Using Coupled Inductors to Enhance Transient Performance of Multi-Phase Buck Converters

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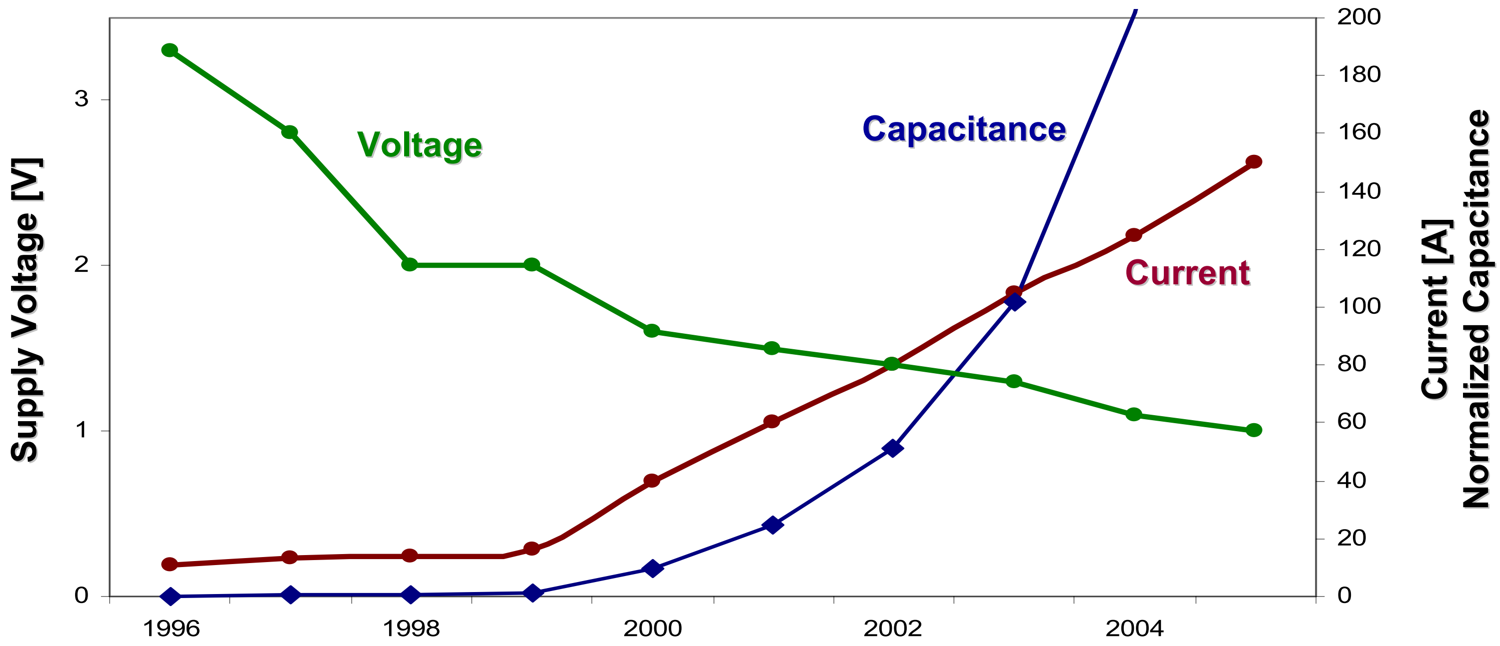
Dartmouth College

Processor Power Supply Trends Increase Capacitance

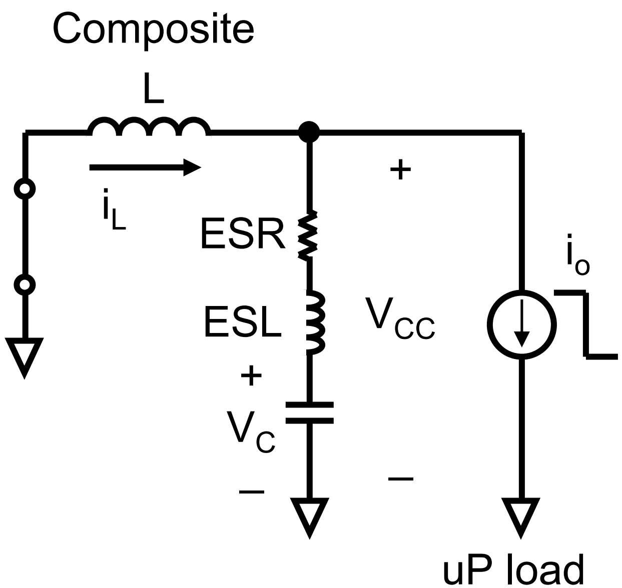


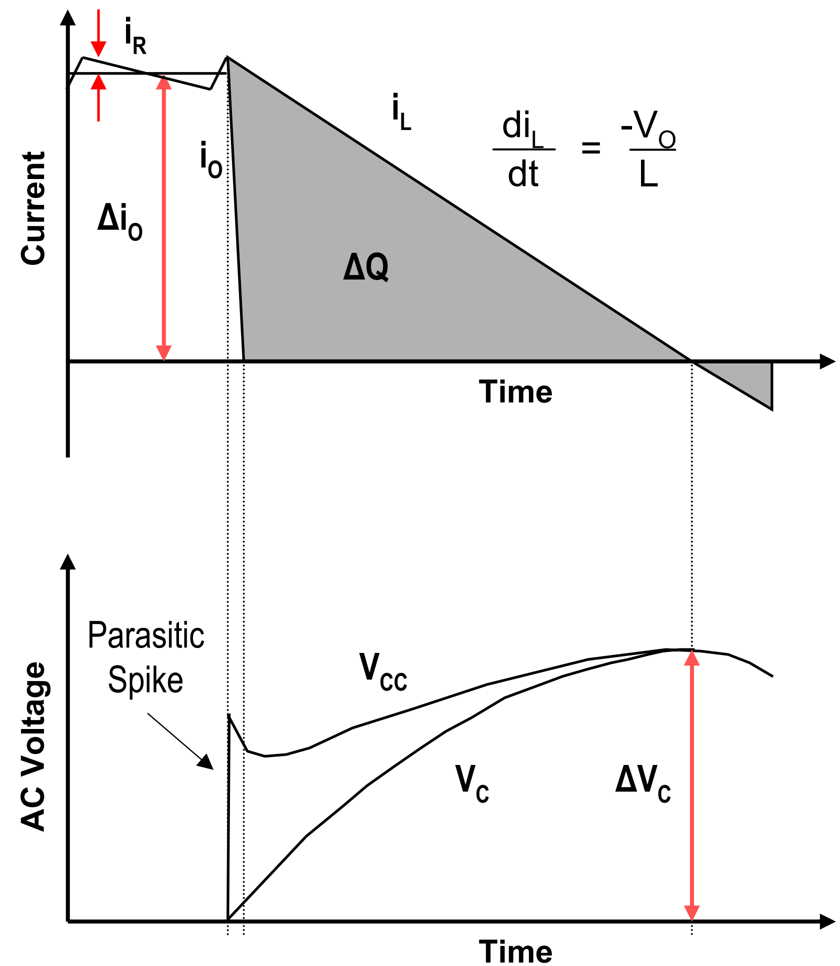
With successive processor generations: $V_{cc} \downarrow$, $I_{cc} \uparrow$

$C \propto (I_{cc} / V_{cc})^2 \Rightarrow$ > 200x increase in C_{out} from '99 to '04

