Control of SMPS – a Refresher

Part 2

Colin Gillmor (APP, HPC)

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

Control of SMPS – a Refresher:

1. Concepts
2. Transfer Functions
3. Control Systems
4. **Loop Transfer Functions**
    - **Control to Output: G(s)** **Power Stage (Plant)**
    - **Output to Control: H(s)** **Feedback (Control)**
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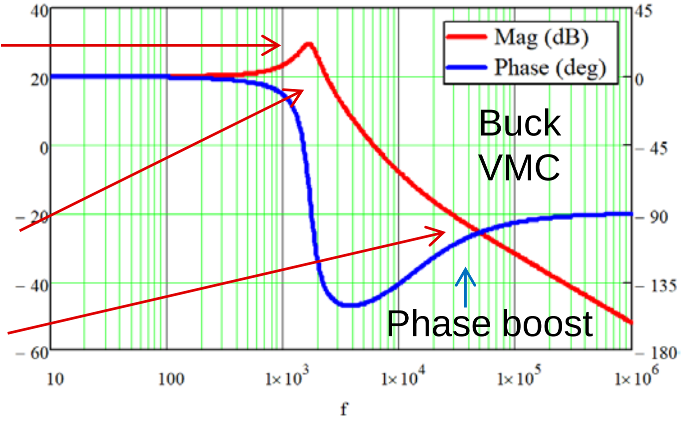
Control to Output Transfer Function: G(s)

- $G(s) = \frac{V_{OUT}}{V_C} = K_{PWM} * K_{LC}(s)$
- Buck Converter in Voltage Mode Control
- Output Inductor/Capacitor resonance
- Phase boost, zero of ESR and Cout
- Type 3 compensation needed (more later)

$$Q_0 = \frac{R_{OUT}}{\sqrt{\frac{L_{OUT}}{C_{OUT}}}}$$

$$\omega_0 = \frac{1}{\sqrt{L_{OUT}\cdot C_{OUT}}}$$

$$\omega_z = \frac{1}{R_{ESR}\cdot C_{OUT}}$$

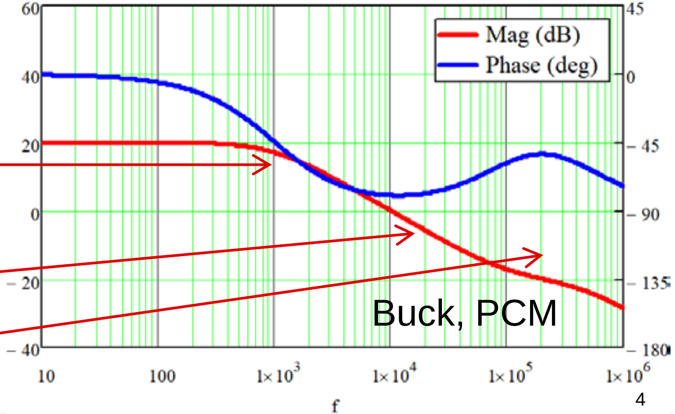


- Buck Converter in Peak Current Mode
- First order characteristic
- Phase boost, zero of ESR and Cout
- Type 2 compensation (more later)
- Ref 3

$$\omega_{p1} = \frac{1}{C_{OUT}\cdot R_{OUT}}$$

$$\omega_z = \frac{1}{R_{ESR}\cdot C_{OUT}}$$

$$\omega_{p2} = K\cdot\frac{1}{L_{OUT}}$$



Control to Output Transfer Function: G(s)

