Switched-mode buck converter with “voltage mirror” regulation topology

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AvaTekh's SMVM-based SMPS control topologies

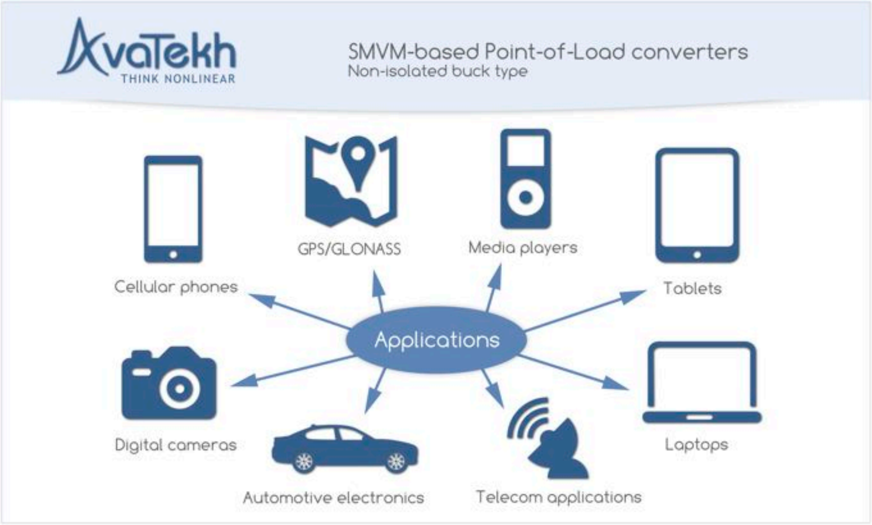
One-shop solution for point-of-load (PoL) DC/DC conversion

AvaTekh's IP and expertise in time-variant filtering and nonlinear signal processing has led to the development of novel switched-mode power control topologies

- Switched-Mode Voltage Mirror (SMVM) topologies for buck, boost, buck-boost, and other converter types
- Particular focus on PoL non-isolated buck converters
- Wide range of advantages/benefits
  - high efficiency combined with control advantages
  - simplicity of construction and use, and low cost (e.g. low BOM and number of external components)
- Technical advantages translate into $$$

Motivation and highlights

Short-term focus on SMVM-based buck regulators



Motivation and highlights

Deliverable partial “wish list”

- Better, simpler to construct and use, and cheaper?
- Fewer internal/external components, and their wider choice?
    - no oscillator/clocking circuitry, simplified internal compensation, no startup circuits
    - no additional dissipating elements such as current sensors
    - wider range of choice for L&C
    - stability with use of ultra-low ESR caps (**no output ripples needed**)
- Same robust efficient compensation for various configurations/modes?
    - for synchronous/continuous and/or asynchronous/discontinuous
    - for Low Drop-Out and Extreme Down-Conversion (● **“Wide $\boldsymbol{V_{\text{in}}}$”**)
    - no transient and/or startup overshoots/undershoots beyond ripple
    - wide range of ● $\boldsymbol{V_{\text{in}}/V_{\text{out}}}$ and their differentials ● output currents ● switching frequencies
- More efficient?
    - no additional switching losses ● low-power controller ● built-in Power Safe Mode
- Fine continuous-manner control over switching frequency/spectrum and ripples?

