Control of SMPS – a Refresher

Part 1

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

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Concepts:

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)

Control:

- Measure the system
- Compare to reference
- Adjust appropriately


Control can be fun !

Ref 15

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

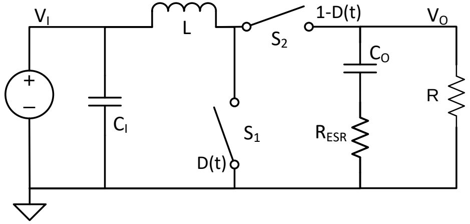
- System does not change with time
- Exceptions at power up, power down, OCP etc
- Switching action in power stage must be averaged

Continuous time assumed

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

Switching frequency does not appear in the transfer function !

SMPS are not linear and are not time invariant !



So we ‘cheat’ and build a model which is LTI ☺

- Linearisation
- State Space Averaging

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

Typical Buck Converter model

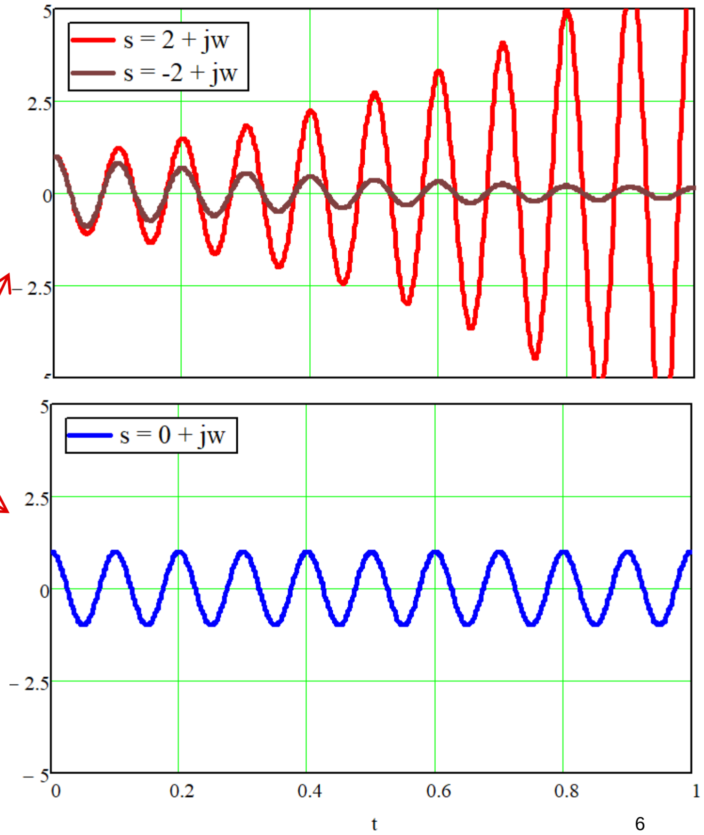
Concepts: Complex Frequency (s)

Complex Frequency: $s = \sigma + j\omega$

σ sets decay rate,

- $\sigma > 0$, increasing: $\sigma < 0$, decaying: $\sigma = 0$, steady state
- We set σ to 0 and so that $s = j\omega$
- 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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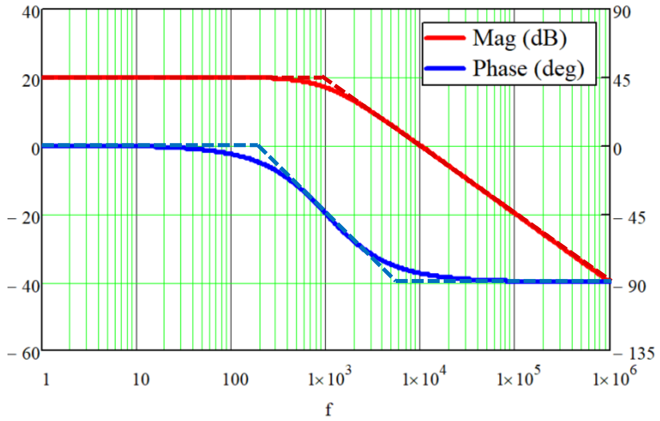
Transfer Functions: Bode Plots

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



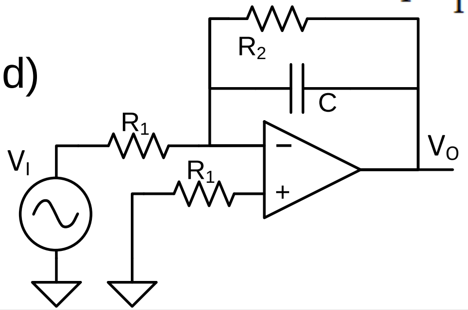
$$G(s) = \frac{-R_2}{R_1} \cdot \frac{1}{1 + \frac{s}{\omega_p}} \quad \text{where} \quad \omega_p = \frac{1}{R_2 \cdot C}$$

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)

Note

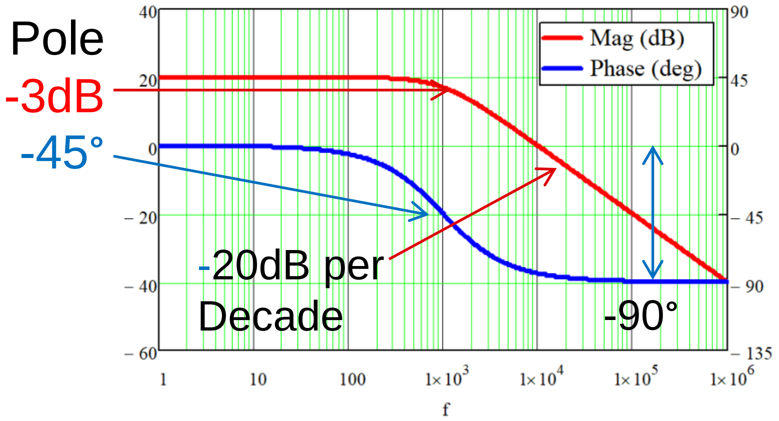
- Magnitude, Amplitude, Gain are equivalent



Transfer Functions: Poles

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

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



Pole

-3dB

-45°

-20dB per Decade

-90°

LF gain is -R2/R1

Gain rolls off at -20dB per decade above ω_0

Gain is flat below ω_0

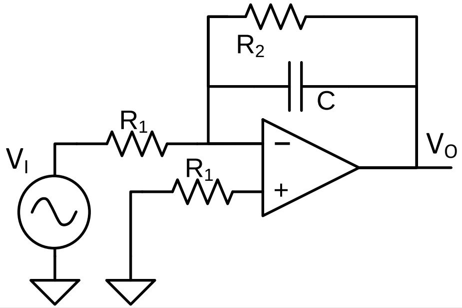
Phase flat below ω_0 /10 and above 10 ω_0

Phase is:

- 0° at LF
- -45° at ω_0
- -90° at HF

Gain is -3dB at ω_0

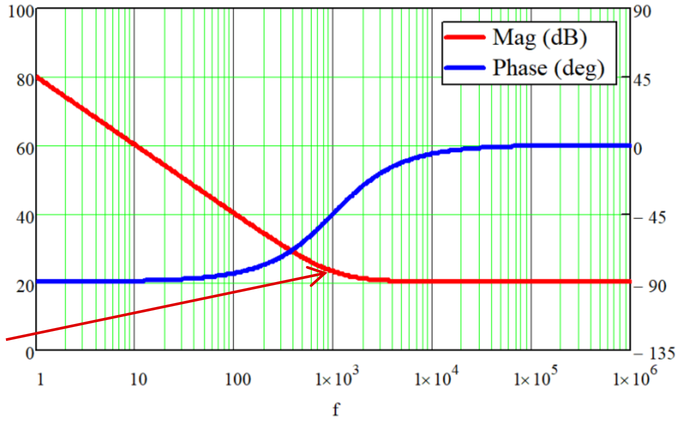
$$f_p = \frac{1}{2\pi\, R_2 C}$$



Transfer Functions: Zeros

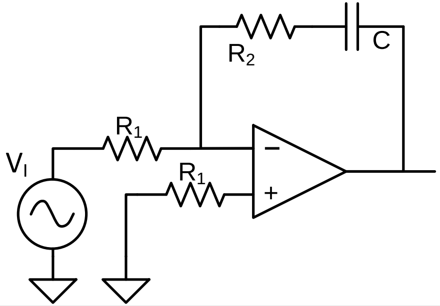
$$G(s) = \frac{-z_1}{z_2} = \frac{-\left(R_2 + \dfrac{1}{sC_1}\right)}{R_1} = \frac{-R_2}{R_1}\left(1 + \frac{1}{sCR_2}\right) = \frac{-R_2}{R_1}\left(1 + \frac{\omega_z}{s}\right)$$

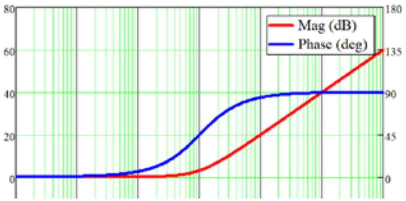
$$G(s) = \frac{-R_2}{R_1}\left(1 + \frac{\omega_z}{s}\right) \quad \text{where} \quad \boxed{\omega_z = \frac{1}{R_2 \cdot C}} \leftarrow \text{Zero}$$



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

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





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

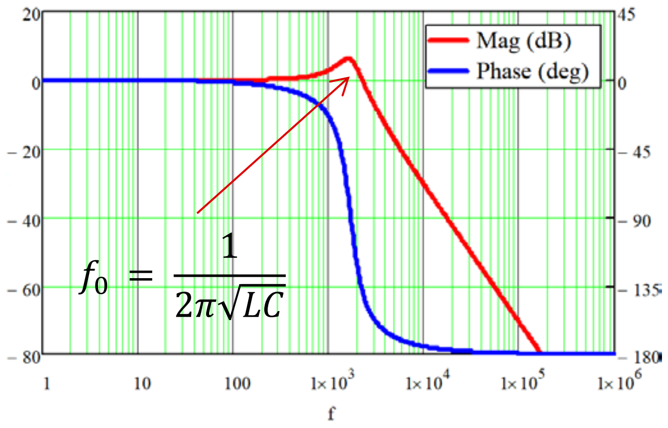
Alternative form

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:

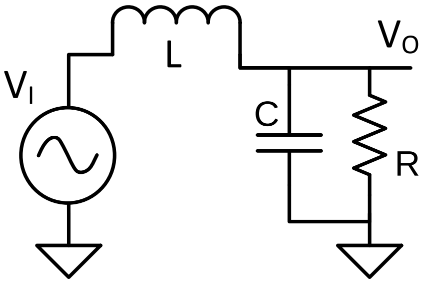
- 0° at LF
- -90° at ω_0
- -180° at HF



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

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

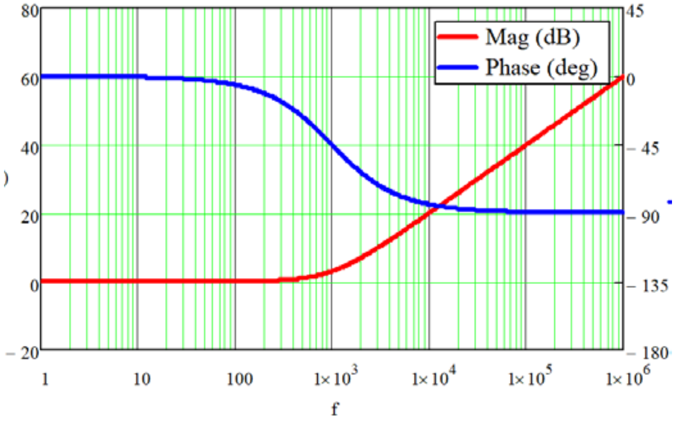
$$Q = \frac{R}{\sqrt{\frac{L}{C}}}$$



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).



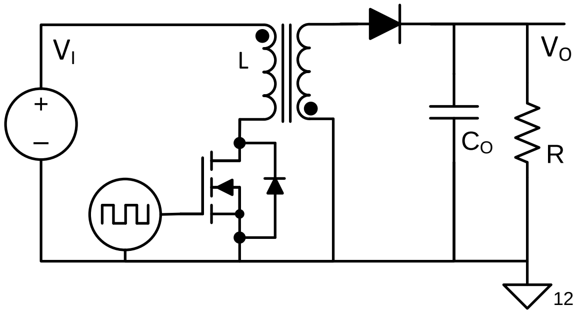
RHPZ: (Right Half Plane Zero)

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

- 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



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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

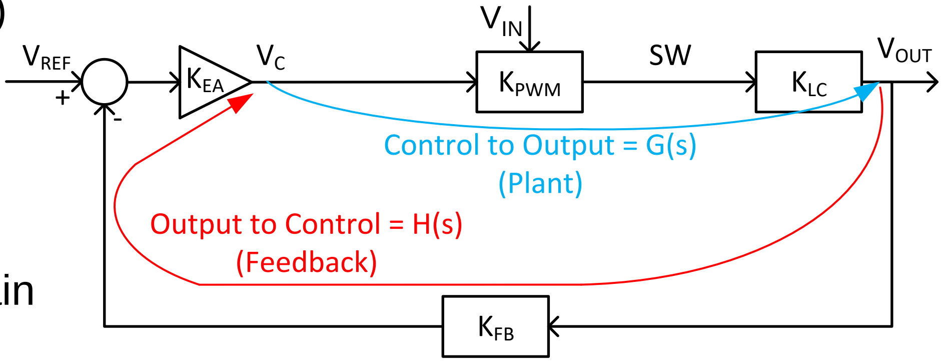
Hysteretic SMPS use Upper and Lower limits on VOUT

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

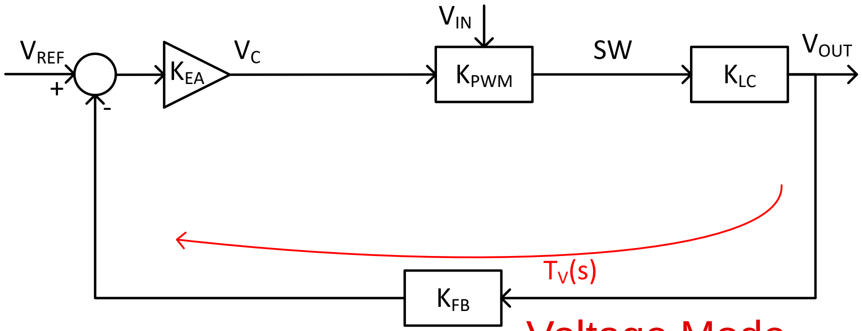
VMC:

- Error Amplifier controls Duty Cycle (D) directly

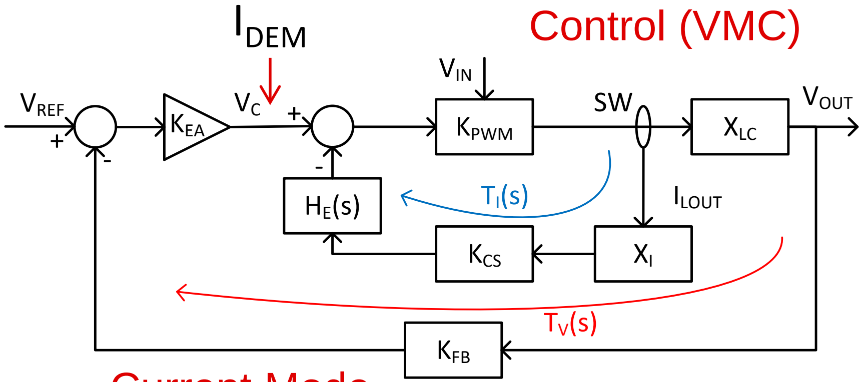
CMC:

- 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

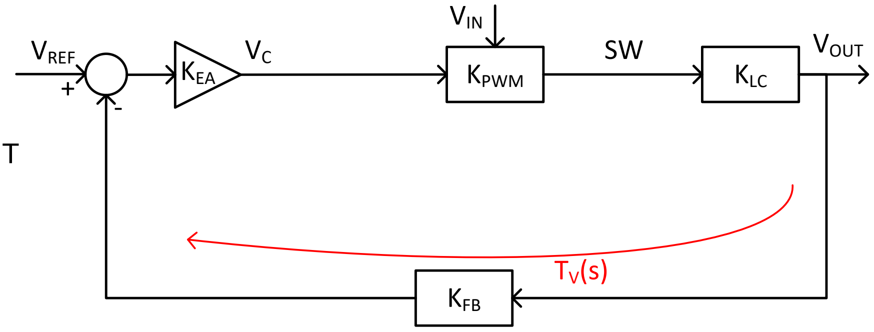


Voltage Mode Control (VMC)



Current Mode Control (CMC)

Control Systems: Voltage Mode Control



Error amplifier output V_C controls D directly

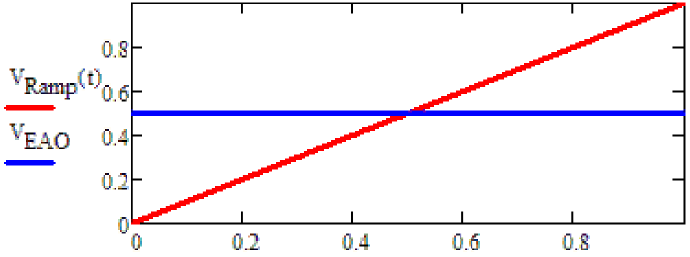
V_{OUT} drops → V_C increases → D increases → V_{OUT} increases

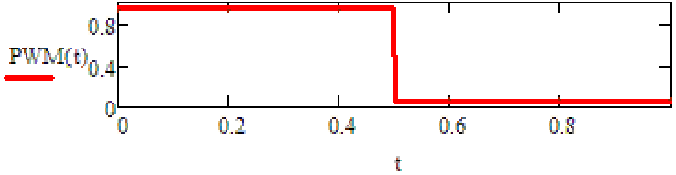
Less noise sensitive than PCM – larger ramp

Easy to implement Voltage Feed Forward

Output Filter appears in the transfer function so

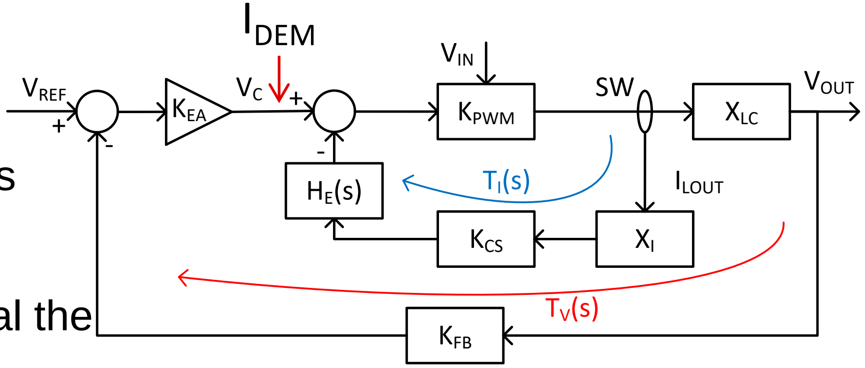
- Control loop bandwidth is lower than with CMC
- More difficult to stabilise than CMC
- Type 3 Compensation (more on this later)





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.

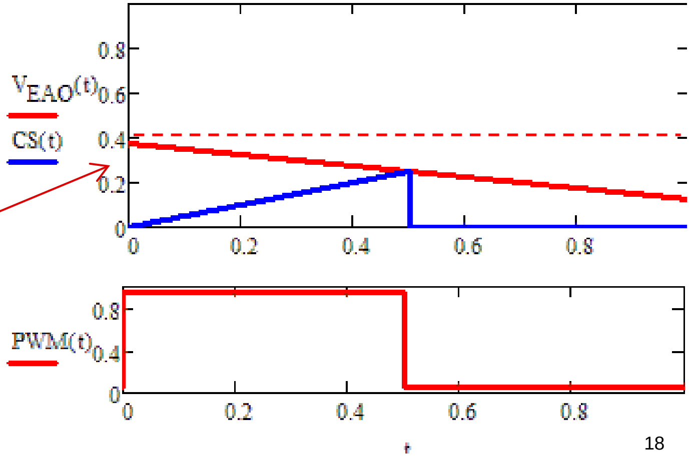
V_{OUT} drops → V_C (I_{DEM}) increases, I_{OUT} increases → V_{OUT} increases