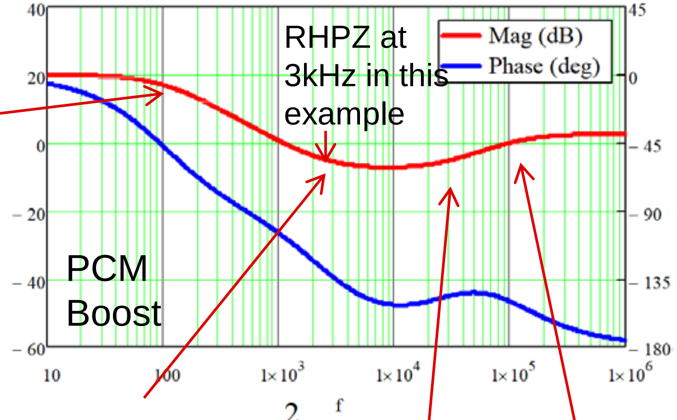
$$G(s) = \frac{V_{OUT}}{V_C} = K_{PWM} * K_{LC}(s)$$

$$\omega_p = \frac{2}{C_{OUT} \cdot R_{OUT}}$$

A right-half-plane zero appears in the transfer function of topologies which deliver energy to the output 180° out of phase with the energy taken from the input.

(in CCM only, Flyback, Boost, Cuk topologies)

(Sheehan: slup340 and Dixon: slup084)



$$\omega_r = \frac{R_{OUT} \cdot (1 - D)^2}{L}$$

$$\omega_L = \frac{K \cdot R_i}{L}$$

Remember - RHPZ: Gain increasing Phase decreasing

- Severely limits the control bandwidth

$$\omega_z = \frac{1}{R_{ESR} \cdot C_{OUT}}$$

Flyback transfer function under PCM

$$G(s) = A_{VC} \cdot \frac{\left(1 - \frac{s}{\omega_r}\right) \cdot \left(1 + \frac{s}{\omega_z}\right)}{\left(1 + \frac{s}{\omega_p}\right) \cdot \left(1 + \frac{s}{\omega_L}\right)}$$

Output to Control Transfer Function: H(s)

This is the feedback system used to close the control loop

We need

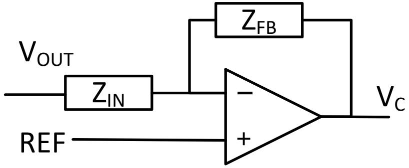
- 180deg phase shift at DC for negative feedback
- High gain at DC, for good regulation
- High loop bandwidth, for good transient response (except PFC)
- Adequate gain and phase margins, for stability

  PM > 45° at 0dB gain

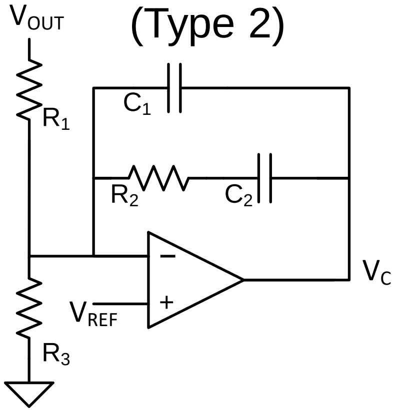
Need to reduce gain to less than 1 before ≈ fsw/10

- Prevent the control loop from ‘seeing’ the switching action
- Ideally gain dropping at -20dB per decade at the cross over
- Makes system less sensitive to component variations

Error Amplifier



More Detail
(Type 2)



Control of SMPS – a Refresher:

1. Concepts
2. Transfer Functions
3. Control Systems
4. Loop Transfer Functions
    - Control to Output: G(s) Power Stage (Plant)
    - Output to Control: H(s) Feedback (Control)
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The Feedback Network: H(s)

