Distributed Power Architectures in Computing Systems

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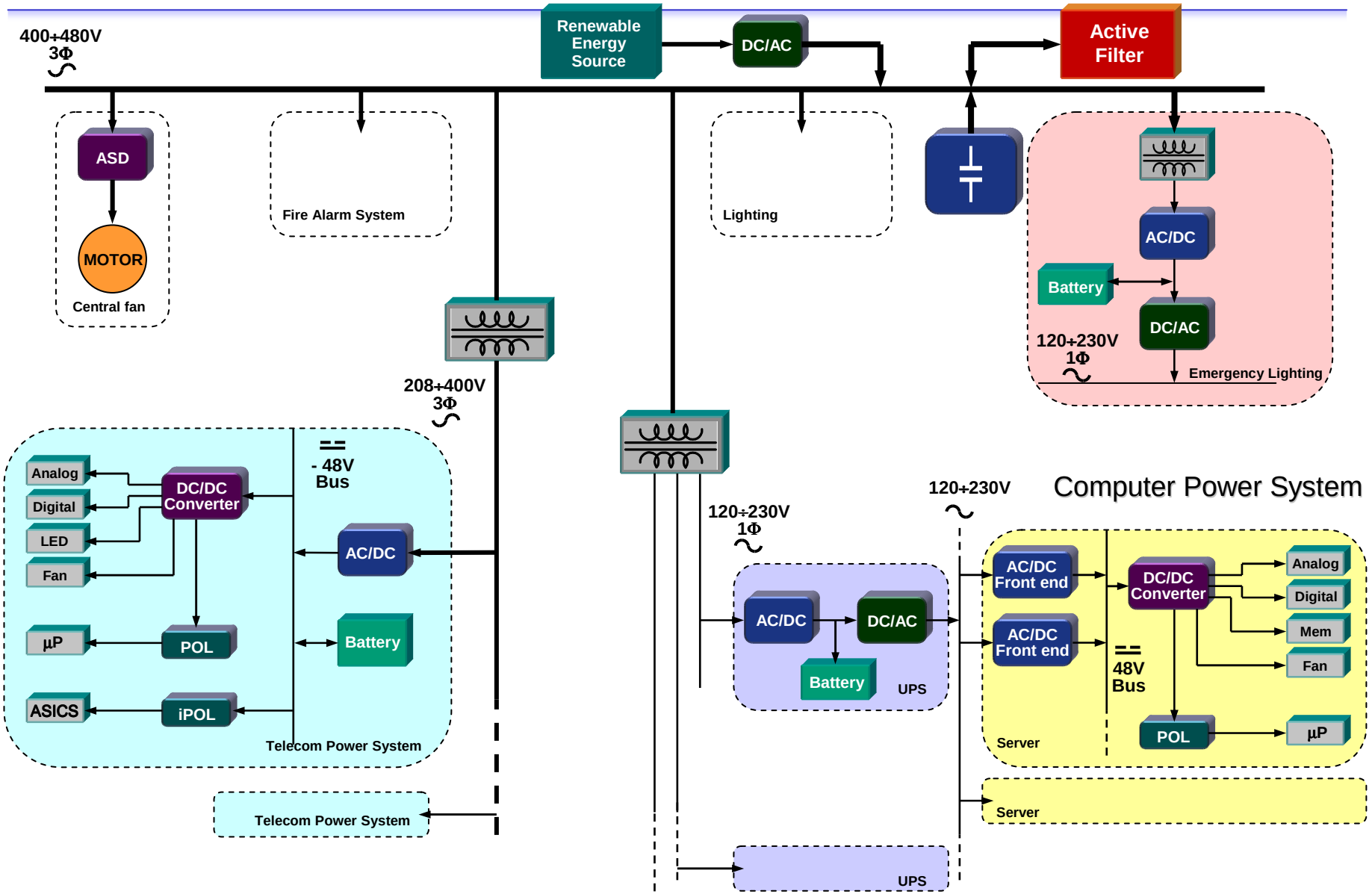
Outline

- Conversion system architectures for DPS
  - Unregulated Intermediate Bus Converters (IBC)
  - Regulated Intermediate Bus Converters
- Isolated Point of Load converters (POLs)
- Non isolated POL: buck interleaved
- Digital control for high-frequency power conversion in Distributed Power Systems: current research activity at the University of Padova

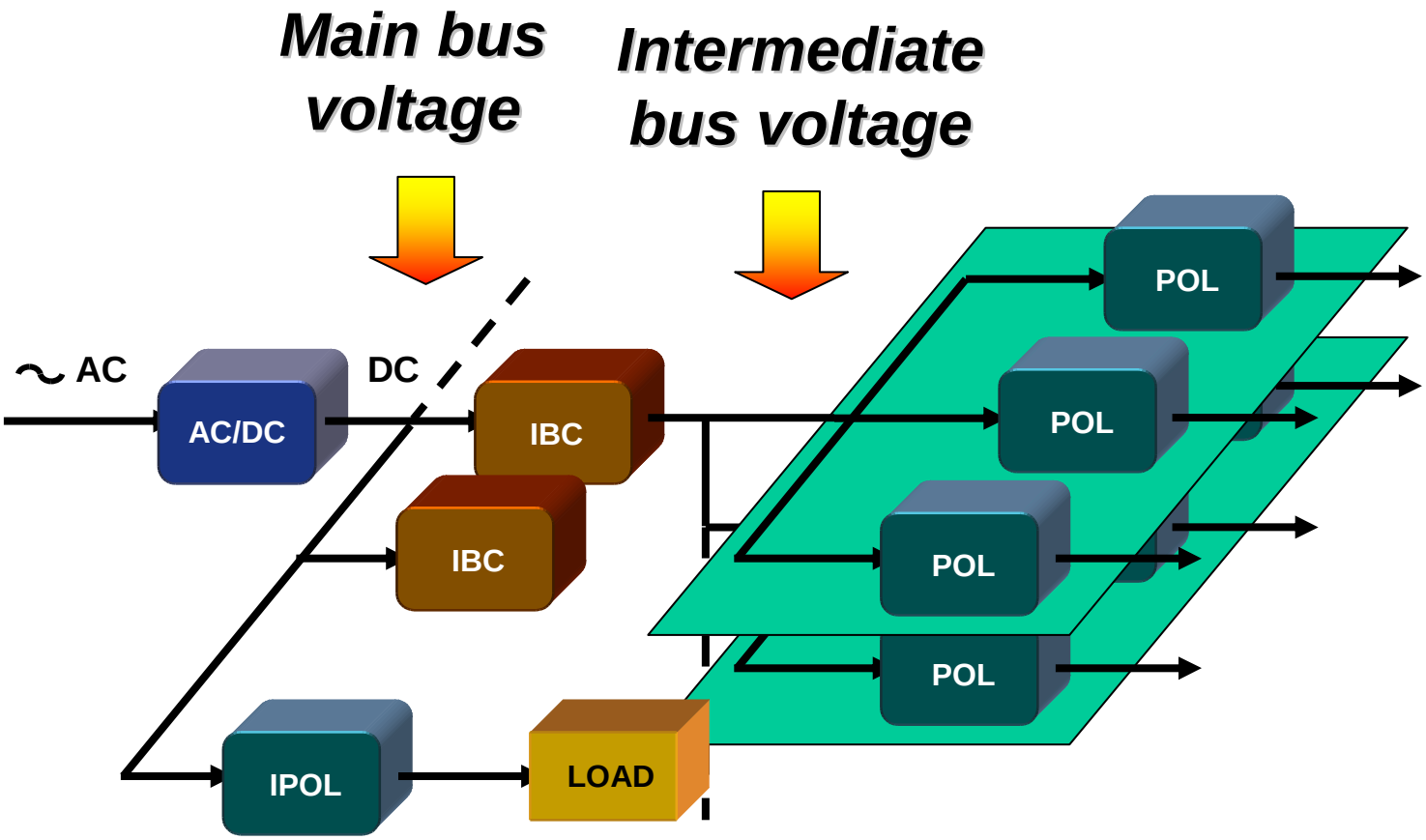
Power Distribution Problem



Power Distribution Problem

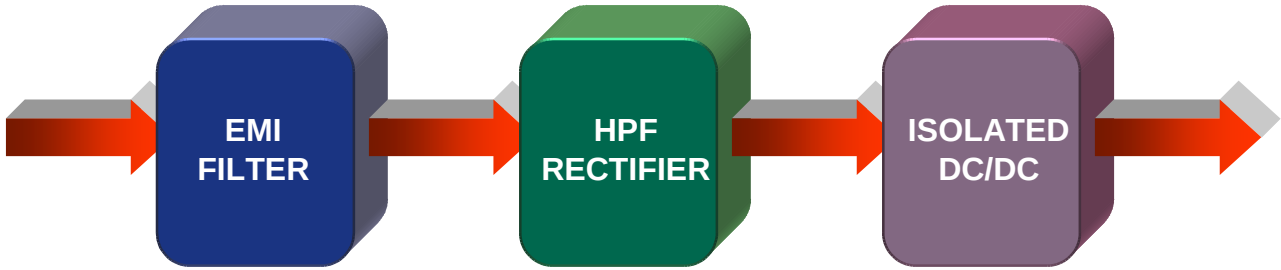
- Very complex Power Management Architectures in Computing & Networking Systems
  - Many low voltage, high current and tightly regulated voltage sources
  - Accurate management for sequencing, tracking and fault management
  - High Power density needed for real estate saving and Thermal management issues
  - Low cost always mandatory in high volume applications

Distributed Power Architectures



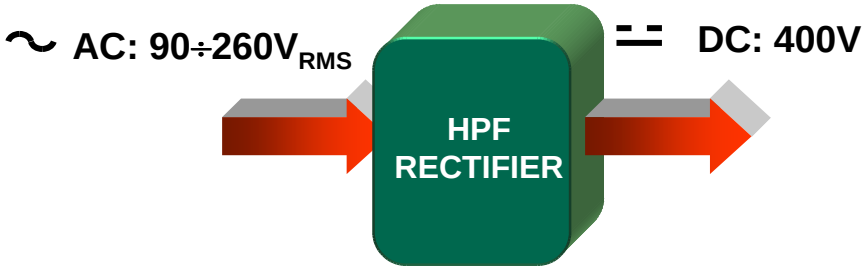
IBC = Intermediate Bus Converter
POL = Point Of Load converter

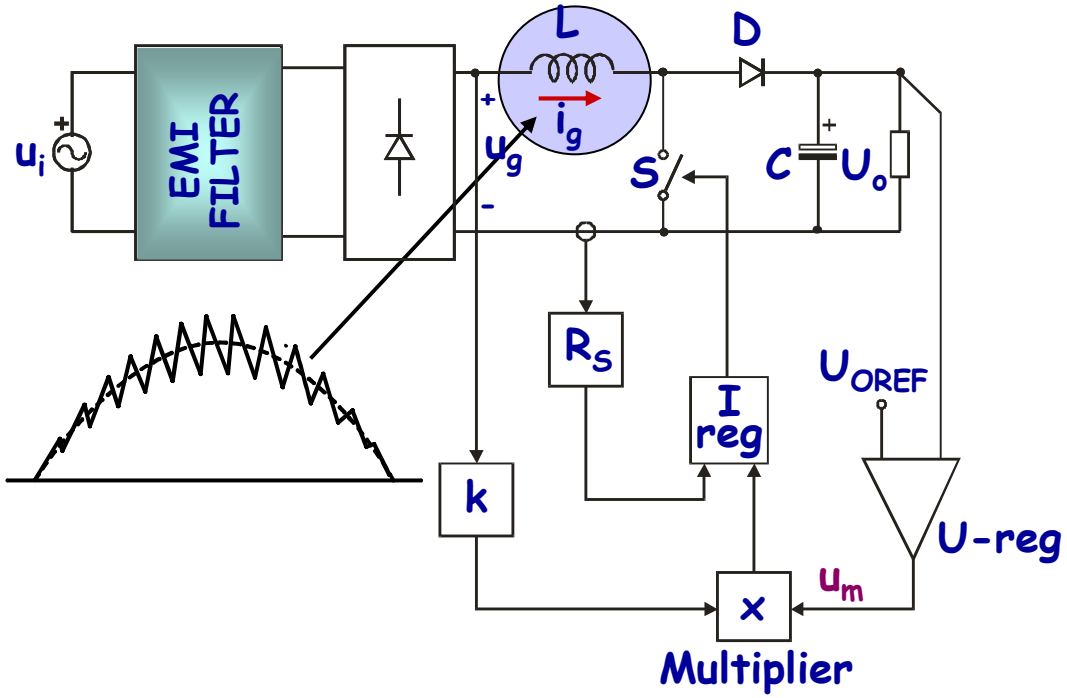
AC-DC Front End



- EMI filter for attenuate high-frequency noise (both conducted and radiated) produced by the switching converters
- High-Power-Factor (HPF) rectifier for low-frequency harmonic standard compliance
- Isolated DC/DC converter for electrical isolation with the main and voltage scaling

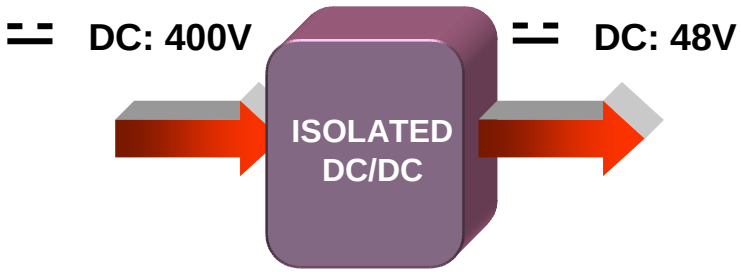
HPF Rectifier

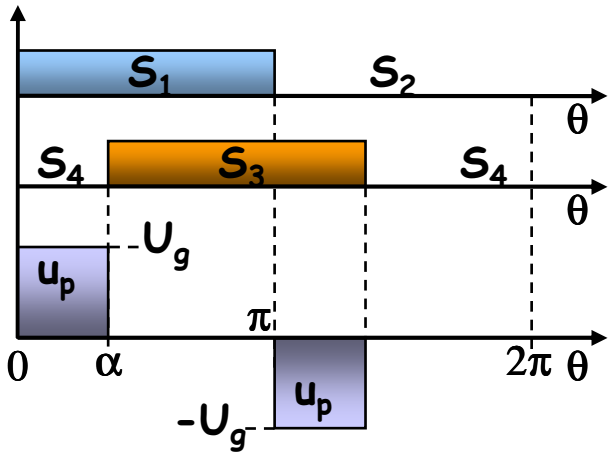


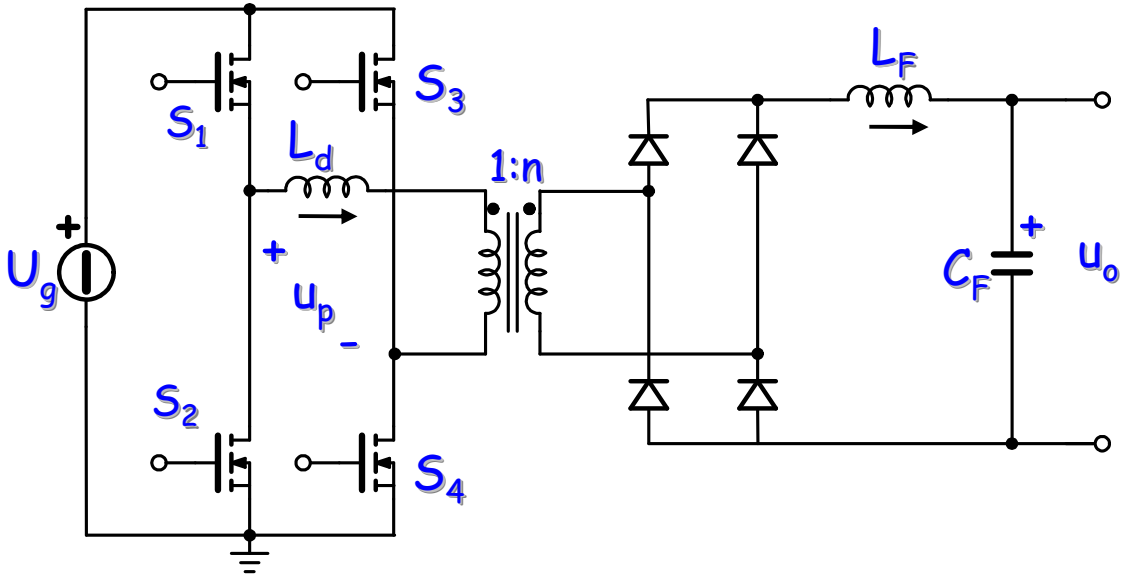


- Boost converter in CCM
- Average current mode
- High power factor
- Output voltage higher than peak input voltage
- Dedicated control IC available

