Current Mode Control

EE5325 Power Management Integrated Circuits

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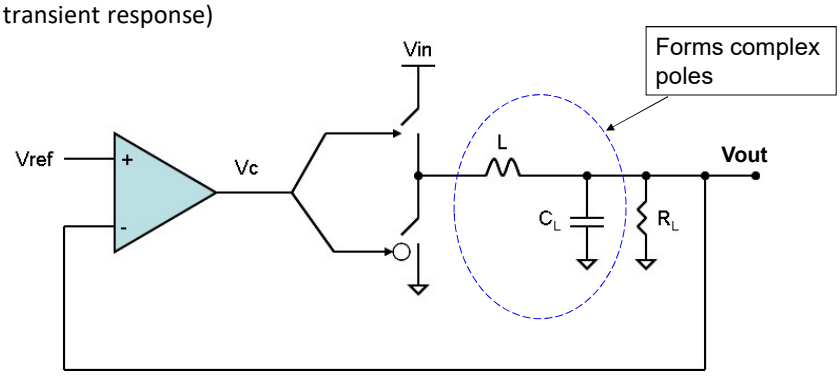
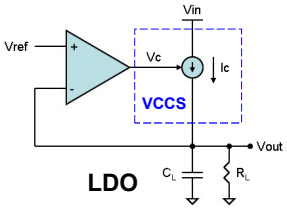
Voltage Mode Control

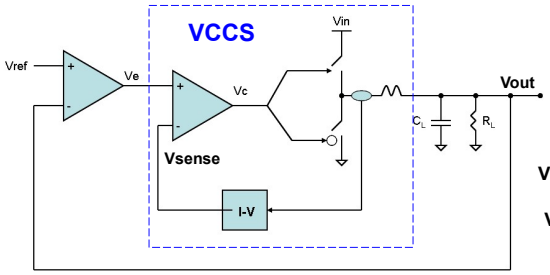
- Switch duty cycle controlled by the error voltage between output and reference
- L and C forms a pair of complex poles which makes the system inherently unstable
- Requires complex PID compensation to achieve high loop BW (good transient response)

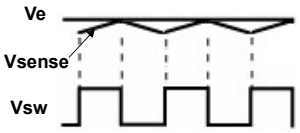


Current Mode Control

- Uses concept of LDO Regulator where output voltage is by controlling the output current using VCVS
- In case of LDO, pass transistor acts as a lossy VCCS hence exhibits poor efficiency
- In case of current controlled dc-dc, Inductor is converted into a lossless VCCS



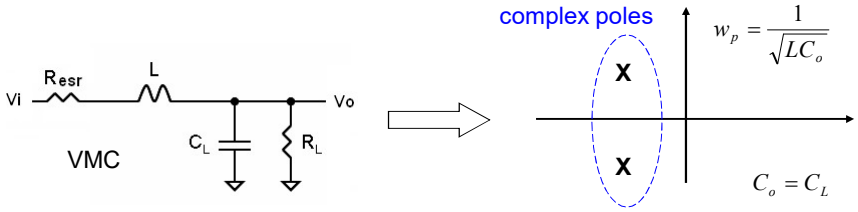


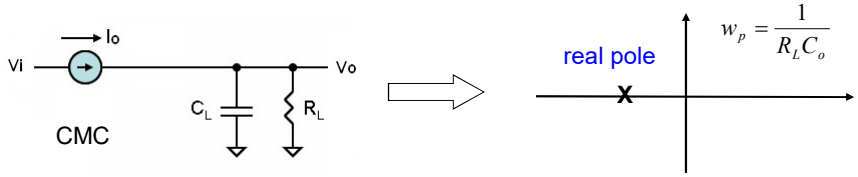


Current Mode Controlled DC-DC

Complex – Real Pole Transformation

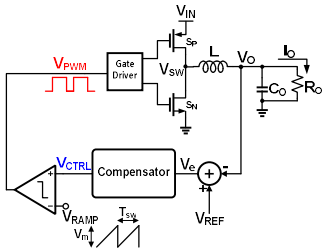
- **Unlike the Voltage Mode controlled, the complex poles due to L & C is converted into real pole because of the inner current loop**

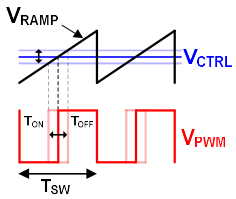




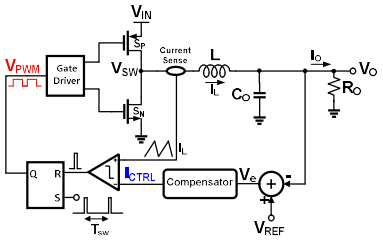
Voltage Mode Vs Current Control

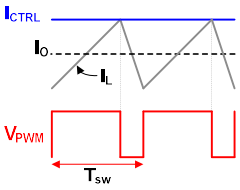
- Duty cycle is controlled only by voltage
- Uses an external ramp





- Duty cycle is controlled by both voltage and current
- Doesn't require external ramp

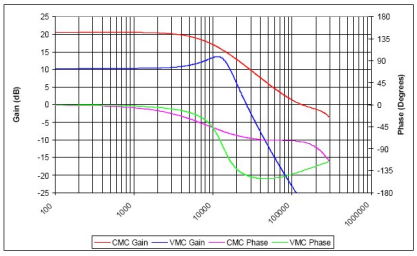




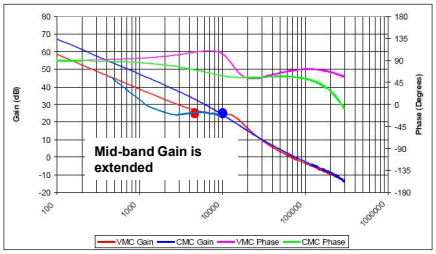
VMC vs CMC Frequency Response

- Phase and Magnitude roll-off is in CMC is not as steep as in VCM
  - Smoother frequency response
- It becomes easier to stabilize the loop due to single pole
  - Only PI (type-II) compensation is required

Brian Lynch, "Current mode vs. voltage mode control in synchronous buck converter", Texas Instruments



Before compensation



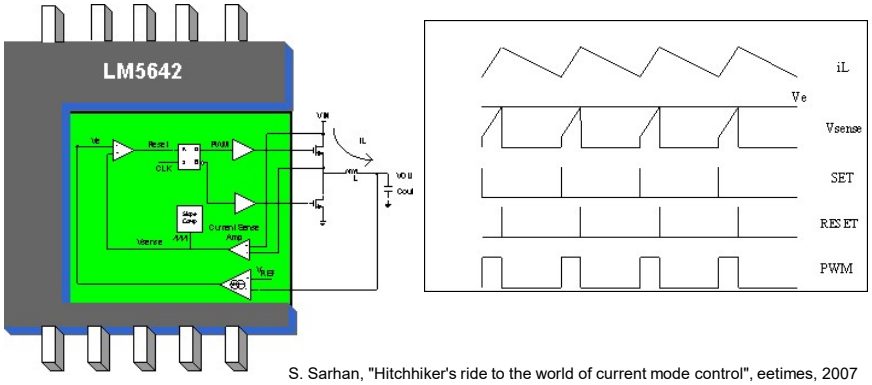
After compensation

Current Mode Control Techniques

- **Peak Current Mode Control**
  - **Peak Current (high side) is used to control the duty cycle**
- **Valley Current Mode Control**
  - **Valley current (low side) is used to control the duty cycle**
- **Emulated Current Mode Control**
  - **Both peak and valley currents are used to control the duty cycle**

Peak Current Mode controlled

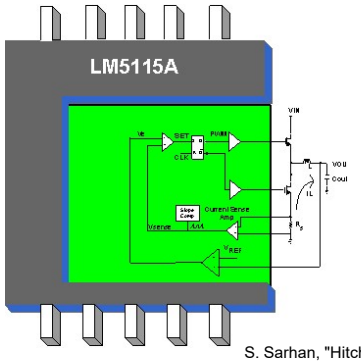
- Senses the peak inductor current information when the power switch is on, then uses it to turn off the switch → trailing edge PWM
- Suffers from sub-harmonic oscillation at duty cycles higher than 50%
- Easy to operate at higher duty cycle but difficult at lower duty cycle

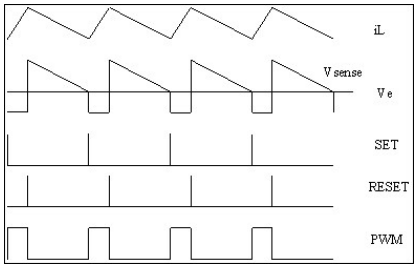


S. Sarhan, "Hitchhiker's ride to the world of current mode control", eetimes, 2007

Valley Current Mode controlled

- Senses the valley inductor current information when the power switch is off, then uses it to turn on the switch → leading edge PWM
- Contrary to Peak CMC, it suffers from sub-harmonic oscillation at duty cycles lower than 50%
- Easy to operate at lower duty cycle but difficult at higher duty cycle

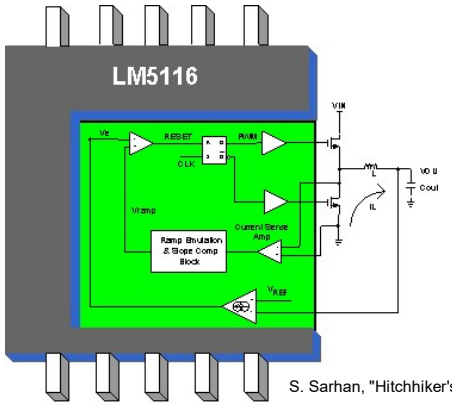


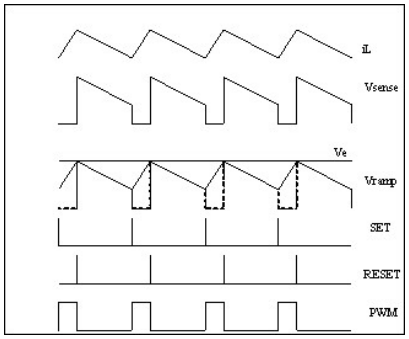


S. Sarhan, "Hitchhiker's ride to the world of current mode control", eetimes, 2007

Emulated Current Mode controlled

- Uses valley current sensing to predict the peak current in order to emulate exact inductor current waveform
- Combines the advantages of valley CMC (low duty cycle operation) and peak CMC (good line transient)





S. Sarhan, "Hitchhiker's ride to the world of current mode control", eetimes, 2007

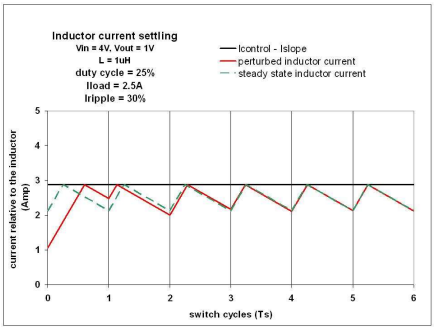
Voltage Mode Control (VMC) vs. Current Mode Control (CMC)

Parameter	VMC	CMC
Line transient	Good with line feedforward $(V_M \alpha V_{IN})$	Good (inherent line feedforward in peak current mode) Bad in valley CMC
Load transient	Good (bandwidth is independent of load current in CCM)	Good at high BW but degrades at lower load current (BW is dependent on load current)
Very low duty cycle operation	Good	Poor
Noise insensitivity	Good	Poor
Compensation	Complex (Type-III)	Simpler (Type-II)

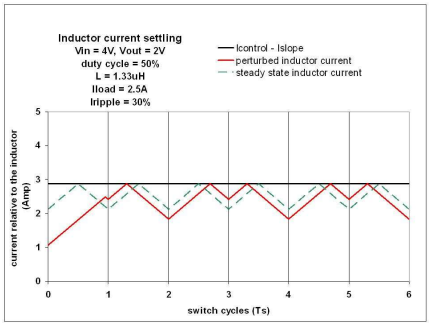
Sub-harmonic Oscillations

- **Caused due to instability in the current loop**

Peak CMC



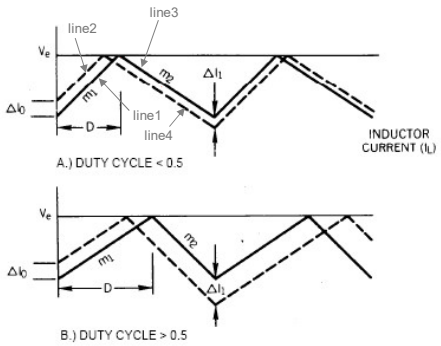
D < 0.5 (Stable)



D > 0.5 (Un-stable)

Current loop instability

- Current Loop suffers from sub-harmonic oscillations when D > 0.5 (for peak CMC) and D<0.5 (for valley CMC)
- This sub-harmonic oscillation is suppressed by adding a compensating ramp in the control signal



Using eq. of straight line

For line1, $I_1 = m_1(T_0) + I_0$

For line2, $I_1 = m_1(T_0-\Delta T_0) + I_0 + \Delta I_0$

Subtracting two eq.

$\Delta T_0 = \Delta I_0/m_1$

similarly line3 and line4 gives

$\Delta I_1 = -m_2 \Delta T_0$

Substituting ΔT_0, we get

$$\Delta I_1 = -\Delta I_0 \left(\frac{m_2}{m_1}\right) \quad (1)$$

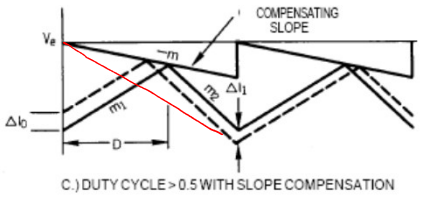
Case-1: D < 0.5 → $m_1 > m_2$ → $\Delta I_1 < \Delta I_0$; stable

Case-2: D = 0.5 → $m_1 = m_2$ → $\Delta I_1 = \Delta I_0$; critically stable

Case-3: D > 0.5 → $m_1 < m_2$ → $\Delta I_1 > \Delta I_0$; unstable

Ramp Compensation

- The current loop is stabilized by adding a small ramp in the current or subtracting the same from error signal



$$\Delta I_1 = -\Delta I_0 \left(\frac{m_2 - m}{m_1 + m}\right) \quad (2)$$

Disturbance after *n* cycles:

$$\Delta i_n = \left(-\frac{m_2 - m}{m_1 + m}\right)^n \cdot \Delta i_0 \quad (3)$$

Hence to ensure the stability of current loop Δi_n should die out → (m2-m) < (m1+m)

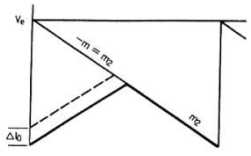
Stability Condition: $\Delta i_n / \Delta i_0 < 1$

Can be achieve by two ways

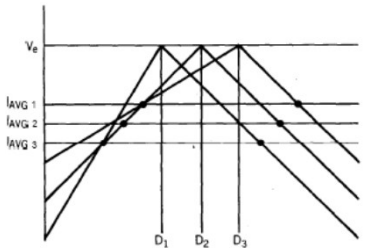
$$m > \frac{1}{2} m_2 \quad \text{or} \quad m > \frac{1}{2}(m_2 - m_1)$$

