

LCC Converter Small Signal Modeling

Brent McDonald

Introduction

- Demanding efficiency requirements are driving engineers to the LLC resonant converter

80 PLUS Certification	115 V Internal Non-Redundant				230 V Internal Redundant			
	% of Rated Load	10%	20%	50%	100%	10%	20%	50%
80 PLUS	–	80%	80%	80%	N/A			
80 PLUS Bronze	–	82%	85%	82%	–	81%	85%	81%
80 PLUS Silver	–	85%	88%	85%	–	85%	89%	85%
80 PLUS Gold	–	87%	90%	87%	–	88%	92%	88%
80 PLUS Platinum	–	90%	92%	89%	–	90%	94%	91%
80 PLUS Titanium	–	–	–	–	90%	94%	96%	91%

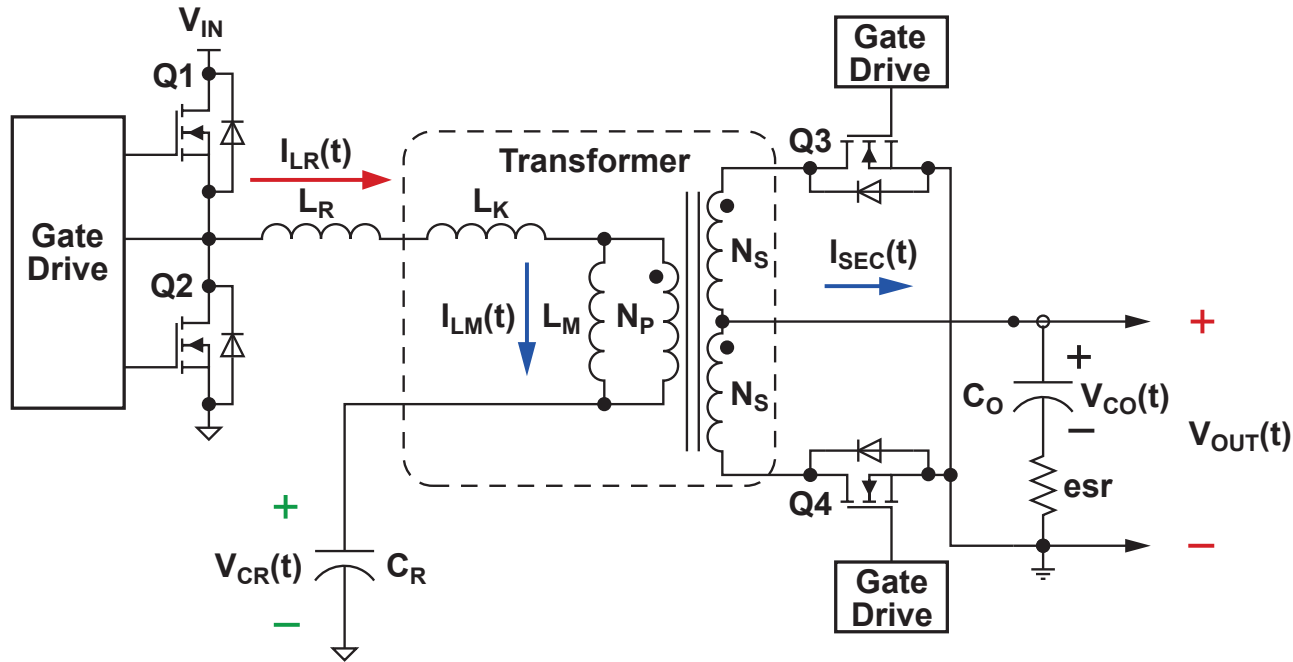
Courtesy: <http://www.plugloadsolutions.com/80PlusPowerSupplies.aspx>

- How do we identify and verify a robust set of compensation values for this converter?

Discussion Outline

- LLC Converter
- Modeling Process
- Case Study
- Tools
- Practical Limitations
- Conclusion

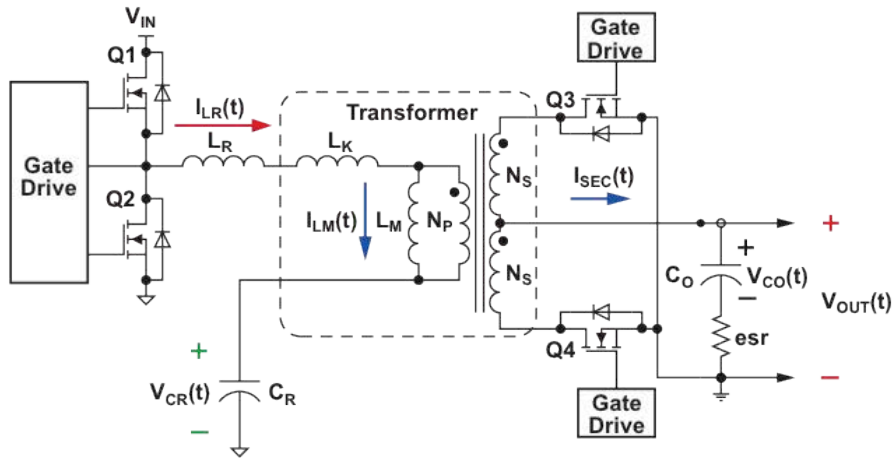
Operating States



State Variables	
$I_{LR}(t)$	
$I_{LM}(t)$	
$V_{CR}(t)$	
$V_{CO}(t)$	

State	Q1	Q2	Q3	Q4
1	ON	OFF	OFF	ON
2	ON	OFF	ON	OFF
3	ON	OFF	OFF	OFF
4	OFF	ON	OFF	ON
5	OFF	ON	ON	OFF
6	OFF	ON	OFF	OFF

Mode: Resonance

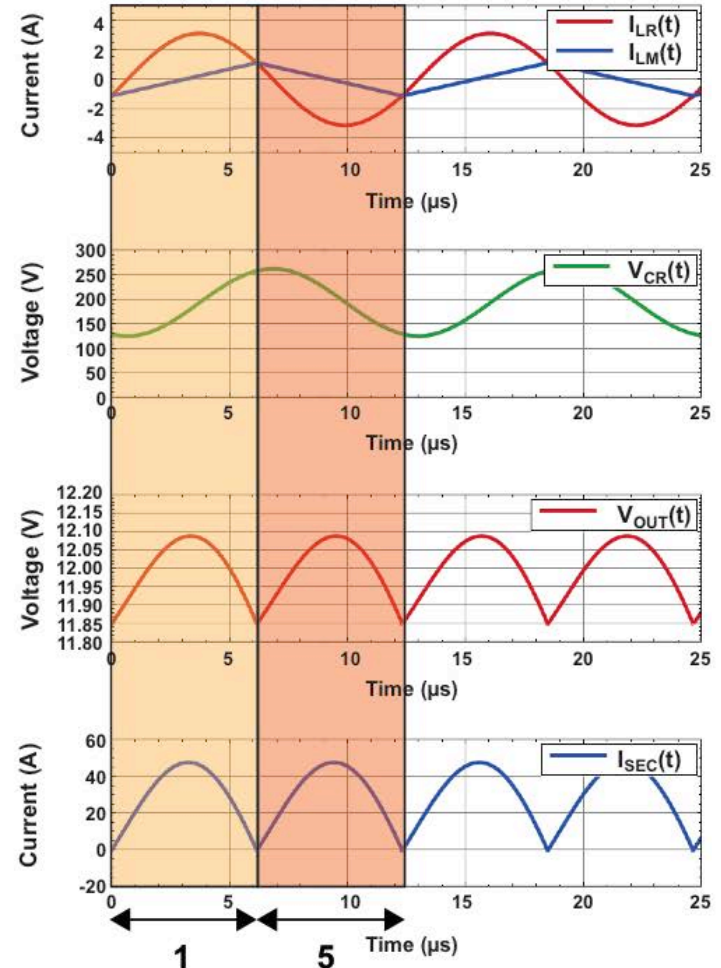


Mode State Sequence: 1 → 5

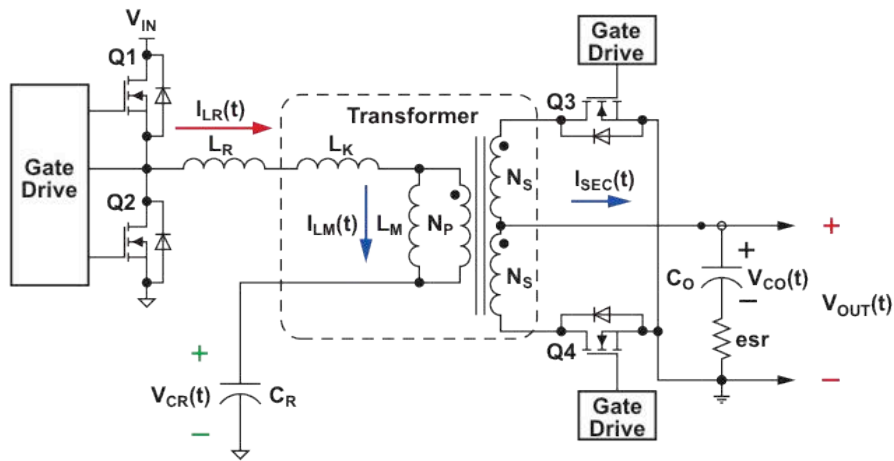
State	Q1	Q2	Q3	Q4
1	ON	OFF	OFF	ON
2	ON	OFF	ON	OFF
3	ON	OFF	OFF	OFF
4	OFF	ON	OFF	ON
5	OFF	ON	ON	OFF
6	OFF	ON	OFF	OFF

$V_{IN} = 387.6 \text{ V}$

LLC Resonant Tank Waveforms

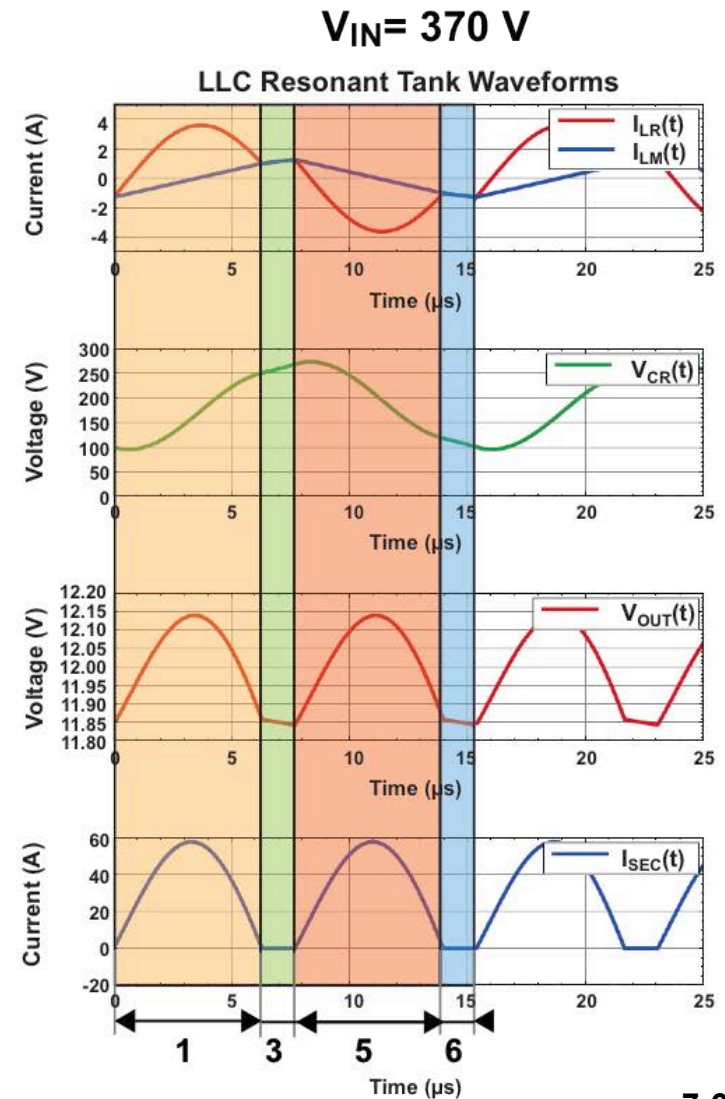


Mode: Below Resonance

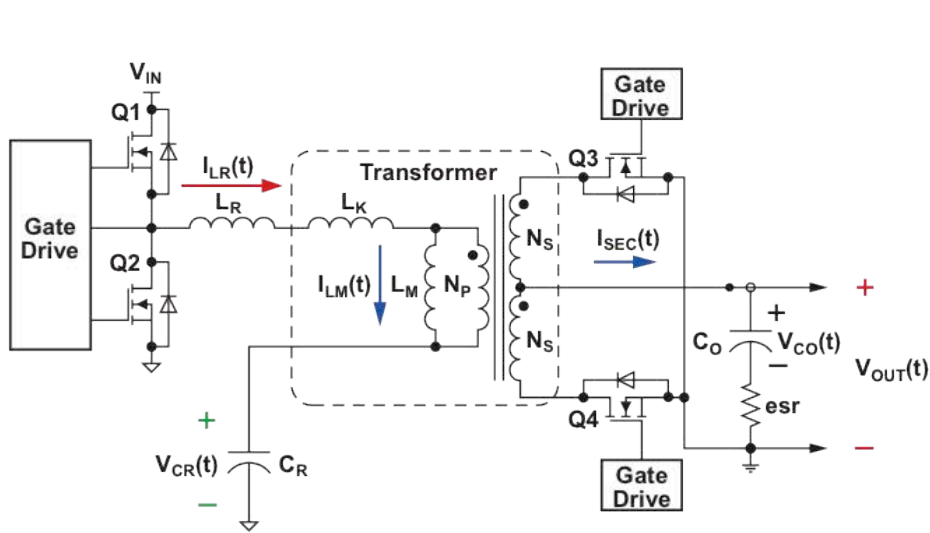


Mode State Sequence: 1 → 3 → 5 → 6

State	Q1	Q2	Q3	Q4
1	ON	OFF	OFF	ON
2	ON	OFF	ON	OFF
3	ON	OFF	OFF	OFF
4	OFF	ON	OFF	ON
5	OFF	ON	ON	OFF
6	OFF	ON	OFF	OFF

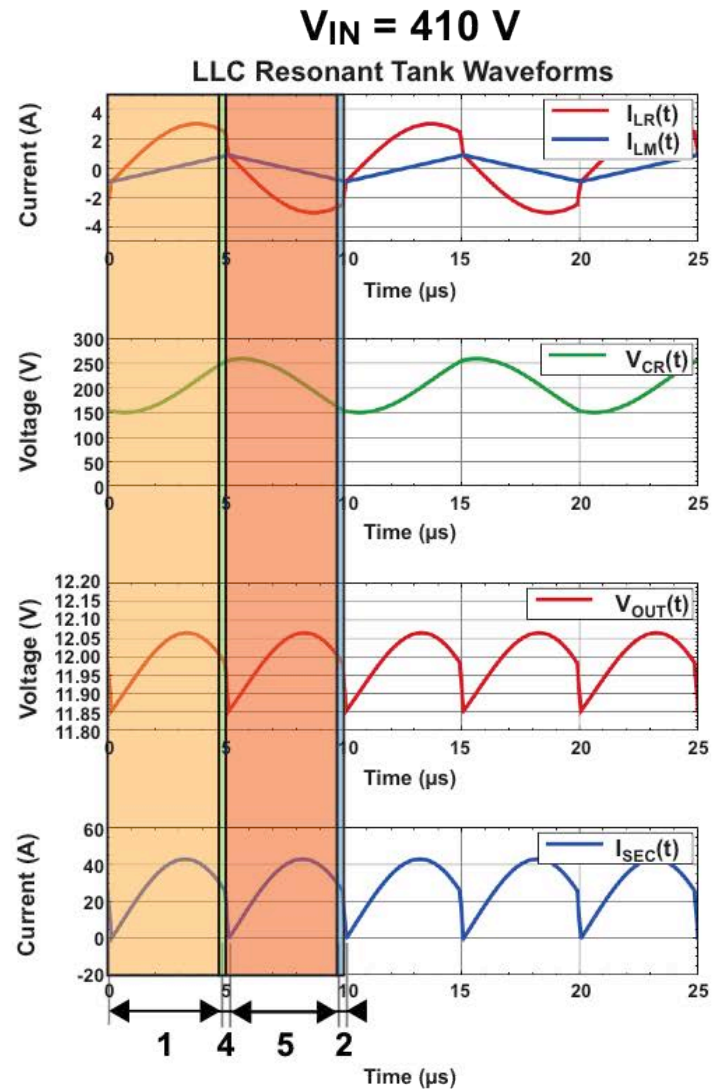


Mode: Resonance



Mode State Sequence: 1 → 4 → 5 → 2

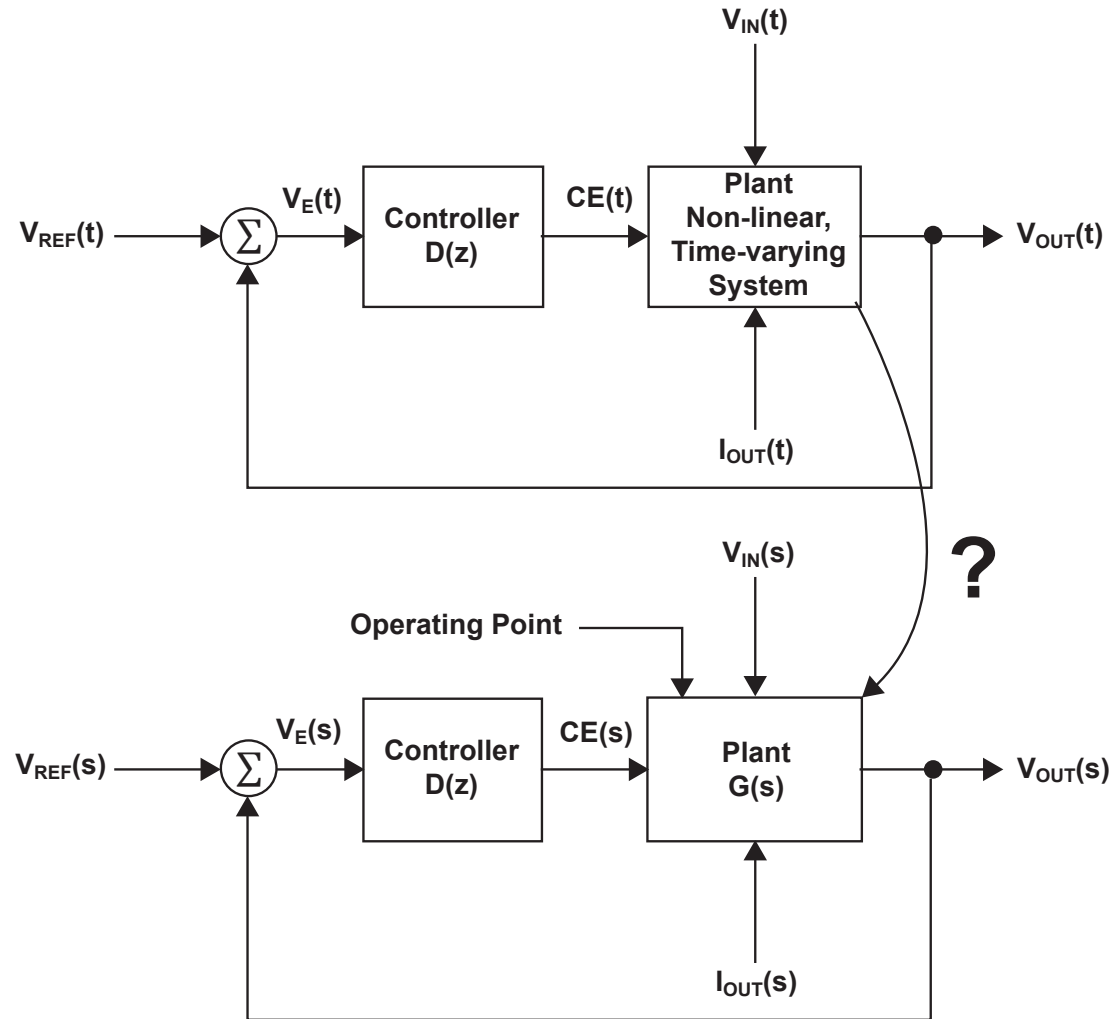
State	Q1	Q2	Q3	Q4
1	ON	OFF	OFF	ON
2	ON	OFF	ON	OFF
3	ON	OFF	OFF	OFF
4	OFF	ON	OFF	ON
5	OFF	ON	ON	OFF
6	OFF	ON	OFF	OFF



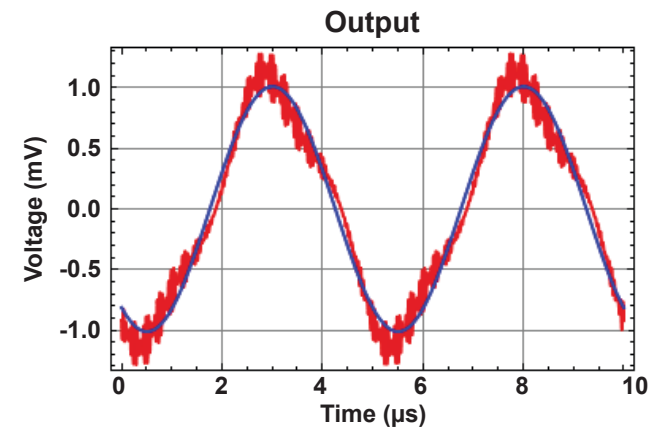
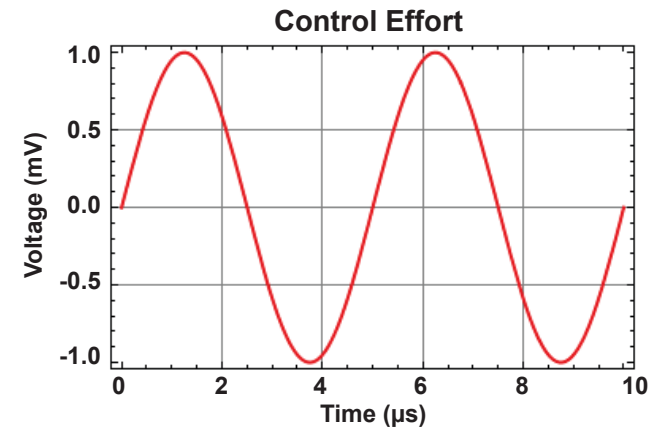
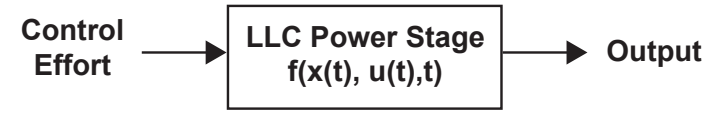
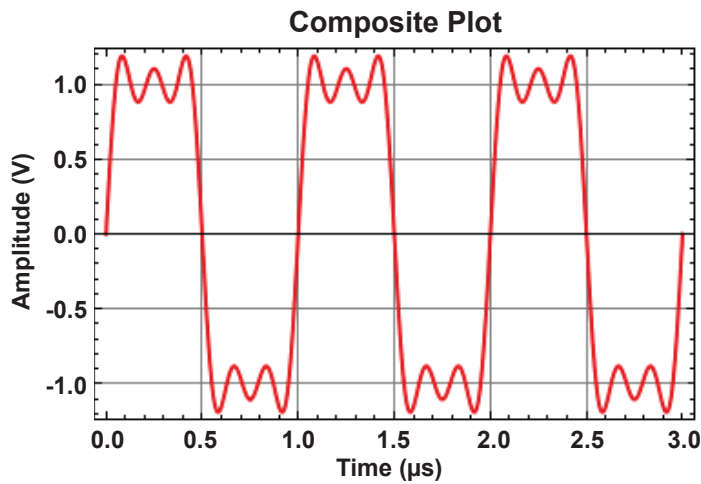
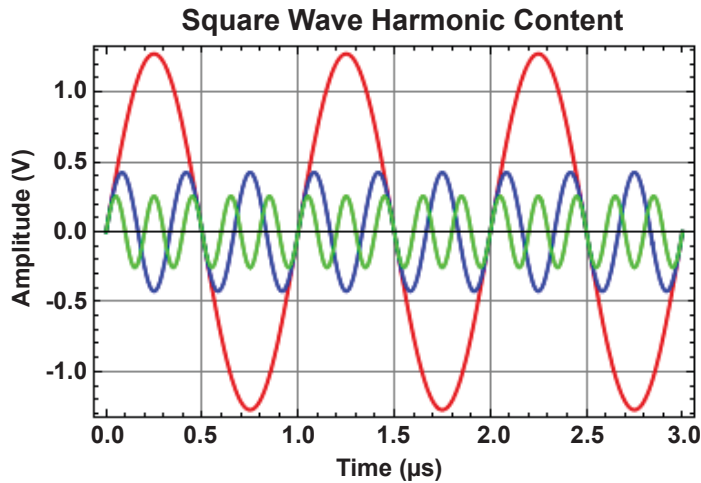
Modeling Process Overview

Fundamental Steps

1. Identify the states and modes used
2. Average the states for the identified mode
3. Calculate DC operating point
4. Linearize the result

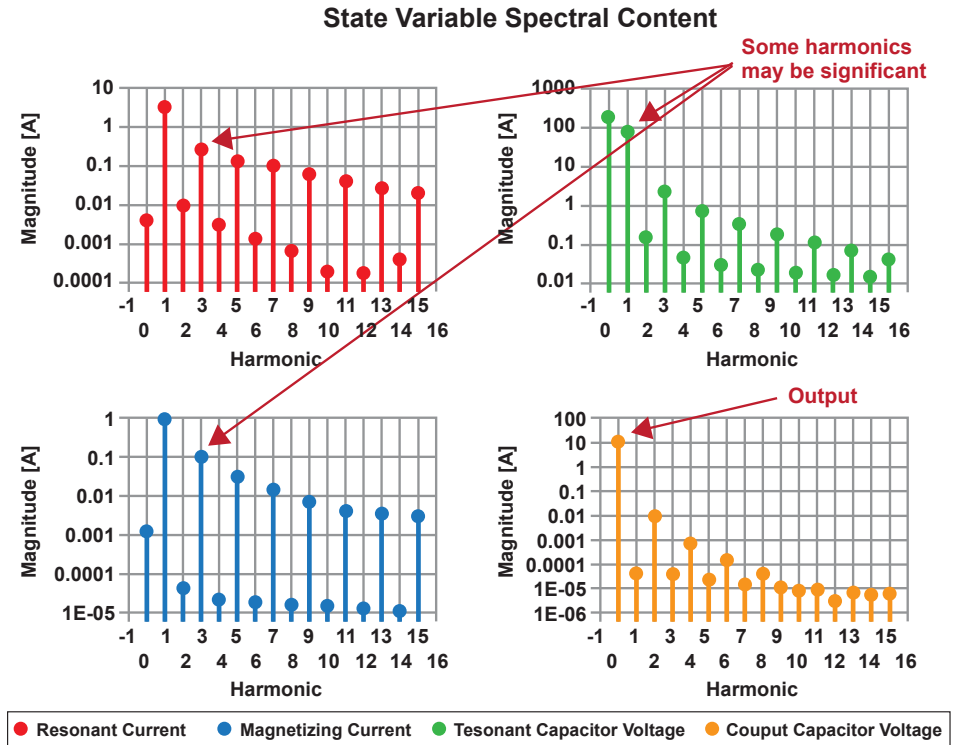
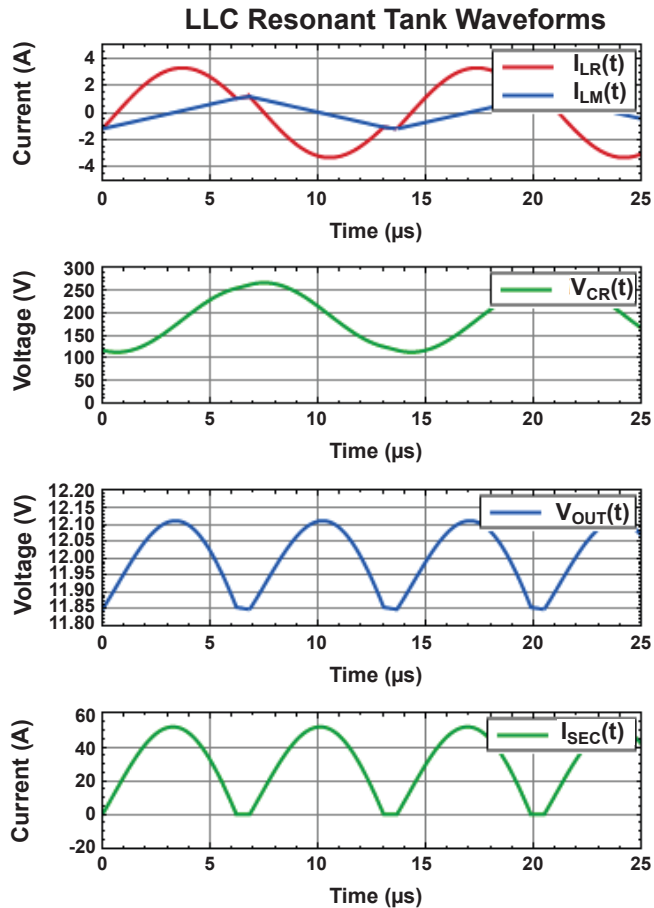


Fourier Series



— Raw Output
— Describing Function Output

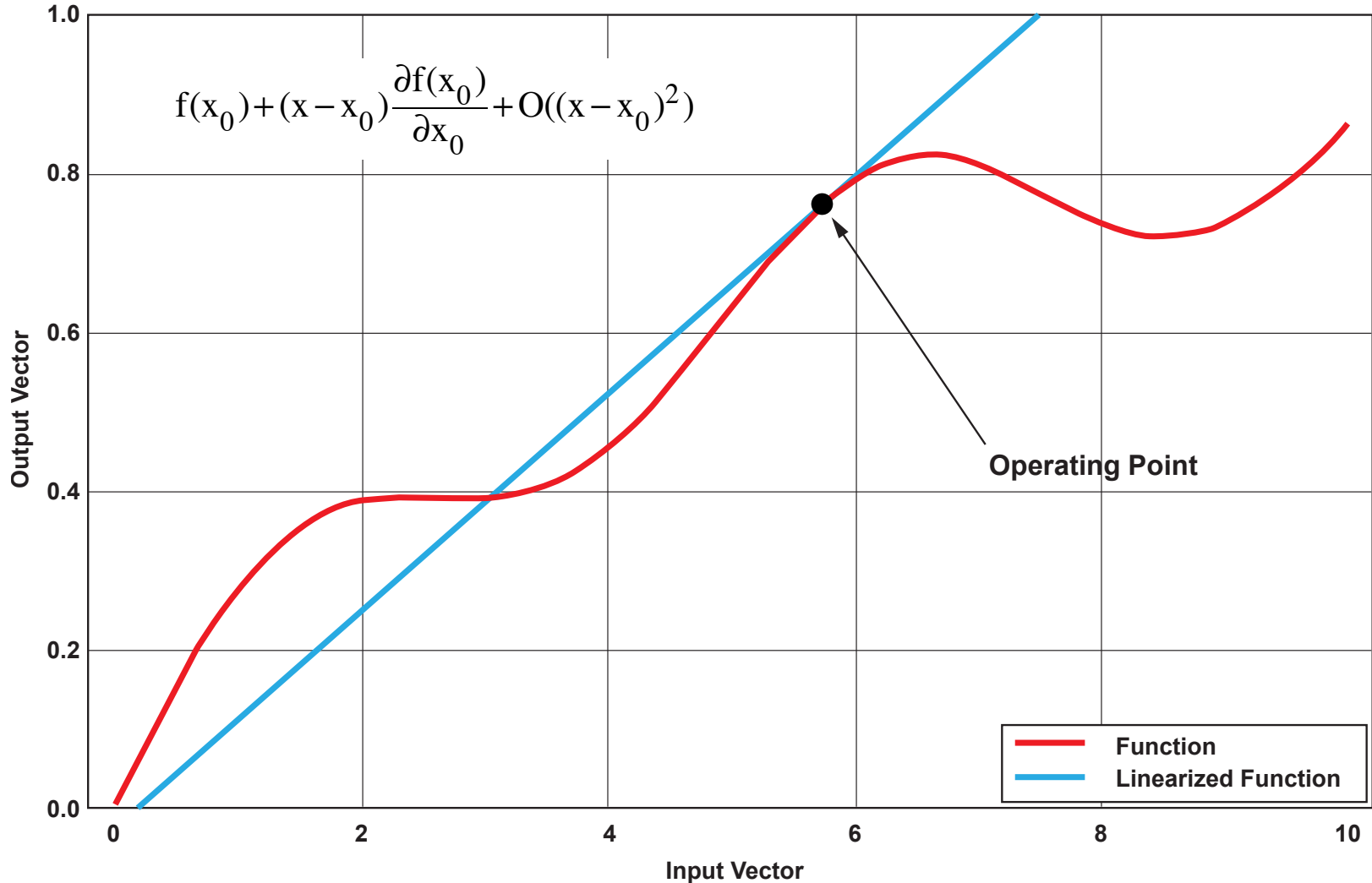
Spectral Considerations



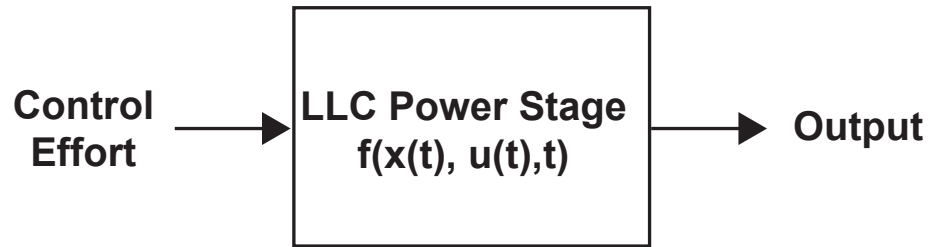
State Variable	Harmonic's Included
$i_{LR}(t)$	1, 3, 5, 7, 9, 11
$i_{LM}(t)$	1, 3, 5, 7
$V_{CR}(t)$	0, 1, 3, 5, 7
$V_{C_{OUT}}(t)$	0

Linearization

Model Linearization



Describing Function Analysis



- **Linear System**
 - $\dot{x}(t) = A \cdot x(t) + B \cdot u(t)$
 - $y(t) = C \cdot x(t) + D \cdot u(t)$
- **Non-Linear System**
 - $\dot{x}(t) = f(x(t) + u(t), t)$
 - $y(t) = g(x(t) + u(t), t)$

$$x^{ss}(t) = X_0^{ss} + \sum_{k=1}^{\infty} \left(X_{ck}^{ss} \cdot \cos(k \cdot \omega_s \cdot t) + X_{sk}^{ss} \cdot \sin(k \cdot \omega_s \cdot t) \right)$$

$$F_{s_k}^{ss} = \frac{2}{T_s} \cdot \sum_{i=1}^Q \int_{T_{i-1}}^{T_i} (A_i \cdot x(t)^{ss} + B_i \cdot U_0) \cdot \sin(k \cdot \omega_s \cdot t) \cdot dt$$

$$F_{c_k}^{ss} = \frac{2}{T_s} \cdot \sum_{i=1}^Q \int_{T_{i-1}}^{T_i} (A_i \cdot x(t)^{ss} + B_i \cdot U_0) \cdot \cos(k \cdot \omega_s \cdot t) \cdot dt$$

Steady State Operating Point

- **LLC + C_{OUT} ⇒ fourth order system**

- **Piecewise linear simulation:**

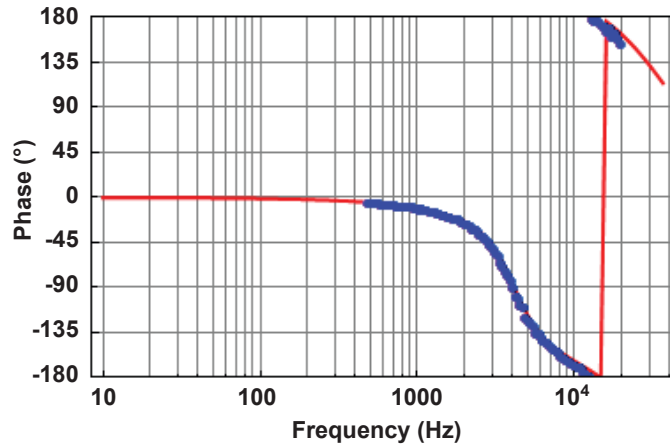
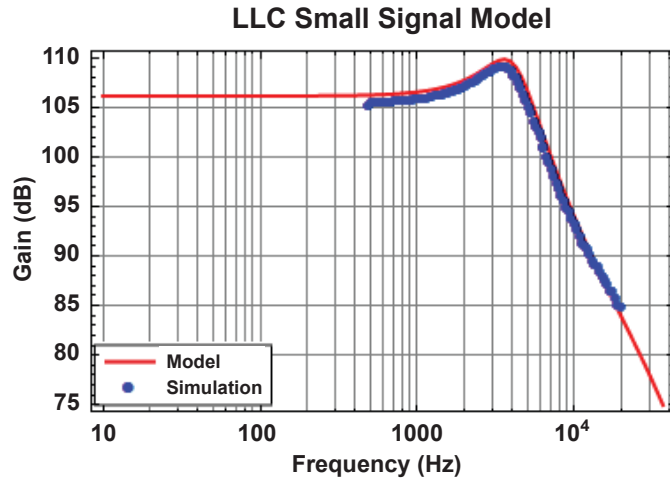
- $\dot{x}_n(t) = A \cdot x_n(t) + B \cdot U$

- $x_n(t_i) = (e^{A \cdot \Delta t} - I) \cdot A^{-1} \cdot B \cdot U + e^{A \cdot \Delta t} \cdot x_n(t_{i-1})$

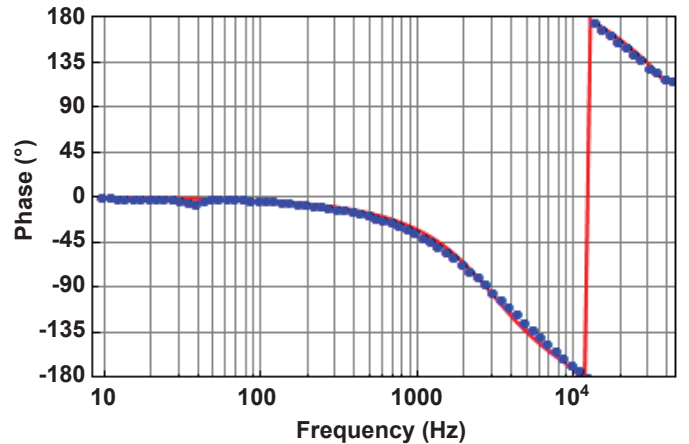
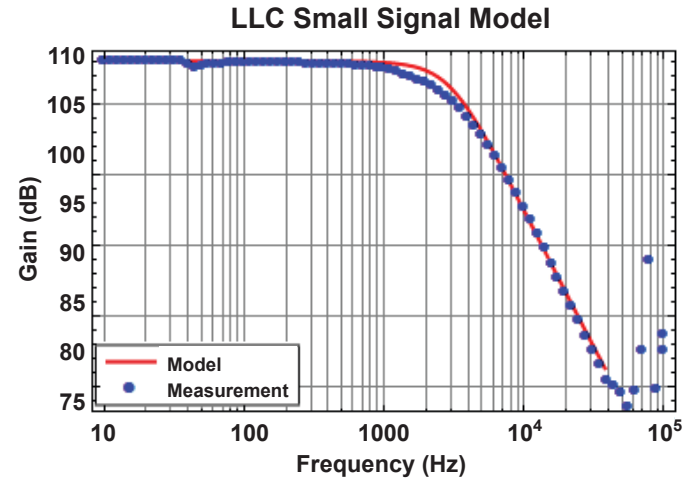
- **Lightning fast, highly accurate results**

Model Validation

Model vs. Circuit Simulation



Model vs. Measurement

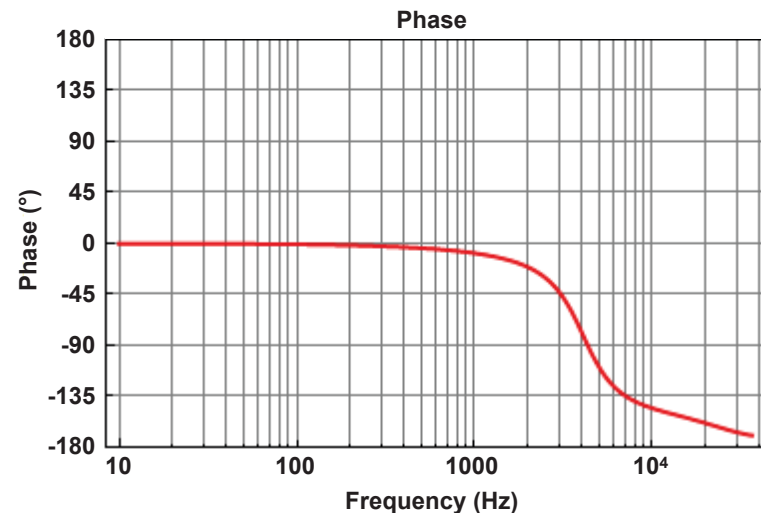
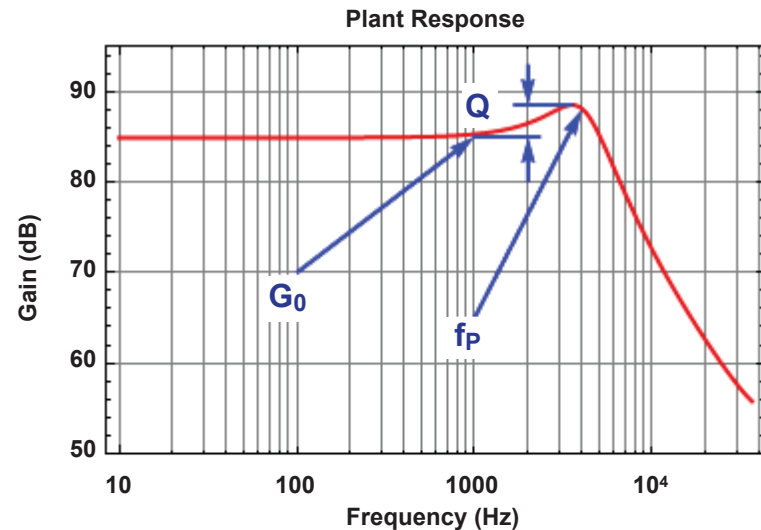


Compensation Objectives

- **Stability**
 - How do we achieve stability?
 - How do we ensure that we have sufficient stability margin for all operating points?
- **Performance**
 - Reference tracking
 - Load transient response
 - Input voltage transient rejection

Plant Analysis

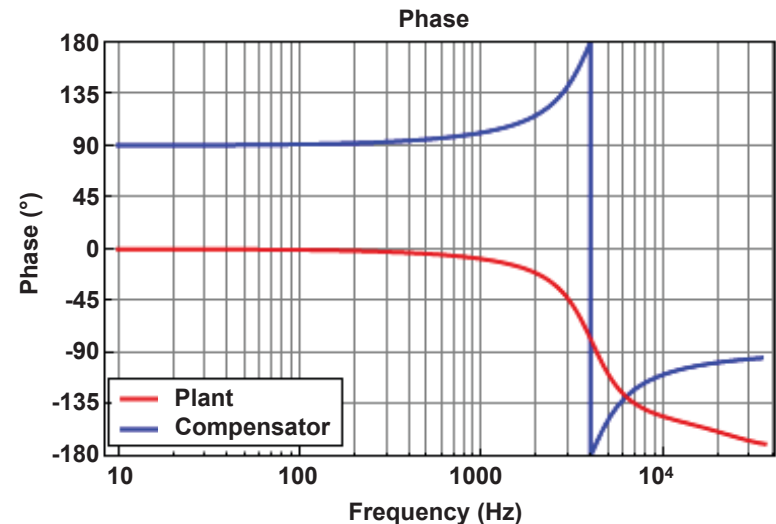
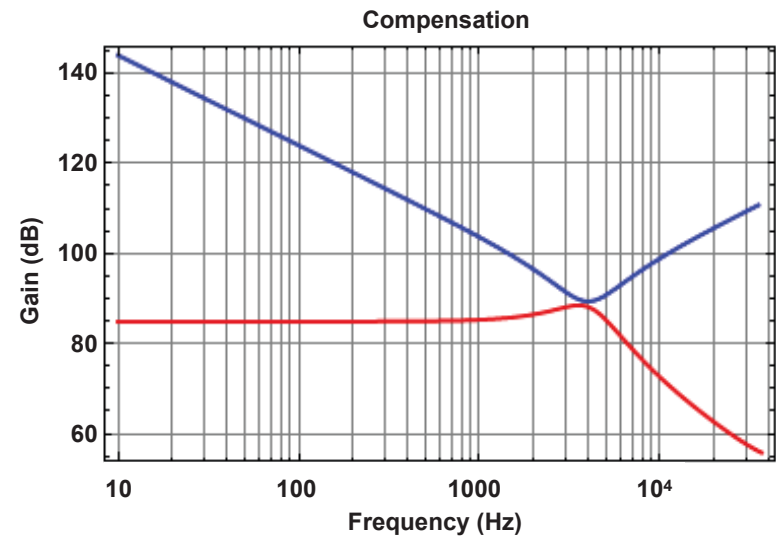
- 4TH order system,
2ND order response
 - $G_0 \sim 85$ dB
 - $Q \sim 1.35$
 - $f_p \sim 4$ kHz
- Stability Objectives
 - $\Phi_m \geq 45^\circ$
 - $g_m \geq 10$ dB



Compensation

$$G_0 \cdot \frac{\left(\frac{s^2}{(2 \cdot \pi \cdot f_Z)^2} + \frac{s}{2 \cdot \pi \cdot f_Z \cdot Q_Z} + 1 \right)}{s}$$

- 1/s term is required to eliminate DC error
- 2 zeros are required for stability
 - $Q_Z = 1.35$
 - $f_Z = 4 \text{ kHz}$

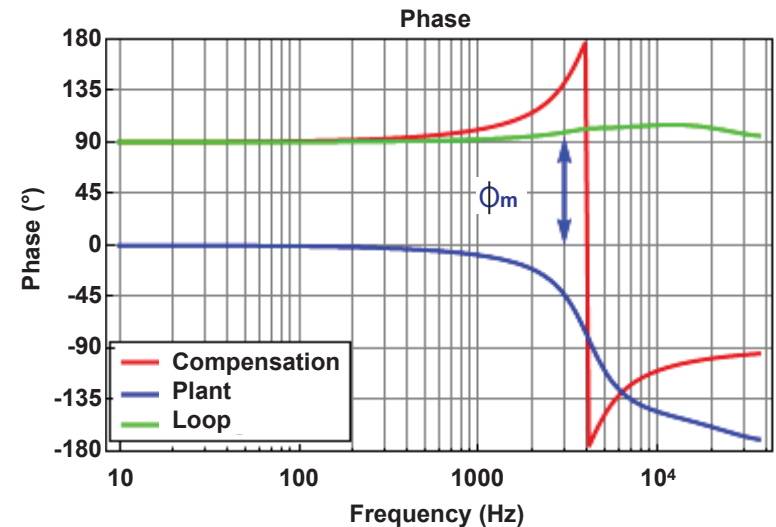
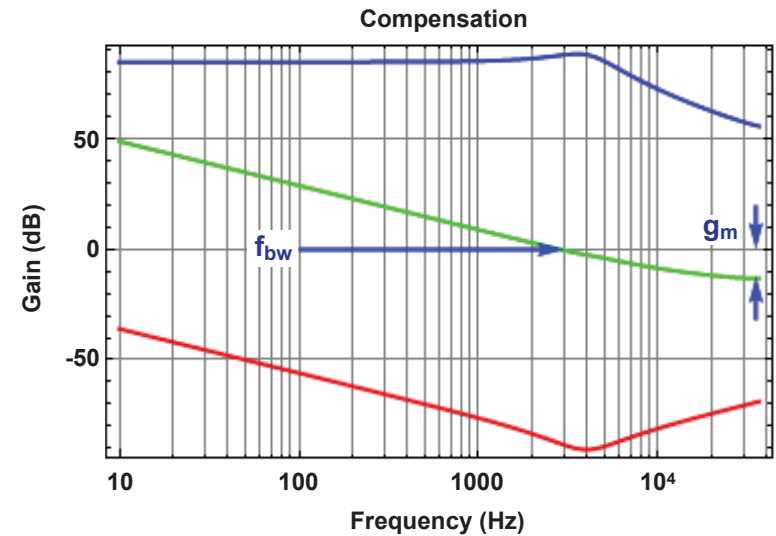


Overall Stability

- $$G_0 \cdot \frac{\left(\frac{s^2}{(2 \cdot \pi \cdot f_Z)^2} + \frac{s}{2 \cdot \pi \cdot f_Z \cdot Q_Z} + 1 \right)}{s}$$
 - $G_0 = 0 \text{ dB}$
 - $Q_Z = 1.35$
 - $f_Z = 4 \text{ kHz}$

- ## Stability Margins

- $\phi_m \cong 95^\circ$
- $g_m \cong 12 \text{ dB}$
- $f_{bw} \cong 3 \text{ kHz}$



Overall Stability with an Extra Pole

$$G_0 \cdot \frac{\left(\frac{s^2}{(2 \cdot \pi \cdot f_Z)^2} + \frac{s}{2 \cdot \pi \cdot f_Z \cdot Q_Z} + 1 \right)}{s \cdot \left(\frac{s}{2 \cdot \pi \cdot f_p} + 1 \right)}$$

– $G_0 = 0 \text{ dB}$

– $Q_Z = 1.35$

– $f_Z = 4 \text{ kHz}$

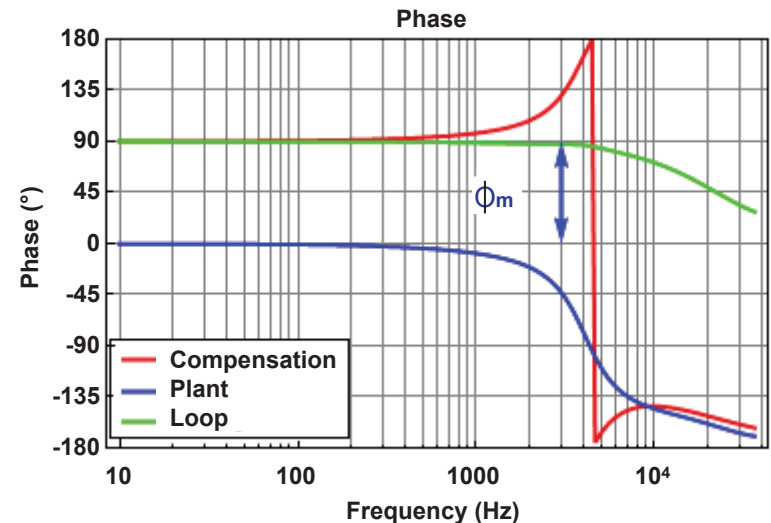
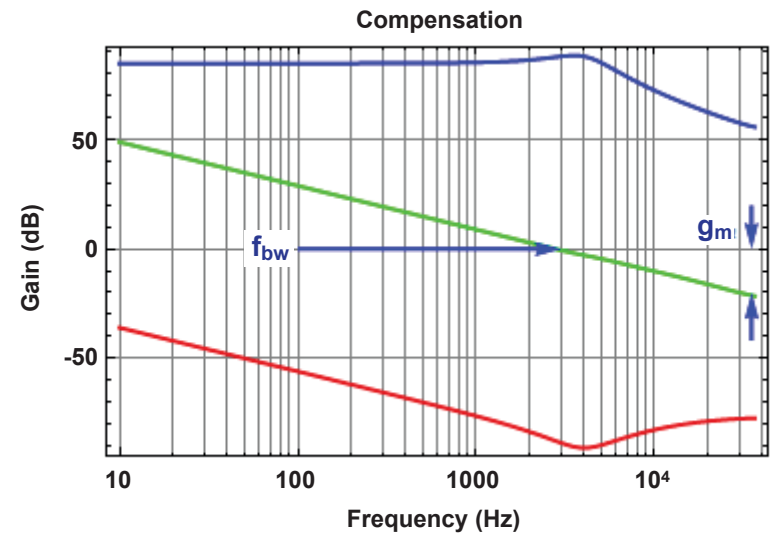
– $f_p = 15 \text{ kHz}$

- **Stability Margins**

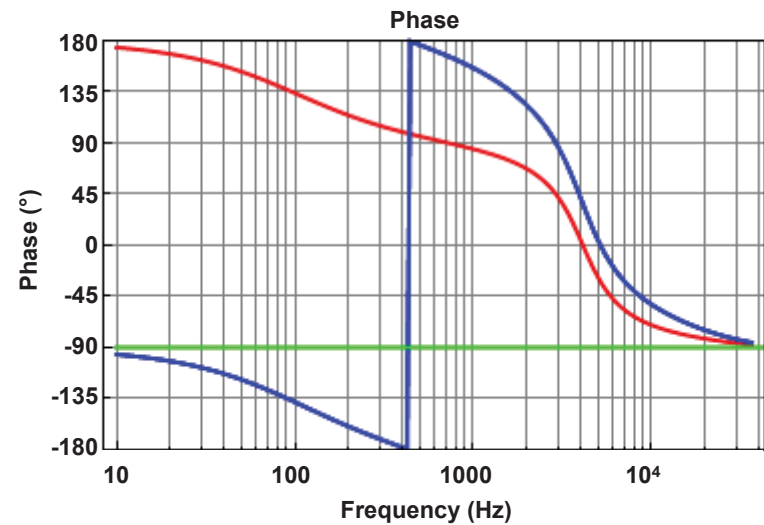
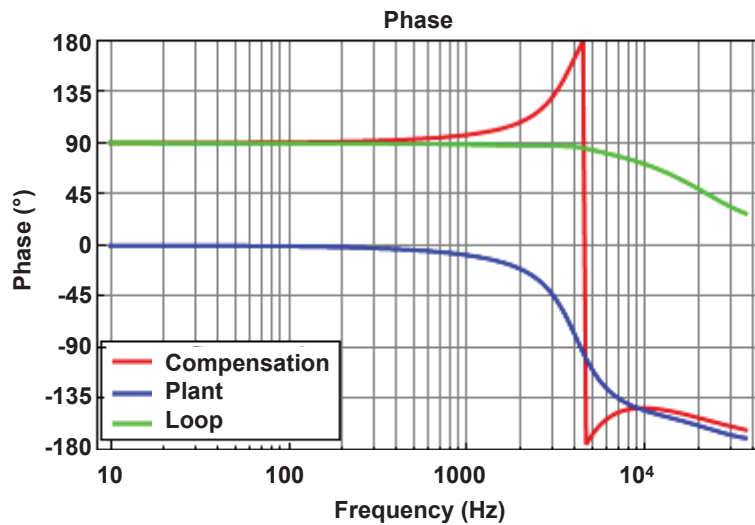
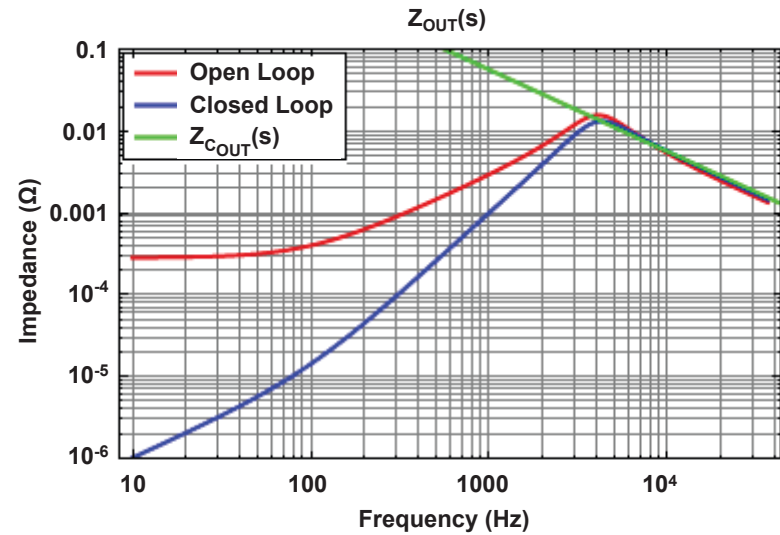
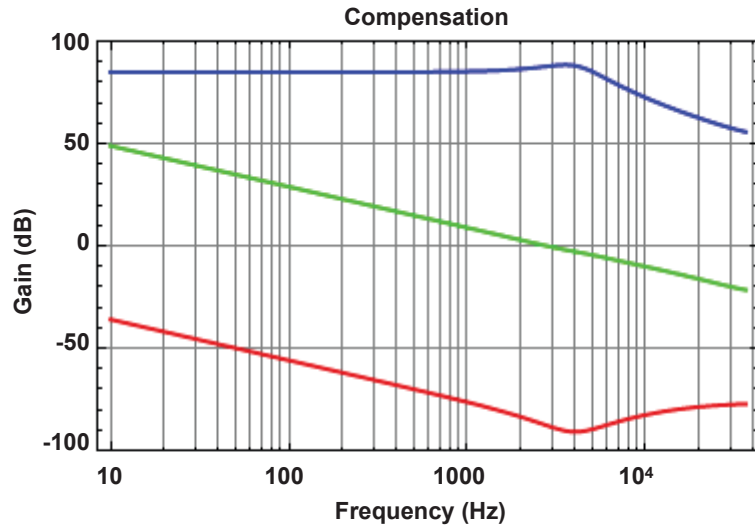
– $\phi_m \cong 90^\circ$

– $g_m \cong 20 \text{ dB}$

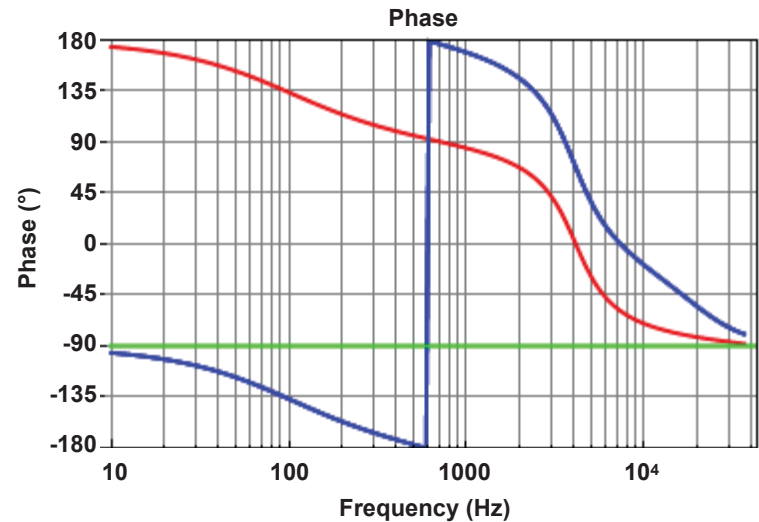
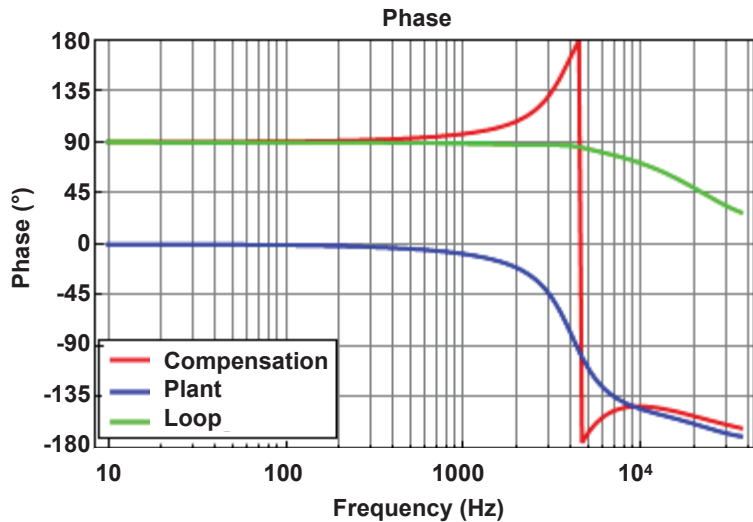
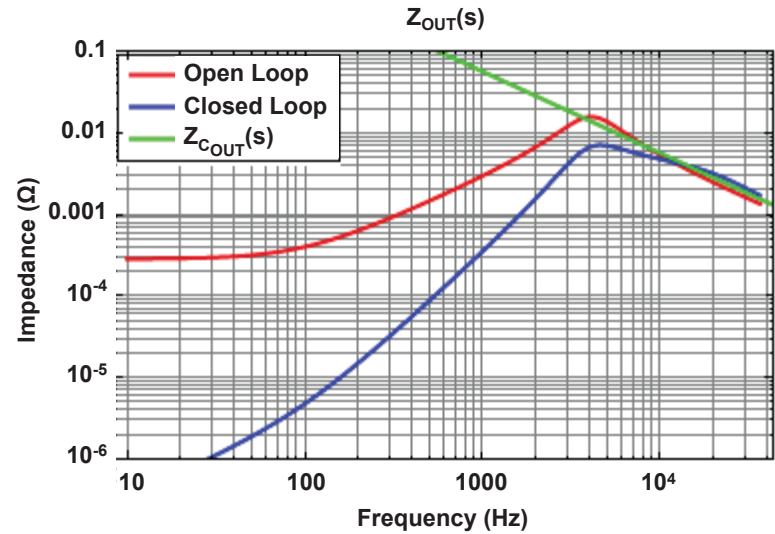
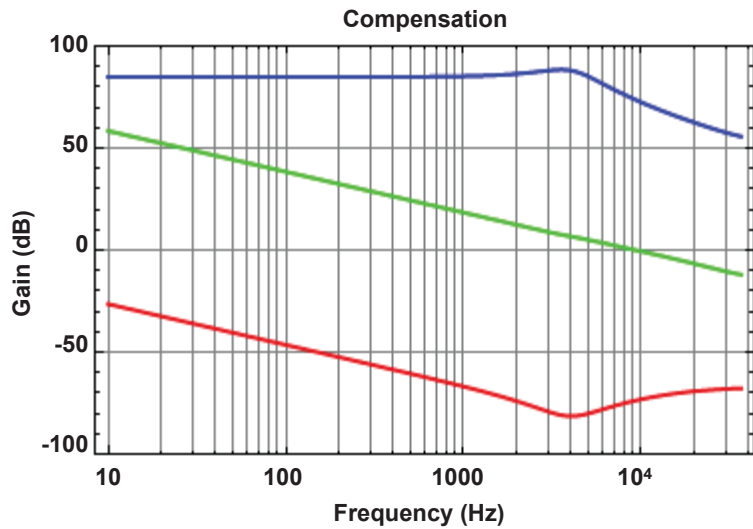
– $f_{bw} \cong 3 \text{ kHz}$



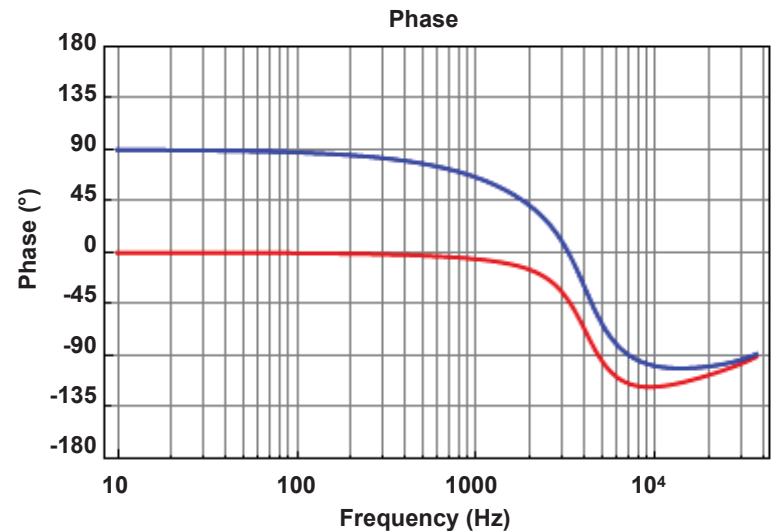
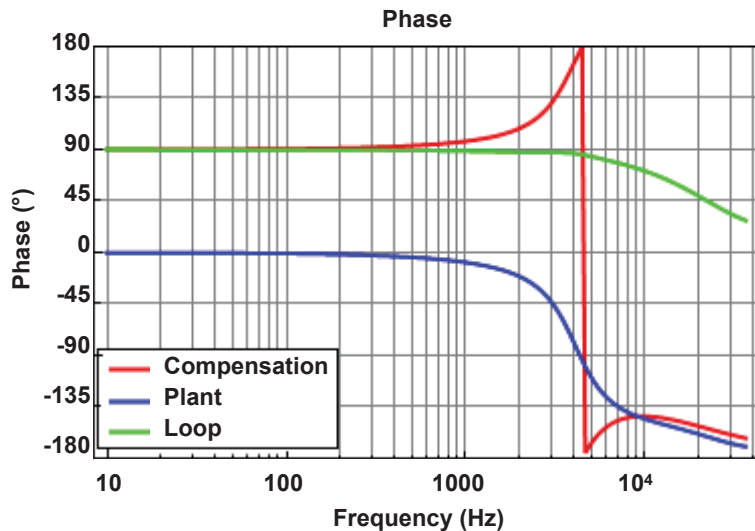
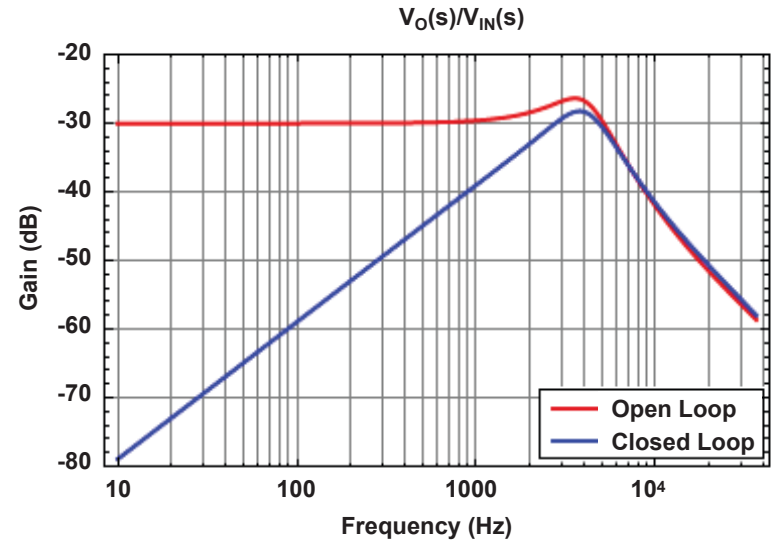
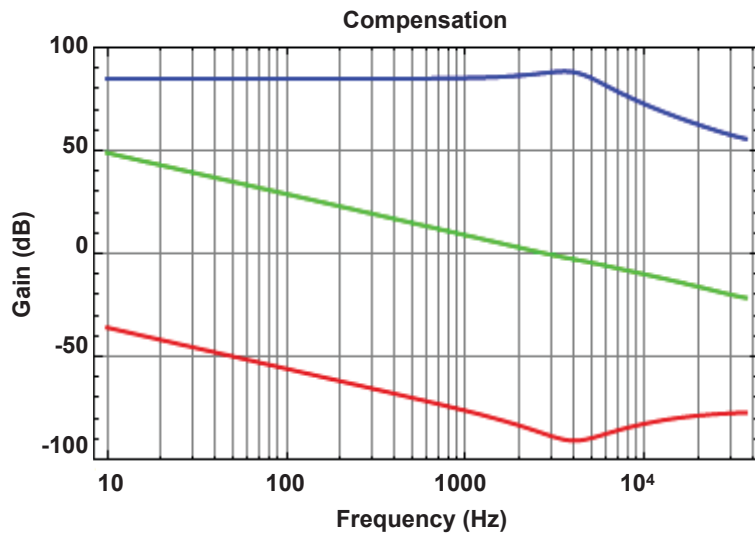
$Z_{OUT}(s)$, $G_0 = 0$ dB



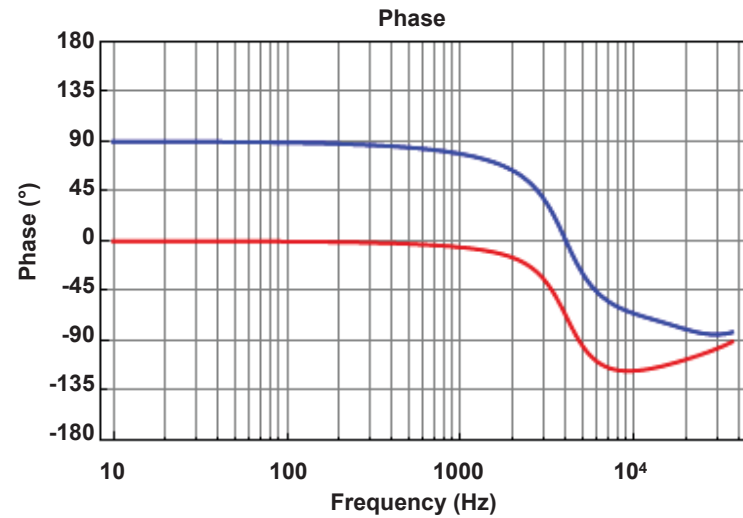
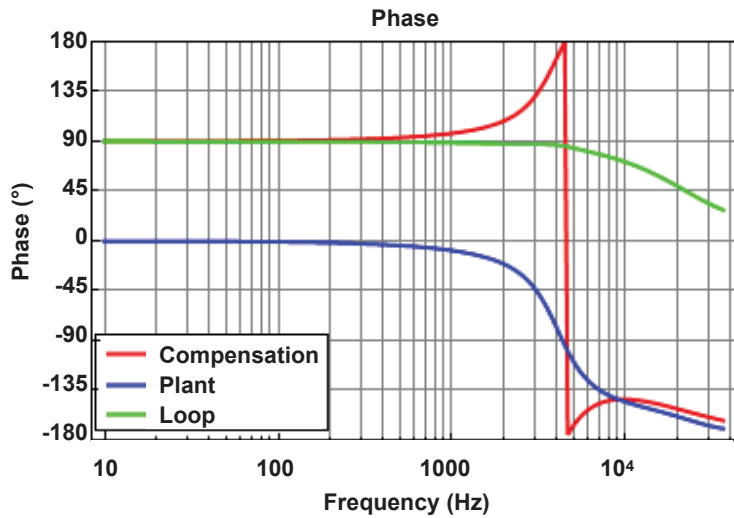
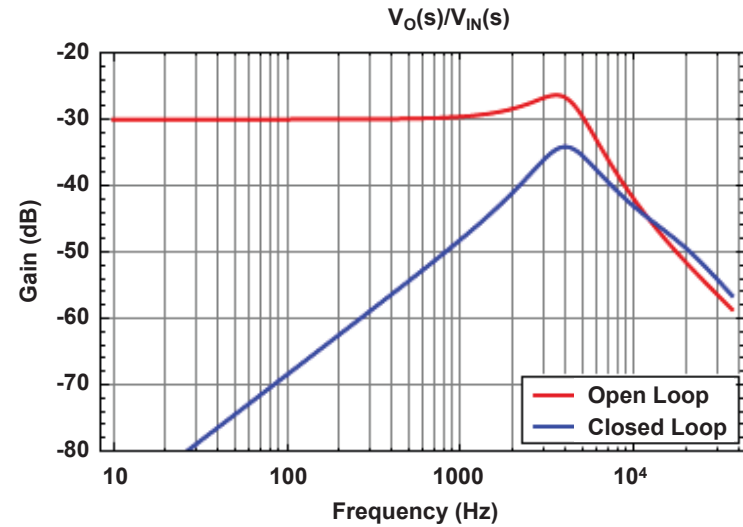
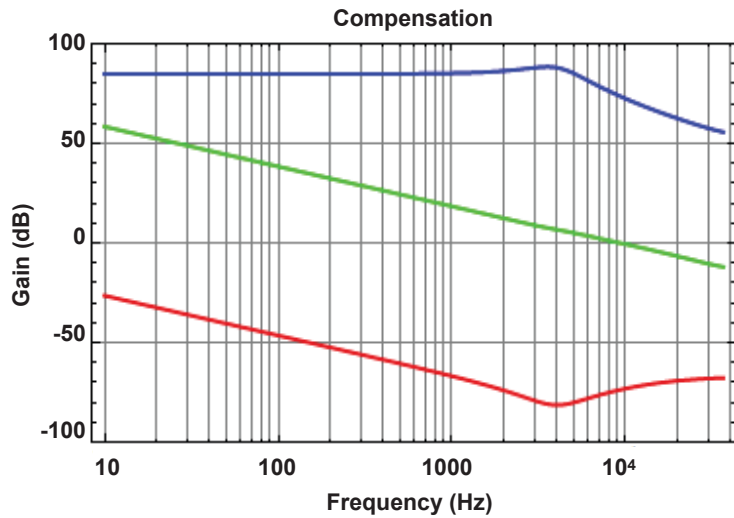
$Z_{OUT}(s)$, $G_0 = 9.5 \text{ dB}$



$$\widehat{V}_{OUT}(s)/\widehat{V}_{IN}(s), G_0 = 0 \text{ dB}$$



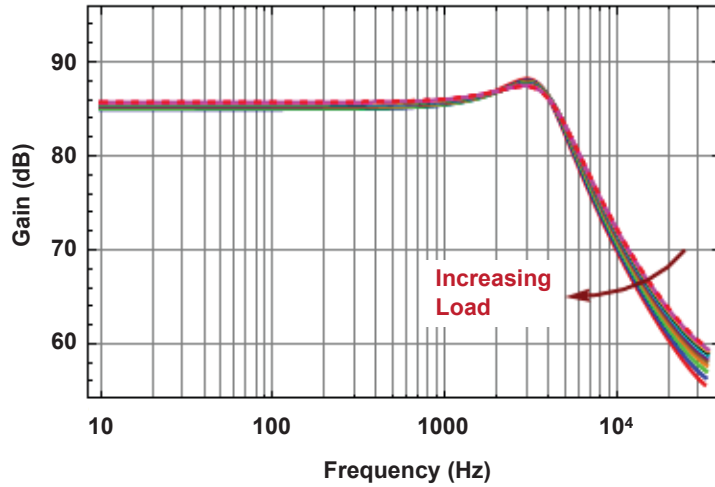
$$\hat{V}_{OUT}(s)/\hat{V}_{IN}(s), G_0 = 9.5 \text{ dB}$$



