Current Programmed Control

ECE 482 Lecture 6
February 12, 2015

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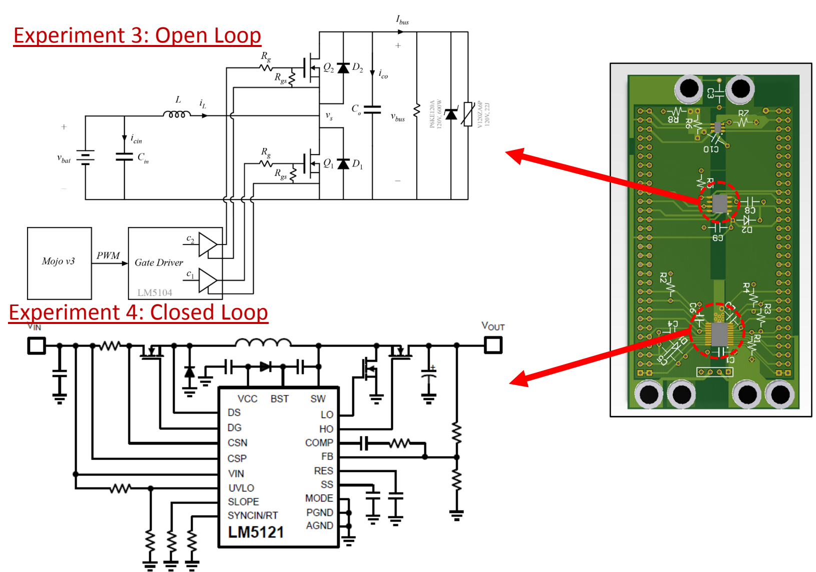
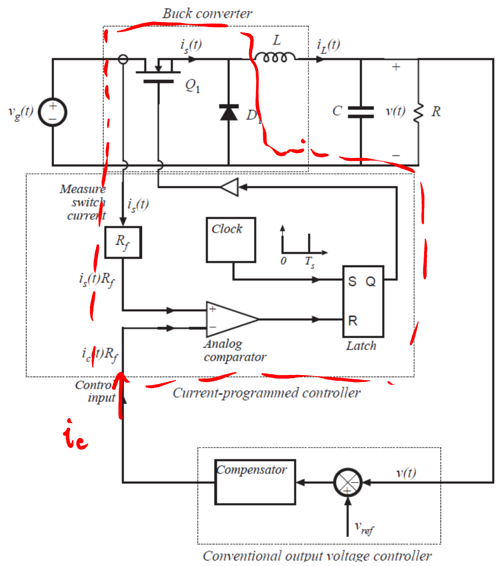
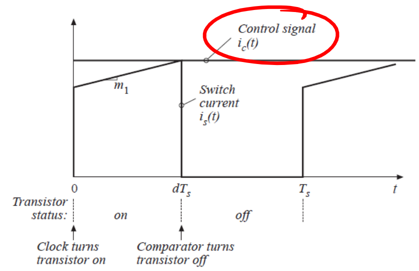
Experiment 4: Closed-Loop Boost



Current Programmed Control (CPM)



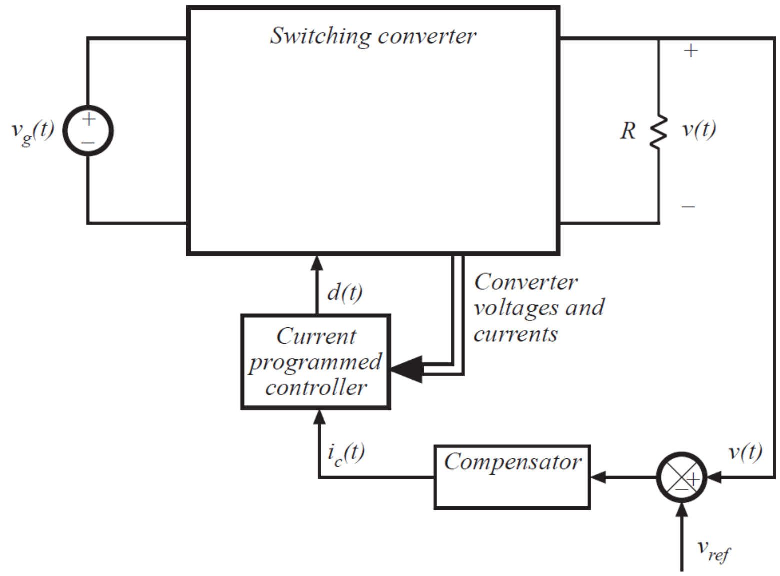
The peak transistor current replaces the duty cycle as the converter control input.