Three generic types of Compensation network

Type 1, 1 pole at origin, no phase boost

Type 2, 1 pole at origin, 1 zero, 1 HF pole,

- phase boost up to 90°

Type 3, 1 pole at origin, 1 zero pair, 1 HF pole pair,

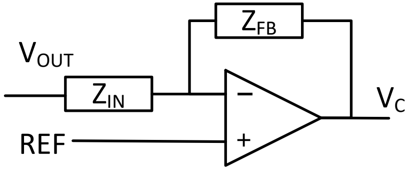
- phase boost up to 180°

The terms PI, PID are used in digital control systems

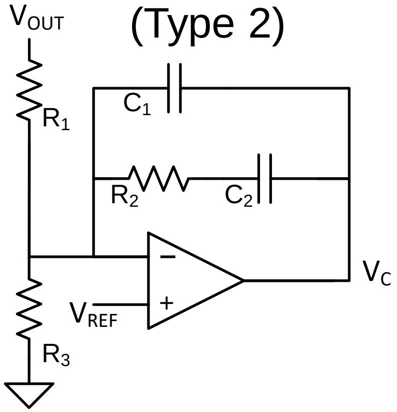
Similar but no direct correlation to the Type 1, 2, 3 classification used here.

Ref 3 VERY Highly Recommended

Error Amplifier



More Detail (Type 2)



Loop Response: Requirements for Stability

Loop Stability: Remember: 0dB = gain of 1

- There is a 180deg phase shift at DC
- System will oscillate (at the crossover frequency) if there is an ADDITIONAL 180° around the loop at the crossover frequency. Ref 4

For Stability

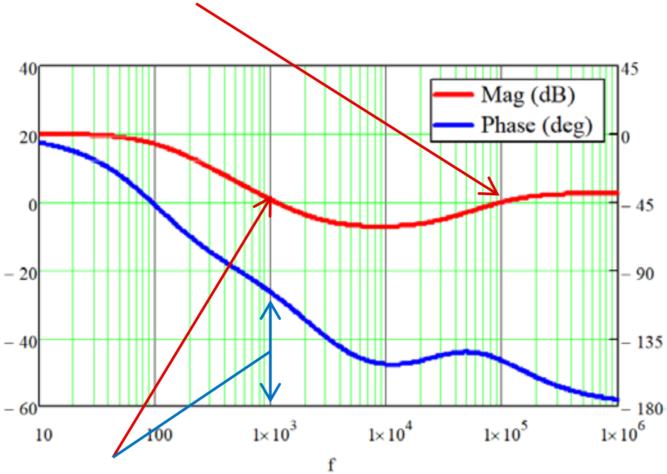
- Phase must be < 180° when the gain goes through 0dB
- Gain must be < 0dB when the phase goes through 180°

Compensation network must be designed for

- Adequate gain and phase margins, for stability
- PM > 45° at 0dB gain

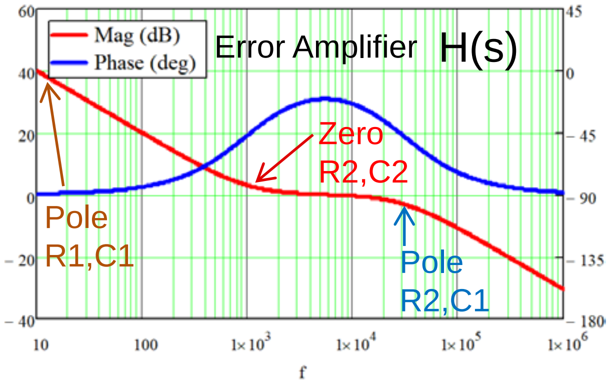
Need to reduce gain to less than 0dB before ≈ fsw/10

Metastable condition if gain pops up above 0dB
To be avoided !