Motivation and highlights

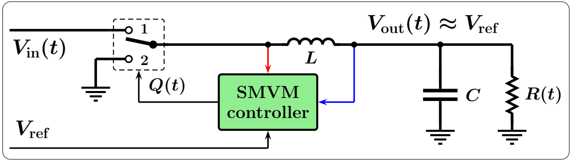
SMVM-based buck: Reiteration

- Tolerance to wide range/fast line and load changes
  - inherent rejection of line disturbances
  - enhanced yet simplified internal regulation for significantly and/or rapidly changing loads
- Independence of regulation from operating point, and tolerance to L&C choices
  - same for heaviest and lightest/open circuit loads in full V_{in} range
  - same for all switching frequencies ● no "minimum controllable ON time" limitation
  - same for synchronous/continuous and/or asynchronous/discontinuous
  - independence from particular inductor and capacitance values for same LC product
- Robustness and stability
  - no transient and/or startup overshoots/undershoots, beyond ripple, for any load change
  - unconditional stability with use of ultra-low ESR caps
- Simplicity of implementation, startup, regulation, and low component count
  - no oscillator/clocking circuitry, simplified internal compensation, no startup circuits
- Low quiescent current (● slows down/stops switching at low/zero load current)
- Fine continuous-manner control over switching frequency/spectrum and ripples

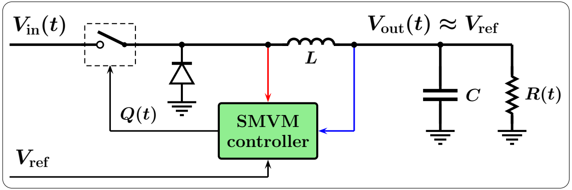
SMVM-based buck controller is clearly distinguishable from other control topologies

While strongly competitive in all technical aspects

Synchronous:



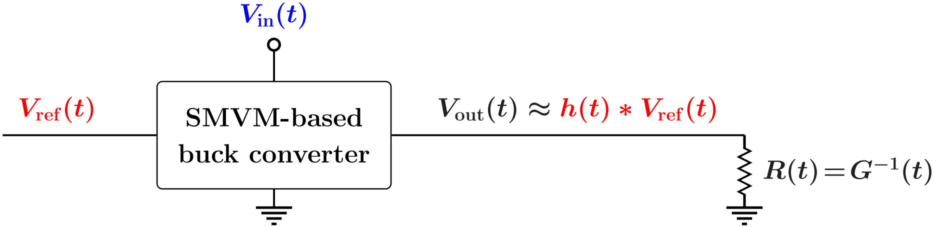
Asynchronous:



- **Exactly same** controller
  - for synchronous and asynchronous configurations
    - in asynchronous configuration, **slows down/stops** switching at low/zero load current
  - for wide range of $V_{\text{in}}/V_{\text{out}}$, their differentials, output currents, switching frequencies

SMVM-based converter

Switched-mode voltage follower (SMVF): Simplified equations for Idealized case of zero ESRs of L and C



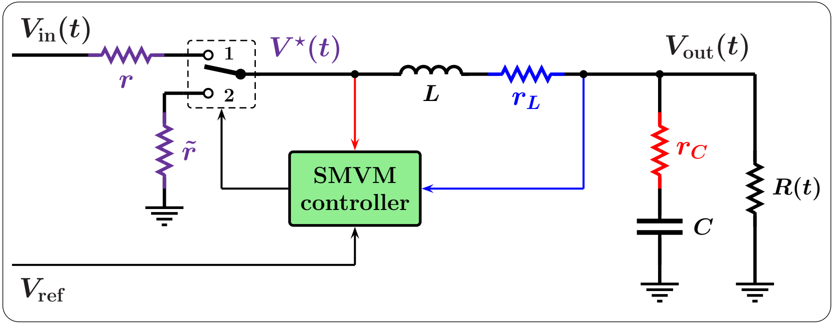
$$V_{\mathrm{out}}(t) = h(t) * V_{\mathrm{ref}}(t) + \delta V(t) \approx h(t) * V_{\mathrm{ref}}(t)$$

– for wide range of inductor and load values

- $h(t)$ is impulse response of **overdamped** 2nd order lowpass filter
- asterisk denotes convolution
    - $V_{\mathrm{out}}(t) \approx V_{\mathrm{ref}}(t) + \Delta V(t) - \tau\, \dot{V}_{\mathrm{out}}(t) - LC\, \ddot{V}_{\mathrm{out}}(t)$
    - τ is large time parameter (e.g. $\tau \gg \sqrt{LC}$)
    - $\Delta V(t)$ is zero-mean voltage (with switching signal PSD)
- $\delta V(t) = h(t) * \Delta V(t)$ is residual ("ripple") zero-mean voltage
- load transients would be of order $L \langle f \rangle \delta V \Delta G$ or smaller ($G = R^{-1}$)

