Mixed-Signal IC Controllers and Low-Volume SMPS Topologies

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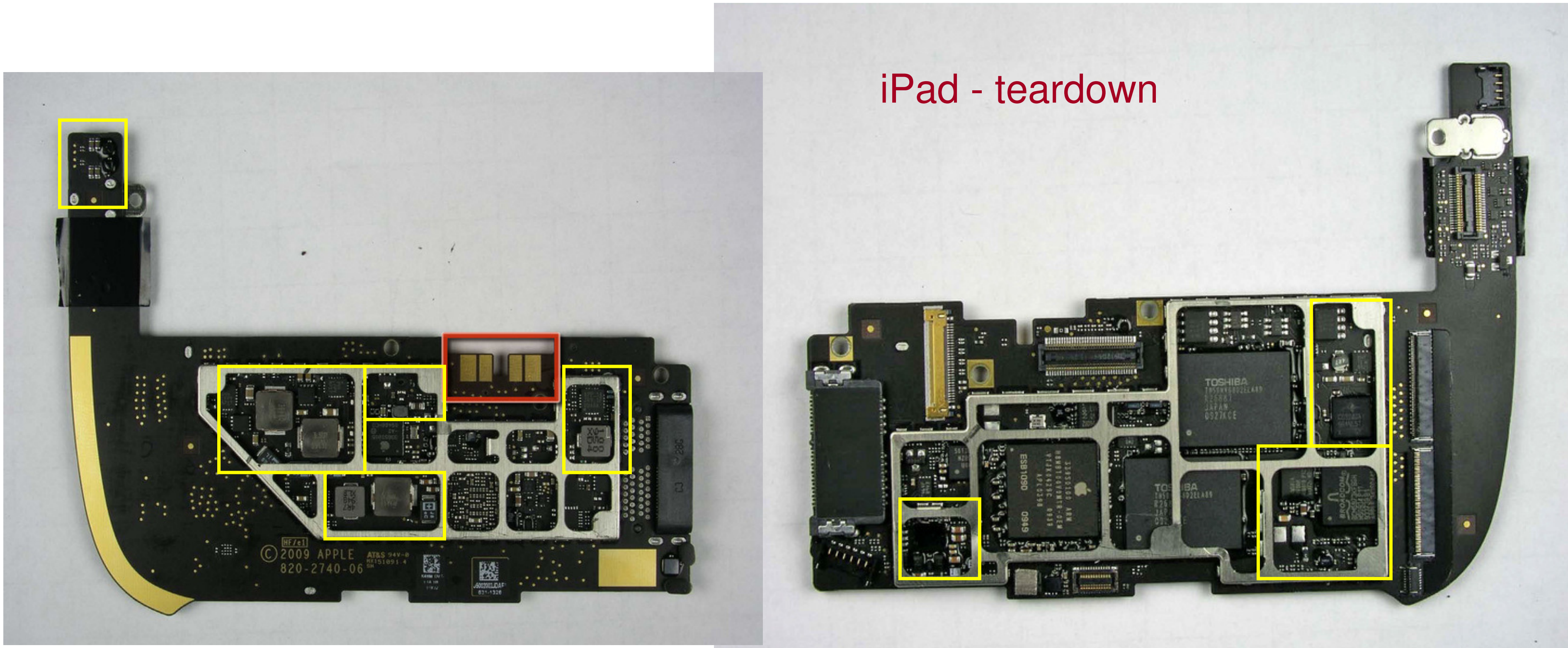
A Low Power (Portable) Application – Rogers Portable Radio

- Allowed a large number of households to have daily access to information
- Reduced power consumption by using more efficient electronic tubes

Main motivation: to reduce the volume and weight of the power supply, by far the largest part of previous radios

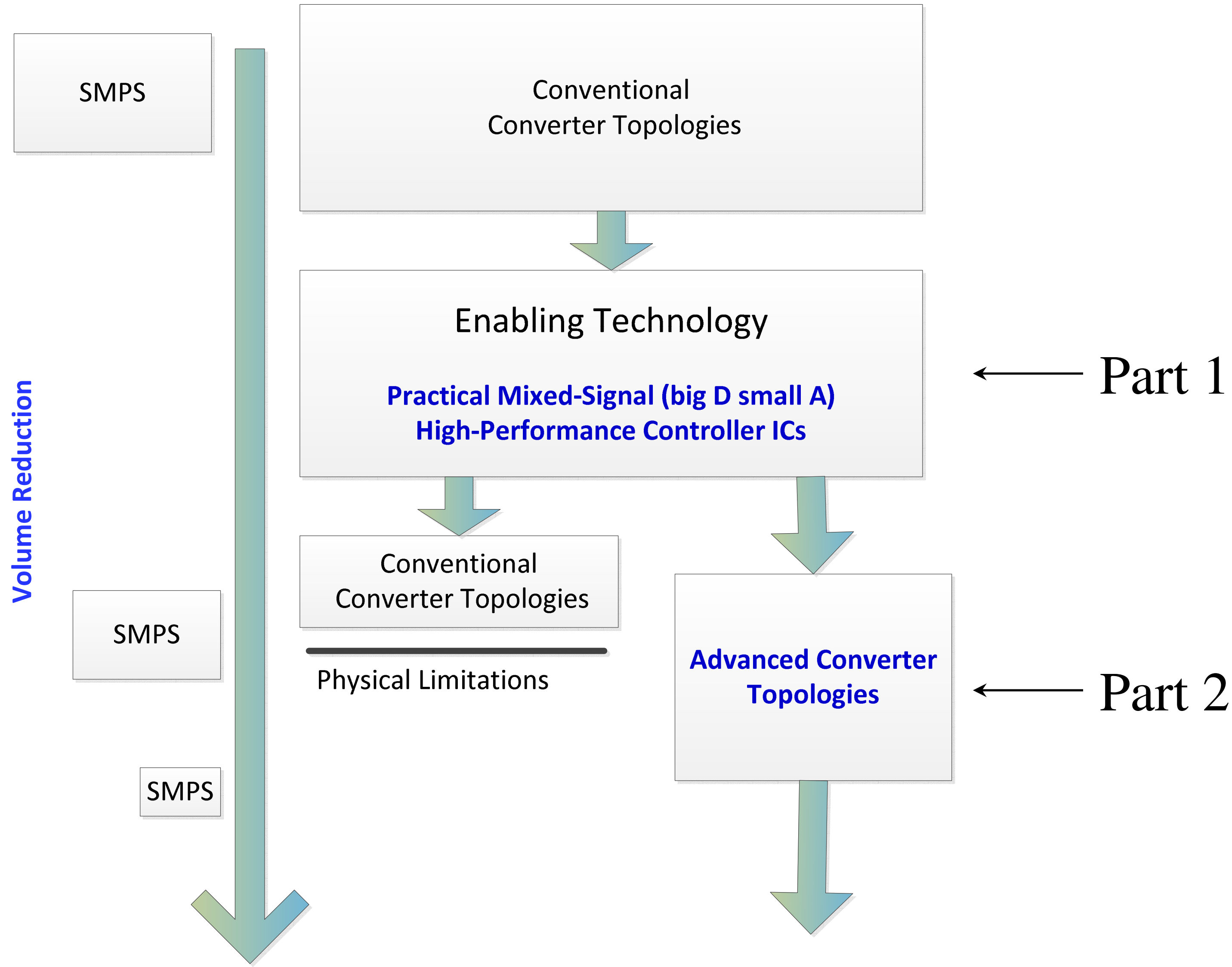
Low Power SMPS in Portable/Consumer Electronics



http://www.ifixit.com/Teardown/iPad-FCC-Teardown/2197/1

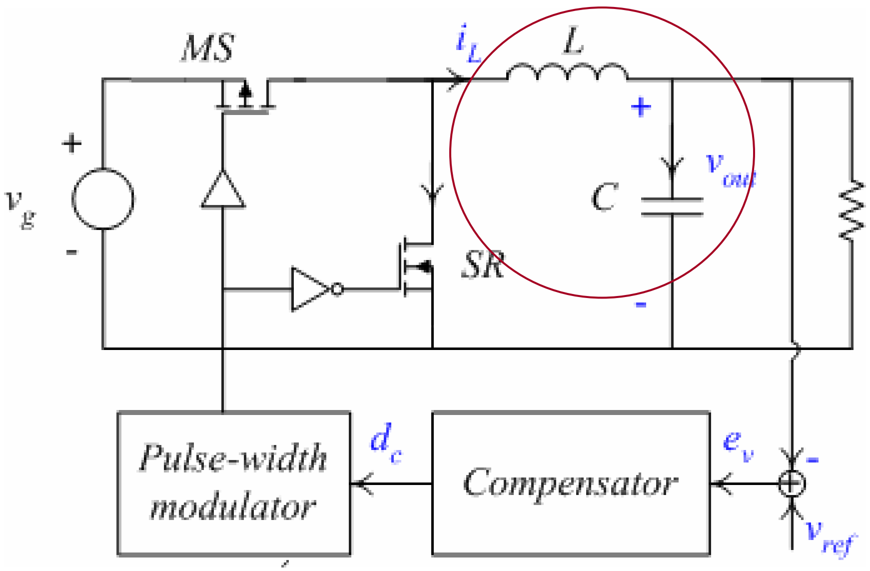
- Dc-dc SMPS occupy between 20% and 80% of the total volume in modern electronics devices, communication equipment, computers…
- Most of the volume occupied by passives and heat sinks

Outline: Two Parts of Presentation



Conventional Methods for Volume Minimization

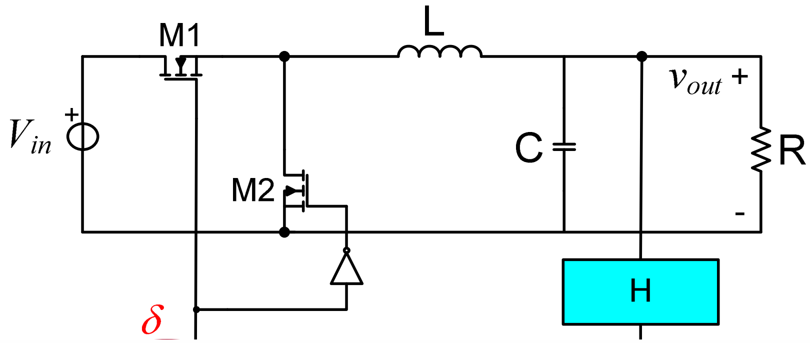
- Operation at high switching frequencies
- Efficiency optimization = flat and high efficiency curve
- Fast dynamic response of the controller + plug and play operation

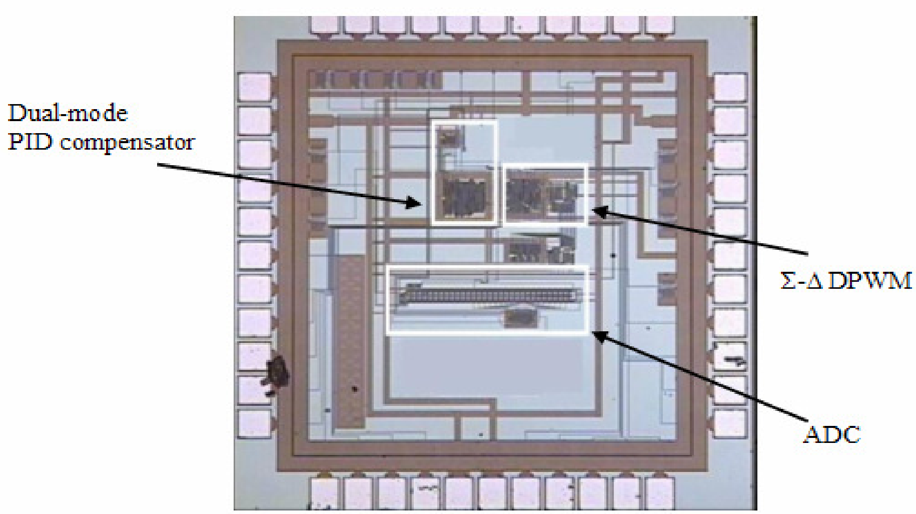


Load current

All three of these goals can be acomplished

Ultra High-Frequency High-Resolution Digital Controller IC



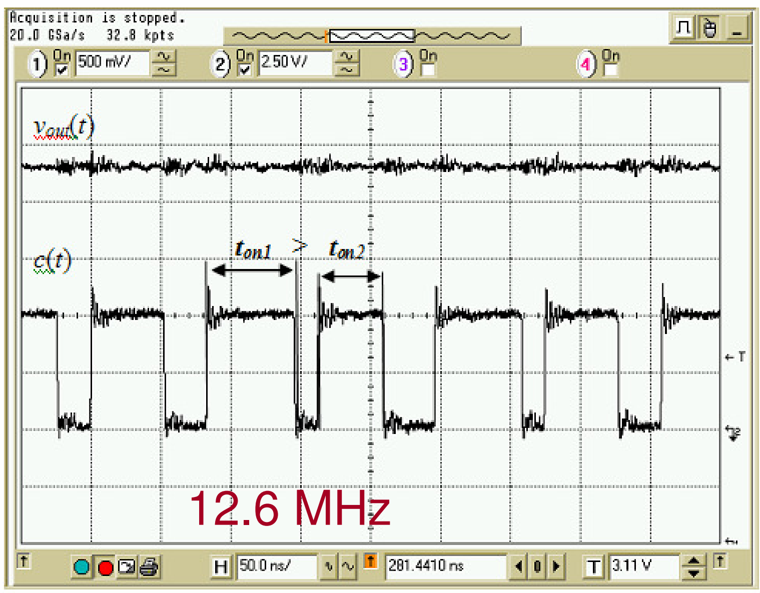


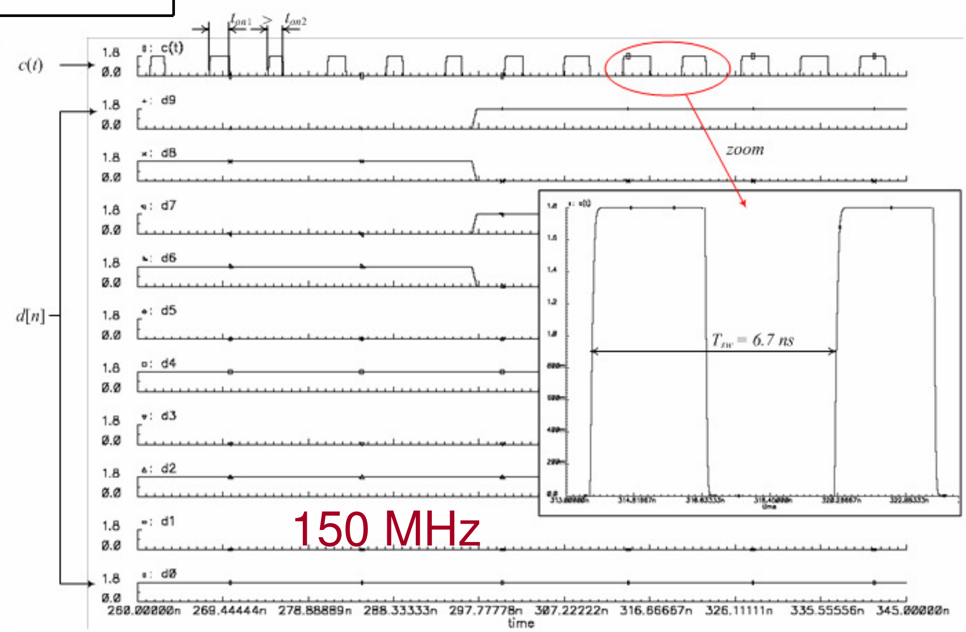
- The duty ratio of a core resolution (high-frequency) DPWM is varied over several switching cycles to achieve high effective resolution.
- The averaging is performed by the switching converter itself (LC filter)
- The output measured with a moving windowed ADC producing just few error signals
- Processing unit reduced since it also operates over a small error range

[1] Z. Lukic, N. Rahman, A. Prodić, "Multibit Σ–Δ PWM Digital Controller IC for DC–DC Converters Operating at Switching Frequencies Beyond 10 MHz," IEEEE Transactions on Power Electronics, Vol.22, Issue.5, October 2007, Pg. 1693-1707 (.pdf).