0dB crossover at 1kHz
Phase Margin ≈ 76°

Loop Response: T(s) = H(s)G(s), Buck PCM

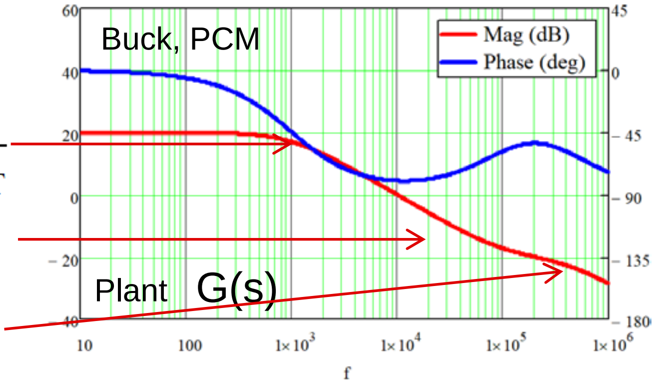


LF Pole

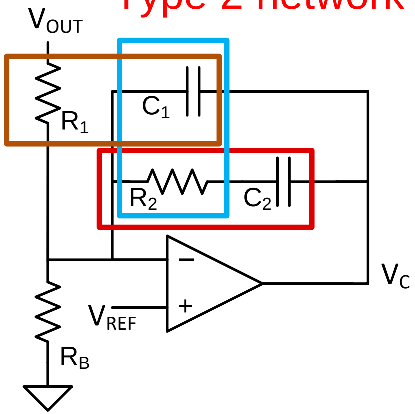
$$\omega_{p1} = \frac{1}{C_{OUT} \cdot R_{OUT}}$$

$$\omega_{z} = \frac{1}{R_{ESR} \cdot C_{OUT}}$$

$$\omega_{p2} = K \cdot \frac{1}{L_{OUT}}$$

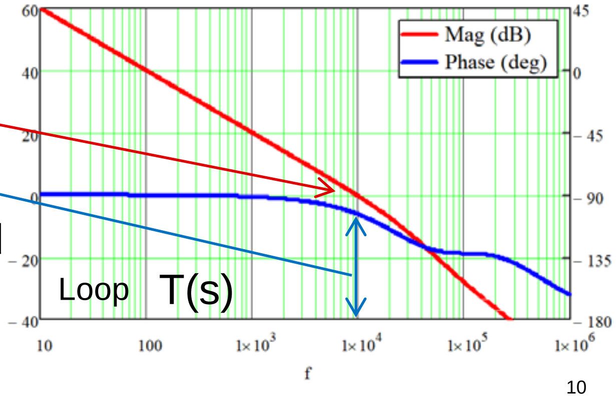


Type 2 network

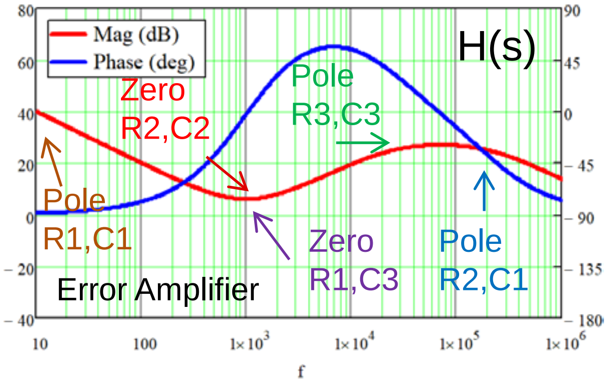


- Loop crossover at 10kHz
- Approx. 76° phase margin
- Inverting input is virtual ground
- R_B attenuates Vout only