SMVM-based converter

Non-zero ESRs

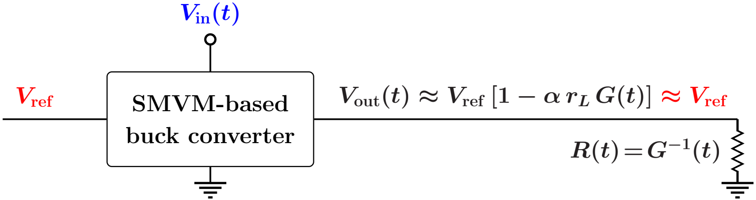


$$V_{\text{out}}(t) \approx A_0(t)\, V_{\text{ref}} + \Delta V'(t) - \tau\, \dot{V}_{\text{out}}(t) - LC\, \ddot{V}_{\text{out}}(t)$$

- $\Delta V'(t)$ is (still) zero-mean voltage
- $A_0(t) \approx 1 - \alpha \frac{r_L}{R(t)}$, where $\alpha \ll 1$ (set internally)
- r_C would affect the ripple magnitude, but not stability

SMVM-based buck converter

Switched-mode voltage follower (SMVF): Non-zero ESRs



$$V_{\text{out}}(t) \approx V_{\text{ref}} \times \left[1 - \alpha \frac{r_L}{R(t)}\right] \approx V_{\text{ref}}$$

– where $\alpha \ll 1$ is set internally

- Akin to a voltage source with the EMF $\mathcal{E} = V_{\text{ref}}$ and the internal resistance $\alpha r_L \ll r_L$
  - ignoring the ripple voltage
- Voltage $V_{\text{ref}}\, r_L / R(t)$ is directly available internally, and for a known non-zero r_L can be used to measure the load current without extra dissipation
  - to disable the high-side switch for overload protection
  - to disable the low-side switch at light loads to enable discontinuous (Power Safe) mode

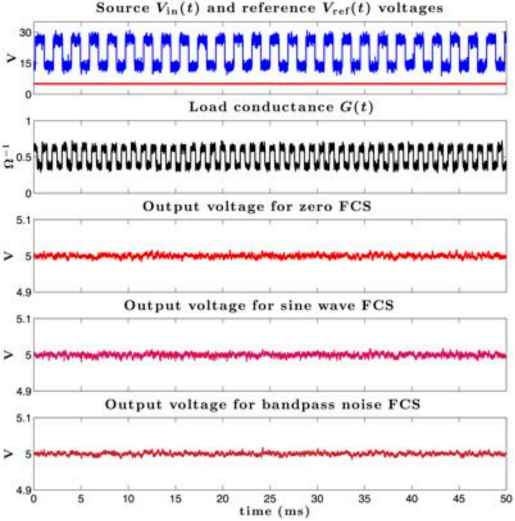
Optional control of switching frequency/spectrum

Basic principle

- Switching frequency of the basic SMVM-based buck is in general variable, and relates to the input voltage $V_{\rm in}$ as $\langle f\rangle \propto \mathbf{V_{ref}\left(1 - V_{ref}/\langle V_{in}\rangle\right)}$
  - constant for constant $V_{\rm in}$
  - nearly constant for variable $V_{\rm in}$ in Extreme Down Conversion mode ($V_{\rm ref}/\langle V_{\rm in}\rangle \ll 1$)
  - no “minimum controllable ON time” limitation
- Adding to the reference voltage a component with a frequency content that is negligible at low frequencies (e.g., $< (2\pi\tau)^{-1}$) and is noticeable at higher frequencies (e.g., $\gg (2\pi\tau)^{-1}$) would not significantly affect the output voltage
- Such a component, however, would noticeably affect the frequency composition of the switch control signal
- In practice, a low-level internal or external frequency control signal (FCS) can be supplied
  - FCS can **stabilize** or **dither** switching frequency without affecting the output