Current Programmed Control

- Covered in Ch. 12 of *Fundamentals of Power Electronics*
- Advantages of current programmed control:
  - Simpler dynamics —inductor pole is moved to high frequency
  - Simple robust output voltage control, with large phase margin, can be obtained without use of compensator lead networks
  - It is always necessary to sense the transistor current, to protect against overcurrent failures. We may as well use the information during normal operation, to obtain better control
  - Transistor failures due to excessive current can be prevented simply by limiting $i_c(t)$
  - Transformer saturation problems in bridge or push-pull converters can be mitigated
- A disadvantage: susceptibility to noise

A Simple First-Order Model



The First-Order Approximation

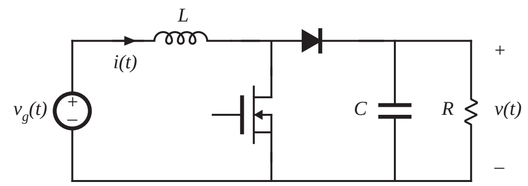
$$\left\langle i_L(t) \right\rangle_{T_s} = i_c(t)$$

- Neglects switching ripple
- Yields physical insight and simple first-order model
- Accurate when converter operates well into CCM (so that switching ripple is small
- Accurate when artificial ramp (discussed later) small
- Resulting small-signal relation:

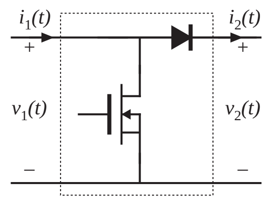
$$i_L(s) \approx i_c(s)$$

Boost Averaged Switch Modeling

Ideal boost converter example

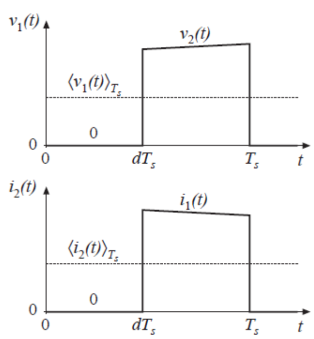


Boost-specific switch network



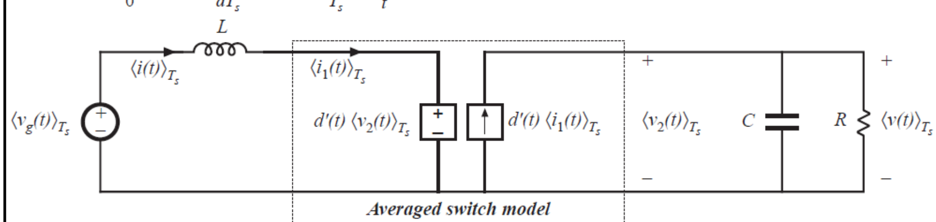
- Averaged switch model goal:
  - Express average of two waveforms ($i_1(t)$, $i_2(t)$, $v_1(t)$, $v_2(t)$)in terms of the other two

Previous Definitions



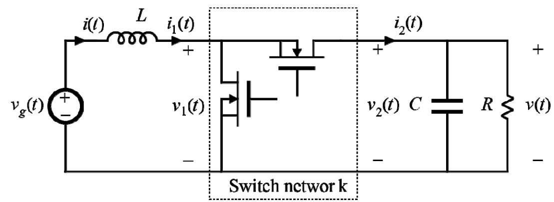
Average the waveforms of the dependent sources:

$$\left\langle v_1(t) \right\rangle_{T_s} = d'(t) \left\langle v_2(t) \right\rangle_{T_s}$$
$$\left\langle i_2(t) \right\rangle_{T_s} = d'(t) \left\langle i_1(t) \right\rangle_{T_s}$$