Ref 3



Loop Response: T(s) = H(s)G(s), Buck VMC



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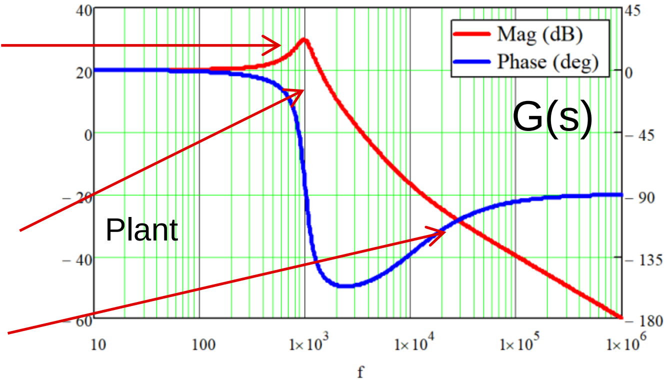
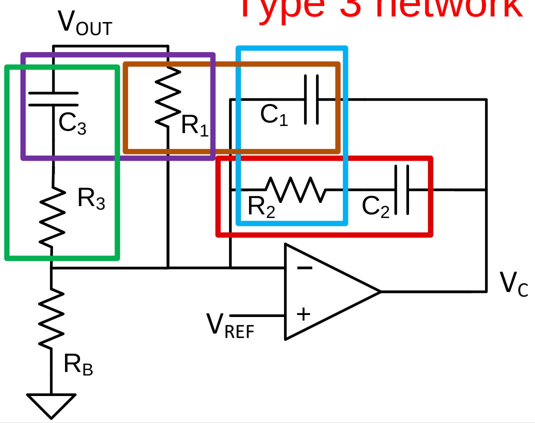
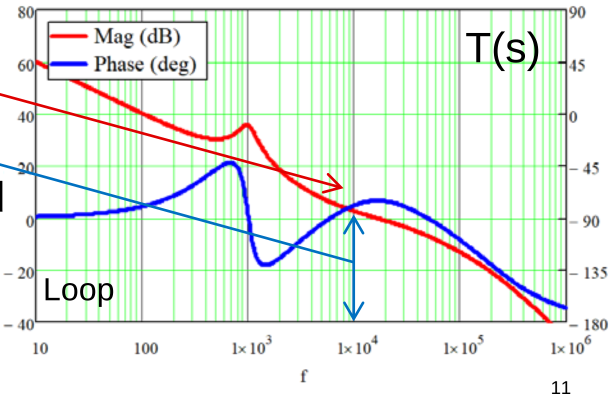


Type 3 network



- Loop crossover at 10kHz
- Approx. 90° phase margin
- Inverting input is virtual ground
- R_B attenuates Vout only

Ref 3



The TL431:

Reference + Error Amplifier in one IC

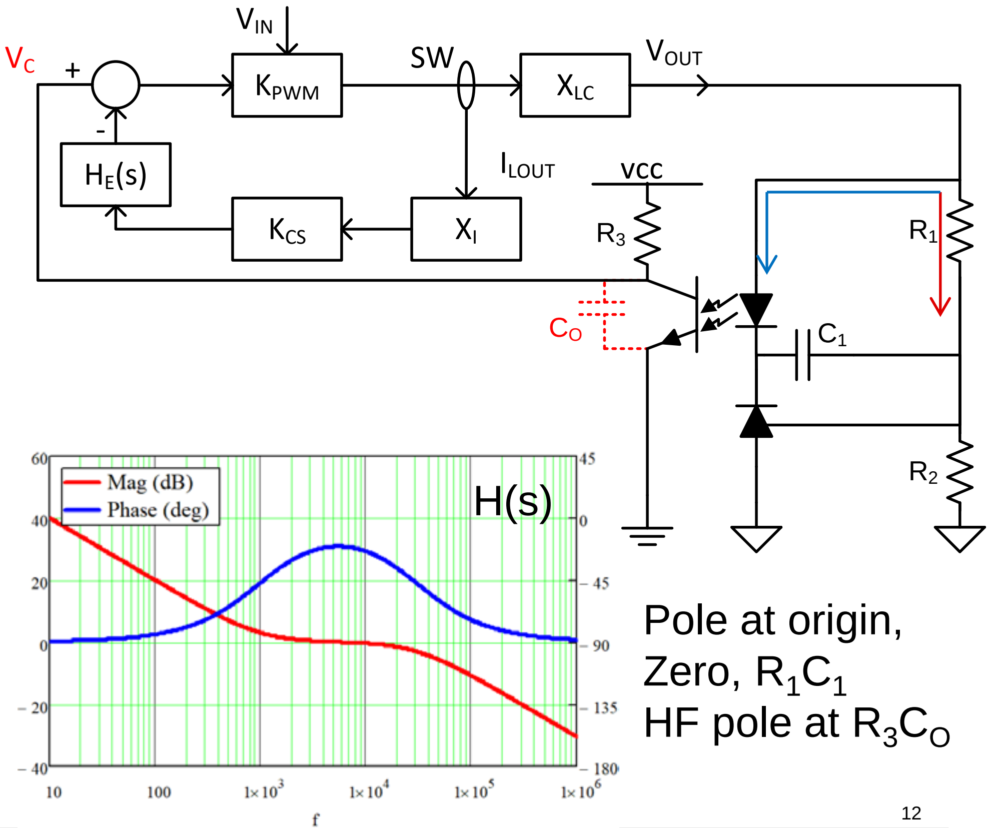
Type 2 compensator shown here,

- 1 pole at origin,
- 1 zero,
- 1 HF pole, phase boost up to 90°

Ref 5

Ref 6 (VERY highly Recommended)

- Optocoupler has pole due to parasitic output capacitance C_O



Pole at origin,
Zero, R_1C_1
HF pole at R_3C_O

The TL431:

High V_{OUT} (> ≈ 36V) or Low V_{OUT} (< ≈ 3V)

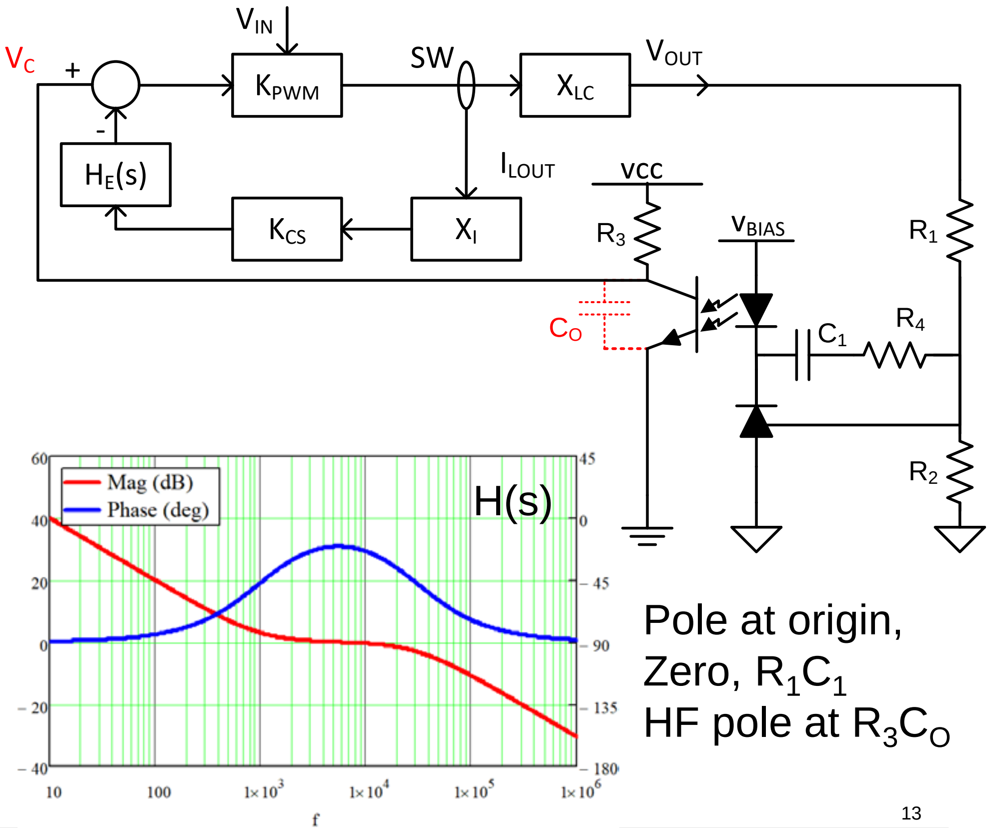
- Connect LED to a fixed bias rail.