Optional control of switching frequency/spectrum

Switching signal spectra

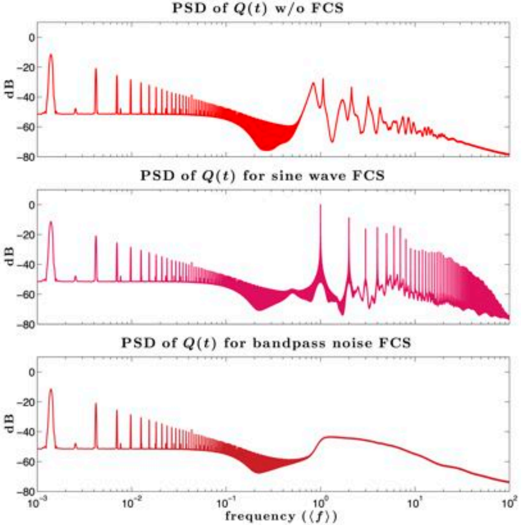

Source $V_{\rm in}(t)$ and reference $V_{\rm ref}(t)$ voltages

Load conductance $G(t)$

Output voltage for zero FCS

Output voltage for sine wave FCS

Output voltage for bandpass noise FCS

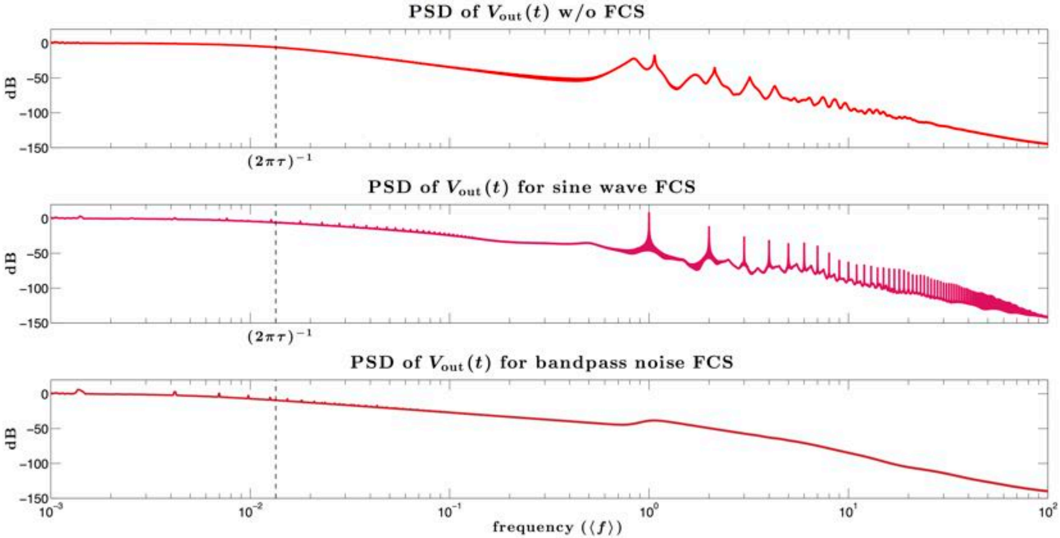

PSD of $Q(t)$ w/o FCS

PSD of $Q(t)$ for sine wave FCS

PSD of $Q(t)$ for bandpass noise FCS

Optional control of switching frequency/spectrum

Output voltage spectra



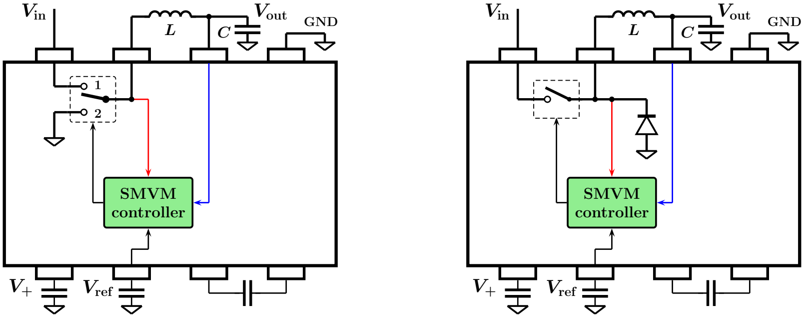
PSD of $V_{\mathrm{out}}(t)$ w/o FCS

PSD of $V_{\mathrm{out}}(t)$ for sine wave FCS

