TI Technology Days 2010

Loop Compensation with SwitcherPro

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SwitcherPro™

What is SwitcherPro™?

1. SwitcherPro™ allows you to design power supplies with Texas Instruments TPS40K™ controllers, TPS60xxx low-power DC/DC converters and SWIFT™ (TPS54xxx) point-of-load step-down DC/DC products.

2. Use this tool to create, manage and share custom designs.

3. It provides EVM designs that you can use for reference or starting points for custom designs. In addition, passive components such as inductors and CICLON MOSFETs are now included in both the online and desktop applications.

4. The desktop application now allows more flexibility in creating designs since there is no need to be connected to the internet. Design and go at your own pace.

Switcher Pro Status & Development

Upcoming Developments

New Parts

V3.8 Release	Jun 11, 2010	115	TPS54225
		116	TPS54226
		117	TPS54325
		118	TPS54326
		119	TPS54319
		120	TPS61220
		121	TPS61221
		122	TPS61222
		124	TPS62060
		125	TPS62065
		126	TPS62067

V3.9 Release	Jul 30, 2010	127	TPS40197
		128	TPS53311
		129	TPS54060-Inverting
		130	TPS61200
		131	TPS61201
		132	TPS61202
		133	TPS54320
		134	TPS54618
		135	TPS62233
		136	TPS62234
		137	TPS62235
		138	TPS62236
		139	TPS62237
		140	TPS62238
		141	TPS62239
		142	TPS622310
		143	TPS622311
		123	TPS54521

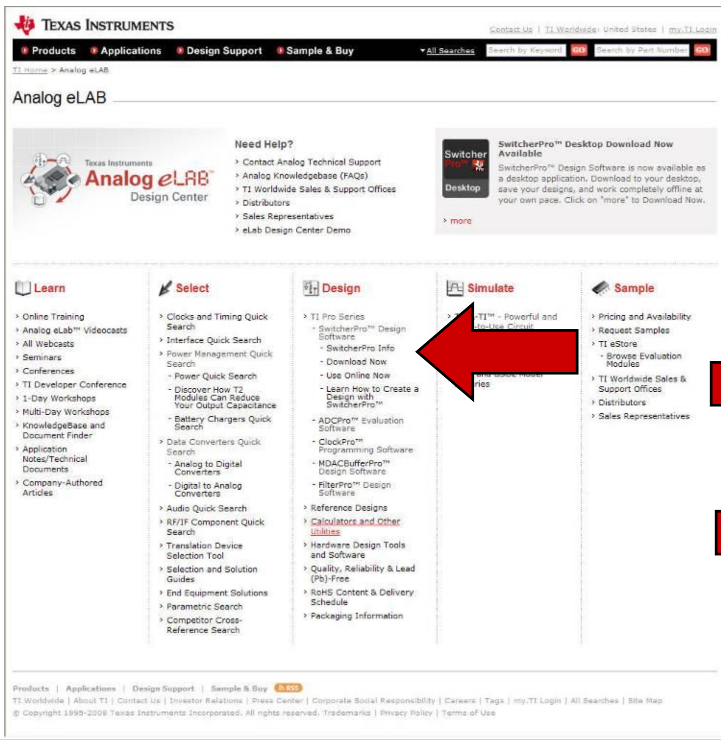
114 parts + 52 EVMs released

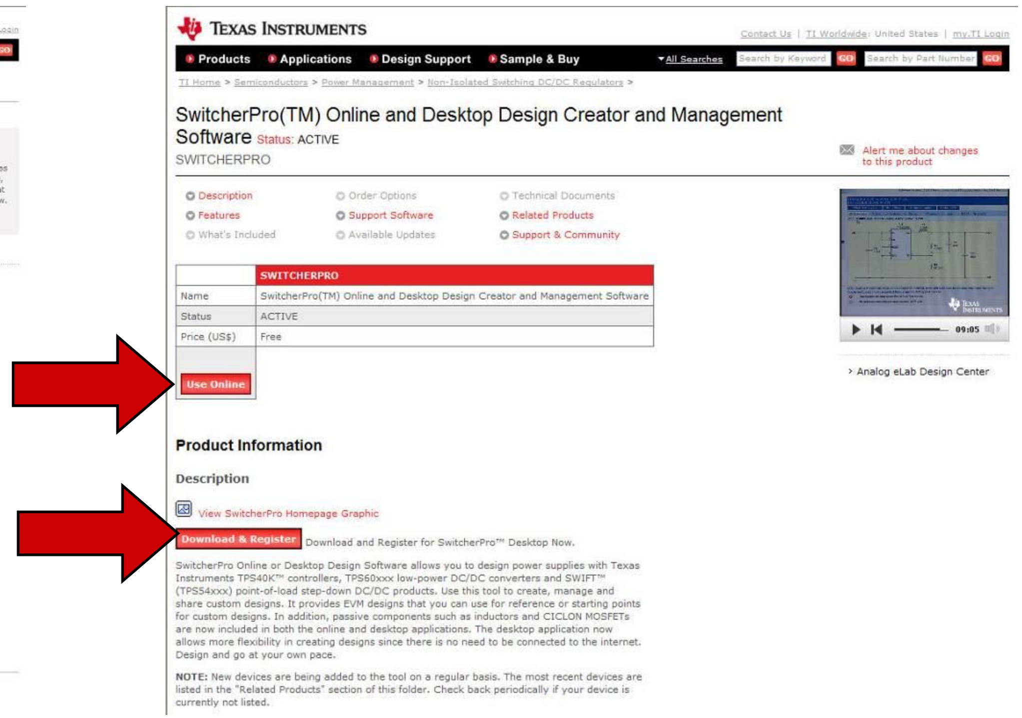
Latest Developments:

- TPS63020
- TPS54260
- TPS54240

Where to Find It

- www.ti.com/analogelab (“Design” Section)
- www.ti.com/switcherpro (Tool Folder)
- www.ti.com/switcherpro-dt (Desktop download)





Use Online or on Your Desktop

Web Based Version

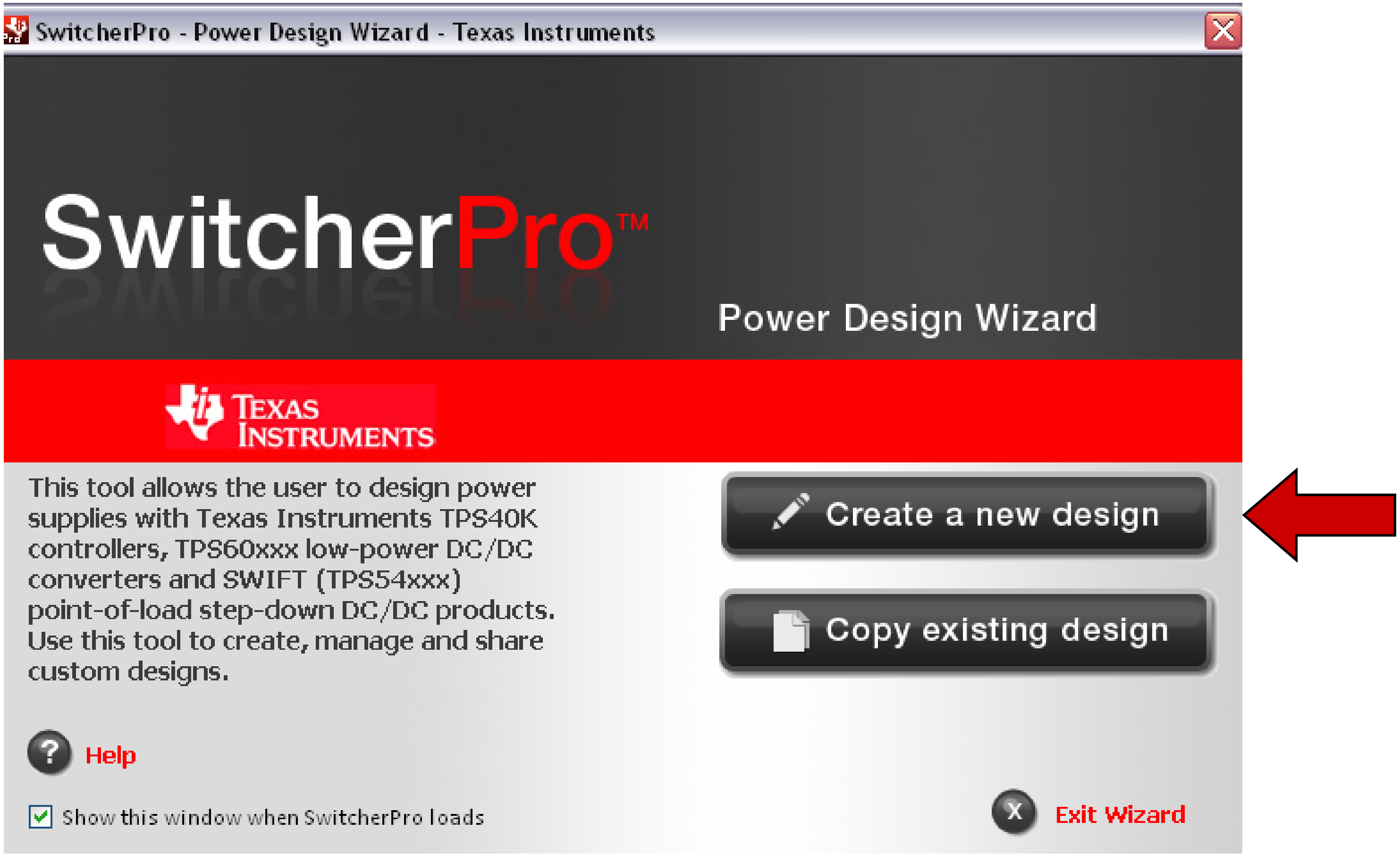
- Requires no installation
- Always the most recent version of the tool
- Accessible through my.TI
- Allows users to access data anywhere at anytime via a web browser
- ‘Support Forum’ link changed to point to TI E2E community site

Desktop Version

- No need for internet access
- Design anytime, anywhere
- Automatically updates to current version

SwitcherPro – Design Wizard

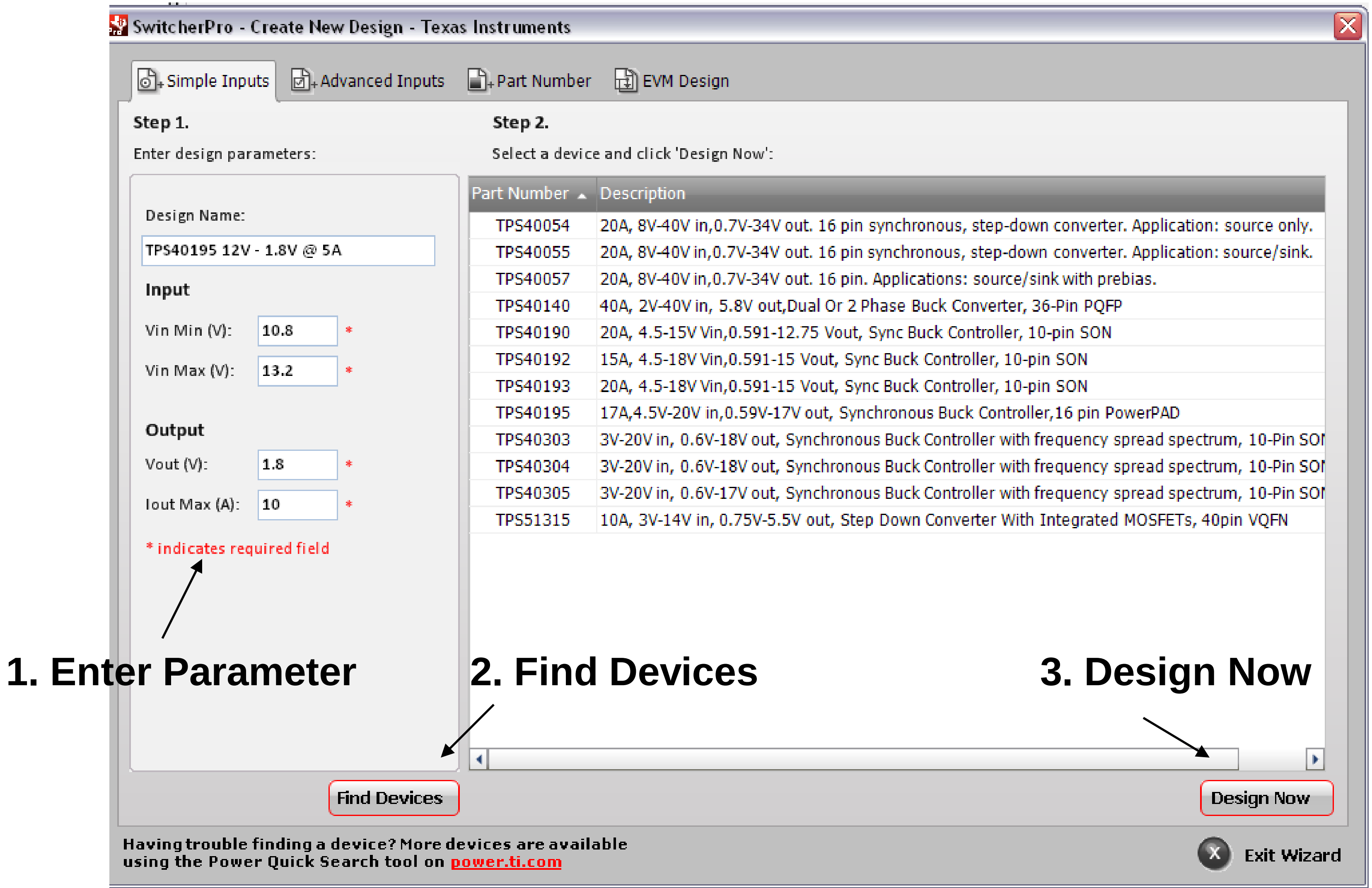
SwitcherPro has a flexible interface that allows users to develop solutions from a variety of families of DC/DC controllers and converters



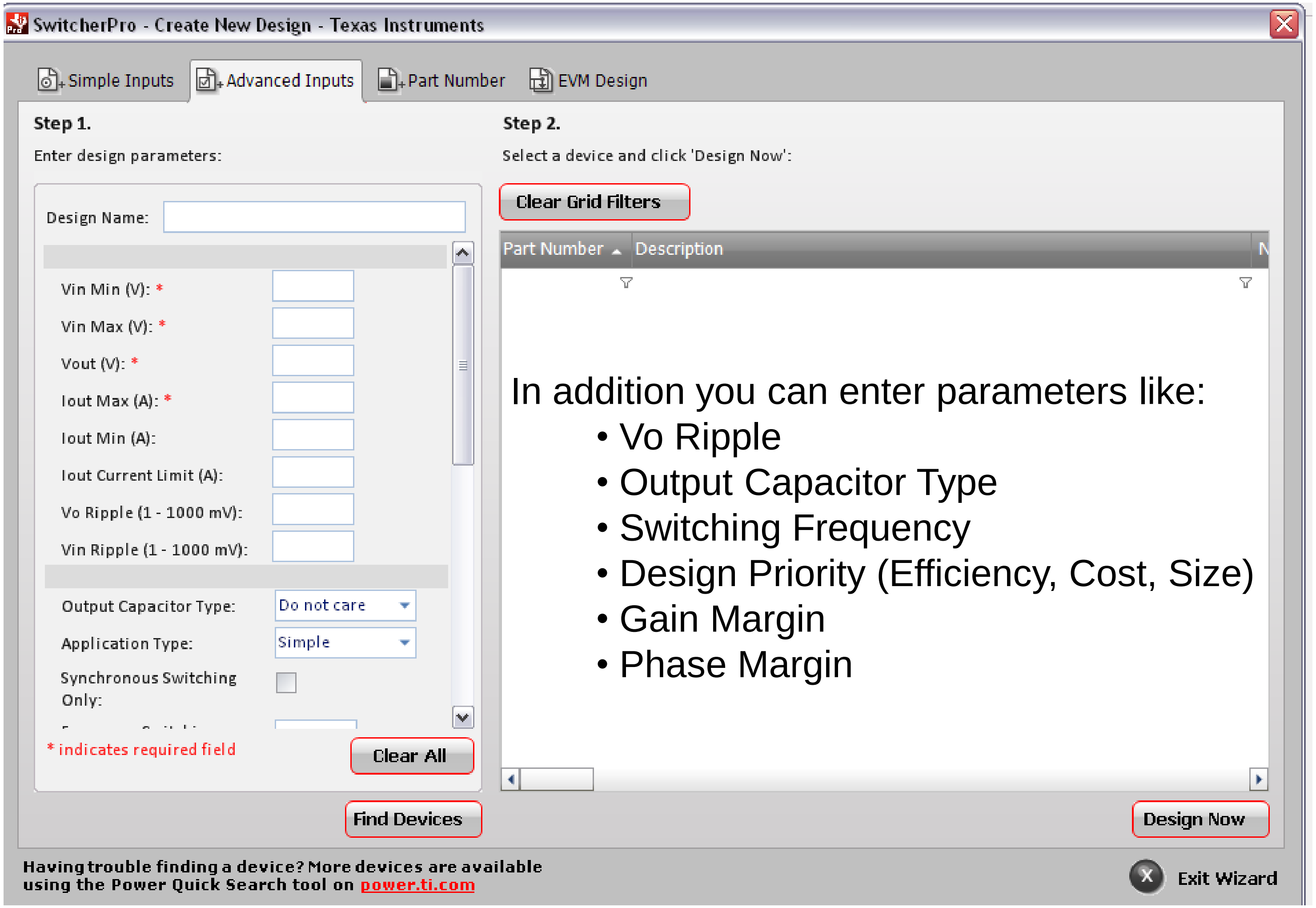
SwitcherPro – Design Wizard

Create Design either by selecting a device or by entering specifications

SwitcherPro – Design Wizard



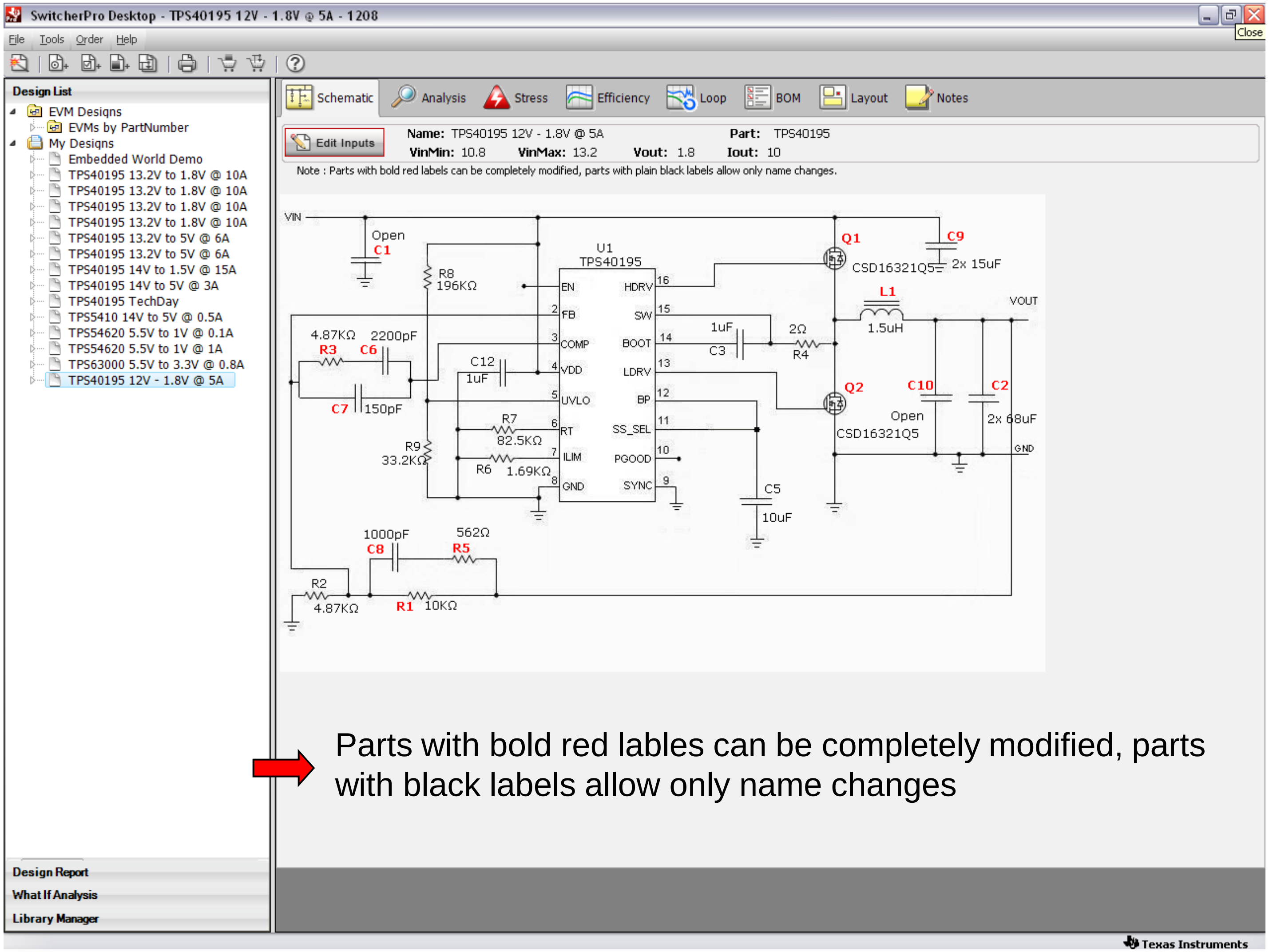
Design Wizard – Advanced Inputs



In addition you can enter parameters like:

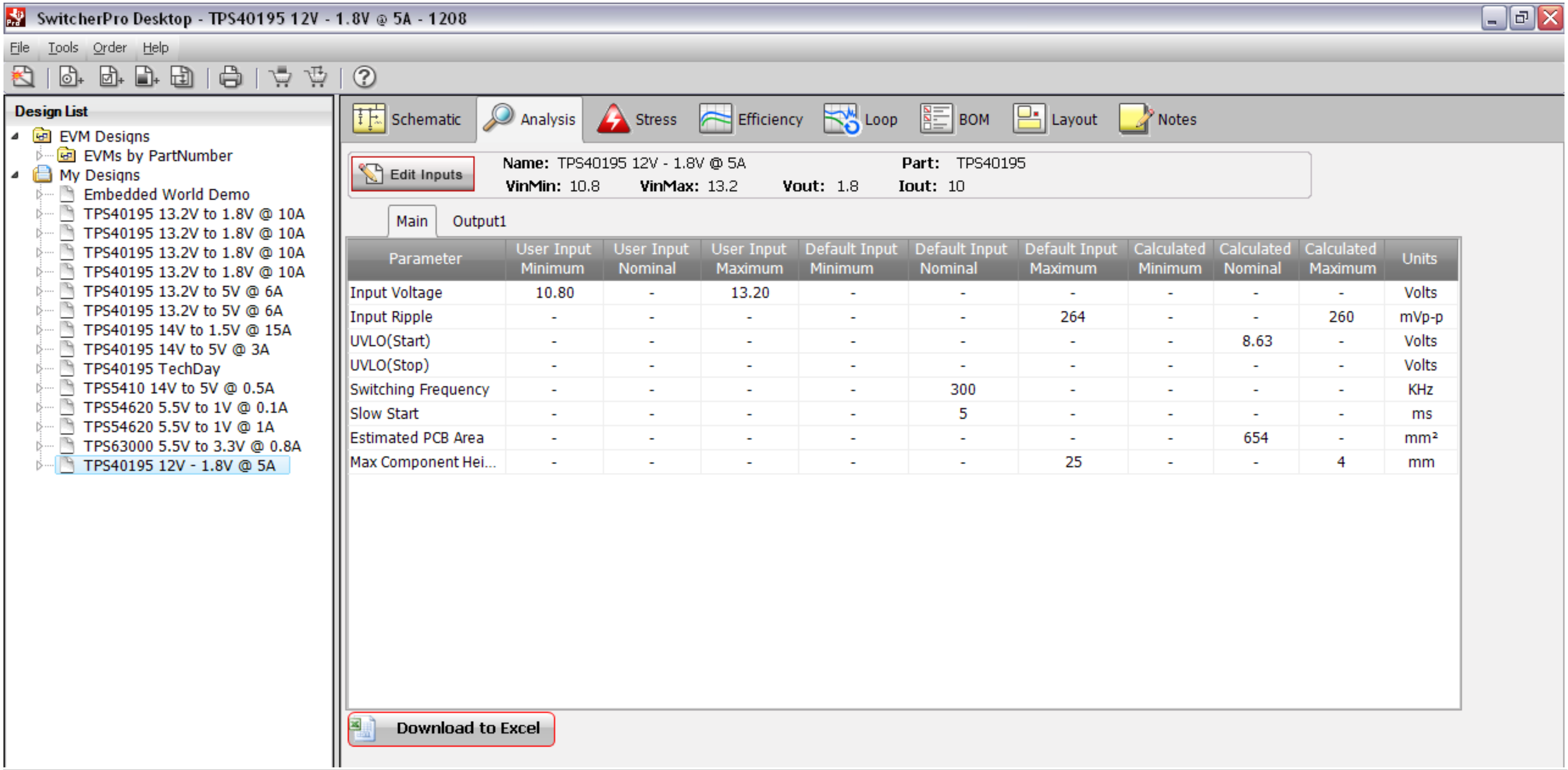
- Vo Ripple
- Output Capacitor Type
- Switching Frequency
- Design Priority (Efficiency, Cost, Size)
- Gain Margin
- Phase Margin

Design List – Schematic



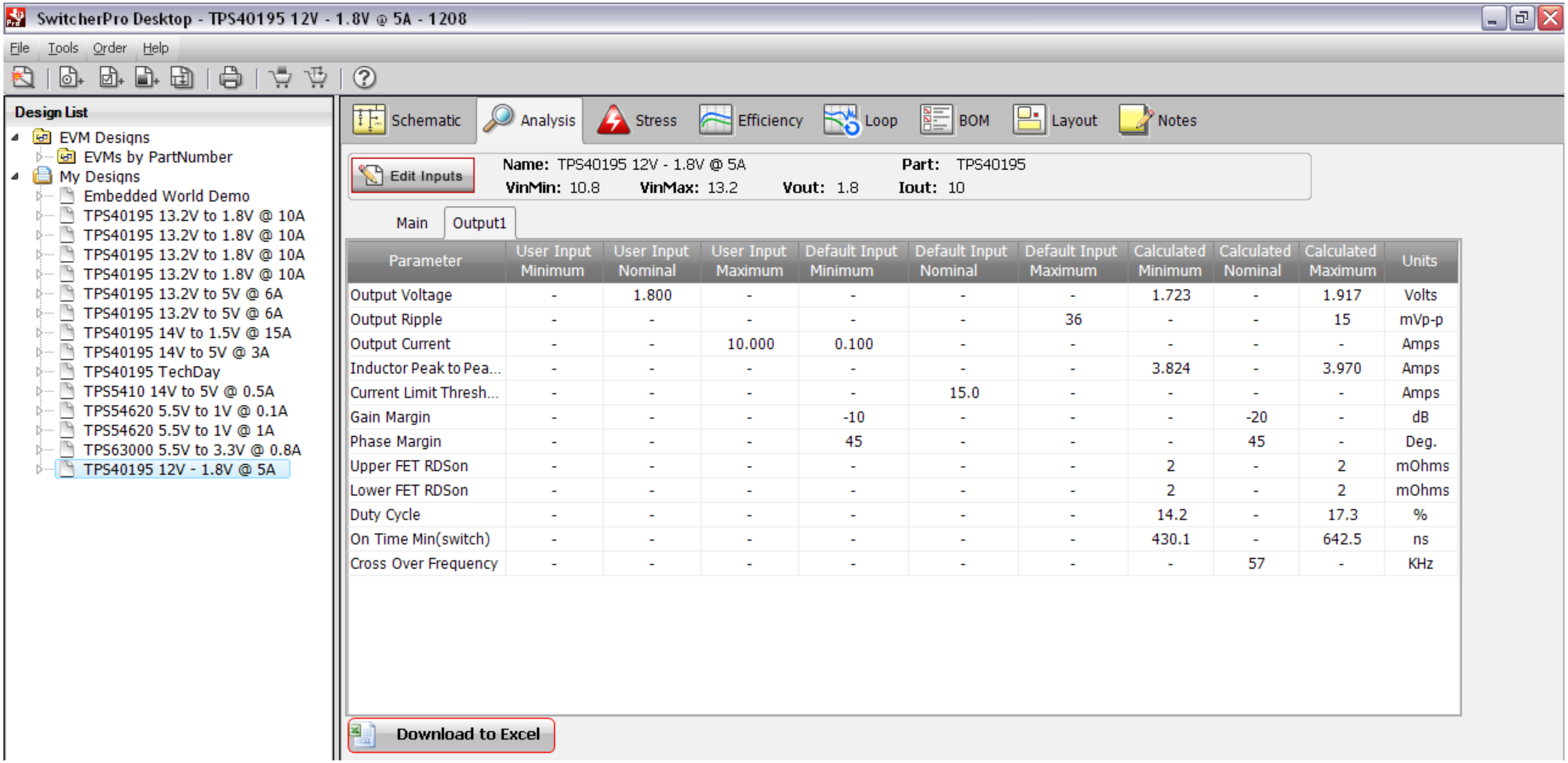
Parts with bold red lables can be completely modified, parts with black labels allow only name changes

Design List – Analysis Main



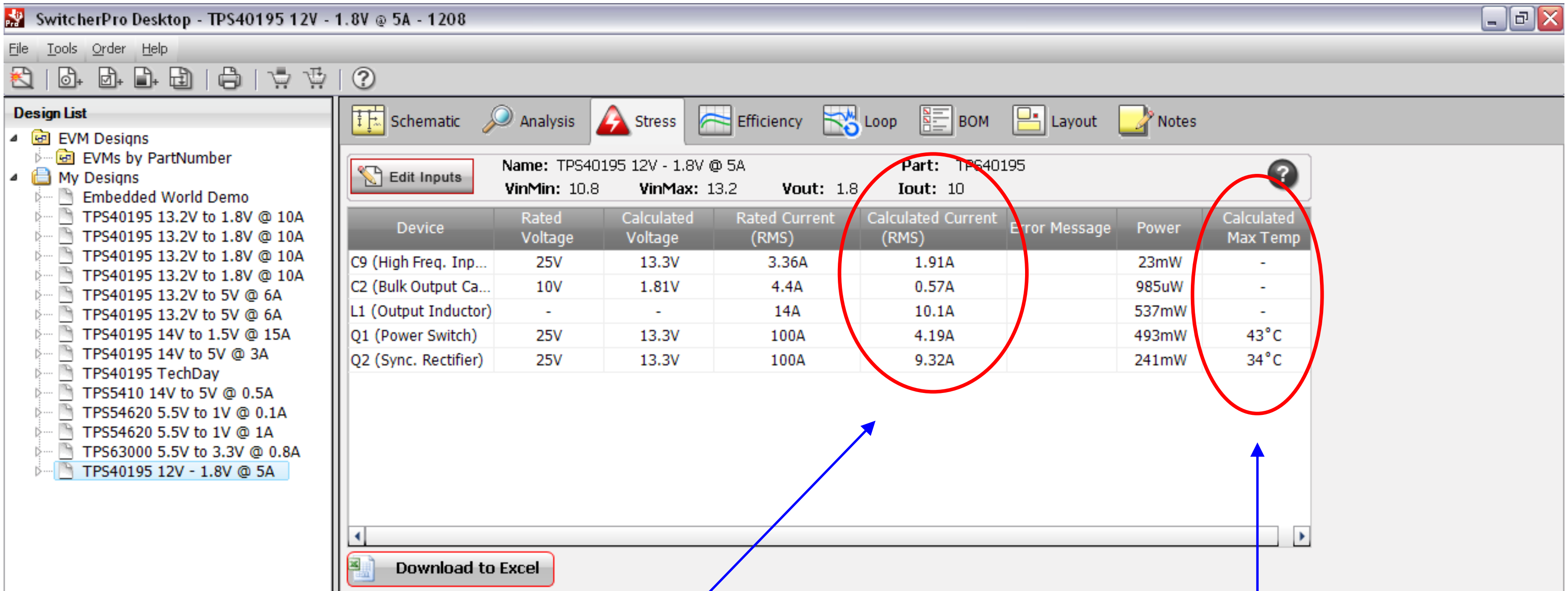
- Get an overview about basic informations like, input voltage, output voltage, input ripple, switching frequency or estimated PCB area

Design List – Analysis Output1



Parameter	User Input Minimum	User Input Nominal	User Input Maximum	Default Input Minimum	Default Input Nominal	Default Input Maximum	Calculated Minimum	Calculated Nominal	Calculated Maximum	Units
Output Voltage	-	1.800	-	-	-	-	1.723	-	1.917	Volts
Output Ripple	-	-	-	-	-	36	-	-	15	mVp-p
Output Current	-	-	10.000	0.100	-	-	-	-	-	Amps
Inductor Peak to Pea...	-	-	-	-	-	-	3.824	-	3.970	Amps
Current Limit Thresh...	-	-	-	-	15.0	-	-	-	-	Amps
Gain Margin	-	-	-	-10	-	-	-	-20	-	dB
Phase Margin	-	-	-	45	-	-	-	45	-	Deg.
Upper FET RDSon	-	-	-	-	-	-	2	-	2	mOhms
Lower FET RDSon	-	-	-	-	-	-	2	-	2	mOhms
Duty Cycle	-	-	-	-	-	-	14.2	-	17.3	%
On Time Min(switch)	-	-	-	-	-	-	430.1	-	642.5	ns
Cross Over Frequency	-	-	-	-	-	-	-	57	-	KHz

