Control of SMPS – a Refresher
Part 1

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Control of SMPS – a Refresher:

Agenda

Part 1
1. Concepts
2. Transfer Functions
3. Control Systems

Part 2
4. Loop Transfer Functions
   - Control to Output: G(s) — Power Stage (Plant)
   - Output to Control: H(s) — Feedback (Control)
5. Loop Compensation

Part 3
6. Measuring the Control Loop
7. Summary and other issues
8. References

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Concepts:

Control:

- Measure the system
- Compare to reference
- Adjust appropriately

Controllability:

- What variables can we use to control the system's state
- Eg: Switching Frequency, Duty Cycle, Handlebars

Observability:

- How can we determine the system's state
- Eg: Measure Vout, Vin, Iout, Inductor Current, Eyes

Reachability:

- Does the control system have enough authority to do what we want it to do?
- Eg: Transient response, Trim range, Current limit

  Start-up time, Lean limits (aka, training wheels)

Concepts: LTI, Linear Time-Invariant

Linearity f(a+b) = f(a) + f(b) , f(k*a) = k*f(a)

- System response doesn't depend on the load power or current
- Non-Linear at OCP, OVP, Enhanced Dynamic Response etc

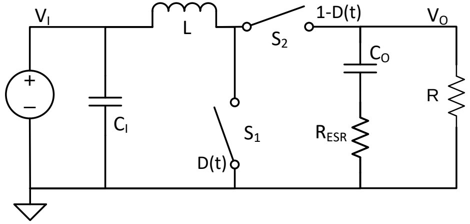
Time Invariance

- System does not change with time
- Exceptions at power up, power down, OCP etc
- Switching action in power stage must be averaged

Continuous time assumed

- Time variable is continuous and can take up any value
- Assumption is valid up to about 20% of switching frequency

SMPS are not linear and are not time invariant !



So we 'cheat' and build a model which is LTI ☺

- Linearisation
- State Space Averaging

$$G(s) = A_{VC} \cdot \frac{1 + \frac{s}{\omega_z}}{1 + \frac{s}{Q_0 \cdot \omega_0} + \frac{s^2}{\omega_0^2}}$$

Switching frequency does not appear in the transfer function !

Typical Buck Converter model

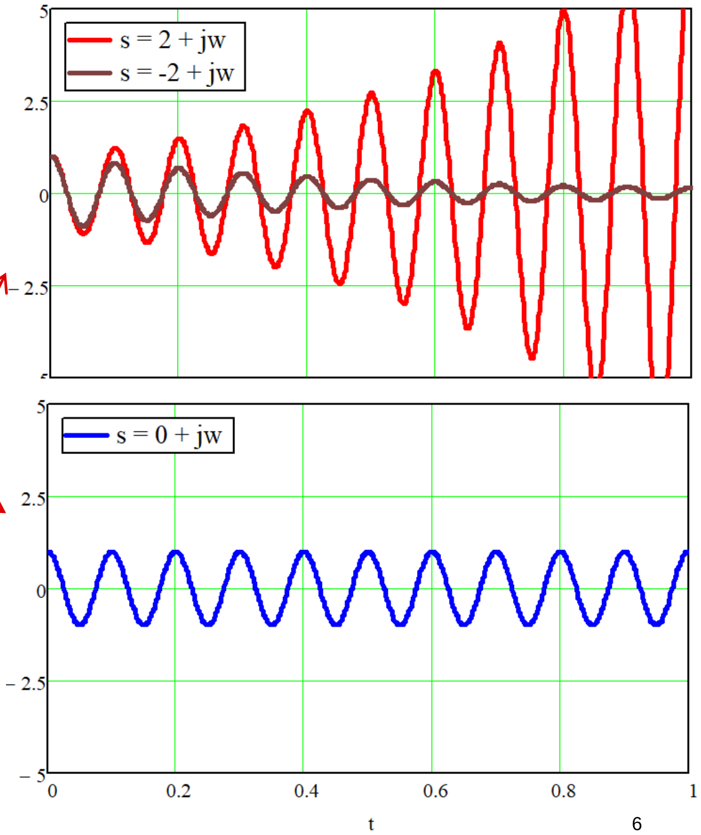
Concepts: Complex Frequency (s)

Complex Frequency: s = σ + jω

σ sets decay rate,

- σ > 0, increasing: σ < 0, decaying: σ = 0, steady state
- We set σ to 0 and so that s = jω
- ω is the frequency of the underlying sine wave

$$V_i(t) = \mathrm{Re}\left(V_m \cdot e^{\sigma \cdot t} \cdot \cos(\omega \cdot t + \varphi)\right)$$



y(s) contains Magnitude and Phase information.