Isolated DC/DC

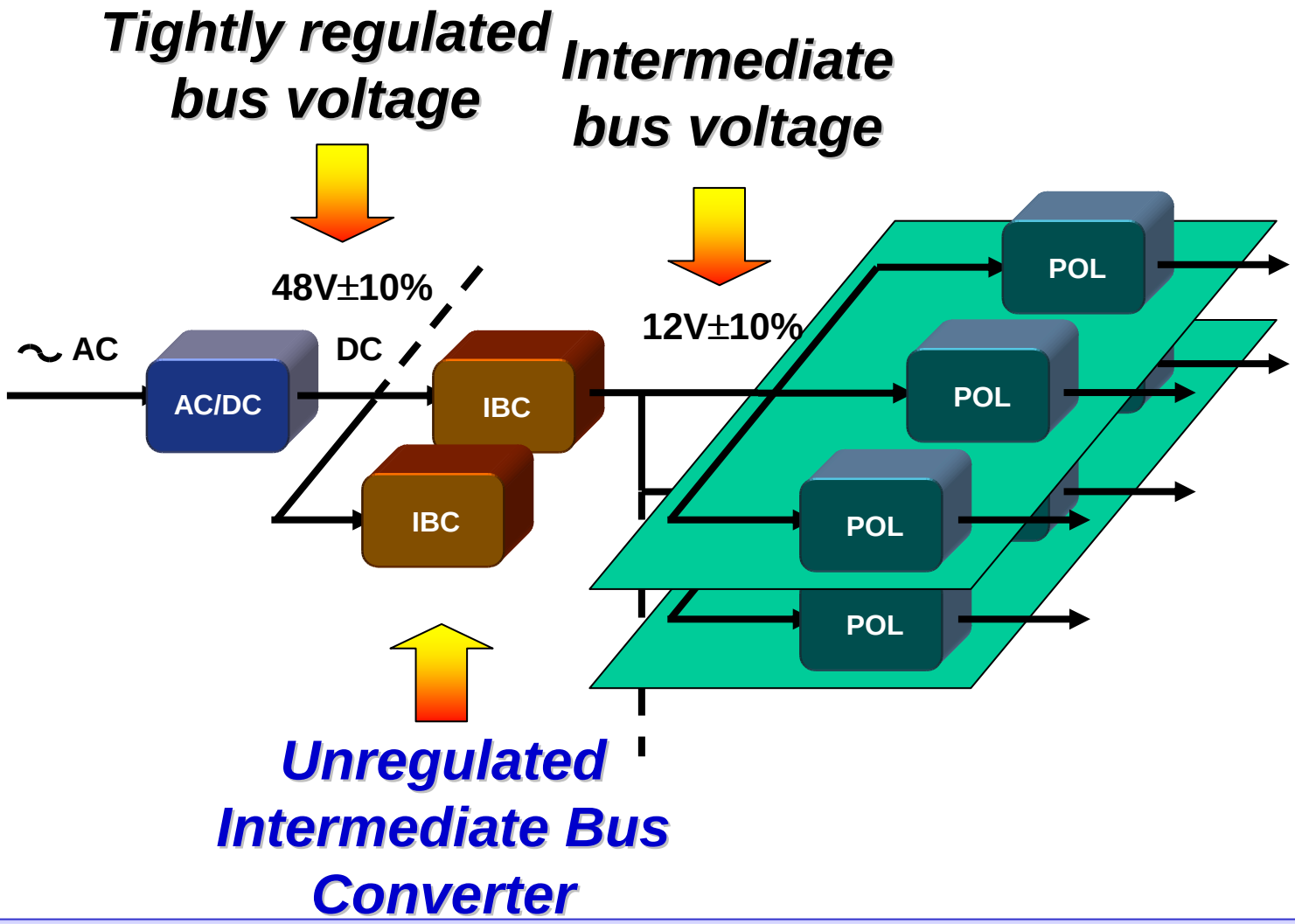






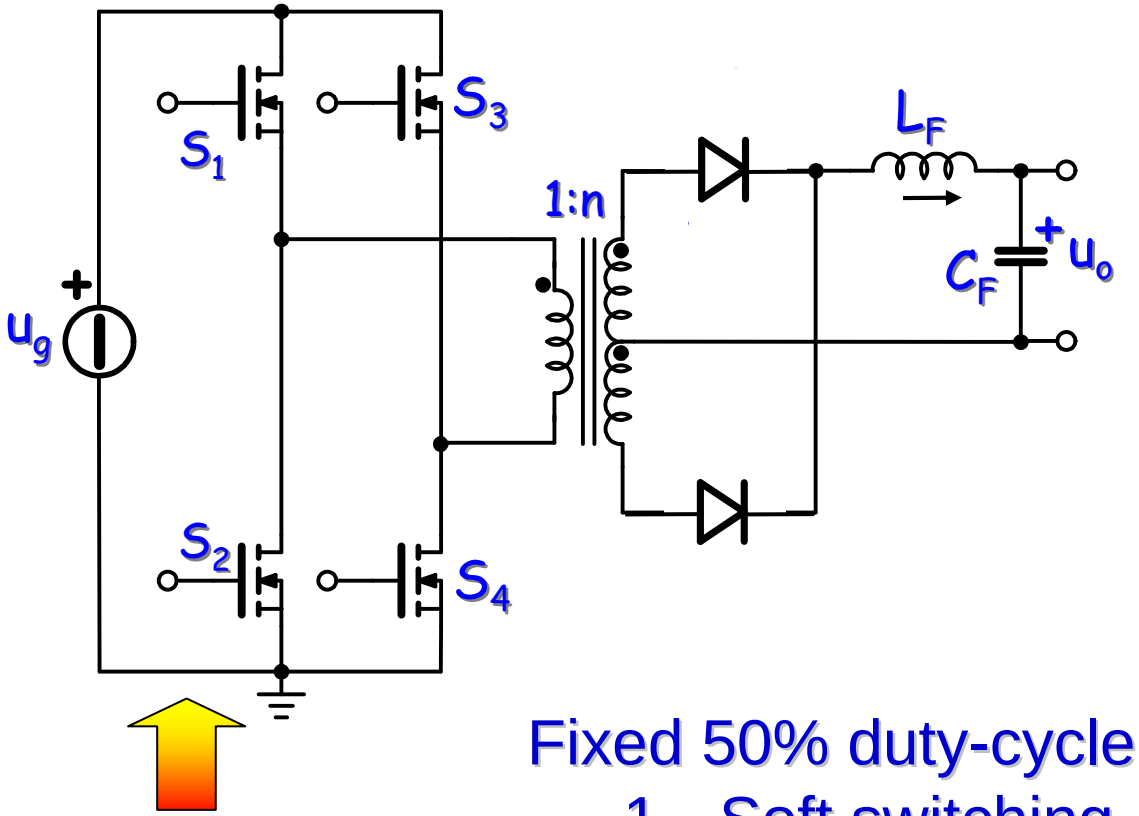
- Phase-shift modulated Full-bridge converter
- Soft switching operation exploiting the transformer leakage inductance

Narrow Input IBCs



Example of Unregulated IBC

IBC



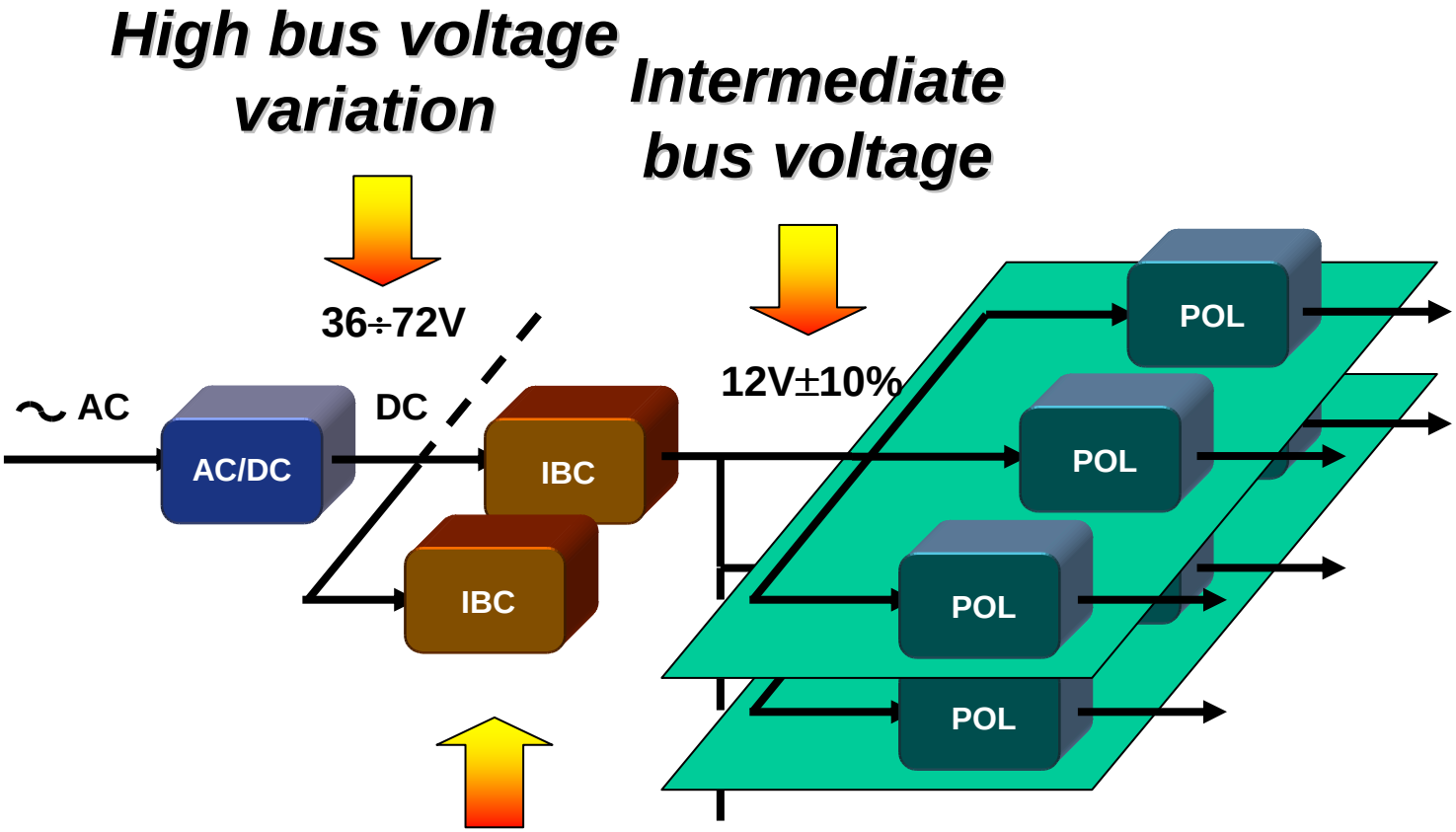
Full-bridge, half-bridge or push-pull primary stage

Fixed 50% duty-cycle:

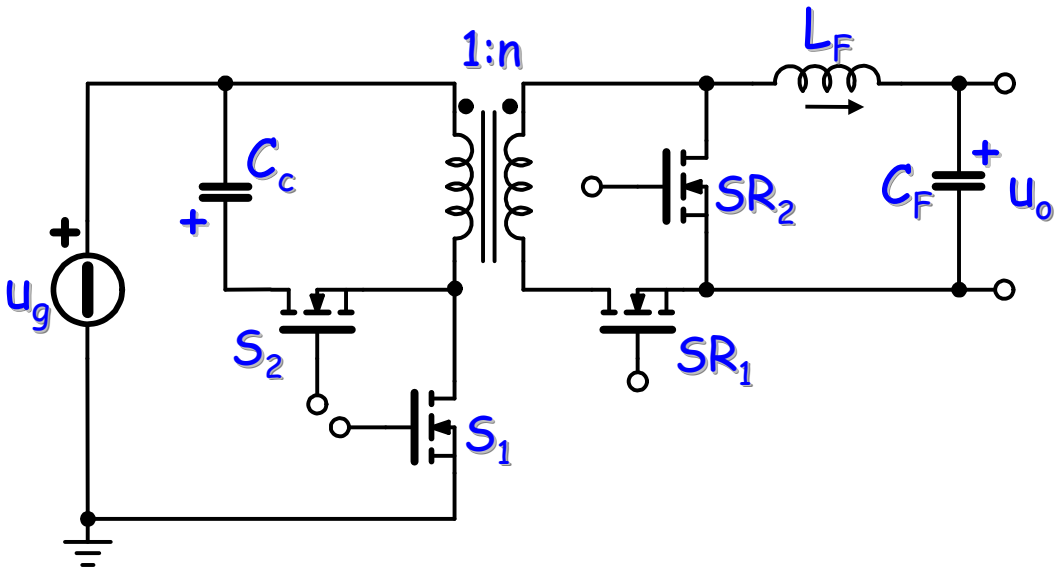
1. Soft switching
2. Small output inductor
3. Synchronous rectification