Processor decoupling is becoming prohibitively large and expensive

Ideal Unloading Transient Review



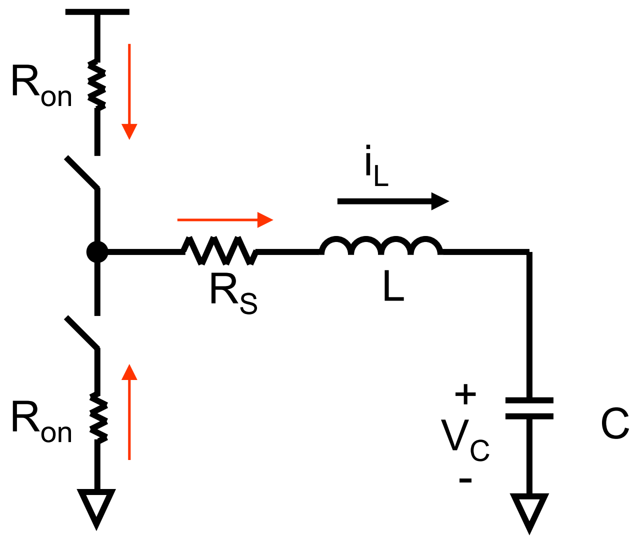


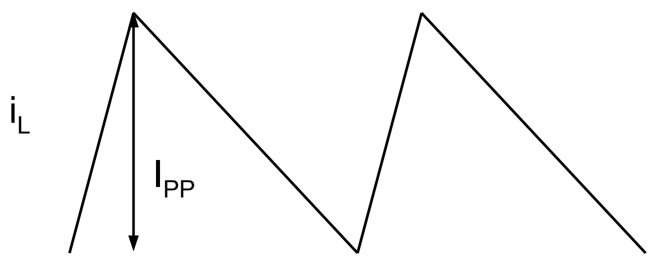
- Parasitic spike ∝ ESR, ESL

$$\Delta V_C = \frac{1}{2} \cdot \frac{L(\Delta i_O + i_R)^2}{V_{CC} \cdot C}$$

Minimize C through smaller L

Small L Hurts Steady-State





$$I_{PP} = \frac{V_{in} - V_{out}}{L} DT$$

Increased AC current and conduction loss

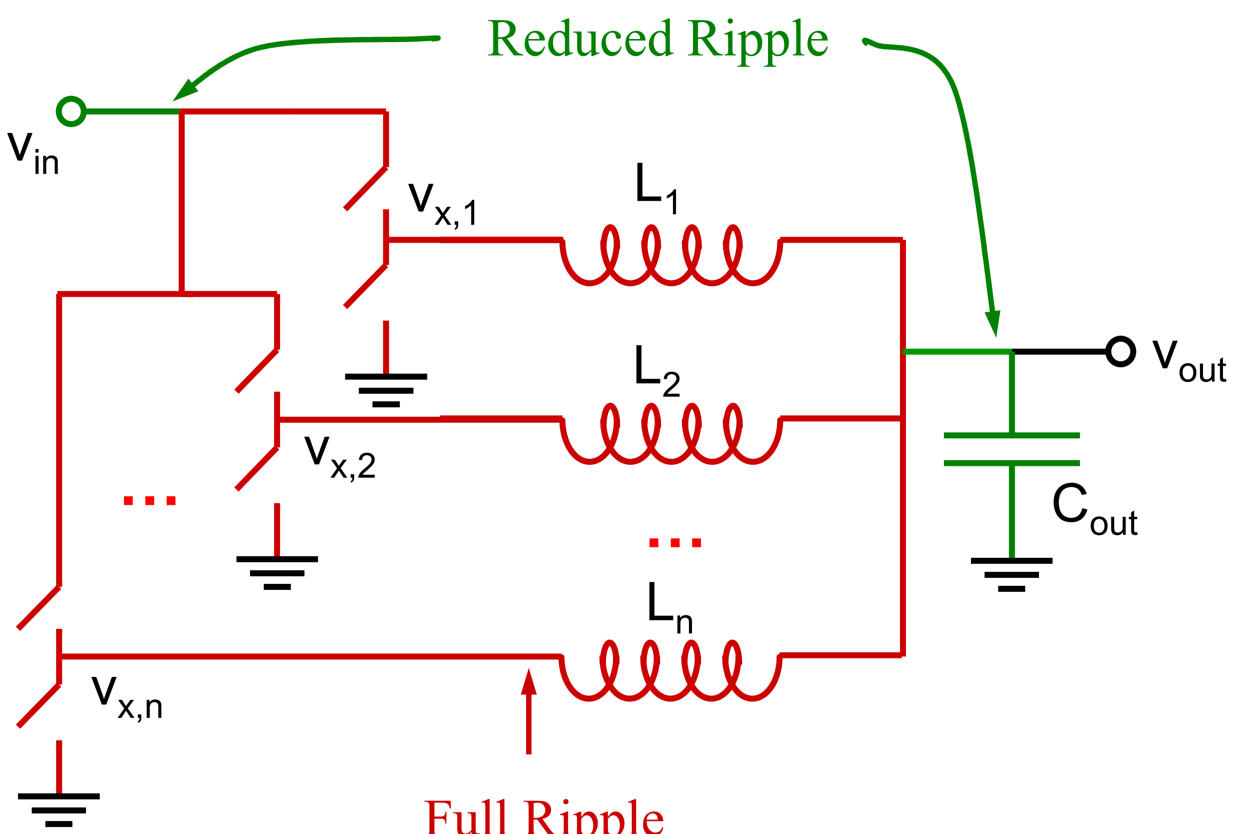
Fundamental trade-off with L:

- Large L→Slow response and large C_{out} requirement
- Small L→High current ripple and loss

Volterra's Patented Coupled Buck Topology

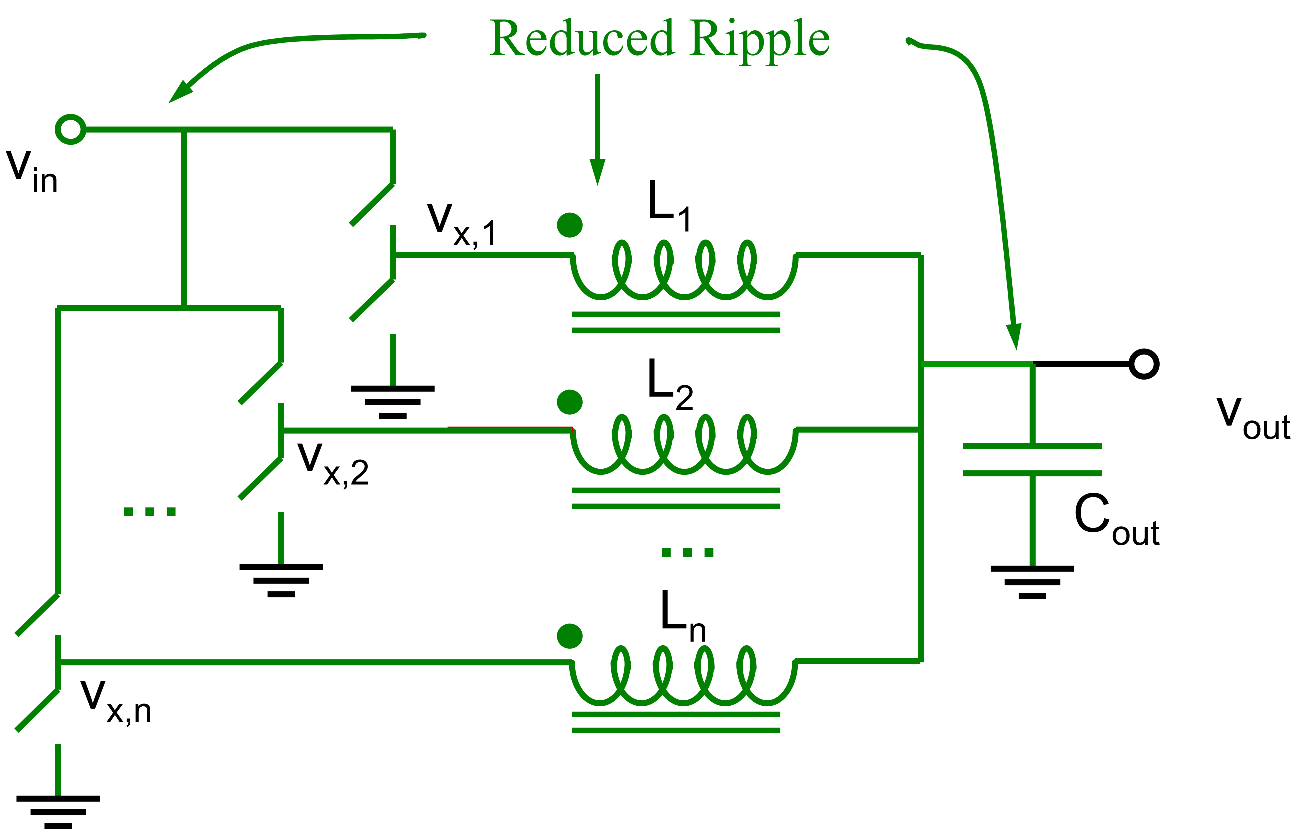
- Multi-phase converter magnetically coupled to cancel AC flux and ripple current
- Single magnetic structure replaces multiple discrete inductors
- Enables use of smaller inductor values to improve transient without increasing current ripple
- Allows significant reduction in output capacitance

Conventional Multi-Phase Buck



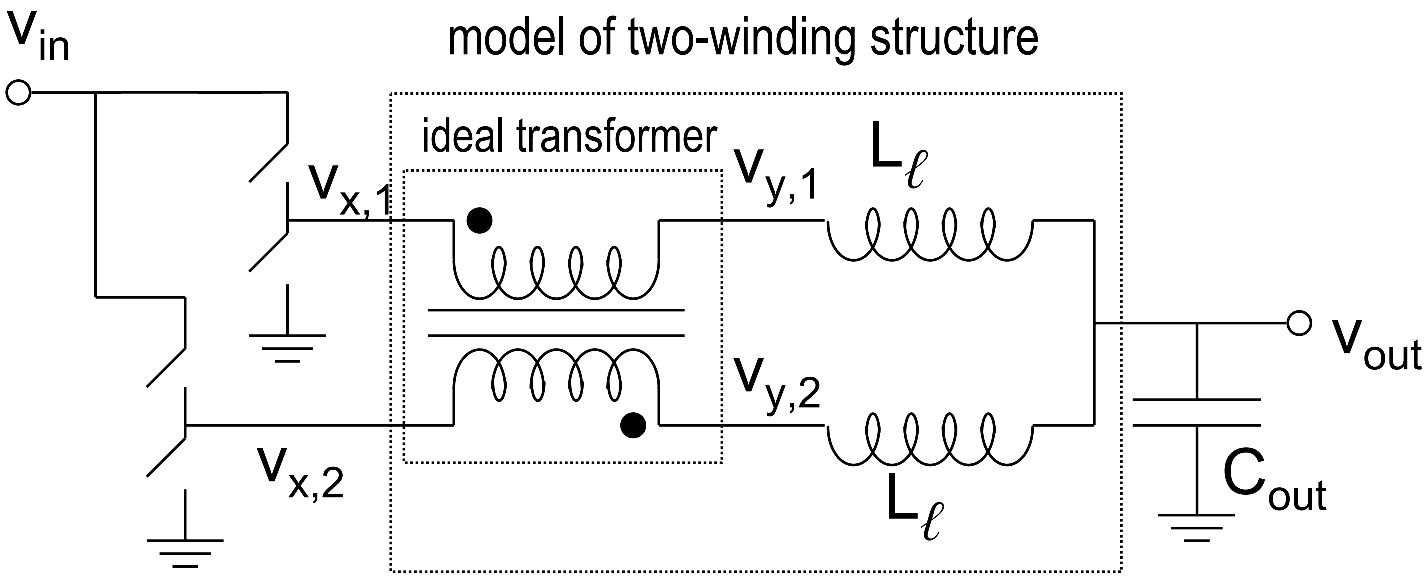
Current ripple cancellation in capacitors reduces voltage ripple

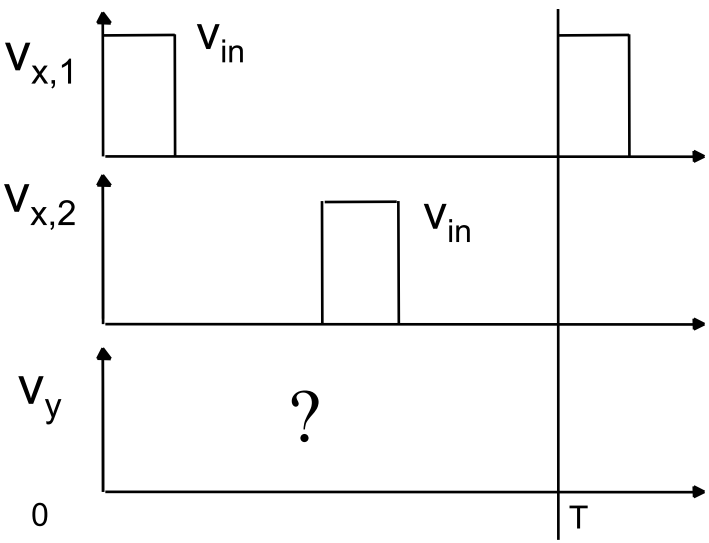
Volterra's Coupled Buck



With coupled inductor, the ripple cancellation is extended to inductors and switches

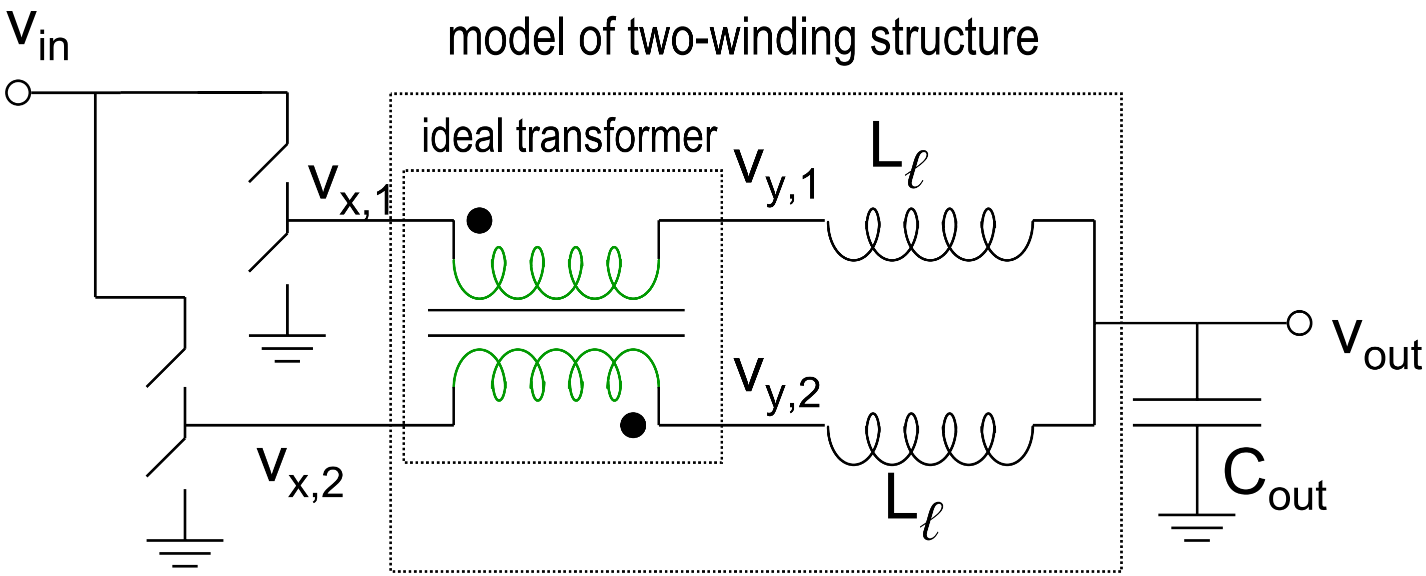
Circuit Model for Two-Winding Structure

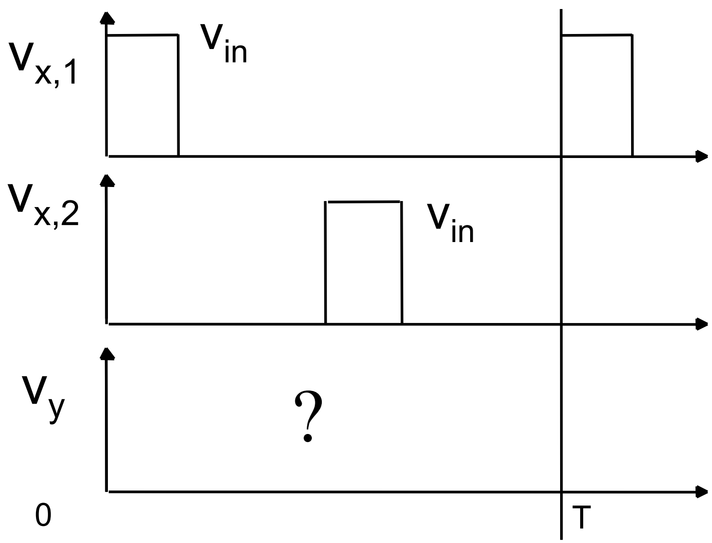




Steady-state, ideal coupling:

Circuit Model for Two-Winding Structure

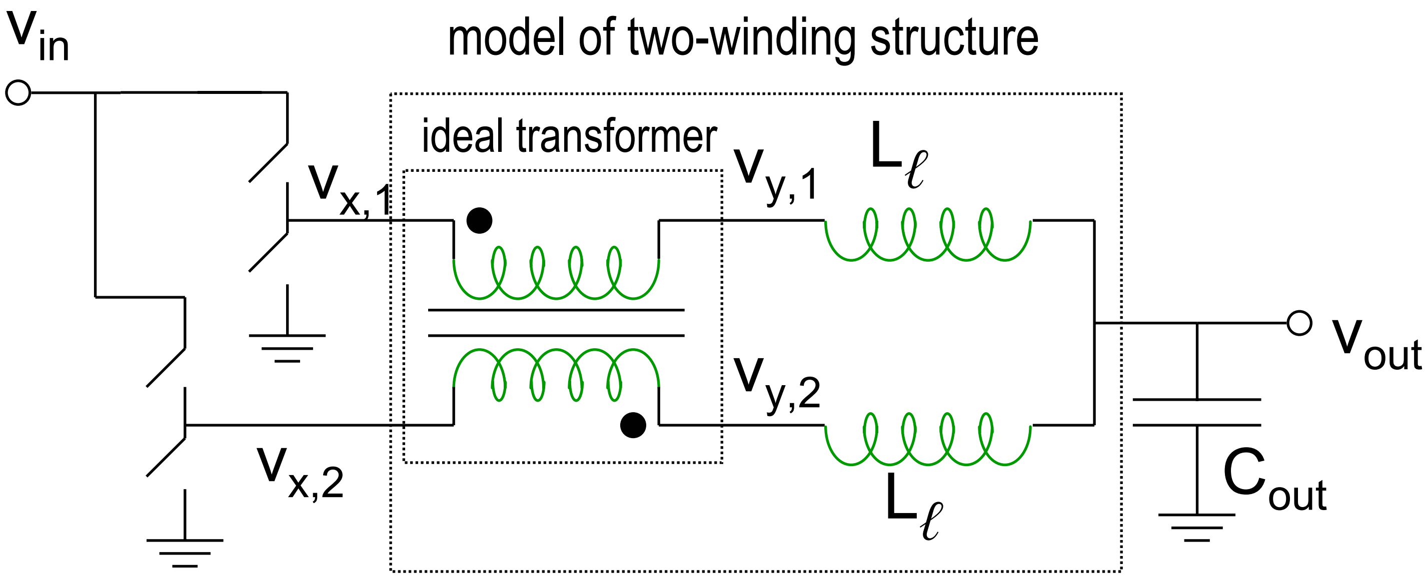


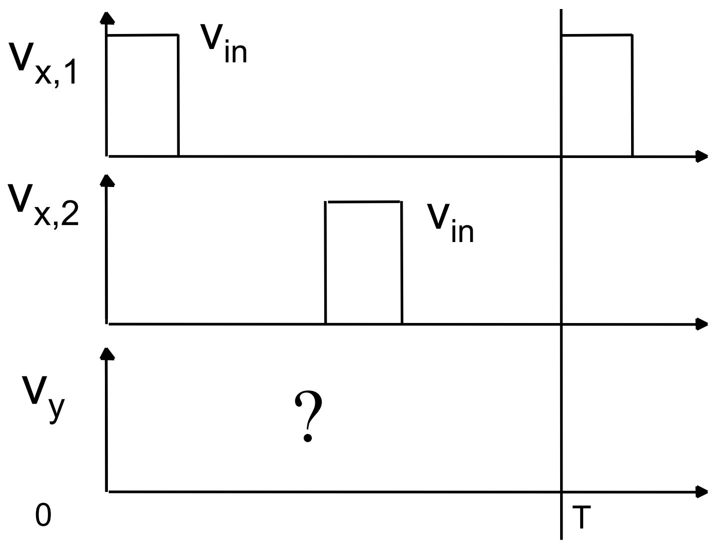


Steady-state, ideal coupling:

- Transformer ac currents equal.

Circuit Model for Two-Winding Structure





Steady-state, ideal coupling:

- Transformer ac currents equal.
- Inductor ac currents equal.

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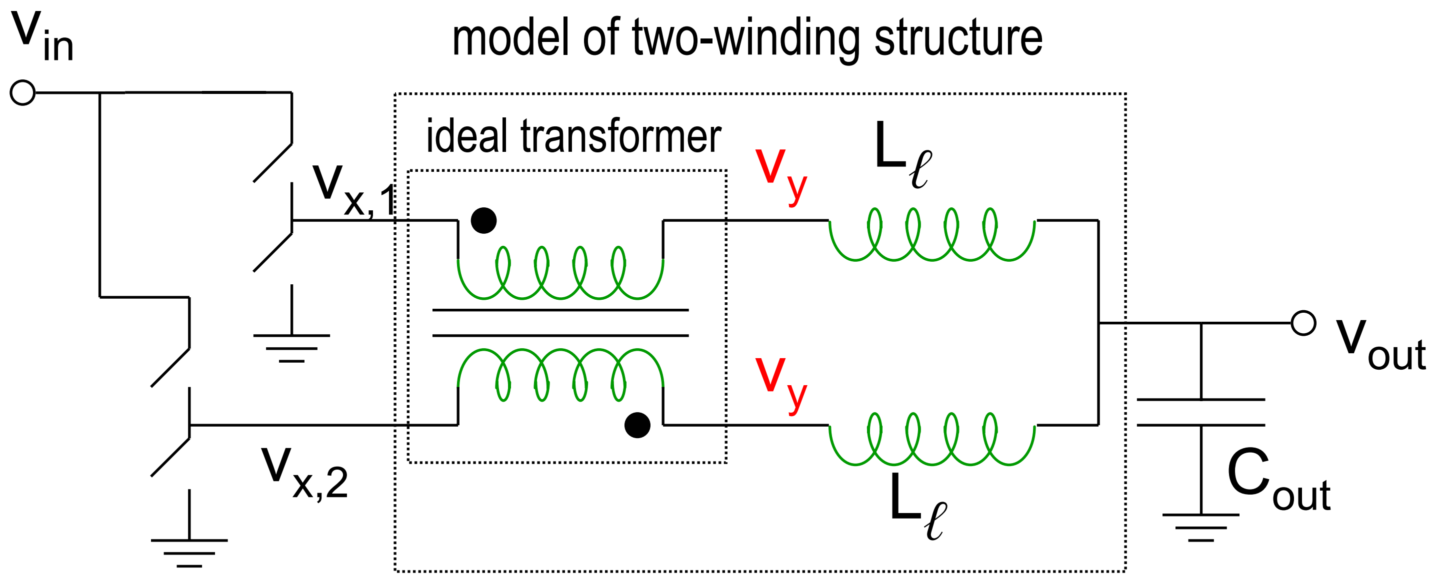
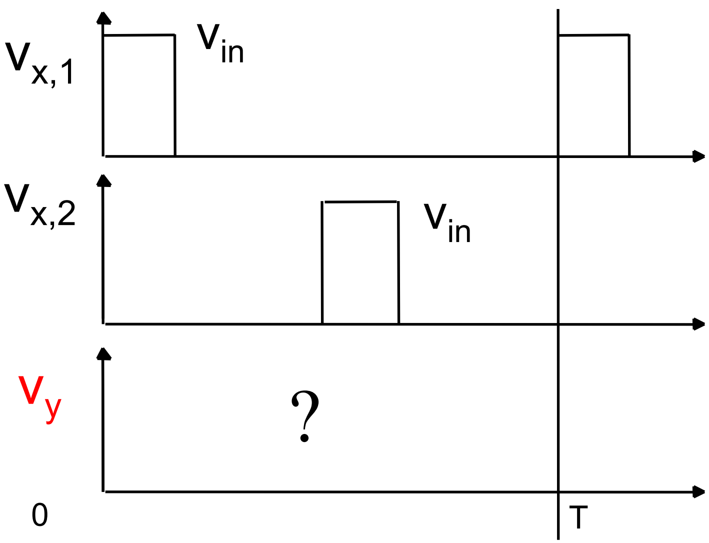
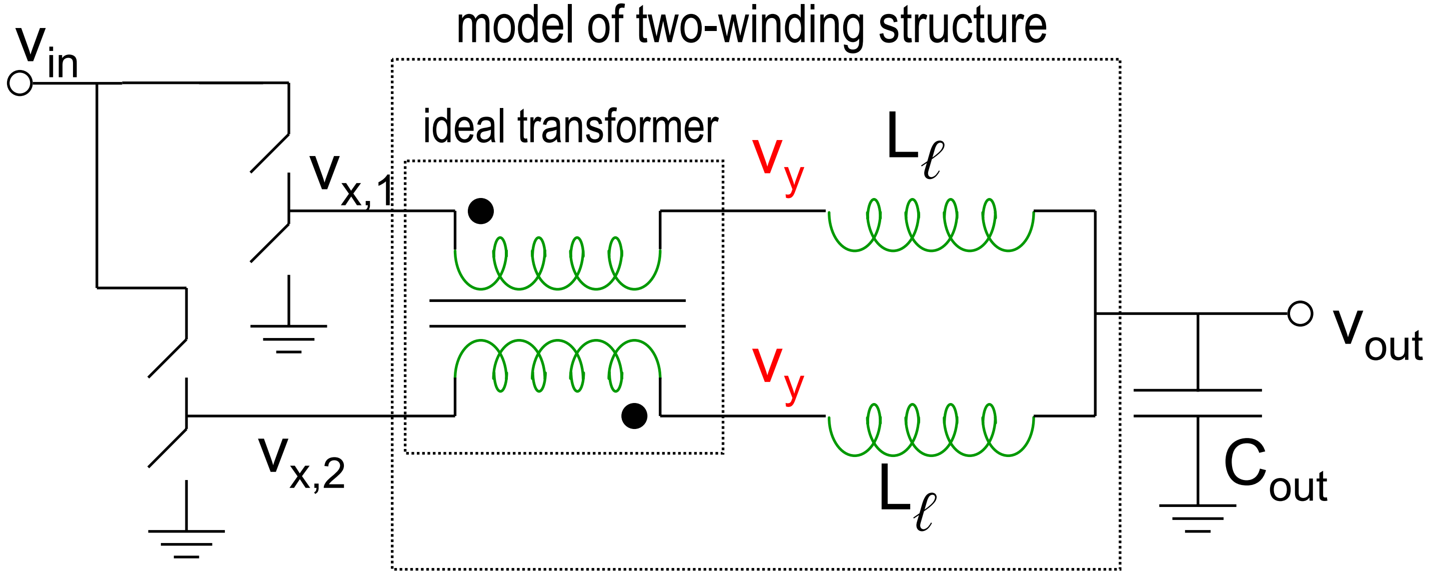


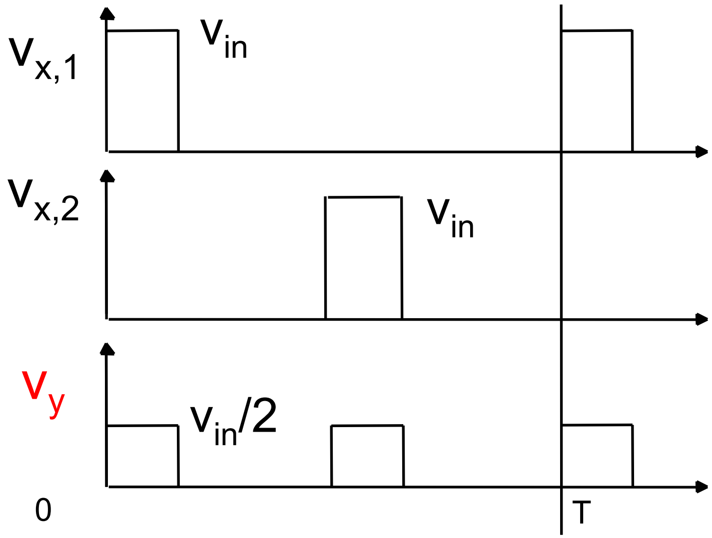


Steady-state, ideal coupling:

- Transformer ac currents equal.
- Inductor ac currents equal.
- Equal L_ℓ's have equal voltage for equal ac current.

Circuit Model for Two-Winding Structure



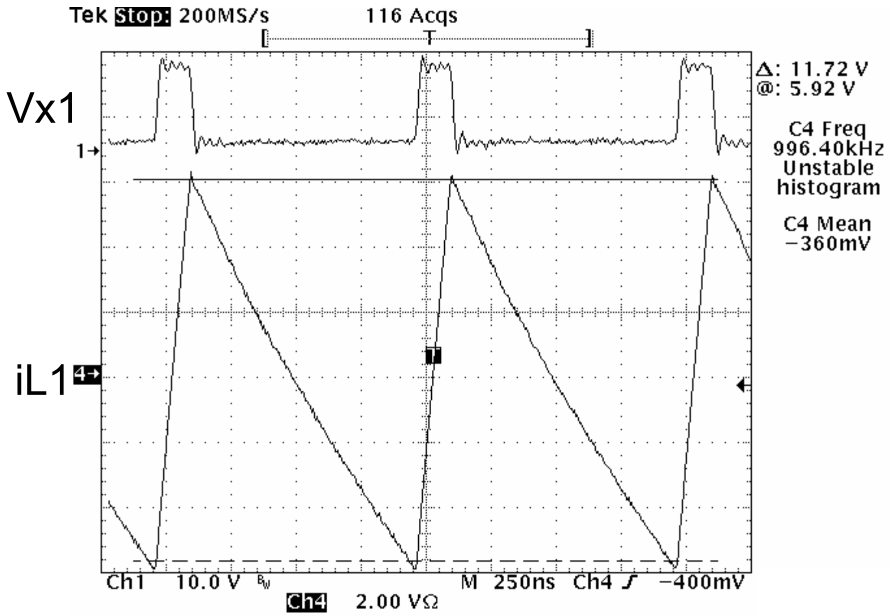


Steady-state, ideal coupling:

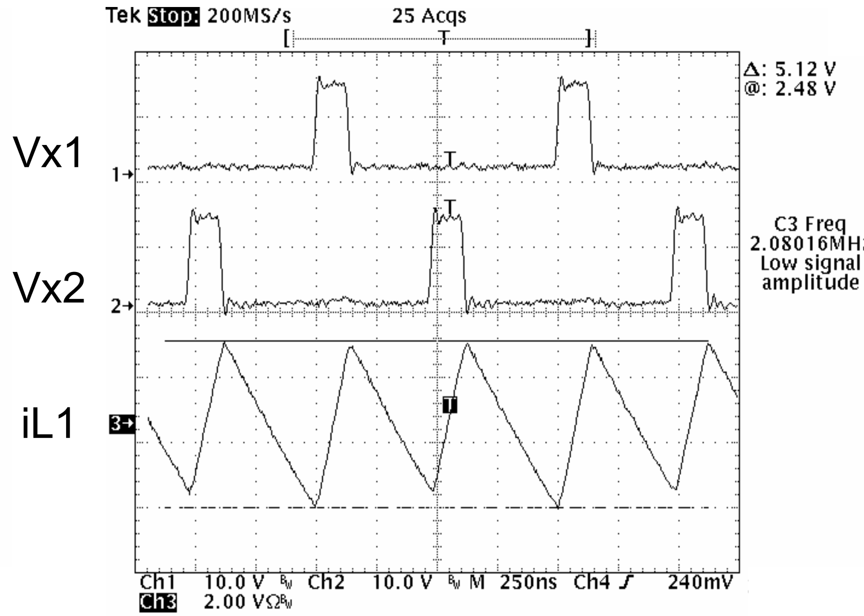
- Transformer ac currents equal.
- Inductor ac currents equal.
- Equal L_ℓ's have equal voltage for equal ac current.
- v_y's equal, equal to average of v_x's
- Like doubling switching frequency, halving V_{in}.

Ripple Current Reduction

uncoupled, ΔIpp = 11.72A



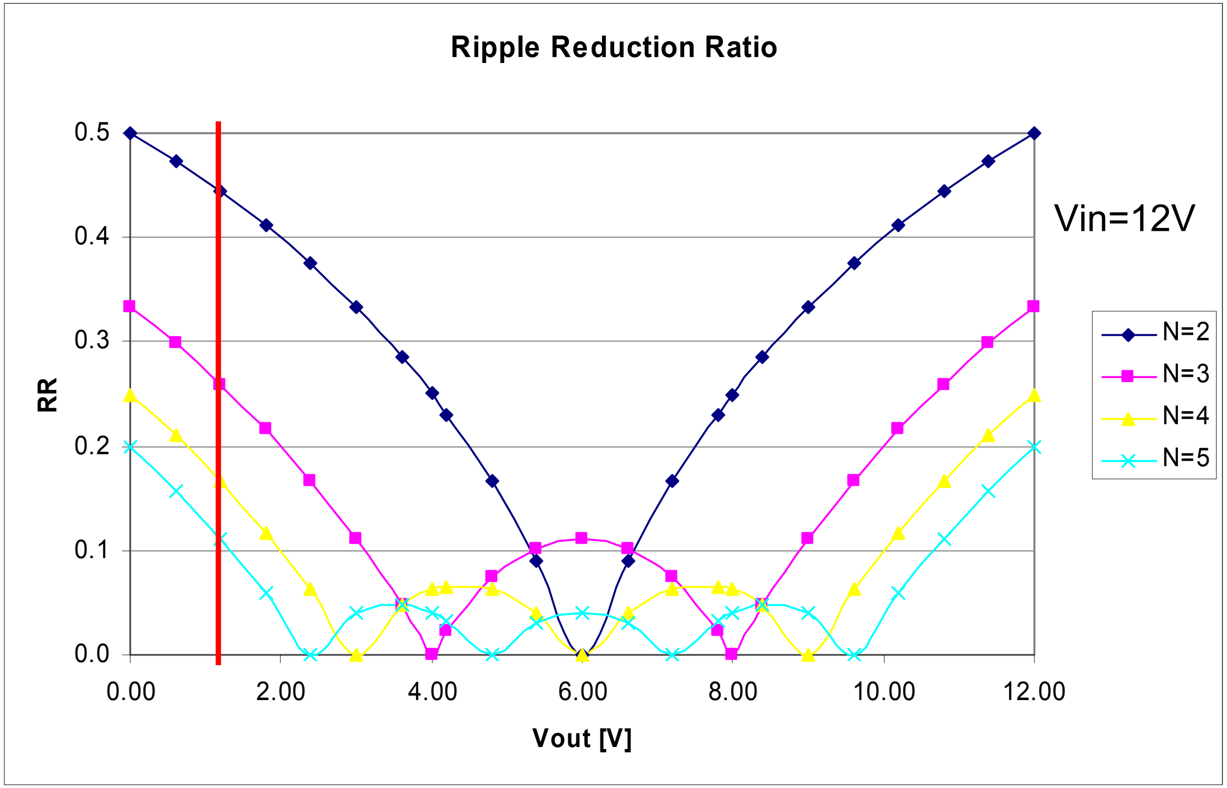
coupled, ΔIpp = 5.12A



- 2-phase buck converter with V_{in}=12V,V_{out}=1.6V,f_s=1MHz
- Same phase inductance (125nH), same probe scale

The ripple is reduced by more than 2x of the uncoupled

Ripple Reduction Ratio



$$\frac{\Delta i_{L,coup}}{\Delta i_{L,uncoup}} = \frac{1/n - D}{1 - D}$$

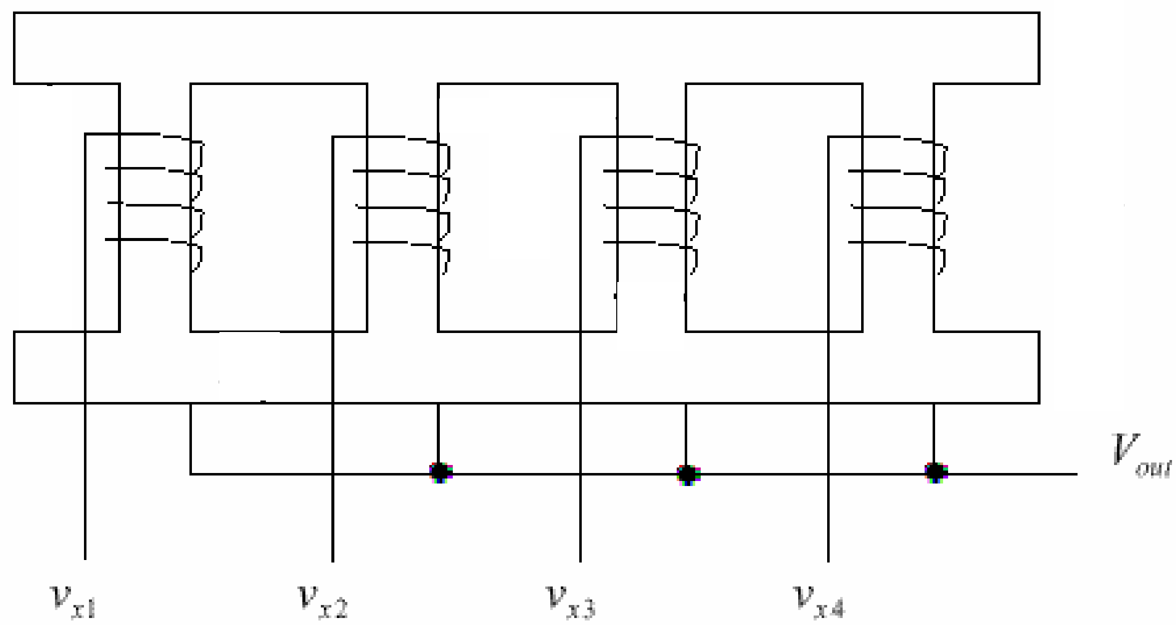
Example:
Vout=1.2V

N	RR
2	44.4%
3	25.9%
4	16.7%
5	11.1%

- Compared with same inductance value, without coupling

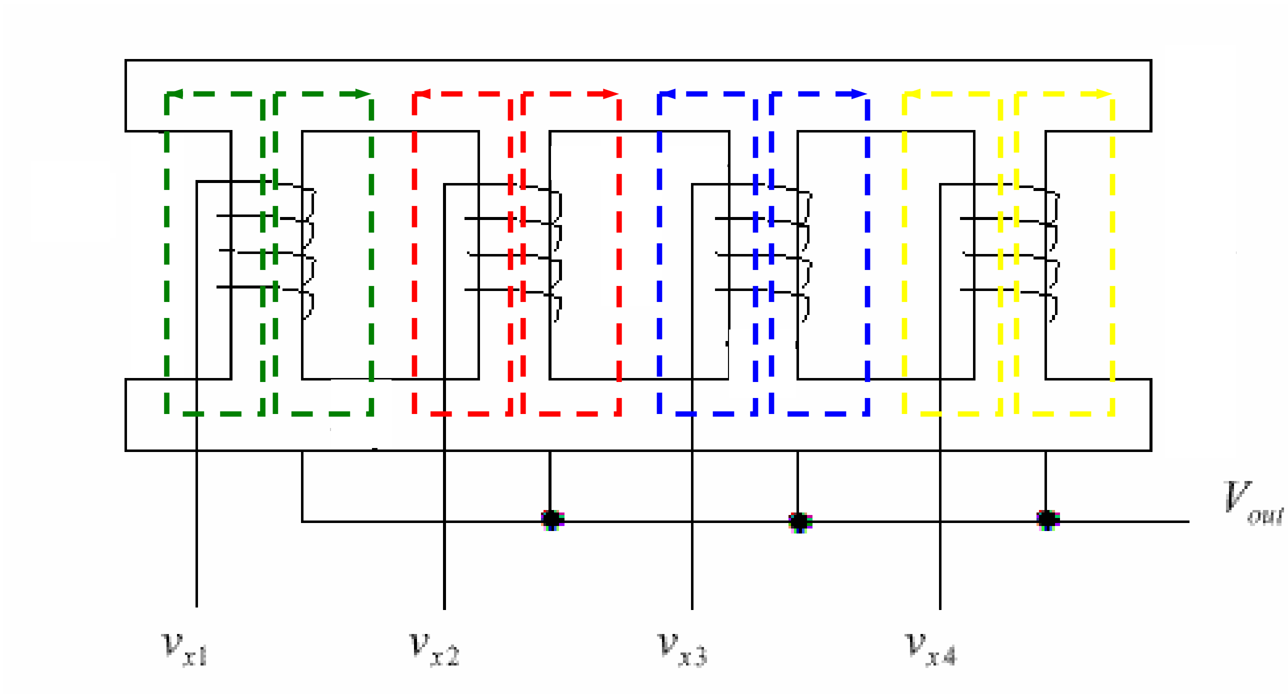
Multi-phase coupling enables greater ripple cancellation

Multi-Phase Coupled Inductor



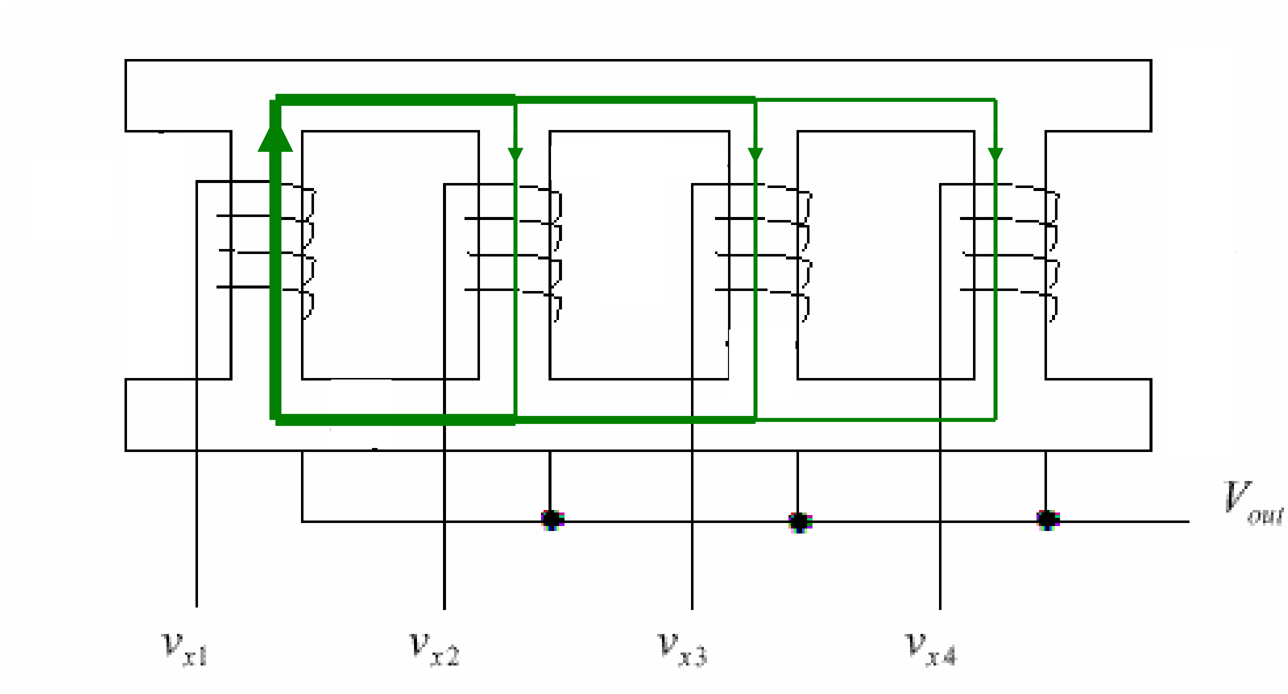
- The “ladder” structure has the best coupling

DC Flux Path



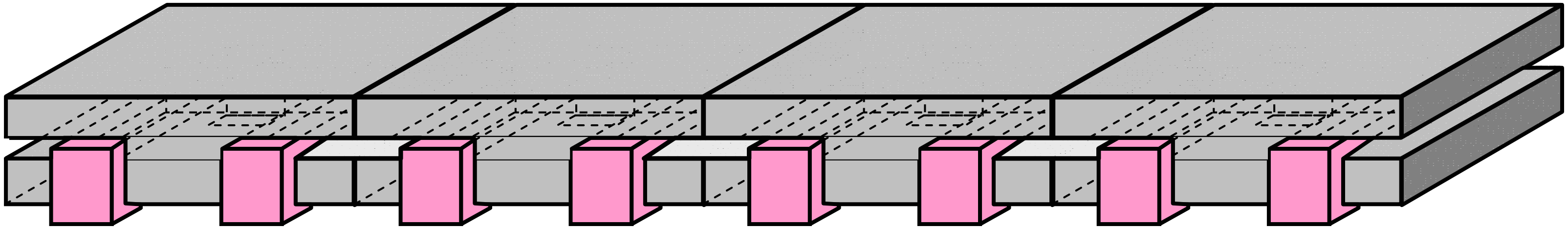
- DC flux generated by each winding goes through high reluctance path

AC Flux Path



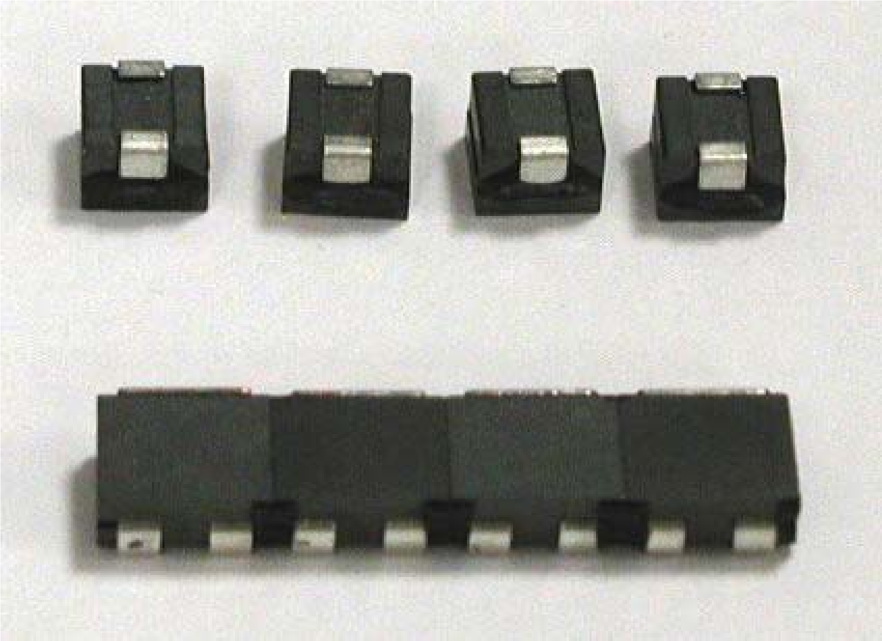
- AC flux generated by each winding goes to others through low reluctance path

Patented Structure



- Multi-phase coupled inductor structure
  - Scalable to n-phase
  - Surface mount
  - Production worthy

Photo of 4-Phase Inductor

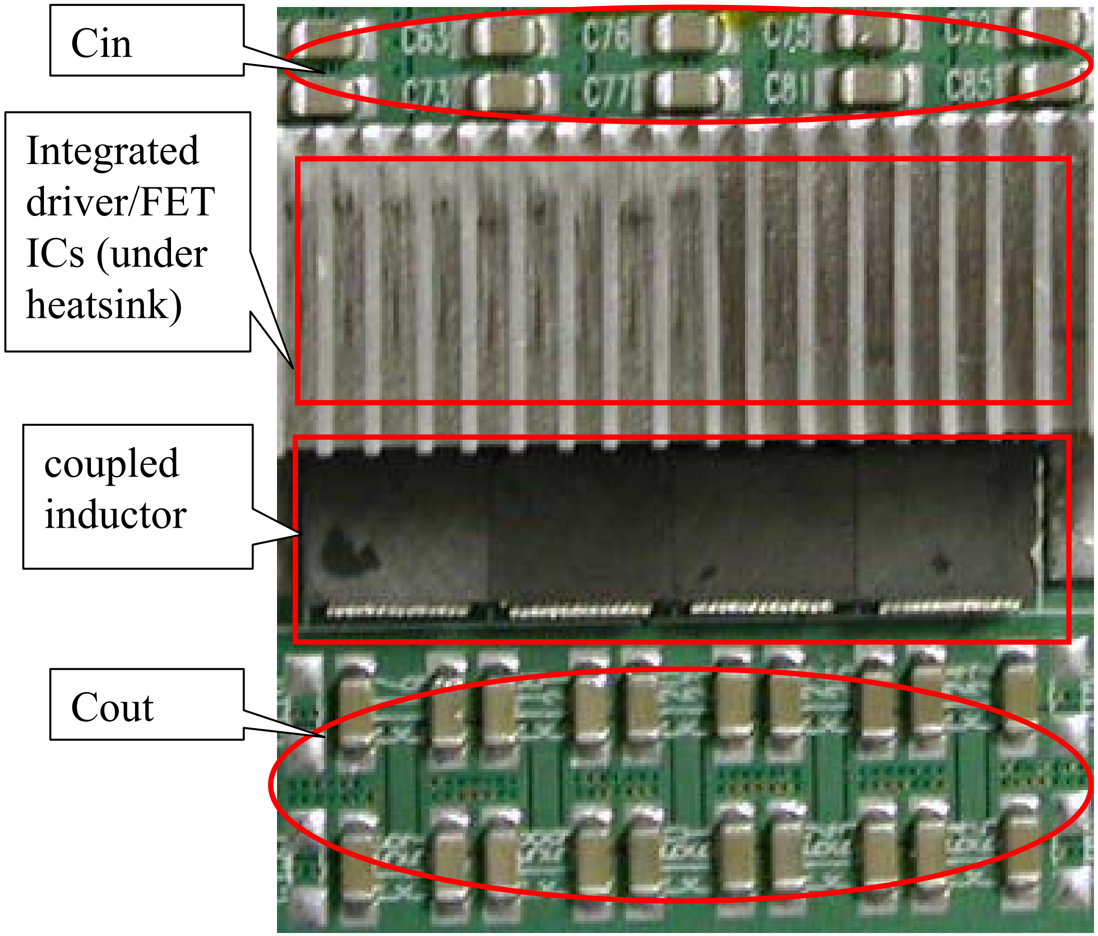


4 discrete 100nH inductors

4-phase 50nH coupled inductor

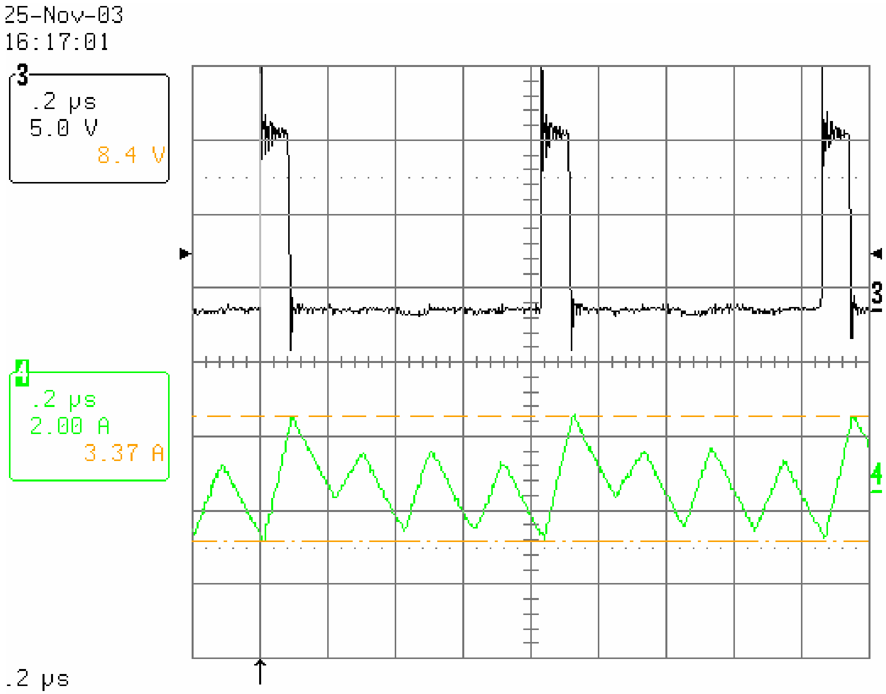
- 4-phase coupled inductor sample
  - 4 identical core cells
  - Each cell is 9mm x 7mm x 4mm
  - Per phase inductance is 50nH
  - Magnetizing inductances are 279nH, 479nH, 472nH, 273nH

System Test Setup

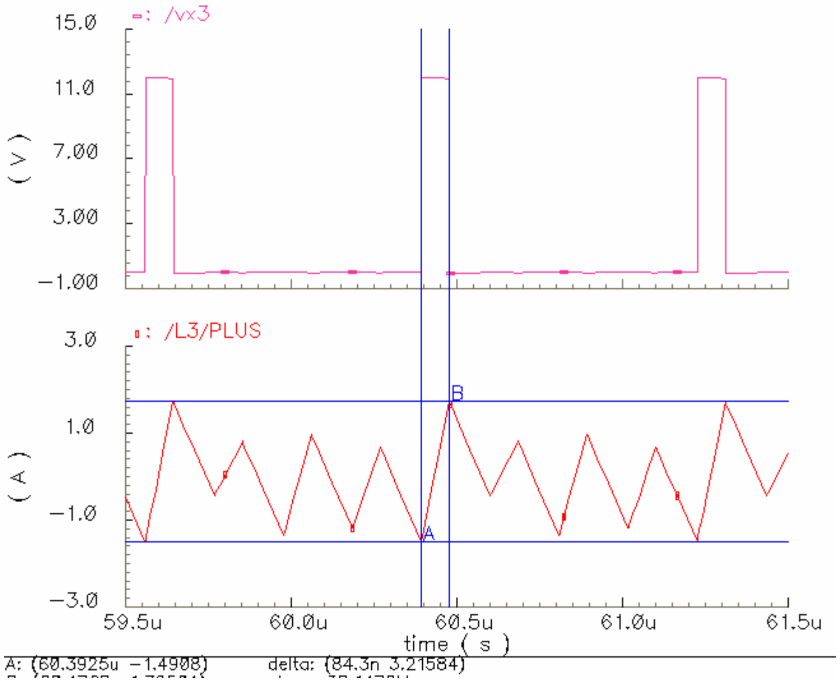


- 4 phase coupled buck
- 50nH per phase
- Small bank of MLCC output capacitors
- Volterra's power delivery chipset with integrated FETs & Drivers

Steady State Waveforms



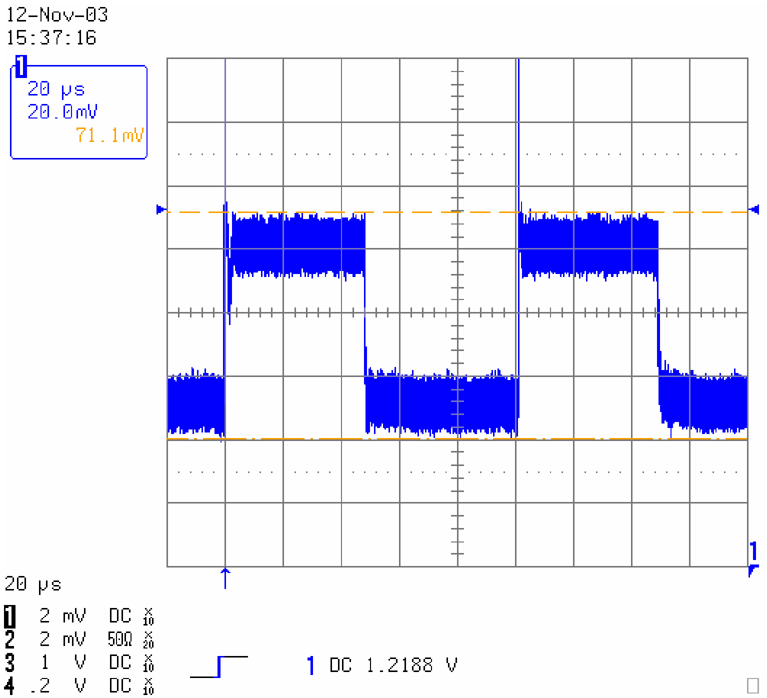
Measurement

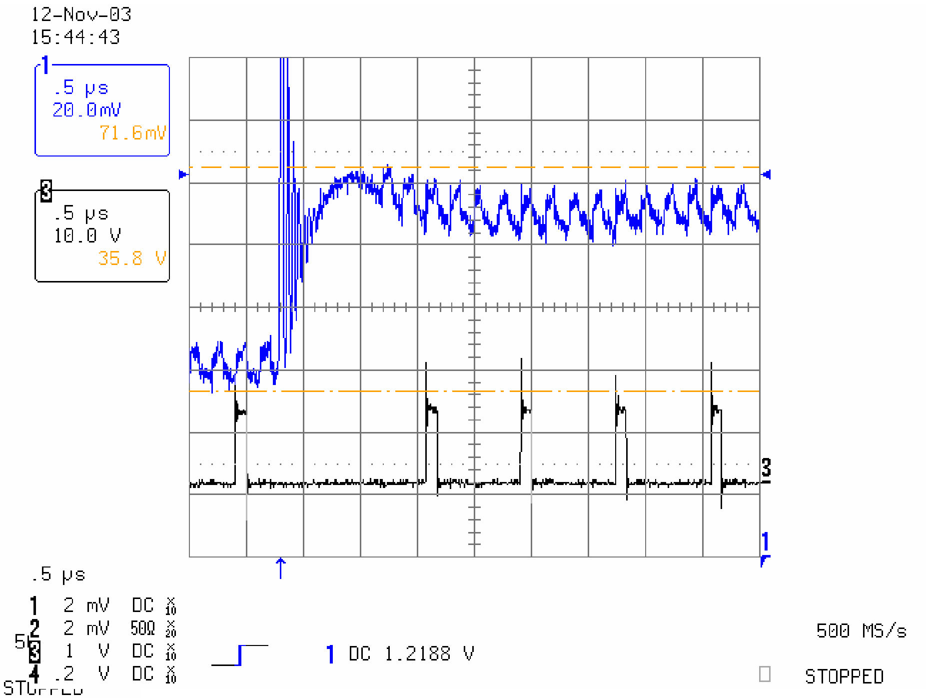


Simulation

- 12V/1.2V/1.2MHz/4-phase
- Current probed by inserting extra wire in series
- For phase 2, Ipp = 3.4A. Other phases measured similar Ipp.