PSD of $V_{\mathrm{out}}(t)$ for bandpass noise FCS

Few performance examples

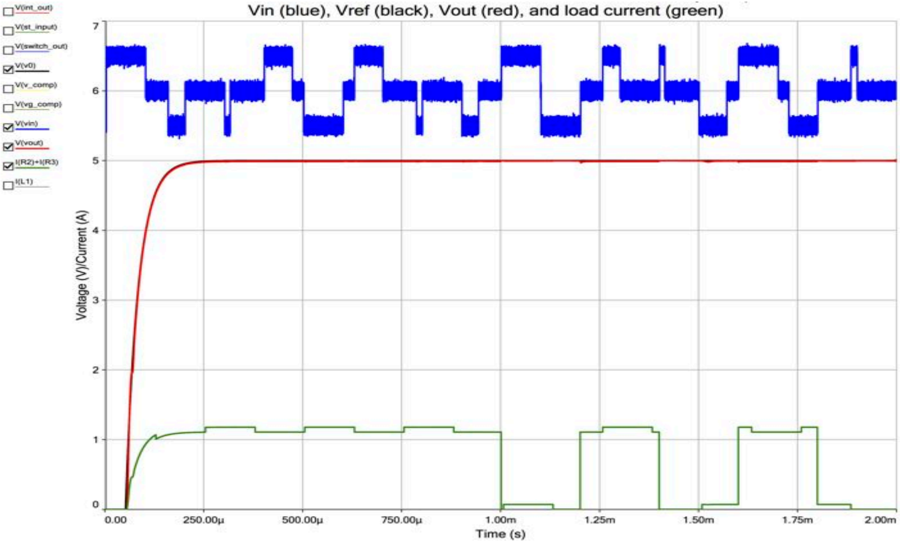
Discrete-component implementation



- Full discrete-component prototype of an SMVM buck controller
  - Simple analog circuit
    - 3 Op-Amps controller (single-supply, low bandwidth/gain/slew rate)
    - +2 Op-Amps for bias voltages
    - tolerant to long-term gain and bias drifts
  - Output voltage from zero to twice Op-Amps' supply voltage V_+ ($0 < V_{\text{out}} < 2V_+$)

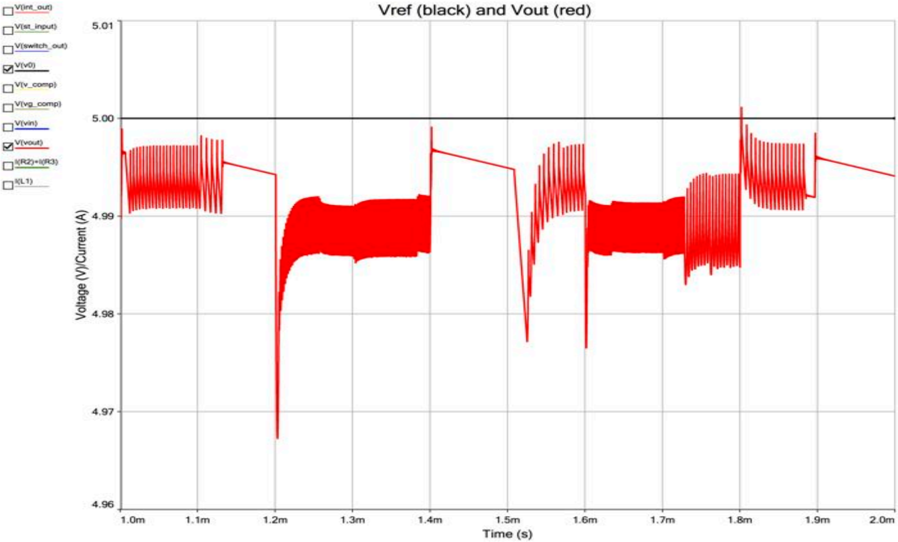
Few performance examples: LDO conversion, asynchronous configuration (I)