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

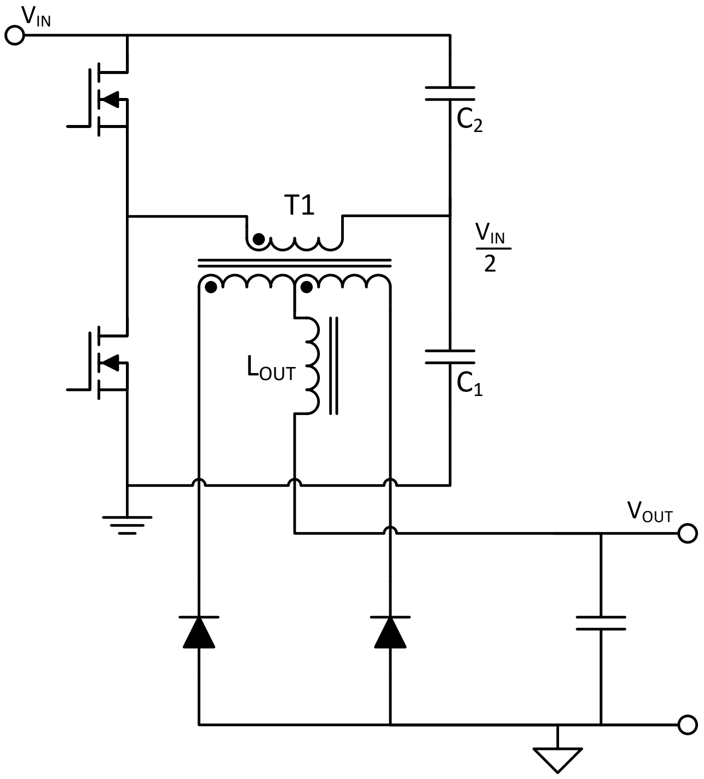
Described in Ref 13

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



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

Control of SMPS – a Refresher

End of Part 1

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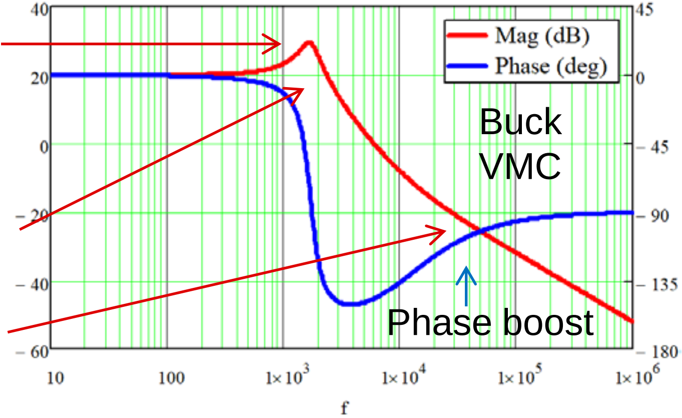
Control to Output Transfer Function: G(s)

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

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

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

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

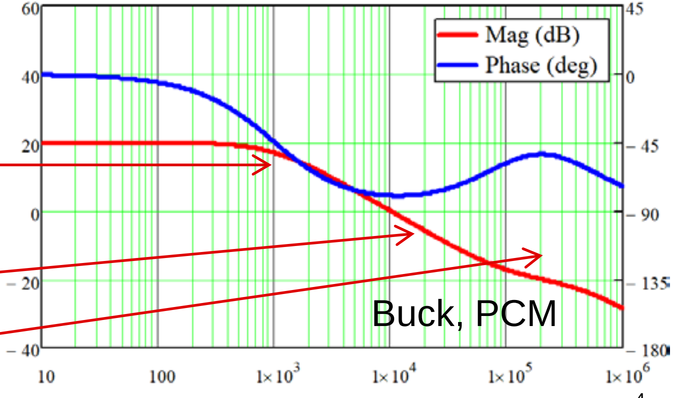


- Buck Converter in Peak Current Mode
- First order characteristic
- Phase boost, zero of ESR and Cout
- Type 2 compensation (more later)
- Ref 3

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

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

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



Control to Output Transfer Function: G(s)

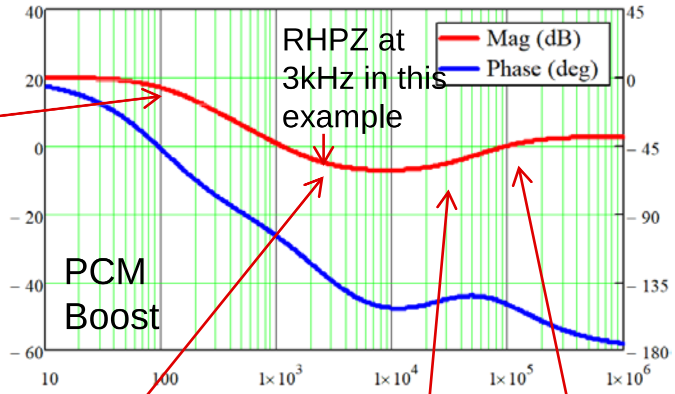
$$G(s) = \frac{V_{OUT}}{V_C} = K_{PWM} * K_{LC}(s)$$

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

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)



RHPZ at 3kHz in this example

PCM Boost

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

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

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

Remember - RHPZ: Gain increasing Phase decreasing

- Severely limits the control bandwidth

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

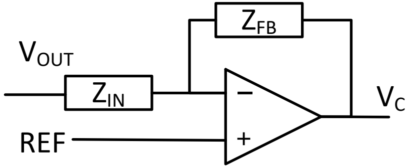
- 180deg phase shift at DC for negative feedback
- High gain at DC, for good regulation
- High loop bandwidth, for good transient response (except PFC)
- Adequate gain and phase margins, for stability

  PM > 45° at 0dB gain

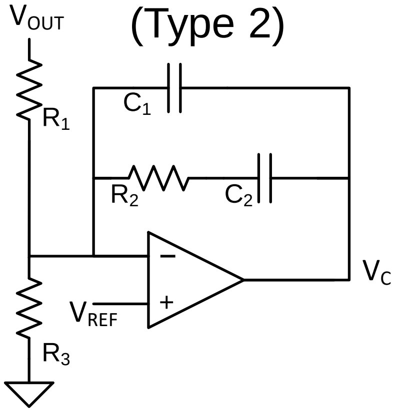
Need to reduce gain to less than 1 before ≈ fsw/10

- 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)



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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,

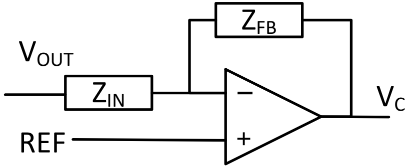
- phase boost up to 180°

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



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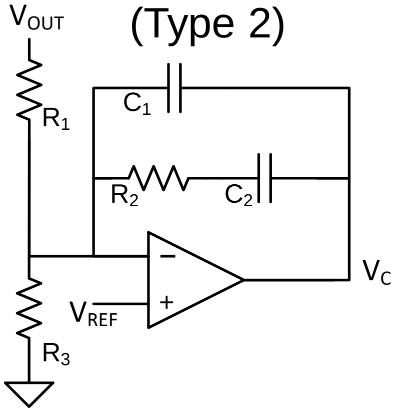


Loop Response: Requirements for Stability

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

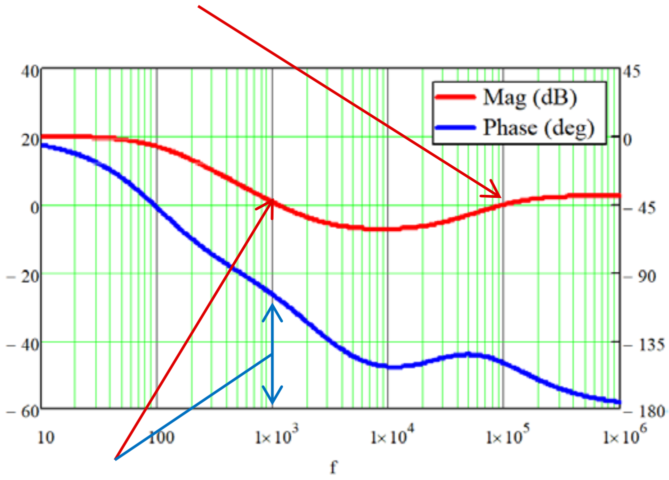
For Stability

- 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

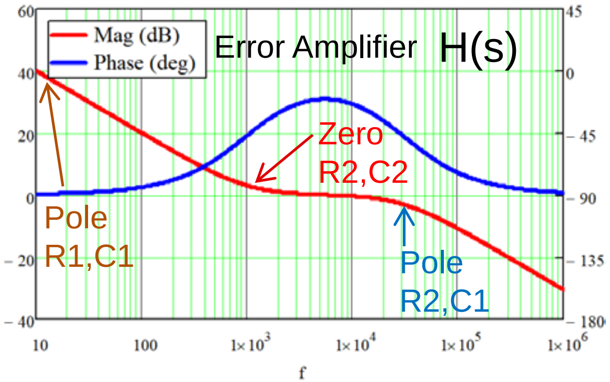
Need to reduce gain to less than 0dB before ≈ fsw/10