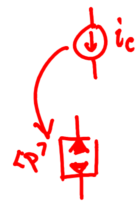
A More Useful Approach

- Instead select $i_1(t)$, $i_2(t)$

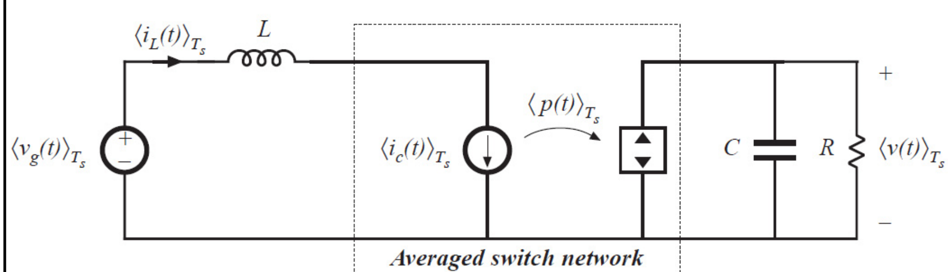


$\langle i_1 \rangle = i_c$ → looks like

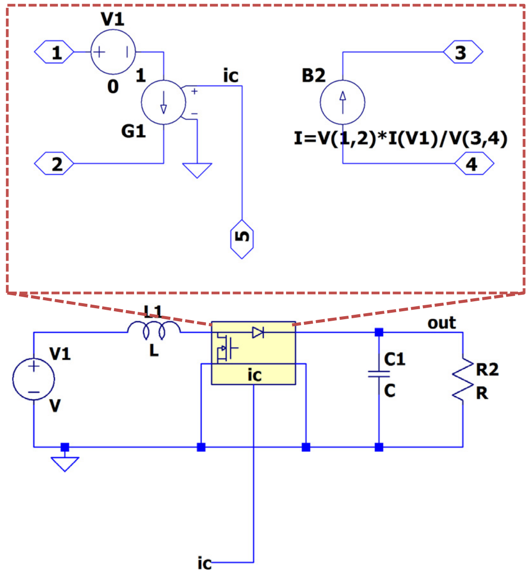
$\langle i_2 \rangle = i_c \frac{\langle N_1 \rangle}{\langle N_2 \rangle}$ → looks like



Large-Signal Nonlinear Model



Implementation in LTSpice



Perturb and Linearize

$\langle i_1 \rangle = I_1 + \hat{i}_1$

$i_c = I_c + \hat{i}_c$

$\vdots$

(1) $\langle i_1 \rangle = i_c$

(2) $\langle i_2 \rangle = \dfrac{i_c \langle v_1 \rangle}{\langle v_2 \rangle}$

(1) $I_1 + \hat{i}_1 = I_c + \hat{i}_c$ DC: $I_1 = I_c$ ss AC: $\hat{i}_1 = \hat{i}_c$

(2) $(I_2 + \hat{i}_2)(V_2 + \hat{v}_2) = (I_c + \hat{i}_c)(V_1 + \hat{v}_1)$

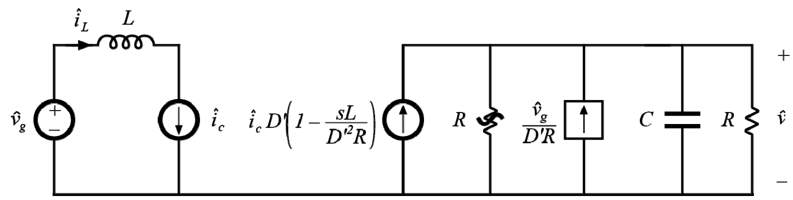
$I_2 V_2 + \cancel{\hat{i}_2 \hat{v}_2} + \hat{i}_2 V_2 + I_2 \hat{v}_2 = I_c V_1 + \cancel{\hat{i}_c \hat{v}_1} + I_c \hat{v}_1 + V_1 \hat{i}_c$

DC: $I_2 V_2 = I_c V_1$

AC: $\hat{i}_2 = \dfrac{I_c \hat{v}_1 + V_1 \hat{i}_c - I_2 \hat{v}_2}{V_2}$

Take DC solution for V_1, I_2 & $V_2 = V$

Boost CCM CPM Small-Signal Model



CPM Transfer Functions

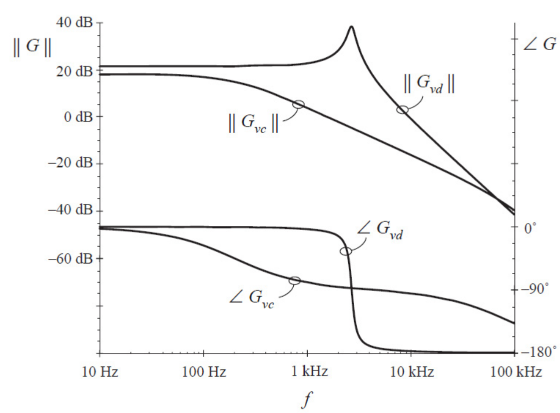
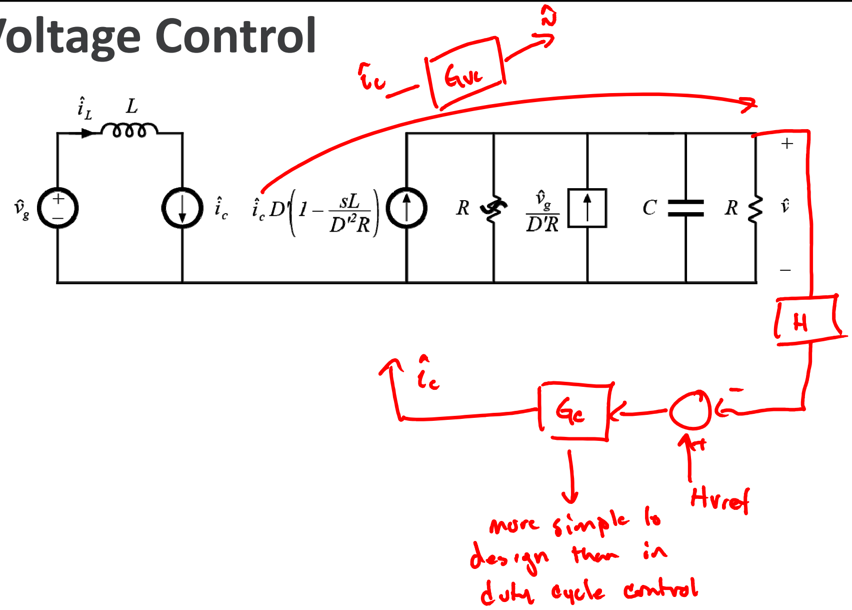


Fig. 12.28 Comparison of CPM control with duty-cycle control, for the control-to-output frequency response of the buck converter example.