$\langle V_{\text{in}} \rangle = 6\ V$, $V_{\text{ref}} = 5\ V$; $L = 1.5\,\mu\text{H}$ ($100\,\text{m}\Omega$ ESR), $C = 68\,\mu\text{F}$ ($5\,\text{m}\Omega$ ESR); nominal switching frequency 600 kHz



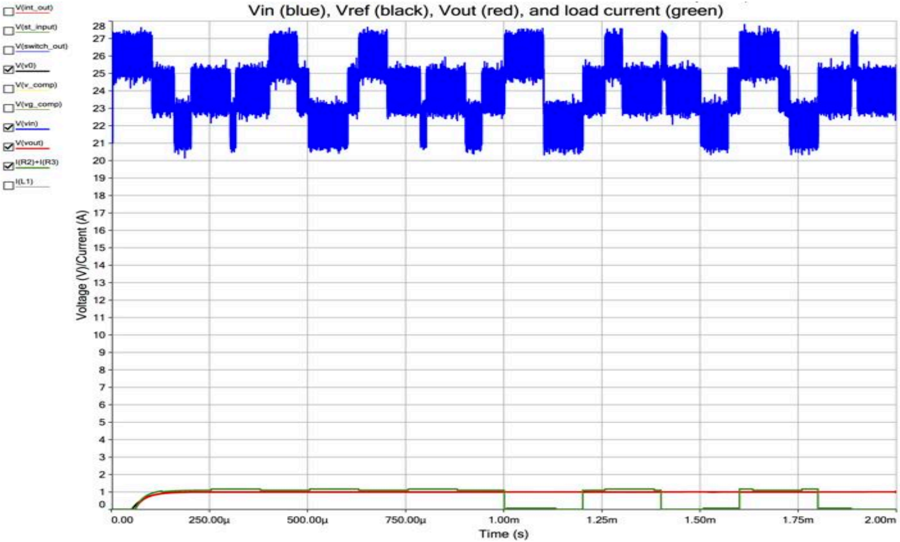
Few performance examples: LDO conversion, asynchronous configuration (II)

$\langle V_{\text{in}} \rangle = 6\ V$, $V_{\text{ref}} = 5\ V$; $L = 1.5\,\mu\text{H}$ (100 mΩ ESR), $C = 68\,\mu\text{F}$ (5 mΩ ESR); nominal switching frequency 600 kHz



