Influence of Slope Compensation on Operating Modes of Current Mode Controlled Converters

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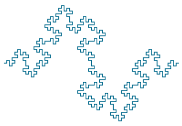


Introduction

- current mode controlled converters
  - basic ones covered: buck, boost and buck-boost
- peak limiting technique
- nonlinear dynamics modeled, beyond linear model
- slope compensation (artificial ramp) influence analyzed
- discontinuous conduction modes focused

Peak Limiting CMC Nonlinear Dynamics

- control variable is the peak value of the inductor current
- large signal behavior of interest
  - nonlinear (switching) effects included
  - limit cycle analyzed
  - open loop over output voltage, control variable kept constant
- different types of period-1 limit cycle instability observed
  - certain values of circuit parameters cause unstable period-1 limit cycle ...
  - ... which can result in multiplying period of initial orbit, period-n operation
  - ... or eventually lead to chaos
  - when and where?

Peak Limiting CMC Nonlinear Dynamics

- continuous conduction mode
  - subharmonic oscillations occur for $D > 0.5$
- discontinuous conduction mode
  - orbits always periodic due to the interval of discontinuity
  - infinite number of periodic discontinuous modes, period-n
  - with very large period number n orbits resemble chaos
  - constant current loaded converters exhibit unstable period-1 limit cycle for $D > 0.5$
- slope compensation as a solution

Slope Compensation

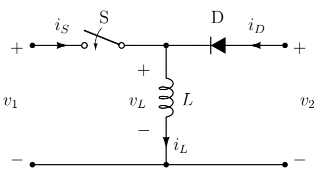
- artificial ramp signal with predefined slope
  - added to the switch current sense signal
  - aims to stabilize limit cycle to period-1 operation
- designed for continuous conduction mode
  - ... and could cause minor effects in discontinuous conduction mode ... ?
- reshaping trajectories
  - could change period number of periodic DCM orbit
  - and could push periodic DCM orbit into chaotic CCM

Nonlinear Dynamic Model

- adequate model which can predict subharmonic behavior
  - iterative mapping, keeps track of discrete values
  - no averaging in the model core
  - simple enough, computer aided numerical simulation
  - frequency domain avoided
- predicts boundaries between different operating modes

Switching Cell Iterative Map

- generalized model derived
  - covers all basic DC–DC converters
  - reduce to s switching cell as s common, essential part
  - identify inductor voltages, during charge (v_1) and discharge (v_2) phase



converter	Buck	Boost	Buck-Boost
v_1	$V_{IN} - V_{OUT}$	V_{IN}	V_{IN}
v_2	$-V_{OUT}$	$V_{IN} - V_{OUT}$	V_{OUT}

Switching Cell Iterative Map

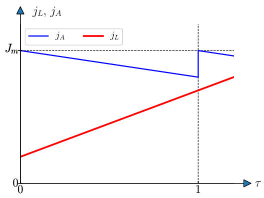
- normalized model
  - avoid units and make equations simpler
  - $m_X = \frac{v_X}{V_{IN}}$
  - $\tau = \frac{t}{T_S}$
  - $j_X = \frac{f_S L}{V_{IN}} i_X$
  - normalized inductor current charge and discharge slopes represented by normalized voltages
  - $m_L = \frac{d j_L}{d \tau}$

Switching Cell Iterative Map

- identifies irregular (non-period-1) inductor current patterns
- three different possibilities over one cycle possible
  - (1) switch conducts during whole cycle
  - switch and diode conduct alternately
    - (2) no interval of discontinuity
    - (3) interval of discontinuity when both are off
- global conditions $m_1 > 0$, $m_2 < 0$, and $m_A < 0$
- constant current load assumed

Switching Cell Iterative Map

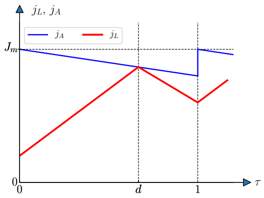
- switch conducts during the whole cycle



- $j_L(1) = j_L(0) + m_1$
  - under condition $j_L(0) < J_m + m_A - m_1$
  - inductor current does not reach the control peak value

Switching Cell Iterative Map

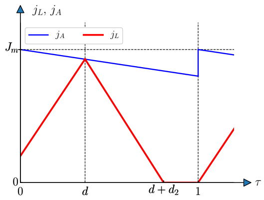
- switch and diode conduct without a discontinuity interval



- $J_m + m_A\, d = j_L(0) + m_1\, d$
  - switch conducts
  - $j_A(d) = J_m + m_A\, d$ peak is influenced by the artificial ramp
- $j_L(1) = J_m + m_A\, d + m_2\ (1 - d)$
  - diode conducts until the end of the cycle
  - under condition $J_m + m_A d + m_2\ (1 - d) > 0$