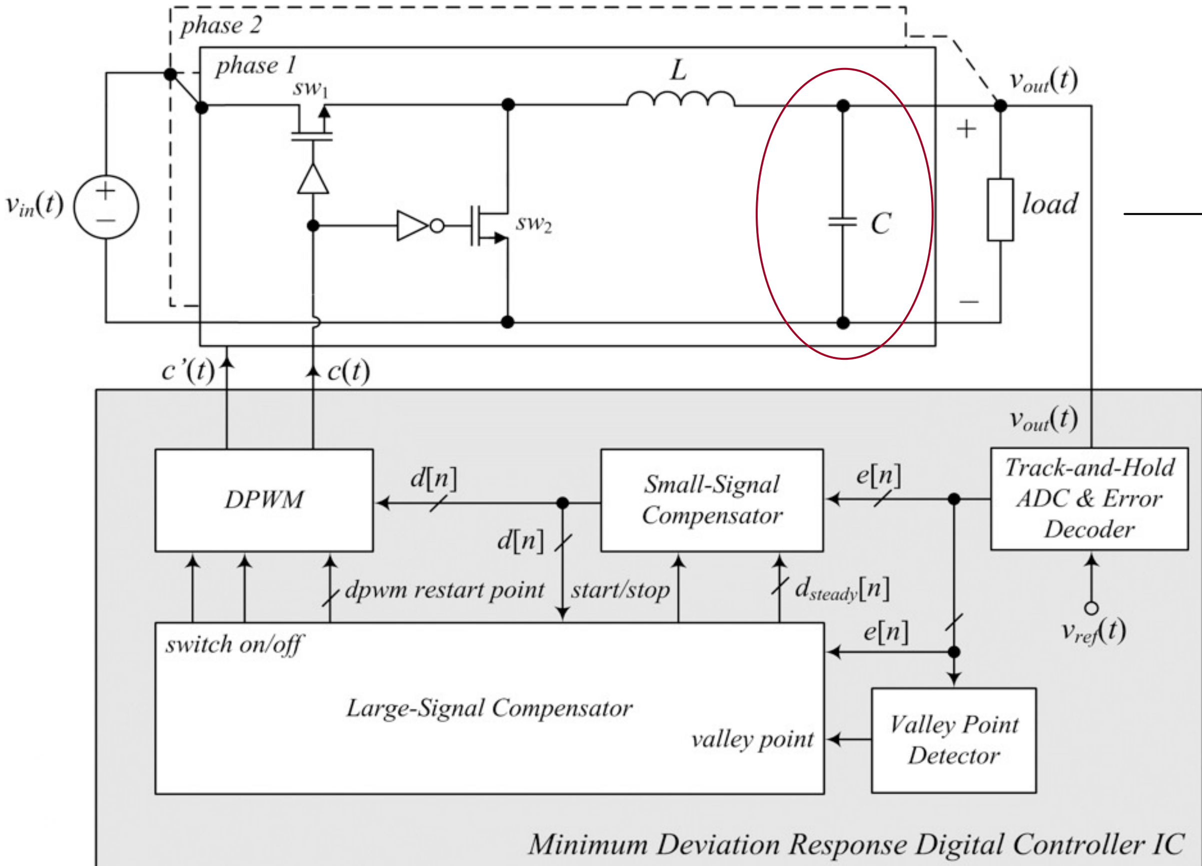
Ultra High-Frequency Digital Controller IC Results

DPWM switching frequency	Programmable, 400 kHz to 150 MHz
DPWM effective resolution	10-bit
Controller area	0.14 mm[2]
Σ-Δ Modulator current consumption	Sub 10 µA/MHz

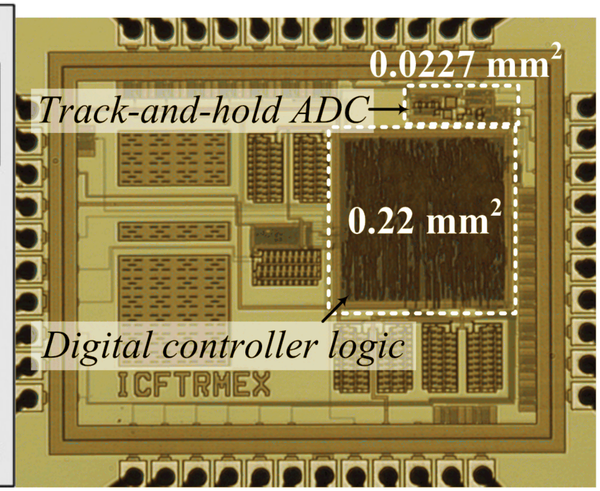




Minimum Deviation Controller IC [2]

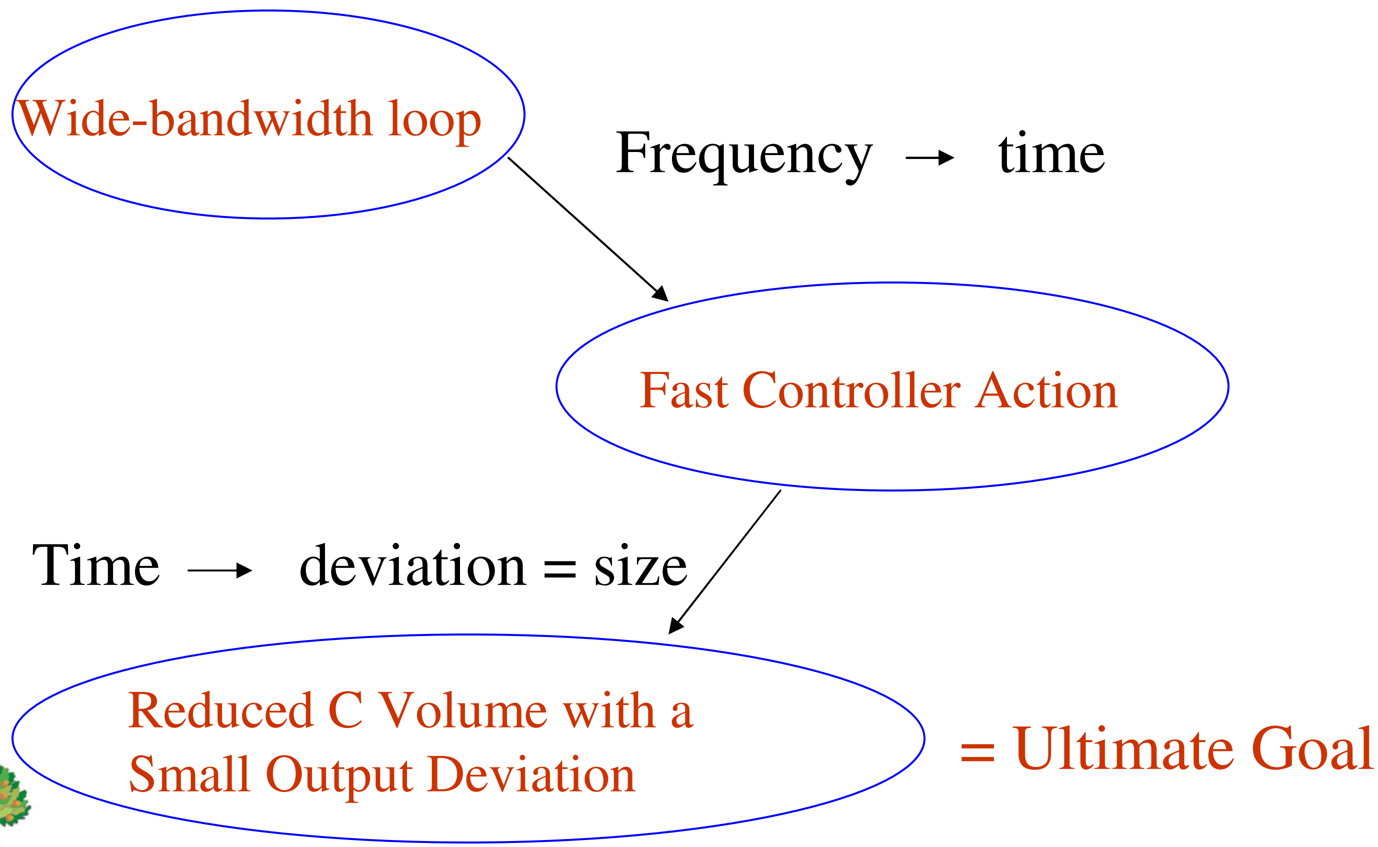


Load current

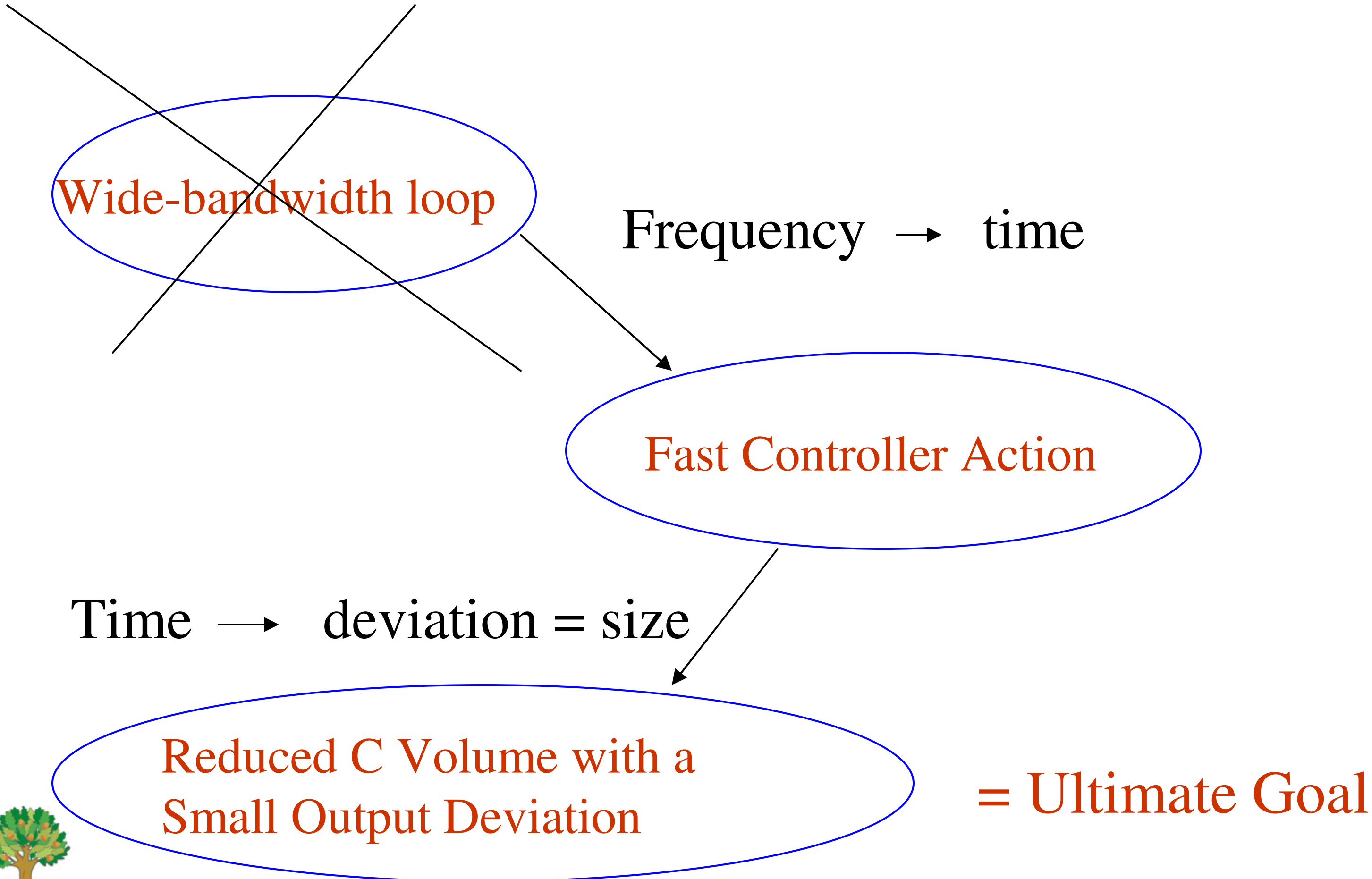


[2] A. Radic, Z. Lukic. A. Prodic, and R. de Nie, "Minimum Deviation Digital Controller IC for DC-DC Switch-Mode Power Supplies," IEEEE Transactions on Power Electronics, Vol.28, Issue.2, February 2013.

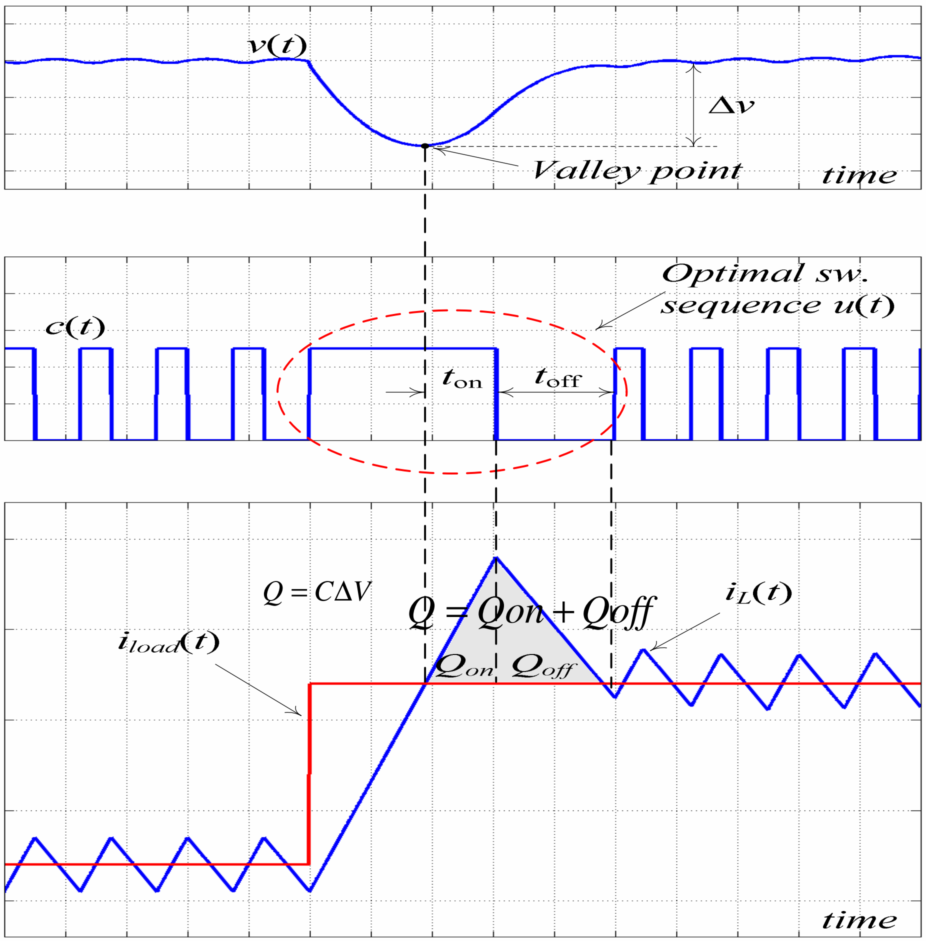
Conventional Controller Design



Time-Optimal Controller

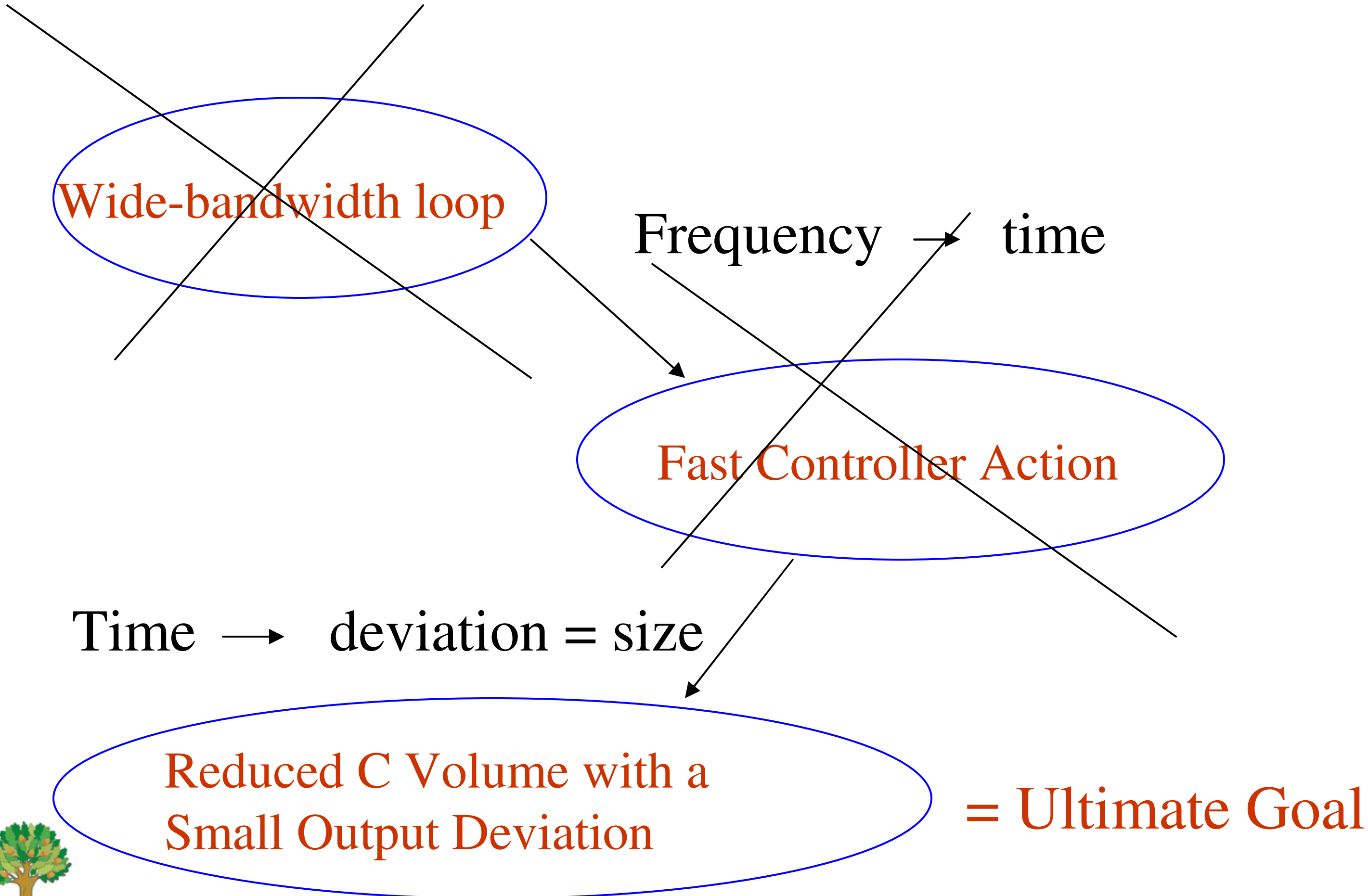


Time-Optimal Control

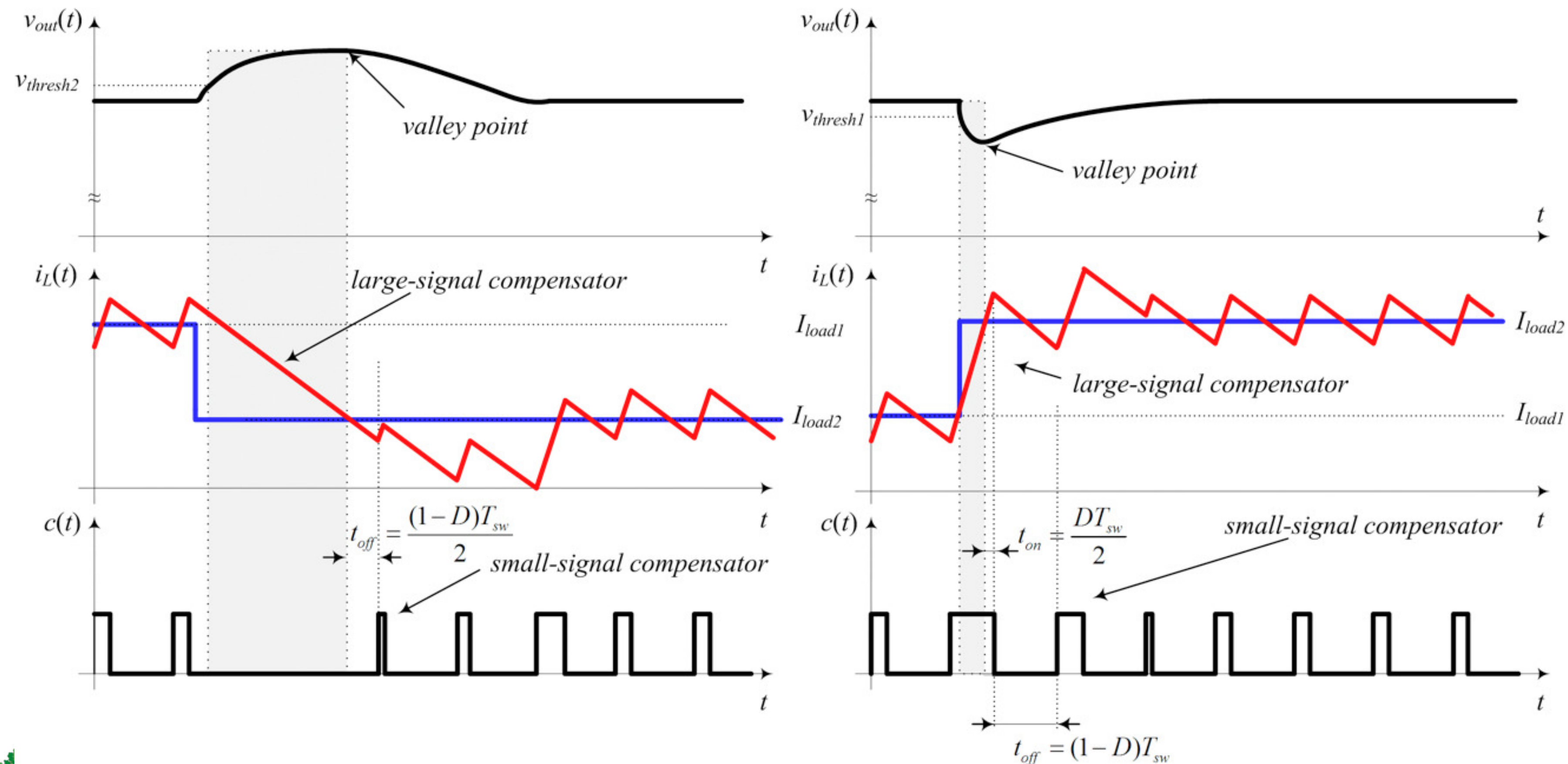


- Overly large peak inductor current, i.e. inductor might need to be overdesigned
- Fairly complex calculations
- Need to know LC values
- Very sensitive to time delays

Minimum Deviation Controller

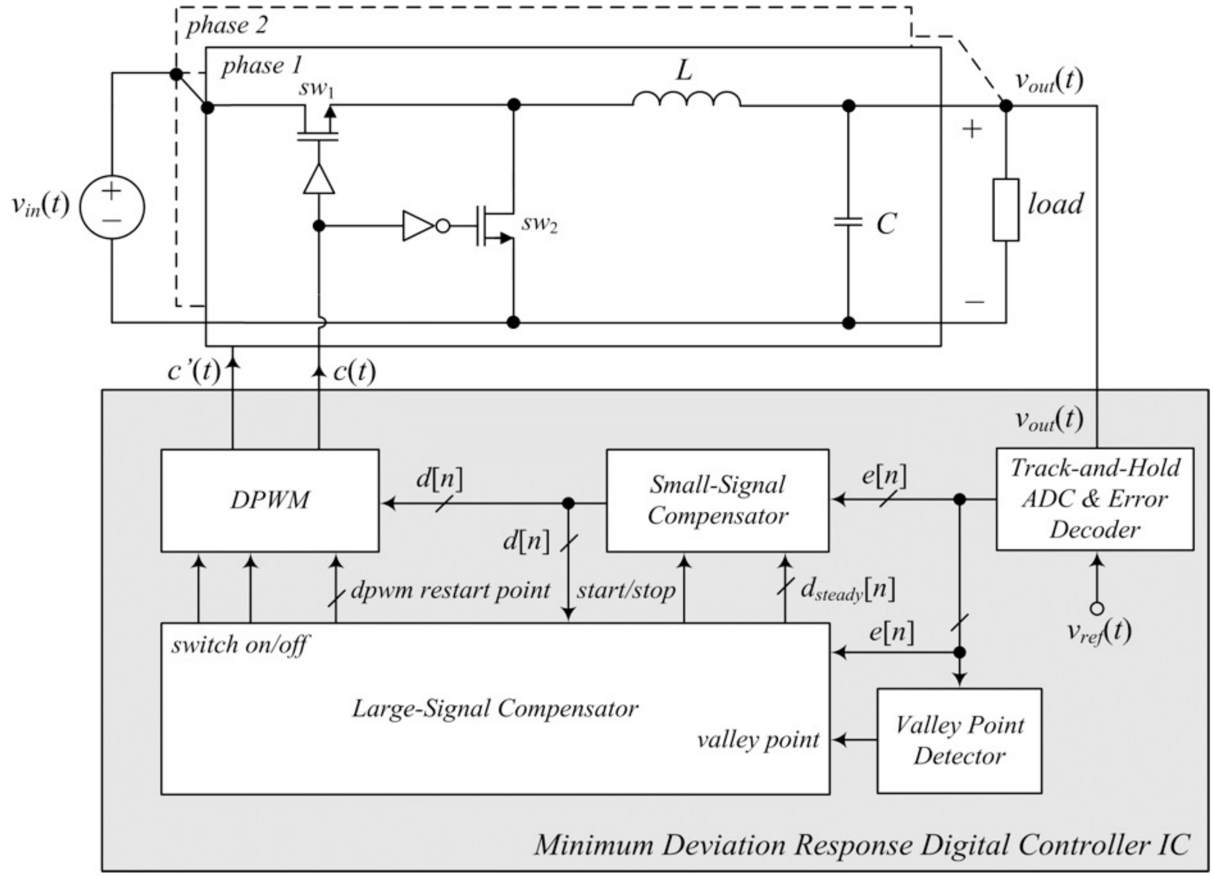


Minimum (Optimum) Deviation Controller



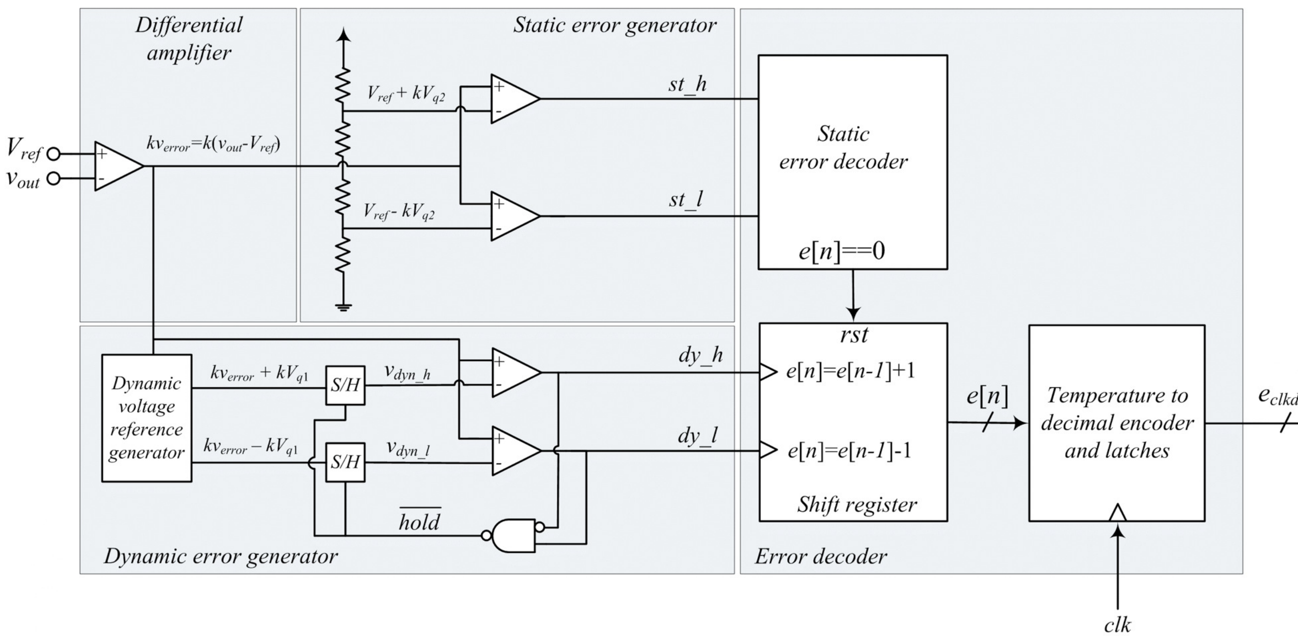
- No current overshoot, no need to know converter parameters, simple calculations