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

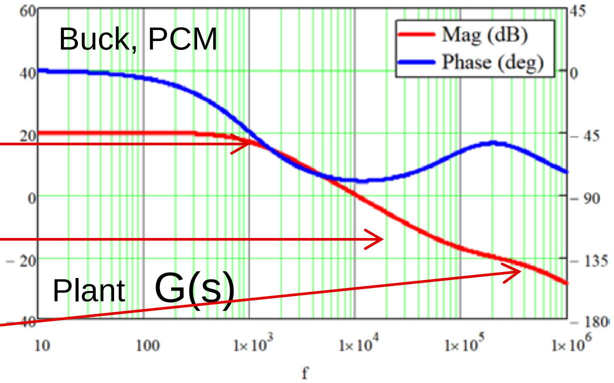


LF Pole

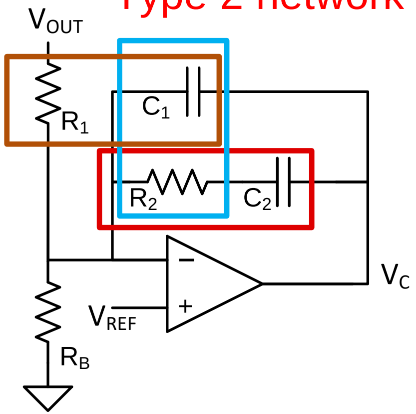
$$\omega_{p1} = \frac{1}{C_{OUT} \cdot R_{OUT}}$$

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

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

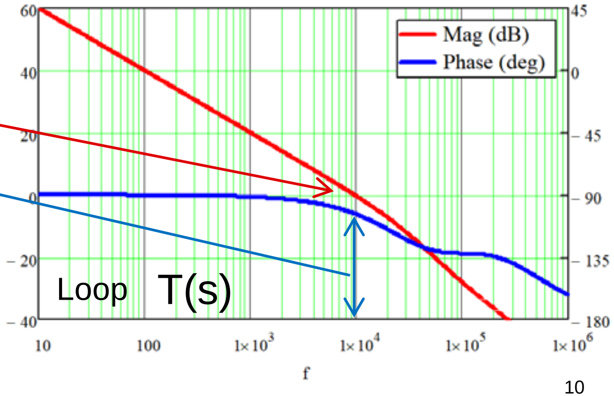


Type 2 network

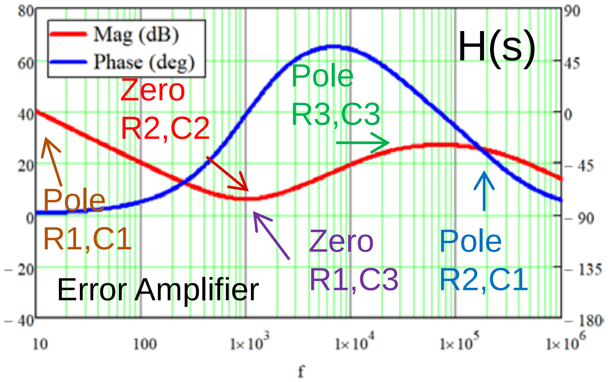


- Loop crossover at 10kHz
- Approx. 76° phase margin
- Inverting input is virtual ground
- R_B attenuates Vout only

Ref 3



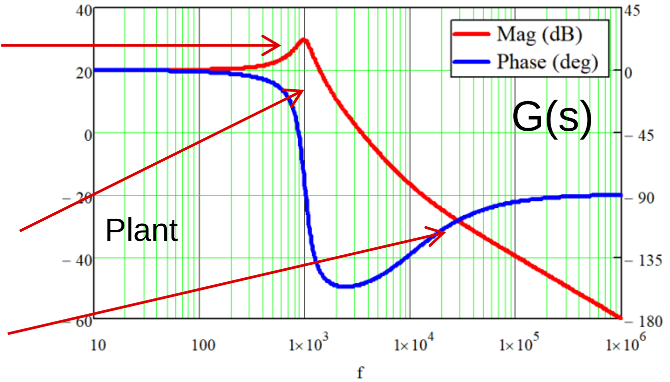
Loop Response: T(s) = H(s)G(s), Buck VMC



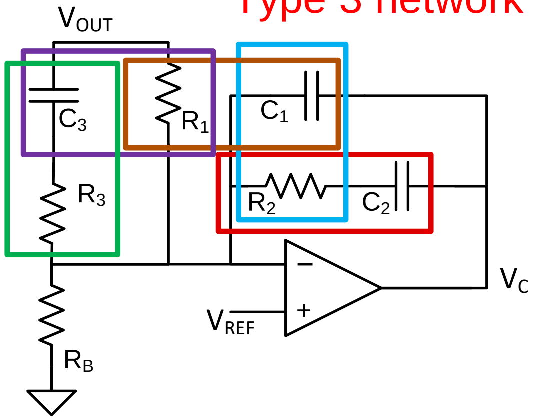
$$Q_0 = \frac{R_{OUT}}{\sqrt{\frac{L_{OUT}}{C_{OUT}}}}$$