Switching Cell Iterative Map

- switch and diode conduct followed by a interval of discontinuity



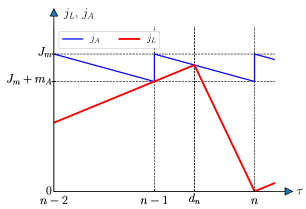
- occurs when previous condition is not fulfilled
- $j_L(1) = 0 = J_m + m_A\, d + m_2\, d_2$
  - diode conducts for $d_2 = -\frac{J_m + m_A\, d}{m_2}$
  - interval of discontinuity until the beginning of the next cycle

Mode Boundaries

- boundary map
  - distinguishes continuous from discontinuous conduction mode
  - and stable limit cycle from unstable
- stable period-1 CCM operation
  - well known $\left|\frac{m_2 - m_A}{m_1 - m_A}\right| \leq 1$
- stable period-1 DCM operation
  - $i_L(1) = i_L(0) = 0$ condition
  - $J_m < \frac{m_2\,(m_1 - m_A)}{m_2 - m_1}$
- the rest is period-n ...
  - continuous with $n \to \infty$? discontinuous?

Mode Boundaries

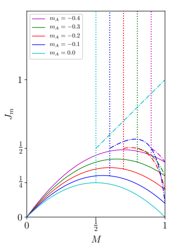
- CCM vs DCM period-n operation
  - no discontinuity means without complete inductor current discharge
  - large control peak value prevents full discharge



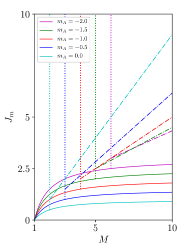
- $J_m < J_{m_{max}} = \frac{m_A^2 - m_1 m_2}{m_1 - m_A}$ for DCM
  - $J_m + m_A + m_1\, d = J_m + m_A\, d$ when switch conducts
  - $0 = J_m + m_A\, d + m_2\ (1 - d)$ when diode conducts

Mode Boundaries Map

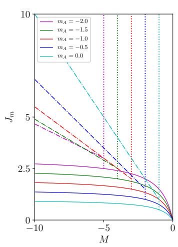
- mapping (M, J_m) plane into operation mode regions
  - m_A as a parameter
  - **full line** for period-1 DCM
  - **dotted line** for period-1 CCM
  - **dash-dot line** for higher period-n DCM – CCM boundary



(a) Buck converter



(b) Boost converter



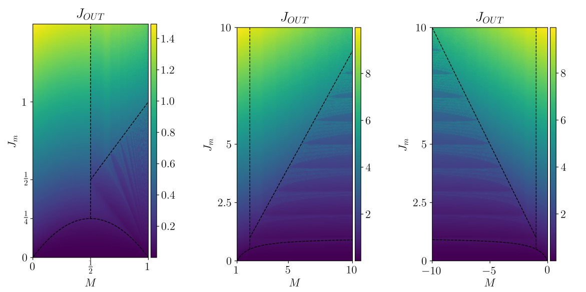
(c) Buck-boost converter

Output Current Map

- dependence of the output current on the output voltage and the control variable
  - averaging introduced at this point
  - normalized output current related to averaged normalized inductor current
  - $\langle j_L \rangle = \langle j_S \rangle + \langle j_D \rangle$
  - $\langle j_S \rangle$ and $\langle j_D \rangle$ obtained from iterative map equations
  - (M, J_m) plane
  - m_A is fixed
  - numerical simulations performed

Output Current Map

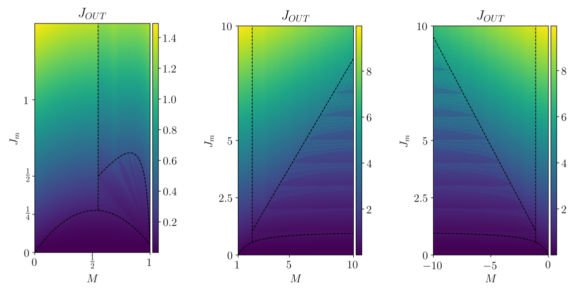
- normalized output current value in (M, J_m) plane
  - without artificial ramp



(a) Buck converter (b) Boost converter (c) Buck-boost converter

Output Current Map

- normalized output current value in (M, J_m) plane
  - $m_A = -0.05$
  - matching with analytical mode boundaries
- DCM area has fractal like appearance



(a) Buck converter (b) Boost converter (c) Buck-boost converter

Conclusion

- peak limiting current mode control
- artificial ramp influence
- large signal behavior
- discontinuous conduction modes
- map of modes derived
- map of modes depends on m_A
- orbits could enter chaotic continuous conduction mode or large period number discontinuous conduction mode
- artificial ramp influence in discontinuous conduction mode should not be neglected