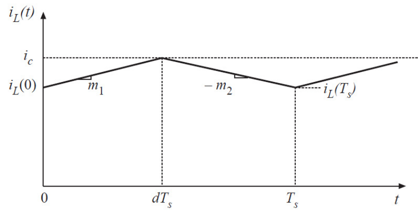
Voltage Control



CPM Oscillations for D>0.5

- The current programmed controller is inherently unstable for $D > 0.5$, regardless of the converter topology
- Controller can be stabilized by addition of an artificial ramp

Inductor Current Waveform in CCM



Inductor current slopes m_1 *and* $-m_2$

buck converter

$$m_1 = \frac{v_g - v}{L} \qquad -m_2 = -\frac{v}{L}$$

boost converter

$$m_1 = \frac{v_g}{L} \qquad -m_2 = \frac{v_g - v}{L}$$

buck–boost converter

$$m_1 = \frac{v_g}{L} \qquad -m_2 = \frac{v}{L}$$

Volt-Second Balancing

First interval:

$$i_L(dT_s) = i_c = i_L(0) + m_1 dT_s$$

Solve for d:

$$d = \frac{i_c - i_L(0)}{m_1 T_s}$$

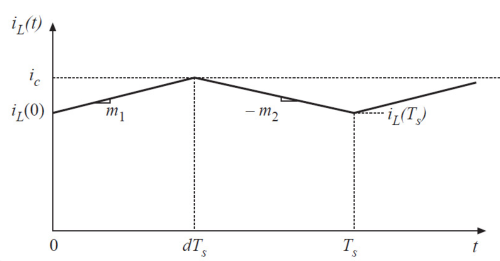
Second interval:

$$i_L(T_s) = i_L(dT_s) - m_2 d' T_s$$
$$= i_L(0) + m_1 dT_s - m_2 d' T_s$$

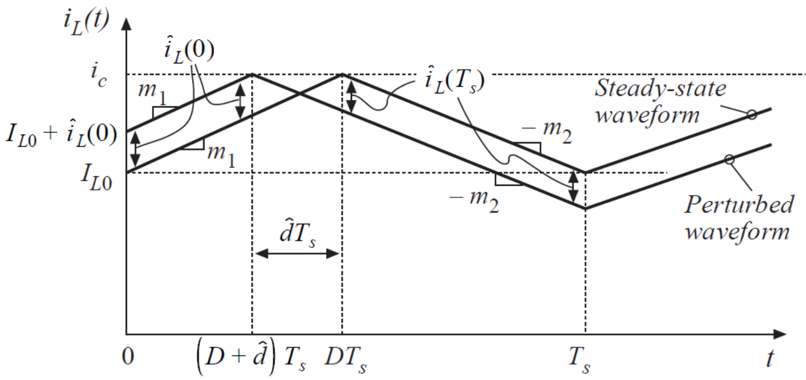
In steady state:

$$0 = M_1 D T_s - M_2 D' T_s$$

$$\frac{M_2}{M_1} = \frac{D}{D'}$$

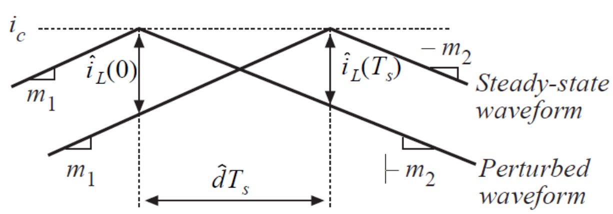


Introducing a Perturbation



Change in Inductor Current Over T_s

magnified view



$$\hat{i}_L(0) = -m_1 \hat{d} T_s$$

$$\hat{i}_L(T_s) = m_2 \hat{d} T_s$$

$$\hat{i}_L(T_s) = \hat{i}_L(0)\left(-\frac{m_2}{m_1}\right)$$

$$\hat{i}_L(T_s) = \hat{i}_L(0)\left(-\frac{D}{D'}\right)$$

Final Value of Inductor Current

$$\hat{i}_L(T_s) = \hat{i}_L(0)\left(-\frac{D}{D'}\right)$$

$$\hat{i}_L(2T_s) = \hat{i}_L(T_s)\left(-\frac{D}{D'}\right) = \hat{i}_L(0)\left(-\frac{D}{D'}\right)^2$$

$$\hat{i}_L(nT_s) = \hat{i}_L((n-1)T_s)\left(-\frac{D}{D'}\right) = \hat{i}_L(0)\left(-\frac{D}{D'}\right)^n$$

$$\left|\hat{i}_L(nT_s)\right| \rightarrow \begin{cases} 0 & \text{when } \left|-\frac{D}{D'}\right| < 1 \\ \infty & \text{when } \left|-\frac{D}{D'}\right| > 1 \end{cases}$$

For stability: $D < 0.5$

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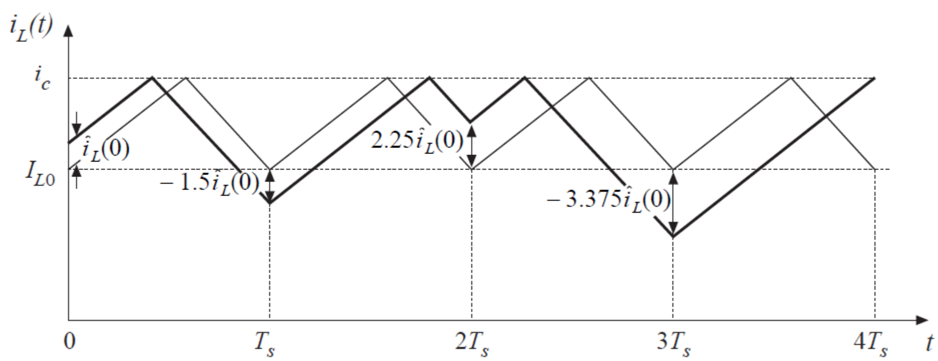
Example: Unstable operation for D=0.6

$$\alpha = -\frac{D}{D'} = \left(-\frac{0.6}{0.4}\right) = -1.5$$



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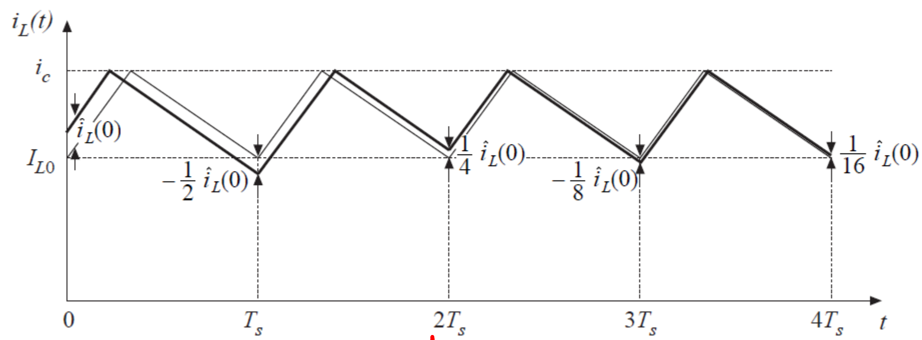
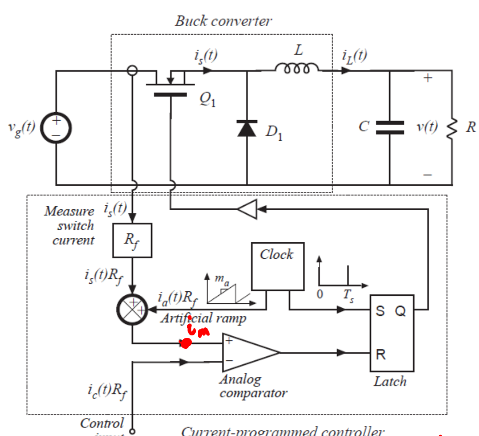
Example: Stable operation for D=1/3

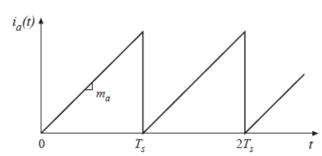
$$\alpha = -\frac{D}{D'} = \left(-\frac{1/3}{2/3}\right) = -0.5$$



Dynamics here ignored by assumption $\langle i_L \rangle = i_c$

Stabilization Through Artificial Ramp



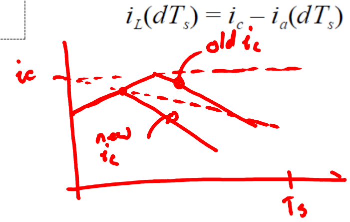


Now, transistor switches off when

$$i_a(dT_s) + i_L(dT_s) = i_c$$

or,

$$i_L(dT_s) = i_c - i_a(dT_s)$$



Final Value of Inductor Current

First subinterval:

$$\hat{i}_L(0) = -\hat{d}T_s\left(m_1 + m_a\right)$$

Second subinterval:

$$\hat{i}_L(T_s) = -\hat{d}T_s\left(m_a - m_2\right)$$

Net change over one switching period:

$$\hat{i}_L(T_s) = \hat{i}_L(0)\left(-\frac{m_2 - m_a}{m_1 + m_a}\right)$$

After n switching periods:

$$\hat{i}_L(nT_s) = \hat{i}_L((n-1)T_s)\left(-\frac{m_2 - m_a}{m_1 + m_a}\right) = \hat{i}_L(0)\left(-\frac{m_2 - m_a}{m_1 + m_a}\right)^n = \hat{i}_L(0)\,\alpha^n$$

Characteristic value:

$$\alpha = -\frac{m_2 - m_a}{m_1 + m_a} \qquad \left|\hat{i}_L(nT_s)\right| \to \begin{cases} 0 & \text{when } |\alpha| < 1 \\ \infty & \text{when } |\alpha| > 1 \end{cases}$$

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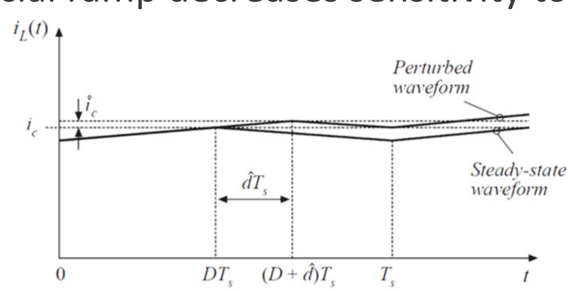
Artificial Ramp: Additional Notes

- For stability, require $|\alpha|<1$
- Common choices:
  - $m_a = 0.5\, m_2$
  - $m_a = m_2$
- Artificial ramp decreases sensitivity to noise

$$\alpha = -\frac{1 - \frac{m_a}{m_2}}{\frac{D'}{D} + \frac{m_a}{m_2}}$$



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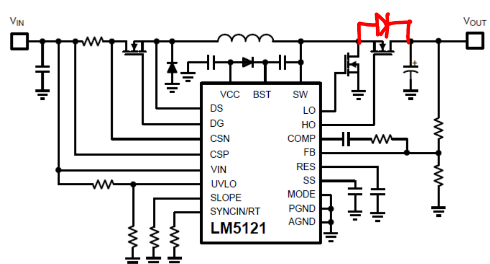
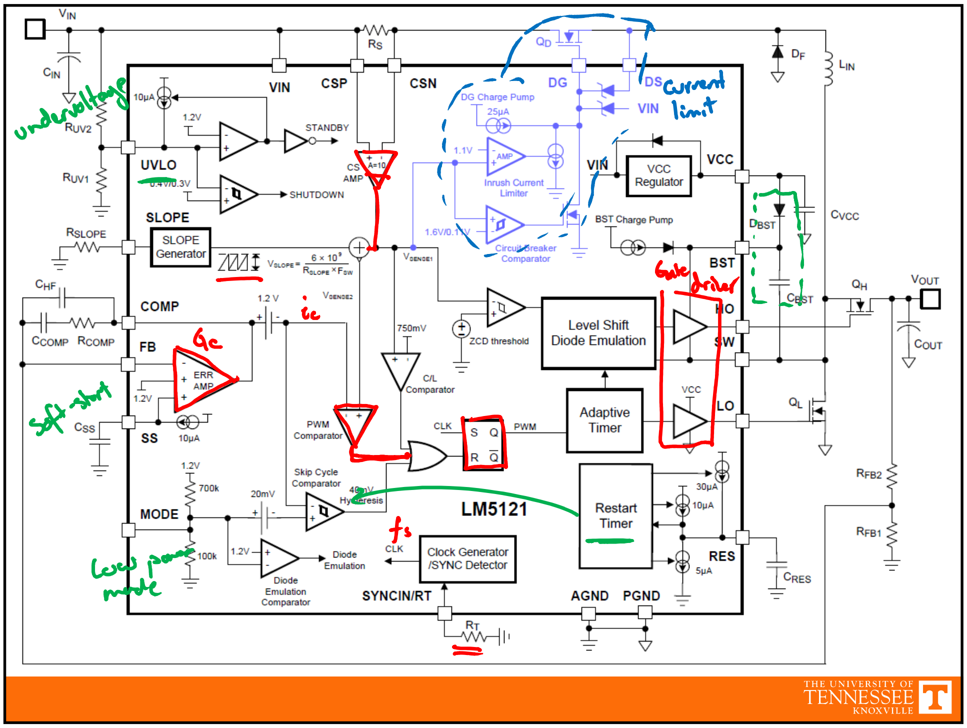
More Accurate Models

- The simple models of the previous section yield insight into the low- frequency behavior of CPM converters
- Unfortunately, they do not always predict everything that we need to know:
  - Line-to-output transfer function of the buck converter
  - Dynamics at frequencies approaching f_s
- More accurate model accounts for nonideal operation of current mode controller built-in feedback loop
- Converter duty-cycle-controlled model, plus block diagram that accurately models equations of current mode controller
- See Section 12.3 for additional info

Application to Experiment 4



- Complex switching controller
- **Read** the datasheet first


VIN
CIN
RUV2
RUV1
RSLOPE
CHF
CCOMP RCOMP
CSS
RS
CSP
CSN
VIN
UVLO
SLOPE
SLOPE Generator
COMP
FB
SS
MODE
STANDBY
SHUTDOWN
CS AMP
A=10
ERR AMP
PWM Comparator
Skip Cycle Comparator
Diode Emulation Comparator
C/L Comparator
ZCD threshold
DG Charge Pump
Inrush Current Limiter
Circuit Breaker Comparator
BST Charge Pump
VCC Regulator
Level Shift Diode Emulation
Adaptive Timer
Restart Timer
Clock Generator /SYNC Detector
LM5121
SYNCIN/RT
AGND
PGND
RES
BST
HO
SW
LO
VCC
DG
DS
QD
DF
LIN
DBST
CVCC
CBST
QH
QL
VOUT
COUT
RFB2
RFB1
CRES
RT
undervoltage
current limit
Gate driver
Gc
ic
soft start
fs
Low power mode
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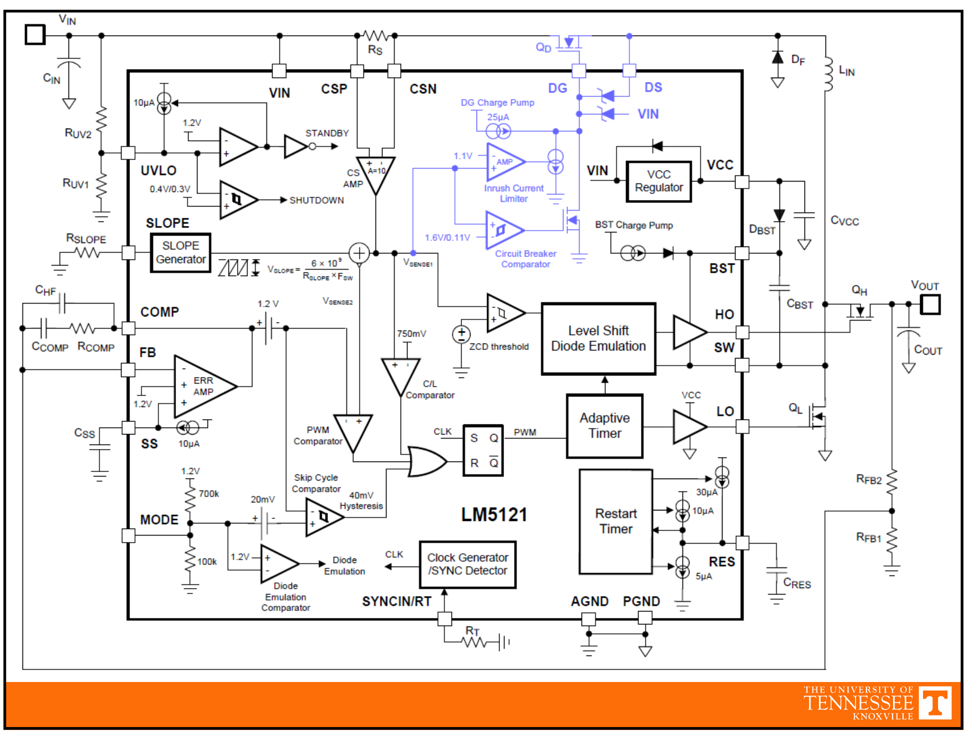
VIN
CIN
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RSLOPE
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CCOMP RCOMP
CSS
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VIN
UVLO
SLOPE
SLOPE Generator
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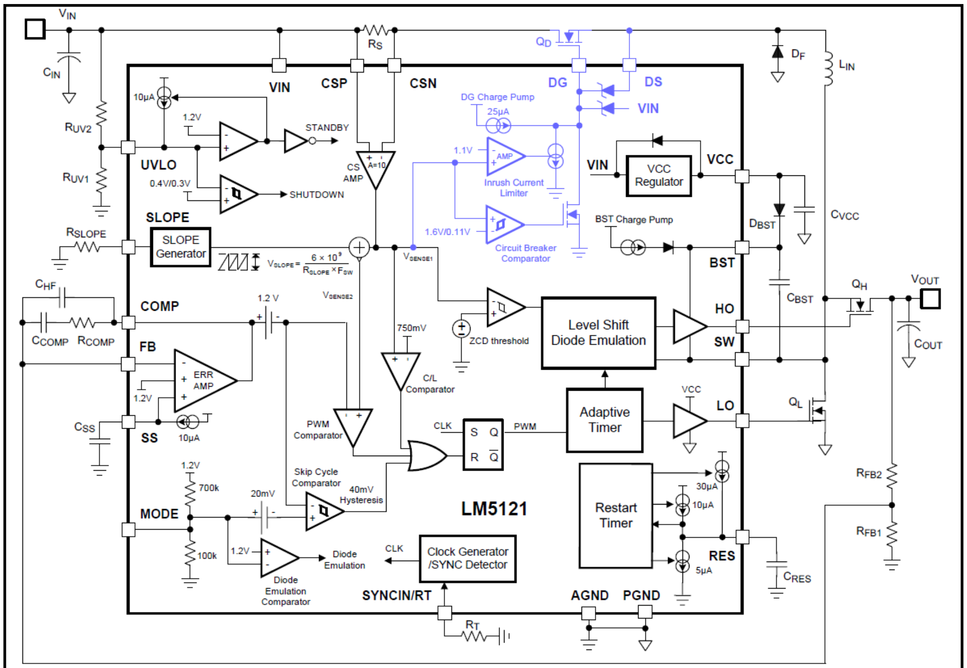