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

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

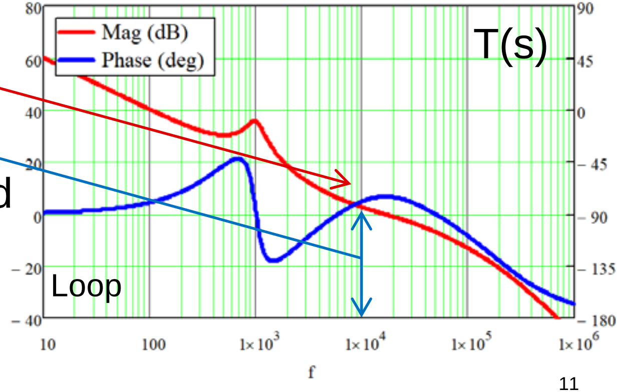


Type 3 network



- 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

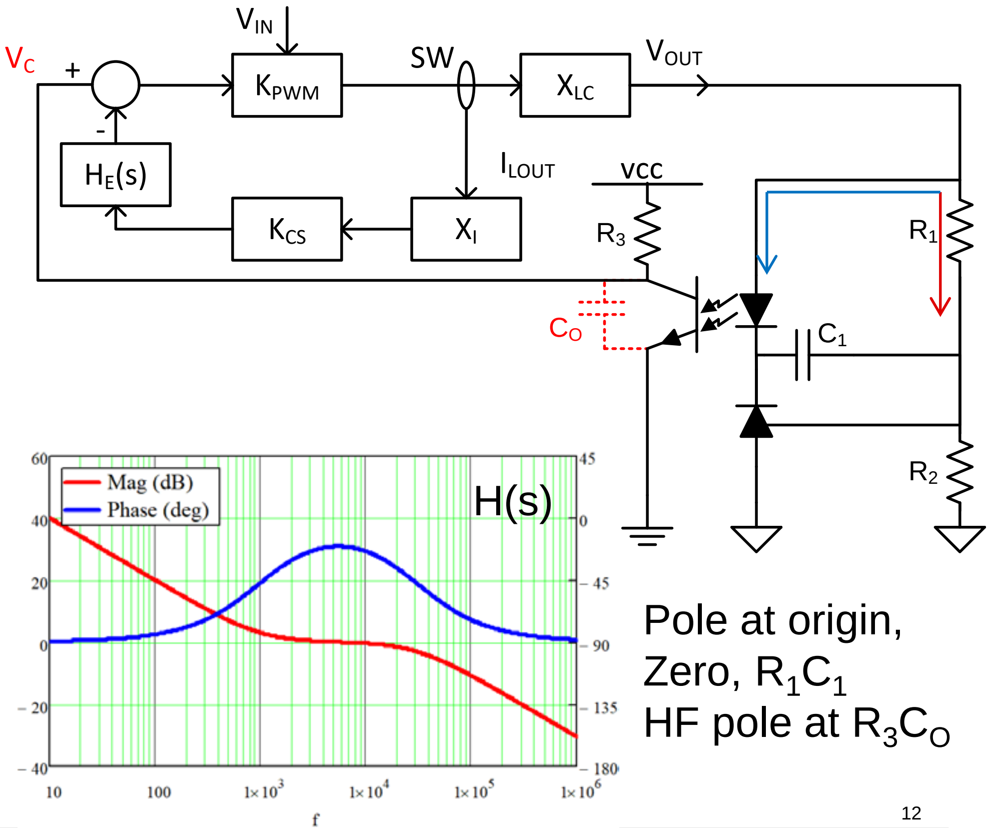
Type 2 compensator shown here,

- 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)

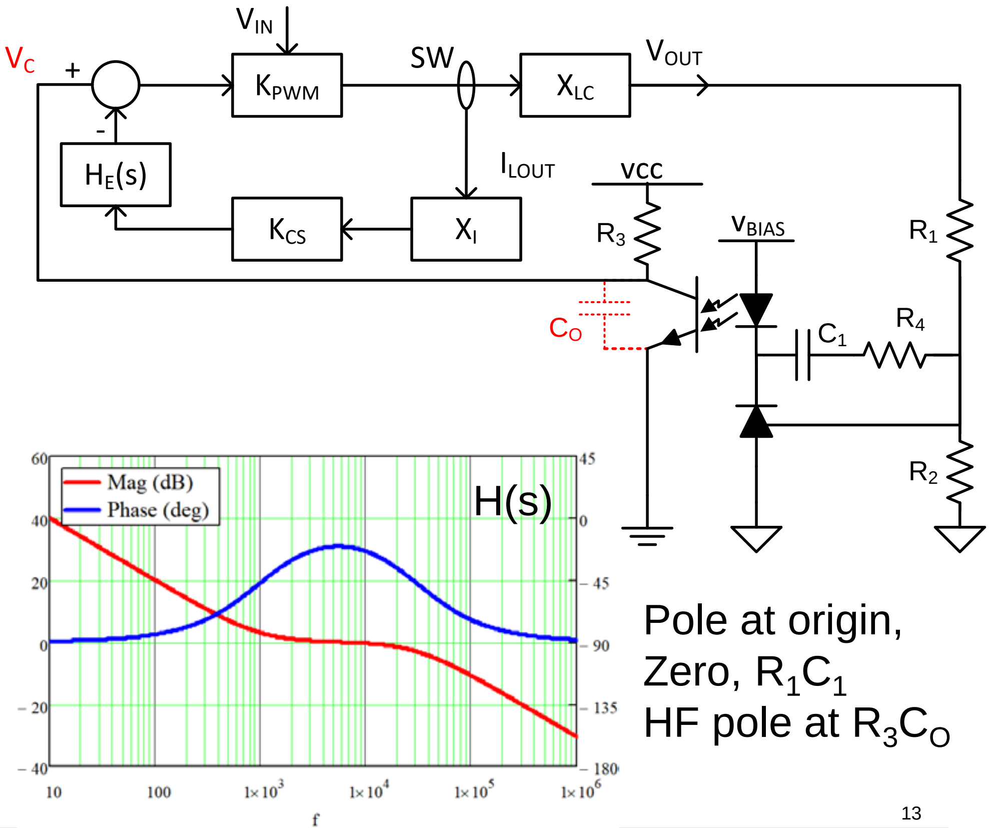
- Connect LED to a fixed bias rail.

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.

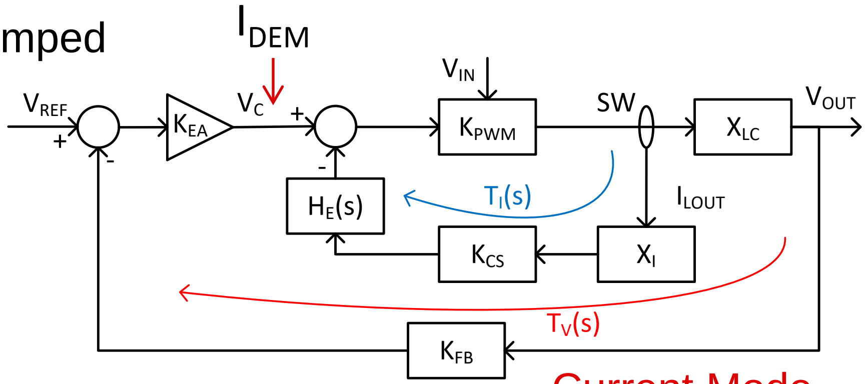
Fix an operating point (Constant I_{DEM}), inject the signal in series with the CS resistor, measure the gain and phase vs frequency

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

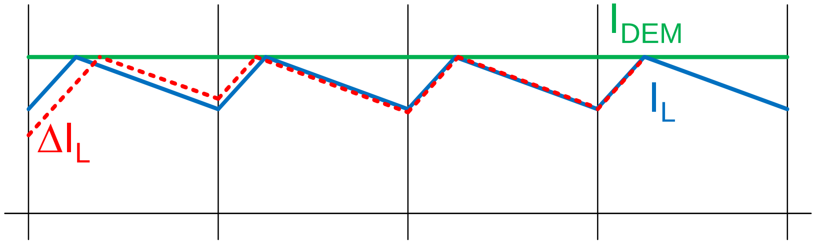
Sub-Harmonic Oscillations: Instability

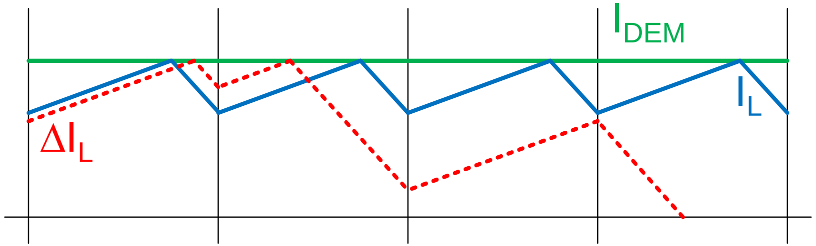
D < 50%, perturbation in inductor current (dotted) dies away.