Open-loop operation

Wide Input IBCs



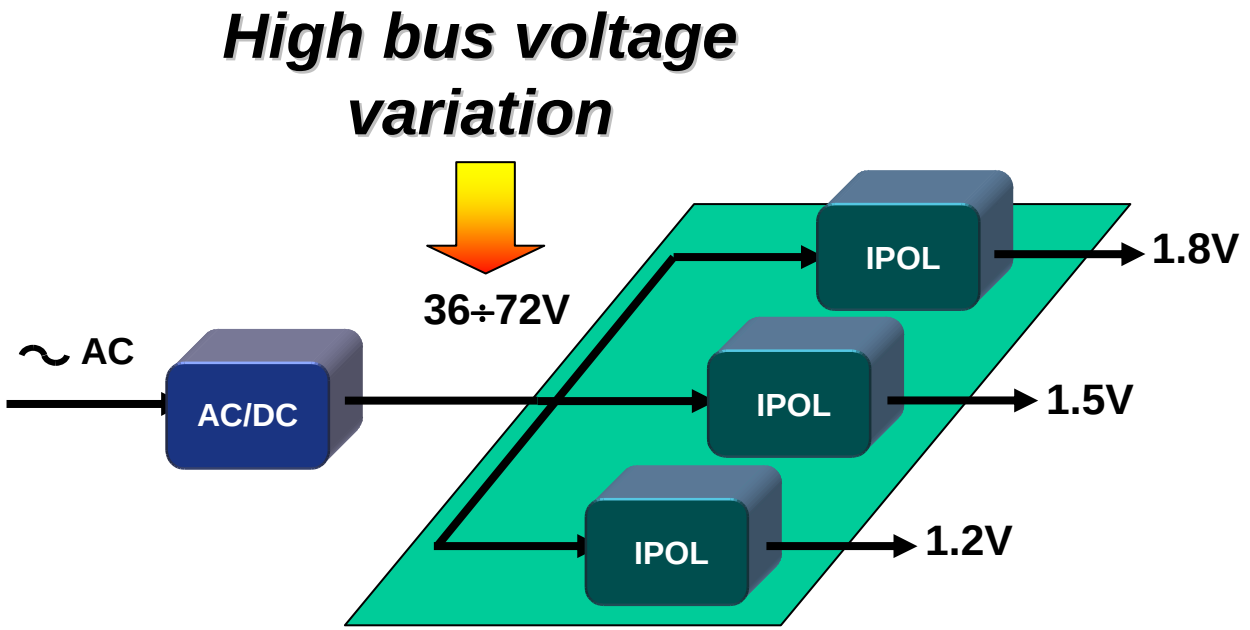
Example of Regulated IBC



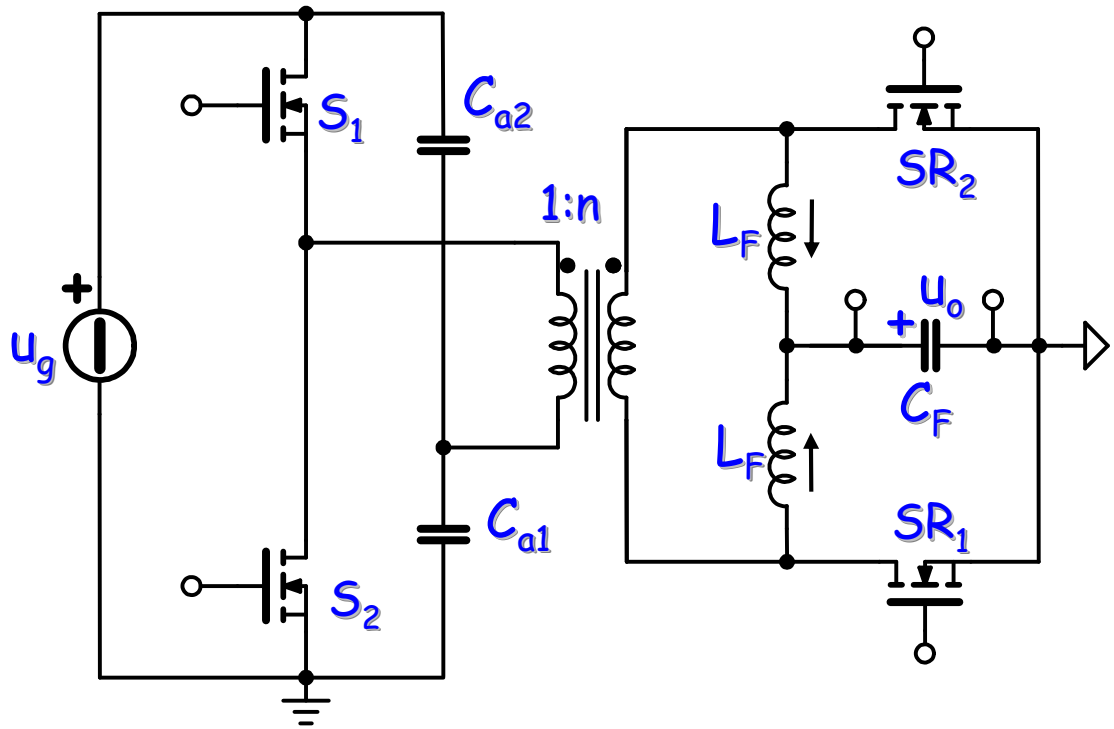
- **Active-clamped for soft switching**
- **Synchronous rectification**
- **Large output inductor**
- **High voltage rating device (60V) for SR**
- ***Switching frequency of the state-of-art: ~300KHz***

Isolated POLs

No intermediate bus voltage

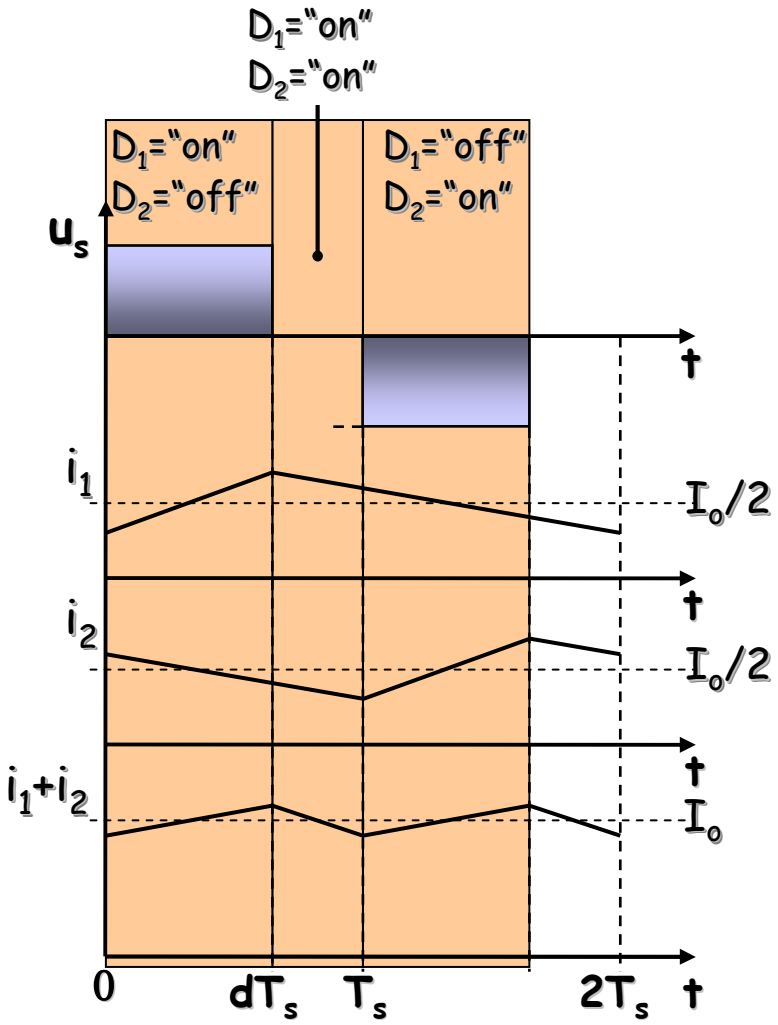


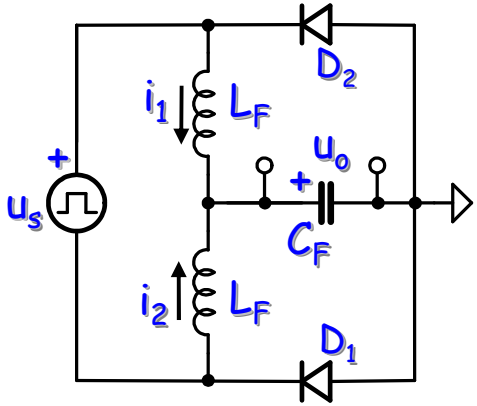
Example of Isolated POL



- Half bridge with current doubler
- Synchronous rectification

Current Doubler





- No center-tapped windings
- Current ripple cancellation
- Splitted load current between the two inductors

Non Isolated Point Of Load Converters

- Voltage Regulator Modules (VRMs)
  - Power trend
  - Interleaved buck converters
  - Current sharing
  - Adaptive voltage positioning
  - Digital control for high-frequency power conversion in Distributed Power Systems: current research activity at the University of Padova

VRM Intel Specifications

Specs VRD 10.x for Intel P4 Prescott

	VRD 10.0 –VRD 10.1
Maximum VID (Voltage Identification)	1.4V
Vcc Ratings (VID)	0.8375-1.6V
VID step	12.5mV
Vcc Tolerance Band (TOB)	± 19mV
Max Load Current	91A for VRD 10.0 115A for VRD 10.1
Voltage identification	6 bit
Over Voltage Protection	VID + 200mV (Proposed)
Over Current Protection	Not fixed (Proposed)
Maximum overshoot voltage allowed over VID	50mV
Maximum overshoot time duration over VID	25µs
Dynamic VID	Up to 61 steps (12.5mV/5µs)
dI_{OUT}/dt_{MAX}	>50A/µs
Load Line Impedance (R_{DROOP})	1mΩ /1.4mΩ

- Low supply voltage
- Small tolerance band
- High load current
- High current slew rate
- Resistive output impedance

Outline

- **Voltage Regulation Modules (VRM)**
  - Power trend
  - **Interleaved buck converters**
  - Current sharing
  - Adaptive voltage positioning
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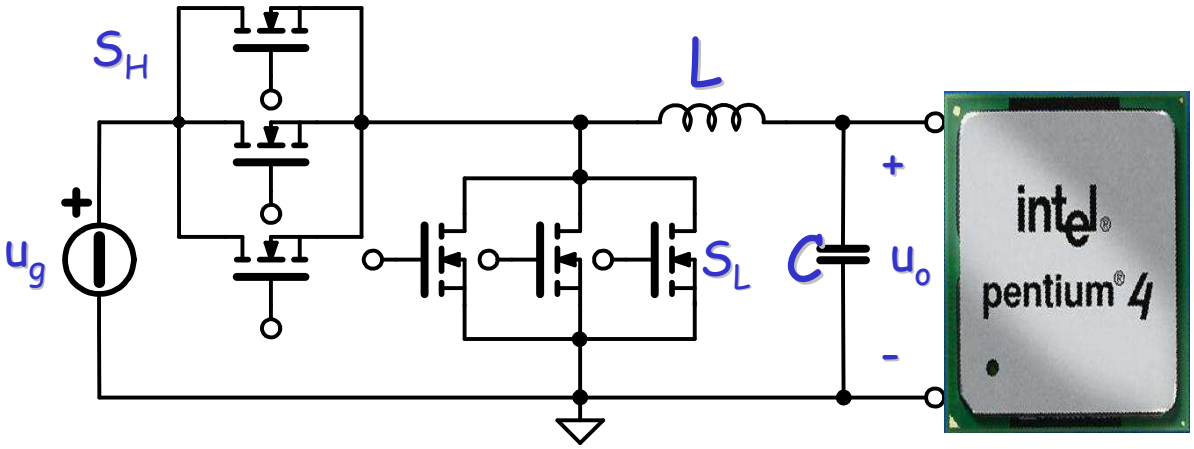
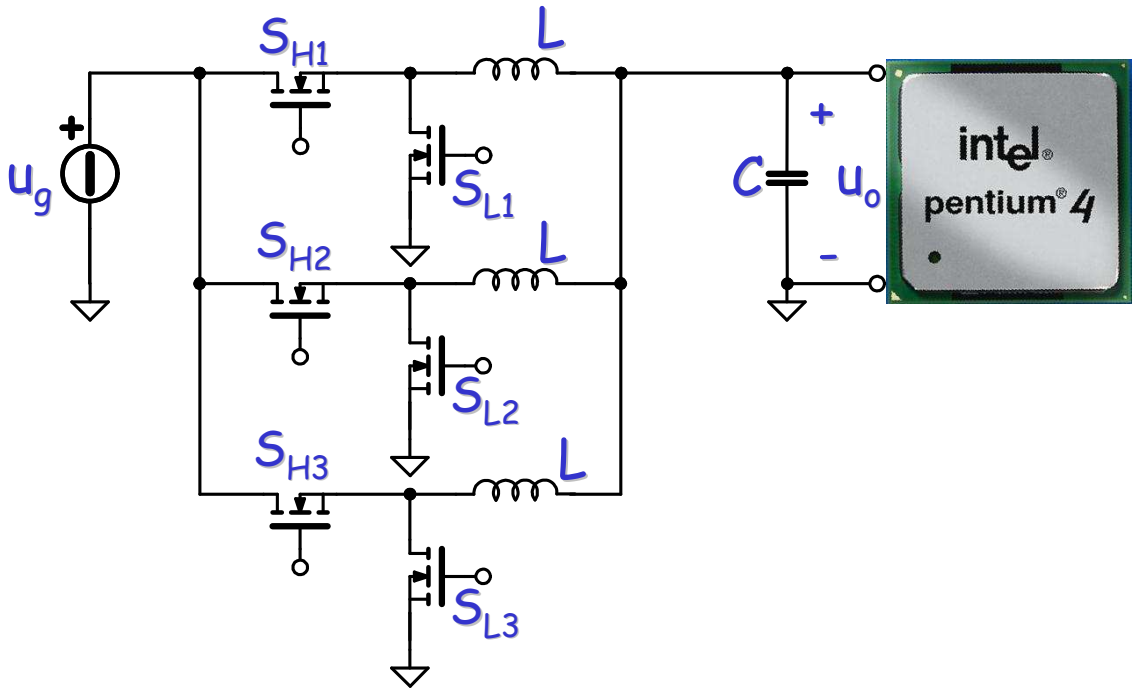
Single-Phase Synchronous Buck Converter

- High load current requires the use of parallel power MOSFETs or parallel power converters



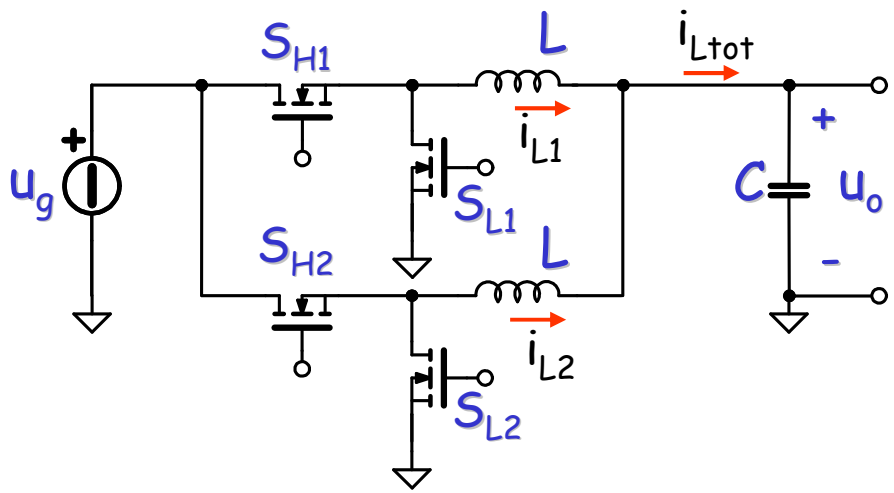
Parallel device approach is not convenient
since interleaved operation reduces output and input ripple

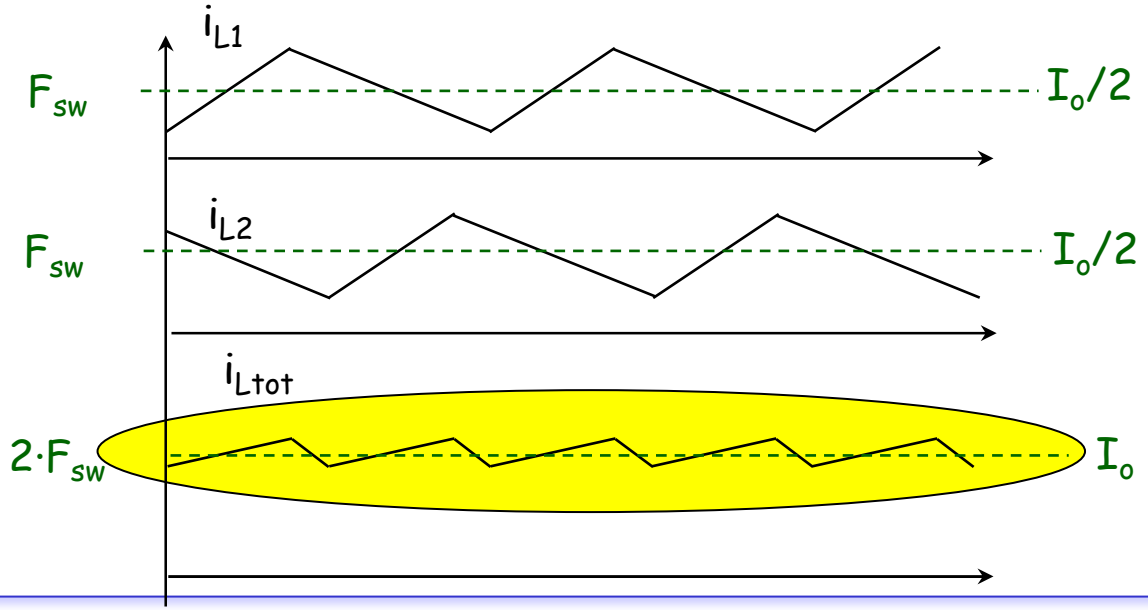
Multiphase Interleaved Buck Converters



- Reduced current level per phase
- Reduced output current ripple
- Reduced input current ripple
- Increased bandwidth (F_{eq}=N F_{sw})