Substituting both the case in (3) results in (m2-m) < (m1+m) hence satisfying the condition of stability

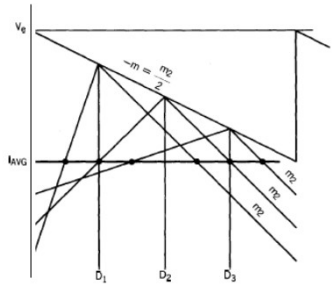
Ideal slope for compensating ramp, m = m2 causes the output to settle in one clock cycle



Ramp Compensation

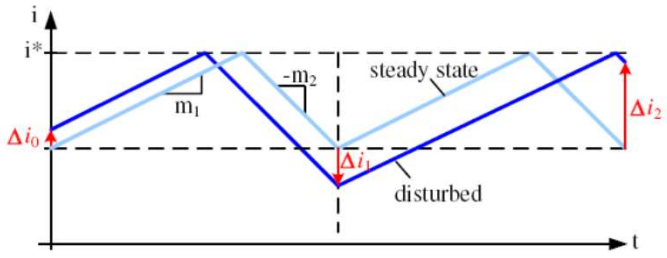


PEAK CURRENT SENSING WITHOUT SLOPE COMPENSATION ALLOWS AVERAGE INDUCTOR CURRENT TO VARY WITH DUTY CYCLE



- AVERAGE INDUCTOR CURRENT IS INDEPENDENT OF DUN CYCLE AND INPUT VOLTAGE VARIATION FOR A SLOPE COMPENSATION OF m = -½ m_2.

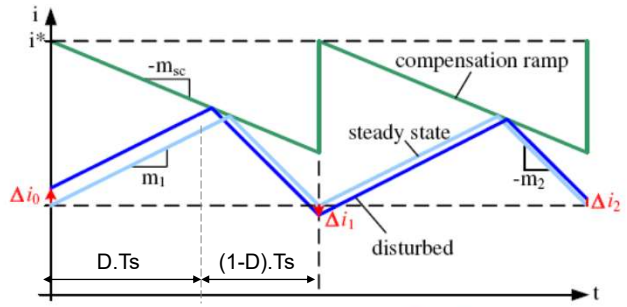
Slope Compensation



Disturbance after *n* cycles: $\Delta i_n = \left(-\frac{m_2}{m_1}\right)^n \cdot \Delta i_0$

Condition for stable operation: $m_1 > m_2 \quad (D < 0.5)$

Slope Compensation



$$\frac{m_2}{m_1}=\frac{D}{1-D}$$

Disturbance after *n* cycles:

$$\Delta i_n=\left(-\frac{m_2-m_{sc}}{m_1+m_{sc}}\right)^n\cdot\Delta i_0$$

Required compensation:

$$m_{sc}>\frac{1}{2}(m_2-m_1)$$

Adaptive Slope Compensation

$$m_{sc}>\frac{1}{2}(m_2-m_1)\rightarrow\frac{1}{2}m_1\left(\frac{m_2}{m_1}-1\right)\qquad(1)$$

$$\frac{m_2}{m_1}=\frac{D}{1-D}=\frac{V_{out}}{V_{in}-V_{out}}\qquad(2)$$ For buck: *D = Vout/Vin*

substituting (2) in (1)

$$\Rightarrow m_{sc}>\frac{1}{2}m_1\frac{V_{in}}{V_{in}-V_{out}}\quad or\quad \frac{m_{sc}}{m_1}>\frac{1}{2}\frac{V_{in}}{V_{in}-V_{out}}$$

$$also\ m_1=\frac{V_{in}-V_{out}}{L}\Rightarrow m_{sc}>\frac{V_{in}}{2L}$$

The optimum slope compensation can be calculated by knowing one of the followings:

- m_1, V_{in} and V_{out}
- V_{in} and L