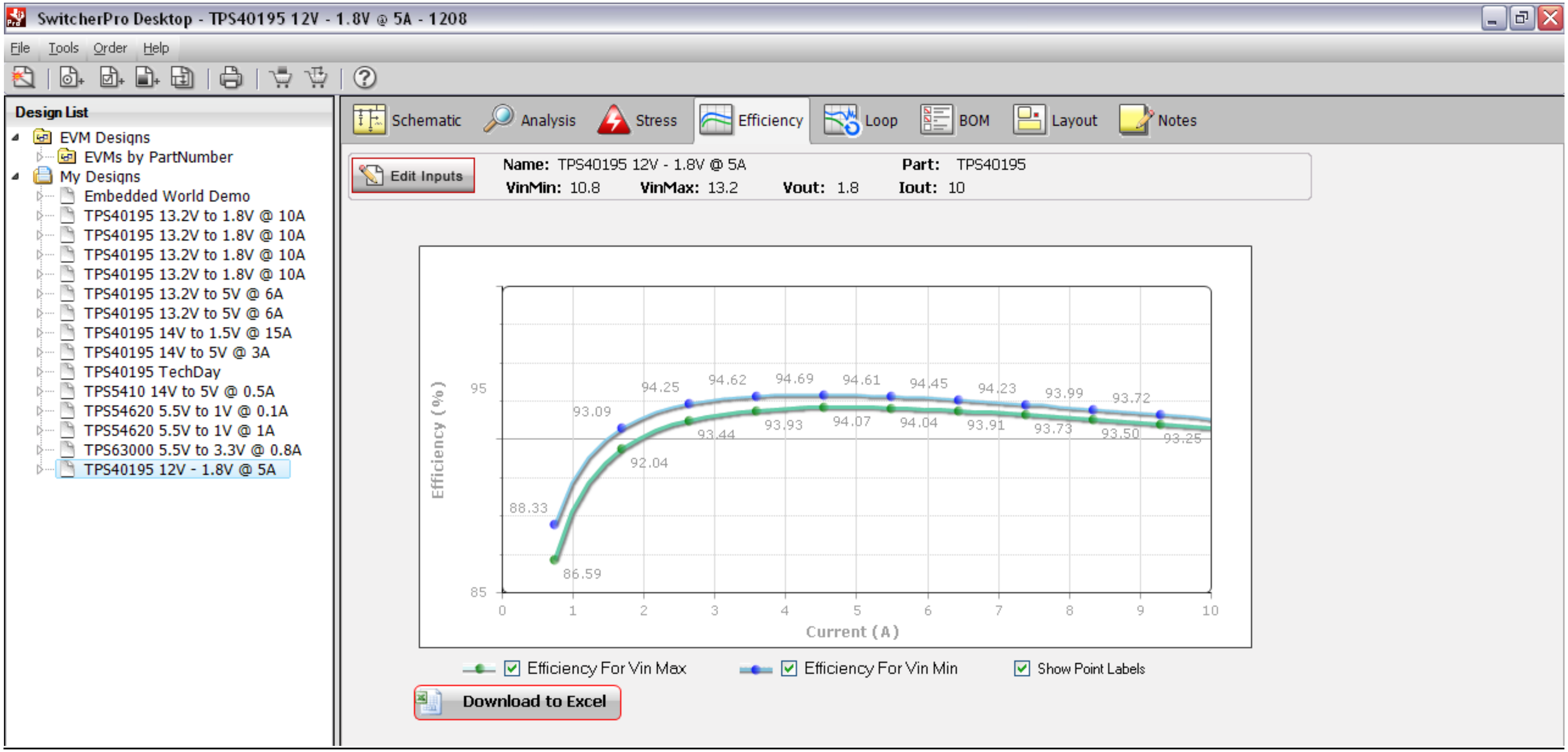
Design List – Stress



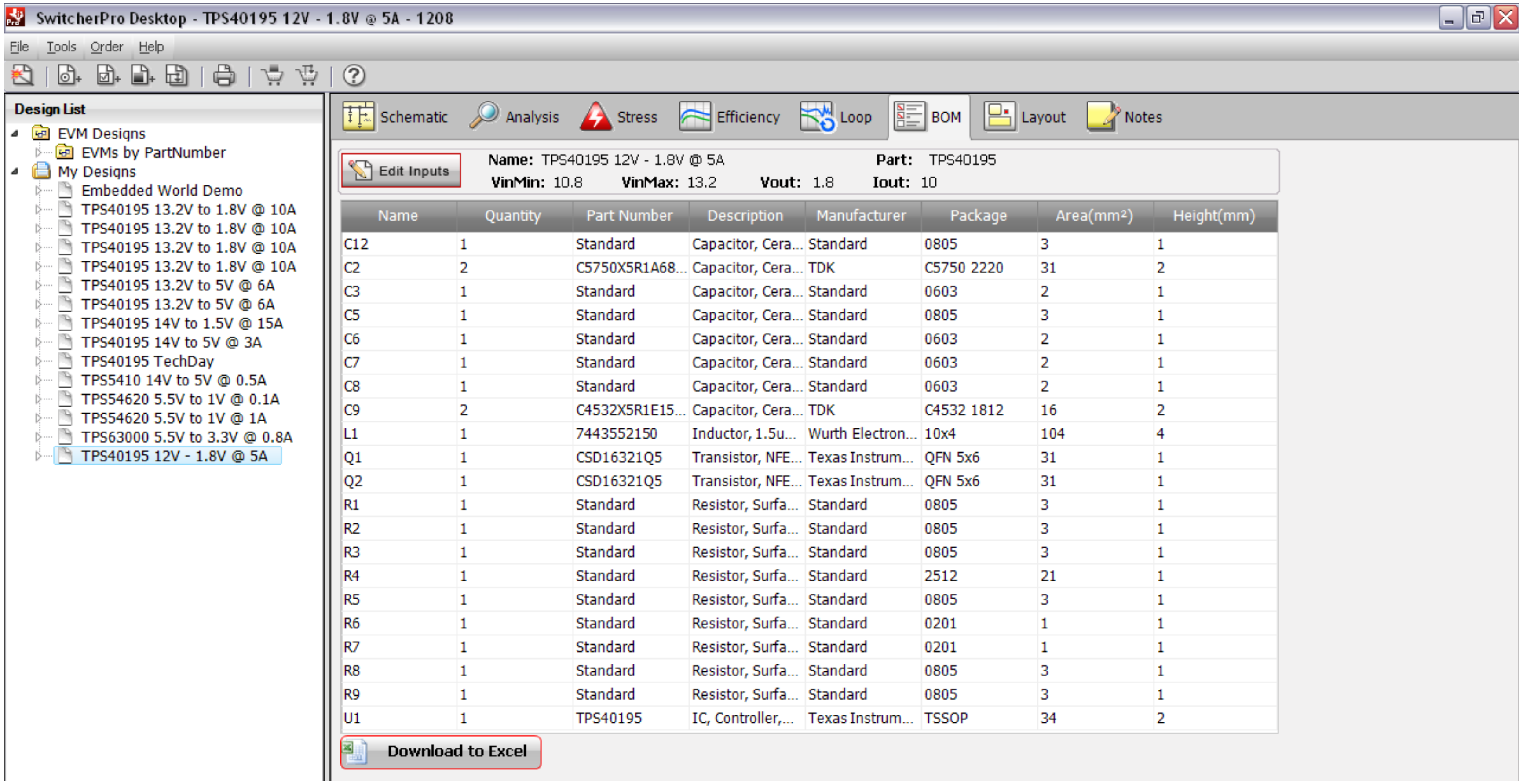
Calculated RMS currents

Calculated max. Temperature

Design List – Efficiency

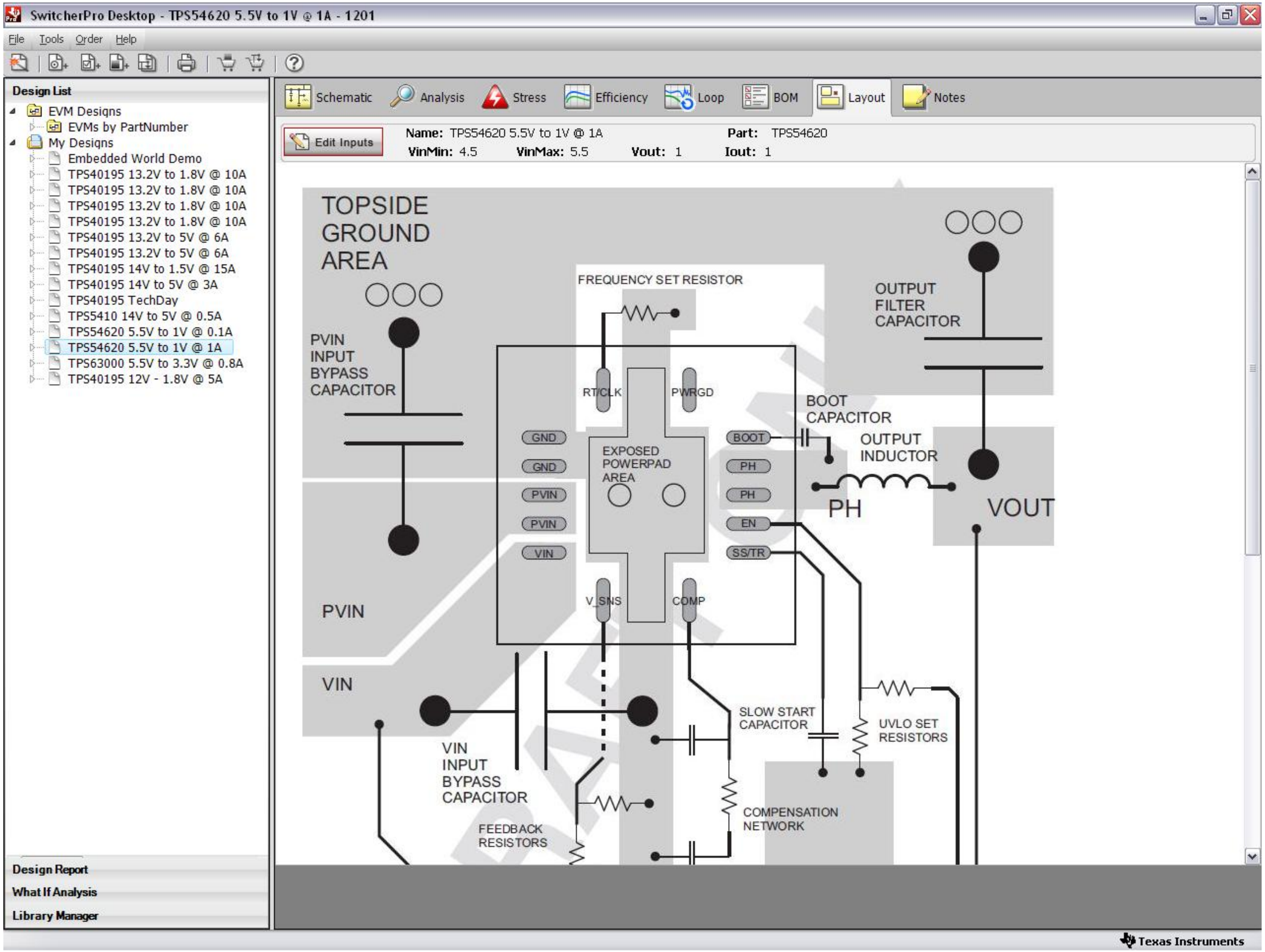


Design List – BOM



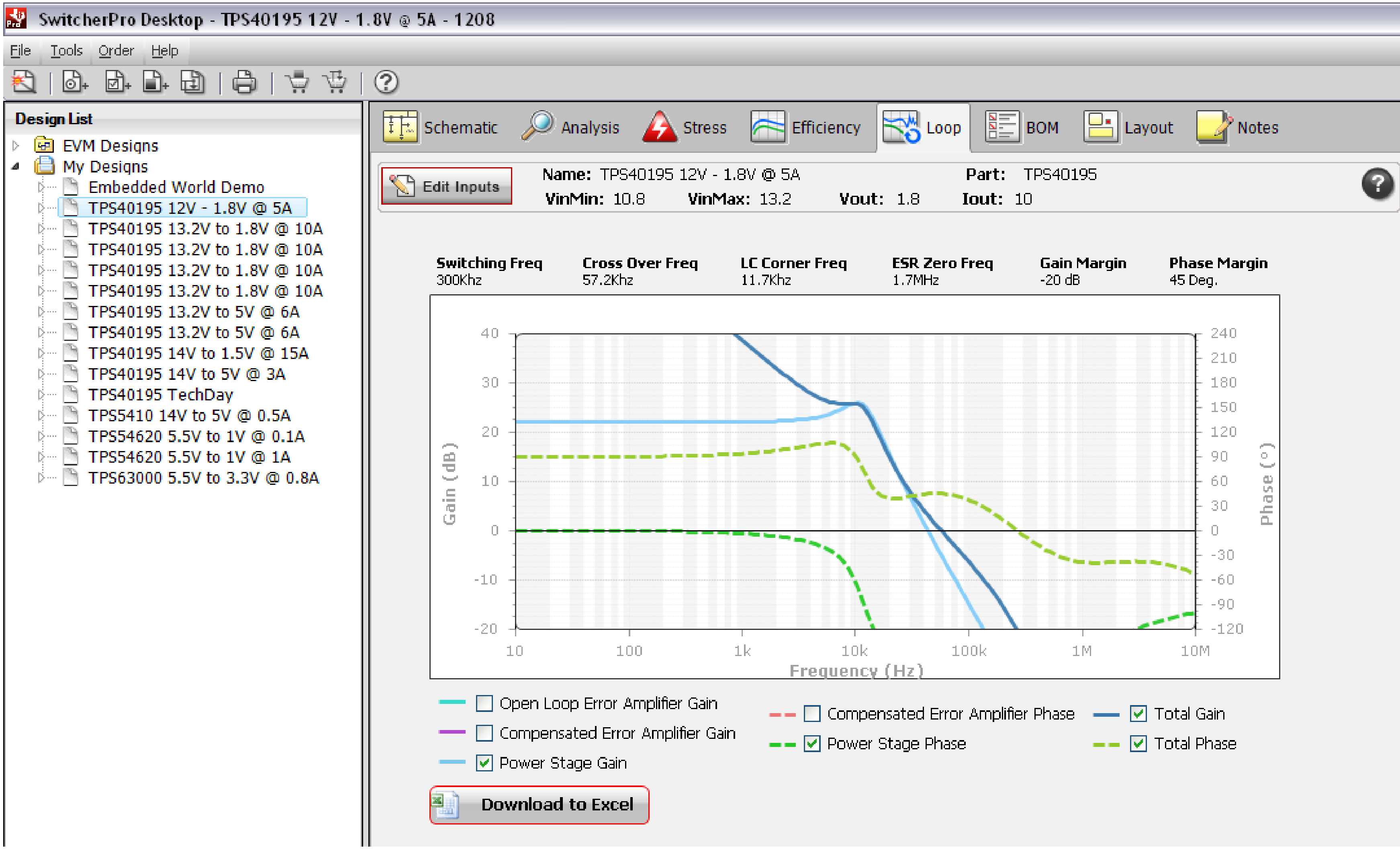
Name	Quantity	Part Number	Description	Manufacturer	Package	Area(mm²)	Height(mm)
C12	1	Standard	Capacitor, Cera...	Standard	0805	3	1
C2	2	C5750X5R1A68...	Capacitor, Cera...	TDK	C5750 2220	31	2
C3	1	Standard	Capacitor, Cera...	Standard	0603	2	1
C5	1	Standard	Capacitor, Cera...	Standard	0805	3	1
C6	1	Standard	Capacitor, Cera...	Standard	0603	2	1
C7	1	Standard	Capacitor, Cera...	Standard	0603	2	1
C8	1	Standard	Capacitor, Cera...	Standard	0603	2	1
C9	2	C4532X5R1E15...	Capacitor, Cera...	TDK	C4532 1812	16	2
L1	1	7443552150	Inductor, 1.5u...	Wurth Electron...	10x4	104	4
Q1	1	CSD16321Q5	Transistor, NFE...	Texas Instrum...	QFN 5x6	31	1
Q2	1	CSD16321Q5	Transistor, NFE...	Texas Instrum...	QFN 5x6	31	1
R1	1	Standard	Resistor, Surfa...	Standard	0805	3	1
R2	1	Standard	Resistor, Surfa...	Standard	0805	3	1
R3	1	Standard	Resistor, Surfa...	Standard	0805	3	1
R4	1	Standard	Resistor, Surfa...	Standard	2512	21	1
R5	1	Standard	Resistor, Surfa...	Standard	0805	3	1
R6	1	Standard	Resistor, Surfa...	Standard	0201	1	1
R7	1	Standard	Resistor, Surfa...	Standard	0201	1	1
R8	1	Standard	Resistor, Surfa...	Standard	0805	3	1
R9	1	Standard	Resistor, Surfa...	Standard	0805	3	1
U1	1	TPS40195	IC, Controller,...	Texas Instrum...	TSSOP	34	2

PCB Layout

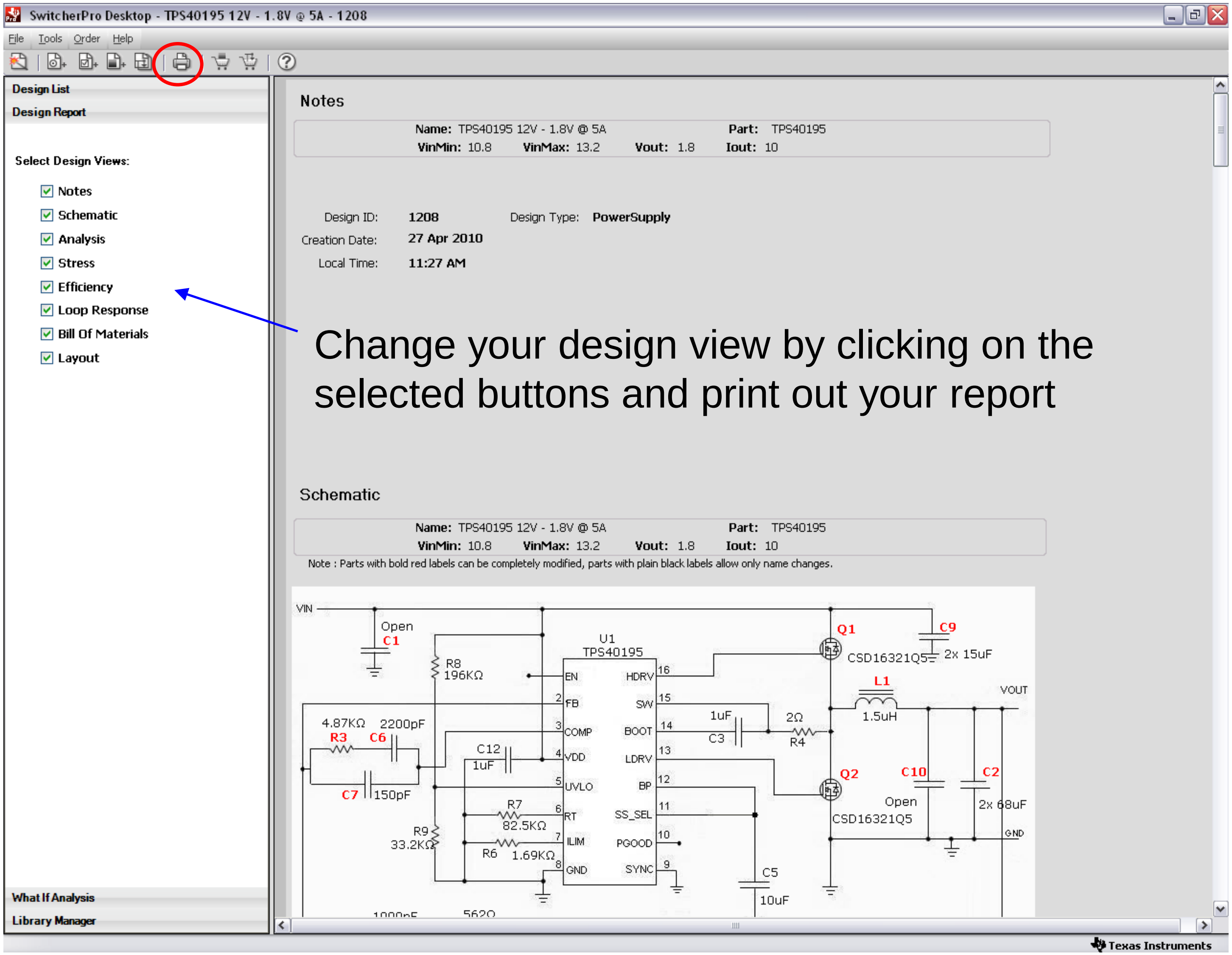


Texas Instruments

Closed Loop Analysis

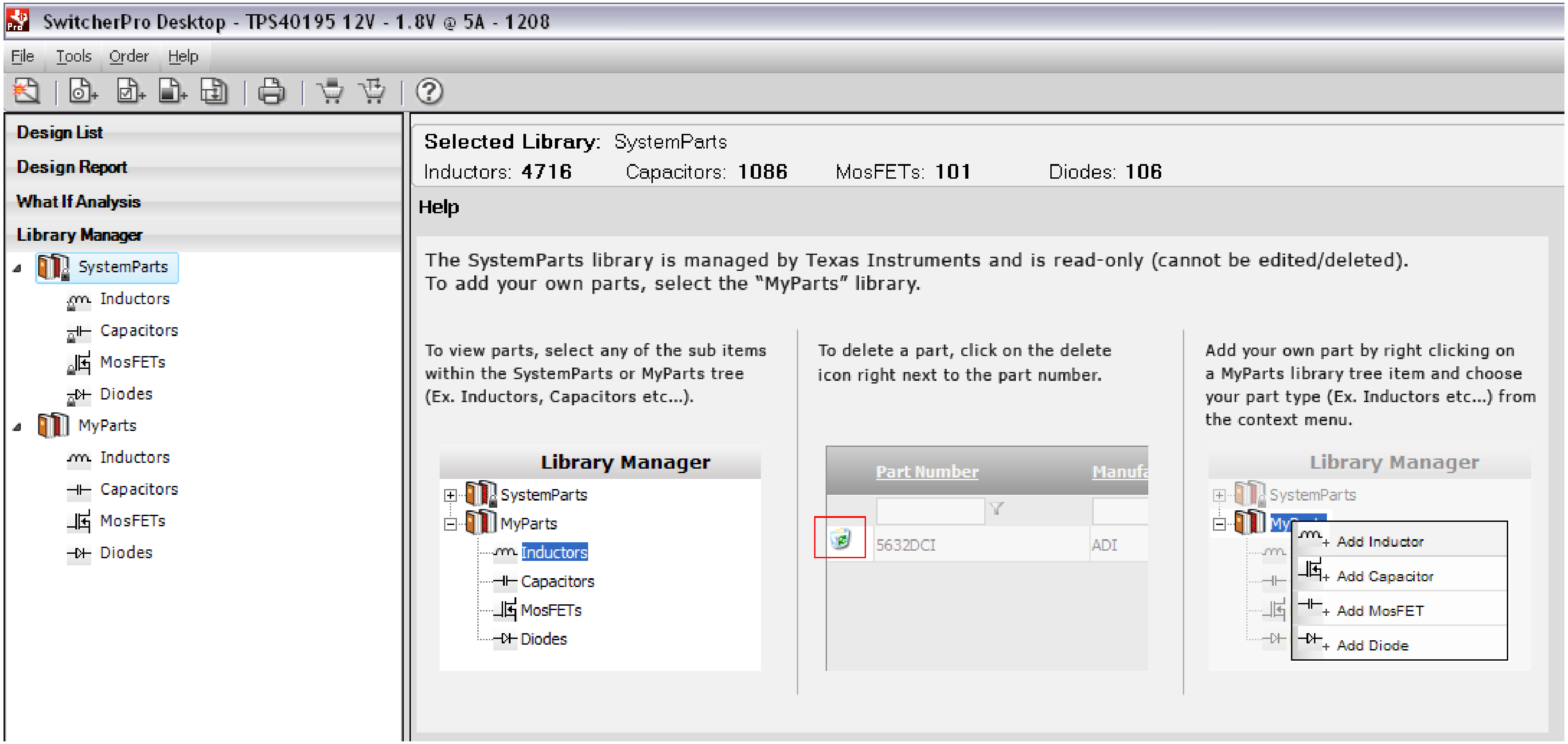


Design Report



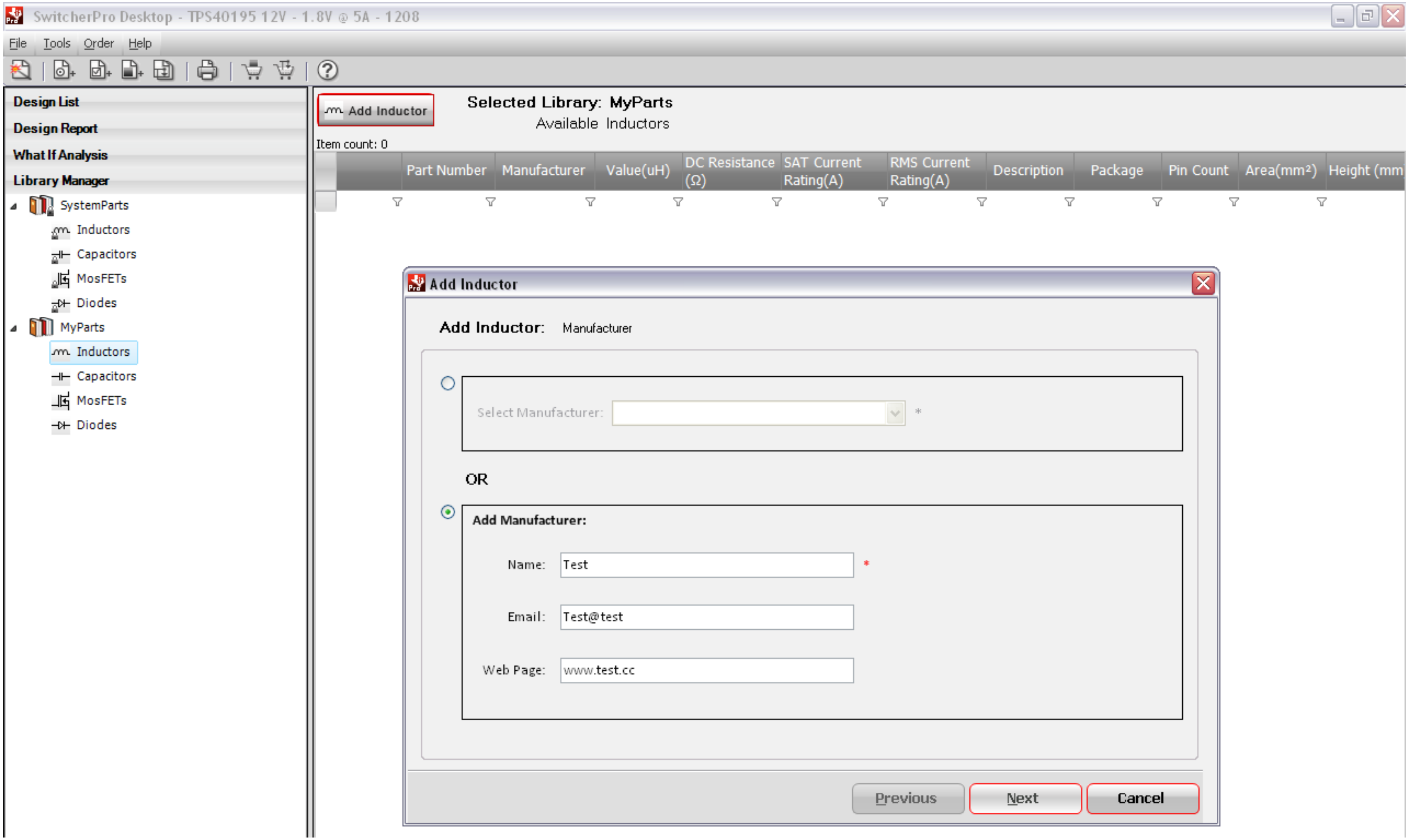
Change your design view by clicking on the selected buttons and print out your report

Library Manager



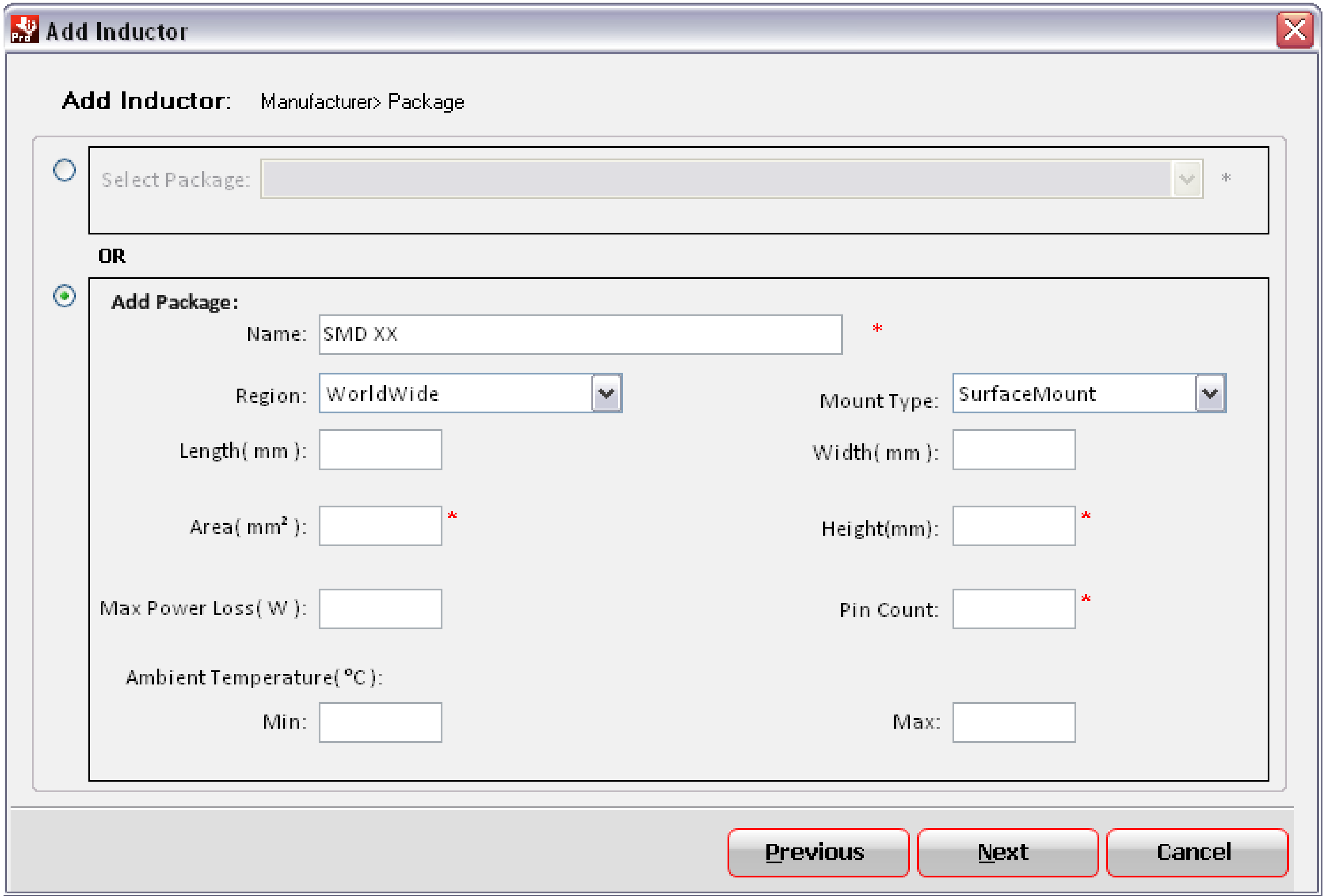
Inductors: 4716
Capacitors: 1086
MosFETs: 101 incl. TI NexFET MosFETS → http://www.ti.com/ww/en/analog/dualcool/index.shtml
Diodes: 106

Add new parts



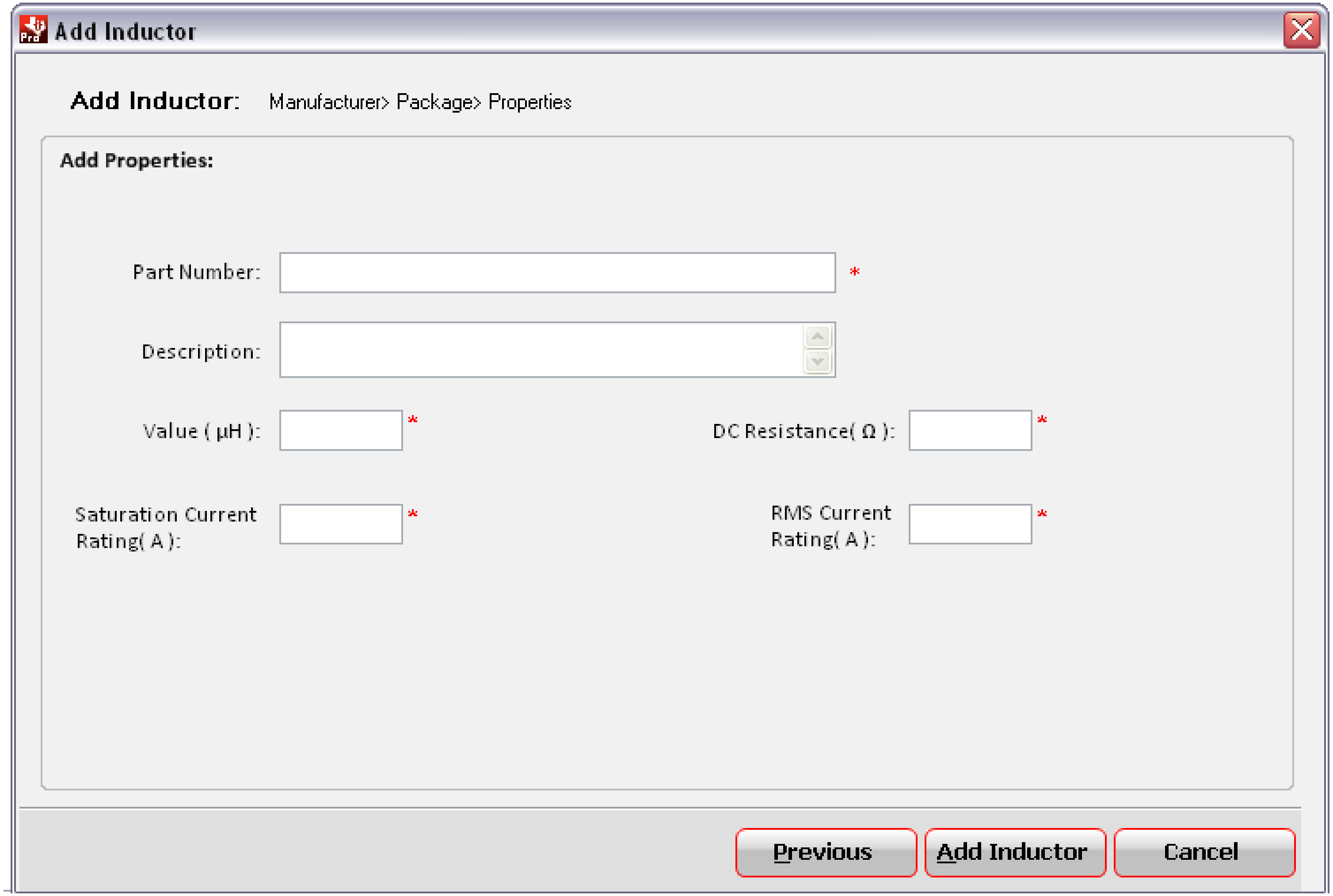
➡ Add your own parameters for Inductors, Capacitors, MosFETs and Diodes

Add new parts



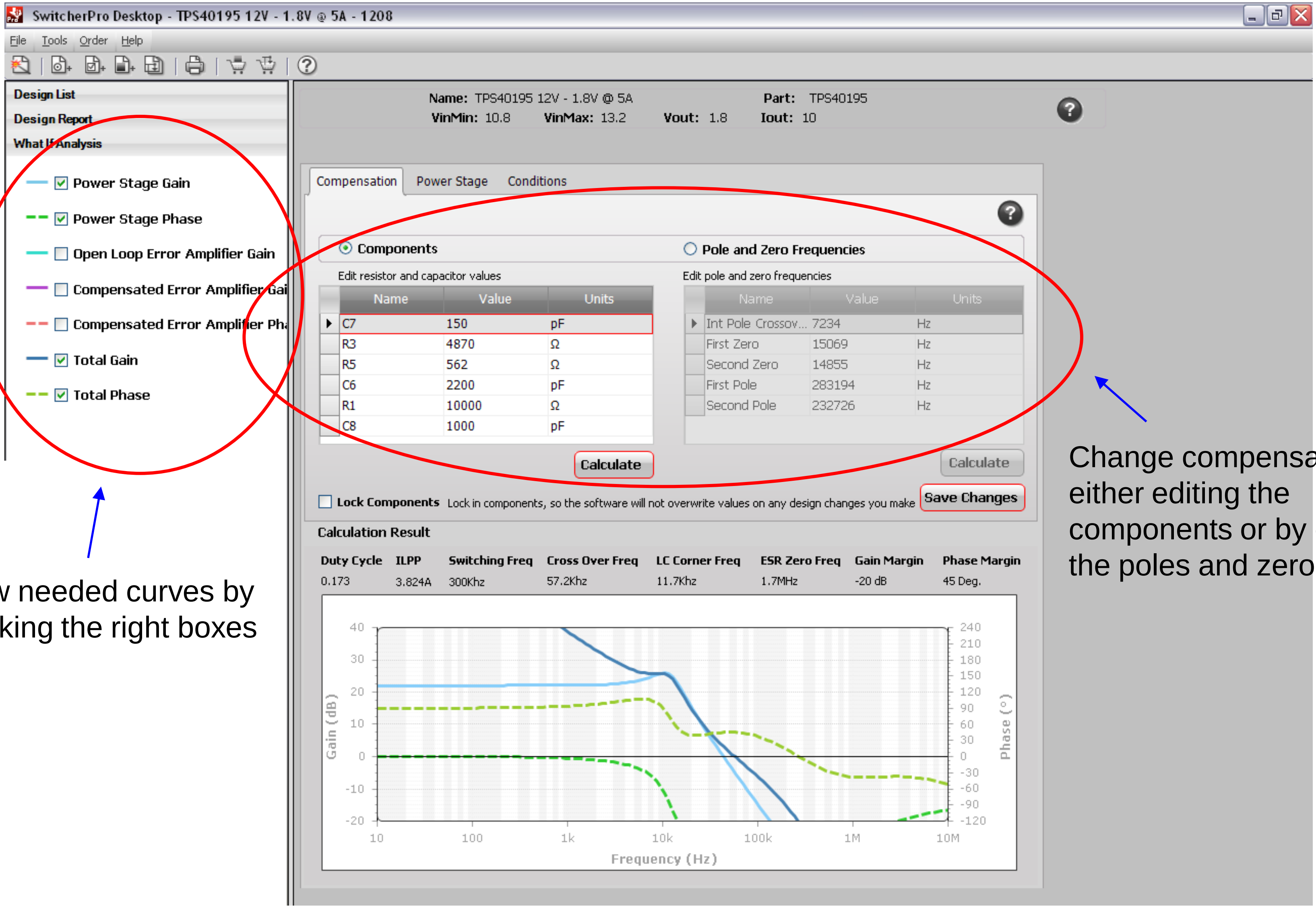
Enter Name, Area, Height and Pin count of your new part

Add new parts



Enter Part Number, Value, DC resistance, I_{SAT} and I_{RMS}

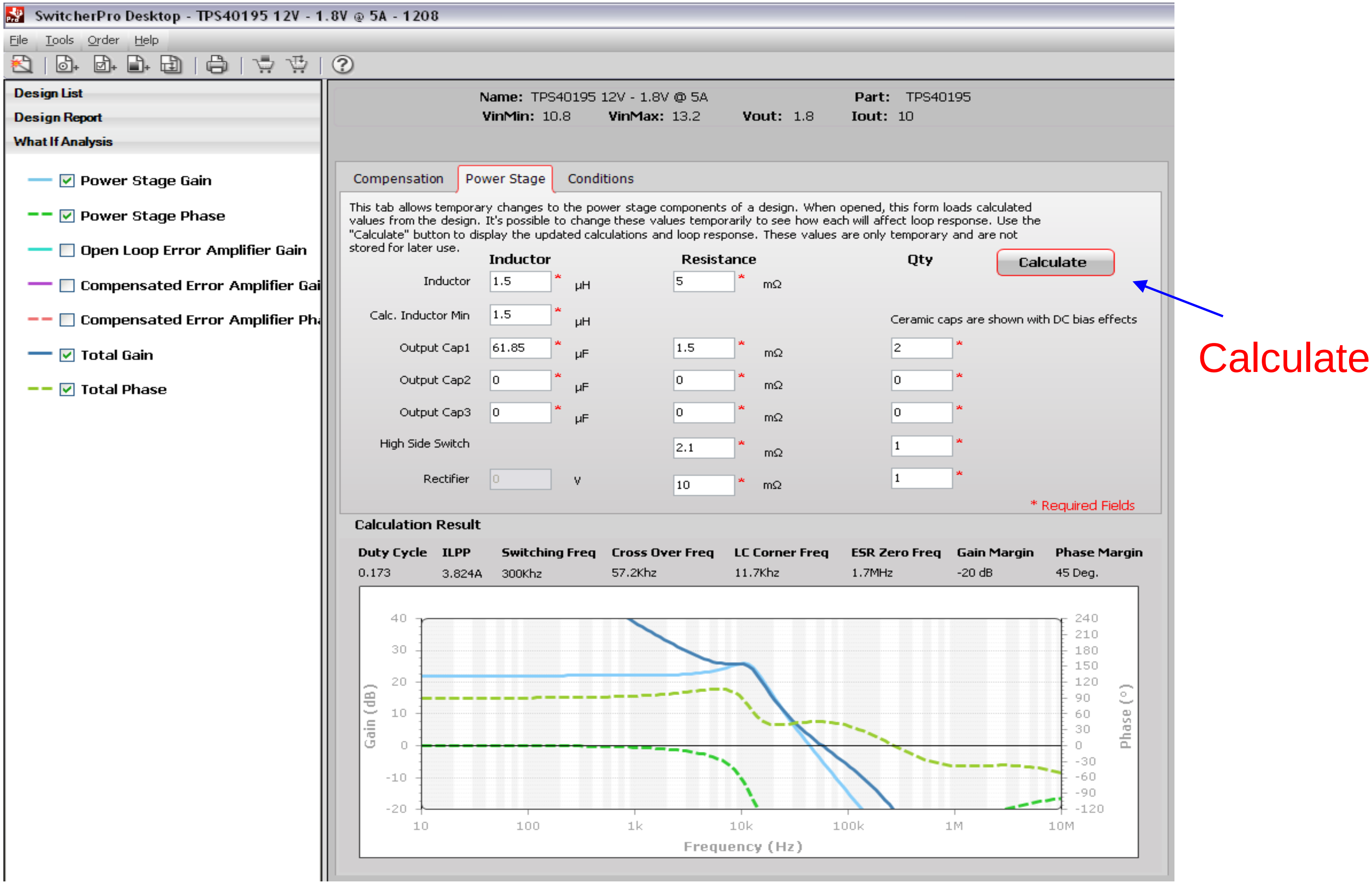
What-If Analysis



Change compensation by either editing the components or by changing the poles and zeros

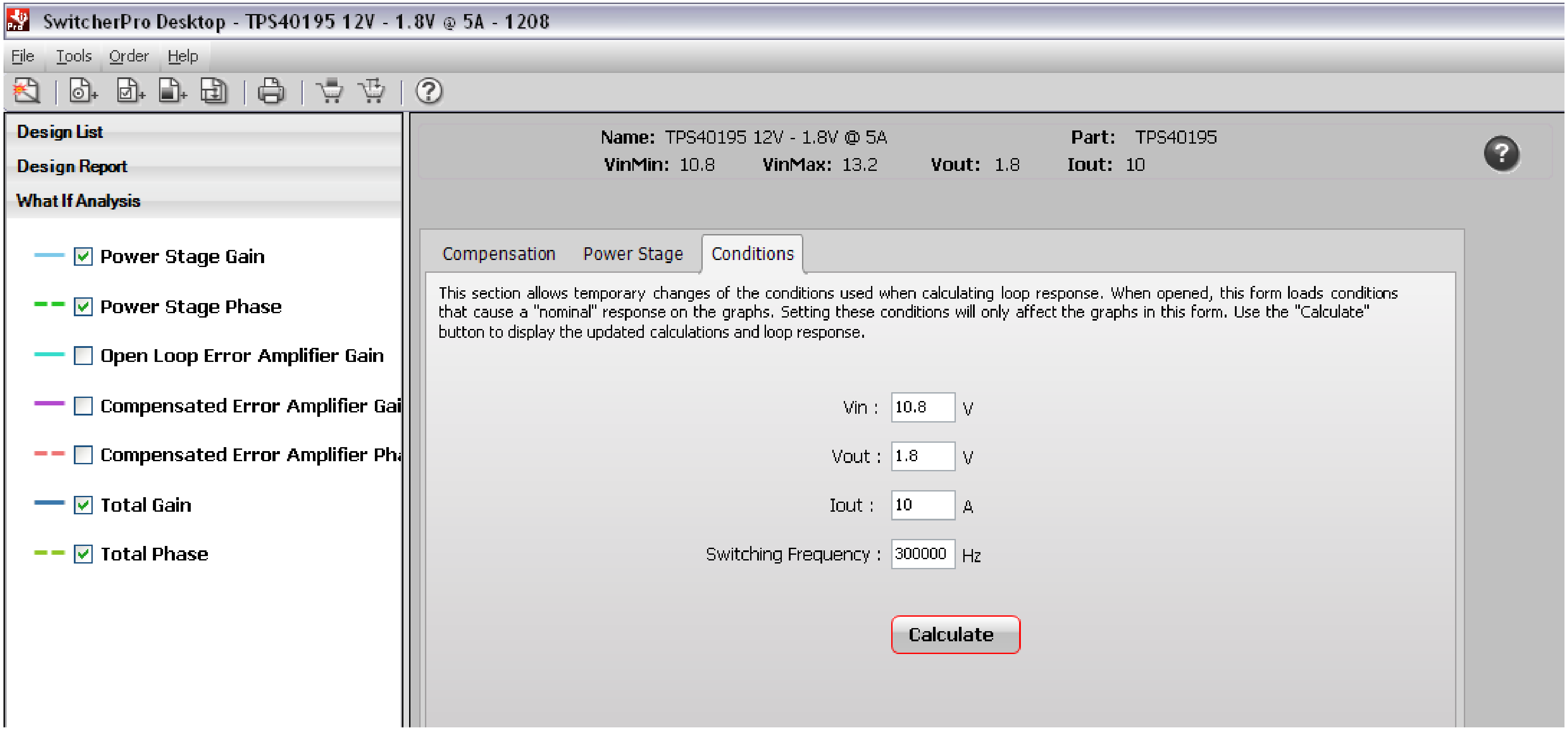
Show needed curves by checking the right boxes

What-If Analysis – Power Stage



Change Inductor, Capacitor and FET values to simulate different LC filter stages configurations

What-If Analysis - Conditions



Simulate different switching frequencies, different input-, output voltages and output currents

SwitcherPro Help

- Quick start training videos allow users to get up to speed quickly with short 3-5 minute help videos from the tool folder on www.ti.com
- Help files within SwitcherPro give users more details about functions and features

Support Software

Video for The Design Manager in SwitcherPro (slac126.wmv, 28353 KB)
18 Jan 2007 wmv

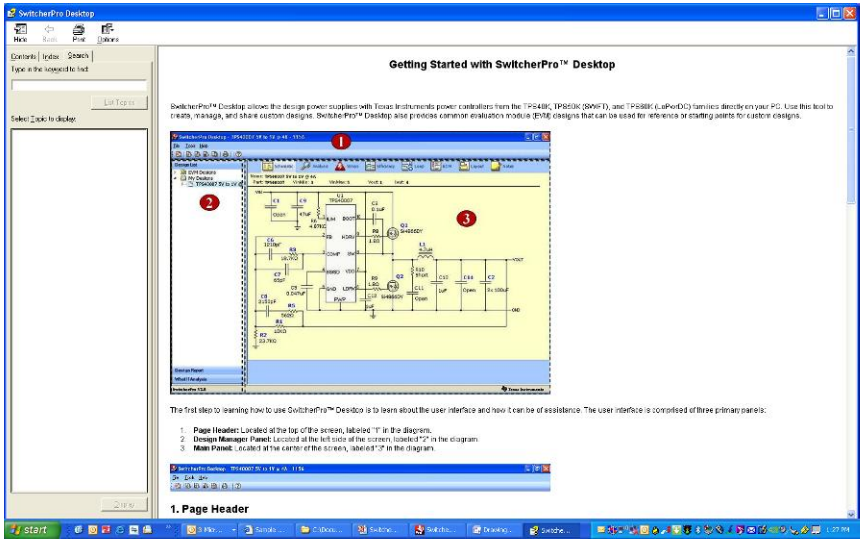
Video for The Design Manager in SwitcherPro (slac126.zip, 23505 KB)
18 Jan 2007 zip

Video for Creating Designs in SwitcherPro (slac125.wmv, 16444 KB)
18 Jan 2007 wmv

Video for Creating Designs in SwitcherPro (slac125.zip, 12934 KB)
18 Jan 2007 zip

Video for Changing/Filtering Parts in SwitcherPro (slac124.wmv, 26584 KB)
18 Jan 2007 wmv

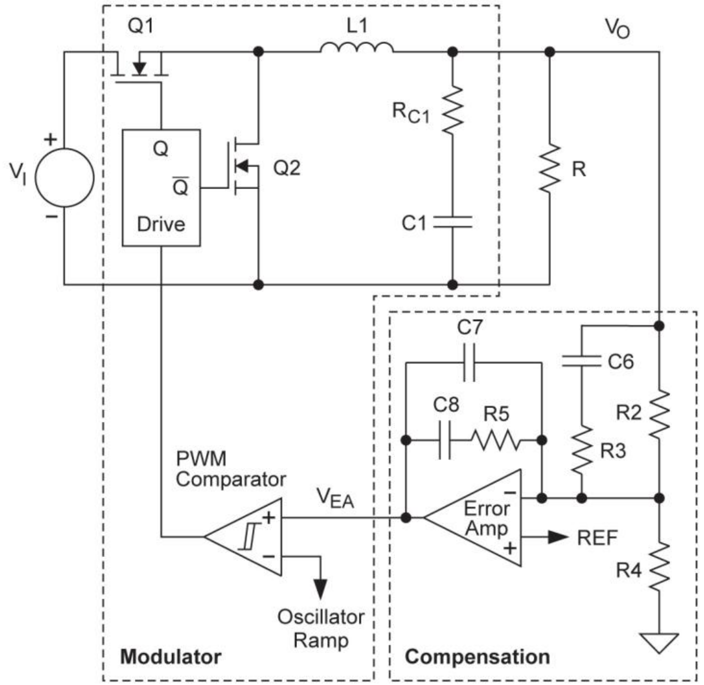
Video for Changing/Filtering Parts in SwitcherPro (slac124.zip, 21911 KB)
18 Jan 2007 zip

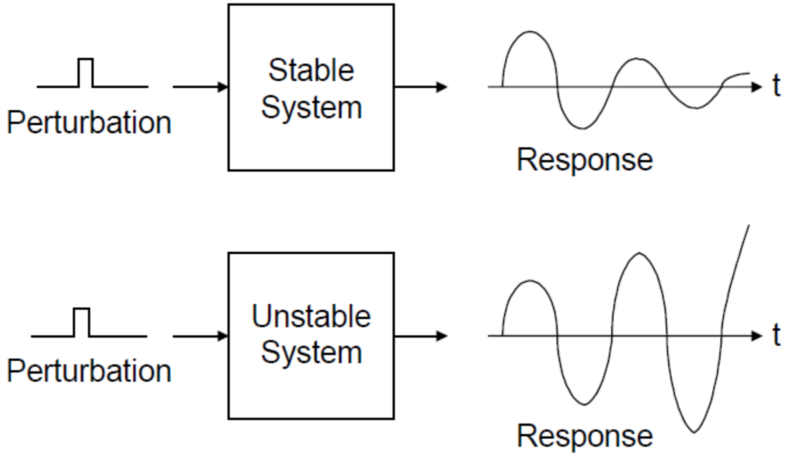


Loop Compensation Basics

Main task of a regulator
Keep the voltage regulated

- Power supply is a closed loop system with negative feedback
- The feedback loop ensures that the output voltage is constant and independent of variations in
  - Input voltage
  - Load current
- The feedback loop "compensates" for changes in the input voltage or load current
- For a stable loop, negative feedback is required





<u>Control Loop consisting of:</u>

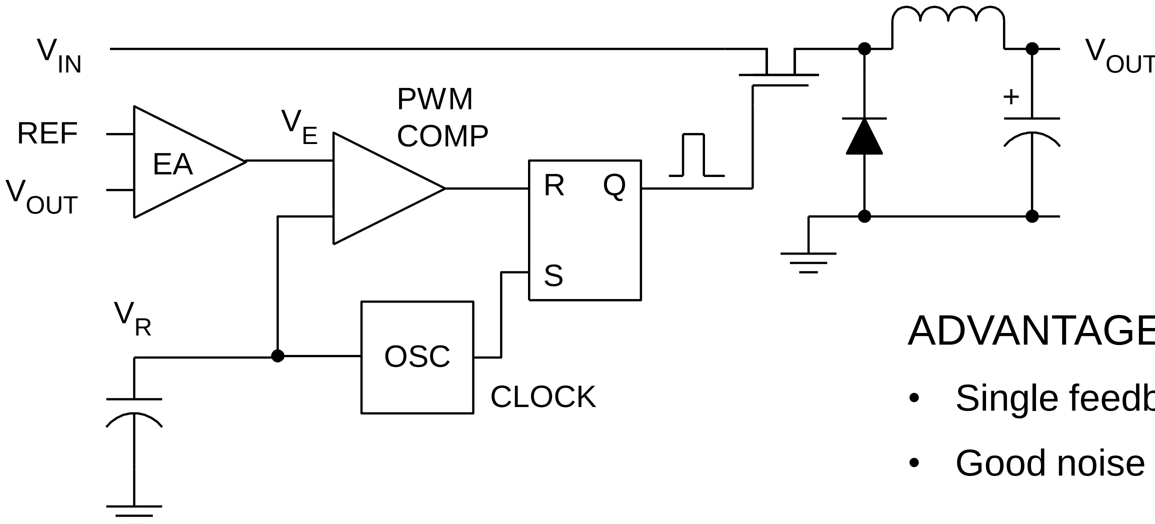
- Modulator:

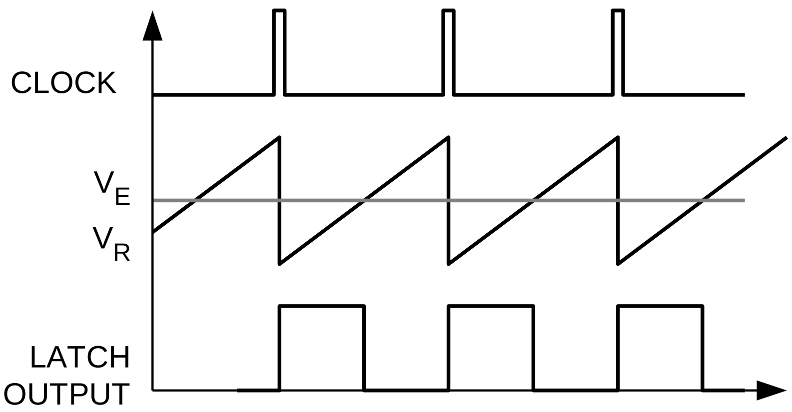
  Oscillator / PWM comparator / PwrStage
- Compensator:

  E/A, Compensation network

Control Loop Topologies

Voltage Mode





ADVANTAGES

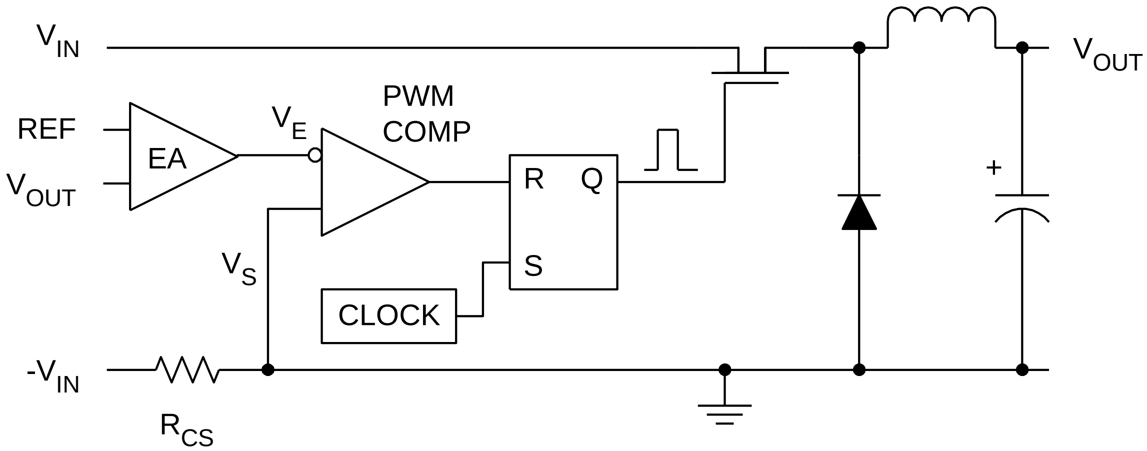
- Single feedback loop
- Good noise margin

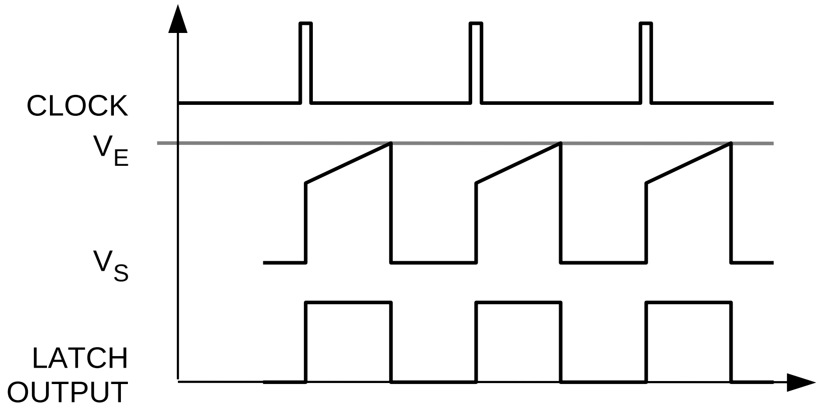
DISADVANTAGES

- Slow dynamic response
- Double-pole compensation – Type III
- Output caps affect comp
- V_{IN} affects loop gain

Control Loop Topologies

Current - Mode





ADVANTAGES

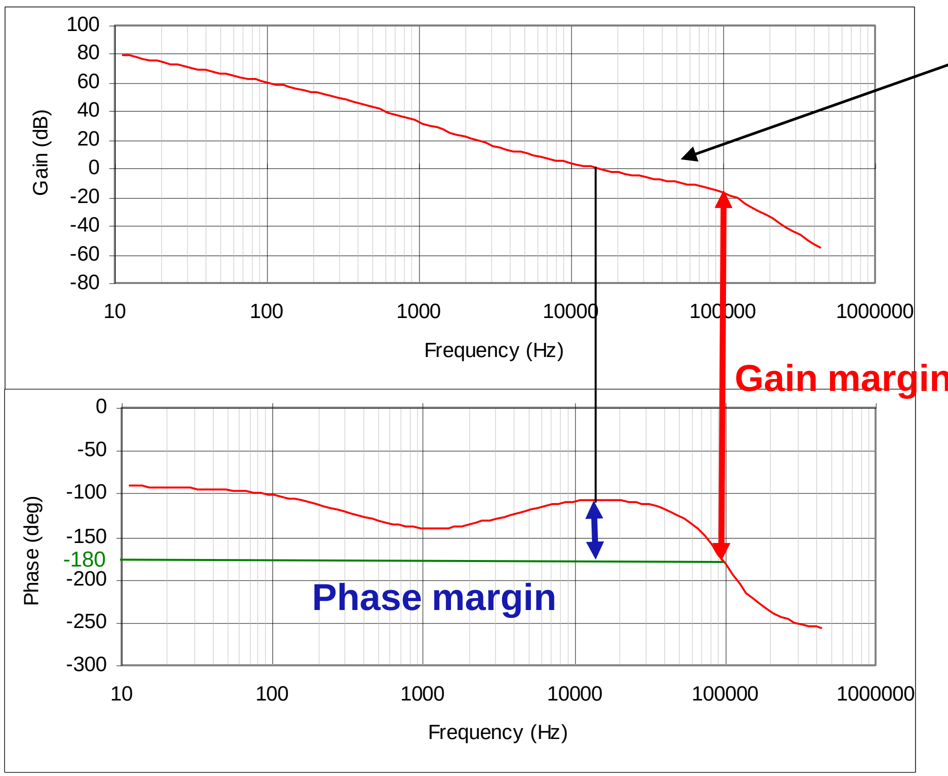
- Fast response to output current changes
- Single-pole compensation
- Parallelability with load sharing

DISADVANTAGES

- Noise sensitivity to current spikes
- Two feedback loops

Phase and Gain Plots

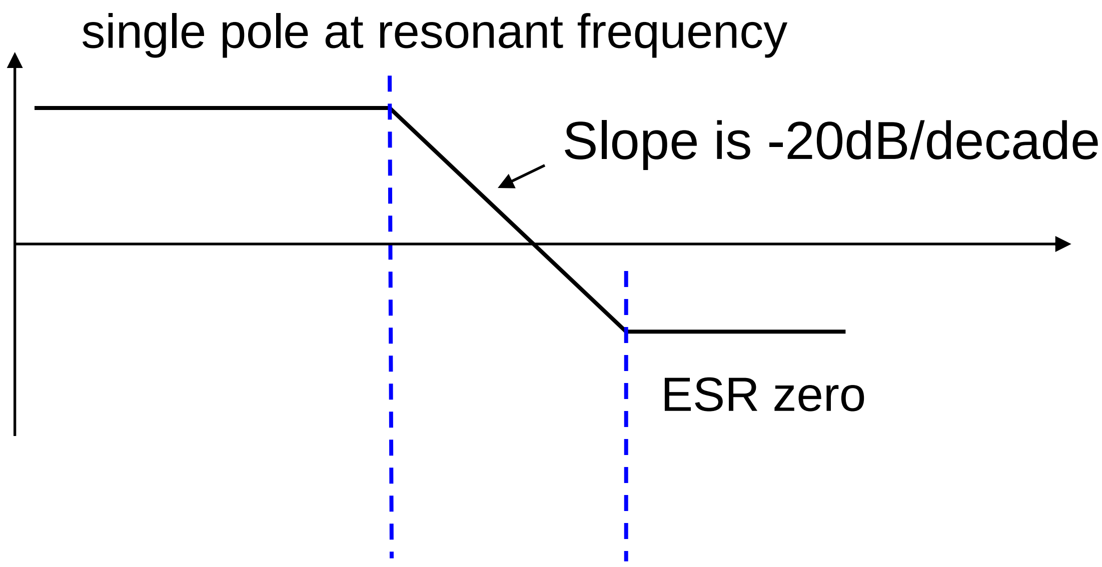
Stability criteria: A minimum value for both the gain and phase margin of a power supply.
In power supply design, a power supply is typically defined to be stable if the gain margin is greater than 6 dB and the phase margin is greater than 45º.
The requirement for stability is typically met if the overall gain crosses 0 dB with a slope of –20 dB/decade



- Phase Margin @ 0dB Gain
- $180^o – 110^o = 70^o$ of Phase Margin
- 45^o to 90^o of Phase Margin is the target for a stable design

Output Filter and Power Stage

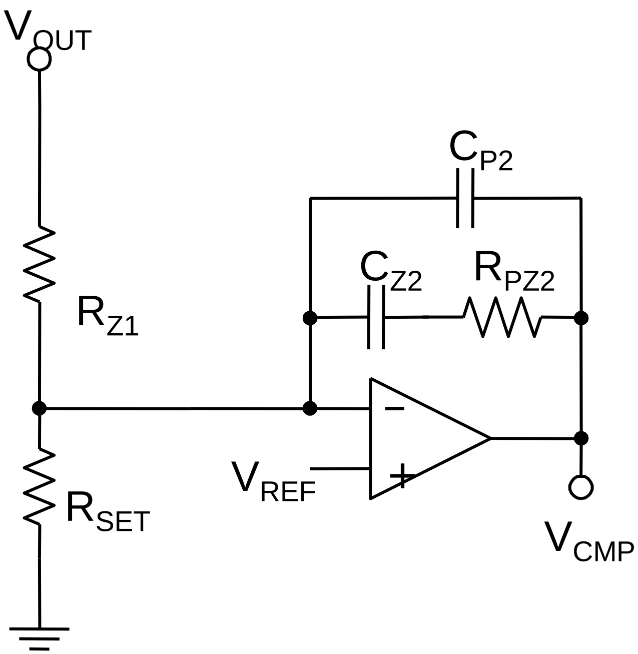
- 1st Order System adds a pole at resonant frequency
- Output capacitor ESR will add a zero

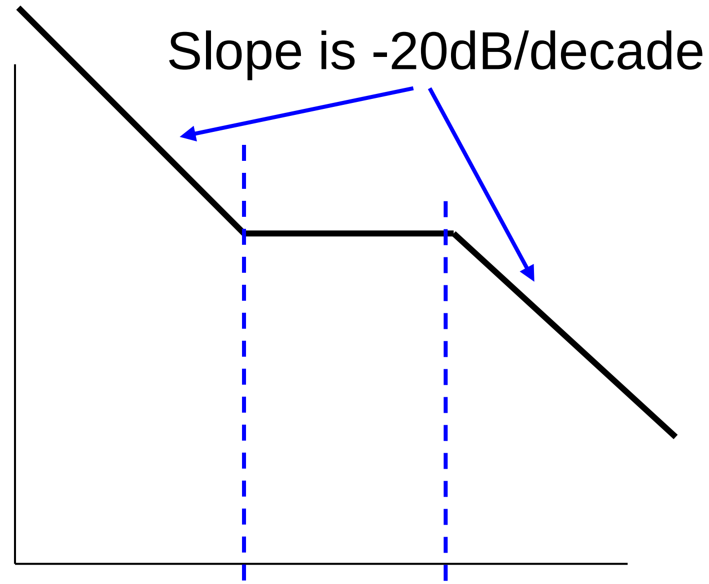


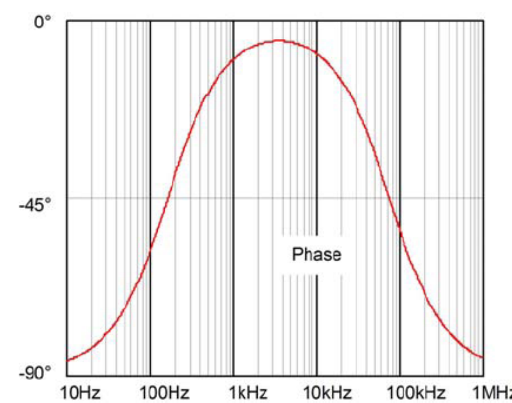
$$f_R = \frac{1}{2\pi \times C \times R_{LOAD}}$$

$$f_{ESR\_Zero} = \frac{1}{2\pi \times ESR \times C_O}$$

Compensation Networks – Type II





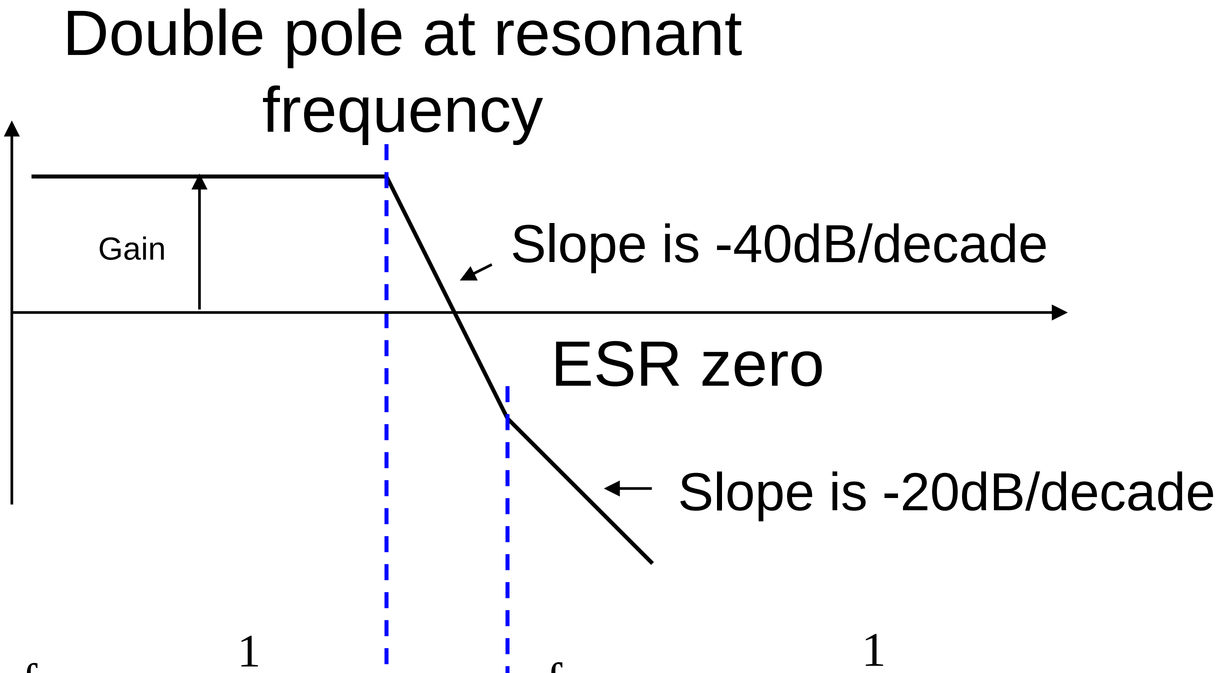


- Type 2.
  - Two poles one at origin and one set by R_{PZ2} & C_{P2}
  - One Zero set by R_{PZ2} & C_{Z2}

$$f_{Z1} = \frac{1}{2\pi \times R_{PZ2} \times C_{Z2}} \qquad f_{P1} = \frac{1}{2\pi \times R_{PZ2} \times C_{P2}}$$

Output Filter and Power Stage

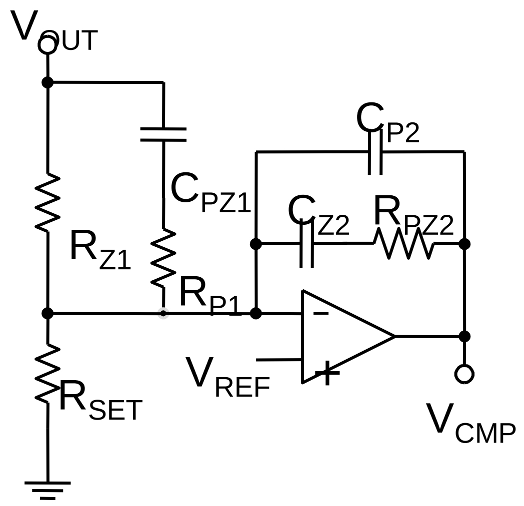
- Output filter is an LC response
- Output capacitor ESR will add a zero

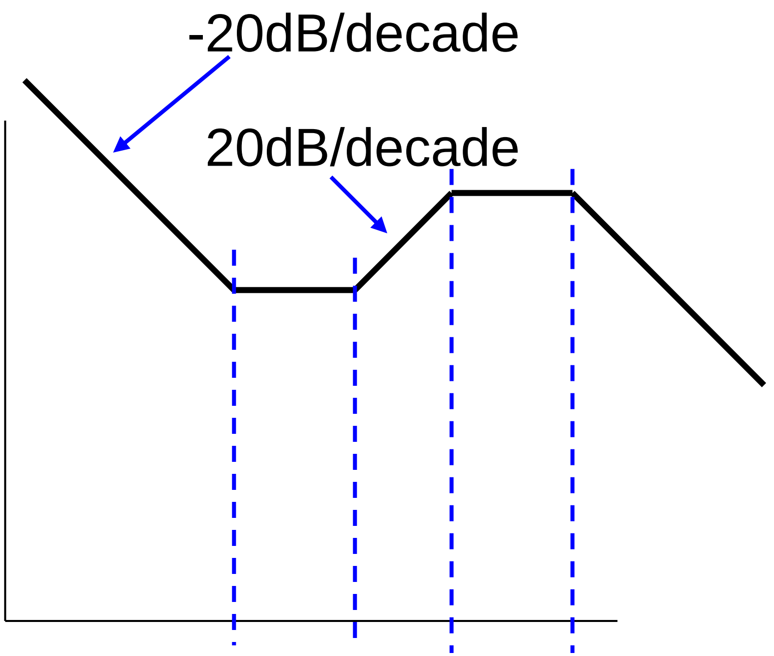


$$f_{LC} = \frac{1}{2\pi \times \sqrt{L \times C_O}}$$

$$f_{ESR\_Zero} = \frac{1}{2\pi \times ESR \times C_O}$$

Compensation Networks – Type III

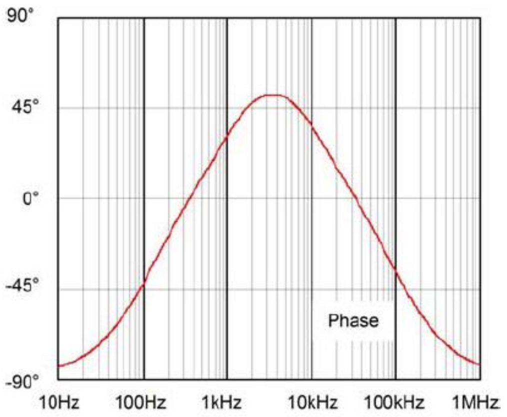




- Type 3.
  - Three poles one at origin, one set by R_{PZ2} & C_{P2} and one by R_{P1} & C_{PZ1}
  - Two zeros one set by C_{Z2} & R_{PZ2} and one by R_{Z1} & C_{PZ1}

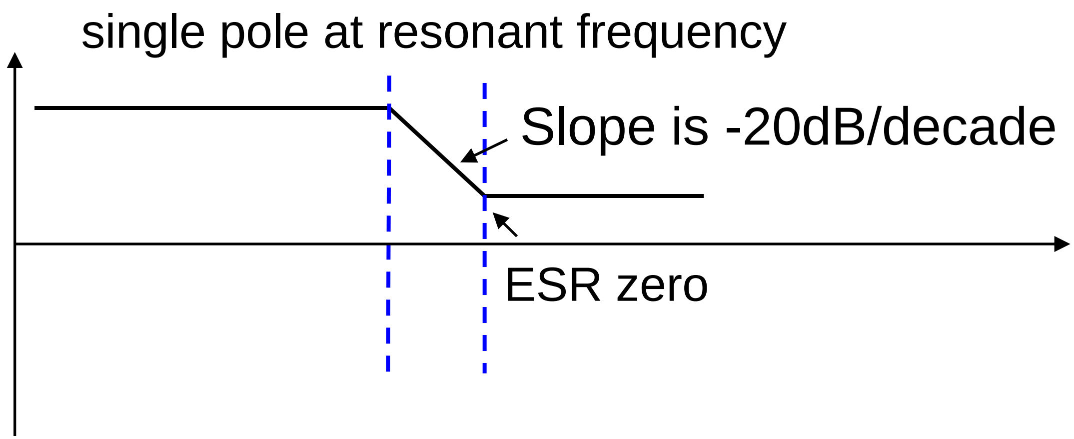
$$f_{Z1} = \frac{1}{2\pi \times R_{Z1} \times C_{PZ1}} \qquad f_{P1} = \frac{1}{2\pi \times R_{P1} \times C_{PZ1}}$$

$$f_{Z2} = \frac{1}{2\pi \times R_{PZ2} \times C_{Z2}} \qquad f_{P2} = \frac{1}{2\pi \times R_{PZ2} \times C_{P2}}$$



Output Filter and Power Stage

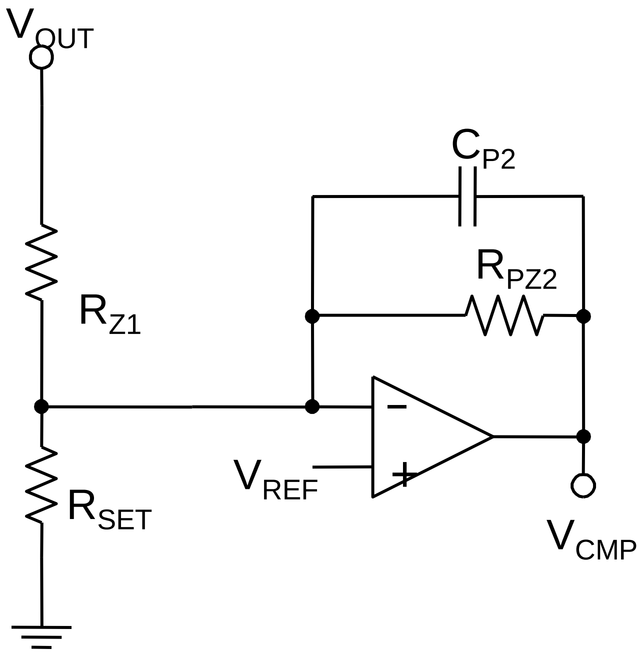
- 1st Order System adds a pole at resonant frequency
- Output capacitor ESR will add a zero

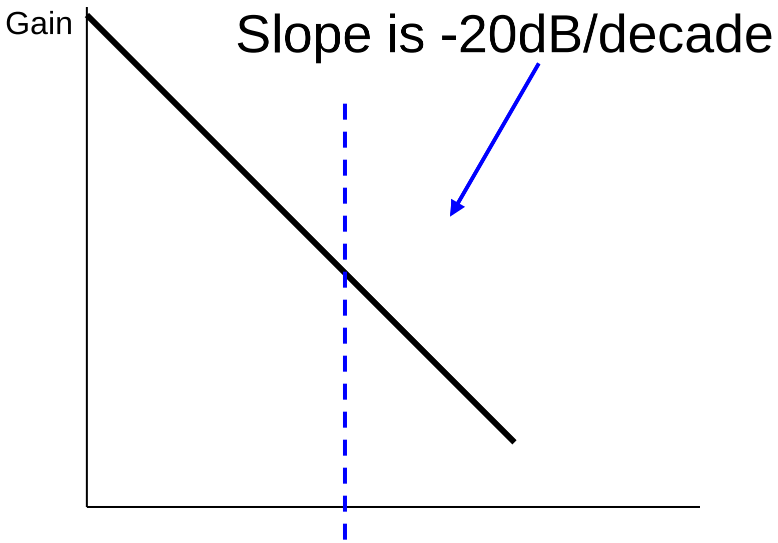


$$f_R = \frac{1}{2\pi \times C \times R_{LOAD}}$$

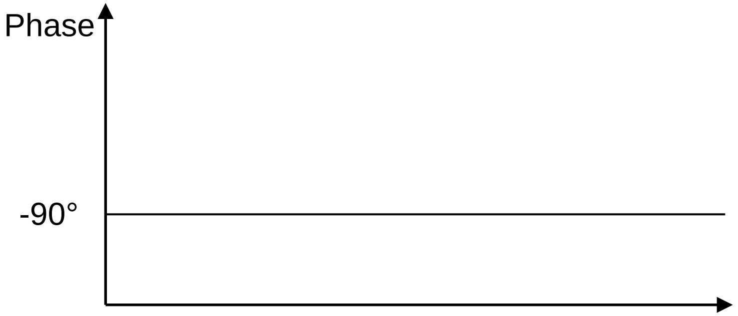
$$f_{ESR\_Zero} = \frac{1}{2\pi \times ESR \times C_O}$$

Compensation Networks – Type I





$$f_{DP} = \frac{1}{2\pi \times R_{PZ2} \times C_{P2}}$$



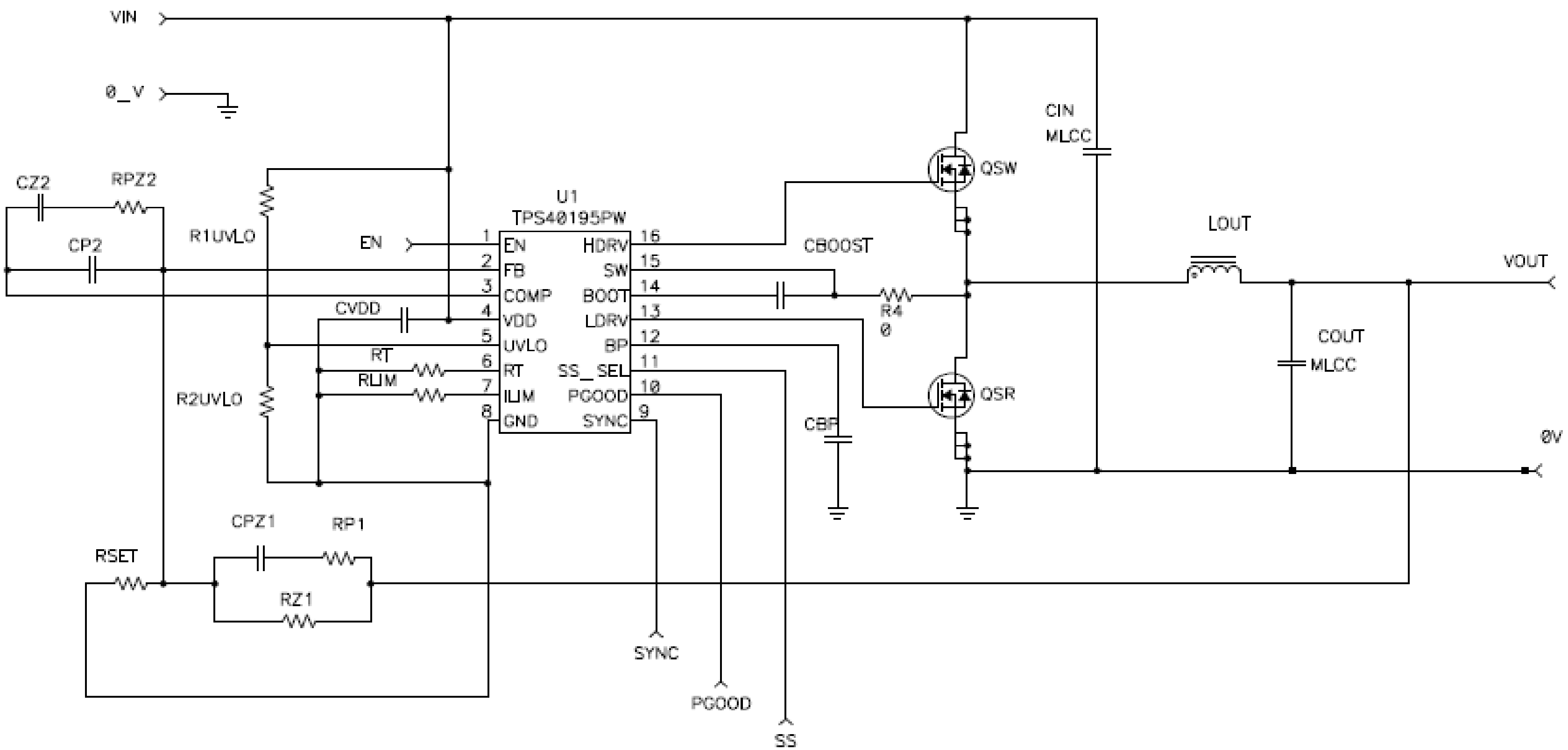
- Type 1.
  - One pole set by R_{PZ2} & C_{P2}

Loop Compensation
Step by Step Design Procedure

DC/DC Design Example

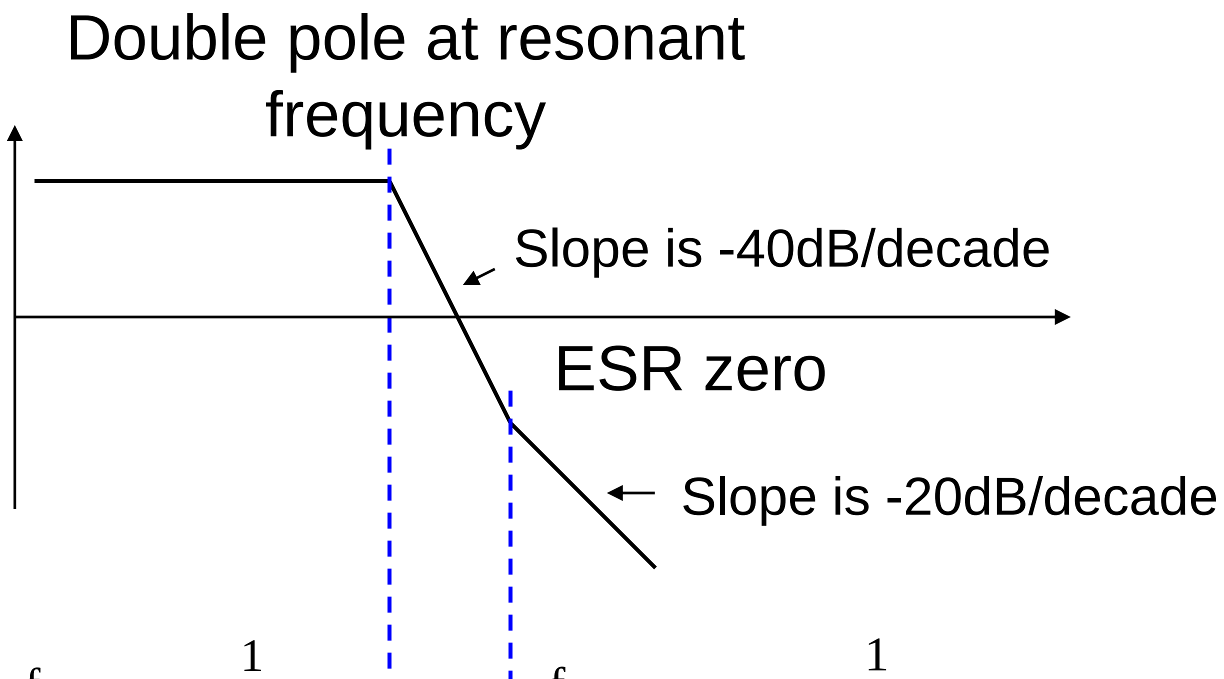
Input Voltage:	10.8V -13.2V
Output Voltage:	1.8V
Output Current:	10A
Controller:	TPS40195
Datasheet:	V_{RAMP}= 1V

TPS40195 Schematic



Output Filter and Power Stage

- Output filter is an LC response
- Output capacitor ESR will add a zero



$$f_{LC} = \frac{1}{2\pi \times \sqrt{L \times C_O}}$$

$$f_{ESR\_Zero} = \frac{1}{2\pi \times ESR \times C_O}$$

Step-by-Step Compensation

- Draw PWM and LC filter gain.
  - PWM gain (no Voltage Feed Forward)

$$\mathrm{DCGAIN} = 20 \times \mathrm{LOG}\left(\frac{V_{IN}}{V_{\mathrm{RAMP}}}\right) = 20 \times \mathrm{LOG}\left(\frac{12}{1}\right) = 21.6\,\mathrm{dB}$$

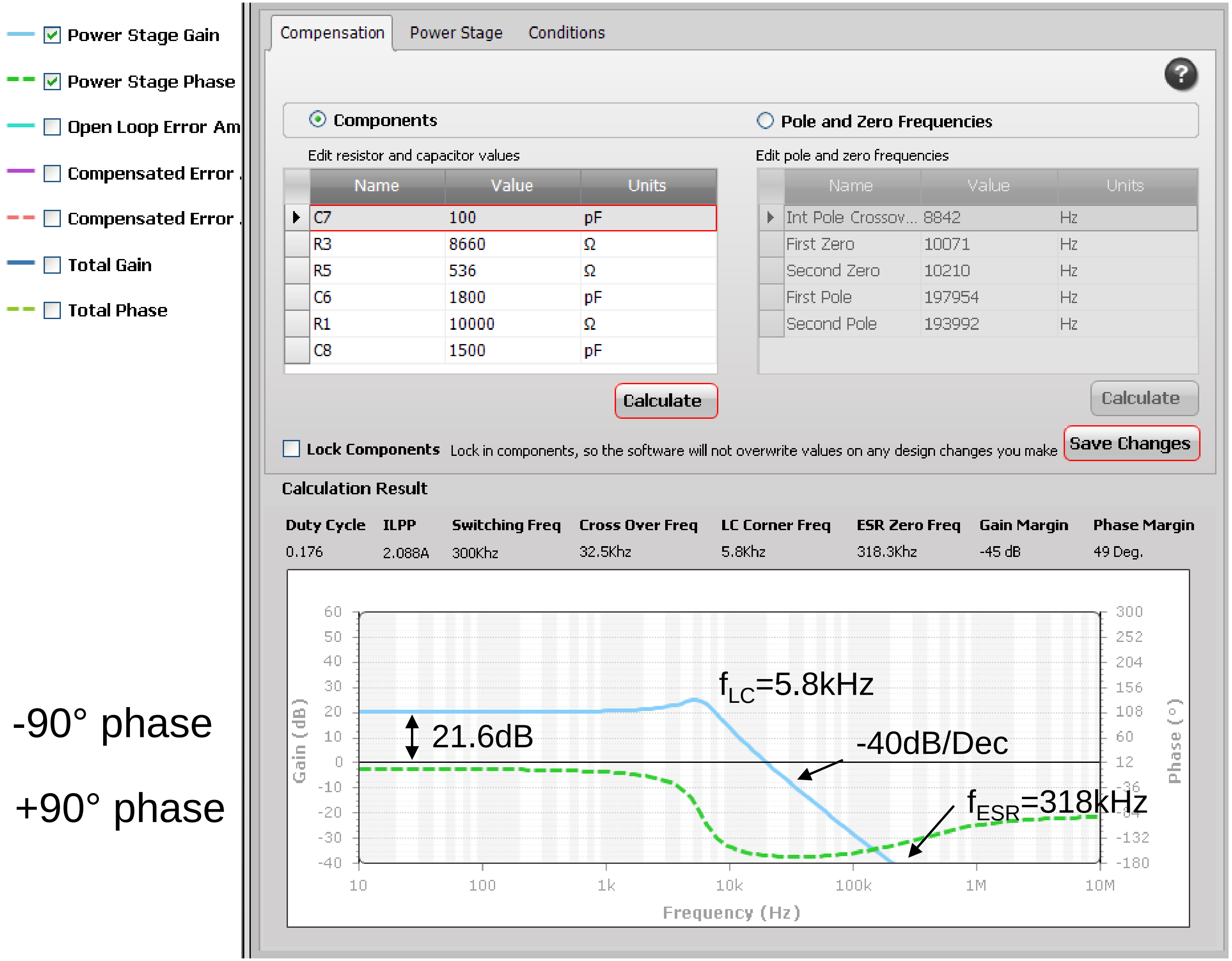
  - LC filter resonant frequency

$$f_{\mathrm{LC\_Pole}} = \frac{1}{2\pi \times \sqrt{L \times C_O}} = \frac{1}{2\pi \times \sqrt{2.5\mu H \times 300\mu F}} = 5.8kHz$$

  - Maximum ESR zero

$$f_{\mathrm{ESR\_Zero}} = \frac{1}{2\pi \times \mathrm{ESR} \times C_O} = \frac{1}{2\pi \times 1.66m\Omega \times 300\mu F} = 318kHz$$

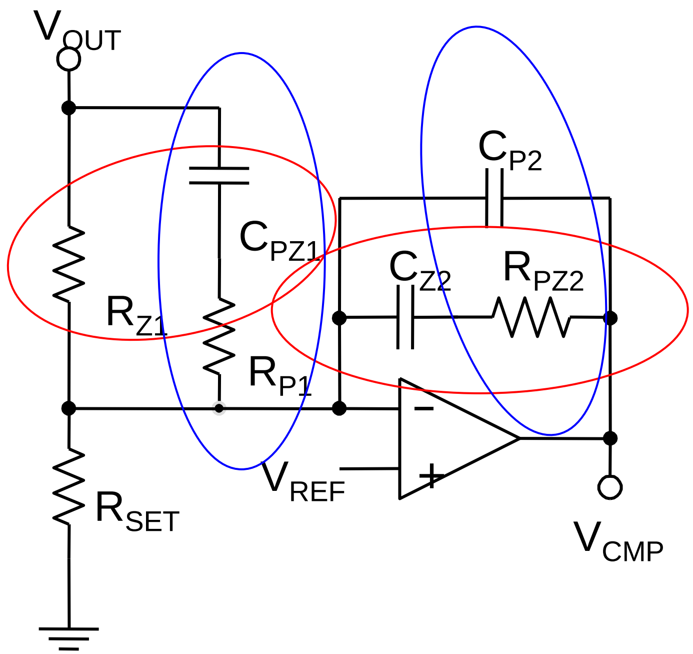
Power Stage Gain + Power Stage Phase

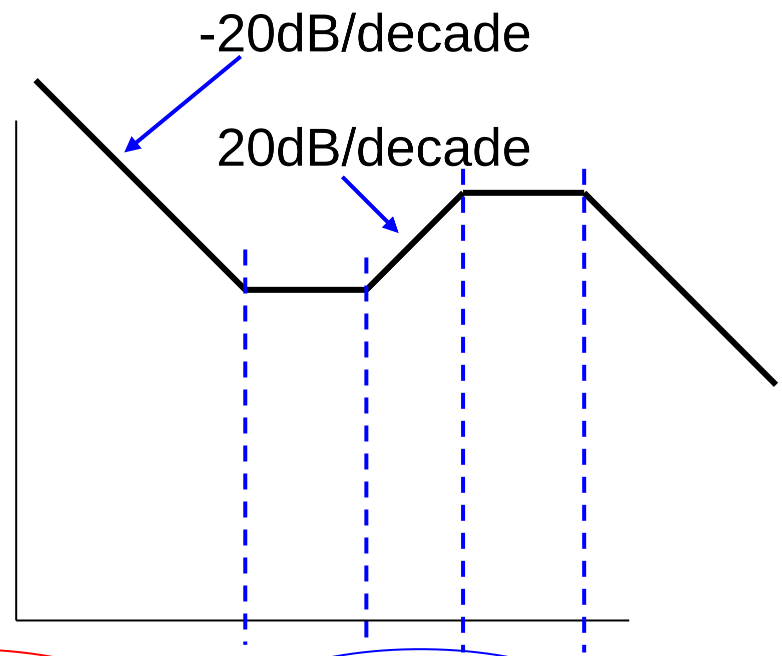


Pole: -90° phase

Zero: +90° phase

Compensation Network – Type III





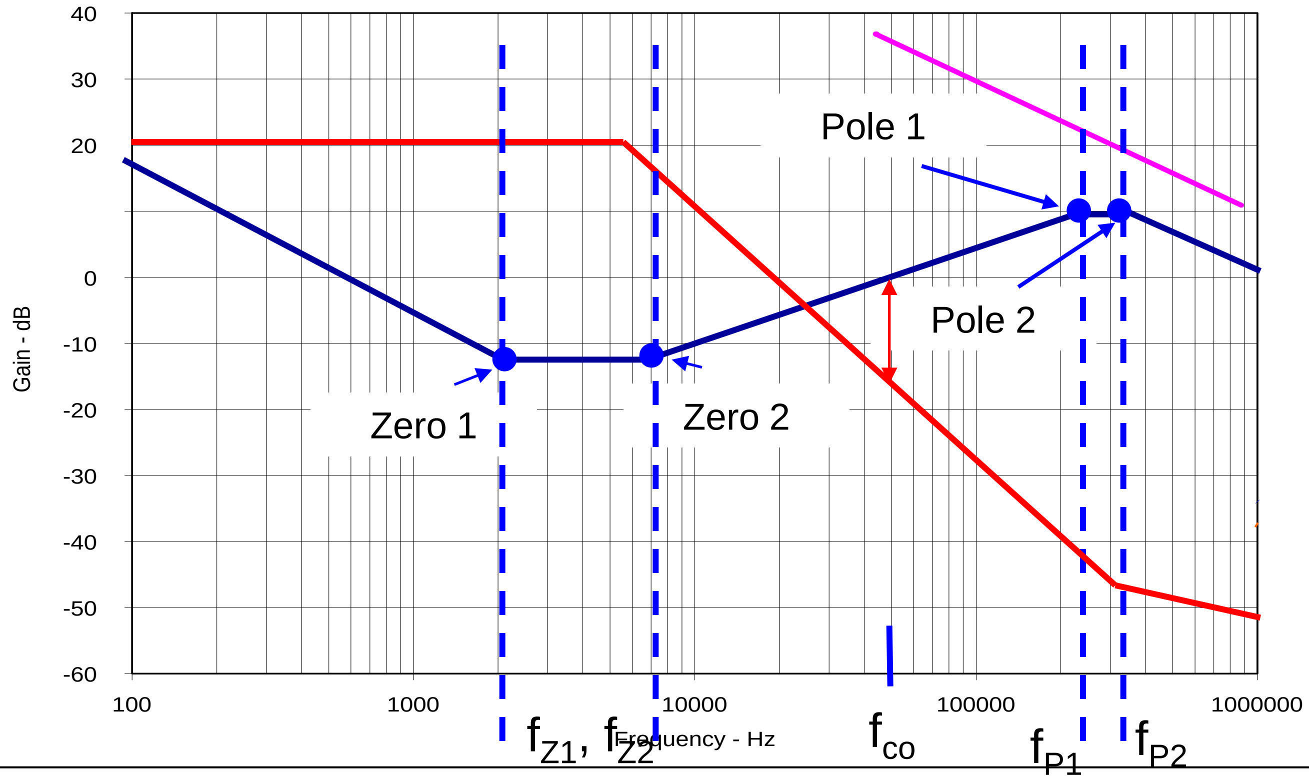
$$f_{Z1} = \frac{1}{2\pi \times R_{Z1} \times C_{PZ1}} \qquad f_{P1} = \frac{1}{2\pi \times R_{P1} \times C_{PZ1}}$$

$$f_{Z2} = \frac{1}{2\pi \times R_{PZ2} \times C_{Z2}} \qquad f_{P2} = \frac{1}{2\pi \times R_{PZ2} \times C_{P2}}$$

- Type III
  - Three poles one at origin, one set by R_{PZ2} & C_{P2} and one by R_{P1} & C_{PZ1}
  - Two zeros one set by C_{Z2} & R_{PZ2} and one by R_{Z1} & C_{PZ1}

Step-by-Step Compensation

- Select cross over frequency f_{co}, between $f_s/4$ to $f_s/10$. Select 50kHz.
- The high frequency gain must be such that the over all system has 0 dB at the required crossover frequency $\longrightarrow$ 15.8dB
- Use type III network.