Multi-Phase Interleaved Converters

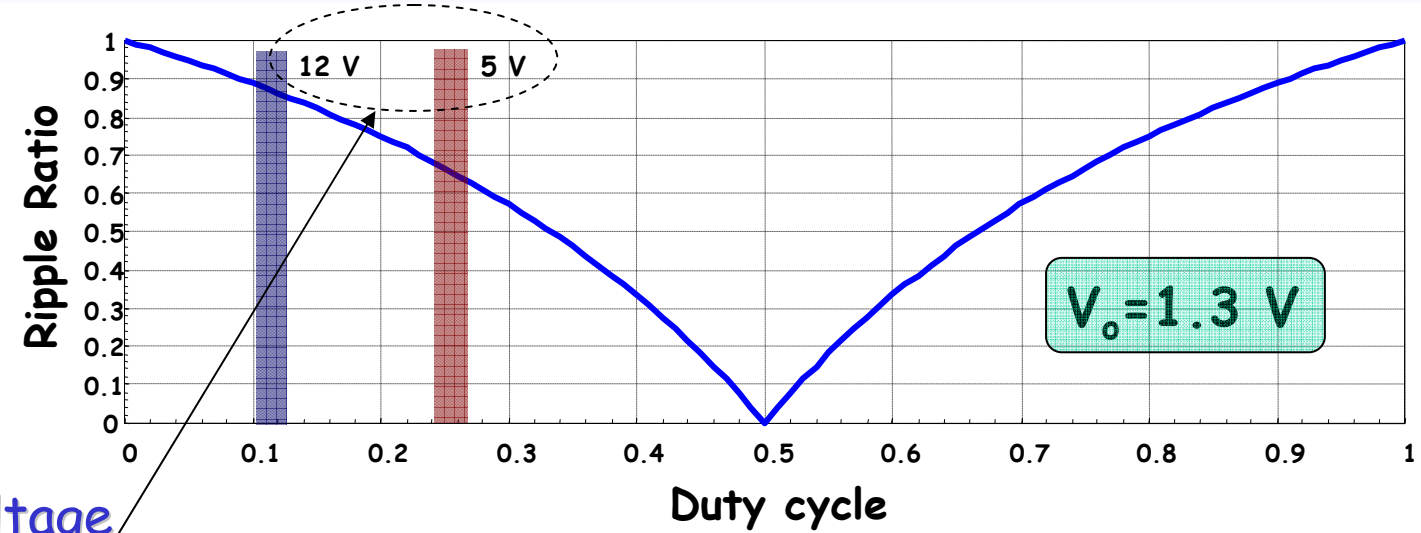




Ripple reduction on output filter

Output Current Ripple Cancellation

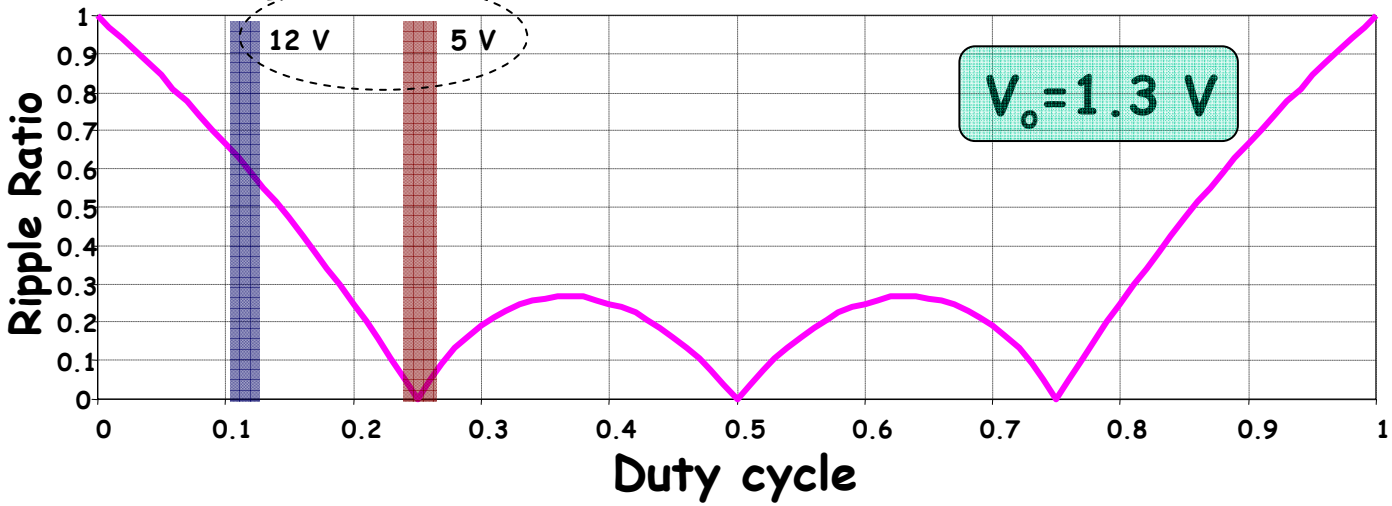
Two phases



Input voltage

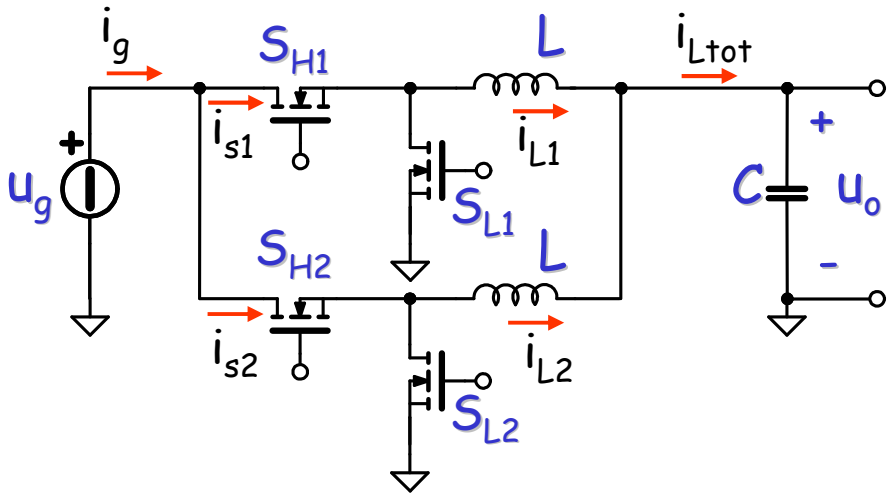
D=0.5 for the best cancellation effect

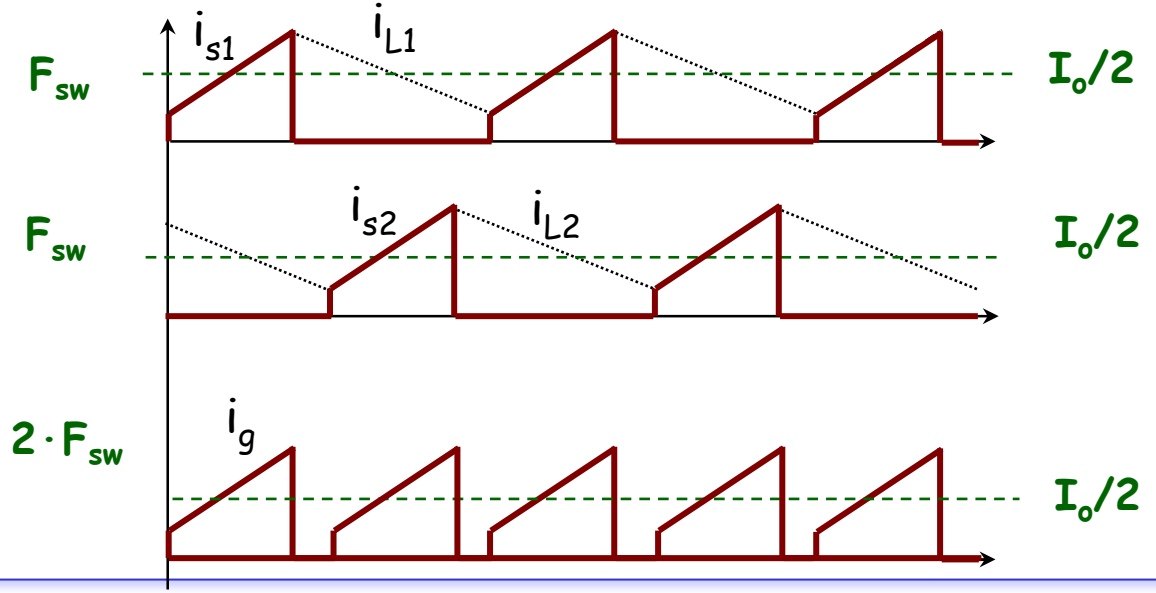
Four phases



D=0.25, 0.5, 0.75 for the best cancellation effect

Multi-Phase Interleaved Converters





Ripple reduction on input current (similar ripple cancellation effect)

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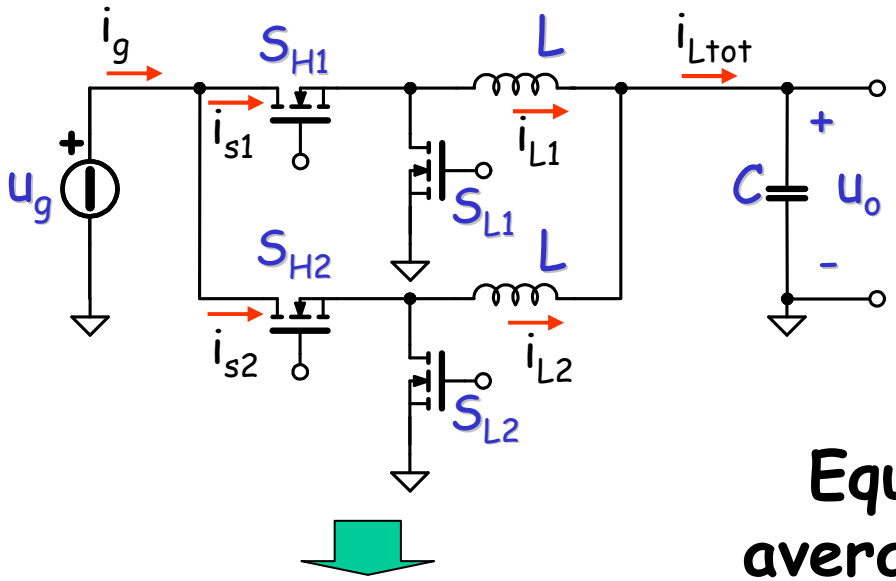
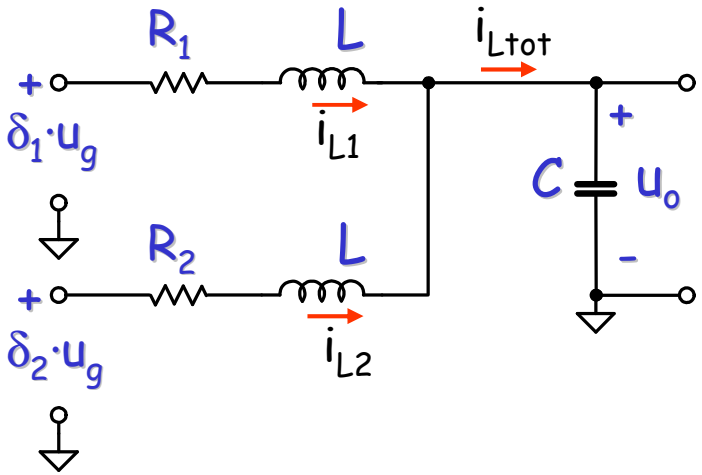
- **Voltage Regulation Modules (VRM)**
  - Power trend
  - Interleaved buck converters
  - **Current sharing**
  - Adaptive voltage positioning
- Digital control for high-frequency power conversion in Distributed Power Systems: current research activity at the University of Padova

Current Sharing in Parallel Channels



Equivalent average model



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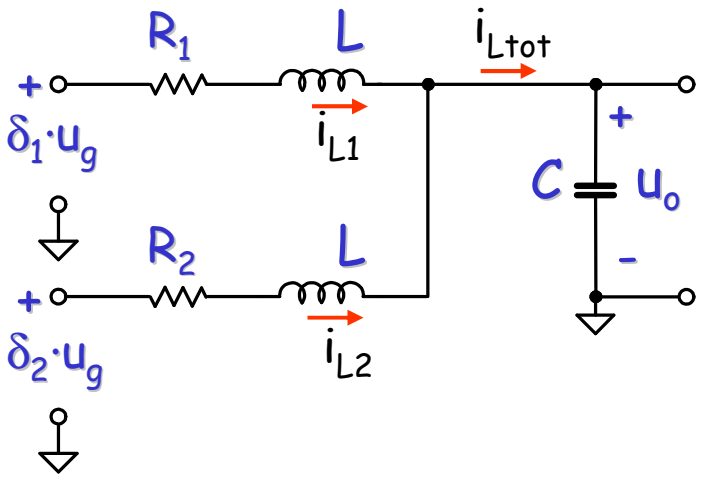


k-channel resistance

$$R_k = R_{dsonk} + R_{Lk} + R_{PCBk}$$

- R_{dsonk}: Mosfet R_{dson}
- R_{Lk}: inductor resistance
- R_{PCBk}: trace resistance (PCB layout)

Dc inductor current mismatch:

$$\Delta i_L = i_{L1} - i_{L2} = 2u_g \frac{\delta_1 - \delta_2}{R_1 + R_2} \left(\frac{1 + \frac{R_2\delta_1 - R_1\delta_2}{2(\delta_1 - \delta_2)} \cdot \frac{1}{R_L}}{1 + \frac{R_1 R_2}{R_1 + R_2} \cdot \frac{1}{R_L}} \right)$$

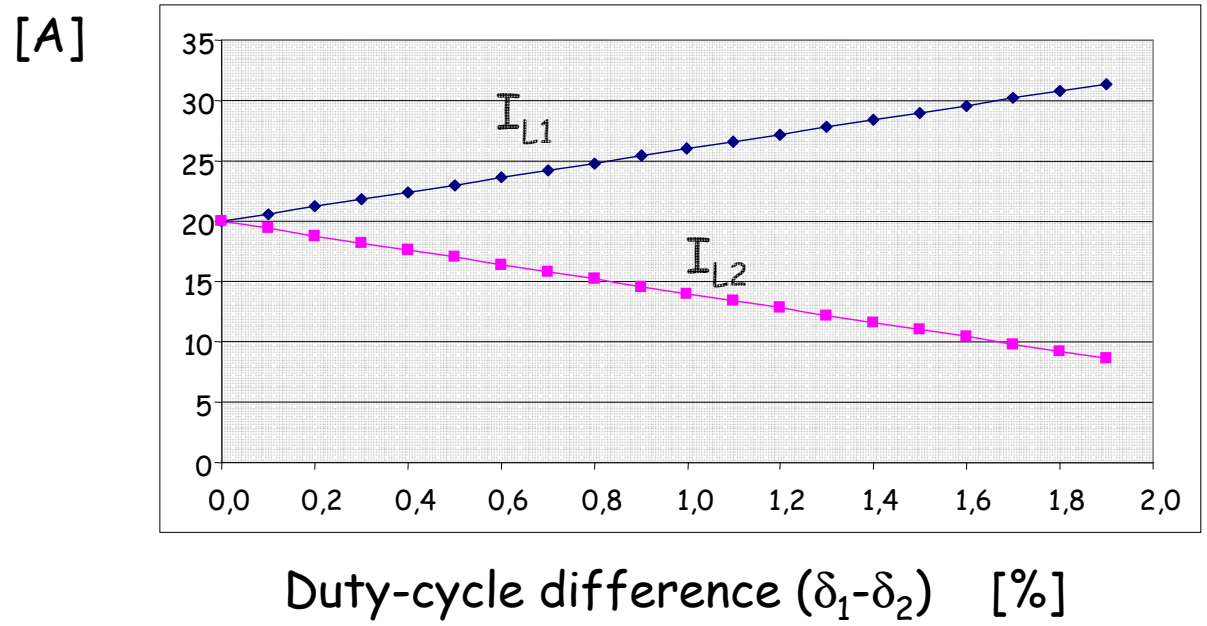
R_L = load resistance

- Unmatched duty cycle
- Unmatched channel resistance

Current Sharing in Parallel Channels

- Even small mismatches of duty-cycle or of channel resistance generate serious current sharing issues
- Example with unmatched duty-cycles:

V_{in}=12V, R_1=R_2=10mΩ, I_o=40A, two channels



- Similar results for small unmatched channel resistances (spread of MOSFET R_{dson}, difference on PCB layout, etc..)