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

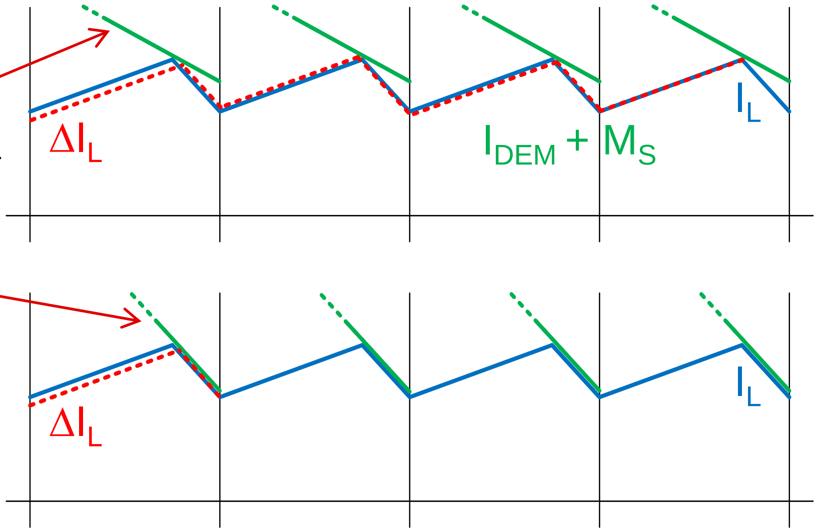
Slope Compensation Ramp stabilises the system

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

Control of SMPS – a Refresher

End of Part 2

Colin Gillmor (APP, HPC)

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Control of SMPS – a Refresher

Part 3

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

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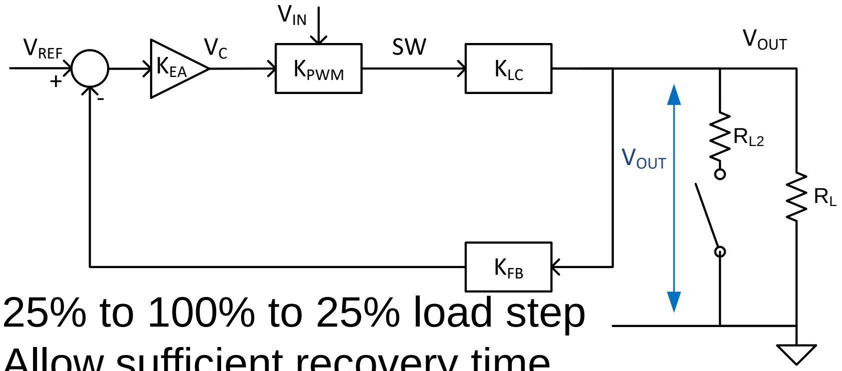
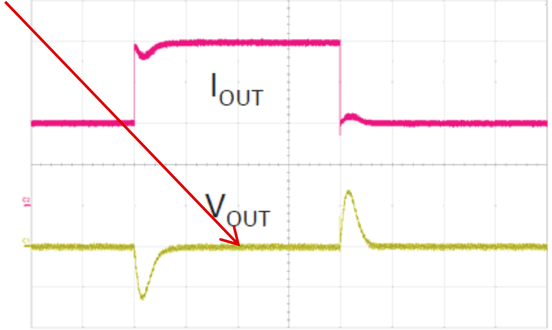
Measuring the control loop:

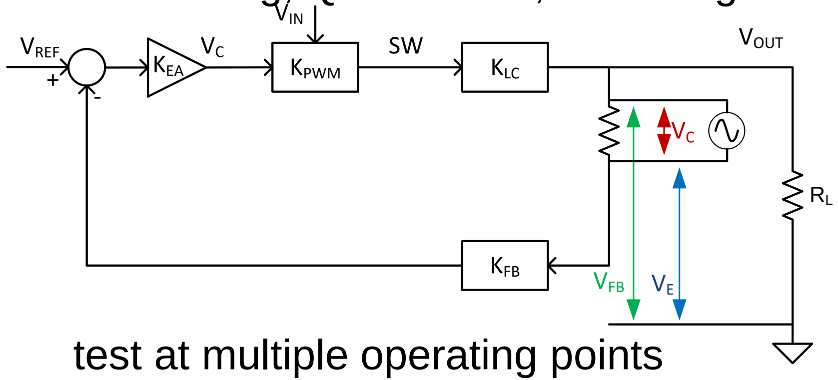
Transient Response
Quick, Qualitative, Large Signal



25% to 100% to 25% load step
Allow sufficient recovery time

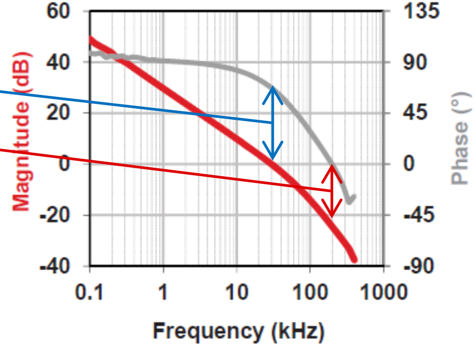


Loop Response
Time Consuming, Quantitative, Small Signal



test at multiple operating points

Loop b/w 30kHz
Phase Margin ≈ 60°
Gain Margin ≈ 20 dB



Laplace Transform →

← Inverse Laplace Transform

Measuring the control loop: Bode Plot

Signal injection:
Isolation transformer couples test signal into circuit

- Wide bandwidth – typ 100Hz to 100kHz

Signal injection location must be chosen carefully

- Low Z looking ‘back’ into the loop, $Z_2(s)$
- High Z looking ‘forward’ around the loop, $Z_1(s)$

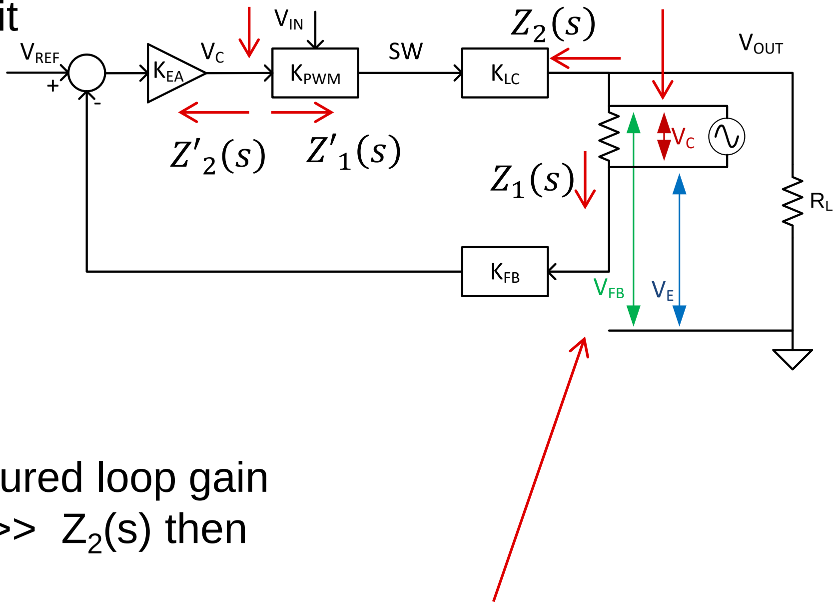
$$T(s) = M(s) * \frac{Z_1(s)}{Z_1(s) + Z_2(s)}$$

Where T(s) is the true loop gain, M(s) is the measured loop gain
$Z_1(s)$ and $Z_2(s)$ are difficult to quantify but if $Z_1(s) >> Z_2(s)$ then

$$T(s) \approx M(s)$$

Signal Injection point alternate.

Signal Injection point preferred

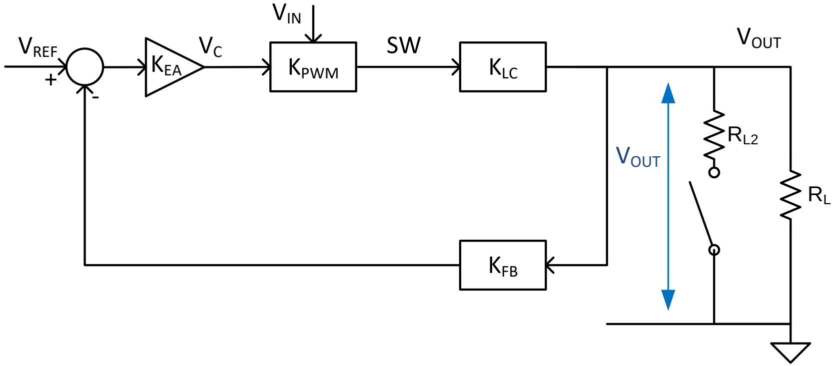


In series with K_{FB} is ideal but meters may limit use at high Vout

Ref 10, Ref 14

Measuring the control loop: Transient Response

Transient Response
Quick, Qualitative, Large Signal



Fourier transform of a step waveform contains components at all frequencies.