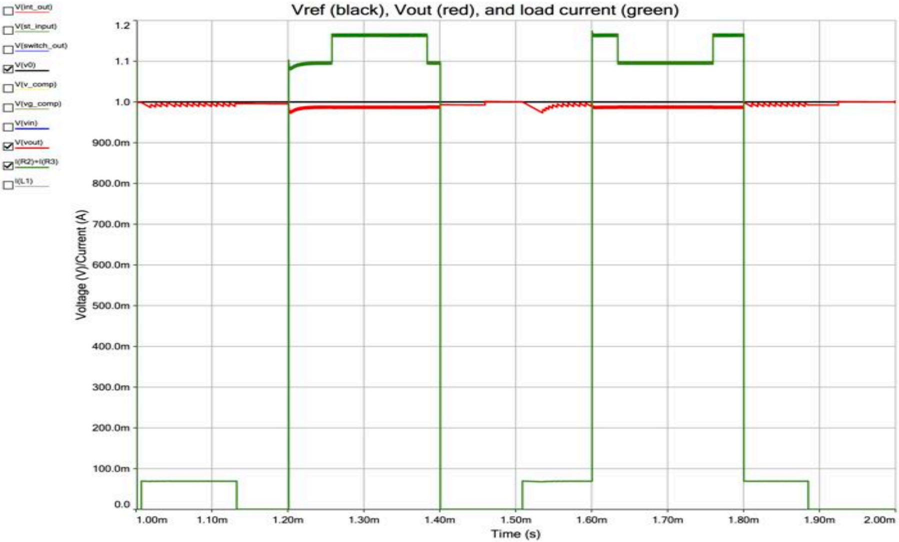
Few performance examples: EDC, asynchronous configuration (I)

$\langle V_{\text{in}} \rangle = 24\ V$, $V_{\text{ref}} = 1\ V$; $L = 1.5\,\mu$H ($100\,\text{m}\Omega$ ESR), $C = 68\,\mu$F ($5\,\text{m}\Omega$ ESR); nominal switching frequency 850 kHz



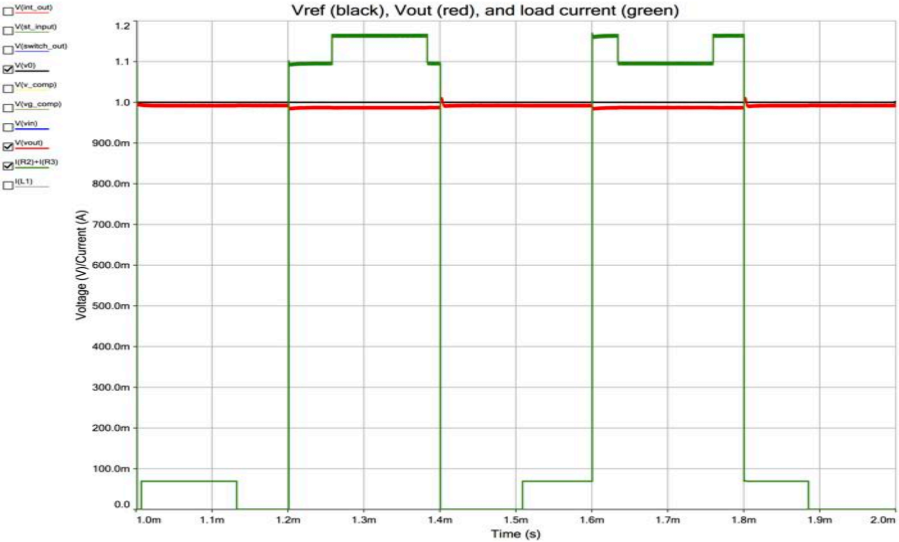
Few performance examples: EDC, asynchronous configuration (II)

$\langle V_{\text{in}} \rangle = 24\ V,\ V_{\text{ref}} = 1\ V;\ \ L = 1.5\,\mu\text{H}$ (100 mΩ ESR), $C = 68\,\mu\text{F}$ (5 mΩ ESR); nominal switching frequency 850 kHz