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  - Current sharing
  - **Adaptive voltage positioning**
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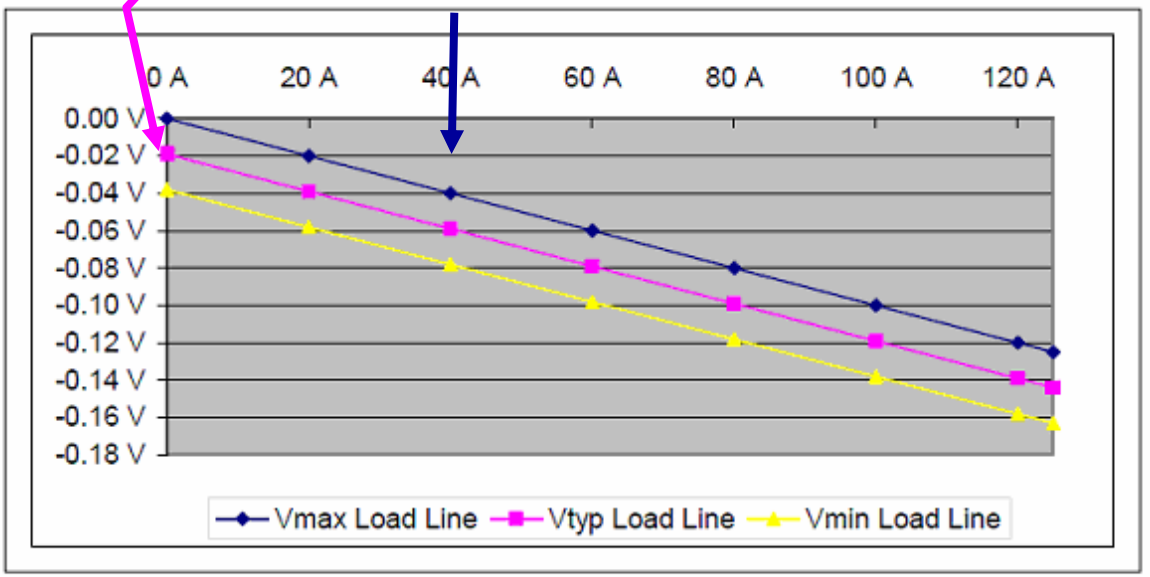
dI_{OUT}/dt_{MAX}	>50A/µs
Load Line Impedance (R_{DROOP})	1mΩ /1.4mΩ

Resistive output impedance

$$V_{TYP,out} = VID - |TOB| - R_{DROOP} \cdot I_{load}$$



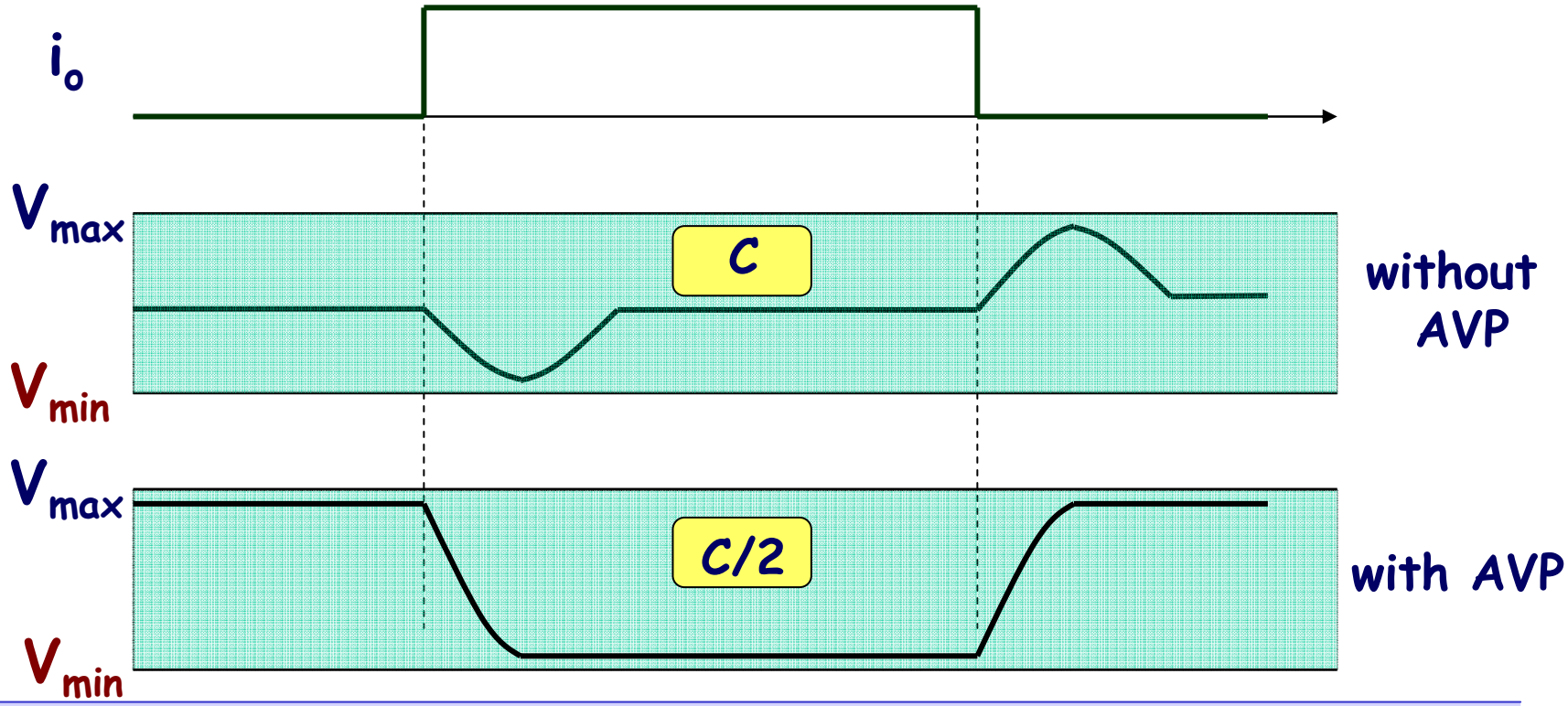
NOTE: 1: Presented as a deviation from VID

2: Socket load line Slope = 1.0 mOhms, TOB = +/-19 mV

"Droop Function" or "Adaptive Voltage Positioning"

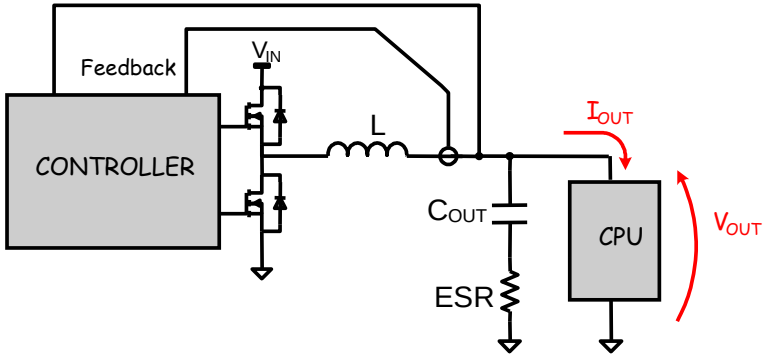
Adaptive Voltage Positioning

- Adaptive voltage positioning (AVP) is required by VRM specs
- AVP is very effective on reducing VRM output caps:
  - For given output caps, output voltage variation is halved
  - For a given output voltage tolerance, output caps are halved

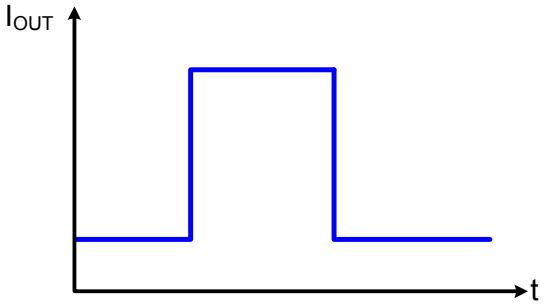


Adaptive Voltage Positioning

- AVP is realized by VRM resistive output impedance
- Number of parallel electrolytic caps is determined by condition: ESR = R_{droop}