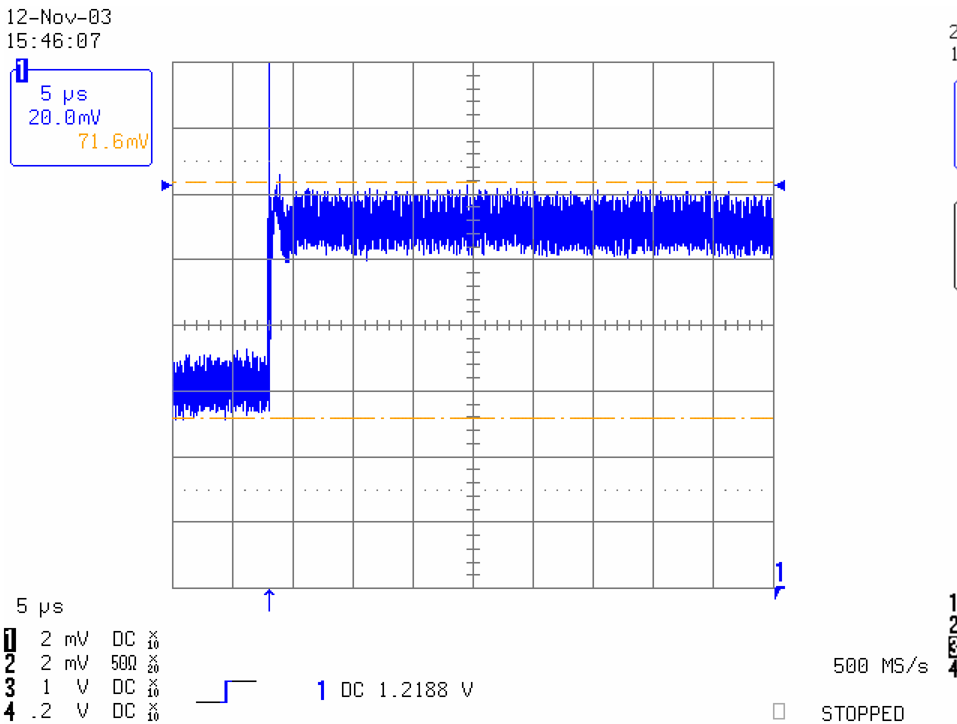
Transient Waveforms



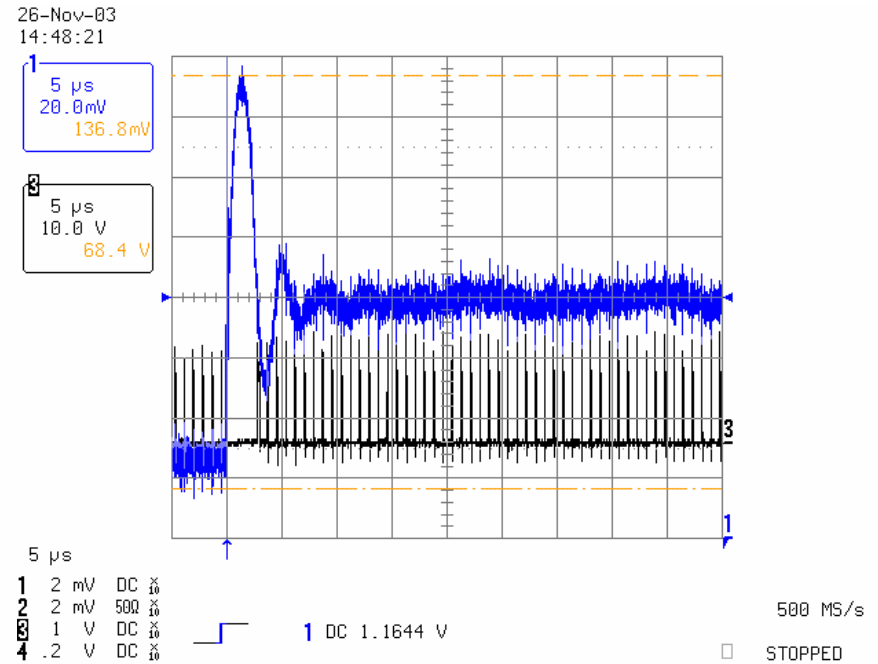


- Load step from 80A to 12.5A (85% load step)
- A small bank of MLCC-only output capacitance
- ΔV is only 71.6mV

Transient Comparison



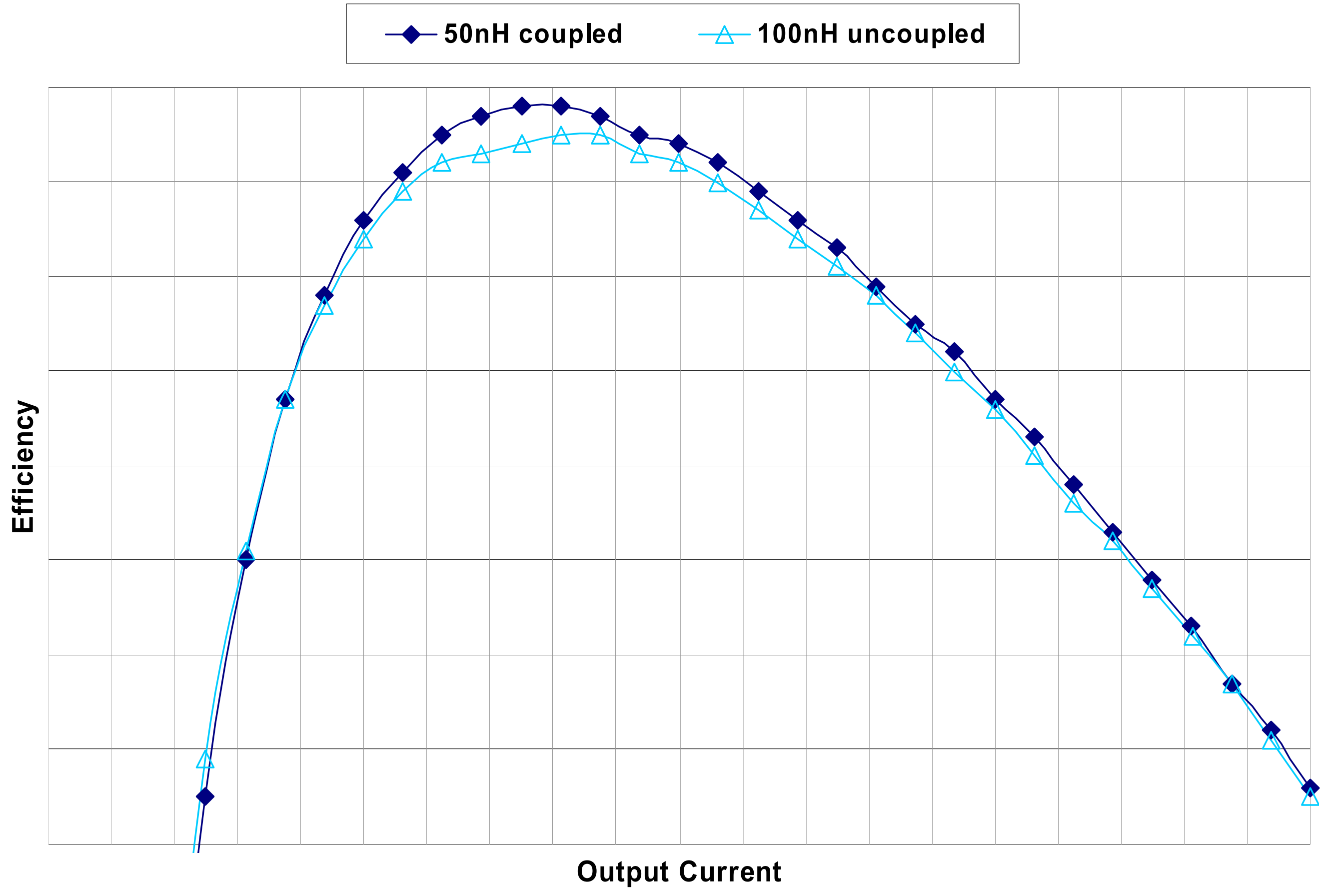
Coupled inductor, 50nH/phase
ΔV = 71.6mV



Uncoupled inductor, 100nH/phase
ΔV = 136.5mV

- Same converter conditions with same load steps and output cap
- Coupled inductor reduces the overall voltage window by half

Efficiency Comparison



- With coupled inductor, transient improves without efficiency penalty
- If using 50nH uncoupled, efficiency is down by 3~4%

Conclusions

- 50% output capacitor reduction is achieved by coupled buck topology without penalty in efficiency
- A production-worthy surface-mount scalable 4-phase coupled inductor is demonstrated
- The 4-phase coupled inductor reduces ripple current by more than 4x from the uncoupled value
- Demanding transient requirement of a modern CPU is met using only a small bank of MLCC capacitors