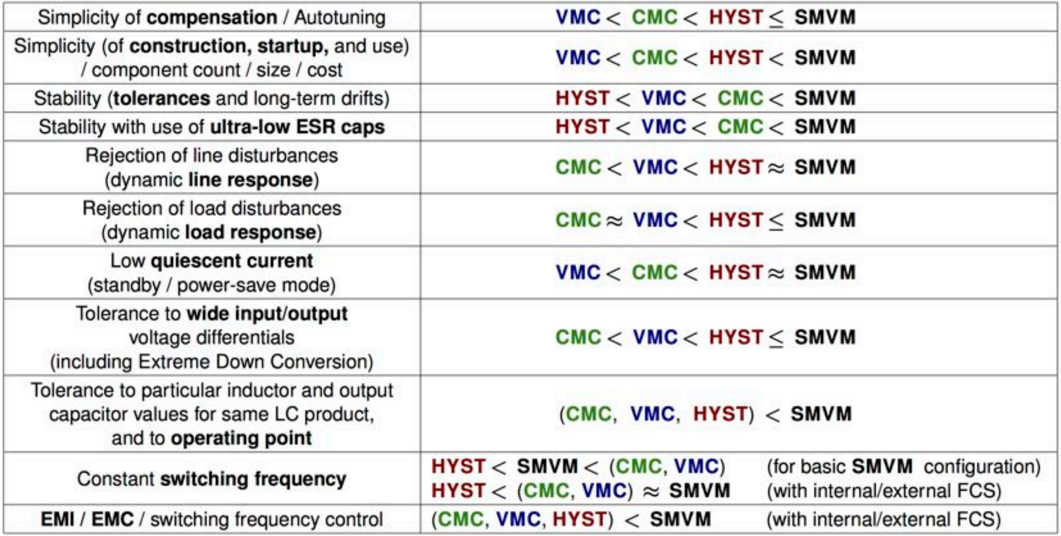
Few performance examples: EDC, synchronous configuration

$\langle V_{\text{in}} \rangle = 24\ V,\ V_{\text{ref}} = 1\ V;\ \ L = 1.5\,\mu\text{H}\ (100\,\text{m}\Omega\ \text{ESR}),\ C = 68\,\mu\text{F}\ (5\,\text{m}\Omega\ \text{ESR})$; nominal switching frequency 850 kHz


Vref (black), Vout (red), and load current (green)

Comparison with different control techniques

REF: S. Maniktala. Voltage-mode, current-mode (and hysteretic control). Nov. 2012. Microsemi Technical Note TN-203



Simplicity of **compensation** / Autotuning	**VMC < CMC < HYST ≤ SMVM**	
Simplicity (of **construction, startup,** and use) / component count / size / cost	**VMC < CMC < HYST < SMVM**	
Stability (**tolerances** and long-term drifts)	**HYST < VMC < CMC < SMVM**	
Stability with use of **ultra-low ESR caps**	**HYST < VMC < CMC < SMVM**	
Rejection of line disturbances (dynamic **line response**)	**CMC < VMC < HYST ≈ SMVM**	
Rejection of load disturbances (dynamic **load response**)	**CMC ≈ VMC < HYST ≤ SMVM**	
Low **quiescent current** (standby / power-save mode)	**VMC < CMC < HYST ≈ SMVM**	
Tolerance to **wide input/output** voltage differentials (including Extreme Down Conversion)	**CMC < VMC < HYST ≤ SMVM**	
Tolerance to particular inductor and output capacitor values for same LC product, and to **operating point**	(**CMC, VMC, HYST**) < **SMVM**	
Constant **switching frequency**	**HYST < SMVM <** (**CMC, VMC**) **HYST <** (**CMC, VMC**) **≈ SMVM**	(for basic **SMVM** configuration) (with internal/external FCS)
EMI / **EMC** / switching frequency control	(**CMC, VMC, HYST**) **< SMVM**	(with internal/external FCS)

Appendix I: About **AvaTekh**

THINK NONLINEAR

- Privately held Kansas corporation
    - incorporated on 22 April 2011
    - http://www.avatekh.com
- Focused on development and commercialization of core intellectual property in time-variant and nonlinear filtering and signal processing
- Strong technical team and solid IP foundation
    - established collaborations with Kansas State University, University of Leicester (UK), University of Kansas, BEA Systems, and ICE Corporation
    - 8 issued US patents
    - this work is supported in part by an SBIR Phase I/IB grant from the National Science Foundation

Appendix II: Disclaimer

Part of the material contained in this presentation is based upon work supported by the National Science Foundation under Grant Number 1314790. However, any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation