Potential Benefits of Integrated Switching Power Converters: Inductive vs. Switched-Capacitor

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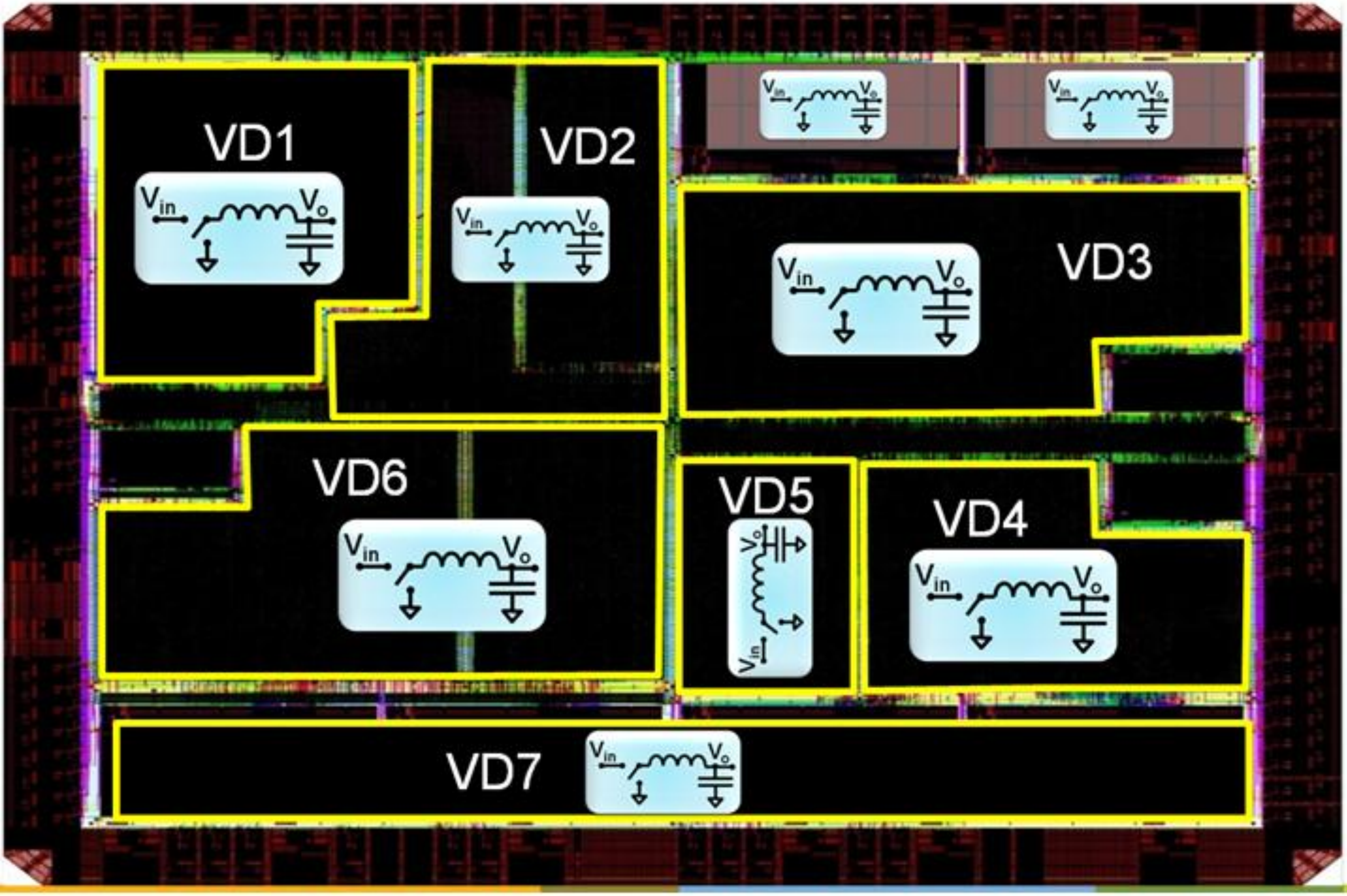
Outline

- Introduction: distributed power systems
- State of the art
- Scalability of inductive power converters
- Scalability of switched-capacitor power converters
- Multiphase designs
- Conclusions

Introduction

Introduction: Power distributed systems

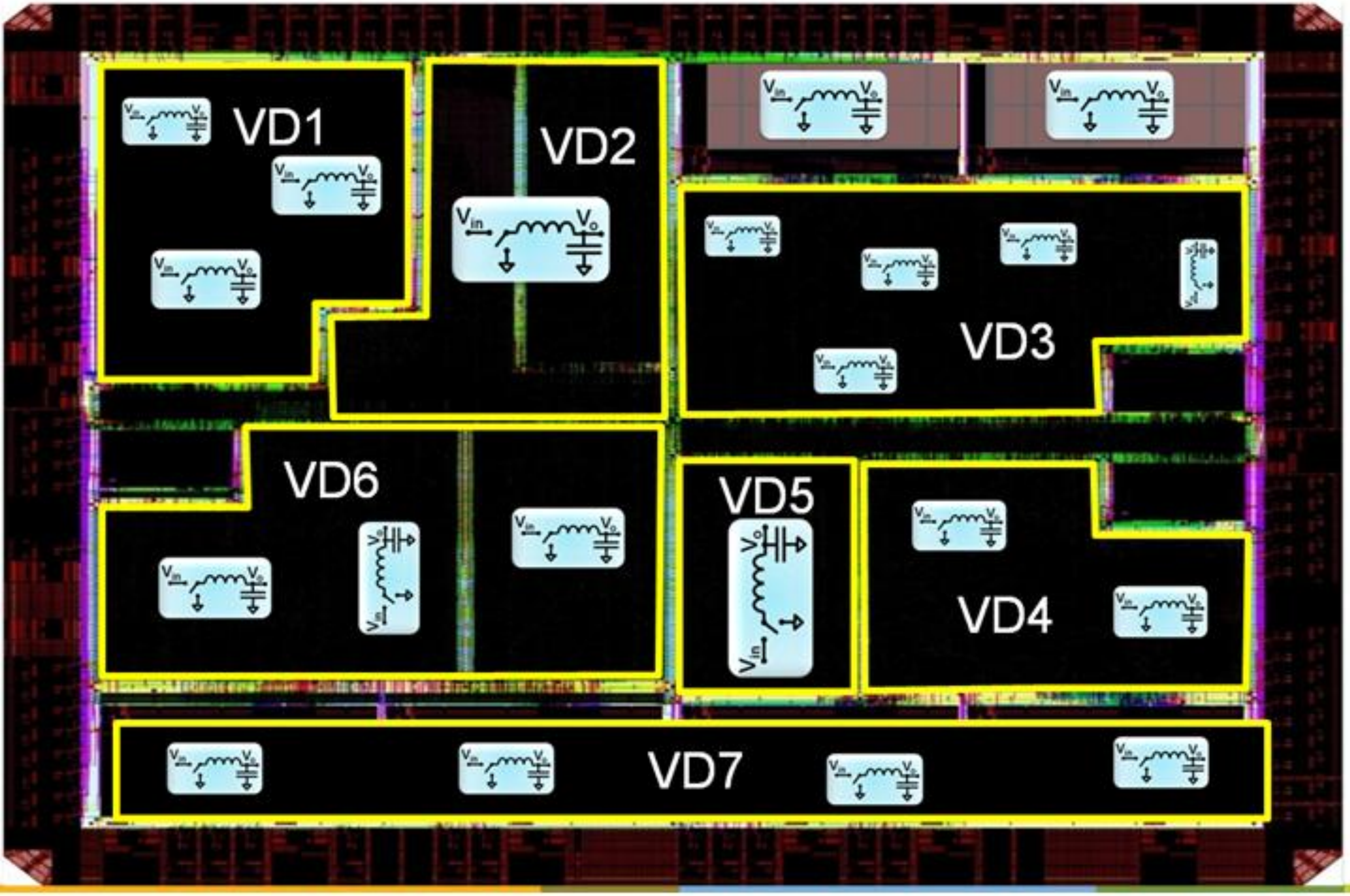
Case 1: One converter per voltage domain



- Efficient generation of different voltage domains
- Adaptability to different specs per block
- Low power converters

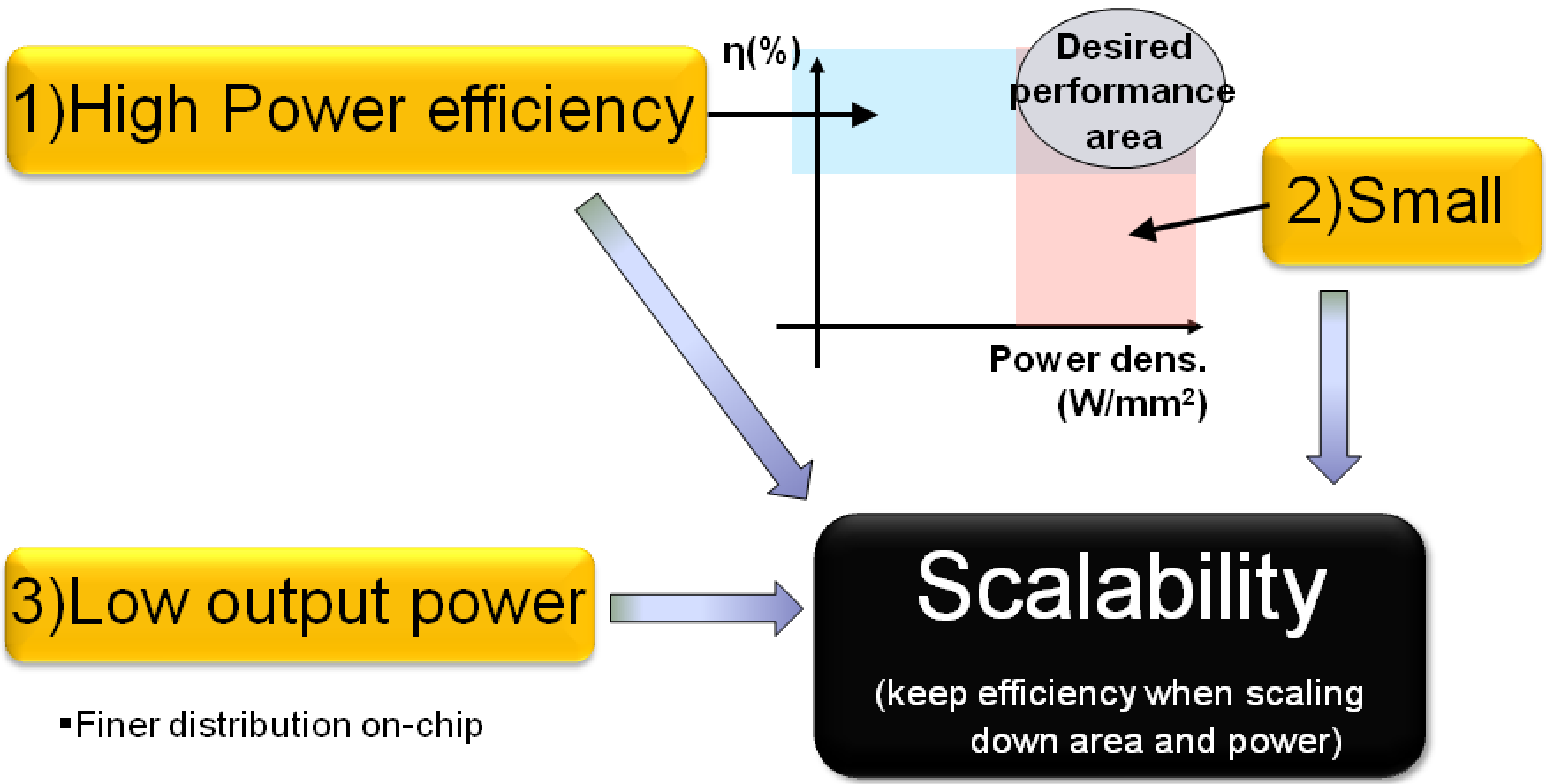
Introduction: Power distributed systems

Case 2: Multiple converters per voltage domain



- Efficient generation of different voltage domains
- Adaptability to different specs per block
- Local regulation
  - Better power distribution
  - Even lower power per converter

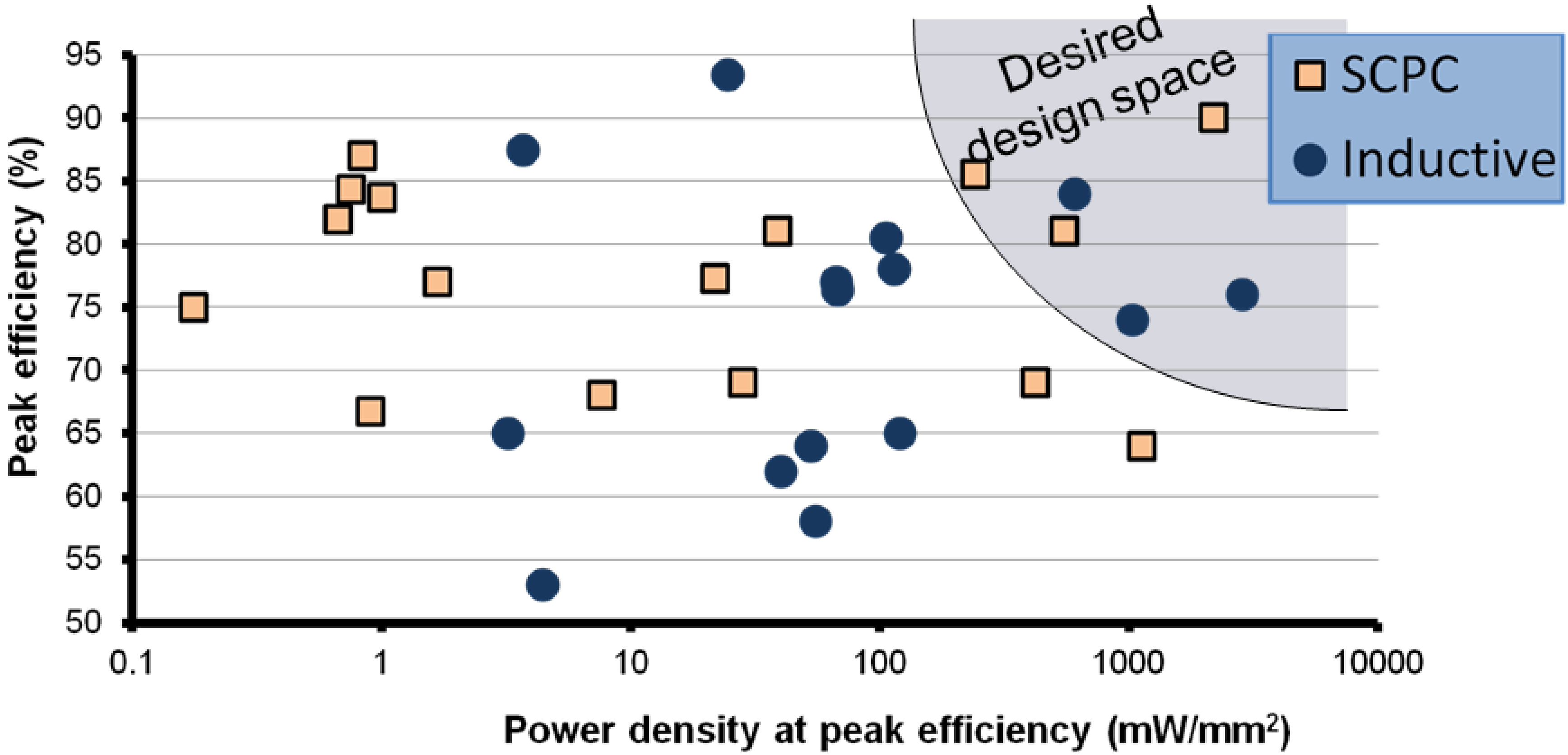
Requirements



- Finer distribution on-chip

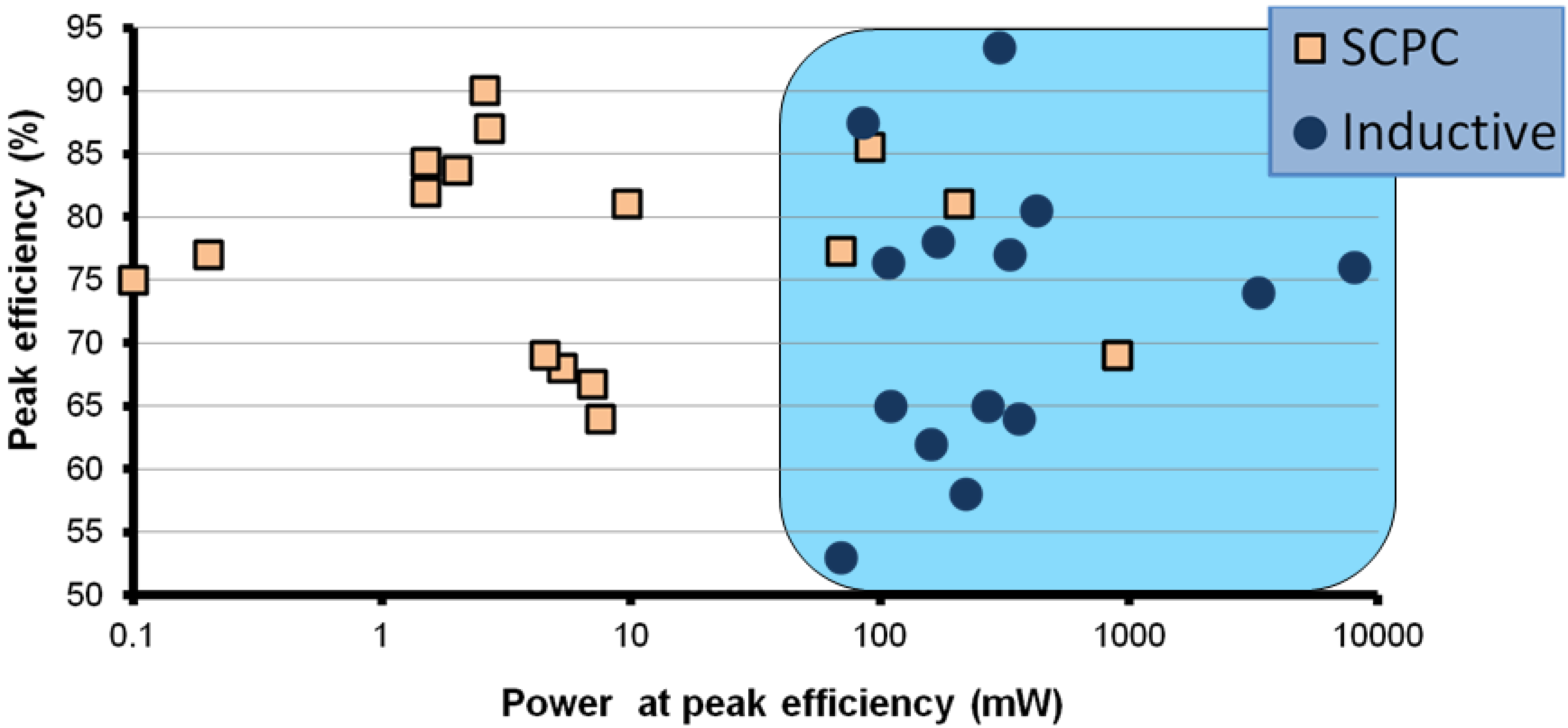
State of the art

State of the art: fully integrated converters



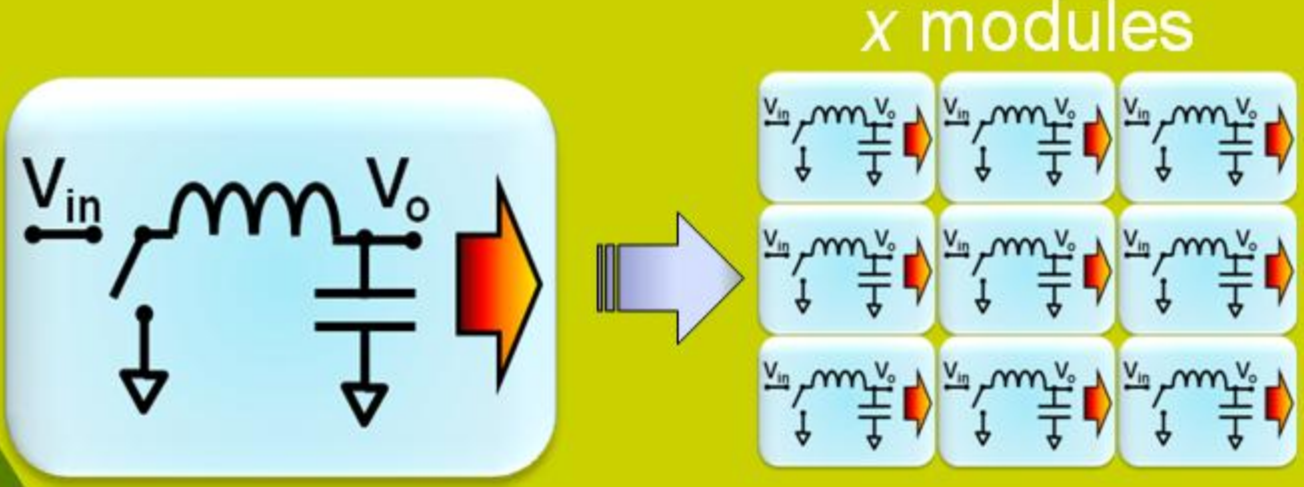
No clear advantage in performance

State of the art: fully integrated converters



Inductive designs always focus on high power

Scalability of inductive converters

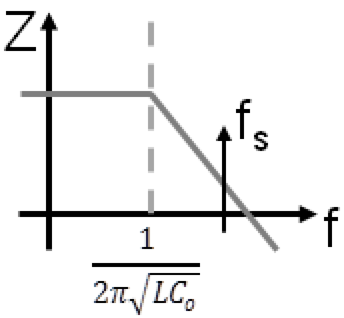


Scalability of inductive converters (I)

Split the converter into 'x' modules:

▪Scale size of L & C_o, to keep constant ΔV_o at constant f_s:

- $C_o \rightarrow C_o/x$
- $L \rightarrow x*L$ (reduce area but increase inductance)



▪Inductor current RMS for CCM buck converter:

$$I_L^2 = I_o^2 + \frac{V_o^2(V_{in} - V_o)^2}{12V_{in}^2 f_s^2 L^2} \xrightarrow{I_o \rightarrow \frac{I_o}{x};\, L \rightarrow xL} I_L^2 \sim \frac{1}{x^2}$$

→Also applies to DCM

▪The switches should also be scaled:

•$R_{on} \rightarrow x*R_{on}$; I_{NMOS} & I_{PMOS} RMS reduces by x^2 $\rightarrow P_{NMOS,PMOS} \sim \frac{1}{x}$

•Switching losses should also reduce with the size of the components (keeping f_s constant) $\rightarrow P_{sw} \sim \frac{1}{x}$

Scalability of inductive converters (II)

Efficiency: $\eta = \dfrac{P_o}{P_o + P_L + P_{N,P} + P_{sw}}$

- Inductor conduction losses:

$P_L = I_L^2 R_L$

$I_L^2 \sim \dfrac{1}{x^2}$

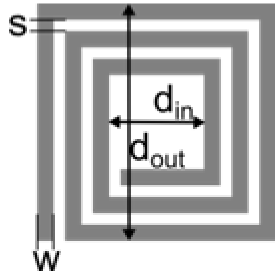
$P_L \sim \dfrac{1}{x} \longrightarrow R_L \sim x$

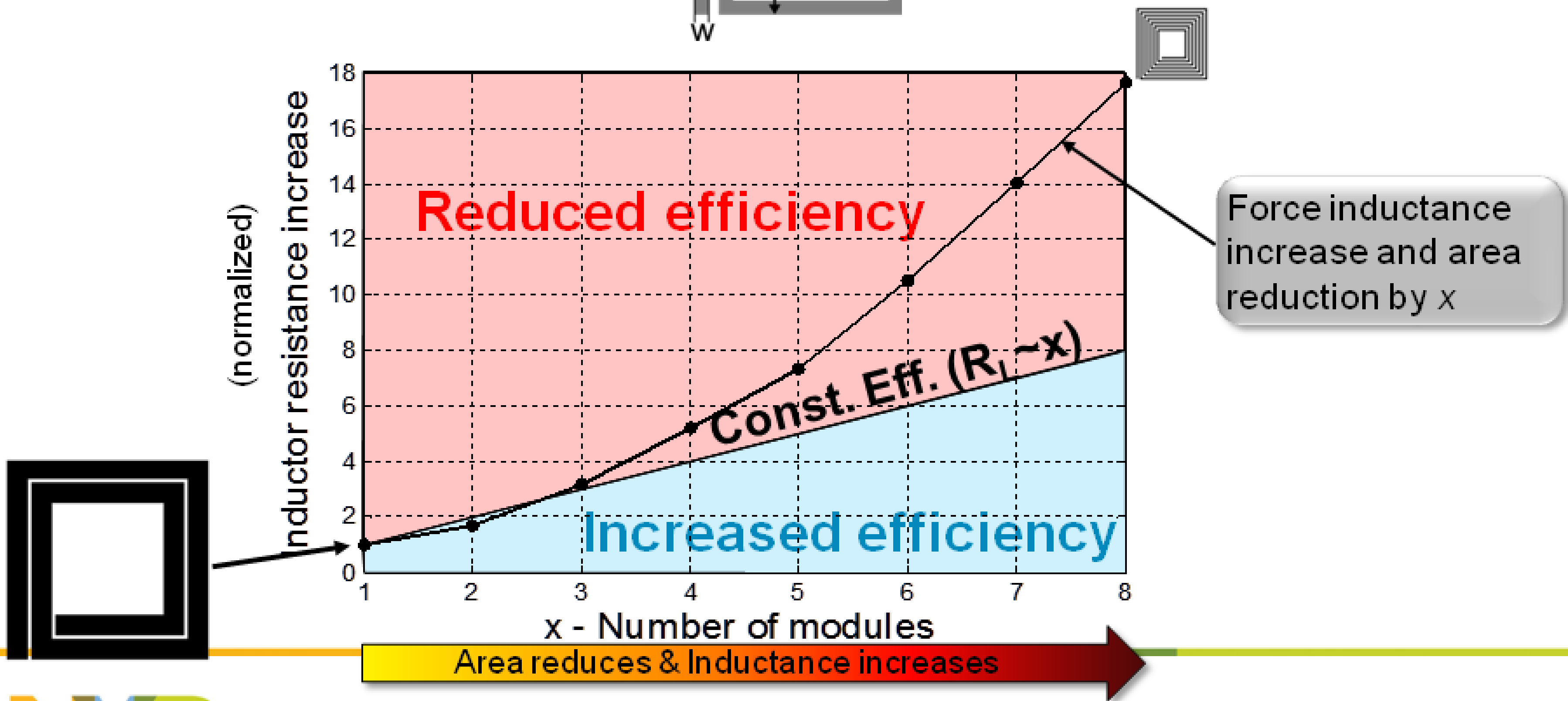
To keep a constant efficiency, the inductor resistance should be proportional to the number of modules (x), so that the inductor losses reduce with the same factor.

Scalability of inductive converters (III)

- Example with planar spiral inductors:

$$L = \frac{K_1 \mu N_L^2 d_{avg}}{1 + K_2 \rho}$$



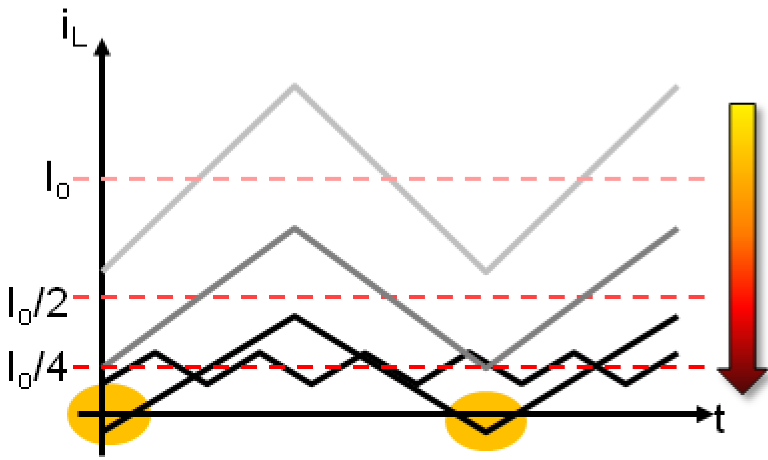


Expressions from: Mohan et al. *"Simple Accurate Expressions for Planar Spiral Inductances"*, JSSC 1999

Scalability of inductive converters (III)

Efficiency of inductive converters will drop when scaling down output power and size

Inductive converters moving to DCM…



- Increasing number of modules (x):
  - Reduces I_o (per modules) → I_o/x
  - Increases L, but not → x*L !!

Increasing switching frequency reduces current ripple at the cost of switching losses increase

High number of modules

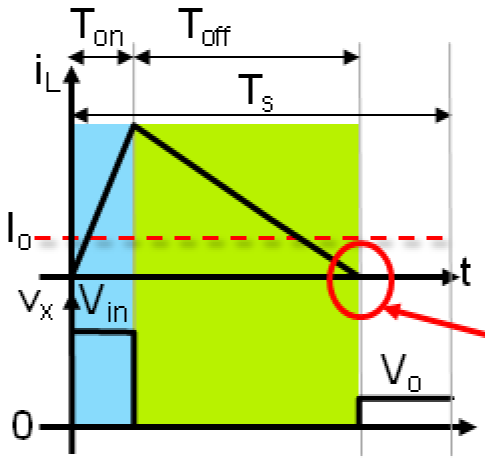
Discontinuous Conduction Mode

- High RMS value $i_L(t)$ → P_{cond} ↑
- Zero-current switching → P_{sw} ↓

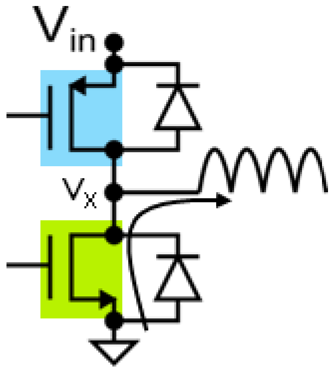
Edge DCM ↔ CCM

Inductor current zero-crossing detection:

Right T_{off} phase duration:

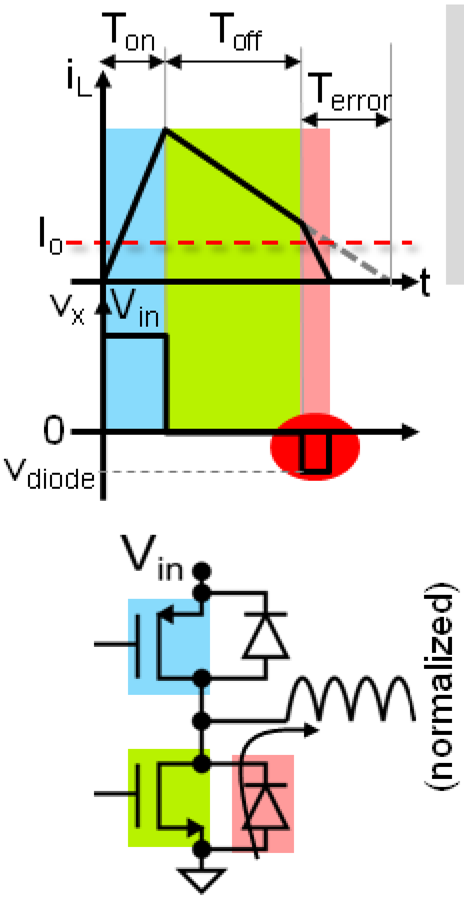


$i_L(t)=0$ detection ends T_{off}



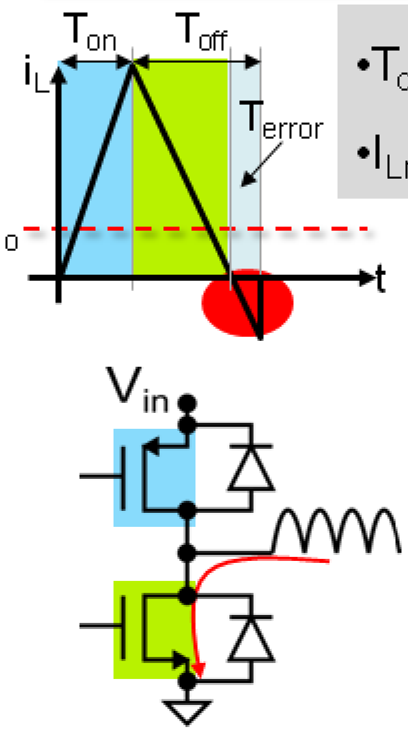
Inductor current zero-crossing detection:

Too short T_{off} phase:



- $T_{on}\uparrow \rightarrow I_{LRMS}\uparrow \rightarrow P_{cond}\uparrow$
- $I_{Lmax}\uparrow \rightarrow P_{sw}\uparrow$
- $i_L{*}V_{diode} \rightarrow P_{cond}\uparrow$

Too long T_{off} phase:



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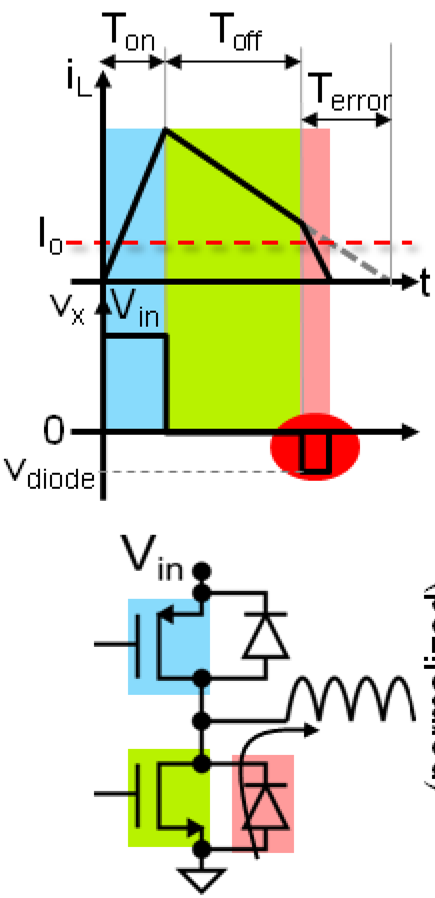

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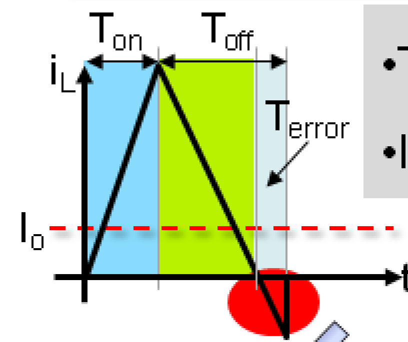

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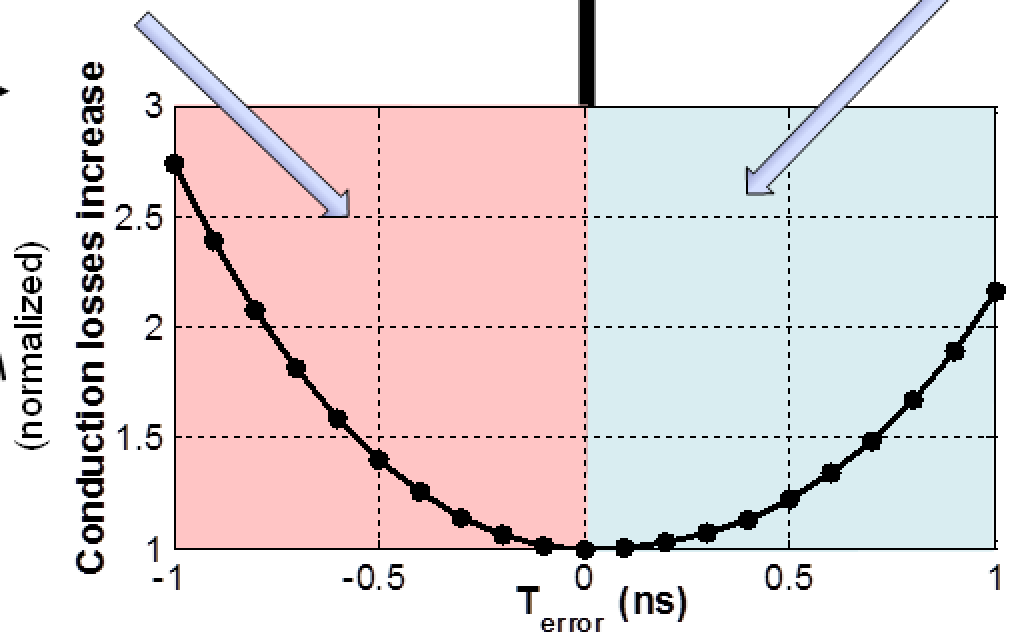
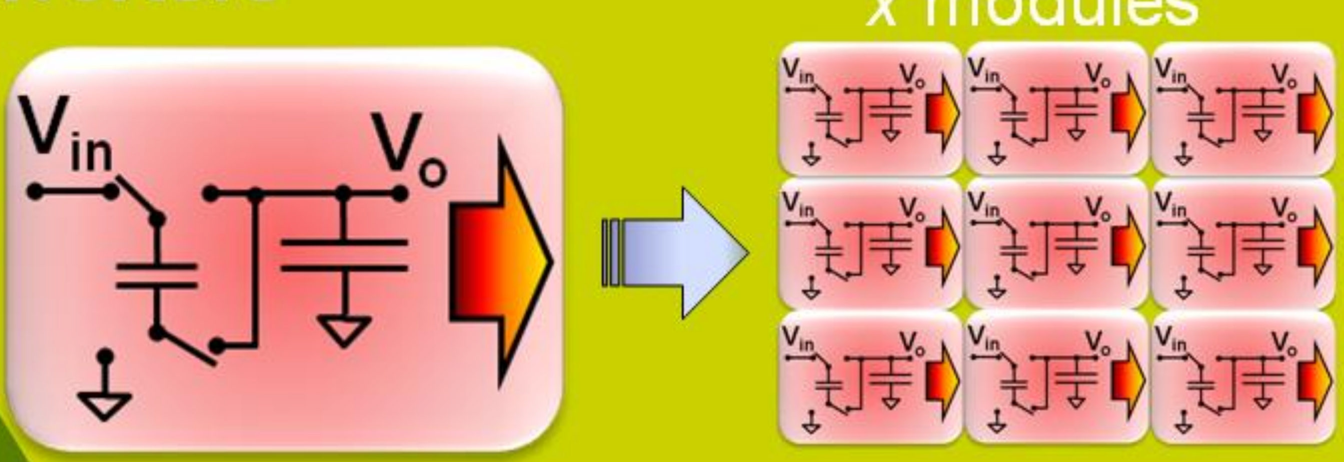


- V_{in}=1.8V
- V_o=1V
- I_o=100mA
- L=2nH
- C_o=7.5nF
- ▪1mm^2 (L and C_o)
- f_s=175MHz
- ΔV_o=5%
- R_{on}=0.1Ω; R_L=0.38Ω
- V_{diode}=0.7V

Inductor current zero-crossing detection:

Very few dedicated i_L=0 detection circuits found for fully integrated inductive converters

Scalability of switched-capacitor converters

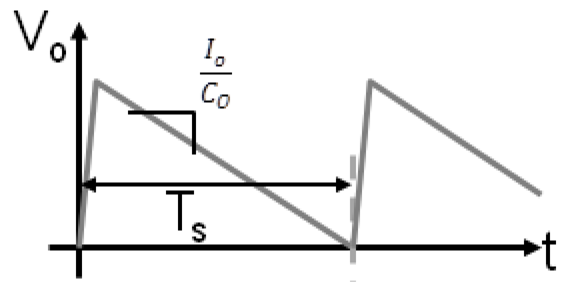


Scalability of switched-capacitor converters (I)

Split the converter into ‘x’ modules:

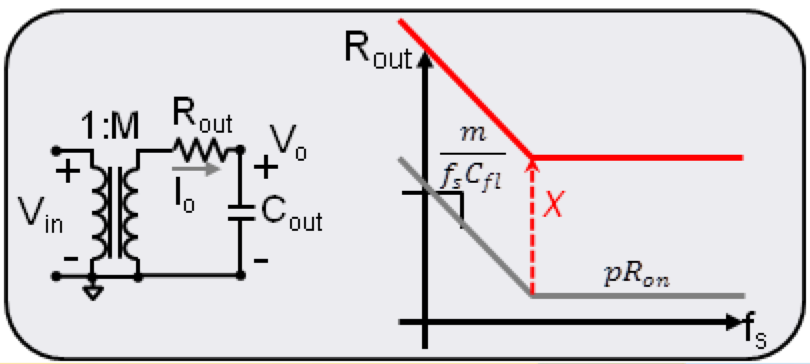
- Scale size of C_o, to keep constant ΔV_o at constant f_s:

$$\Delta V_o = \frac{I_o}{f_s C_o} \xrightarrow{I_o \rightarrow \frac{I_o}{x};\, C_o \rightarrow \frac{C_o}{x}} \Delta V_o = ct.$$



- Output impedance:

$$R_{out} = \sqrt{\left(\frac{m}{f_s C_{fl}}\right)^2 + (pR_{on})^2} \xrightarrow{R_{on} \rightarrow xR_{on};\, C_{fl} \rightarrow \frac{C_{fl}}{x}} R_{out} \sim x$$



- Output power:

$$P_o = MV_{in} I_o - I_o^2 R_{out} \xrightarrow{I_o \rightarrow \frac{I_o}{x};\, R_{out} \rightarrow xR_{out}} P_o \sim \frac{1}{x}$$

Scalability of switched-capacitor converters (II)

- Conduction losses:

$$P_{cond} = I_o^2 R_{out} \xrightarrow{I_o \to \frac{I_o}{x};\, R_{out} \to x R_{out}} P_{cond} \sim \frac{1}{x}$$

- 'Bottom-plate' losses:

$$P_{bot} = f_s V_{in}^2 C_{bot} \xrightarrow{C_{bot} \to \frac{C_{bot}}{x}} P_{bot} \sim \frac{1}{x}$$

- Since switches become smaller driving switching losses will also scale down: $\rightarrow P_{sw} \sim \frac{1}{x}$

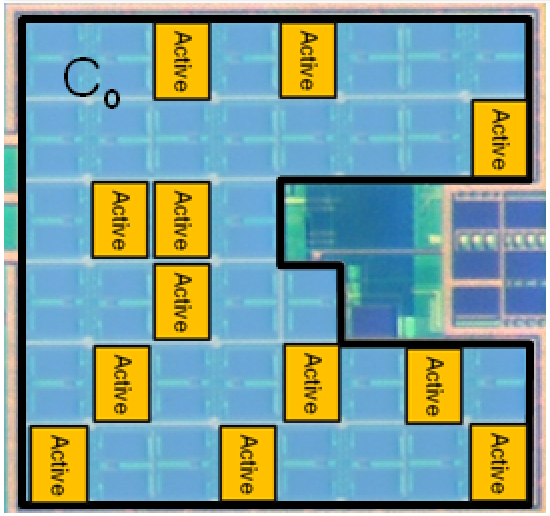
Efficiency of switched-capacitor converters will remain constant when scaling output power and size

$$\eta = \frac{P_o}{P_o + P_{cond} + P_{bot} + P_{sw}}$$

Multiphase designs

Multiphase has been applied to inductive & SC

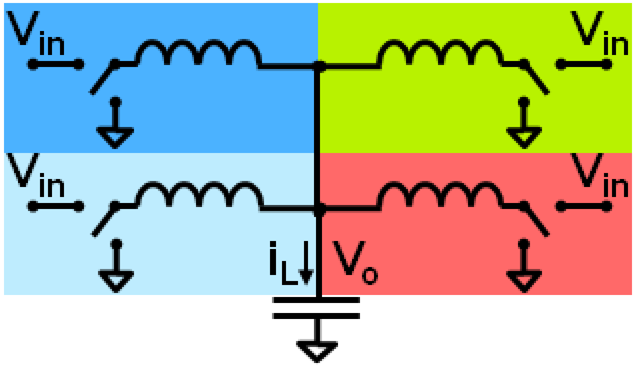
Switched-capacitor:

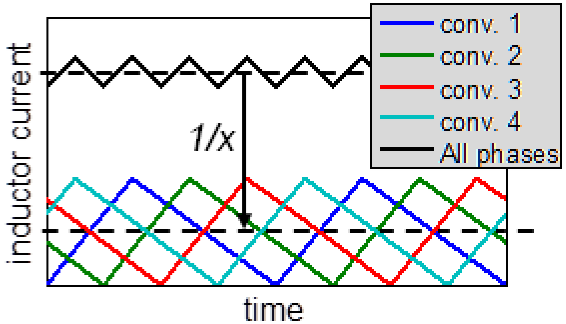


41 modules → Each module[*1]:
- I_o=200µA
- V_{in}=1.6V
- V_o=0.7V
- η=78%
- 0.004mm²

$$C_o = C_T - \frac{C_T}{x} \rightarrow \Delta V_o = \frac{I_o}{f_s C_T (x-1)}$$

Inductive:





- **Effective i_L** → *X* times higher frequency

→ *X* times lower amplitude

$$\Delta V_o \sim \frac{1}{x^2}$$

[*1] Gerard Villar Piqué; ISSCC'12

Multiphase has been applied to inductive & SC

Output capacitance is also determined by the required output impedance

Only applicable to power distribution case 2 (shared output node)

Conclusions

Conclusions

- **No clear advantage** for either kind of converter **in terms of efficiency vs. power density**.
- All the reported integrated inductive converters concentrate in the high range of output power.
- **Inductive converters don't scale size and output power as well as switched capacitor converters.**
- **Switched-capacitor power converters look more promising for distributed power supplies**.
- Multiphase approach improves the performance of both kind of converters but it can not always be applied.

Thank You!

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