Really useful property – a single calculation gives

- Magnitude = Mag[y(s)],
- Phase = arg[y(s)] (radians !)

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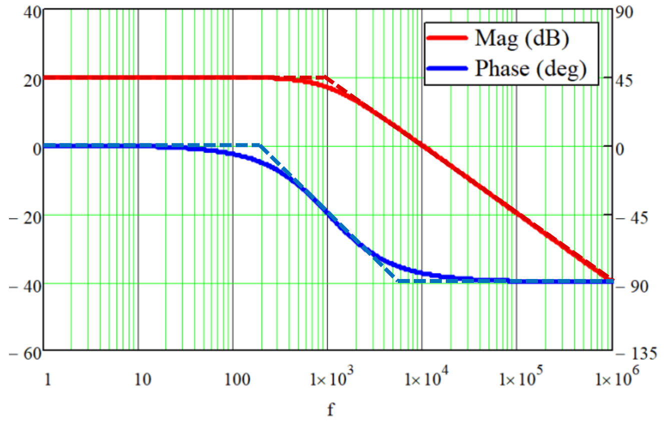
Transfer Functions: Bode Plots

The transfer function is basically $V_o(s) / V_I(s)$

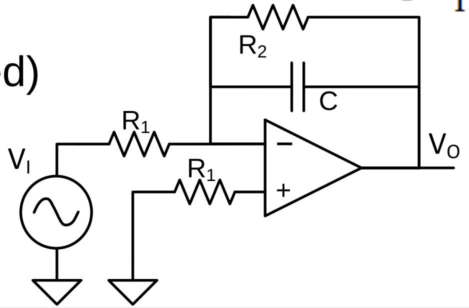
- H(s), G(s), Y(s) etc, etc,
- Calculated or Measured
- A function frequency
- Complex frequency gives Magnitude and Phase



Bode Plot, Magnitude and Phase versus frequency

- Frequency is on a Log scale
- Magnitude in dB: 20 log (V_O/V_I)
- Phase in deg: $\theta_{IN} - \theta_O$
- Can use straight line approximations (dotted)

$$G(s) = \frac{-R_2}{R_1} \cdot \frac{1}{1 + \frac{s}{\omega_p}} \quad \text{where} \quad \omega_p = \frac{1}{R_2 \cdot C}$$



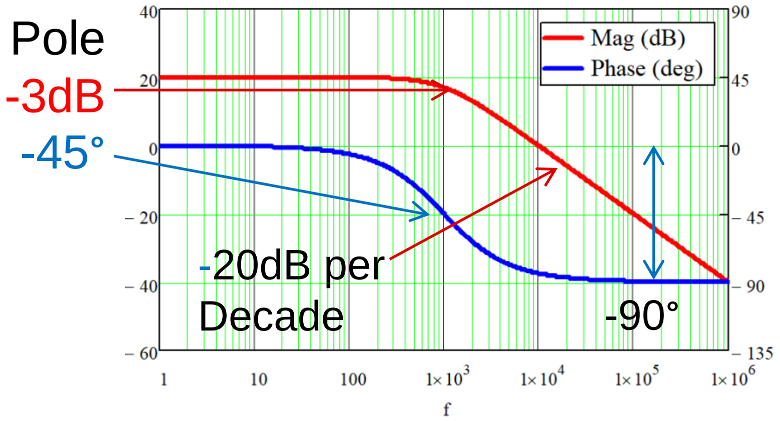
Note

- Magnitude, Amplitude, Gain are equivalent

Transfer Functions: Poles

$$G(s) = \frac{-R_2}{R_1 \cdot (R_2 \cdot sC + 1)} = \frac{-R_2}{R_2} \cdot \frac{1}{1 + sCR_2} = \frac{-R_2}{R_1} \cdot \frac{1}{1 + \frac{s}{\omega_0}}$$

$$G(s) = \frac{-R_2}{R_1} \cdot \frac{1}{1 + \frac{s}{\omega_0}} \quad \text{where} \quad \omega_0 = \frac{1}{R_2 \cdot C}$$



LF gain is -R2/R1

Gain rolls off at -20dB per decade above ω_0

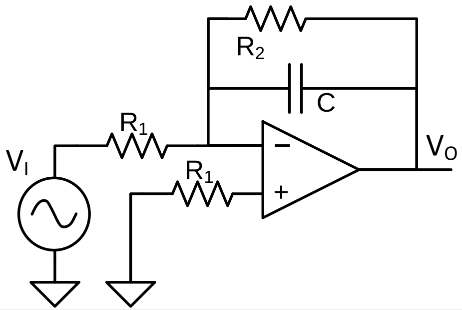
Gain is flat below ω_0

Phase flat below ω_0 /10 and above 10 ω_0

Phase is:

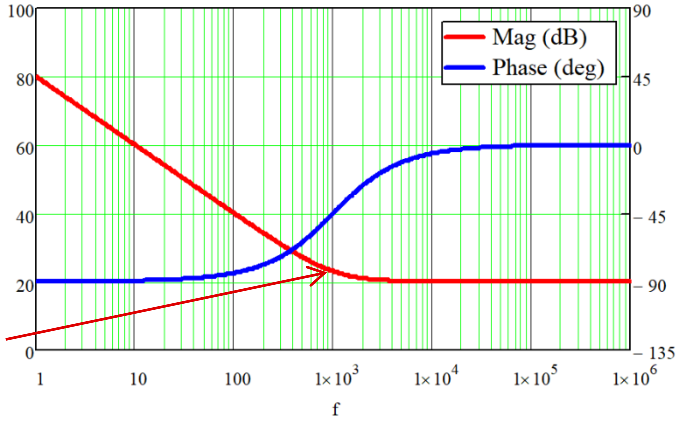
- 0° at LF
- -45° at ω_0
- -90° at HF

Gain is -3dB at ω_0 $\quad f_p = \frac{1}{2\pi R_2 C}$



Transfer Functions: Zeros

$$G(s) = \frac{-z_1}{z_2} = \frac{-\left(R_2 + \frac{1}{sC_1}\right)}{R_1} = \frac{-R_2}{R_1}\left(1 + \frac{1}{sCR_2}\right) = \frac{-R_2}{R_1}\left(1 + \frac{\omega_Z}{s}\right)$$

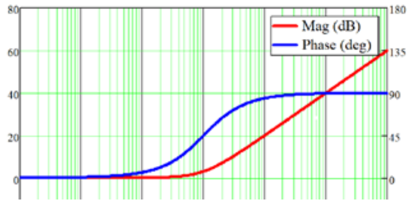


$$G(s) = \frac{-R_2}{R_1}\left(1 + \frac{\omega_Z}{s}\right) \quad \text{where} \quad \omega_Z = \frac{1}{R_2 \cdot C}$$

Zero

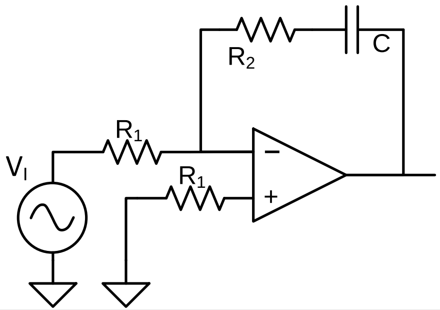
Used in Type 2 compensator to add some phase boost and so increase the phase margin

+3dB at $f_z = \frac{1}{2\pi R_2 C}$



$$G(s) = 1 + \frac{s}{\omega_Z}$$

Alternative form

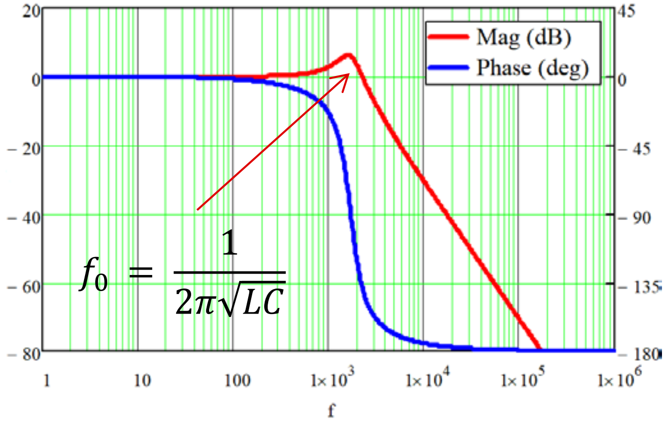


Transfer Functions: Complex Conjugate Poles

Complex Conjugate Poles: Resonance,
Phase decreasing to -180°
Q determines peak response

Gain rolls off at -40dB per decade above ω_0
Phase is:

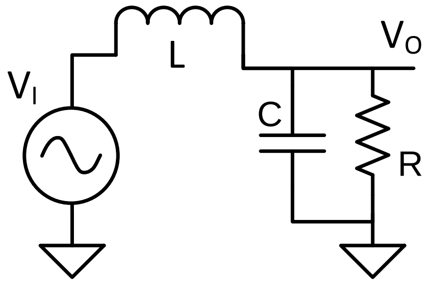
- 0° at LF
- -90° at ω_0
- -180° at HF



$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

$$G(s) = \frac{1}{1 + \frac{s}{Q \cdot \omega_0} + \frac{s^2}{\omega_0^2}}$$

$$Q = \frac{R}{\sqrt{\frac{L}{C}}}$$

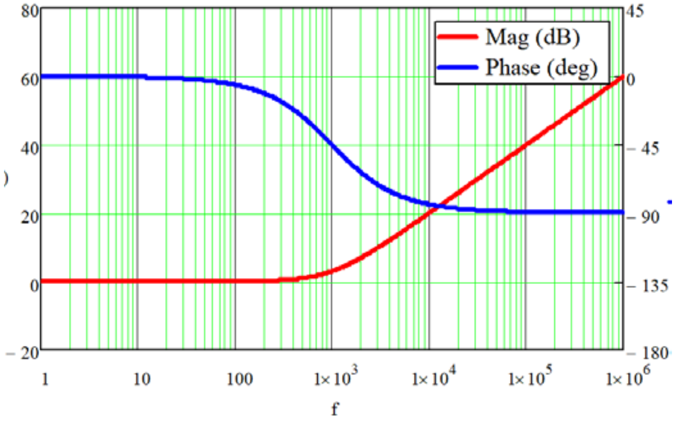


Transfer Functions: Right Half Plane Zero

RHPZ:

- A characteristic of topologies which deliver energy to the output 180° out of phase with the energy taken from the input Flyback, Boost, Cuk, (CCM only).

$$G(s) = 1 - \frac{s}{\omega_r}$$

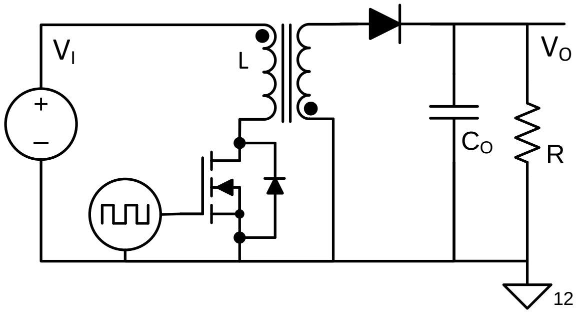


RHPZ: (Right Half Plane Zero)

- Gain increasing Phase decreasing
- Almost impossible to compensate for this
- Must close the loop at frequencies << ω_z

RHPZ is not an issue in Boost PFC

- They must close the loop at very low frequencies for other reasons, typ < 10 Hz .
- Controlled quantity is input current, not output current



Ref 1

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Control Systems: Variables

Many SMPS use Duty Cycle (D) as the control variable

- CCM, PSFB, Push-Pull

Sometimes D and F_{SW} are both used

- Mainly to improve efficiency
- Quasi Resonant, DCM converters
- Conversion ratios are unchanged

$$V_{OUT} = D \cdot V_{IN}$$ Buck Converter

$$V_{OUT} = \frac{1}{1 - D} \cdot V_{IN}$$ Boost Converter

$$V_{OUT} = \frac{D}{1 - D} \cdot V_{IN}$$ Flyback Converter

Conversion factor is a function of D, not of F_{SW}

LLC uses Fsw as the control variable

- One of a large class of resonant converters

$$\mathrm{Gain}(f, Q) = \left| \frac{L_N \cdot f^2}{L_N \cdot f^2 + \left(f^2 - 1\right)\left(1 + j \cdot f \cdot L_N \cdot Q\right)} \right|$$

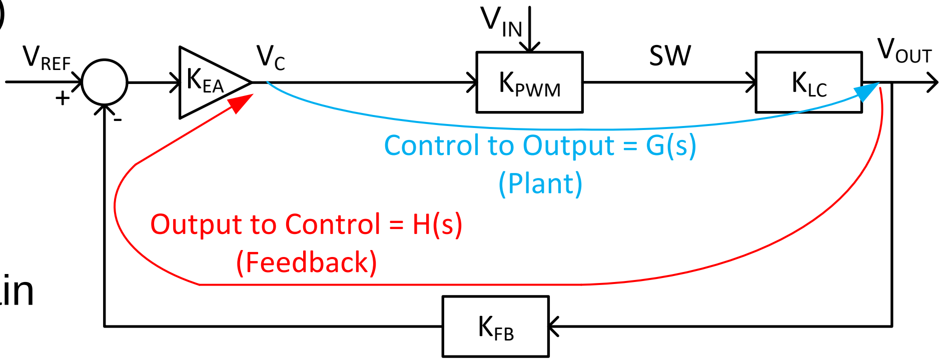
Conversion factor is a function of F_{SW} not of D

Hysteretic SMPS use Upper and Lower limits on VOUT

A Typical Control System:

A typical analog SMPS control system looks something like this Ref 2: Ch6

- $K_{EA}(s)$* Error Amplifier (transfer function as function of complex frequency)
- K_{PWM} Pulse Width Modulator (A Constant)
- $K_{LC}(s)$ Output Filter
- K_{FB} Feedback Potential Divider



- $G(s) = K_{PWM} * K_{LC}(s)$ = Control to Output gain
- $H(s) = K_{FB} * K_{EA}(s)$ = Output to Control gain
- Total loop response $T(s) = G(s) * H(s)$

System measures the output, compares to the reference, makes an adjustment

Two Control Systems: VMC and CMC

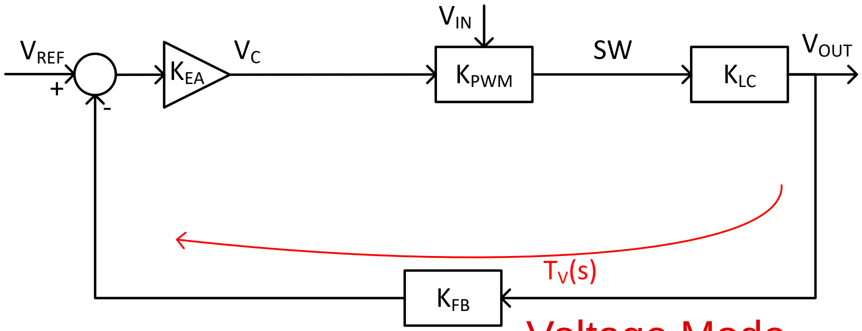
VMC:

- Error Amplifier controls Duty Cycle (D) directly

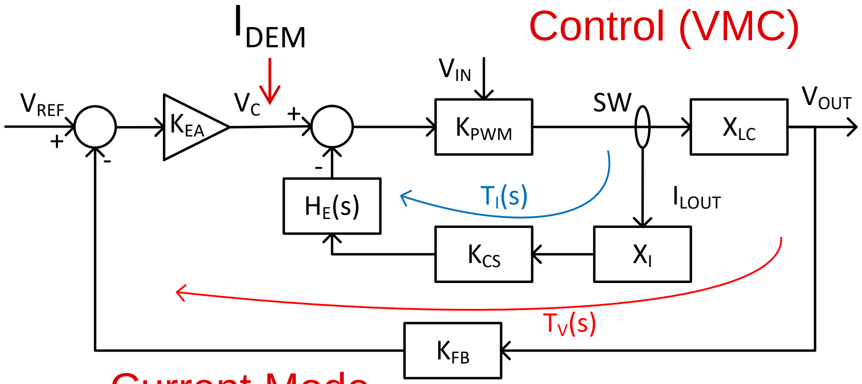
CMC:

- PCM (Peak Current Mode)
- ACM (Average Current Mode)
- Error Amplifier sets I_{DEM} (Current Demand) for inner loop. sometimes called 'COMP'
- Inner loop regulates the output current

Other control methods do exist – not covered here



Voltage Mode Control (VMC)



Current Mode Control (CMC)

Control Systems: Voltage Mode Control

Error amplifier output V_C controls D directly

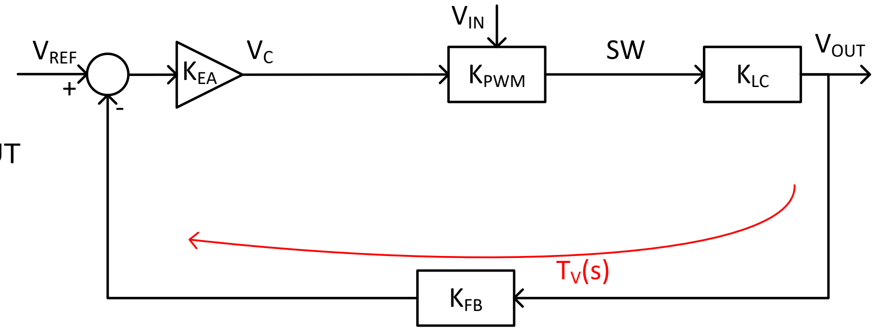
V_{OUT} drops → V_C increases → D increases → V_{OUT} increases

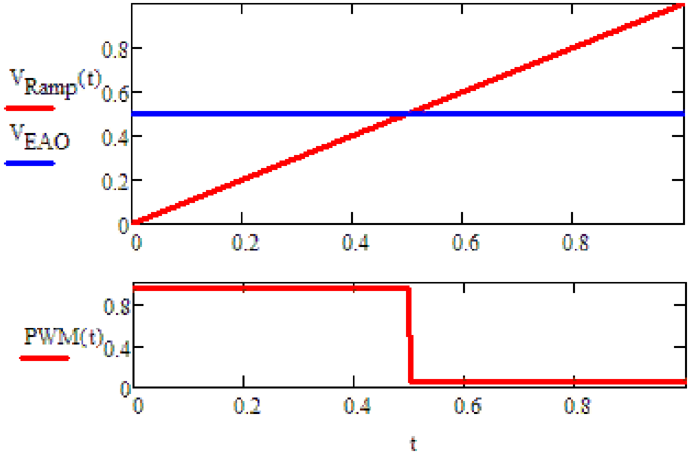
Less noise sensitive than PCM – larger ramp

Easy to implement Voltage Feed Forward

Output Filter appears in the transfer function so

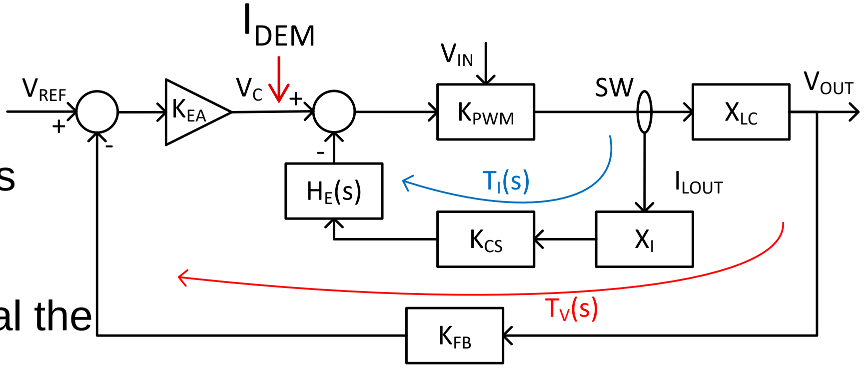
- Control loop bandwidth is lower than with CMC
- More difficult to stabilise than CMC
- Type 3 Compensation (more on this later)





Just because it's more difficult to stabilise doesn't mean that it is impossible to stabilise.