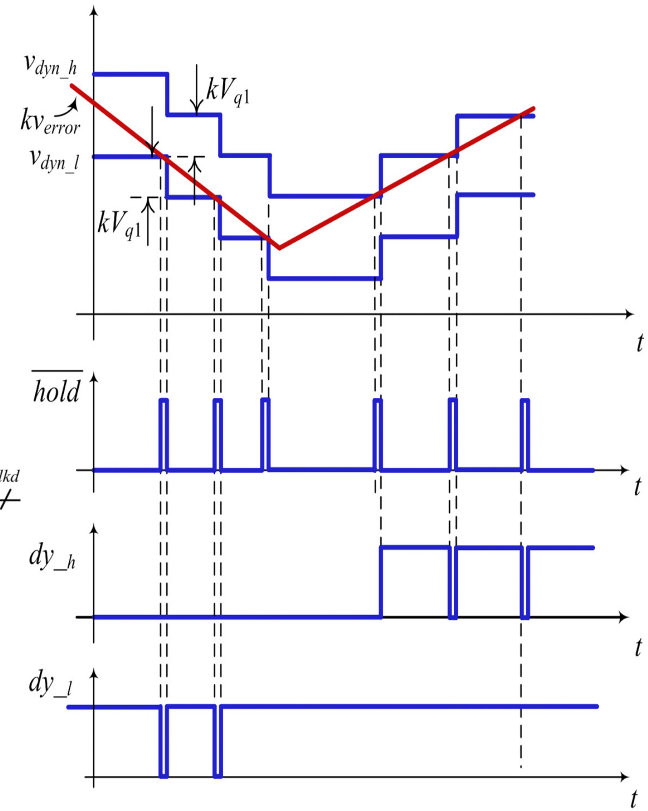
Minimum (Optimum) Deviation Controller



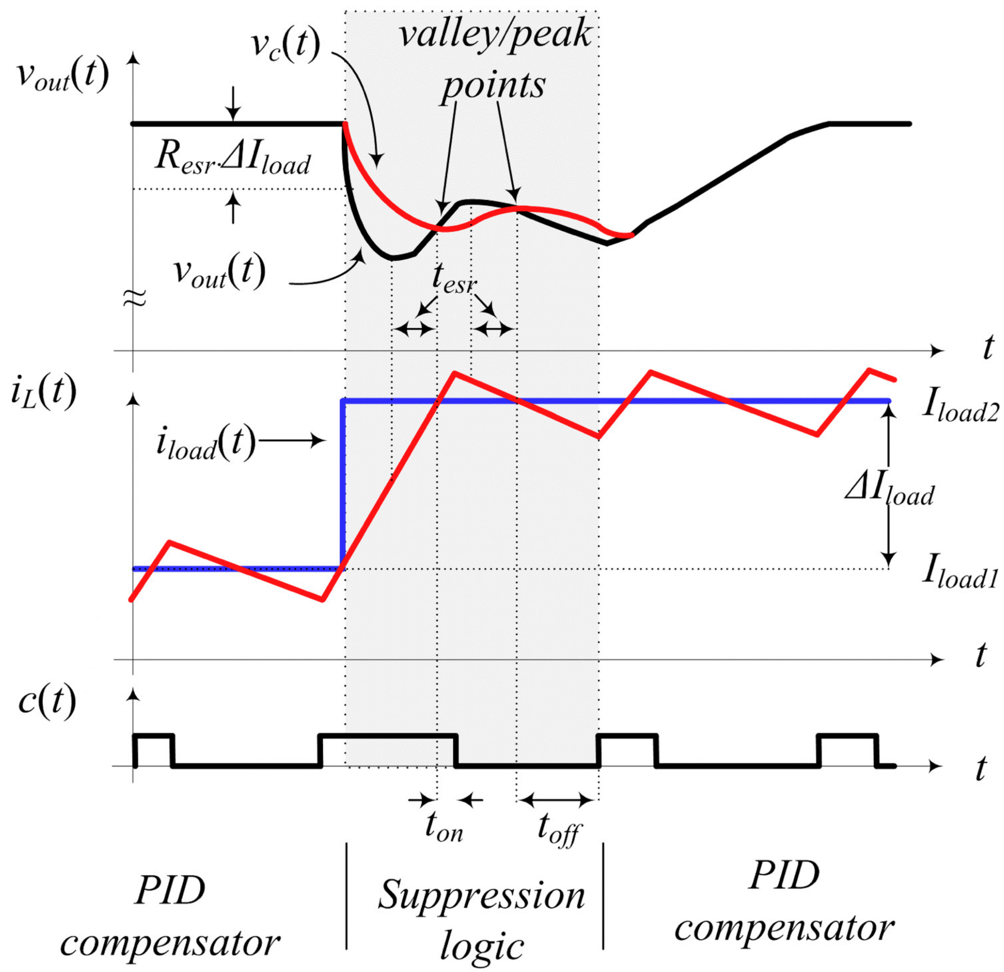
- Only needs to remember *D* before transient

Self-Calibrating SAR Track & Hold ADC

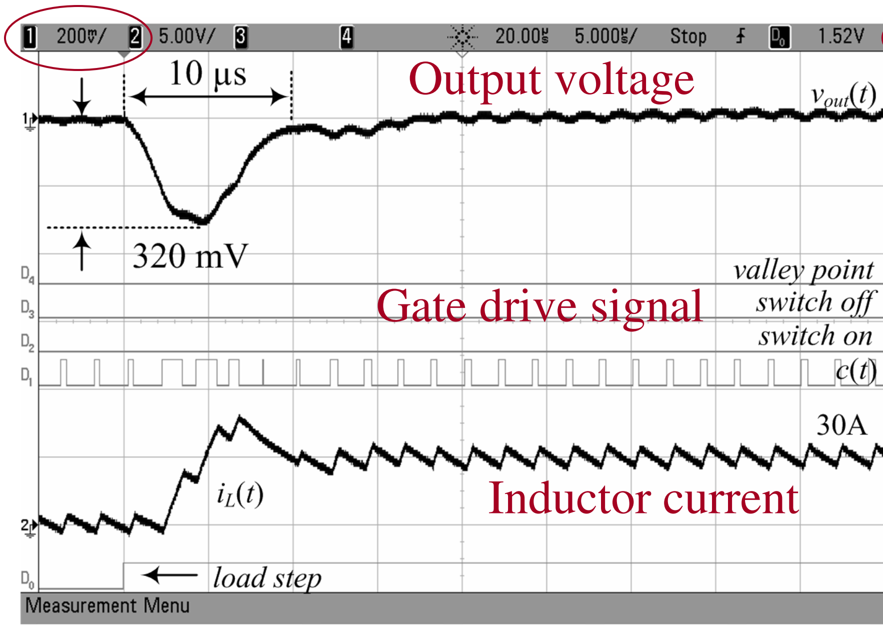




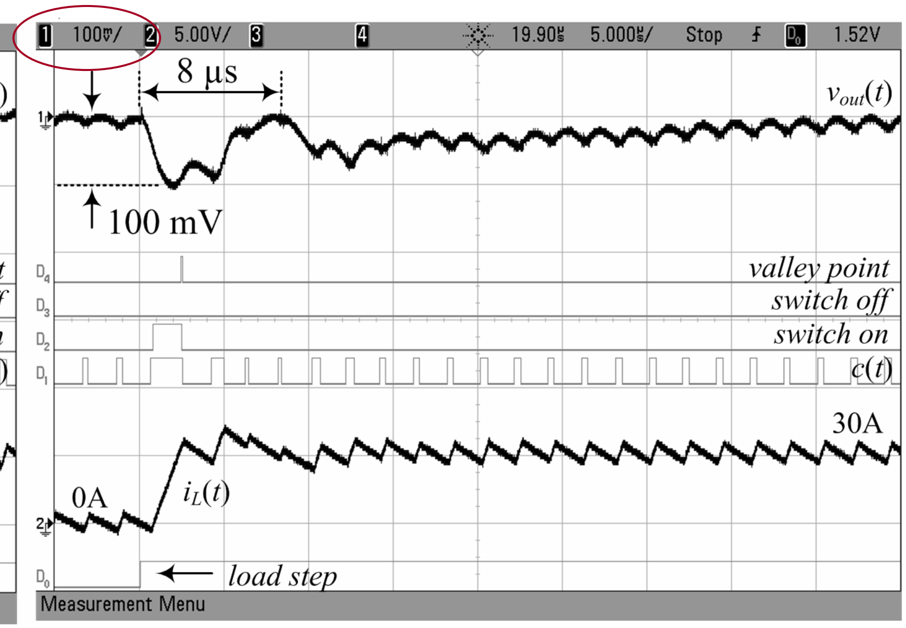
Dual Sampling Mechanism



Practical Implementation (500 kHz VRM)