Load Variation

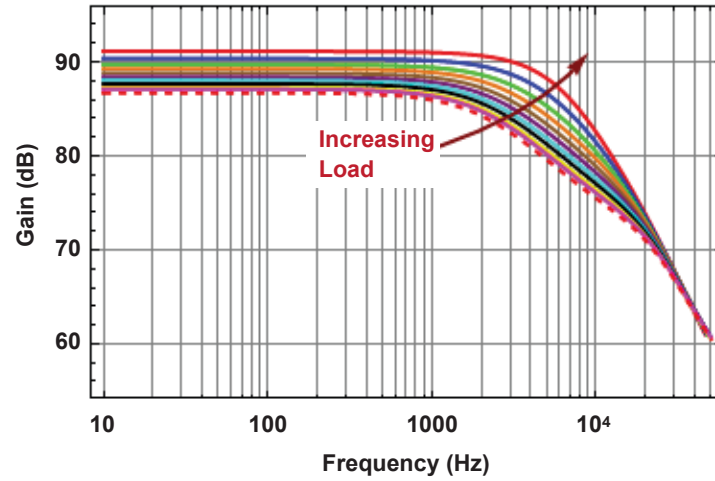
$V_{IN} = 370\text{ V}$

Gain



$V_{IN} = 400\text{ V}$

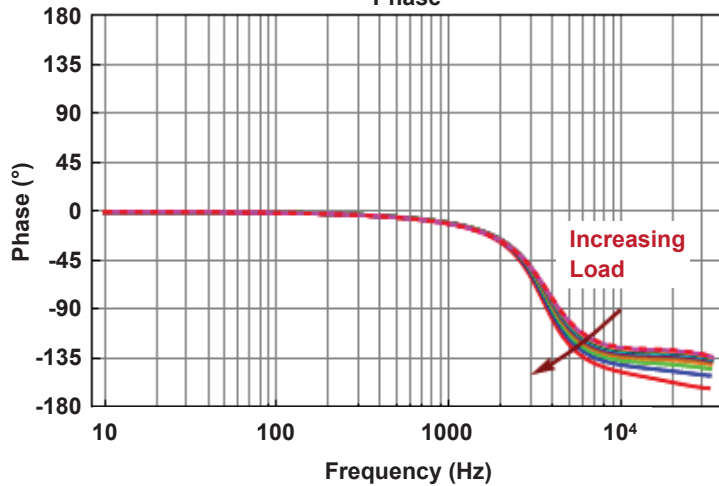
Gain



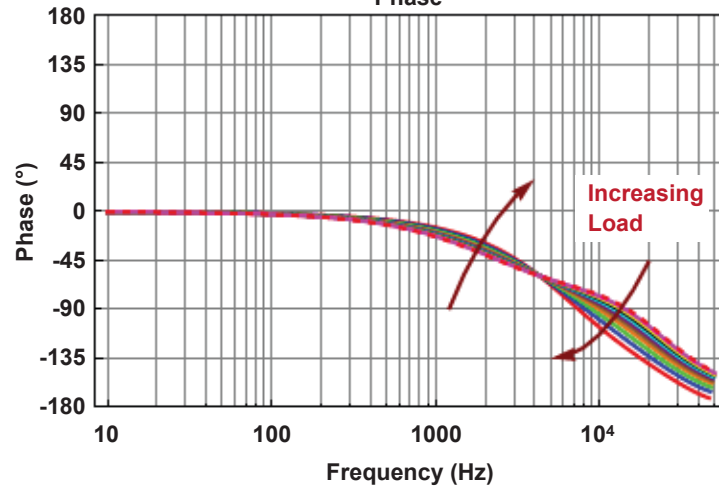
Legend

- 0.4 Ω
- 0.5 Ω
- 0.6 Ω
- 0.7 Ω
- 0.8 Ω
- 0.9 Ω
- 1.0 Ω
- 1.1 Ω
- 1.2 Ω
- 1.3 Ω
- 1.4 Ω

Phase

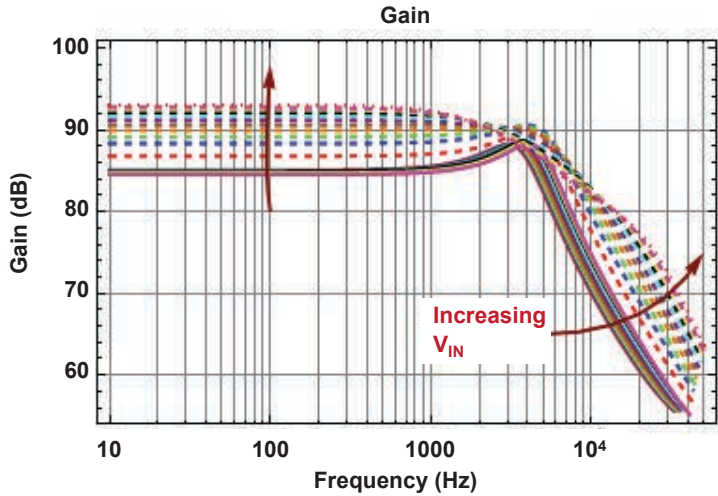


Phase

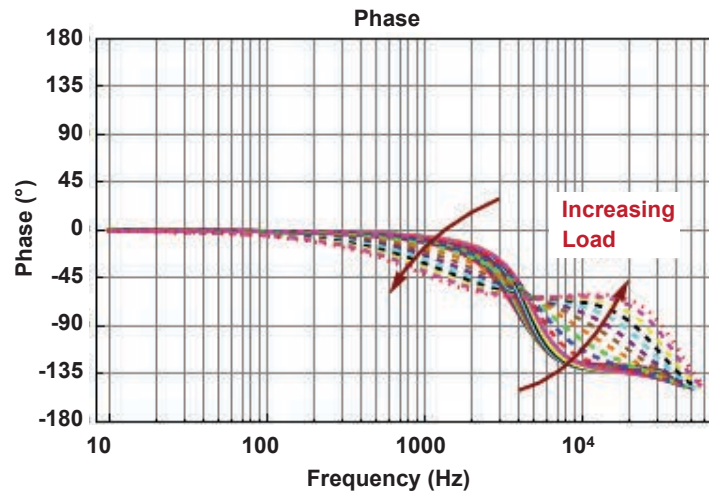
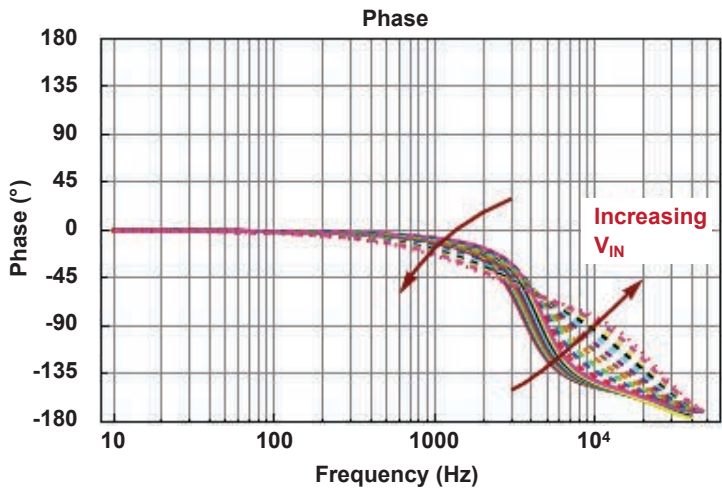
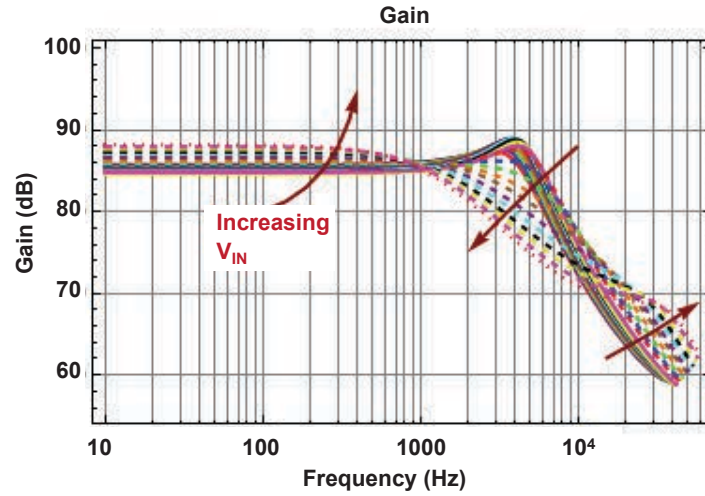


V_{IN} Variation

Load = 0.4 Ω



Load = 1.4 Ω



Legend

- 370 V
- 372 V
- 374 V
- 376 V
- 378 V
- 380 V
- 382 V
- 384 V
- 386 V
- 388 V
- - - 390 V
- - - 392 V
- - - 394 V
- - - 396 V
- - - 398 V
- - - 400 V
- - - 402 V
- - - 404 V
- - - 406 V
- - - 408 V
- · · · 410 V

Fusion Digital Power Designer

Fusion Digital Power Designer - DC-DC LLC @ Address 89d - Page 0x0 - Texas Instruments

File Device Tools Help DC-DC LLC @ 89d - Page 0x0

Design

***Voltage Start Up Loop (Bank #0) Voltage Steady State Loop (Bank #1) Voltage CP Loop (Bank #2) Current Steady State Loop (Bank #3)

Power Stage - Rail #1

Stage Parameters

np	16.000	Io	0.00	A	
ns	1.000	R0	400.00	mΩ	
LR	43.00	μH	Vin	380.00	V
RS	500.00	mΩ	D	50.00	%
LM	530.00	μH	R1	10.28	kΩ
CR	90.00	nF	R2	1.00	kΩ
C0	2.82	mF	C2	2.20	nF
Vout	12.00	V	esr	5.00	mΩ
fs	73.18	kHz			

Half Bridge

Coefficient Set & Alpha Configuration

Coef: Set A (info)

Mode: Complex Zeros (K, Q, Fz) (info)

Use practical limits (info)

K: 4.00E+0 Actual K: 4.00080E+000

1.00 26.63

Q: 1.350E+0 Actual Q: 1.35017E+000

0.01 5.00

Fz: 4.00E+3 Hz Actual Fz: 4.00521E+003

1.00 100000.00

Alpha: 0

Frequency Response

Metrics: Loop Stage Comp

Crossover: 3.53 kHz

Phase Margin: 243.01°

Gain Margin: 18.50 dB

Plot Symbols: 0 dB Cross Zero -180° Cross Pole

Gain - Magnitude

Gain - Phase

Configure

Design

Monitor

Status

Tips & Hints

VIN_OV_FAULT_LIMIT [0x55]
Input voltage that causes an input overvoltage fault.

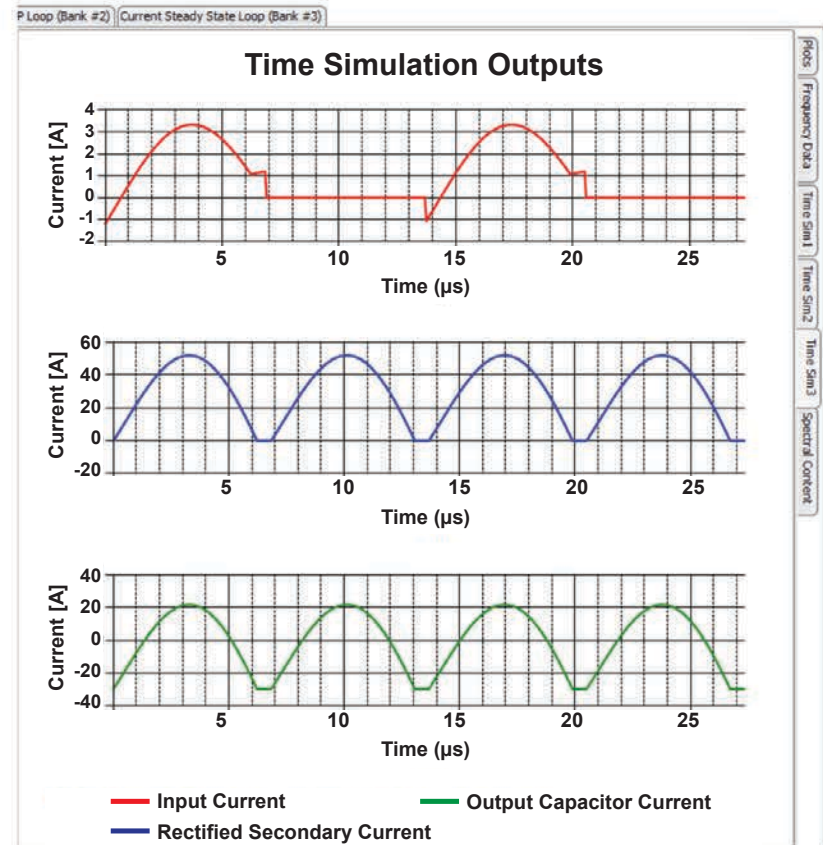
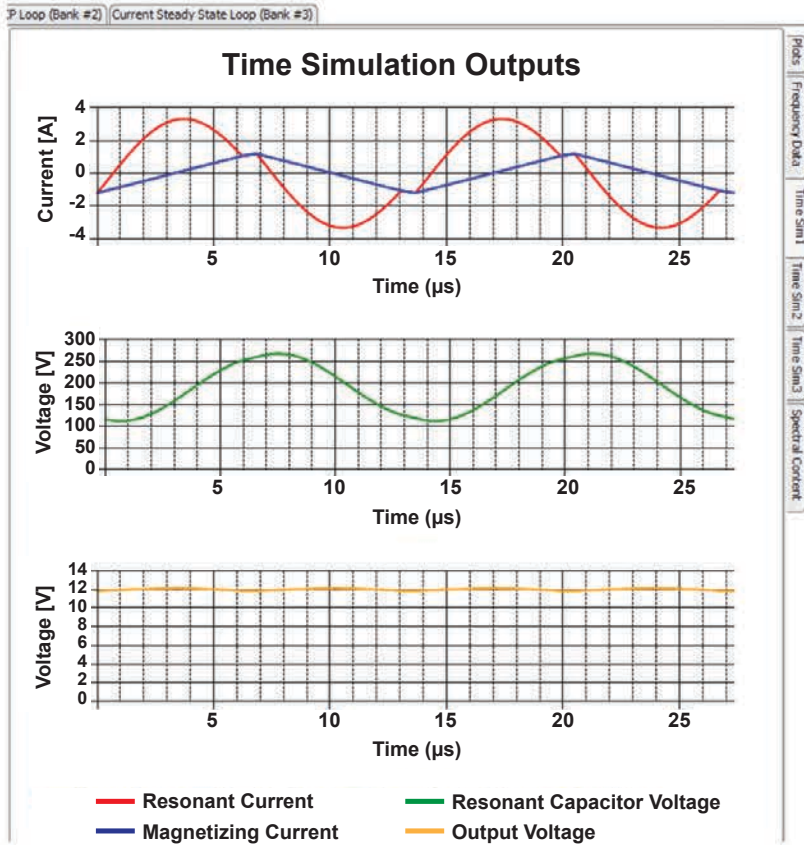
PMBus Log

```

09:05:17.509: USB-SAA #1: CONTROL1 now Low
09:05:28.650: DC-DC LLC @ 89d: FILTER_SELECT [MFR 05,0xD5]: wrote Filter Voltage Loop Start Up is Inactive [0x00] to RAM
09:05:29.541: DC-DC LLC @ 89d: FILTER_SELECT [MFR 05,0xD5]: wrote Filter Voltage Loop Steady State is Inactive [0x01] to RAM
09:05:29.550: DC-DC LLC @ 89d: FILTER_SELECT [MFR 05,0xD5]: wrote Filter Voltage Loop CPCC is Inactive [0x02] to RAM
09:05:29.561: DC-DC LLC @ 89d: FILTER_SELECT [MFR 05,0xD5]: wrote Filter Current Loop Steady State is Inactive [0x03] to RAM
    
```

Fusion Digital Power Designer v1.0.0.21580 [2014-01-06] DC-DC LLC Firmware v0.0.72.2 @ Address 89d USB Adapter v1.0.10 [PEC; 400 kHz] TEXAS INSTRUMENTS | fusion digital power

Time Domain Behavior



Limitations

- Low efficiency scenarios may need additional work to achieve proper correlation
- Does not support PWM or PSM
- Corner cases may exist which limit the accuracy due to numerical approximations
- Additional work may be required to ensure accuracy, especially at higher frequencies

Conclusions

- Analytical predictions of plant pole zero behavior enables more robust compensation
 - Parameter variations
 - Extreme operating conditions
- Independent validation of the DC operating point
- Instant visualization of:
 - Key system waveforms
 - Harmonic content
- Seamless integration with TI standard isolated digital controllers

Future Work

- DC operating point
- Performance metrics
 - $Z_{OUT}(s)$
 - $Z_{IN}(s)$
 - $\widehat{V}_{OUT}(s)/\widehat{V}_{IN}(s)$
- Modulation methods
 - FM
 - PSM
 - PWM
- Additional States & Modes
 - Switching transitions
 - Body diode conduction

IMPORTANT NOTICE

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