Large amplitude Load change

- Typically 25% to 75% to 25% load steps
- 0% to 100% to 0% load steps are also used
-

Load di/dt must be significantly faster than the loop response.

- Electronic Load step function
- Resistor with MOSFET switch

Signal amplitude can be 'buried' in noise

- Apply repeated transients and average the result

Measuring the control loop

Formal relationship between Gain/Phase plot and Transient Response (LTI system)

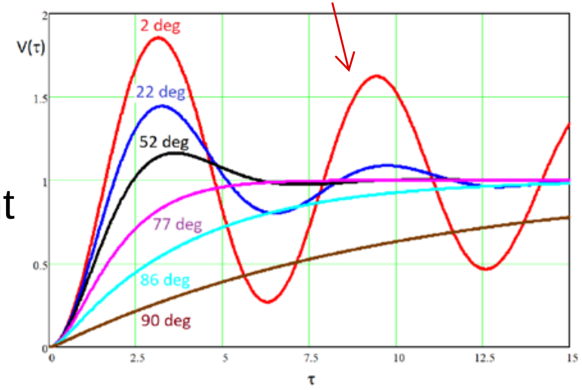
Phase Margin can be estimated from the shape of the transient response

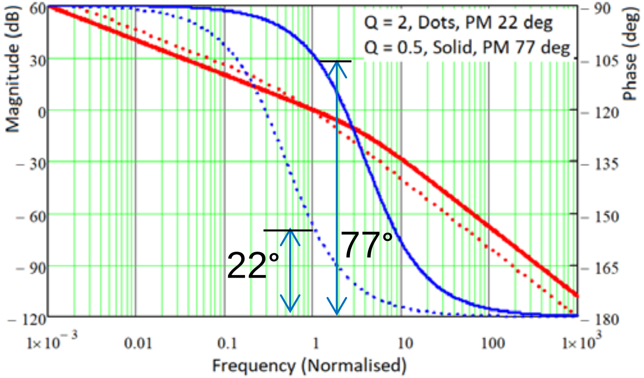
Plots here are normalised to a crossover at 1Hz

Underdamped transient response implies small phase margin

Loop stability can be estimated from a load transient test

Oscillation at crossover frequency of the loop (approx.)





Ref 11, PP342

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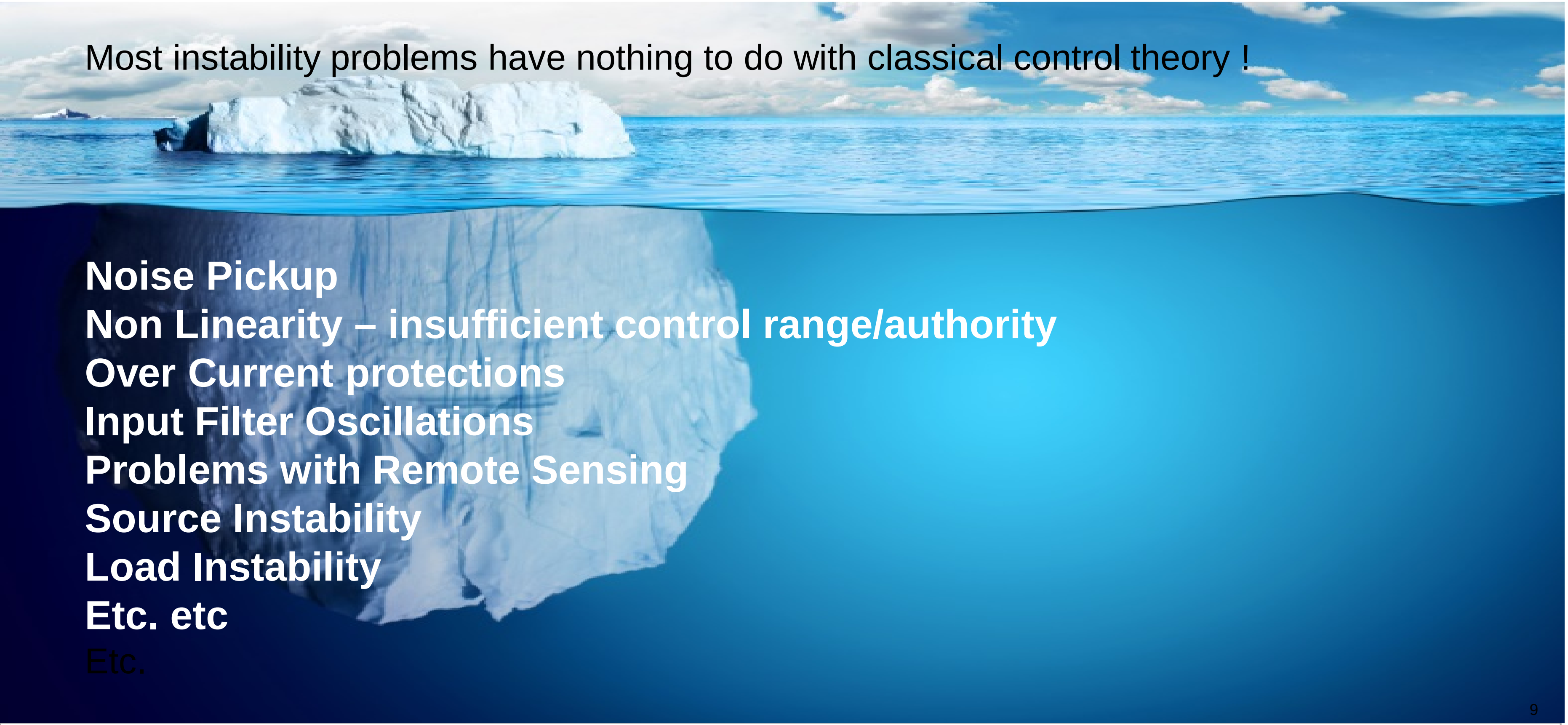
The Iceberg Analogy



Most instability problems have nothing to do with classical control theory !

Noise Pickup
Non Linearity – insufficient control range/authority
Over Current protections
Input Filter Oscillations
Problems with Remote Sensing
Source Instability
Load Instability
Etc. etc
Etc.

Control of SMPS: Summary

Control theory is sometimes thought to be difficult to understand

- Complex Mathematics, Complex Frequency, Laplace Transform, Poles, Zeros etc etc
- An intuitive overview is possible without too much complexity

SMPS control

- Voltage Mode:
- Current Mode: Peak Current Mode, Average Current Mode

Loop Transfer Functions

- Control to Output: G(s), Output to Control: H(s), Complete Loop
- Loop Compensation: Type 1, Type 2, Type 3

Testing

- Gain Phase Measurements (Bode Plot), Transient Tests, Evaluation of results.

References

Control of SMPS – a Refresher:

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Control to Output: $G(s)$	Power Stage (Plant)
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References

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Control of SMPS – a Refresher

End of Part 3

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