Optocoupler CTR has a wide part to part variation and is also a function of -

- LED current,
- Temperature,
- Age.

Perceived to be **unreliable, but main issue is lifetime**

Very useful for crossing an isolation barrier



Pole at origin,
Zero, R_1C_1
HF pole at R_3C_O

Current Loop Stability:

Measuring gain and phase of the current loop is difficult.

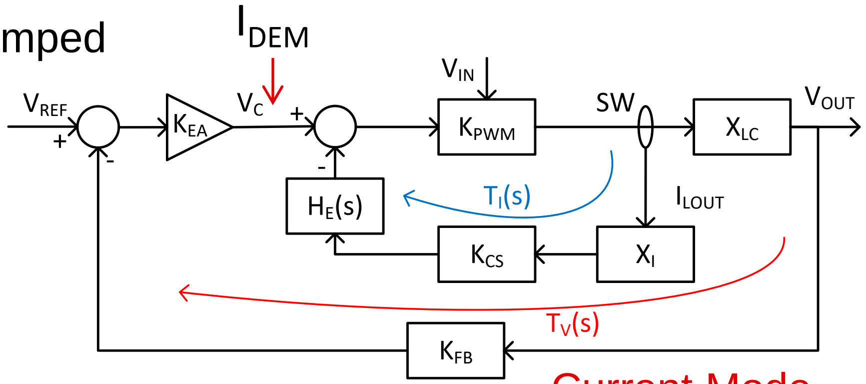
Fix an operating point (Constant I_{DEM}), inject the signal in series with the CS resistor, measure the gain and phase vs frequency

However: Current loop stability is not normally a problem except

In CCM a fixed frequency current loop is unstable for D > 50%, Sub Harmonic Oscillations

Operation at D slightly below 50% can be underdamped

Slope Compensation Ramp needed



Current Mode Control (CMC)

Ref 9

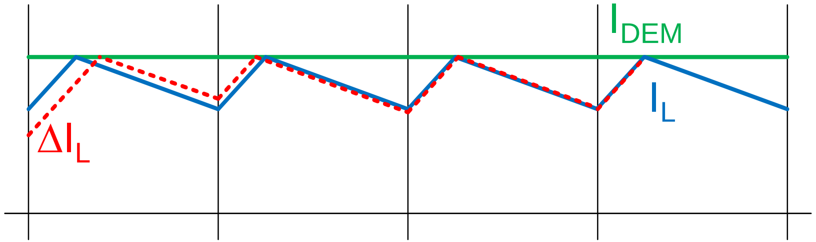
Sub-Harmonic Oscillations: Instability

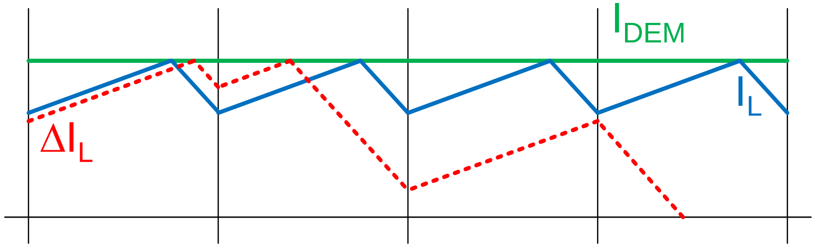
D < 50%, perturbation in inductor current (dotted) dies away.