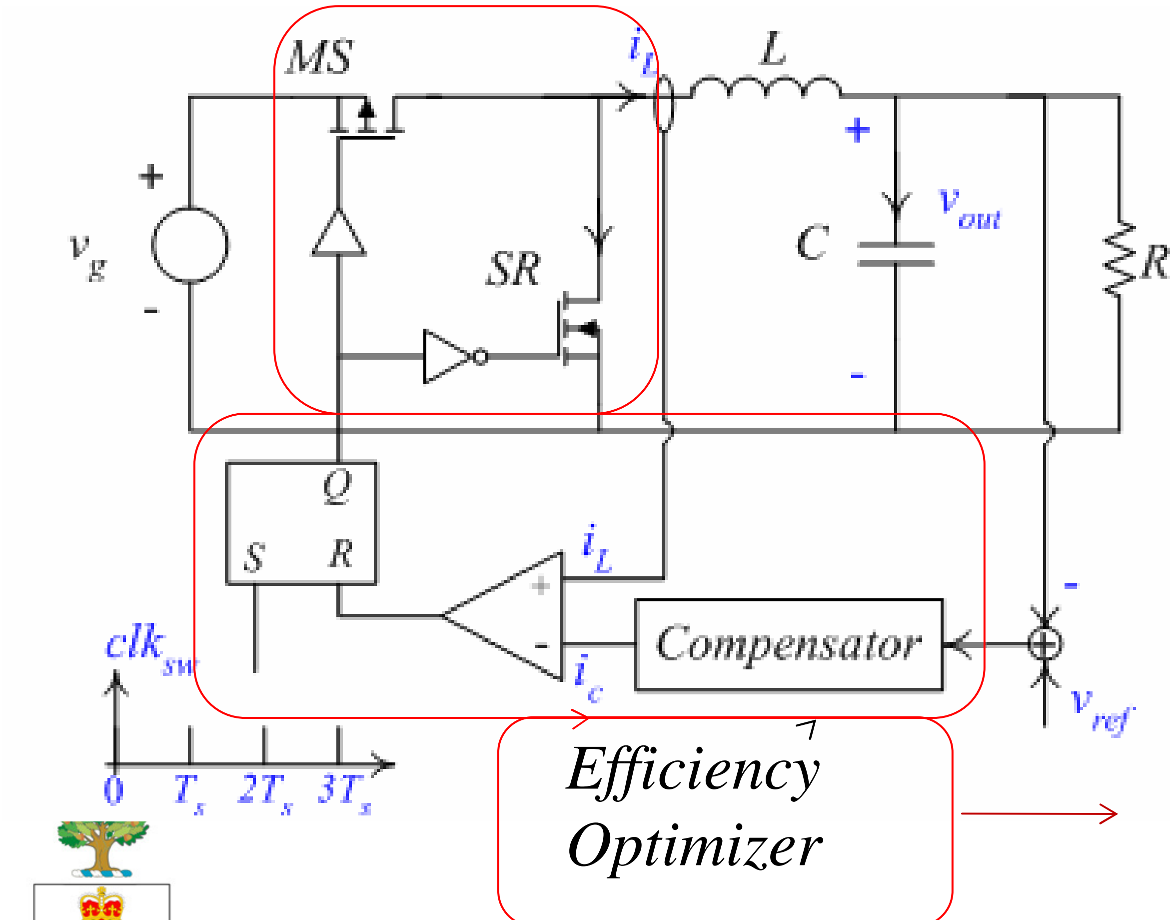


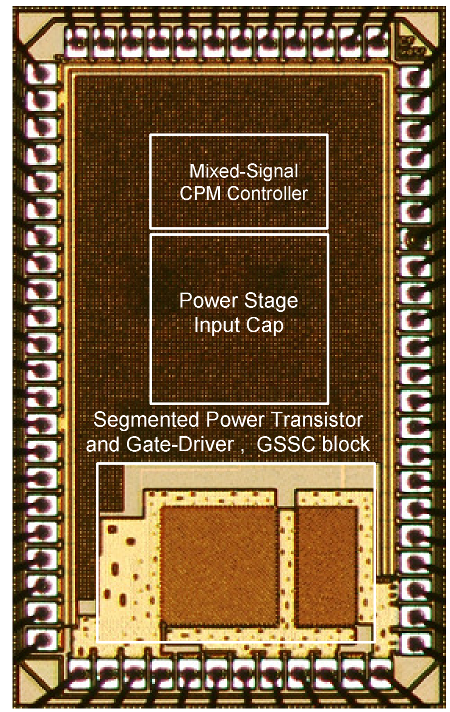
Fast PID



Optimum Deviation

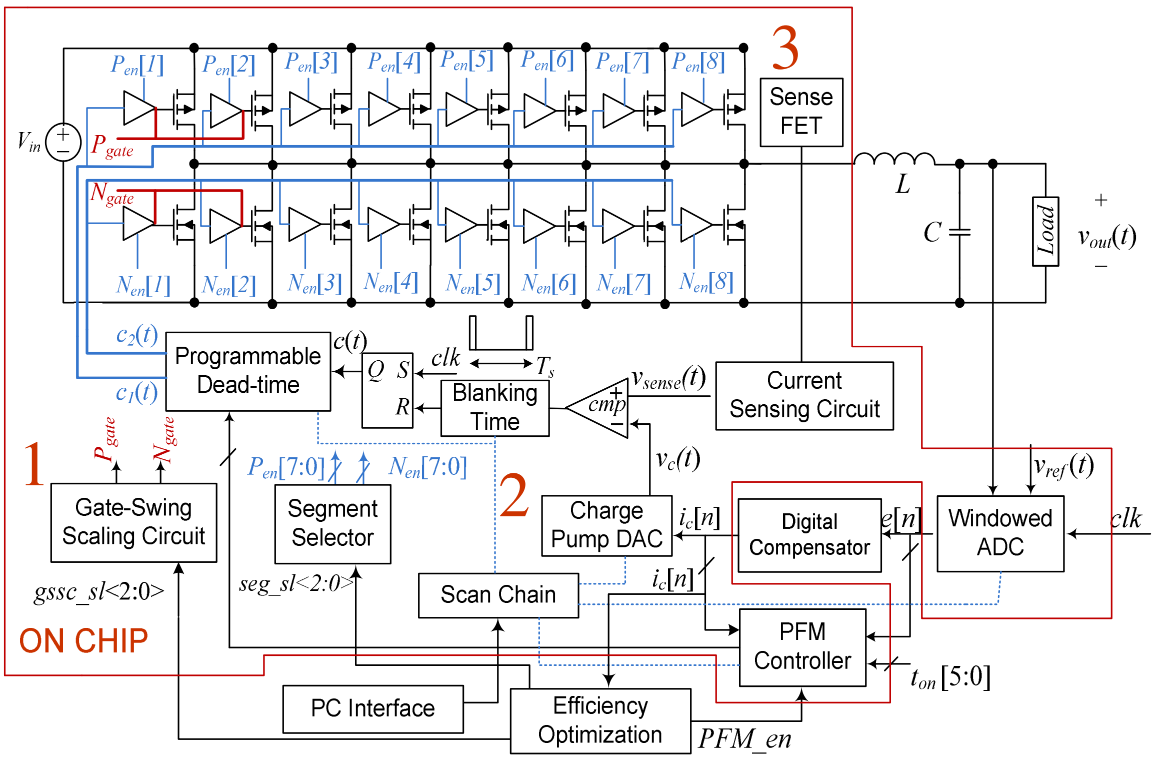
10 MHz Mixed Signal CPM Power Module with Instantaneous Efficiency Optimization [3]





[3] A. Parayandeh, B. Mahdavikkhah, S.M. Ahsanuzzaman, A. Radic, A. Prodic, "A 10 MHz mixed-signal CPM controlled DC-DC converter IC with novel gate swing circuit and instantaneous efficiency optimization," in Proc. IEEE ECCE, 2011, Pg. 1229-1235

IC Block Diagram



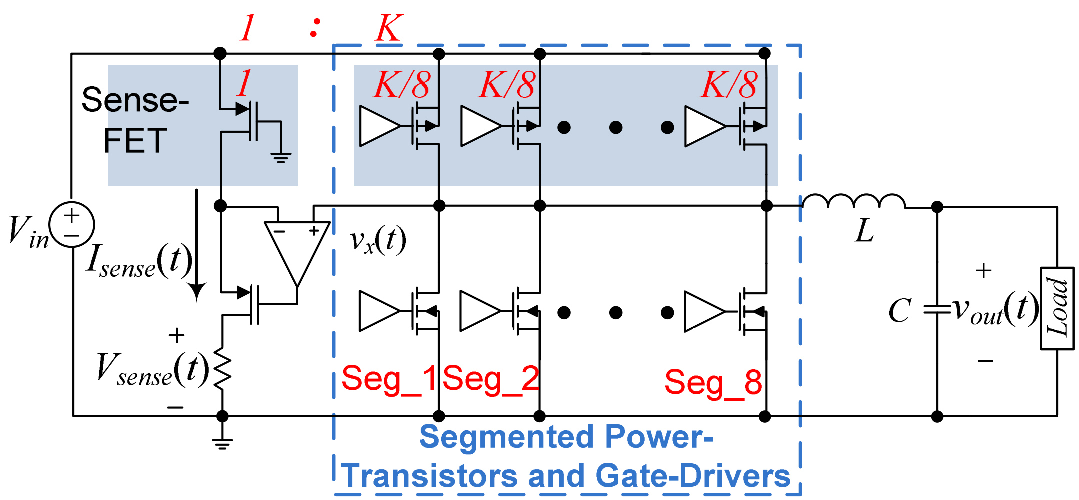
Incorporates:

1. Novel gate swing circuit

2. Modified high-resolution charge-pump based DAC

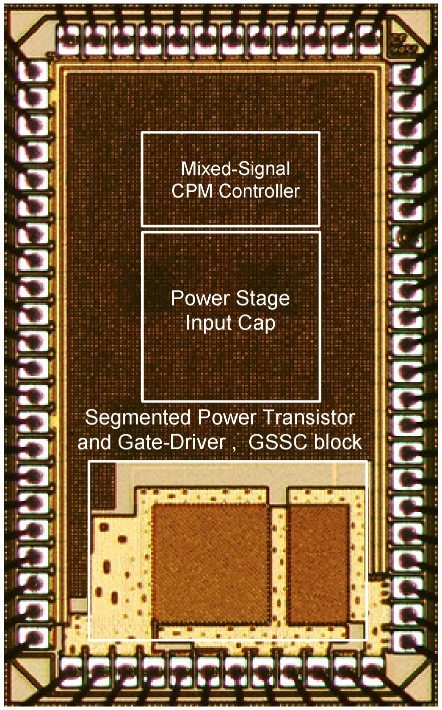
3. Optimized design of current sensing circuit (senseFET)

Low-Power High-Frequency SensFET



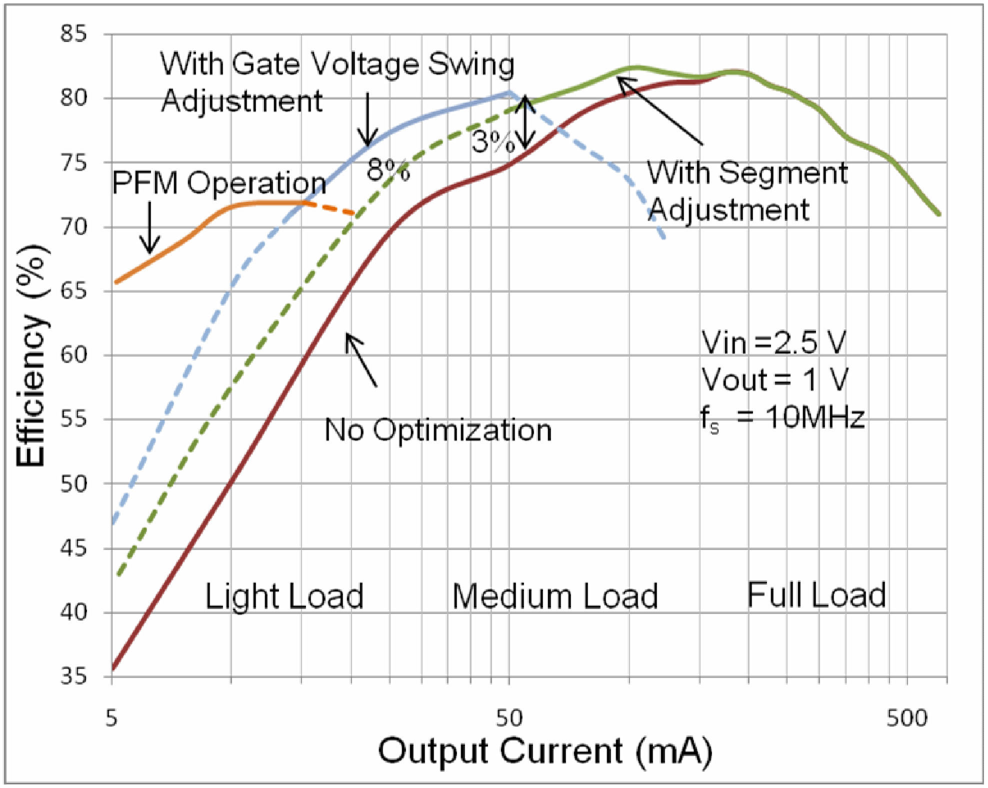
GBW reduced since the amplitude is always relatively large (but not the losses)

IC-Implementation

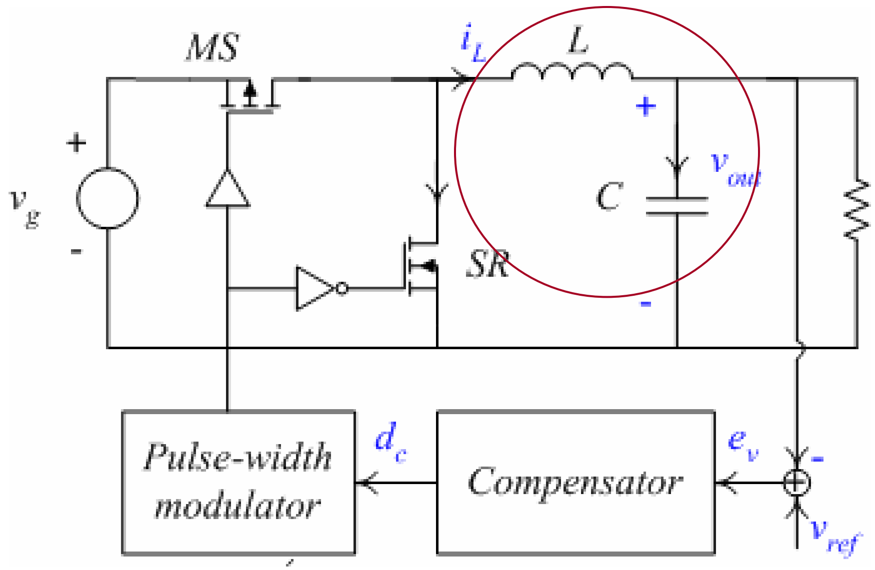


Specifications	Value	Units
CMOS Process	0.13	µm
Area	2.5	mm2
Input Voltage	2.5	V
Output Voltage	0.8-1.3	V
Rated Load	500	mA
Filter L,C	400, 0.9	nH,µF
Switching Frequency ,	10	MHz
Ron Pmos , Nmos	0.26 , 0.234	Ω
Supply Analog , Digital	1.2, 2.5	V
Peak Efficiency	83	%
CPM Controller Current	500	µA
PFM Controller Current	10	µA
Digital Core	200	µA

Experimental Results



Reaching the Physical Limitations Through Hardware-Efficient Mixed-Signal ICs



Load current

✔ High-frequency of operation

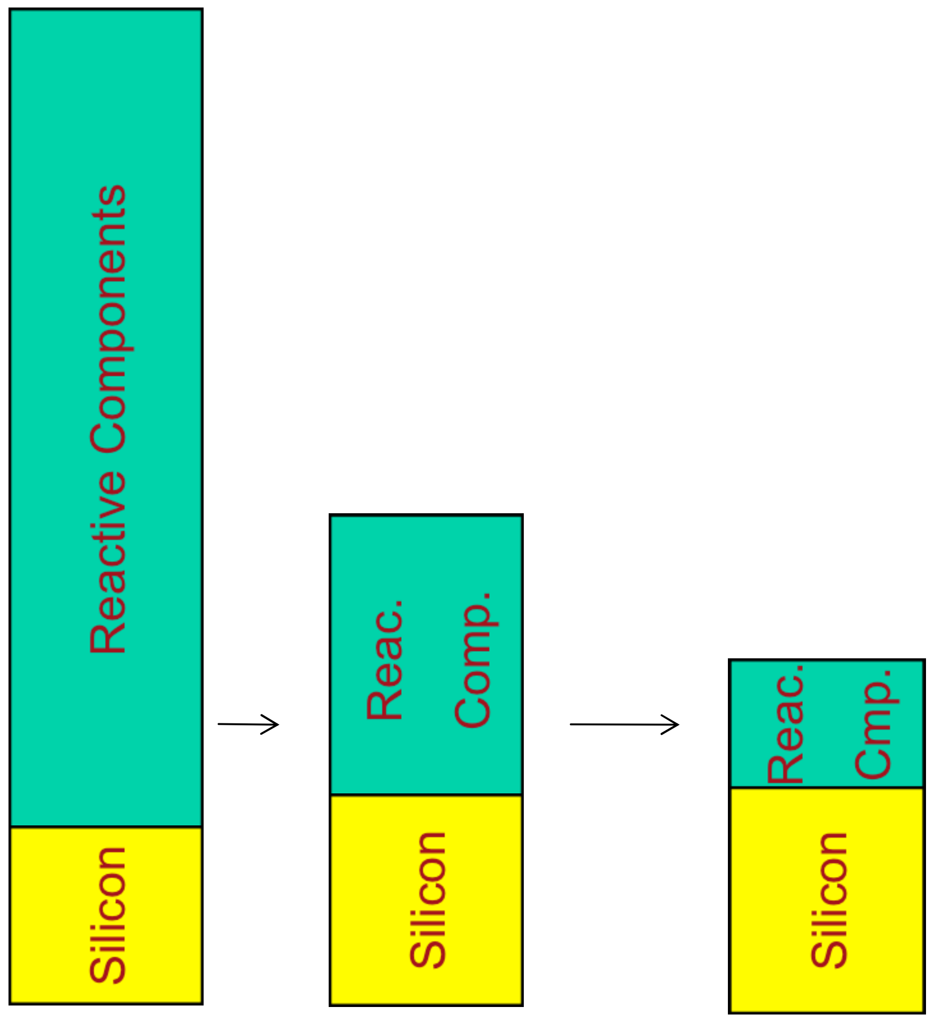
✔ Optimal response with plug and play operation

✔ Relatively flat efficiency curve even during load changes

Moving Forward

Advanced Low-Volume SMPS Topologies

Moving Forward



Overall volume (weight) contribution

- Reduce volume of reactive components through advanced converter and control topologies