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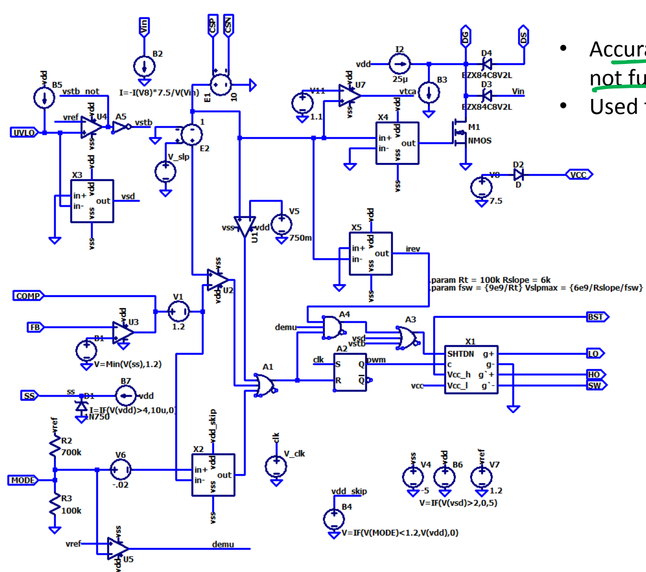
Internal Functional Model in LTSpice



- Accuracy/functionality not fully tested
- Used for insight only

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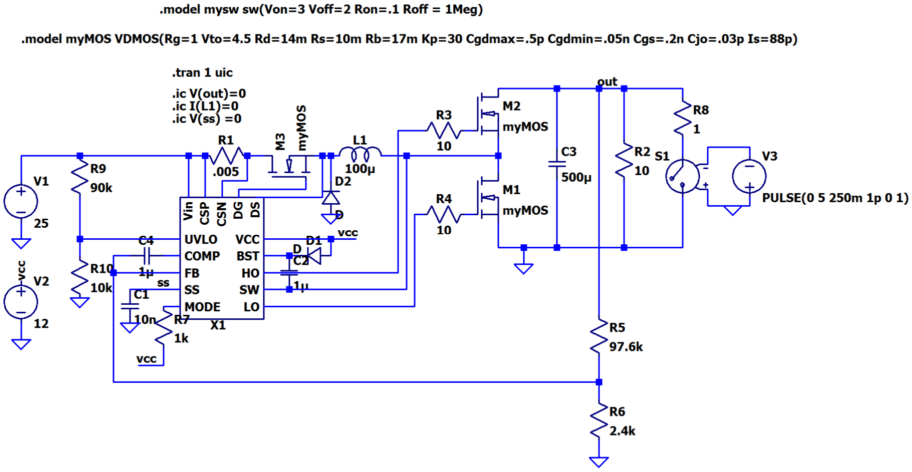
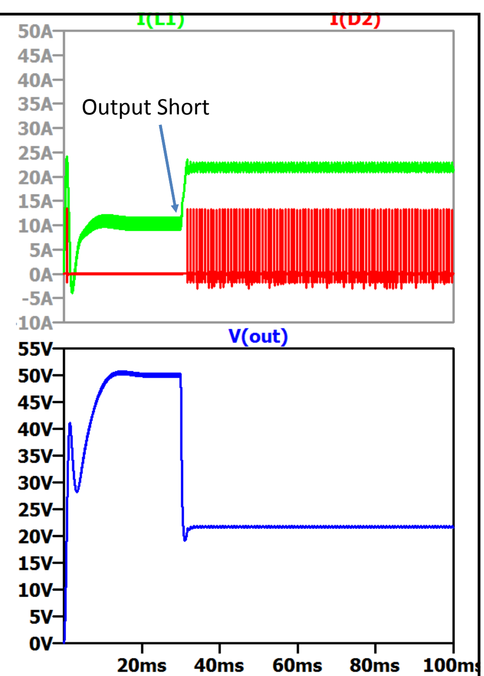
In-Circuit Simulation



Sim Results



A Tip: Debug Internal of Subcircuit