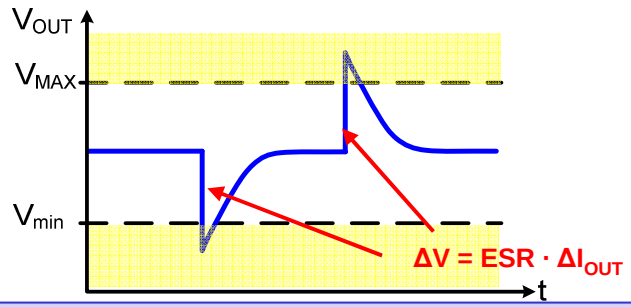


Load step variations

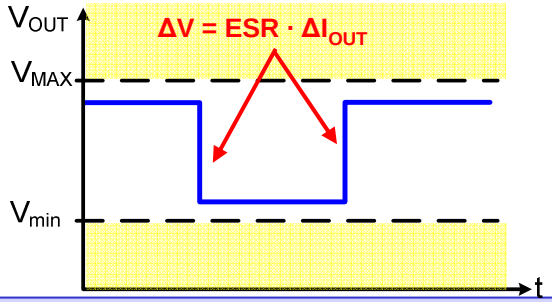


Output voltage

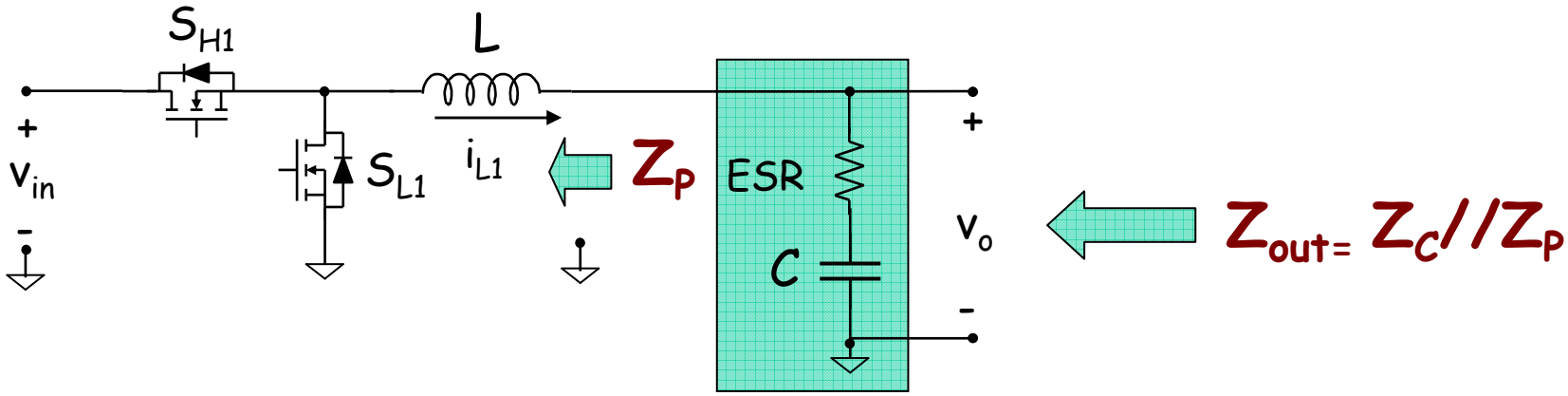
without Droop Function

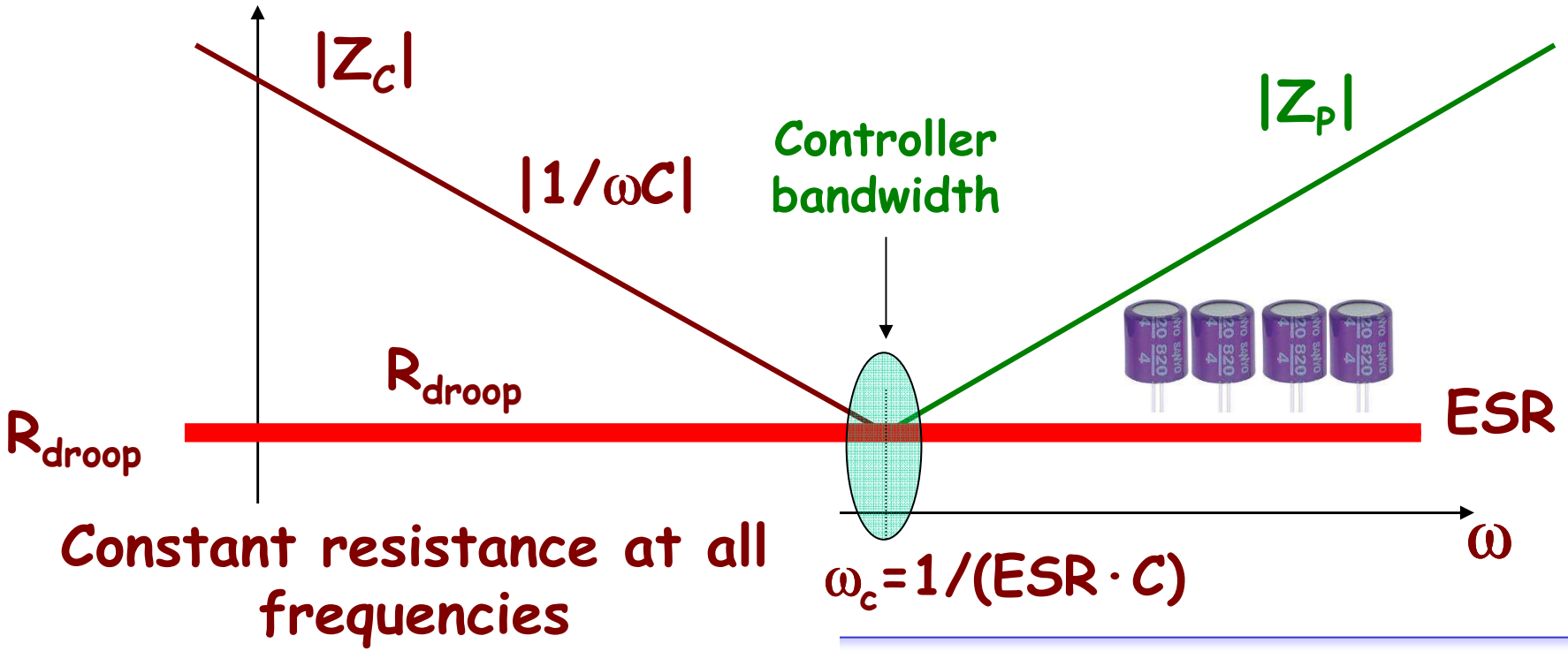


with Droop Function

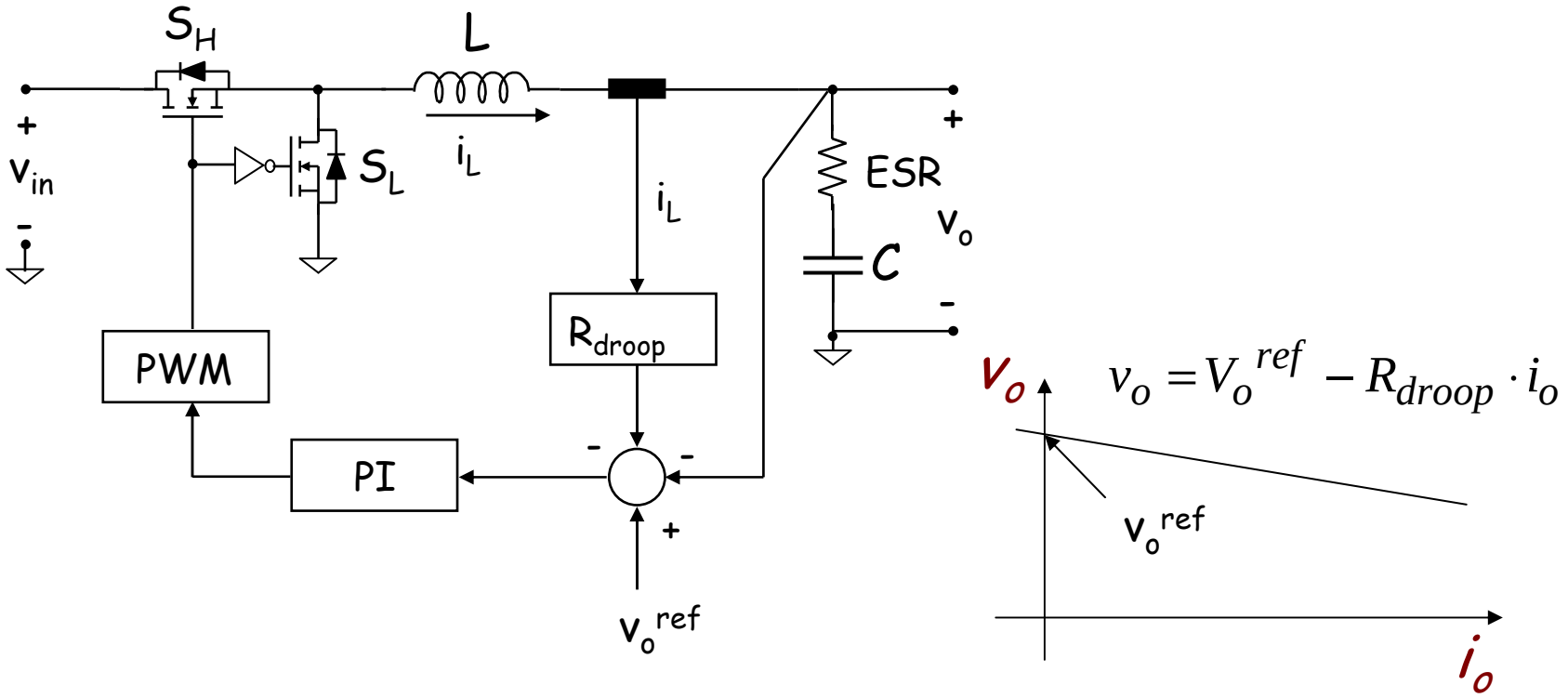


Constant Resistive Output Impedance



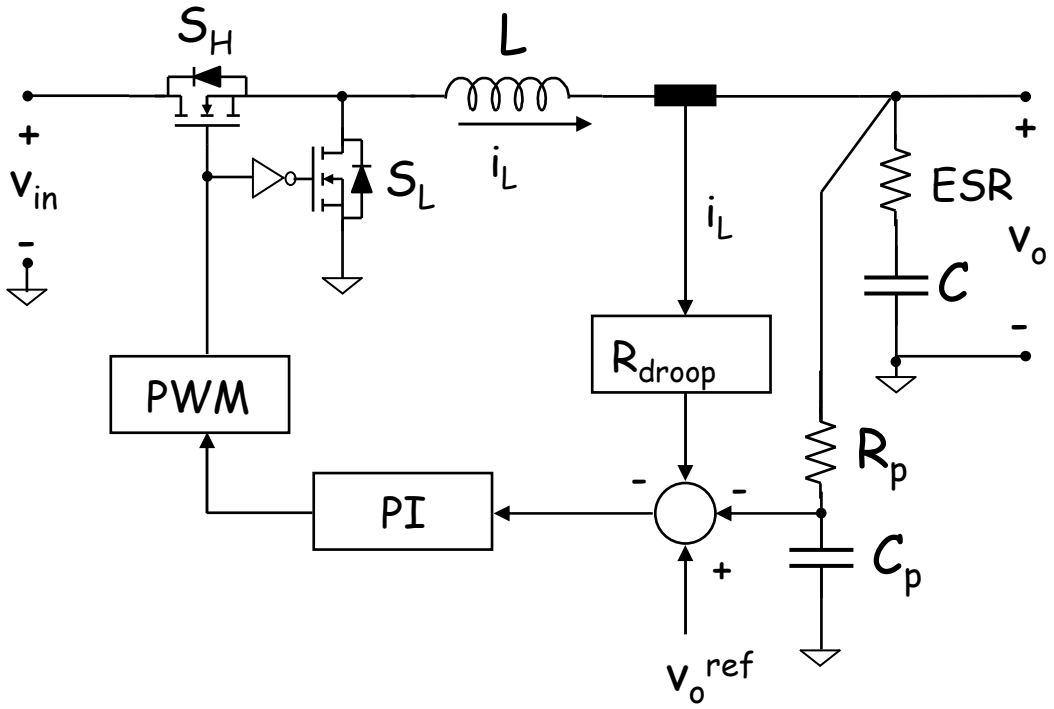


AVP: Control Block Diagram



- Closed-loop control on $v_T = v_o + R_{droop} \cdot i_L$
- PI design so as to impose controller bandwidth $\omega_c = 1/(ESR \cdot C)$ (theoretically no need for high-performance controller)

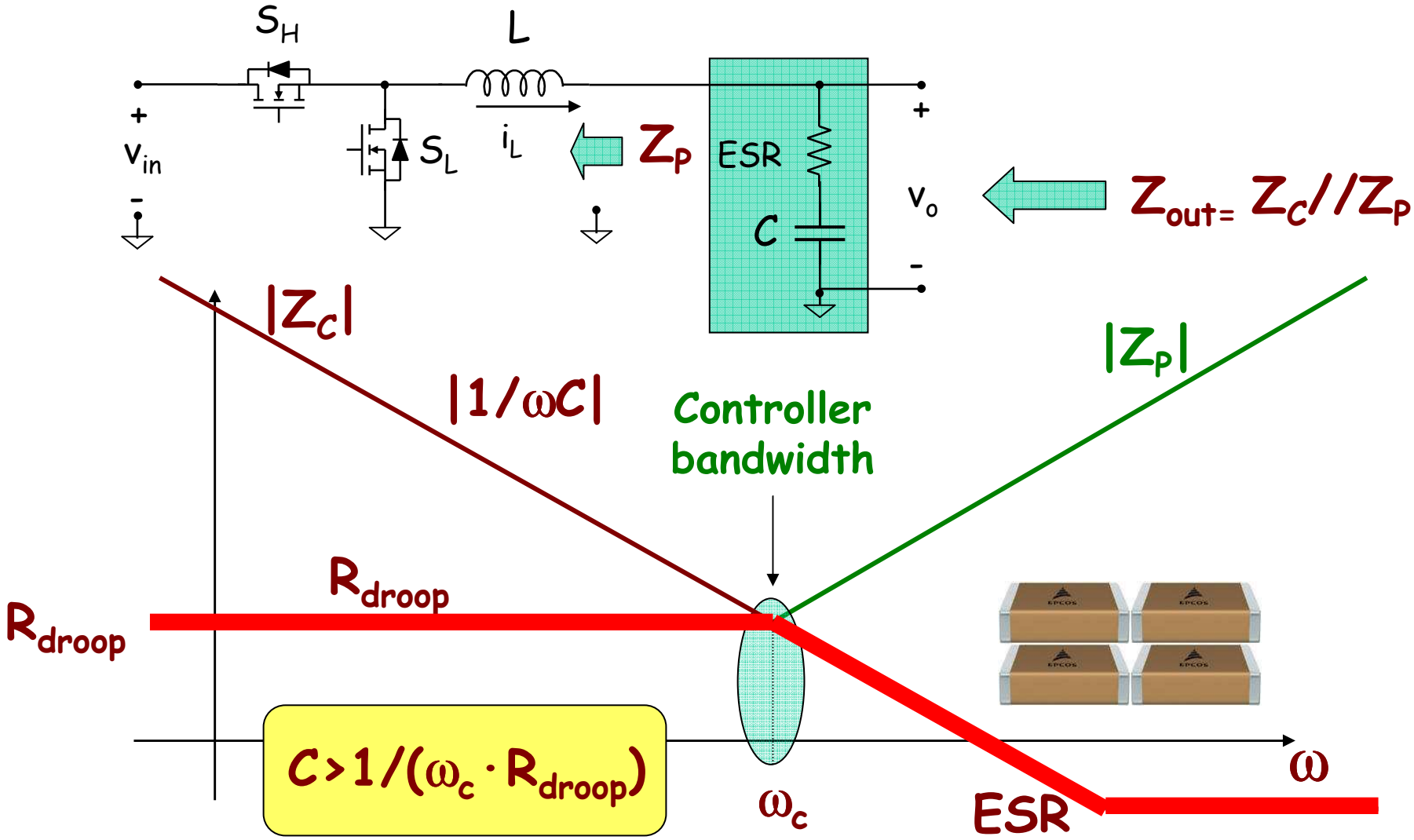
AVP: Control Block Diagram



- Closed-loop control on $v_T = v_o + R_{droop} \cdot i_L$
- PI design so as to impose controller bandwidth $\omega_c = 1/(ESR \cdot C)$
- Use of an additional R_p-C_p to limit precisely controller bandwidth

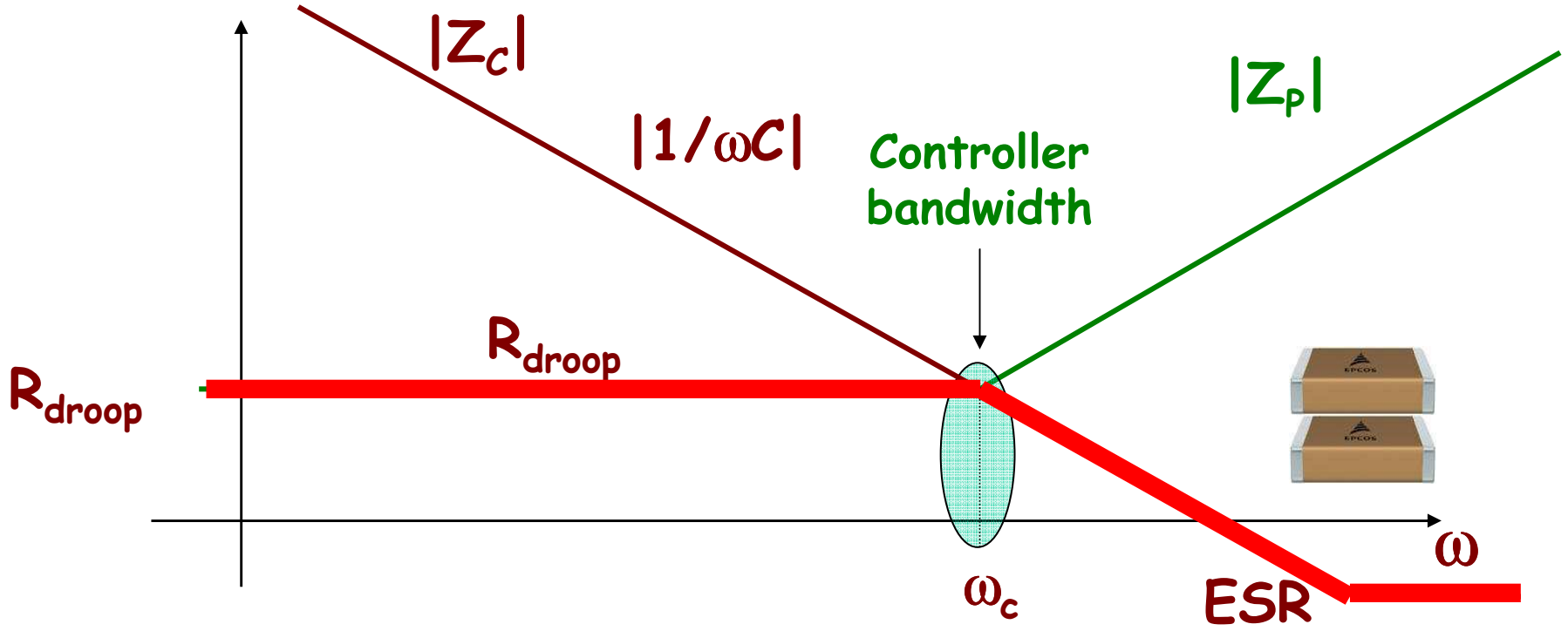
AVP with Ceramic Capacitors

- In ceramic capacitor $ESR < R_{droop}$

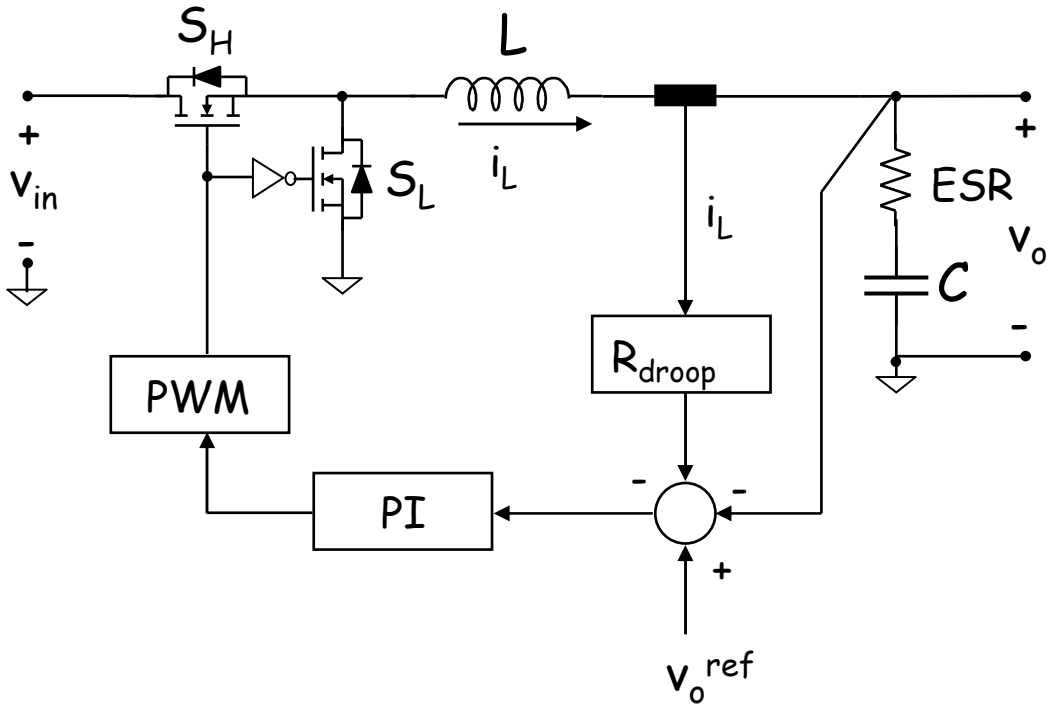


AVP with Ceramic Capacitors

- The higher the control bandwidth, the lower the output capacitor requirement: $C>1/(\omega_c \cdot R_{droop})$
- Need for high-performance controller



AVP: Control Block Diagram



- Same scheme used for electrolytic caps
- Closed-loop control on $v_T = v_o + R_{droop} \cdot i_L$
- PI design so as to have the higher bandwidth (no limitation)

Outline

- Voltage Regulation Modules (VRM)
  - Power trend
  - Interleaved buck converters
  - Current sharing
  - Current sensing
  - Adaptive voltage positioning
- **Digital control for high-frequency power conversion in Distributed Power Systems: current research activity at the University of Padova**

Key Requirements

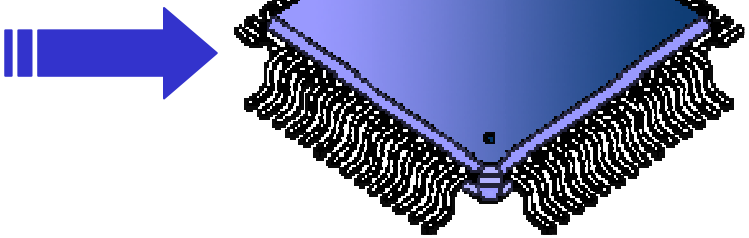
- Tight voltage regulation
  - Calibration for DC steady state & non linear control action for transient response
- High level of power managing
  - Light load efficiency
- High level of monitoring
  - State, I_{out},V_{out}, Temperature and Efficiency monitoring
- Deeply programmed fault action

Digital Control

- Different control methods can be easily managed depending on load, input conditions and state conditions
- Offset compensation and/or auto-tuning features can be added
- Non linear response can easily be achieved
- Complex power management algorithms can be implemented

Digital Control

- Complex control algorithms can be easily implemented to obtain good response



Accuracy

- Built in test for offset compensation
- Adaptive control system
- Non linear response

Digital Control

- Compensation software assisted:
  - No components used for compensation
  - Easy changing compensation, droop and settings by software
  - Auto-tuning techniques

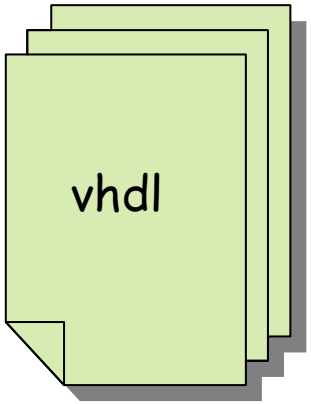
Digital Control

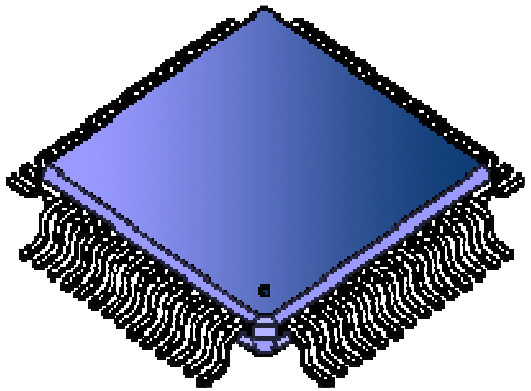
- Technology independent design

(Hardware Description Language - HDL)

Better resources employment

- Lower Time to market (faster design process)
- Intellectual Property - IP
- Easy scaling with advances in fabrication technologies





Critical Issues of Digital Control

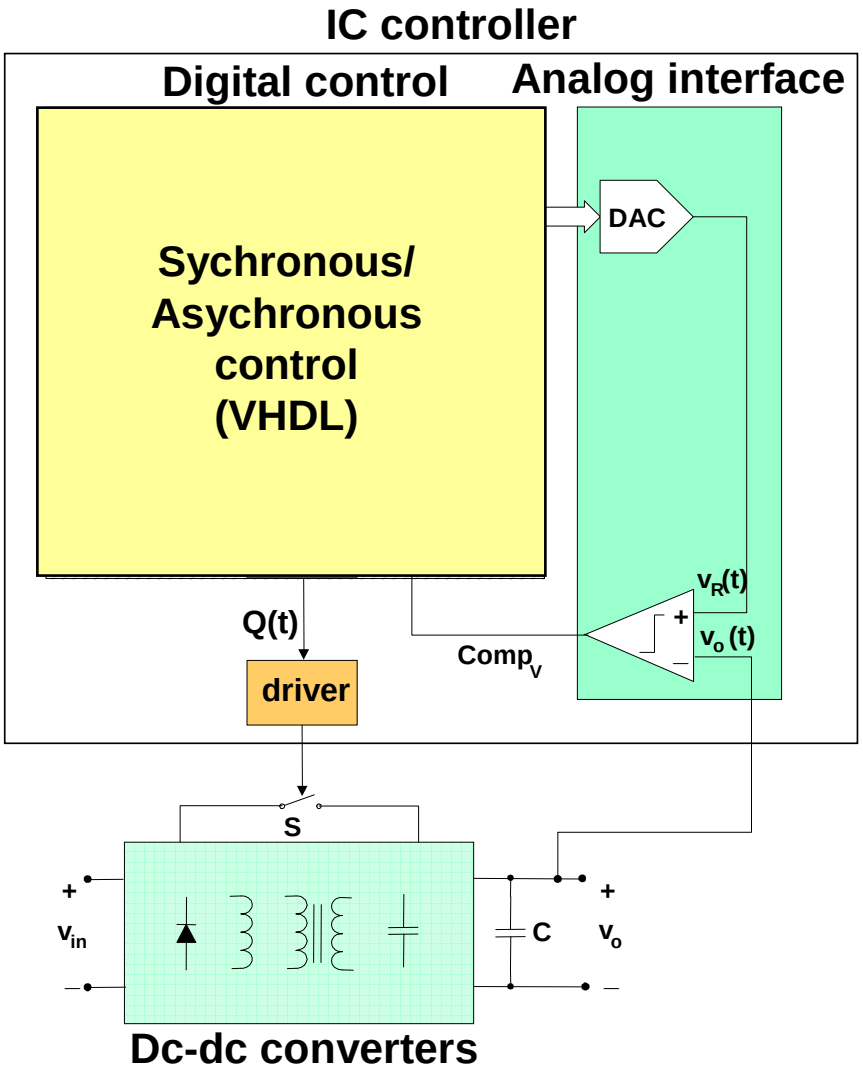
- *Lack of experienced people* in digital design and power electronics
- *Lack of understanding* and research on how to realize simple digital IC which comply with the cost/complexity constraints of computing/telecom applications
  - Specific dedicated digital or mixed-signal ICs are needed (no discrete uC or DSP)
- Quantization effects (limit cycles) and control delays (bandwidth limitation) has to be considered
- Conversion solutions and digital complexity
  - High resolution DPWM
  - High resolution AD and DA converters

Need of simple-mixed signal control architectures

Research Activities in Digital Control

- Investigating the digital advantage
  - Auto-tuning systems
  - Complex power management
- Solving the digital trouble
  - Mixed signal control architectures

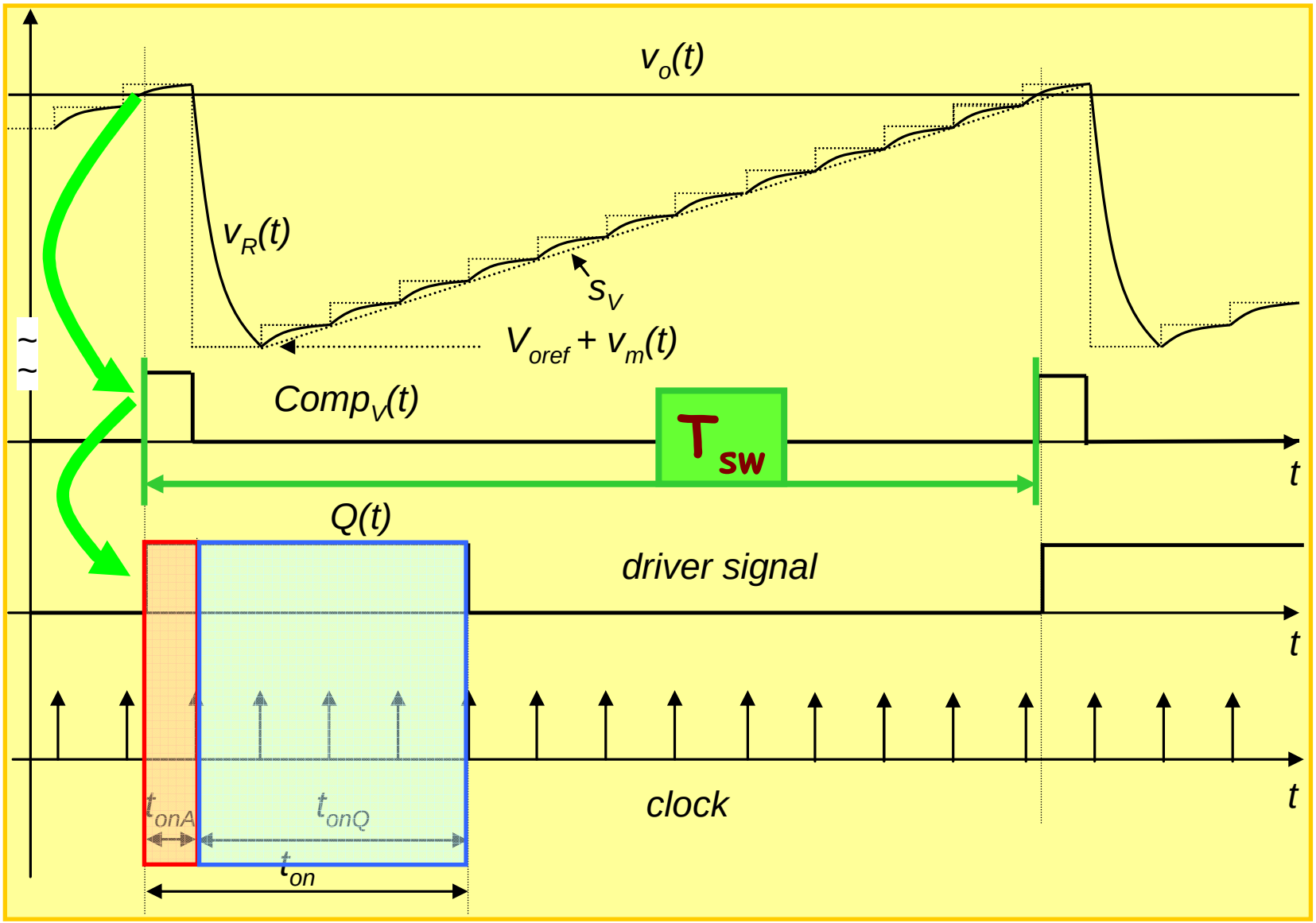
Mixed-Signal Voltage-Mode Control



Features:

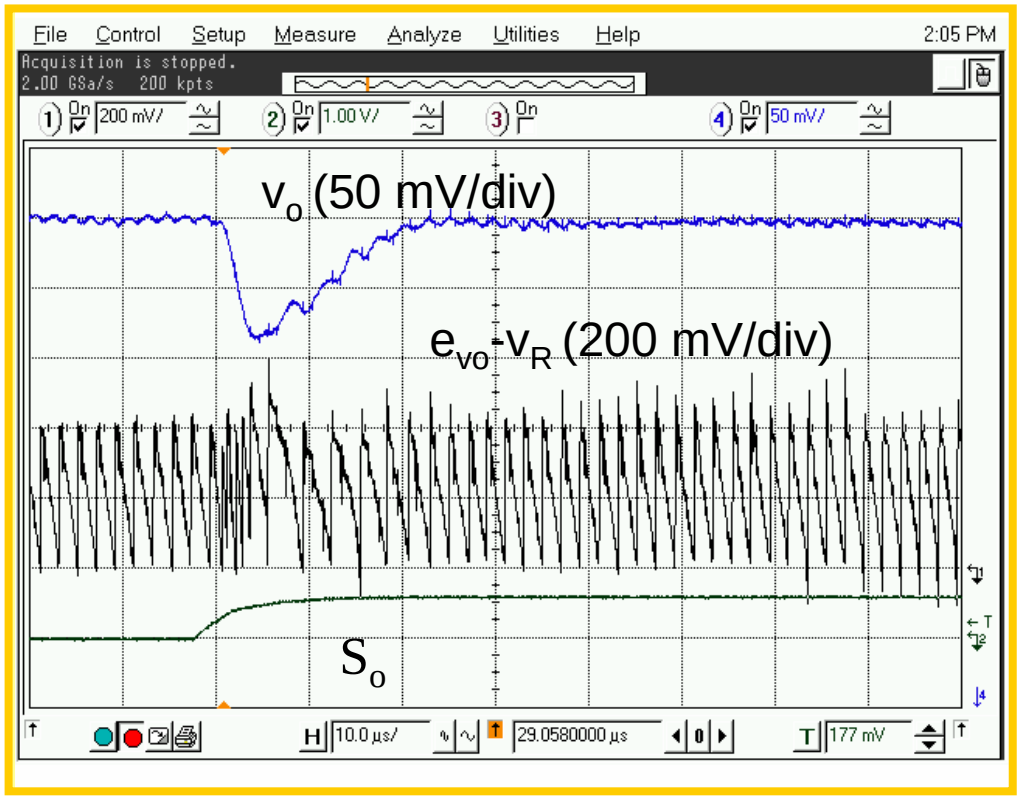
- ✓ Simple analog interface (low-resolution DAC + comparator)
- ✓ No need for ADC and DPWM
- ✓ No quantization effects
- ✓ High dynamic performance

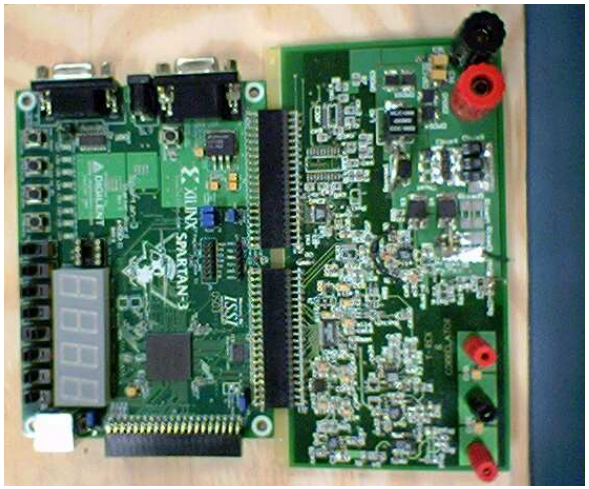
DAC operation



Experimental Results

Load step variation





time: 10 µsec/div

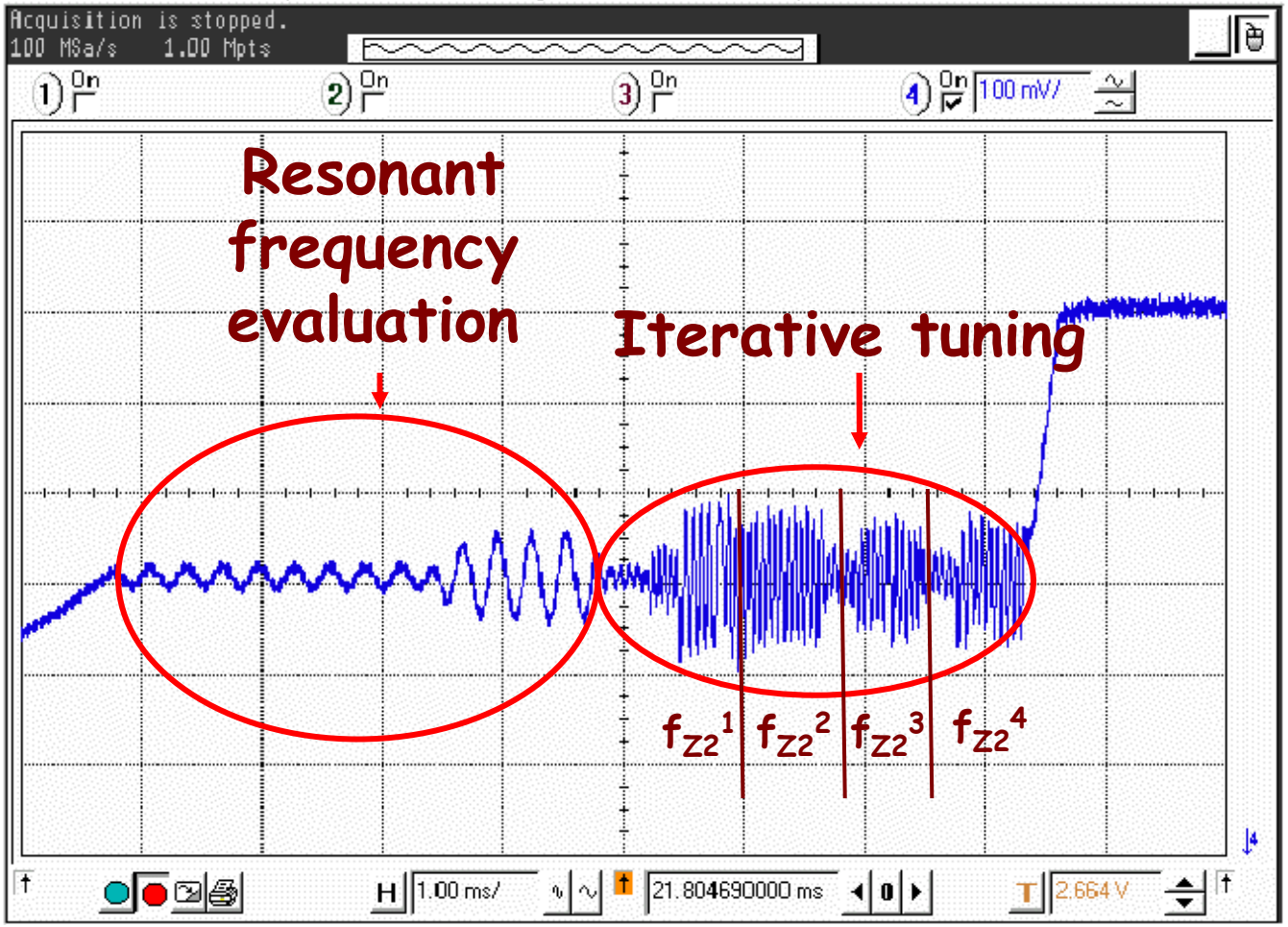
Auto-Tuning System

Objective:

- Investigation of PID autotuning techniques for digitally controlled voltage-mode synchronous buck converters

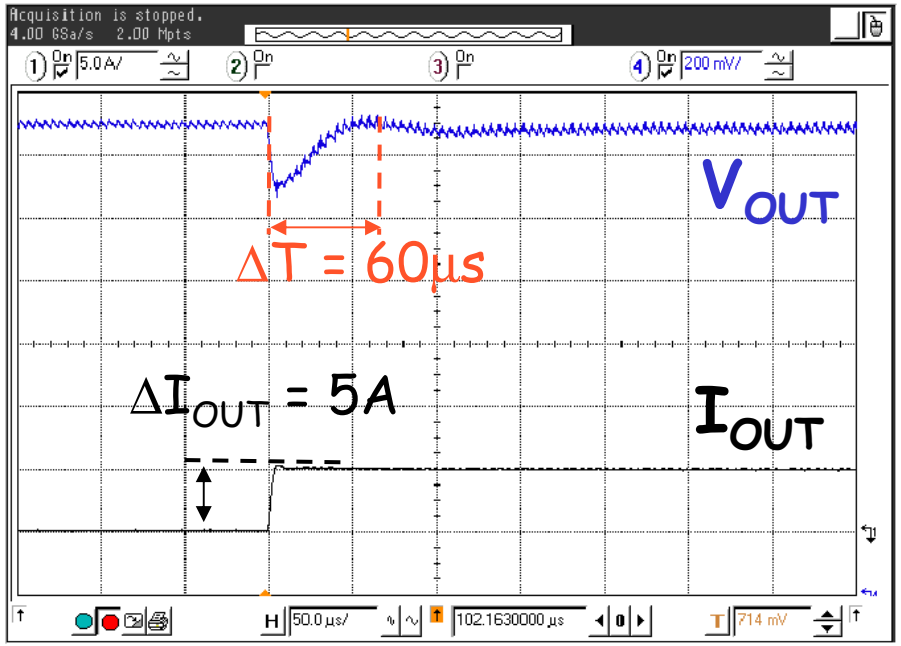
- Features:
  - ✓Closed-loop operation during autotuning
  - ✓Direct autotuning based on specified dynamic requirement without transfer function identification
  - ✓Simple algorithm

Experimental Results



Experimental Results

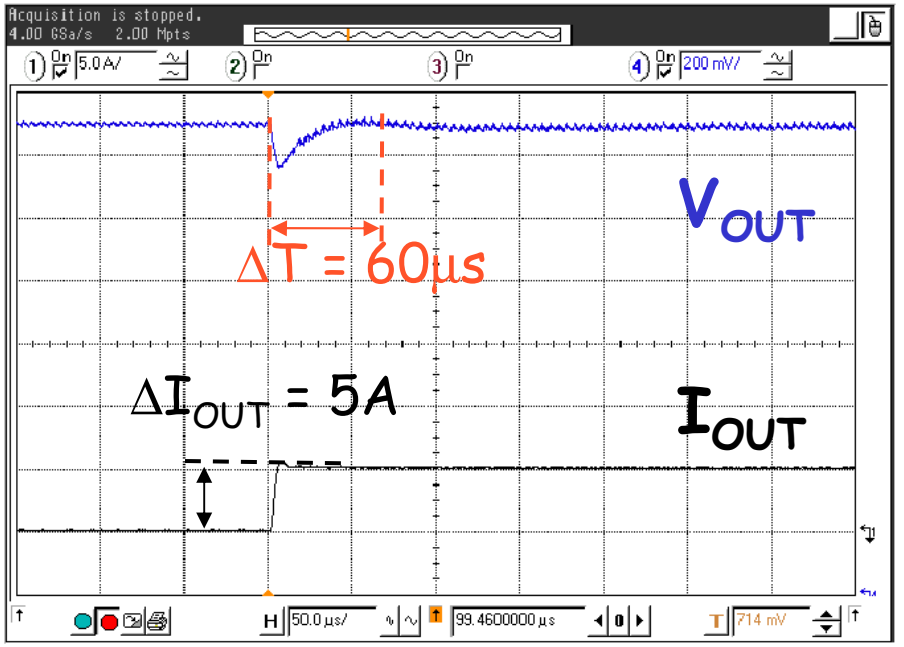
Load step variation after autotuning (f_c=13kHz, m_ϕ=60°)



$C_O = 660\mu F$

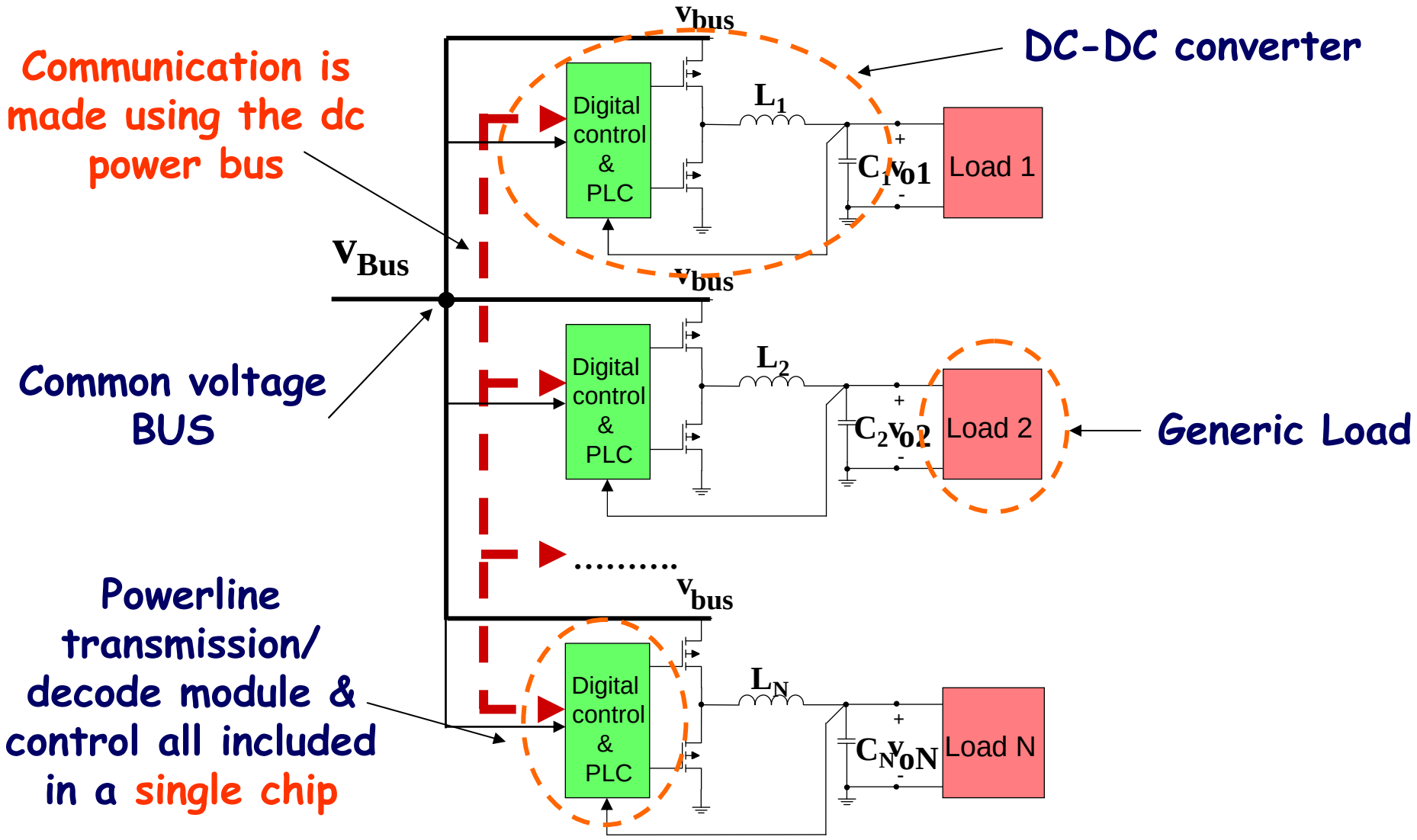
Tantalum caps

$C_O = 1320\mu F$



Power Line Communication

Distributed dc-dc converters sharing the same voltage bus

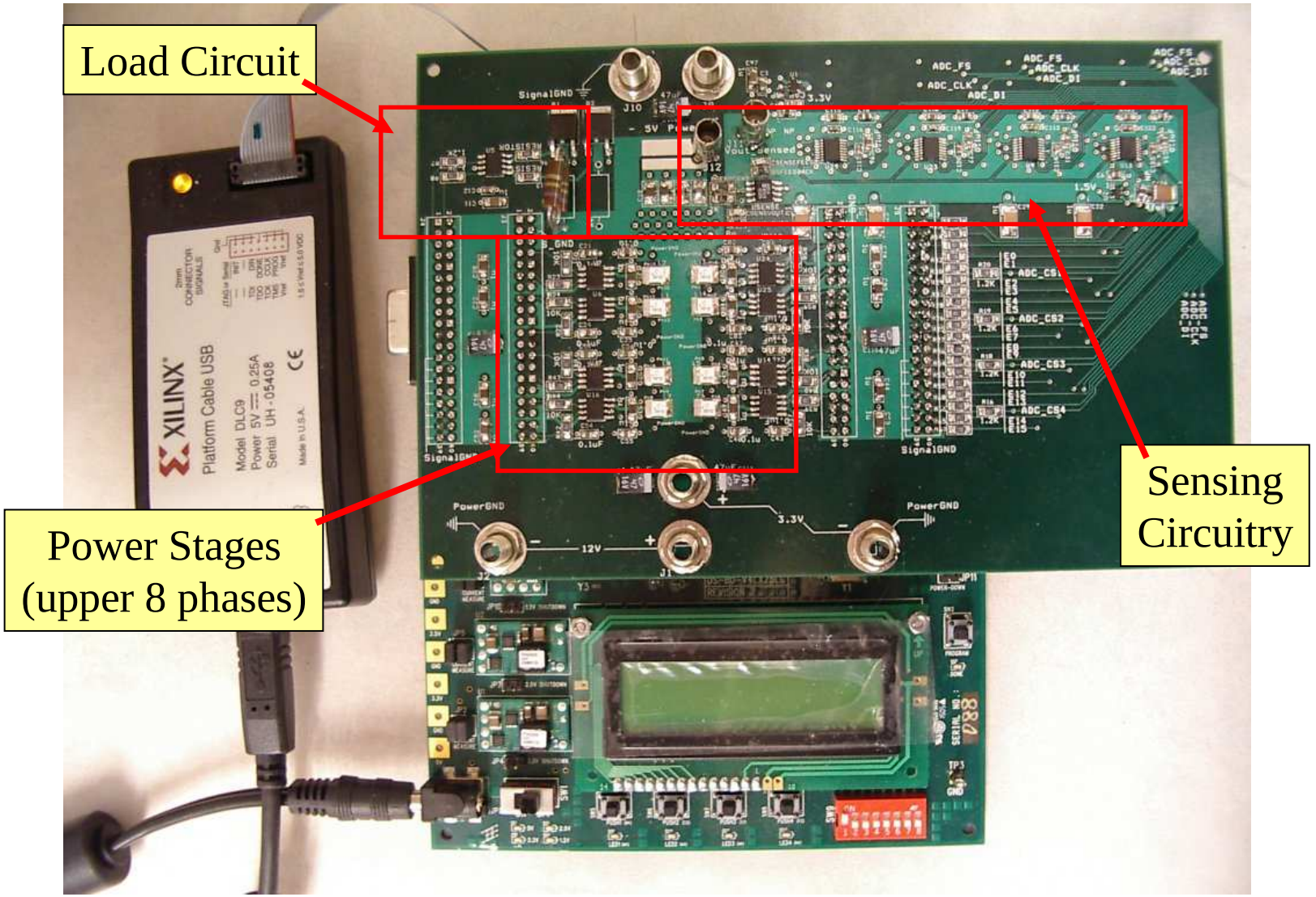


16-Phases Interleaved Buck Converter

- High number of phases enables higher switching frequencies and lower L
- The requirement for precise timing and automatic current sharing call for digital control
- Prototype
  - 16 Phases Buck converter
  - 1.56 MHz Switching Frequency (each channel)
  - ≈25 MHz Sampling Frequency
  - V_{in} = 3 V
  - V_{out} = 1 V, I_{out}=8A
  - q_{ADC} = 16 mV
  - L = 300 nH
  - C_{out} = 30 µF

Project in which our Ph.D student (Daniele Trevisan) was involved during his visit at COPEC (Colorado Power Electronics Center) - Boulder

Digital Control for 16-Phases Buck Converter



Thank you for your attention!