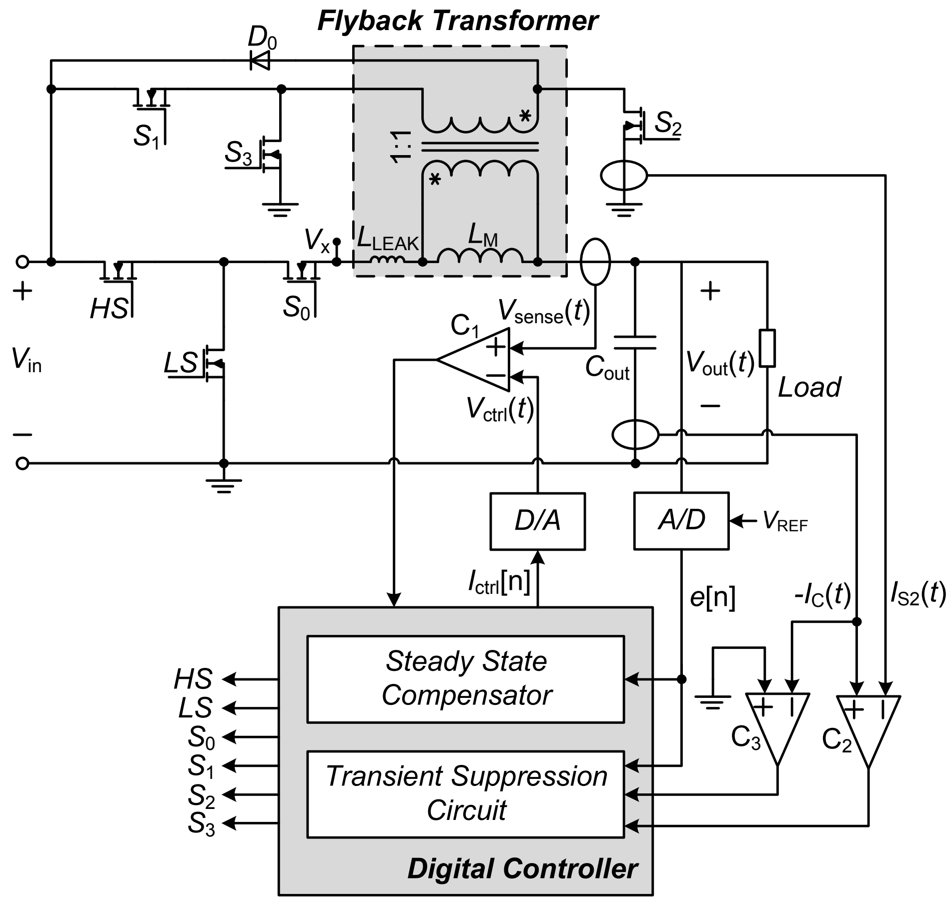
- Allow weight (cost) distribution where the silicon are will be larger than today but the overall volume smaller

- No penalty in efficiency

Flyback Transformer Based Buck (FTBB) with Transient Energy Recycling [4]

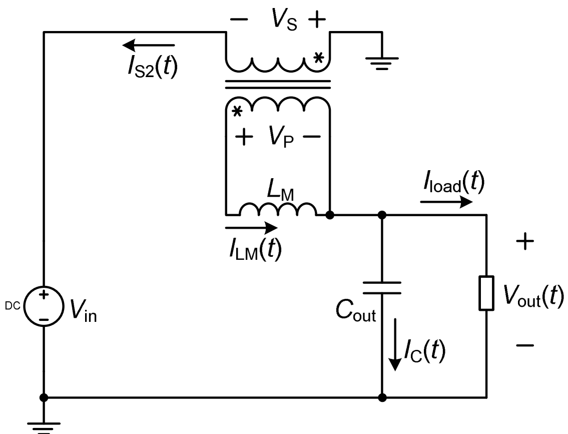
[4] Jing Wang; Prodić, A.; Wai Tung Ng, "Mixed-Signal-Controlled Flyback-Transformer-Based Buck Converter With Improved Dynamic Performance and Transient Energy Recycling," IEEE Transactions on Power Electronics, Vol. 28, Issue. 3, February 2013.

Flyback Transformer Based Buck with Transient Energy Recycling



The buck inductor is replaced with a flyback transformer, and a single extra switch inside the conduction path

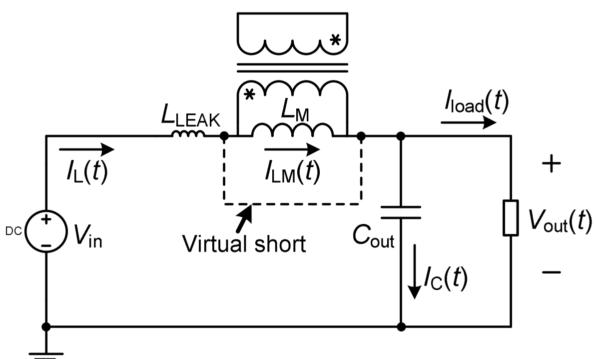
FTBB – Principle of Operation



Heavy-to-light

Current slew rate of magnetizing inductance is $-V_g/L_m$ rather than $-V_{out}/L_m$

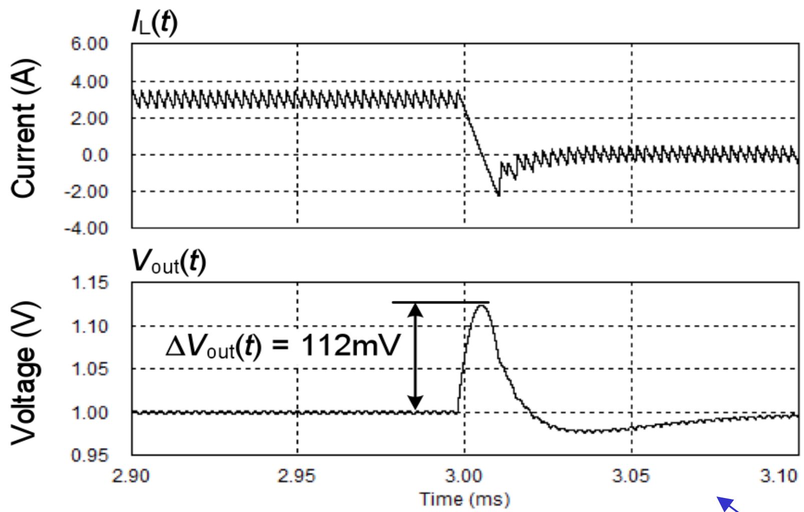
Also, the transient energy is recycled back to the source – two fold effect

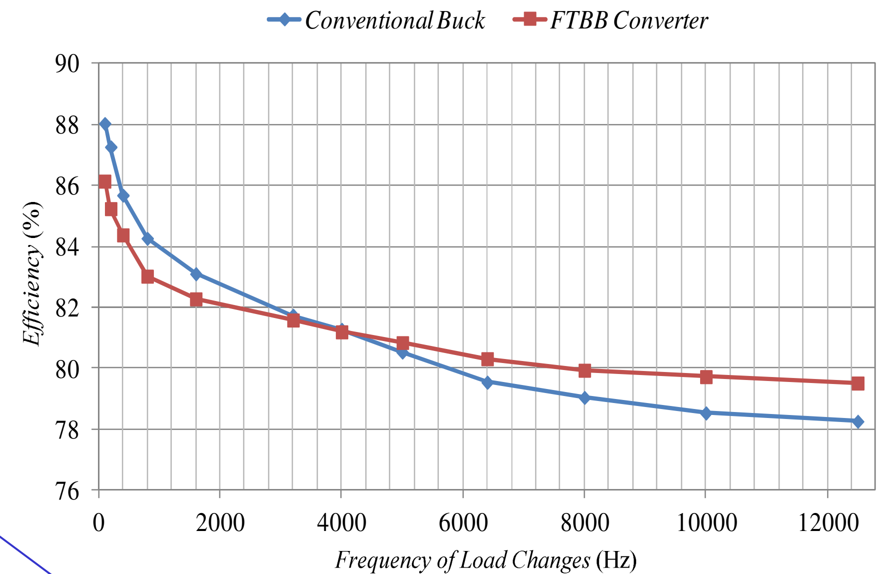


Light-to-heavy

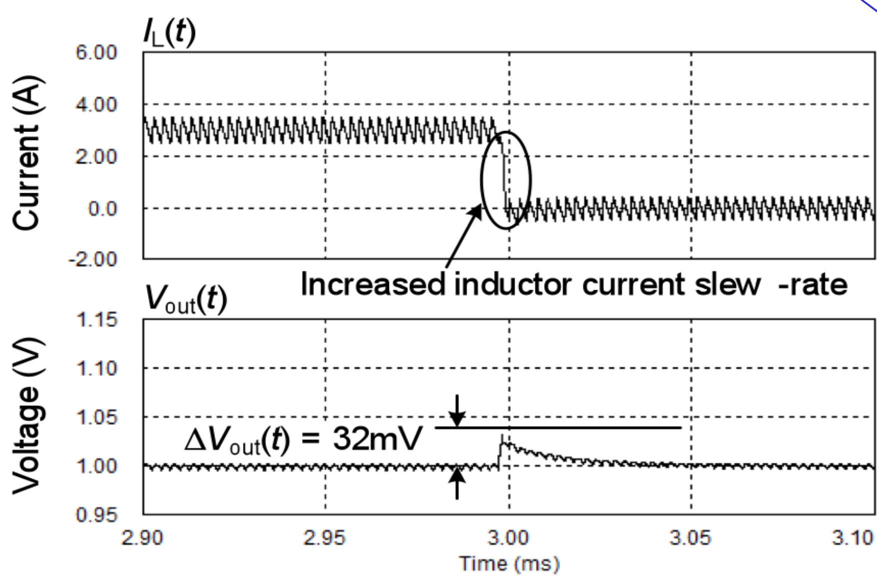
The inductance is reduced to its leakage value

Conventional Minimum-Deviation vs. FTBB





Conventional buck

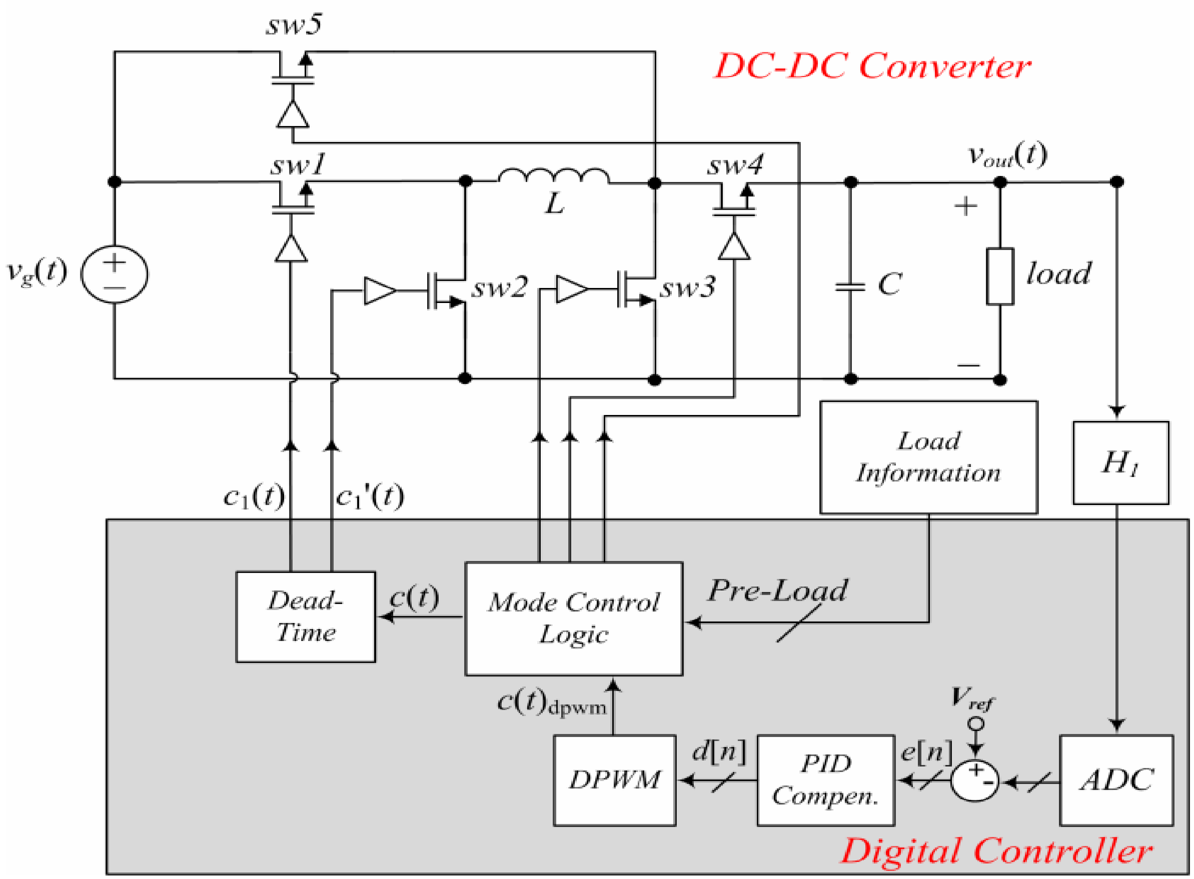


FTBB converter

Load-Interactive Steered-Inductor DC-DC Converter with Transient Energy Recycling [5]

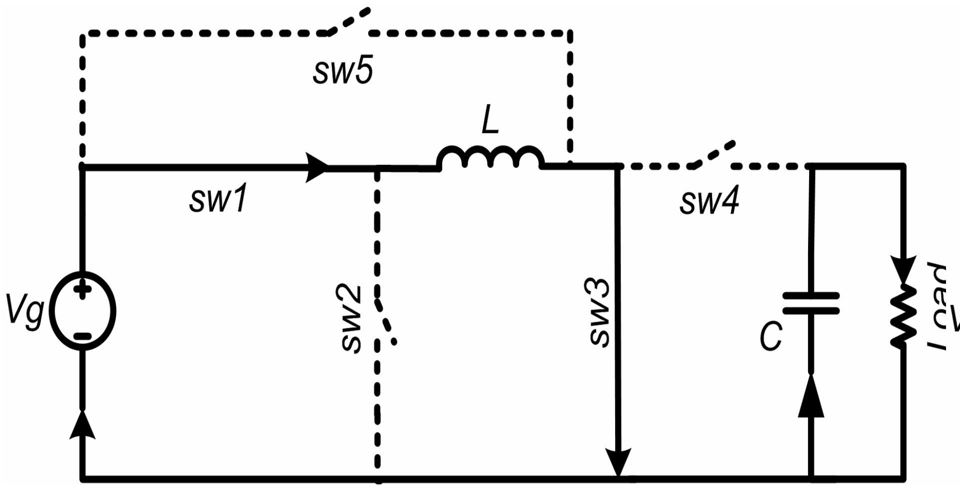
[5] S.M. Ahsanuzzaman, A. Parayandeh, A. Prodic, D. Maksimovic, "Load-interactive steered-inductor dc-dc converter with minimized output filter capacitance," in Proc. IEEE Applied Power Electronics Conference (APEC '10), 2010, Pg. 980-985.

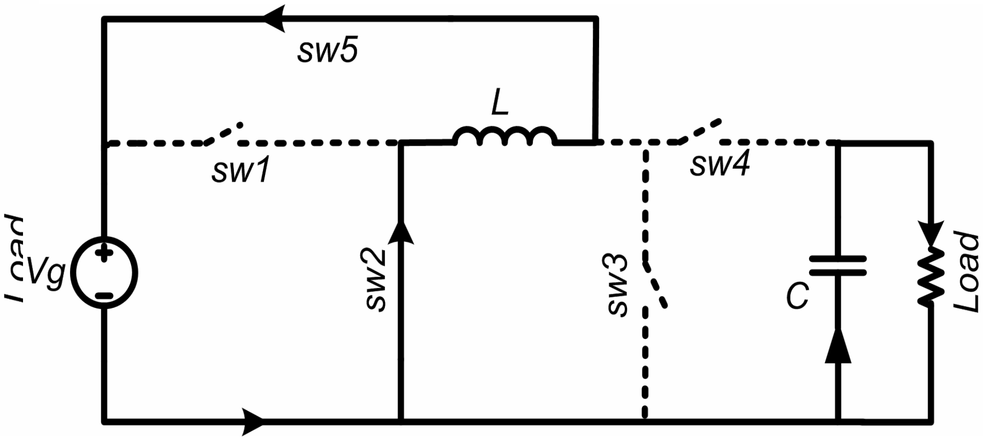
Load Interactive SMPS with Current Steering



- Relies on improved interaction with the digital load
- Theoretically, allows selection of the output capacitor based on the output ripple criteria only.

Steered Inductor Buck-Boost Converter





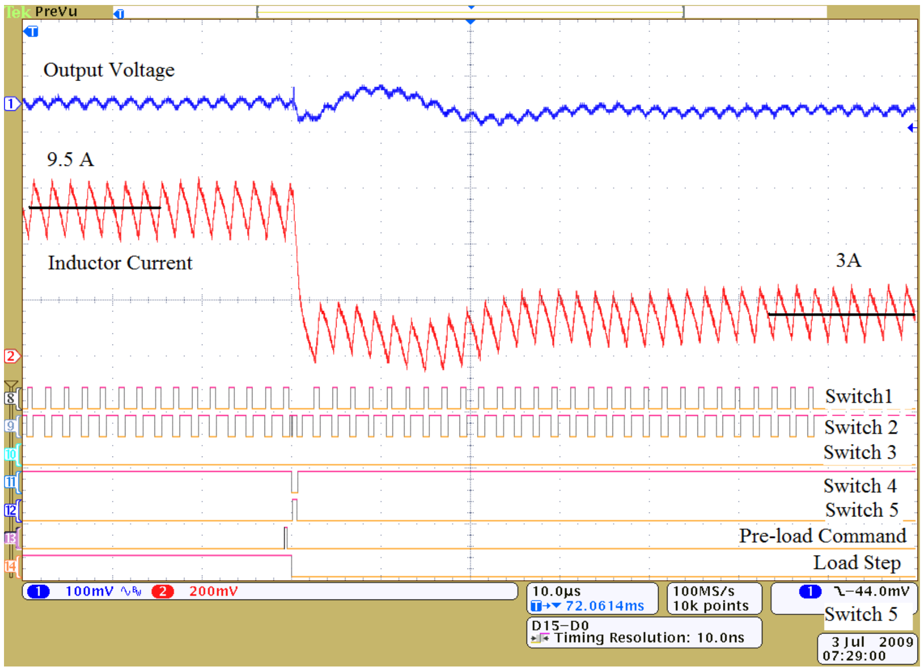
- Light-to heavy pre-transient condition current "pump-up"
- Slew rate is Vg/L vs (Vg-Vout)/L

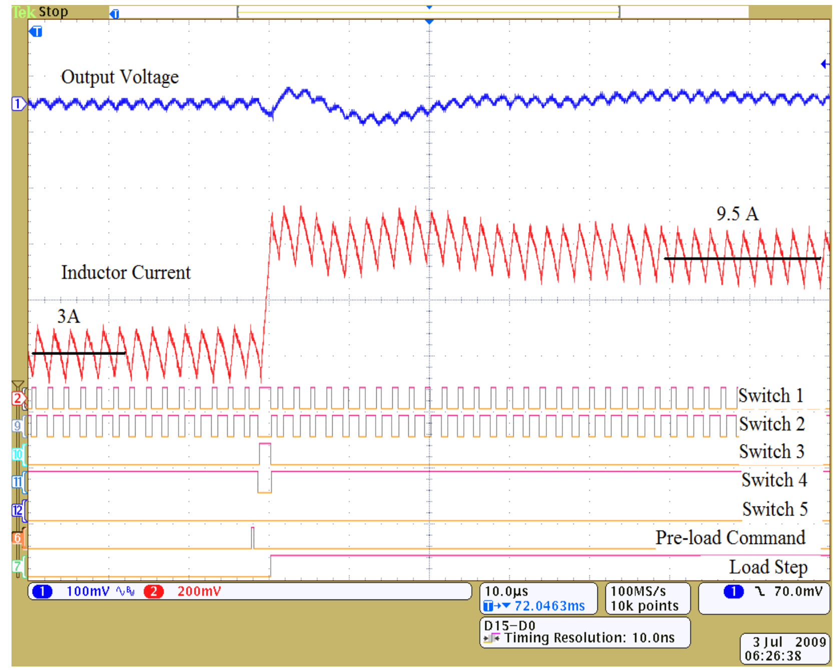
•Heavy-to-light transient ,the current is steered away from the capacitor to the source)

•The current slew-rate is –Vg/L (was -Vout/L in buck mode)

• Energy recycled in this cycle

Load Transient Performance



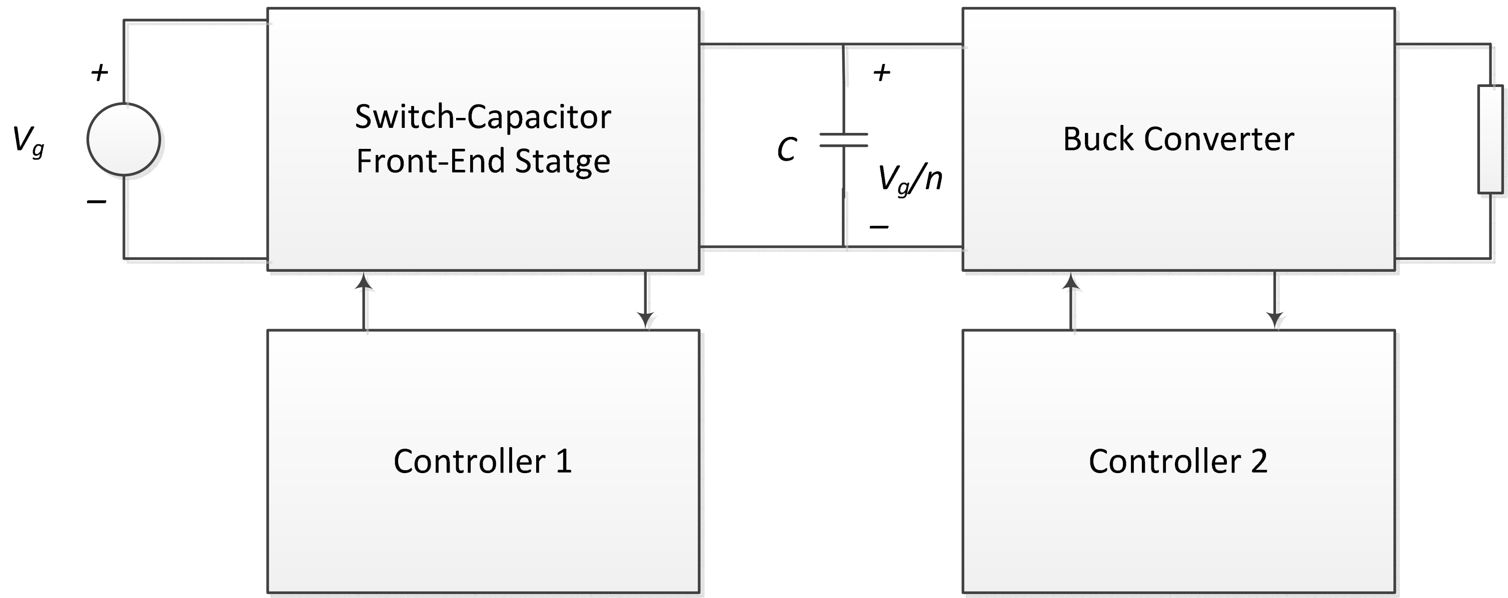


Theoretically, allows reduction of the output capacitor to ripple-limited value

Buck Converter with Merged Capacitive Attenuator [6]

[6] A. Radic, A. Prodic, “Buck Converter With Merged Active Charge-Controlled Capacitive Attenuation,” IEEE Transactions on Power Electronics, Vol. 27, Issue. 3, March 2012.

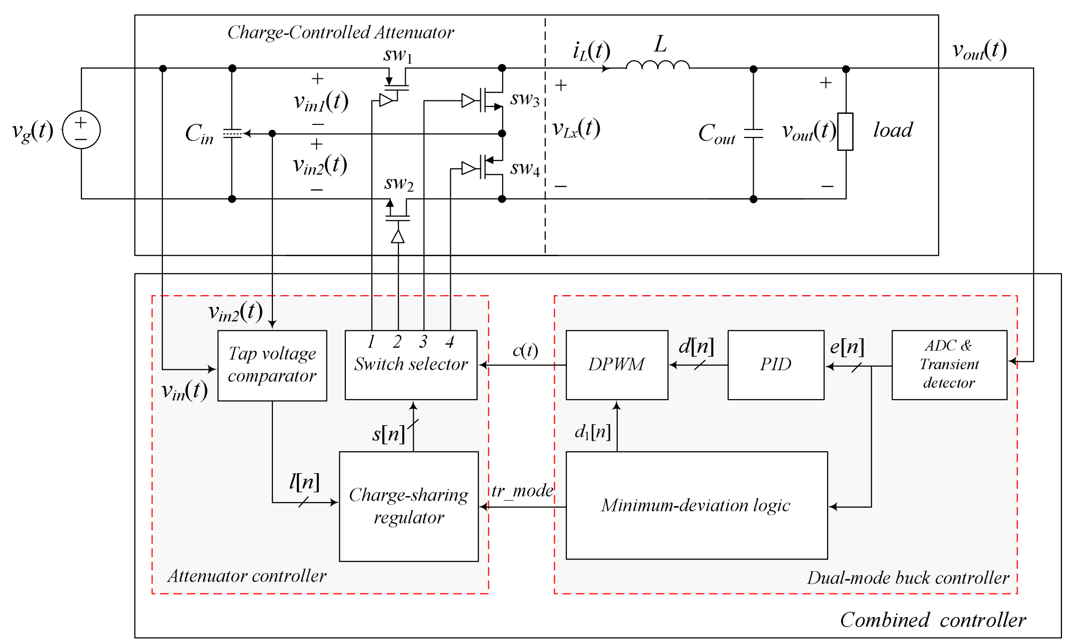
Common Approach: Serial Connection of a Switch Cap Converter And a Converter with Inductor



1. *Reduced output filter volume*

1. *Bulky intermediate balancing cap*
2. *Extra switches in conduction path (at least 4) and at least 6 switches total*
3. *Requires two control loops*

Buck Converter with Merged Capacitive Attenuator



-All switches rated at ½ V_{max} of the conventional buck (no extra conduction losses)

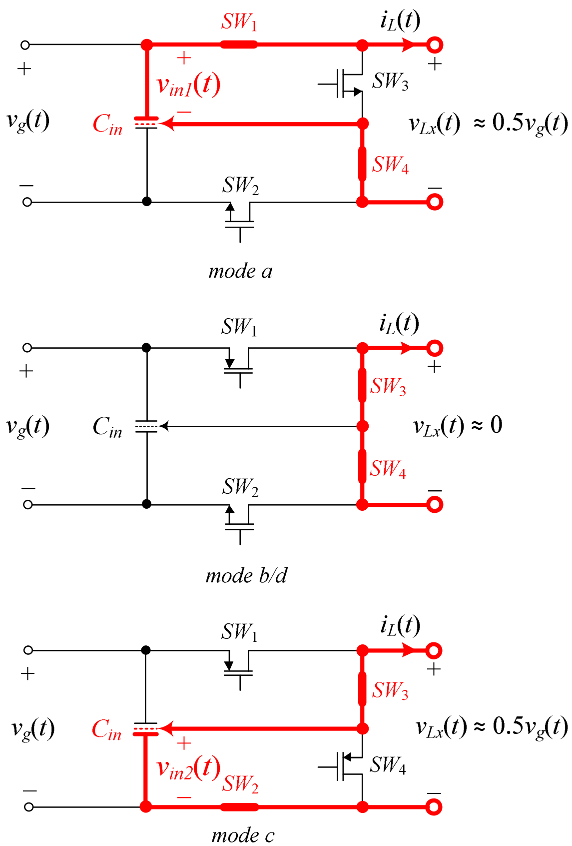
-Switches are shared between the cap stage and buck

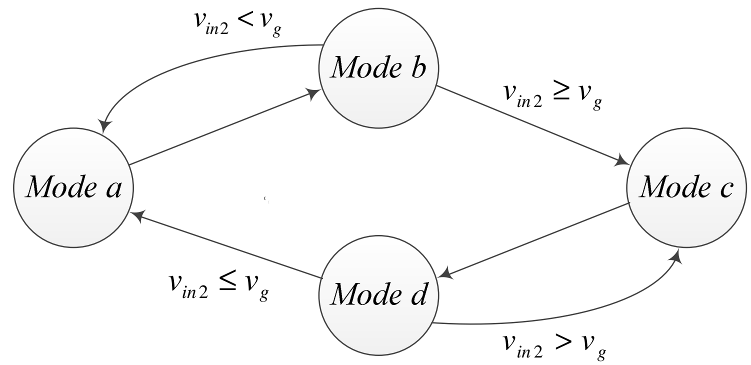
-Lower switching losses than of the conventional buck