Control Systems: Current Mode Control



Peak Current Mode – most common

Average Current Mode – used in some PFC stages

Error amplifier output V_C sets a current demand

Inner current loop forces the output current to equal the current demand.

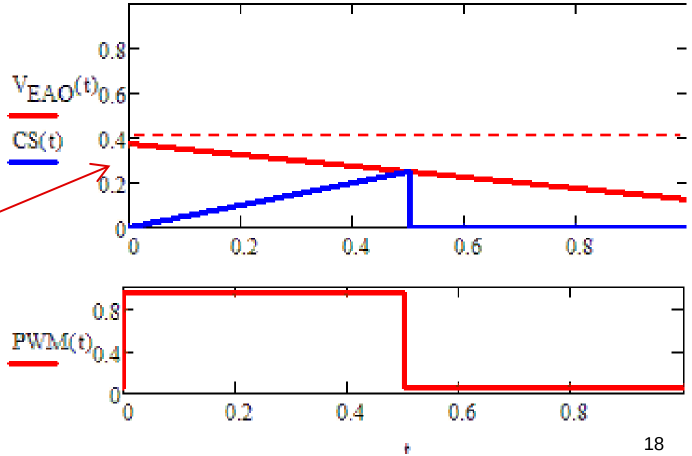
V_{OUT} drops → V_C (I_{DEM}) increases, I_{OUT} increases → V_{OUT} increases

Wider loop bandwidth and easier to stabilise than VMC

Cycle-by-Cycle over current protection

Sub-Harmonic instability, (PCM in CCM)

- Slope Compensation (added to V_{EAO})
- Peak-to-Average ratio not constant – distortion in PFC



Control Systems: PCM Half Bridge instability

Peak Current Mode control of half bridge is unstable

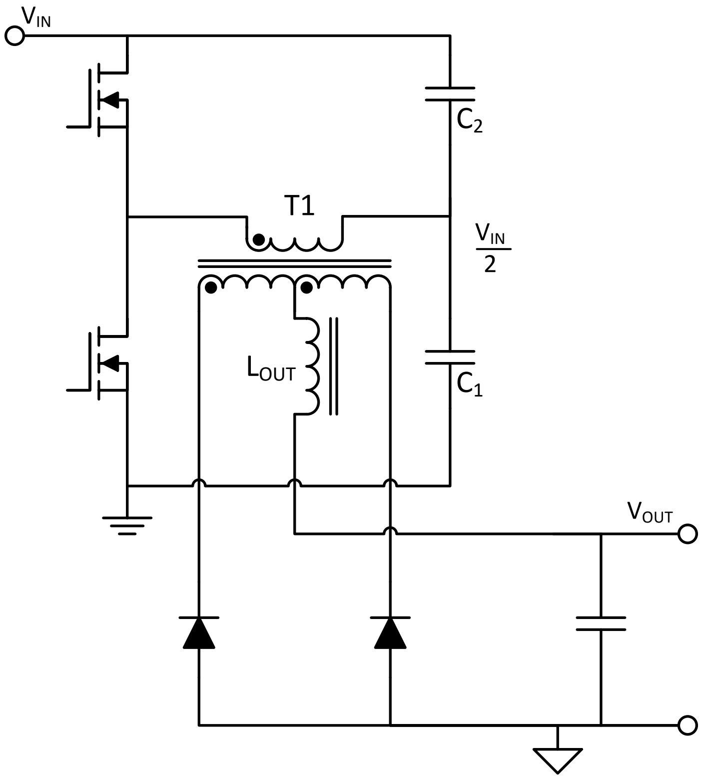
Described in Ref 13

Voltage at centre point of C_1 and C_2 diverges from $V_{IN}/2$

- This is an inherent instability

Solutions

- Use VMC – any half bridge controller
- Use duty cycle copy – UCC28251
- Use Average current limit - LM5039
- Modified CT circuit – see article above



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End of Part 1

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