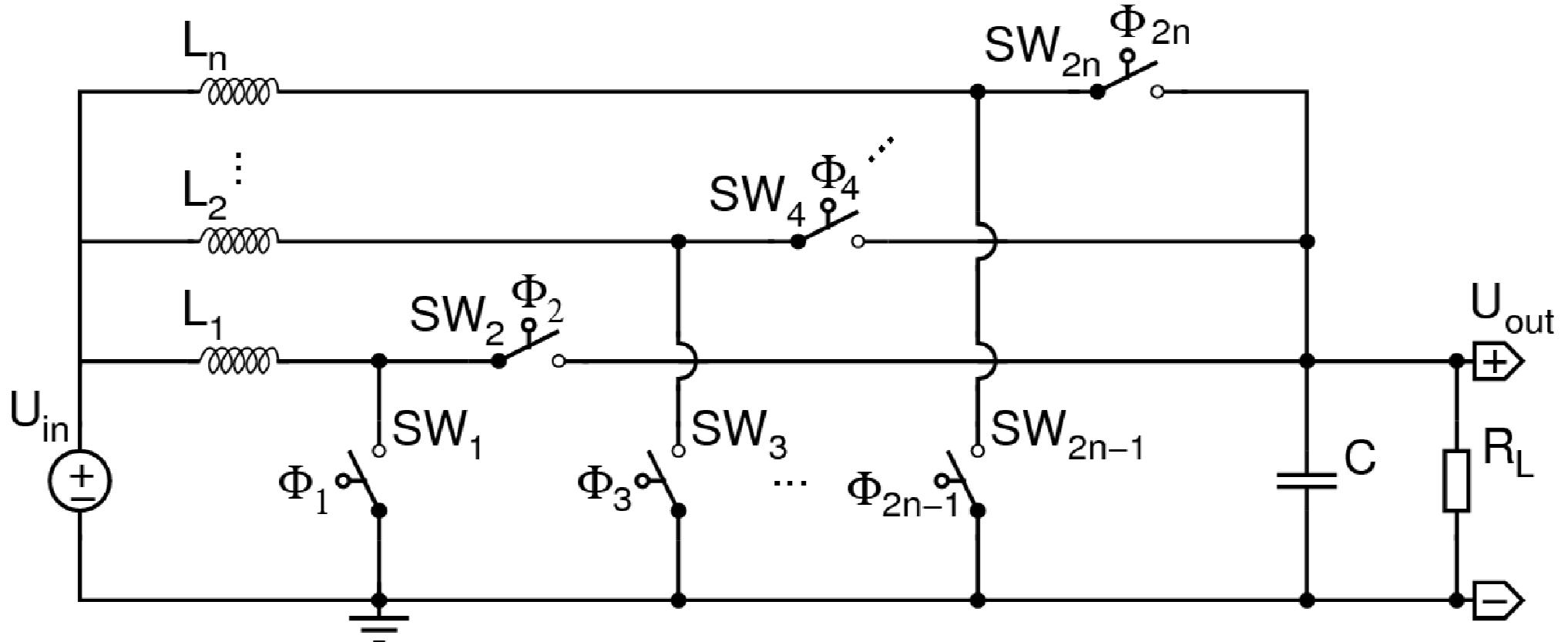
### Discontinuous



# DC-DC conversion

Switched-mode voltage converters

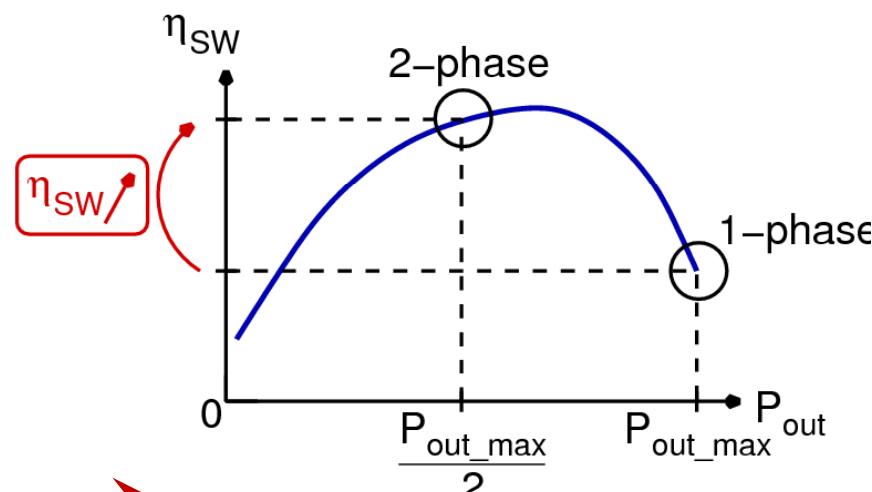
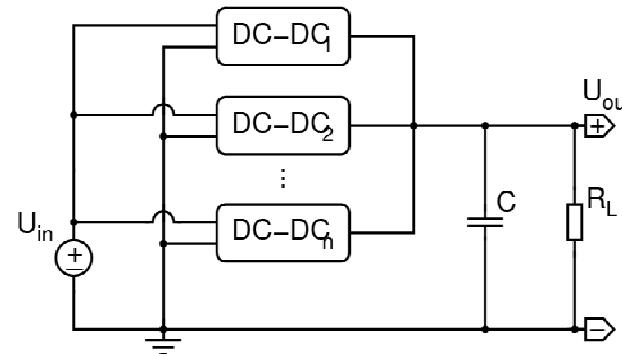
## Inductive converters variations: Multiphase



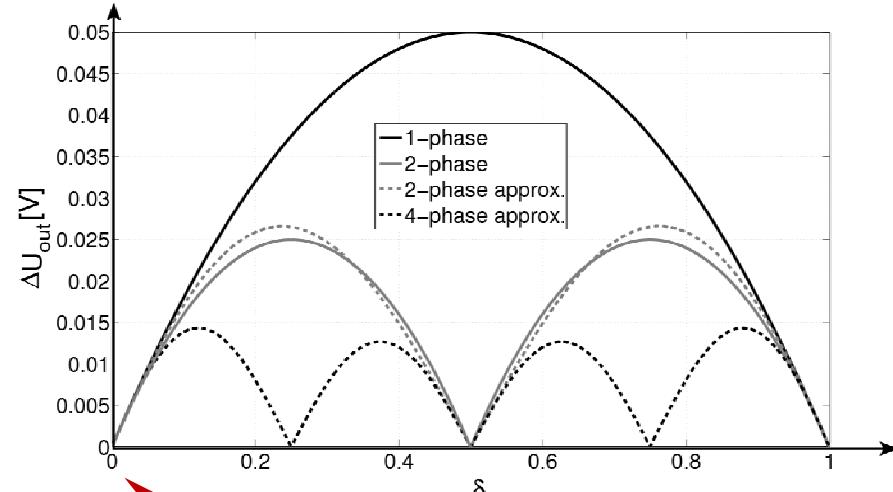
# DC-DC conversion

Switched-mode voltage converters

## Inductive converters variations: Multiphase



More area



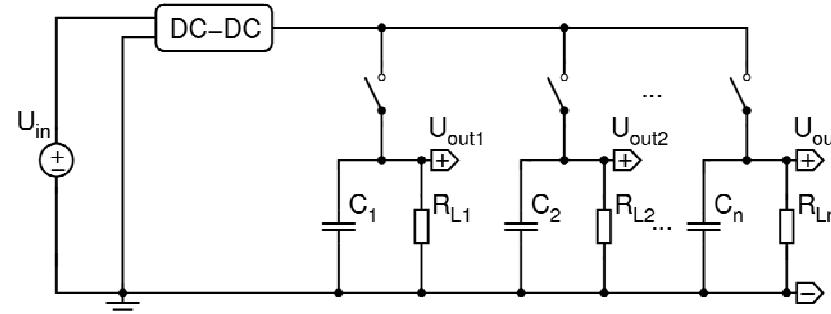
Best for PWM

# DC-DC conversion

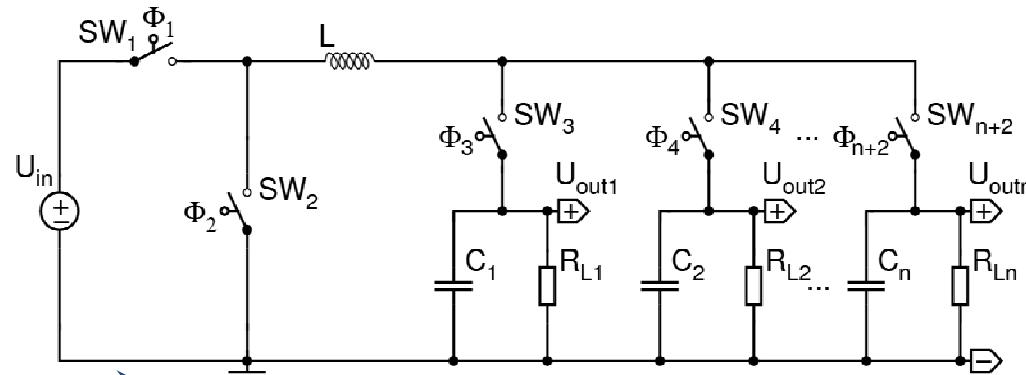
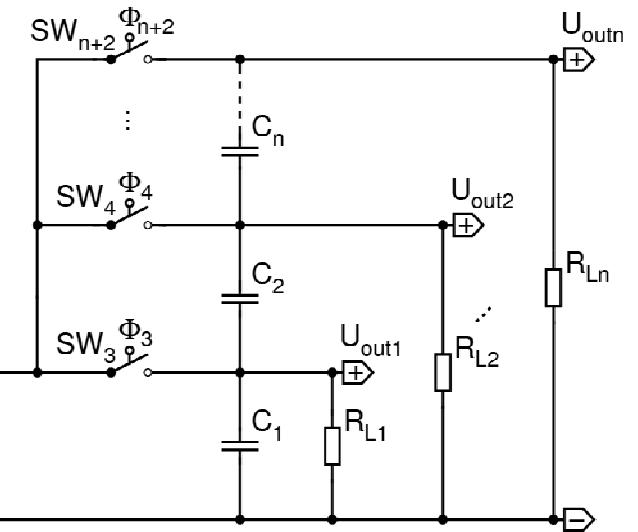
Switched-mode voltage converters

## Inductive converters variations: Multiple-Output

**SIMO**



**SMOC**



**Less Cross Regulation**

**Less Area**

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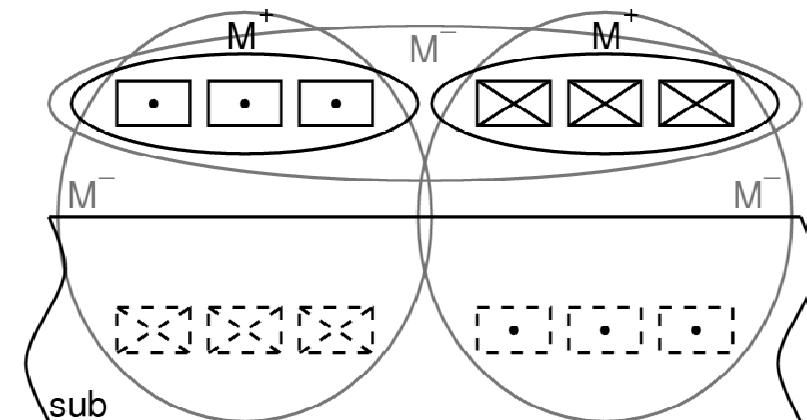
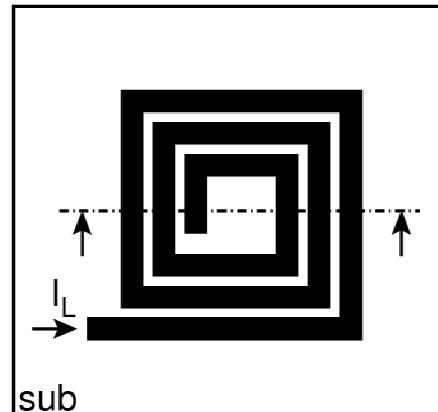
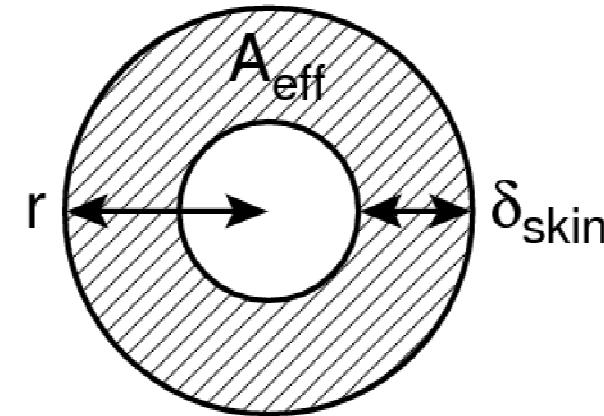
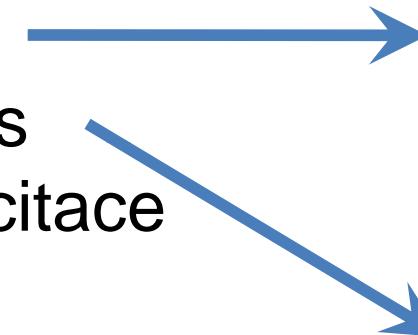
- Introduction
- DC-DC Conversion
- Converter Components
- Control Strategies & Systems
- Implementation Examples
- Conclusions

# Converter components

## Inductors

### Loss effects

- Skin-effect
- Substrate losses
- Substrate capacitance



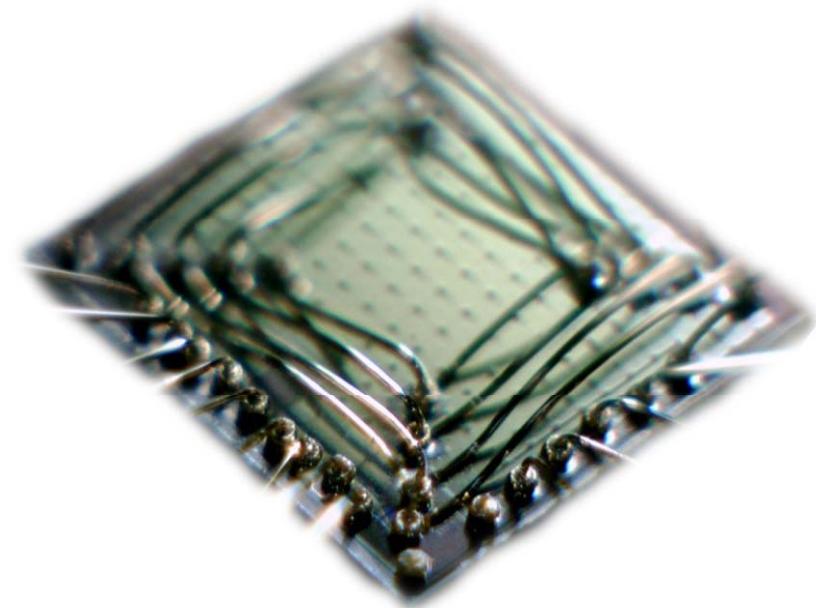
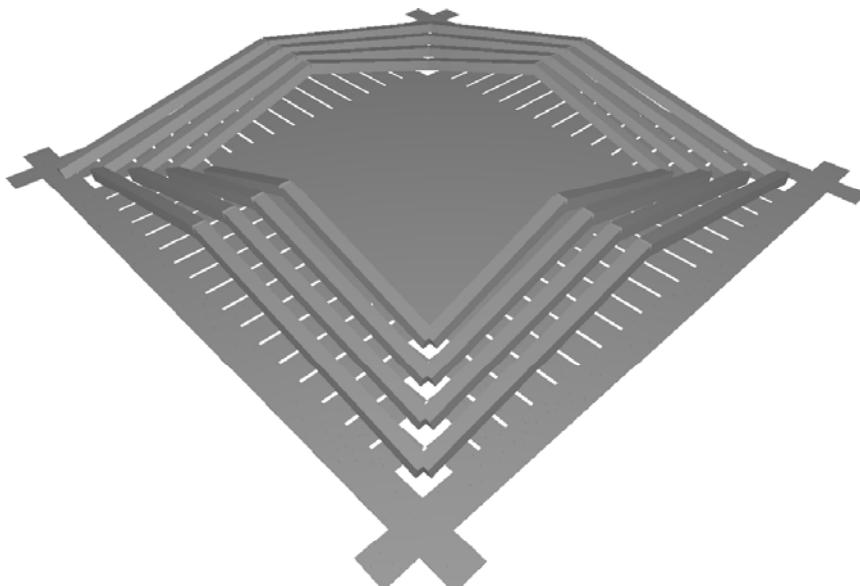
→ **Round conductors & far from substrate/metal**

# Converter components

## Inductors

### Bondwire Inductors

- Can be combined with C underneath (slots!)
- Low series resistance: ca. 50mW/nH @ 100MHz
- Far from substrate
- Good for single-phase & high voltage
- Cannot be scaled well: no multi-phase



# Converter components

## Inductors

### Metal-Track Inductors



M9

Pitch (nm)

M8 566.5

M7 450.1

M6 337.6

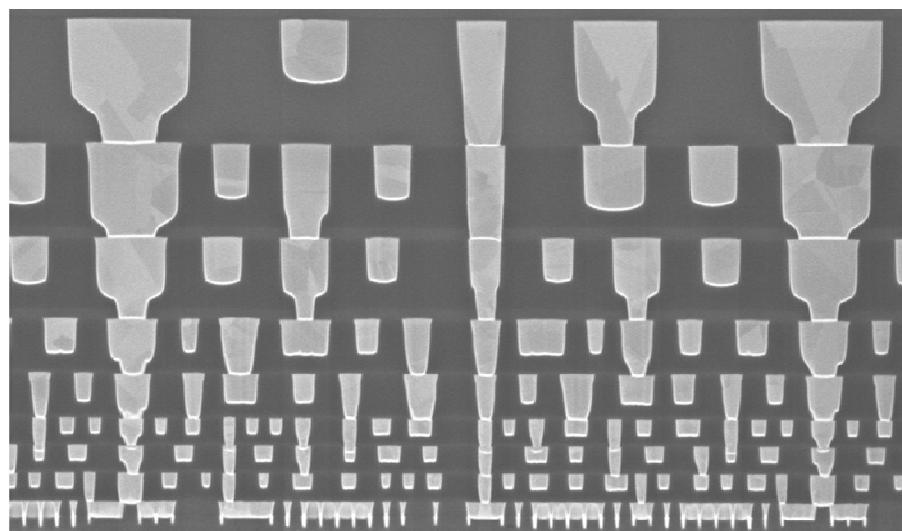
M5 225.0

M4 168.8

M3 112.5

M2 112.5

M1 112.5

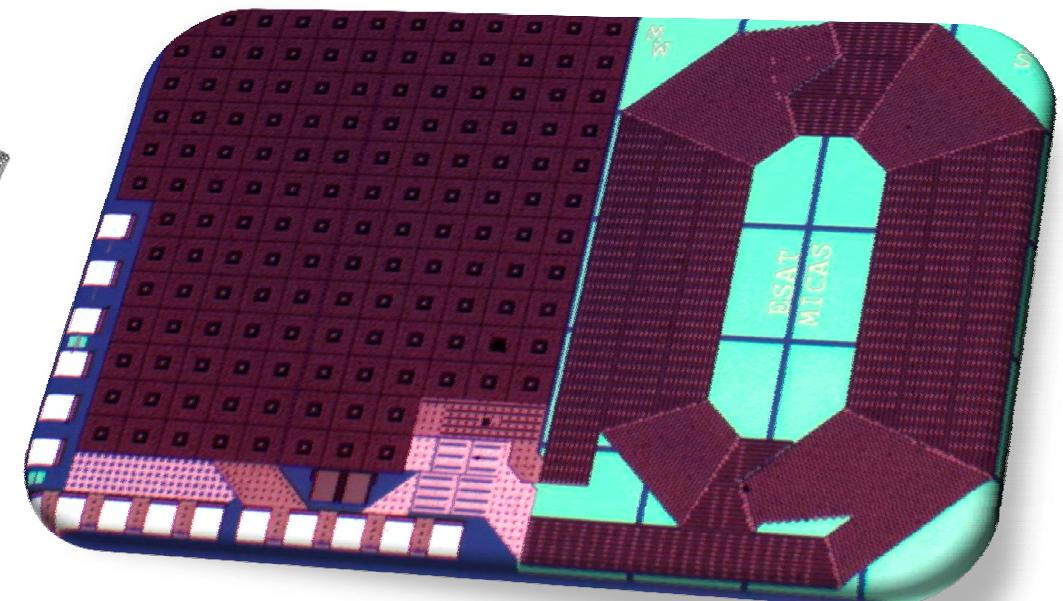
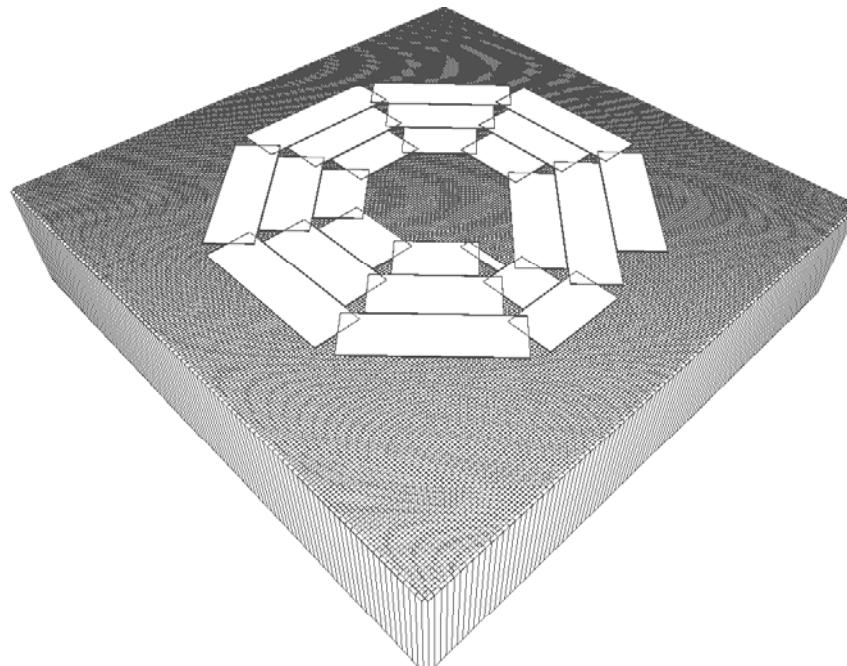


# Converter components

## Inductors

### Metal-Track Inductors

- Good for multi-phase & low voltage
- Cannot be combined with C underneath
- High series resistance: ca. 250mW/nH @ 1GHz
- Close to substrate



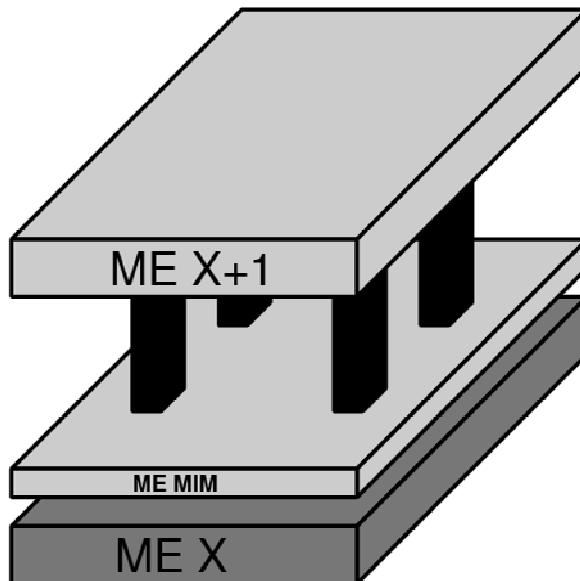
# Converter components

## Capacitors

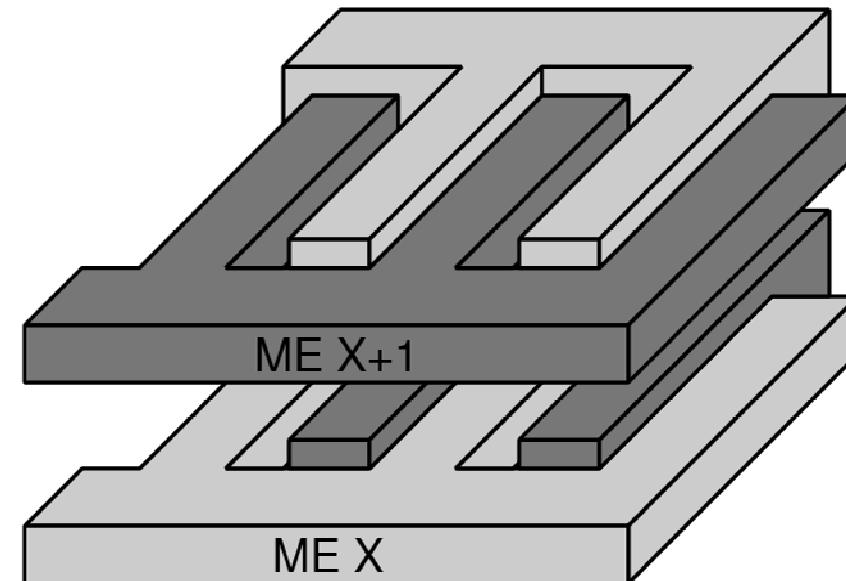
### Metal-Plate Capacitors

- Metal-Insulator-Metal (MIM) : low ESR
- Metal-Oxide-Metal (MOM): high voltage

**MIM**



**MOM**

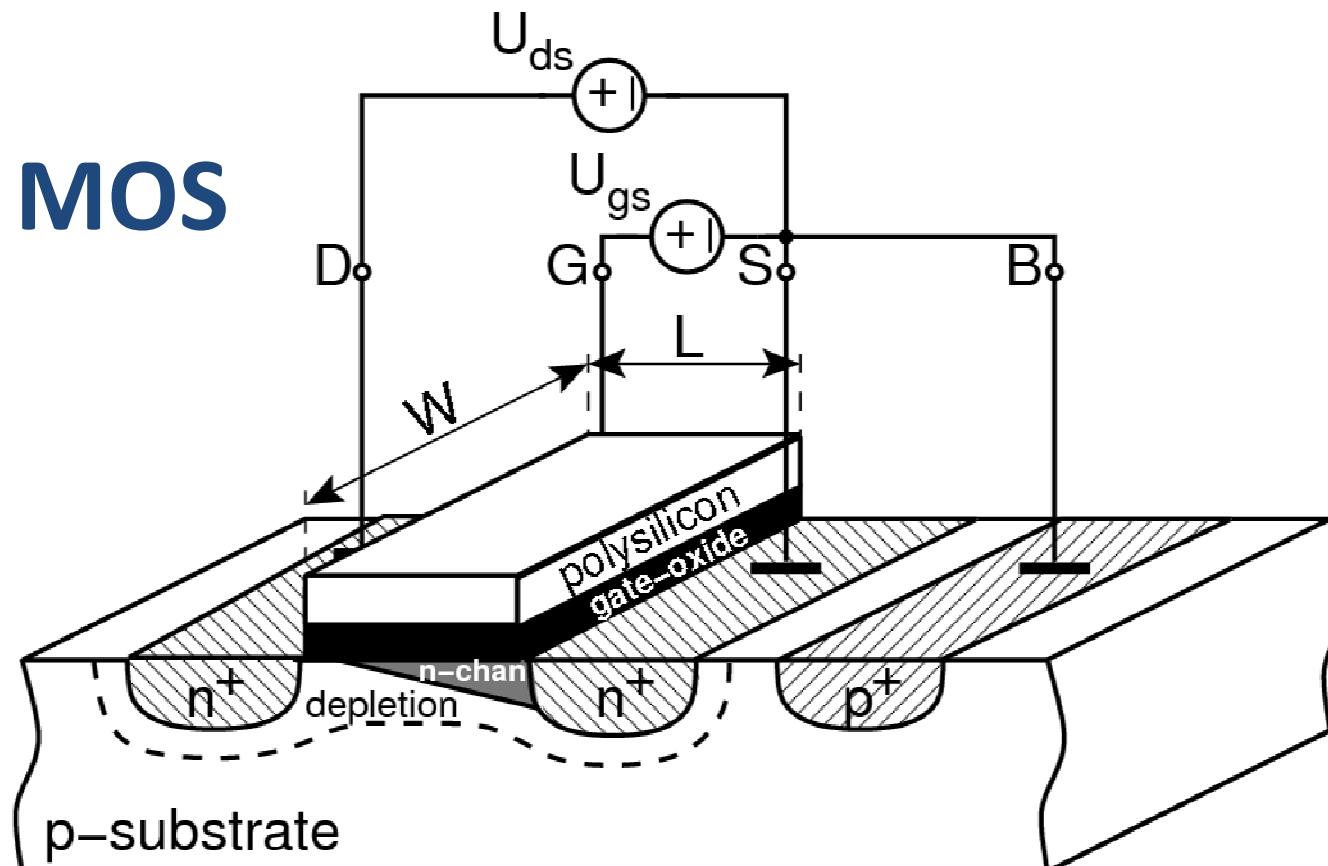


# Converter components

## Capacitors

### MOS Capacitors

- Metal-Oxide-Semiconductor (MOS): high density

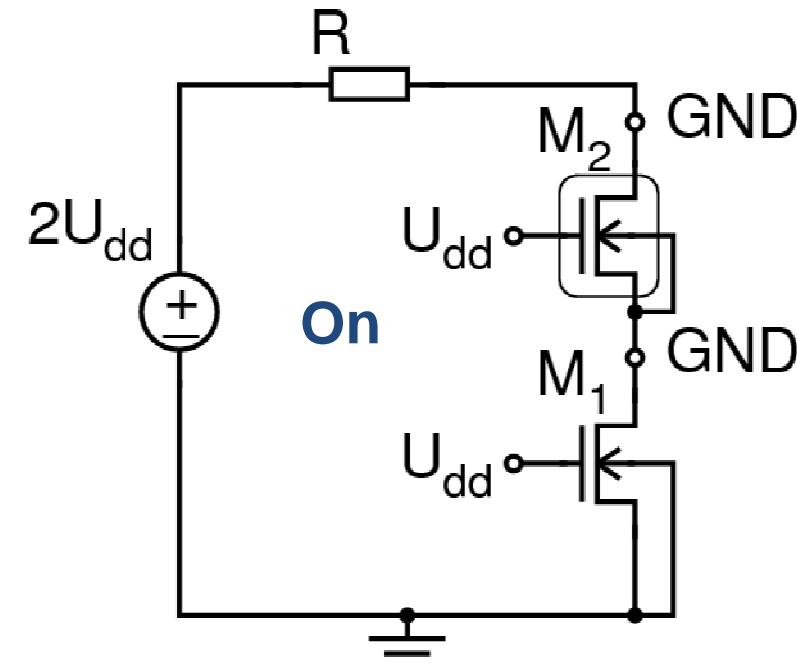
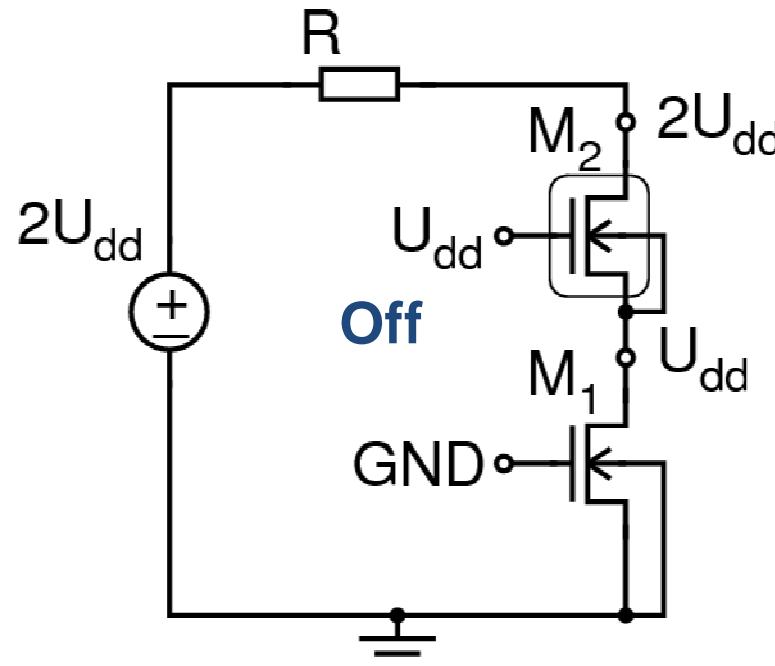


# Converter components

## Switches

### MOSFETS

- Stack switches for higher voltage capability
- Switches become faster in deep-submicron  
**lower operating voltage**

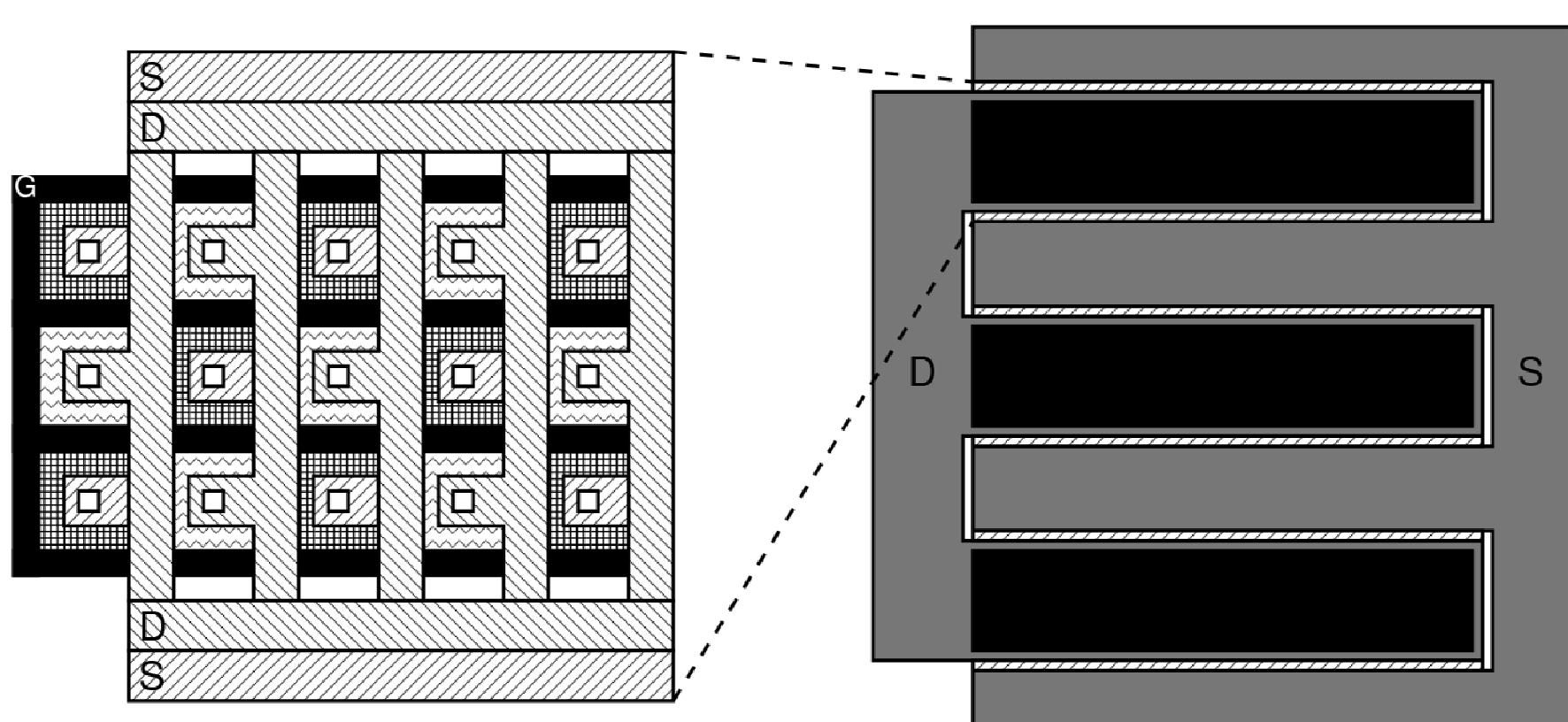


# Converter components

## Switches

### MOSFETS: Lay-Out

- Use adapted waffle-layout for low parasitics



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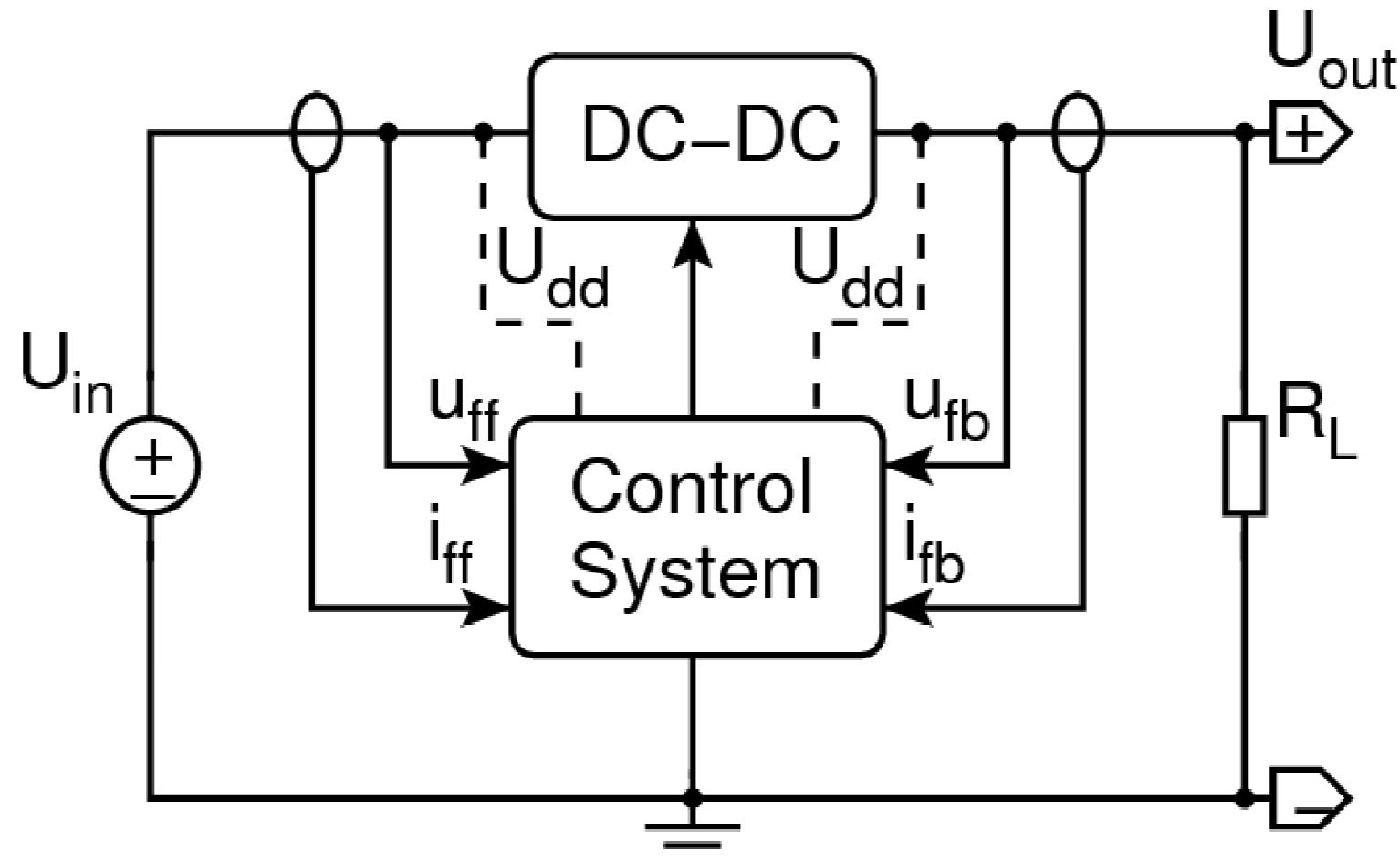
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- **Converter Components**
- **Control Strategies & Systems**
- **Implementation Examples**
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# Control Strategies & Systems

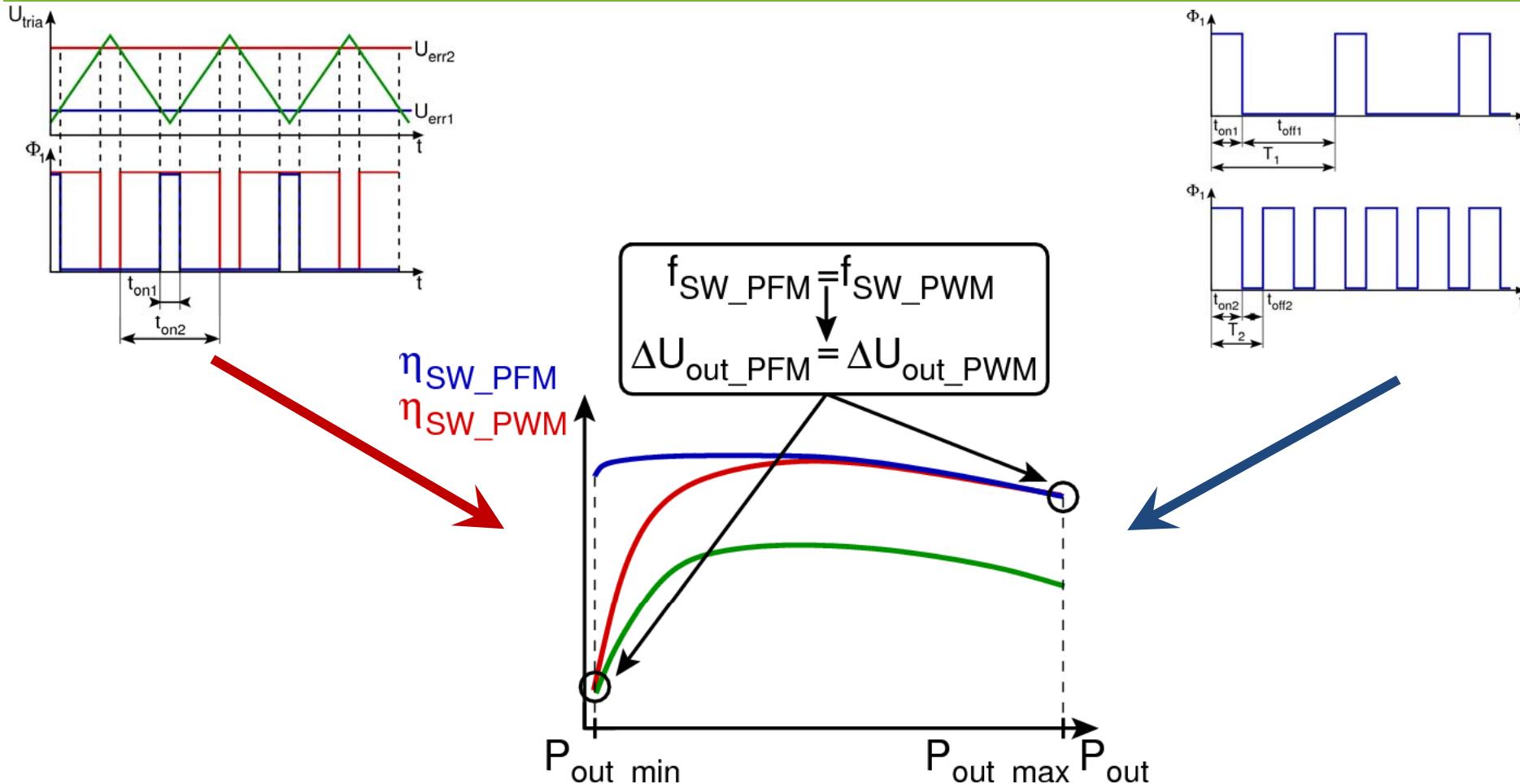
## Principle



# Control Strategies & Systems

## Inductive converter control

### PWM vs PFM

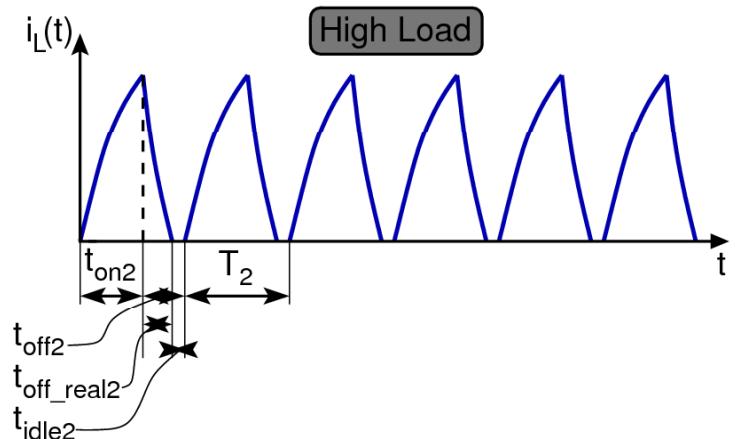
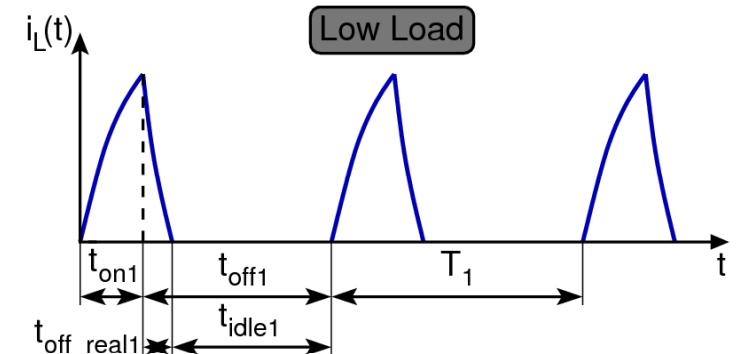
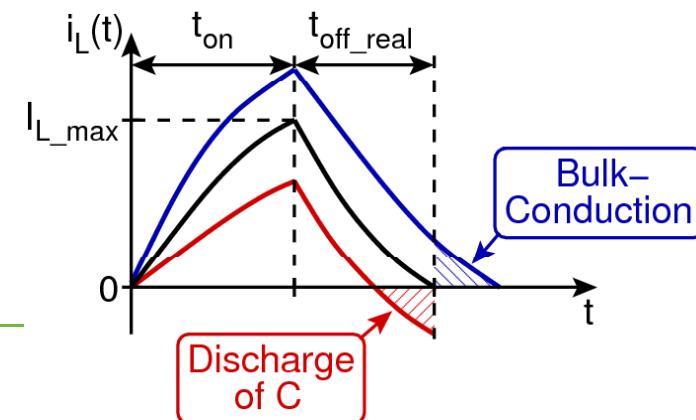


# Control Strategies & Systems

## Inductive converter control

### Constant On/Off-Time: COOT

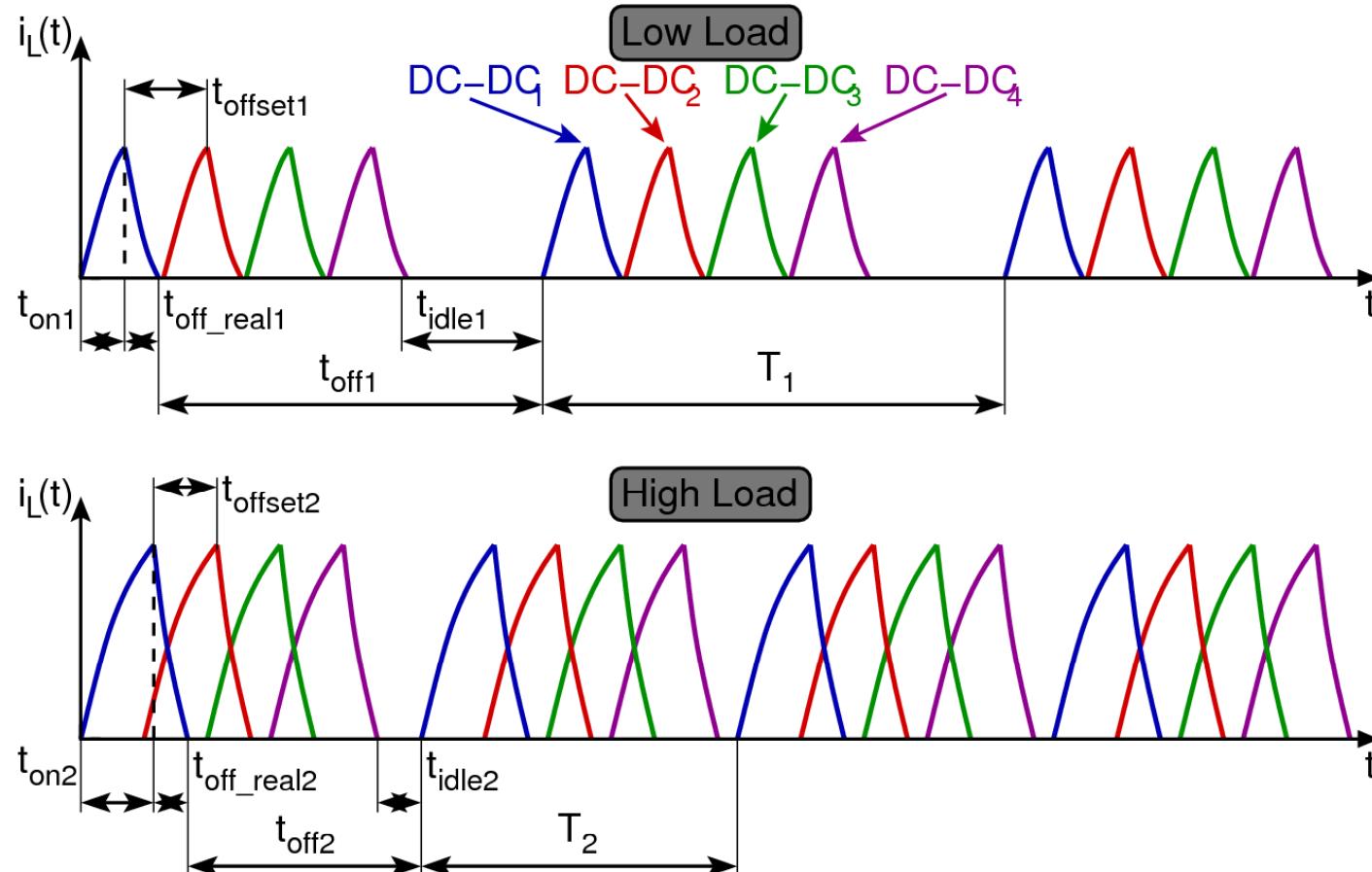
- Higher eff. vs PWM
- No current sensing
- Mostly digital
- Fast transient response
- Fixed voltage ratio
- Load regulation dependant on the ripple



# Control Strategies & Systems

## Inductive converter control

### Semi-Constant On/Off-Time: SCOOT

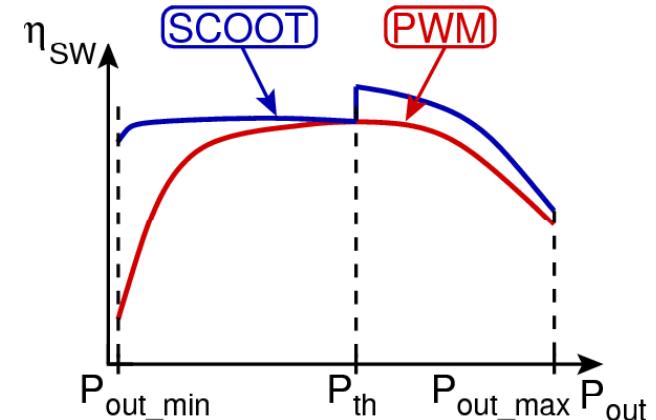
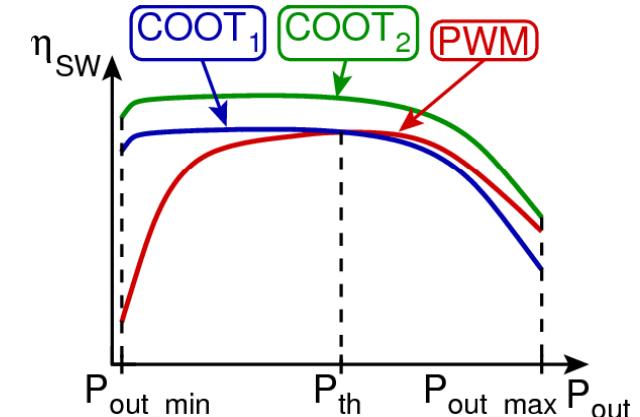


# Control Strategies & Systems

## Inductive converter control

### Semi-Constant On/Off-Time: SCOOT

- Higher eff. range vs COOT
- No current sensing
- Mostly digital
- Fast transient response
- High power density
- Fixed voltage ratio
- Load regulation dependant on the ripple
- No perfect interleaving

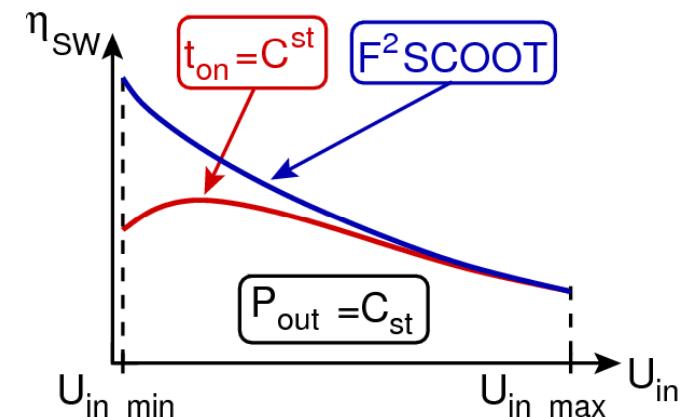
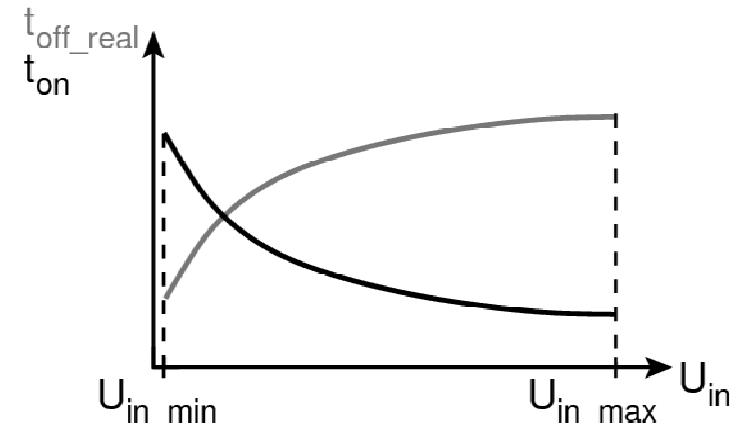


# Control Strategies & Systems

## Inductive converter control

### Feed-Forward Semi-Constant On/Off-Time: F<sup>2</sup>SCOOT

- Higher eff. Vs (S)COOT
- No current sensing
- Mostly digital
- Fast transient response
- Large input voltage range
- Load regulation dependant on the ripple



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# Contents



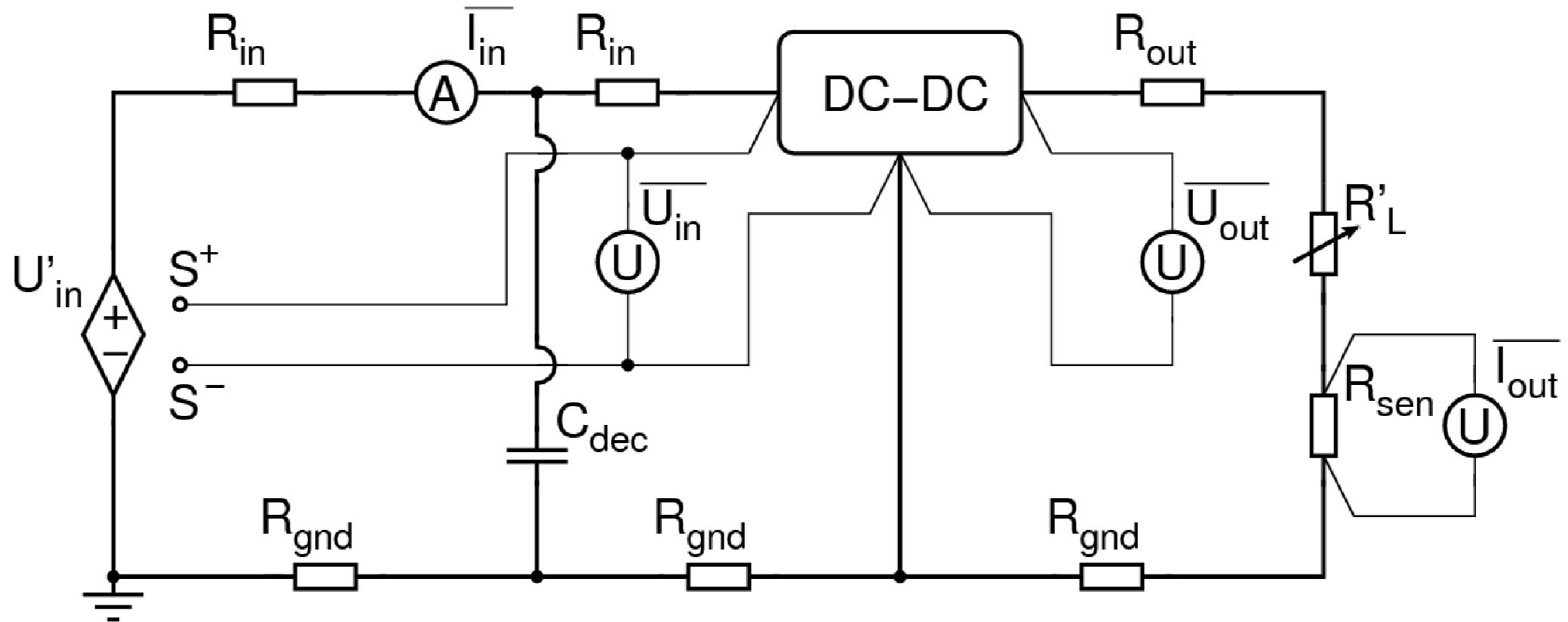
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# Implementation Examples

# Measuring DC-DC converters



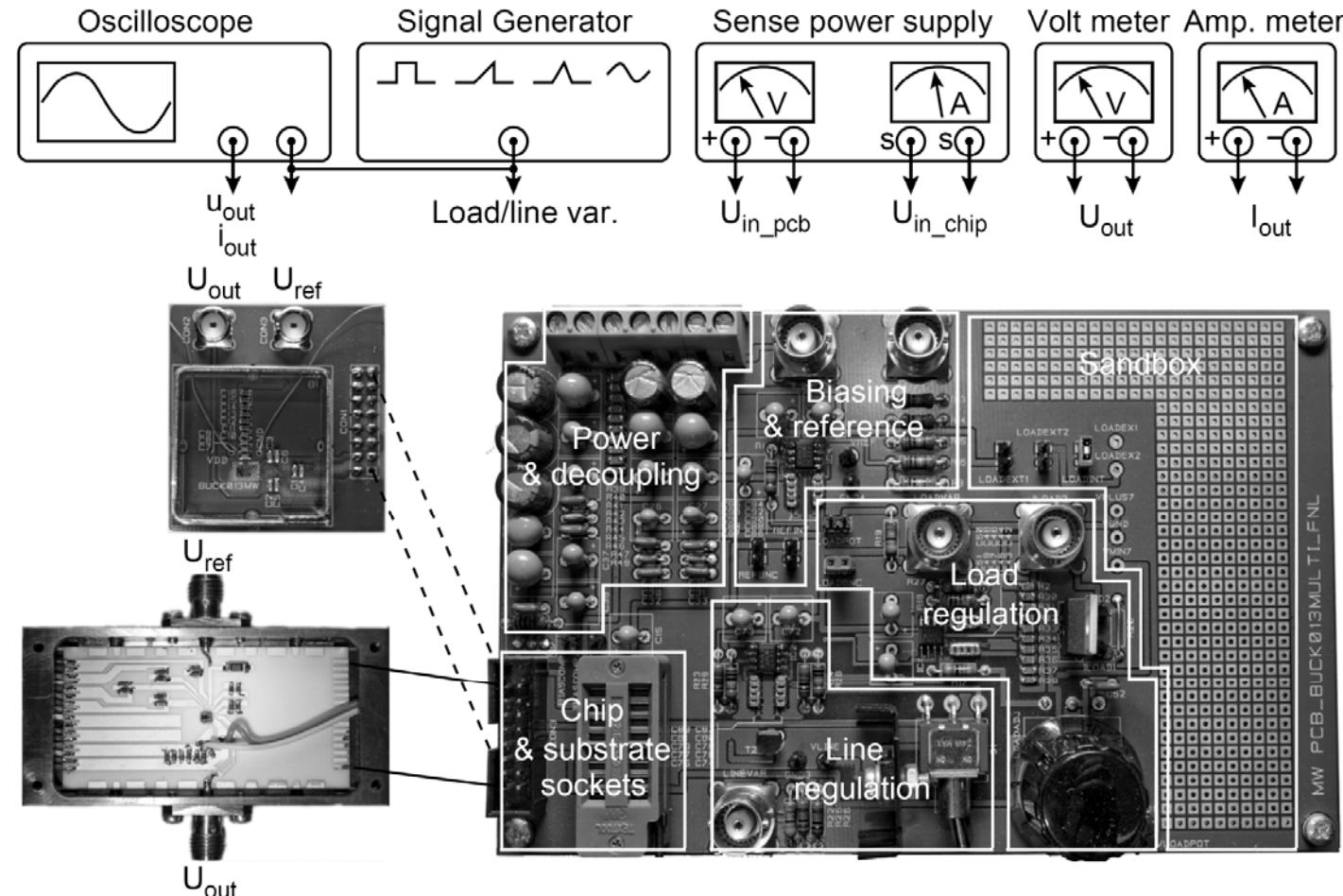
# Principle



# Implementation Examples

## Measuring DC-DC converters

### Practical



# Implementation Examples

## Intermezzo



### Efficiency Enhancement Factor: EEF



**8l/100km**



**4l/100km**

# Implementation Examples

## Intermezzo



### Efficiency Enhancement Factor: EEF

DC-DC <sub>1</sub>	DC-DC <sub>2</sub>
$P_{out} = 1 \text{ W}$ $k_{lin} = k_{SW} = 0.8$ $\eta_{lin} = 80 \%$ $\eta_{SW} = 85 \%$ $\Rightarrow \Delta\eta = \eta_{SW} - \eta_{lin} = 5 \%$	$P_{out} = 1 \text{ W}$ $k_{lin} = k_{SW} = 0.5$ $\eta_{lin} = 50 \%$ $\eta_{SW} = 55 \%$ $\Rightarrow \Delta\eta = \eta_{SW} - \eta_{lin} = 5 \%$
$P_{in\_lin} = 1.25 \text{ W}$ $P_{in\_SW} = 1.18 \text{ W}$ $\Rightarrow \Delta P_{in} = P_{in\_lin} - P_{in\_SW} = 0.07 \text{ W}$	$P_{in\_lin} = 2 \text{ W}$ $P_{in\_SW} = 1.82 \text{ W}$ $\Rightarrow \Delta P_{in} = P_{in\_lin} - P_{in\_SW} = 0.18 \text{ W}$
$EEF = \frac{\Delta P_{in}}{P_{in\_lin}} \Big _{k_{lin}=k_{SW}} = 5.6 \%$	$EEF = \frac{\Delta P_{in}}{P_{in\_lin}} \Big _{k_{lin}=k_{SW}} = 9 \%$

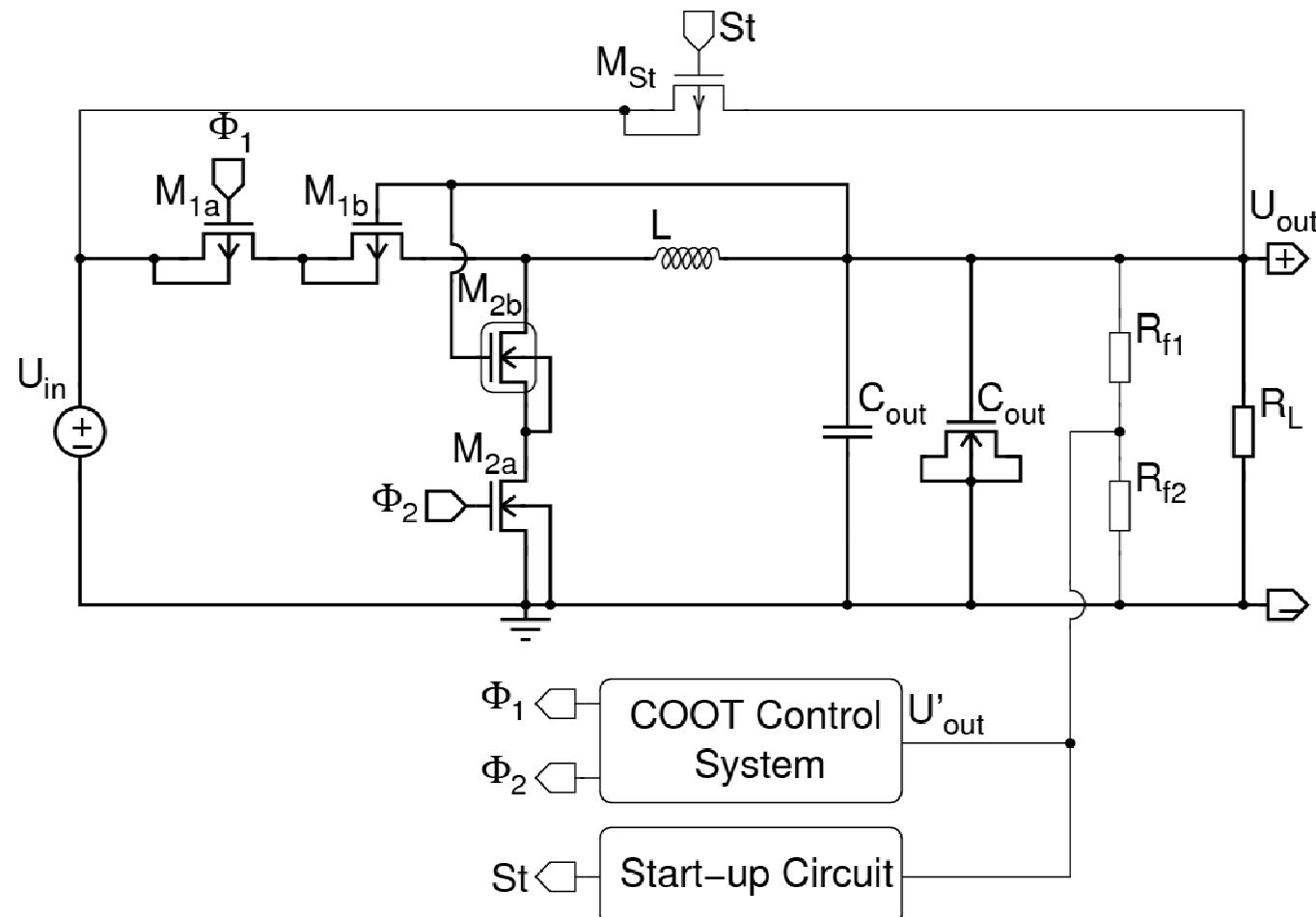


$$EEF = 1 - \frac{\eta_{lin}}{\eta_{SW}} \Big|_{k_{lin}=k_{SW}}$$

# Implementation Examples

## Bondwire Inductor COOT Buck

### Converter Circuit

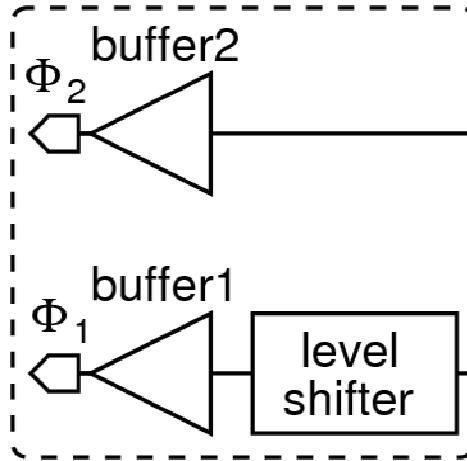


# Implementation Examples

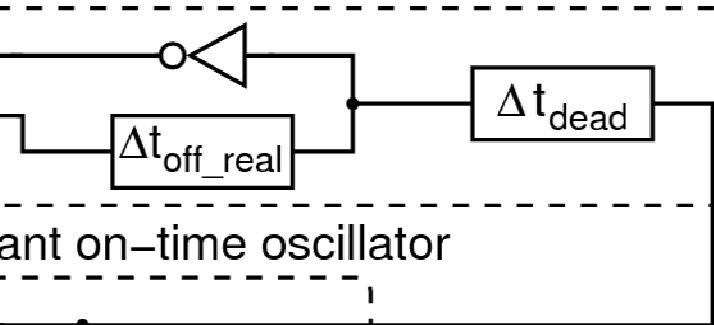
## Bondwire Inductor COOT Buck

### Control Circuit

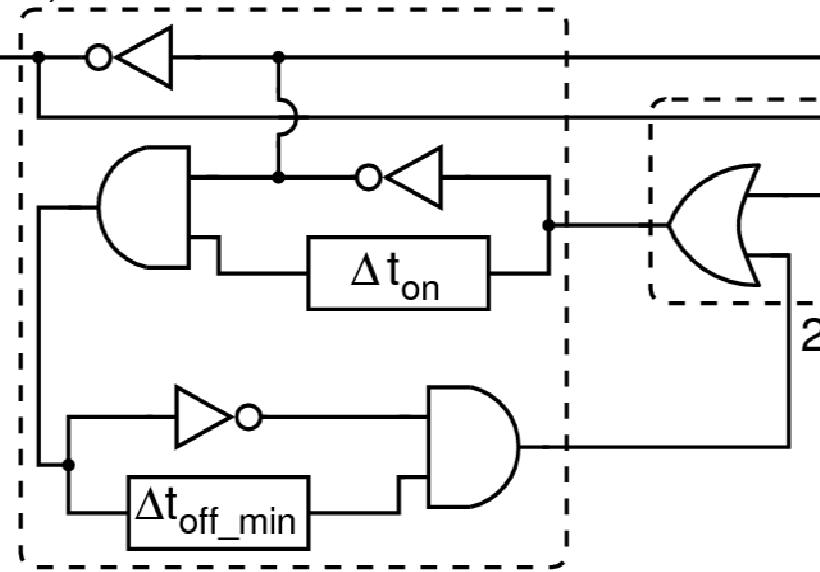
5) buffering & level-shifting



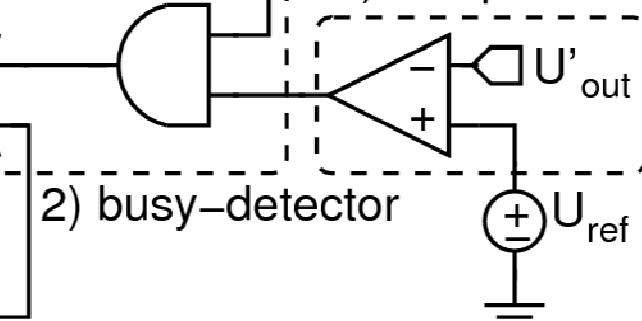
4) constant off-time control



3) constant on-time oscillator



1) comparator

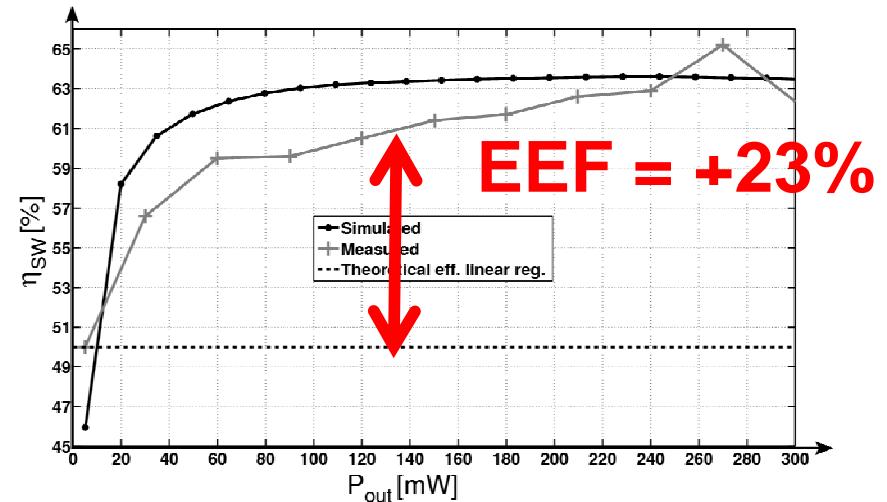
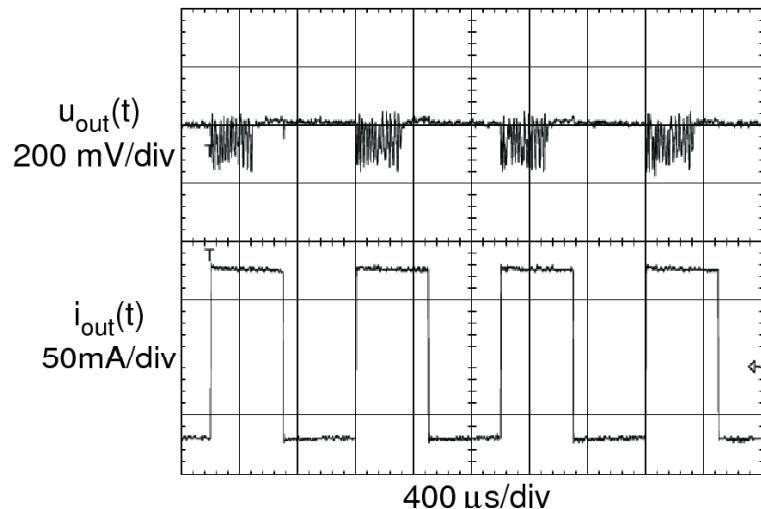


2) busy-detector

# Implementation Examples

## Bondwire Inductor COOT Buck

### Measurements

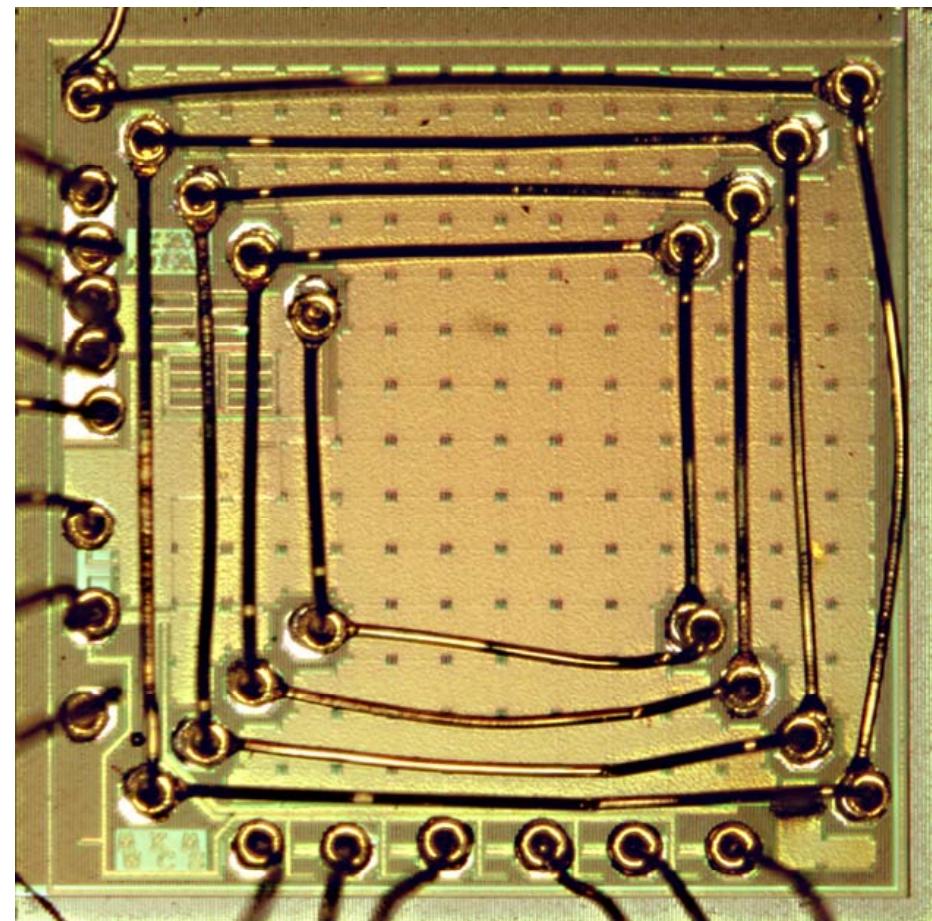
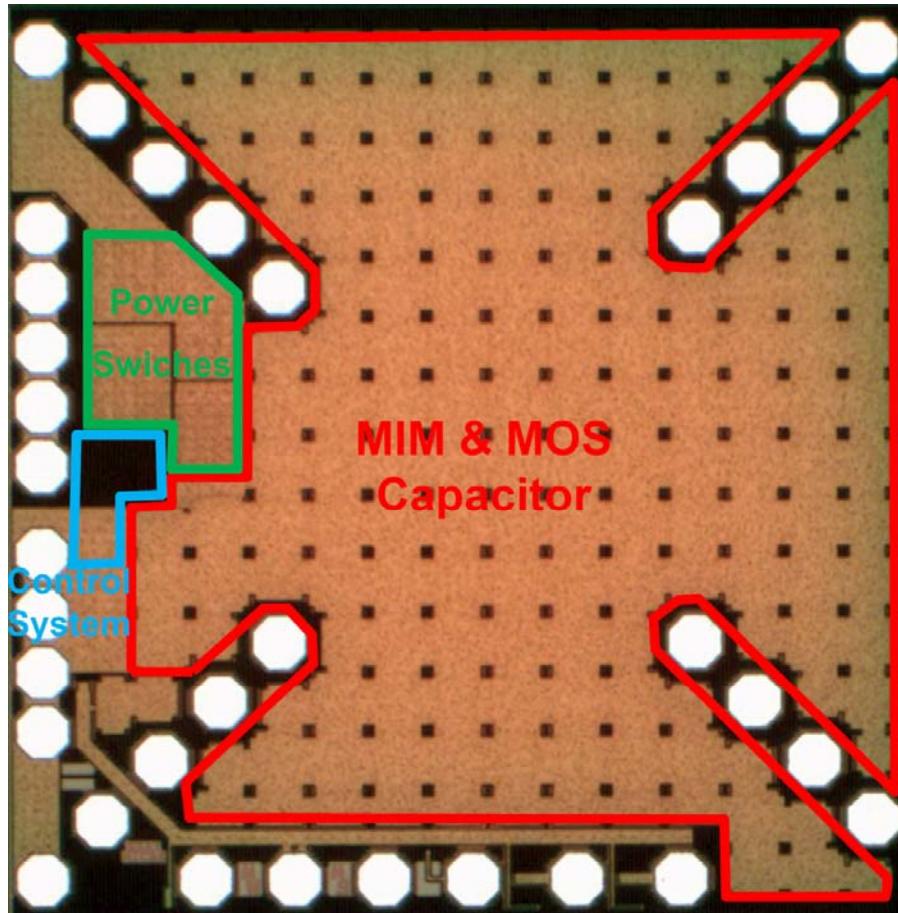


Input voltage range	3 V-4 V
Output voltage range	1.5 V-2.1 V
Output power range	0 mW-300 mW
Switching frequency range	20 Hz-140 MHz
Power efficiency @ $U_{in} = 3.6$ V and $U_{out} = 1.8$ V	65 %
Efficiency Enhancement Factor	23 %
Maximum output ripple @ $P_{out} = 0$ mW	160 mV
Minimum output ripple @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

# Implementation Examples

## Bondwire Inductor COOT Buck

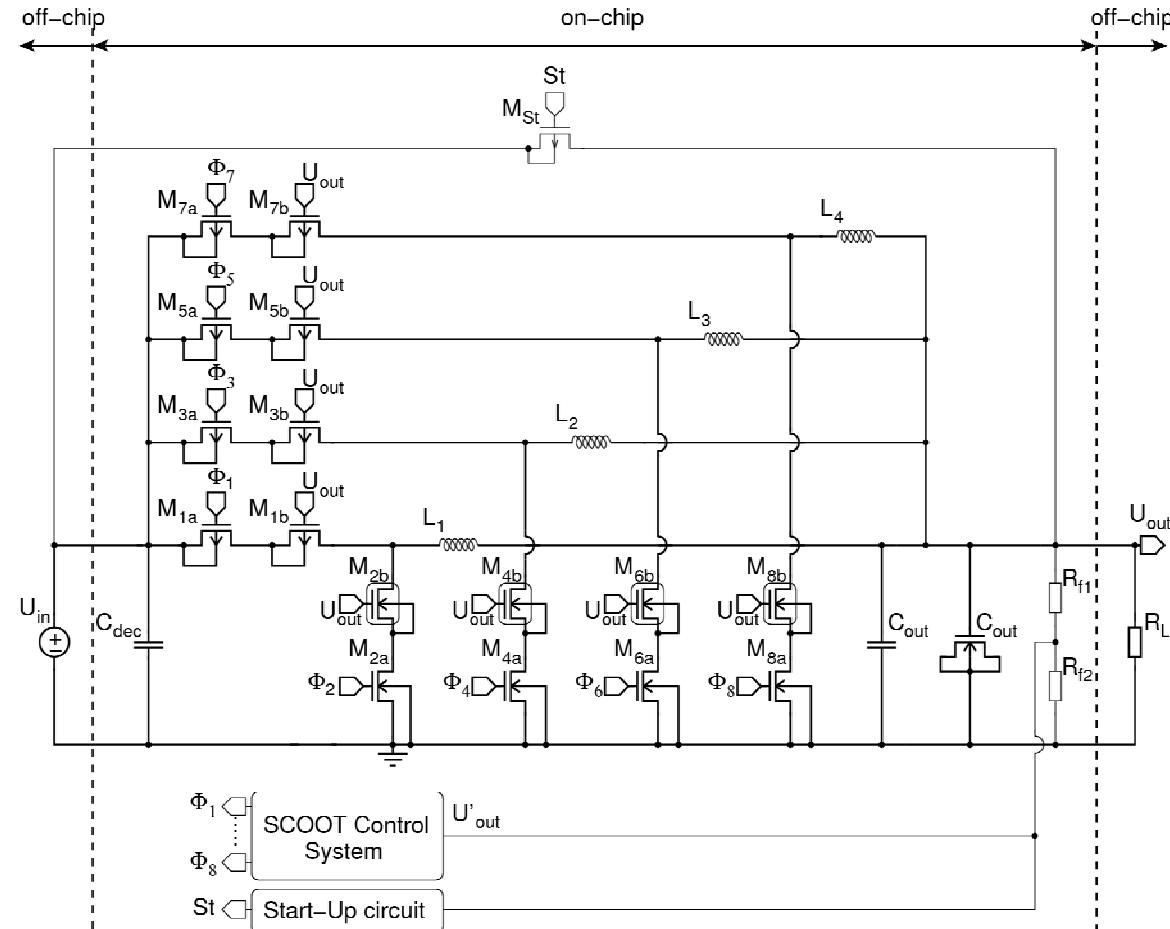
### Photo



# Implementation Examples

## Metal-Track 4-Phase Inductor SCOOT Buck

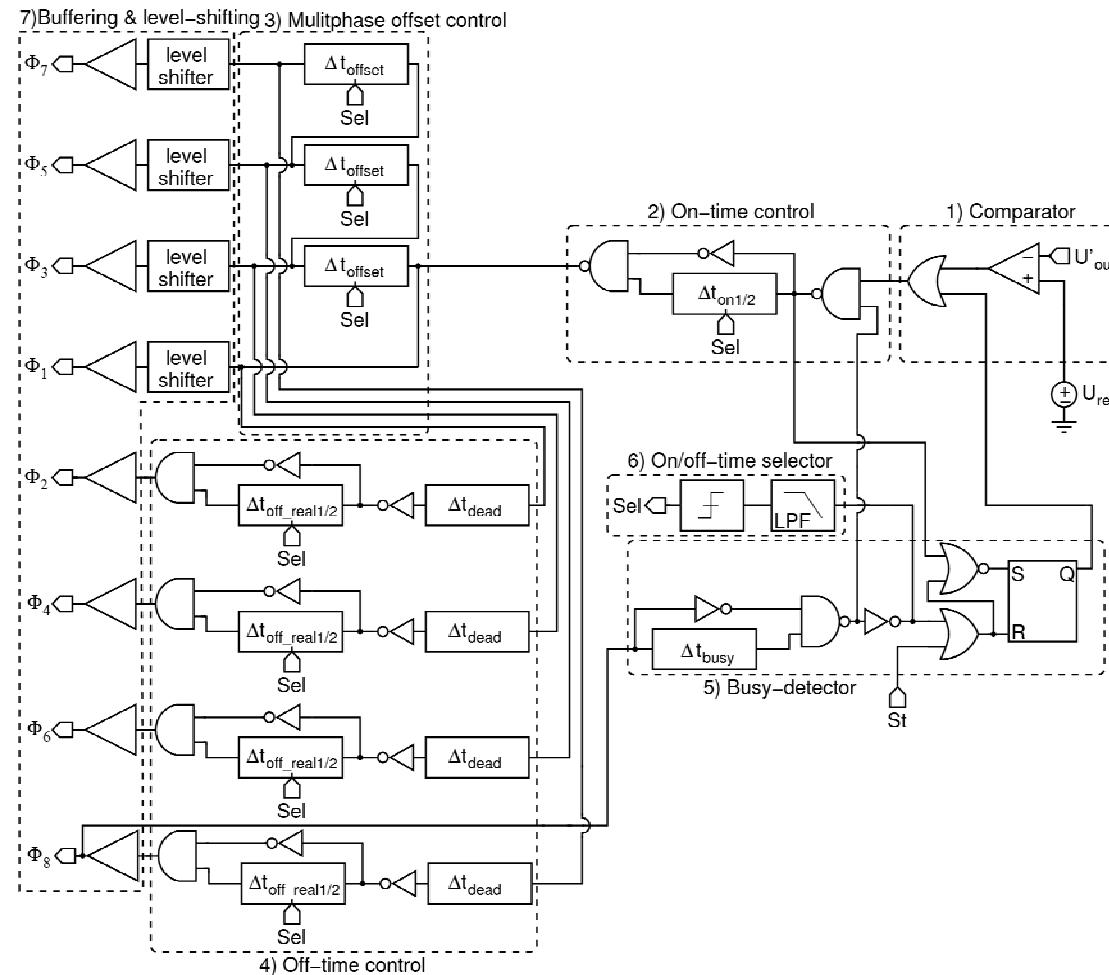
### Converter Circuit



# Implementation Examples

## Metal-Track 4-Phase Inductor SCOOT Buck

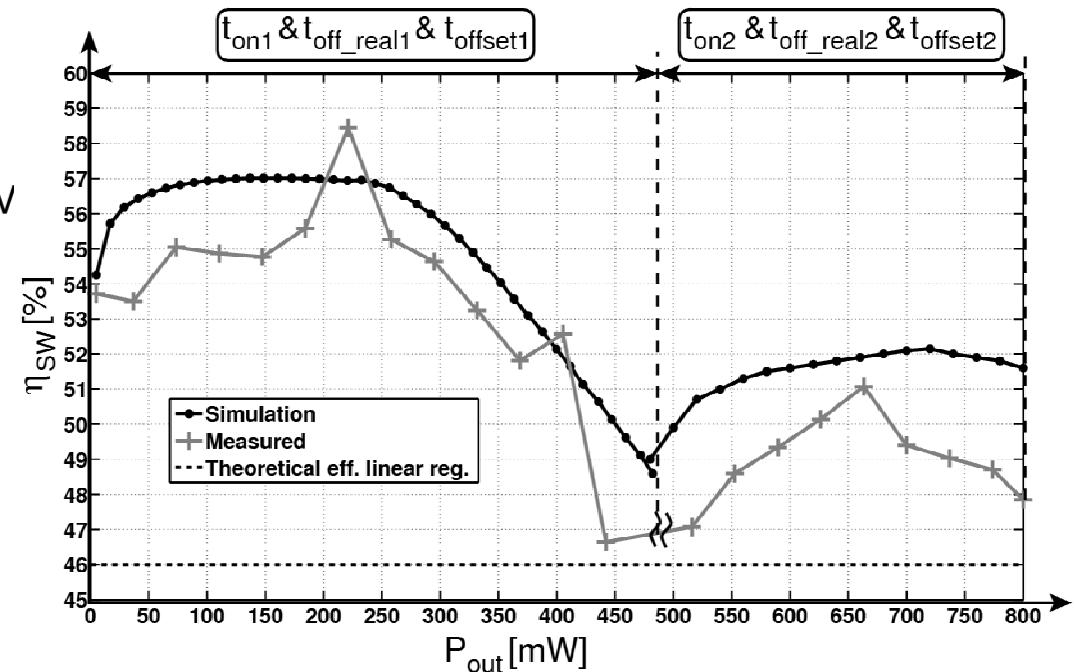
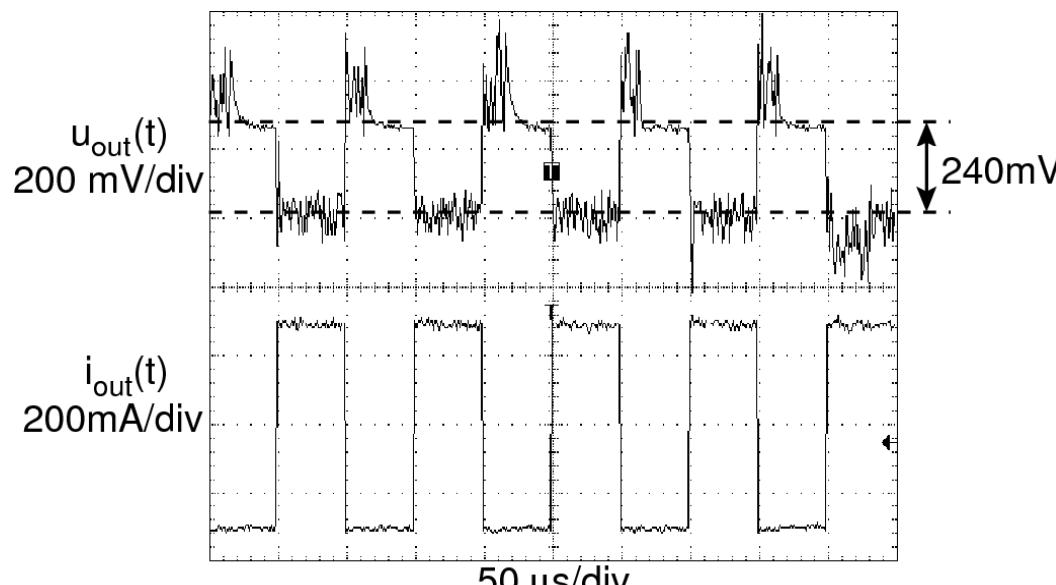
### Control Circuit



# Implementation Examples

## Metal-Track 4-Phase Inductor SCOOT Buck

### Measurements

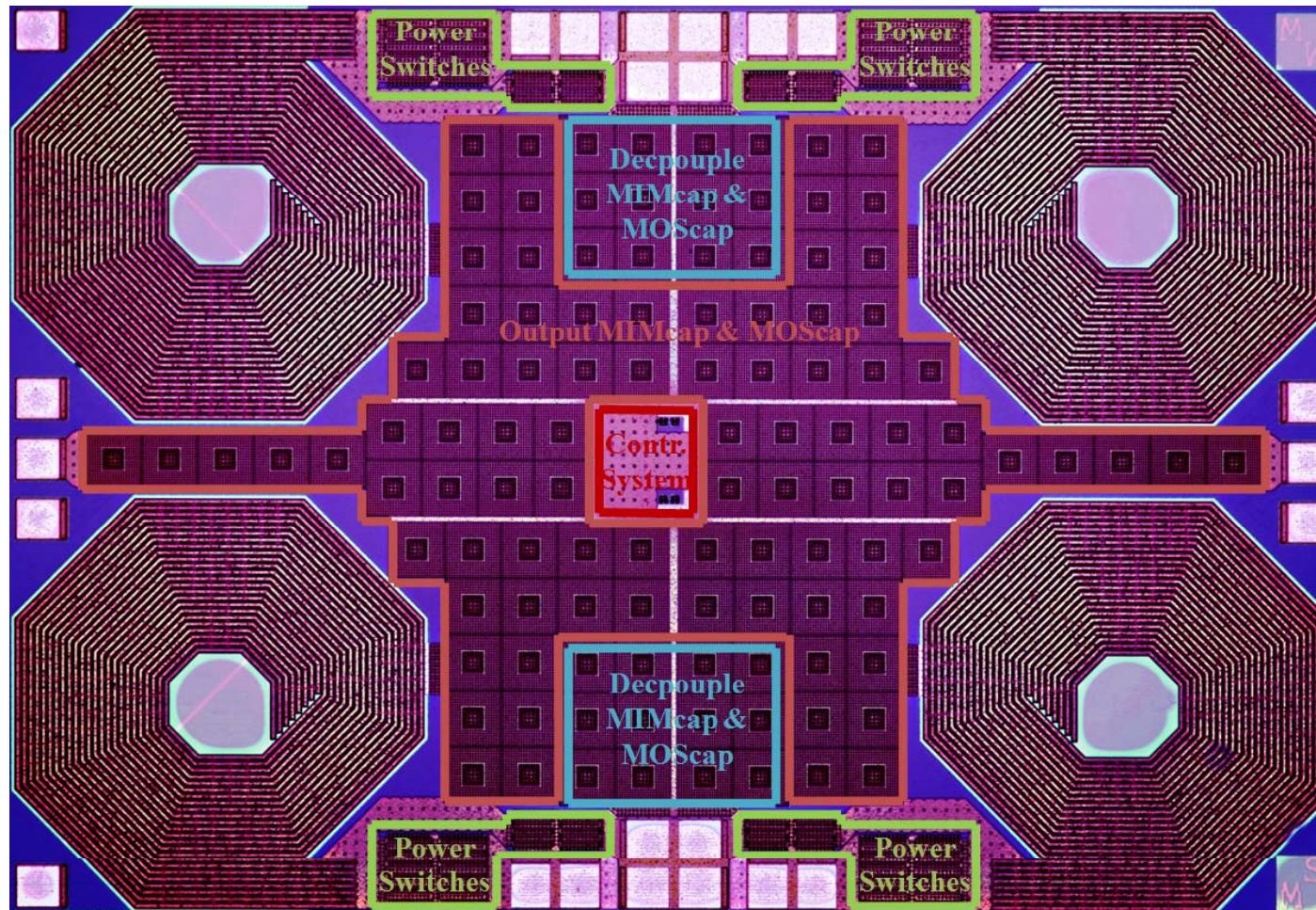


- **Output Power 800mW**
- **Efficiency Enhancement Factor +21%**
- **Power density 213mW/mm<sup>2</sup>**

# Implementation Examples

## Metal-Track 4-Phase Inductor SCOOT Buck

### Photo



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# Contents



- **Introduction**
- **DC-DC Conversion**
- **Converter Components**
- **Control Strategies & Systems**
- **Implementation Examples**
- **Conclusions**

# Conclusions



- Use switched DC-DC converters for higher efficiency
  - Capacitive good for constant voltage ratios
  - Use simple topologies for minimal losses
  - Multi-Phase to boost power
  - Integrating high-Q on-chip passives is crucial
  - Control strategy is determining for efficiency
  - Compare step-down converters through the EEF

# Questions ?



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