-Centre tap voltage maintained constant with the help of buck inductor

- Better transient response than the time-optimal buck

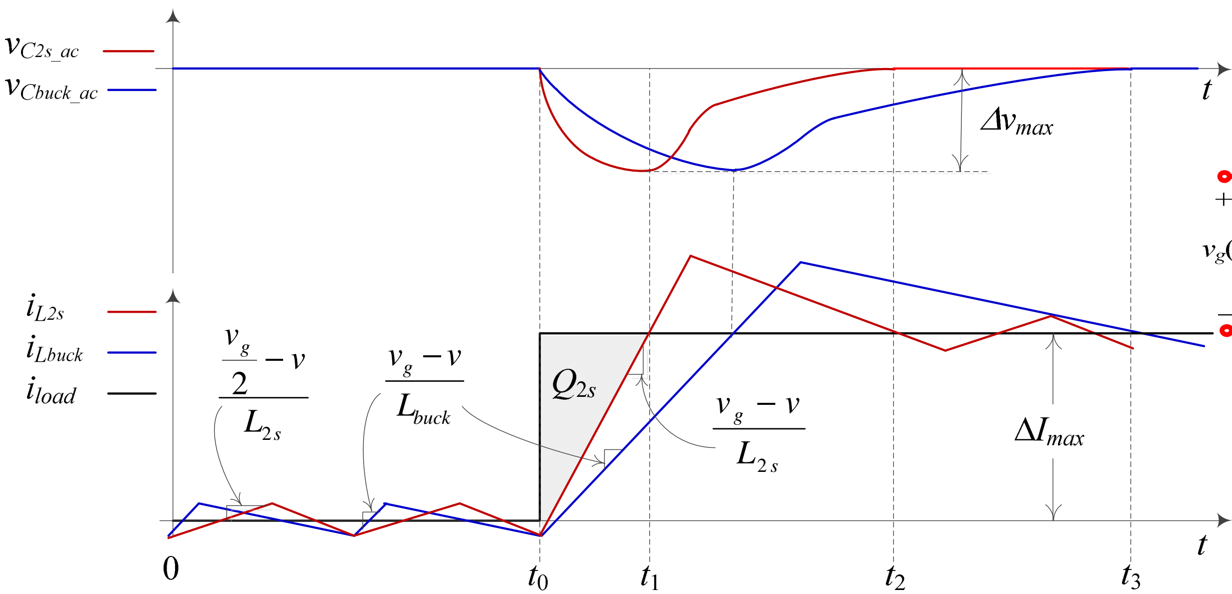
Modes of Operation, Ideal and Practical System

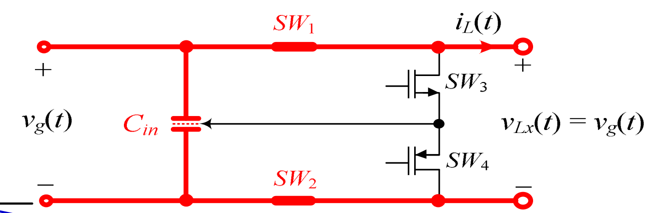




Centre-tap voltage controller operation. Skips regular sequence and takes the charge from the cap with larger voltage until balance is achieved.

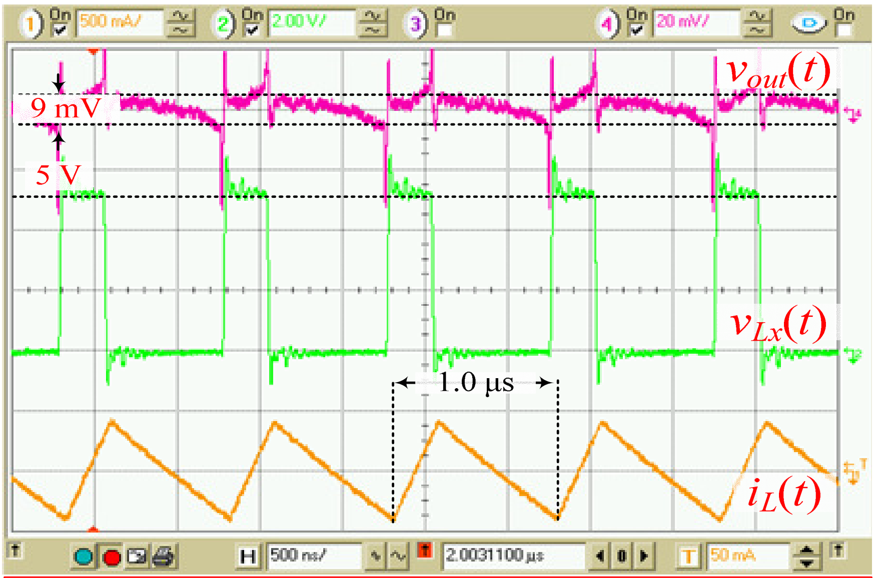
Transient Mode



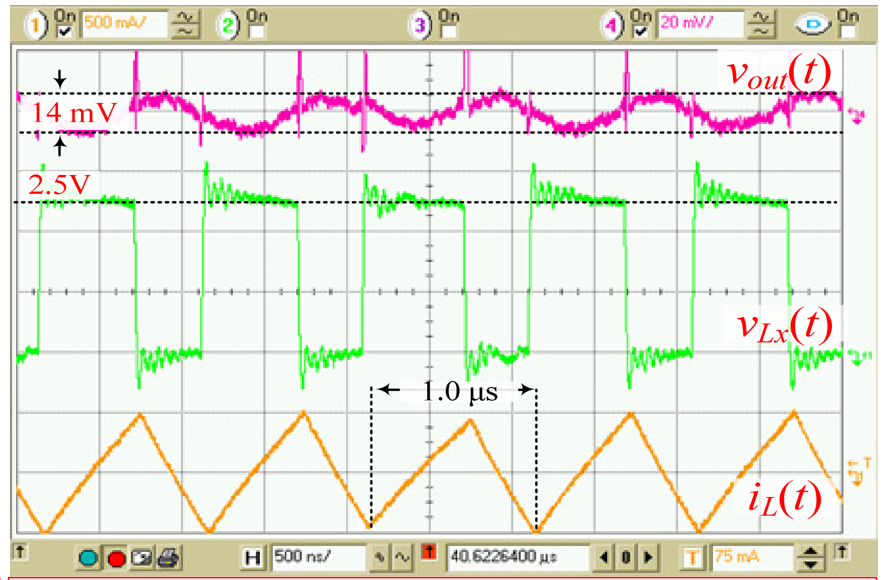


Comparison with a conventional buck

Experimental Results: Comparison with Conv. Buck



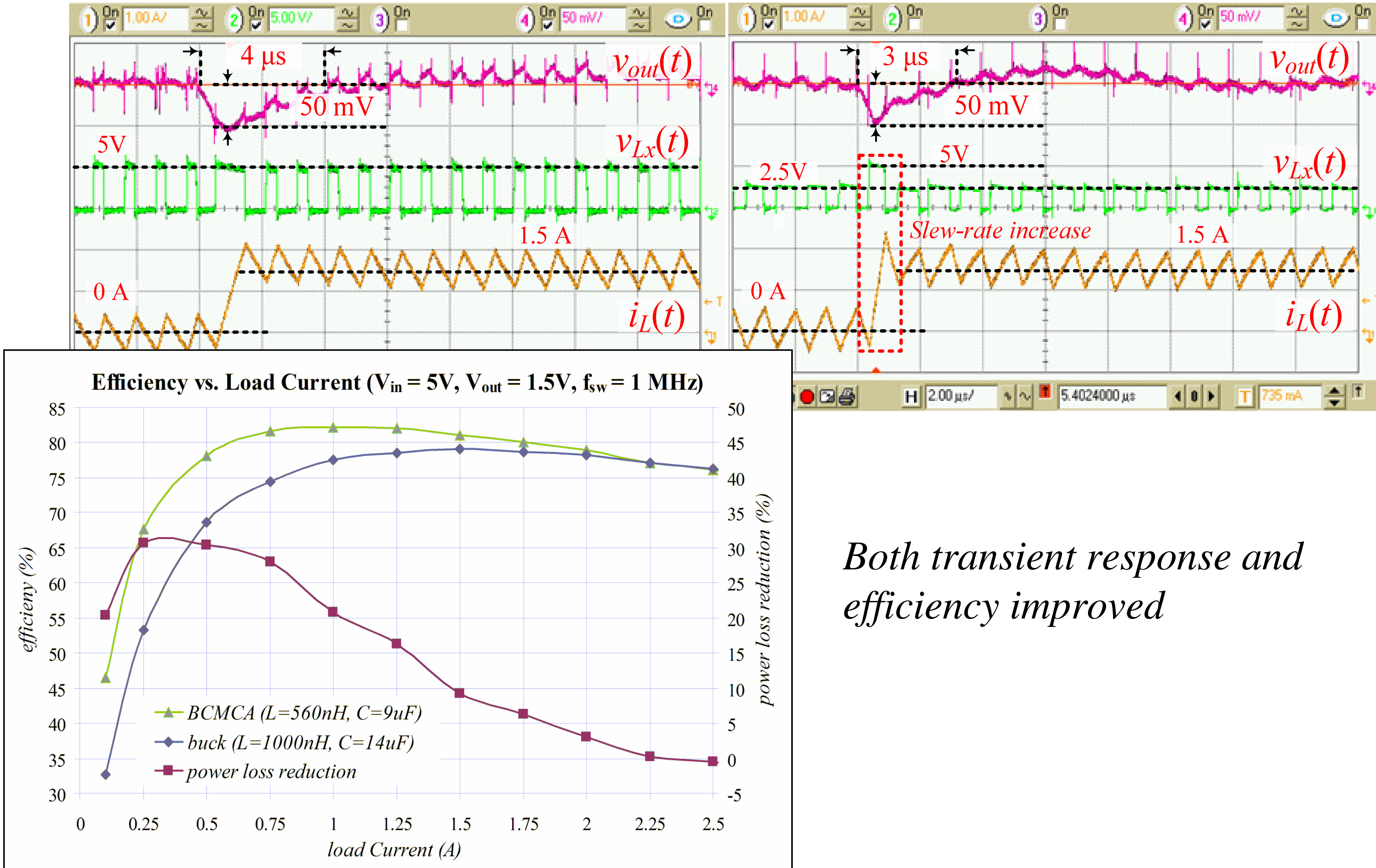
Conventional buck (L=1.0 µH, C=14 µF)



Buck with active charge attenuator (L=560 nH, C=9 µF)

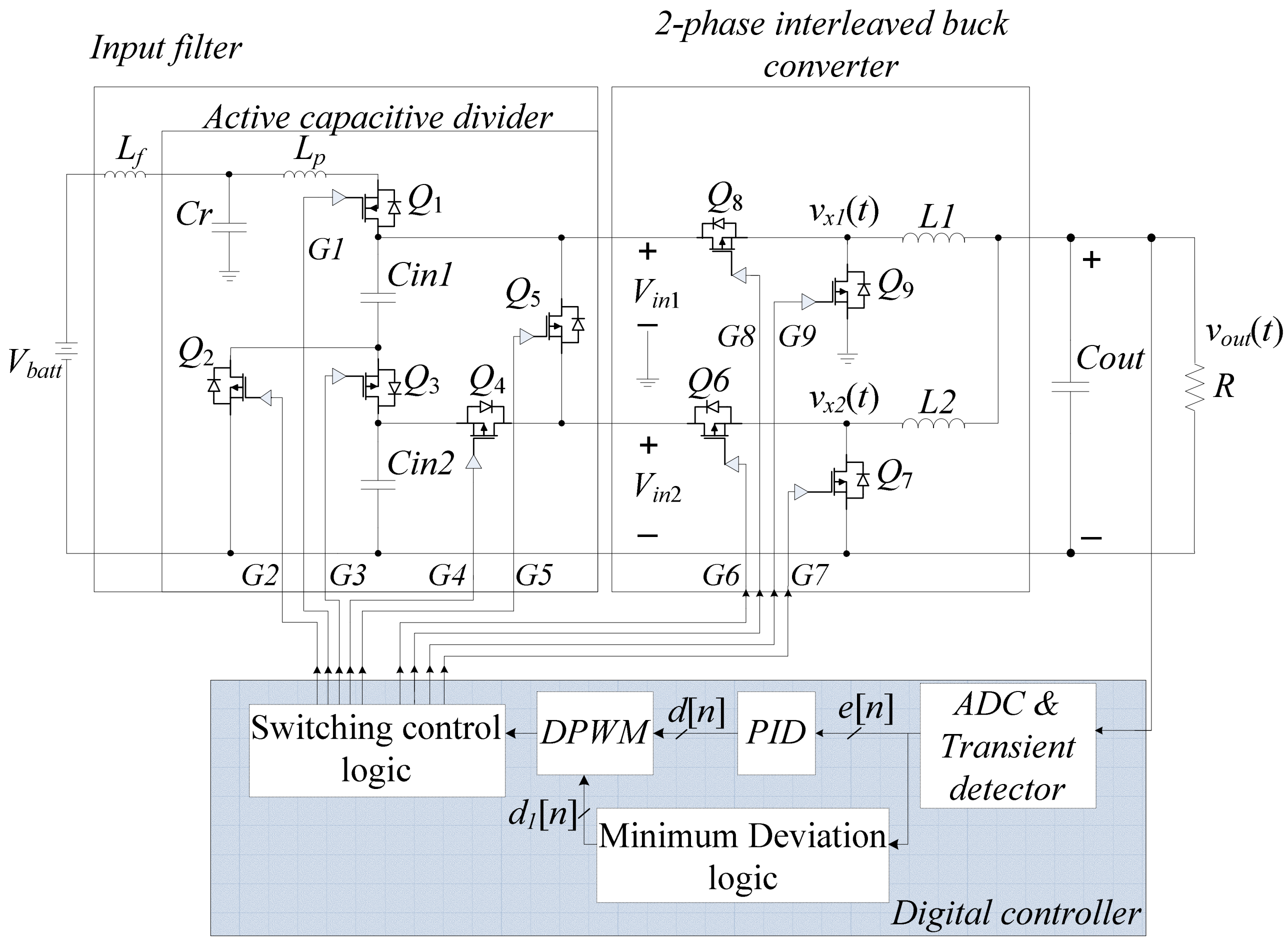
For a 5V to 1 V buck 44% smaller inductor and 35% smaller output capacitor

Experimental Results: Comparison with Con. Buck



Both transient response and efficiency improved

Extension to 2-Phase [7]



L_1 takes the charge from the top inductor and L_2 from the bottom

[7] B. Mahdavikhah, P. Jain, A. Prodic, "Digitally controlled multi-phase buck-converter with merged capacitive attenuator," Applied Power Electronics Conference and Exposition (APEC), 2012 Twenty-Seventh Annual IEEE , vol., no., pp.1083-1087, 5-9 Feb. 2012

Many other examples ……

Conclusion

Digital control allows us to use advanced converter topologies and drastically reduce the volume of SMPS while improving efficiency at the same time.

Thank you