System becomes increasingly underdamped as D increases past 40%

D>50%, perturbation in inductor current does not die away. Current diverges. System is unstable

Characterised by large cycle to cycle variations





Green = Current Demand Signal
Blue = steady state inductor current
Red = perturbed inductor current

Ref 7

Sub-Harmonic Oscillations: Slope Compensation

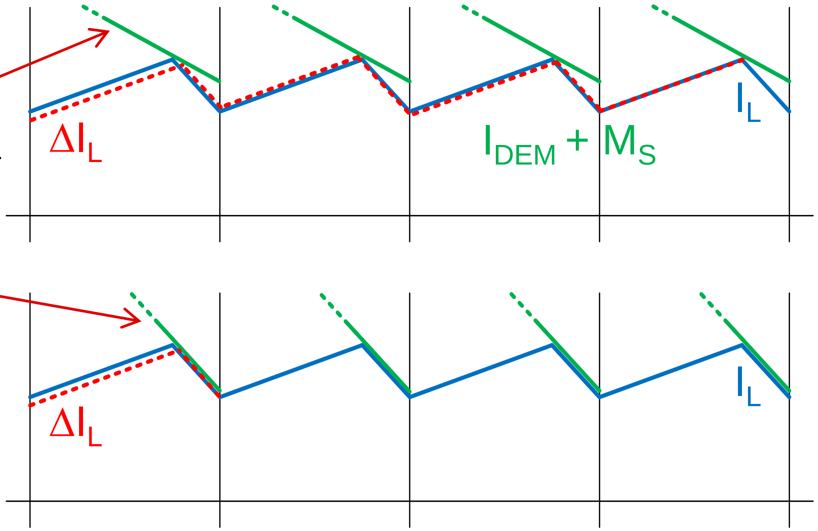
Slope Compensation Ramp stabilises the system

- m_S: at least 50% of inductor current downslope m_L Min Peak to Average error when m_S = -50% m_L
- Fastest recovery when m_S = -100% m_L
- Non-Linear Slope Compensation is possible – rarely used

Slope can be subtracted from I_{DEM} OR Added to the Inductor Current signal

Slope compensation should be added for D > 40%

Response becomes increasingly underdamped as D approaches 50%



Green = Current Demand Signal + Slope Compensation Ramp
Blue = steady state inductor current
Red = perturbed inductor current

Ref 8

References

1/ The Right Half plane Zero, A Simplified Explanation, Dixon: https://www.ti.com/seclit/ml/slup084/slup084.pdf
2/ Fundamentals of Power Supply Design: Mammano: Texas Instruments, 2017
3/ SMPS compensation made easy, Sheehan: https://www.ti.com/seclit/ml/slup340/slup340.pdf
4/ Control Loop Cookbook, Dixon: https://www.ti.com/seclit/ml/slup113/slup113.pdf
5/ Compensation Design with TL431 for UCC28600: http://www.ti.com/lit/an/slua671/.pdf
6/ Designing with the TL431, Ridley: https://www.researchgate.net/publication/280308828_Designing_with_the_TL431_-_the_first_complete_analysis
7/ A more Accurate Current-Mode Control Model, Ridley: https://www.ti.com/seclit/ml/slup122/slup122.pdf
8/ Modelling, Analysis and Compensation of the Current Mode Converter: http://www.ti.com/lit/an/slua101/slua101.pdf
9/ Average Current Mode Control of Switching Power Supplies, Dixon: https://www.ti.com/seclit/ml/slup091/slup091.pdf
10/ Considerations for measuring loop gain in power supplies: https://www.ti.com/seclit/ml/slup386/slup386.pdf
11/ Fundamentals of Power Electronics: Erickson and Maksimovic, ISBN 0-7923-7270-0
12/ Modern Control Systems: Dorf, Addison Wesley, ISBN: 0-201-51713-2
13/ http://www.how2power.com/pdf_view.php?url=/newsletters/1204/articles/H2PToday1204_design_TexasInstruments.pdf
14/ http://venable.biz/uploads/files/01-Technical-Paper-Testing-Power-Sources-for-Stability.pdf

15/ https://en.wikipedia.org/wiki/Bicycle_and_motorcycle_dynamics

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End of Part 2

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