Step-by-Step Compensation

- Place one zero well below the L-C double pole at 5.8 kHz (f_{Z1}=2.1 kHz)
- Place the second zero near the double pole f_{Z2} at 5.8 kHz (f_{Z2} = 6.9kHz)
- Place one pole well above the desired cross over frequency, selected as one sixth the switching frequency, f_{CO} = 50 kHz, f_{P1} = 300 kHz
- Place the second pole near the ESR zero of the output capacitors of 318 kHz. f_{P2} = 318 kHz
- Set R_{Z1} = 51 kΩ

- Calculate C_{PZ1}

$$C_{PZ1} = \frac{1}{2\pi \times R_{Z1} \times f_{Z1}} = 1500nF$$

- Calculate R_{P1}

$$R_{P1} = \frac{1}{2\pi \times C_{PZ1} \times f_{P1}} = 363\Omega \longrightarrow \text{Use } 357\Omega$$

Step-by-Step Compensation

- Calculate R_{PZ2}

$$R_{PZ2} = \frac{R_{Z1} \times R_{P1}}{R_{Z1} + R_{P1}} \times GAIN = 12.7k\Omega$$

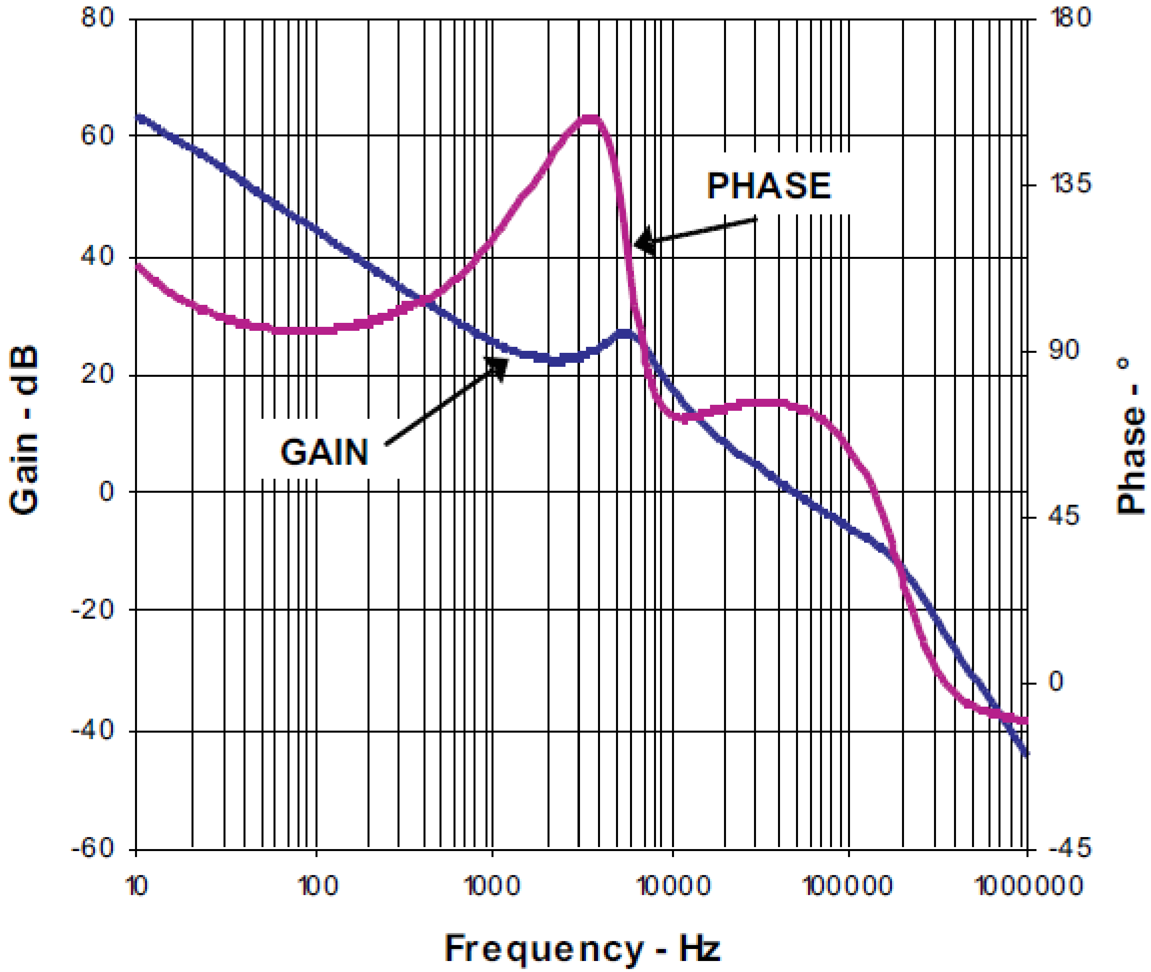
- Calculate C_{Z2}

$$C_{Z2} = \frac{1}{2\pi \times R_{PZ2} \times f_{Z2}} = 1475\,pF \longrightarrow \text{use 2200pF}$$

- Calculate C_{P2}

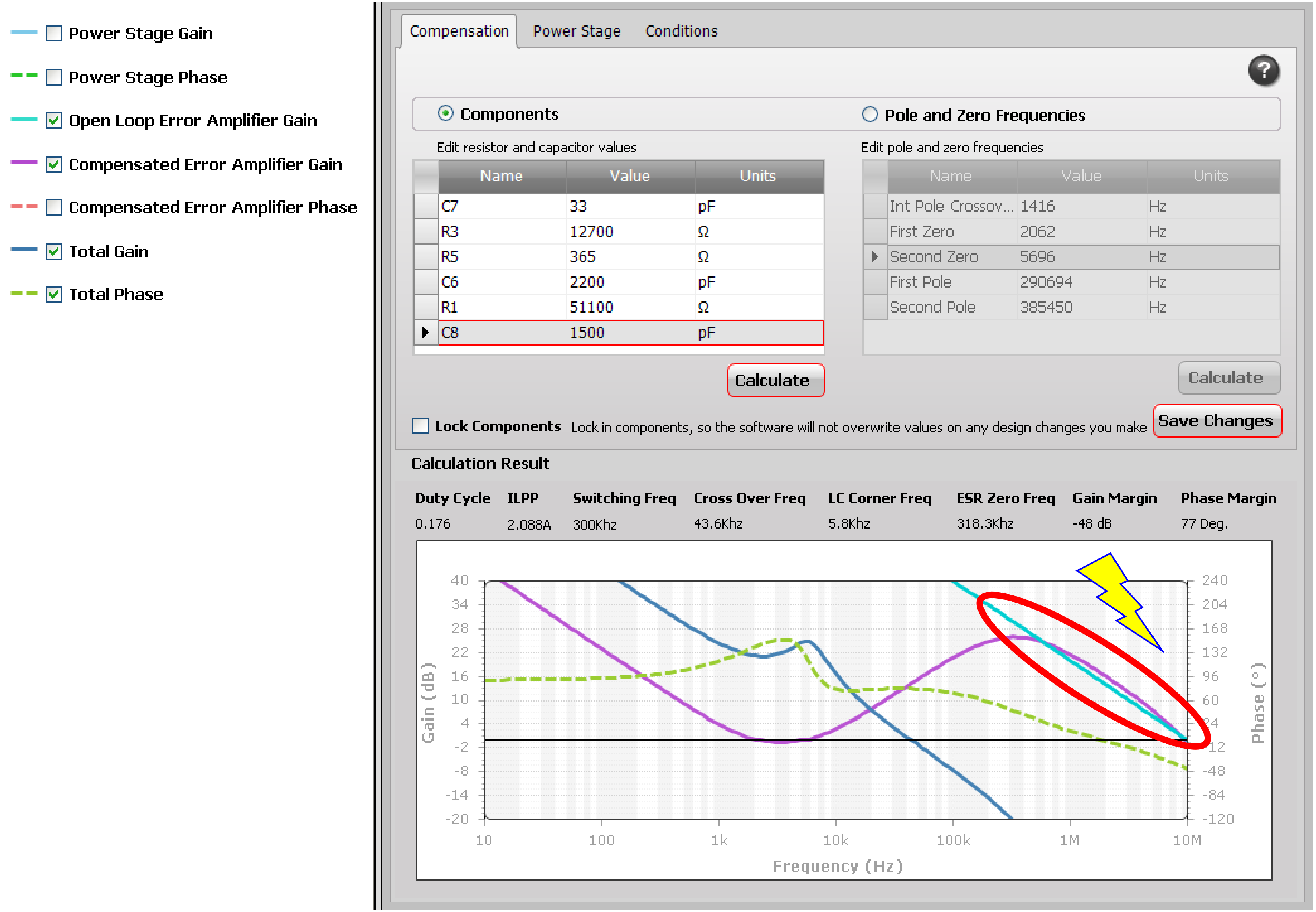
$$C_{P2} = \frac{1}{2\pi \times R_{PZ2} \times f_{P2}} = 37\,pF \longrightarrow \text{use 33pF}$$

Final Bode Plot – Real World

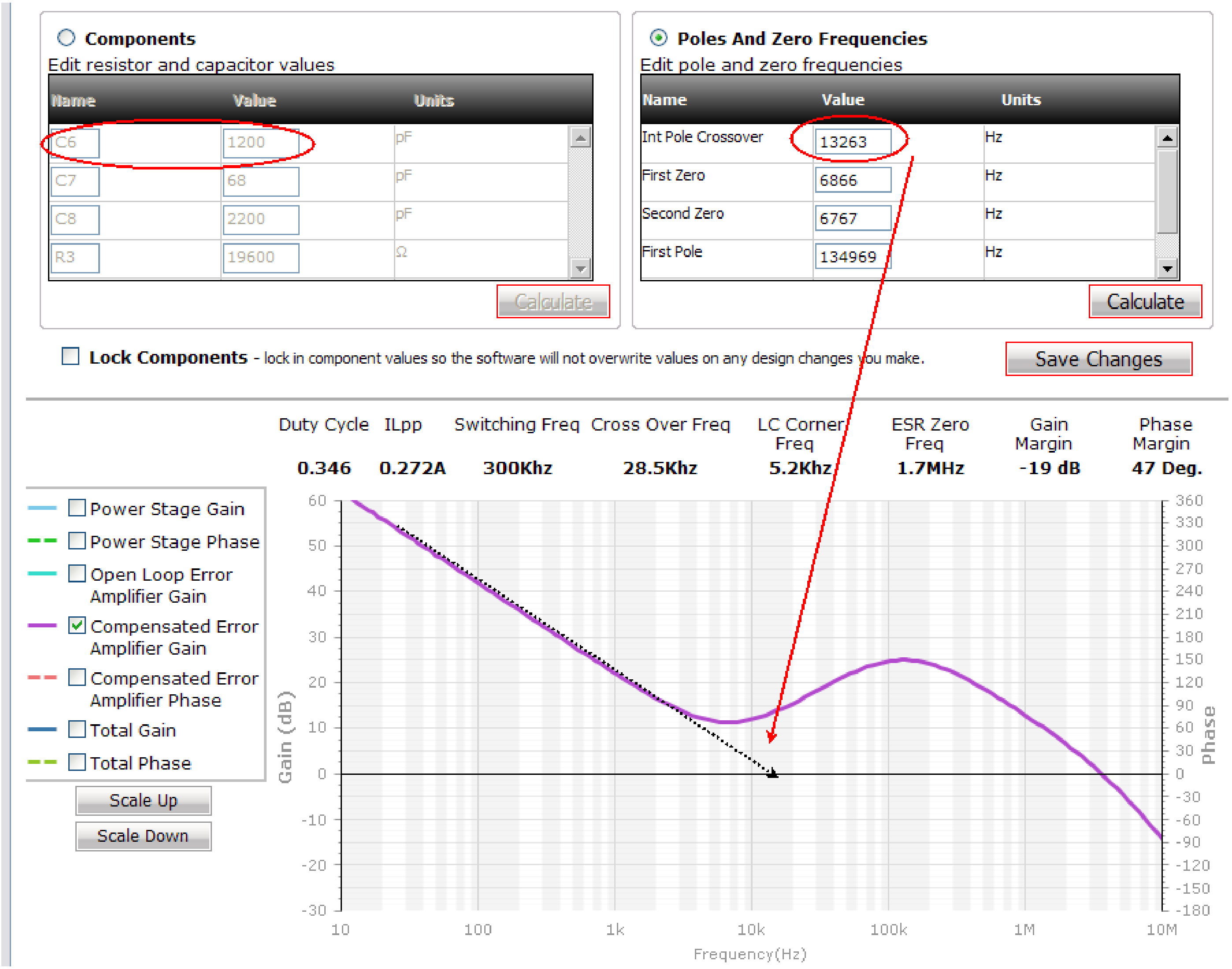


$f_{CO} \approx 45\text{kHz}$
Phase Margin ≈ 70°

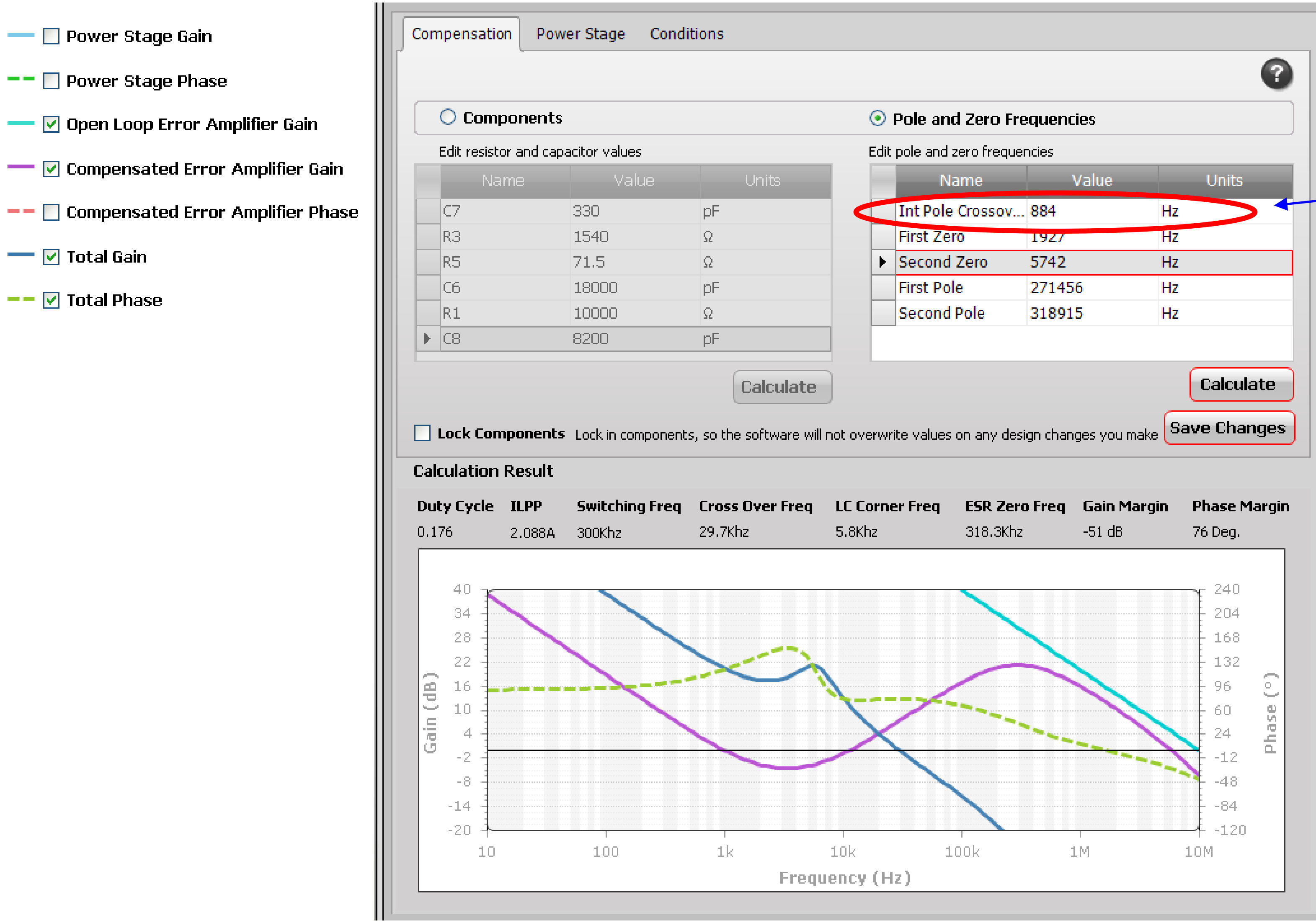
Final Bode Plot – Switcher Pro



Integrator Pole Crossover



Final Bode Plot – Switcher Pro

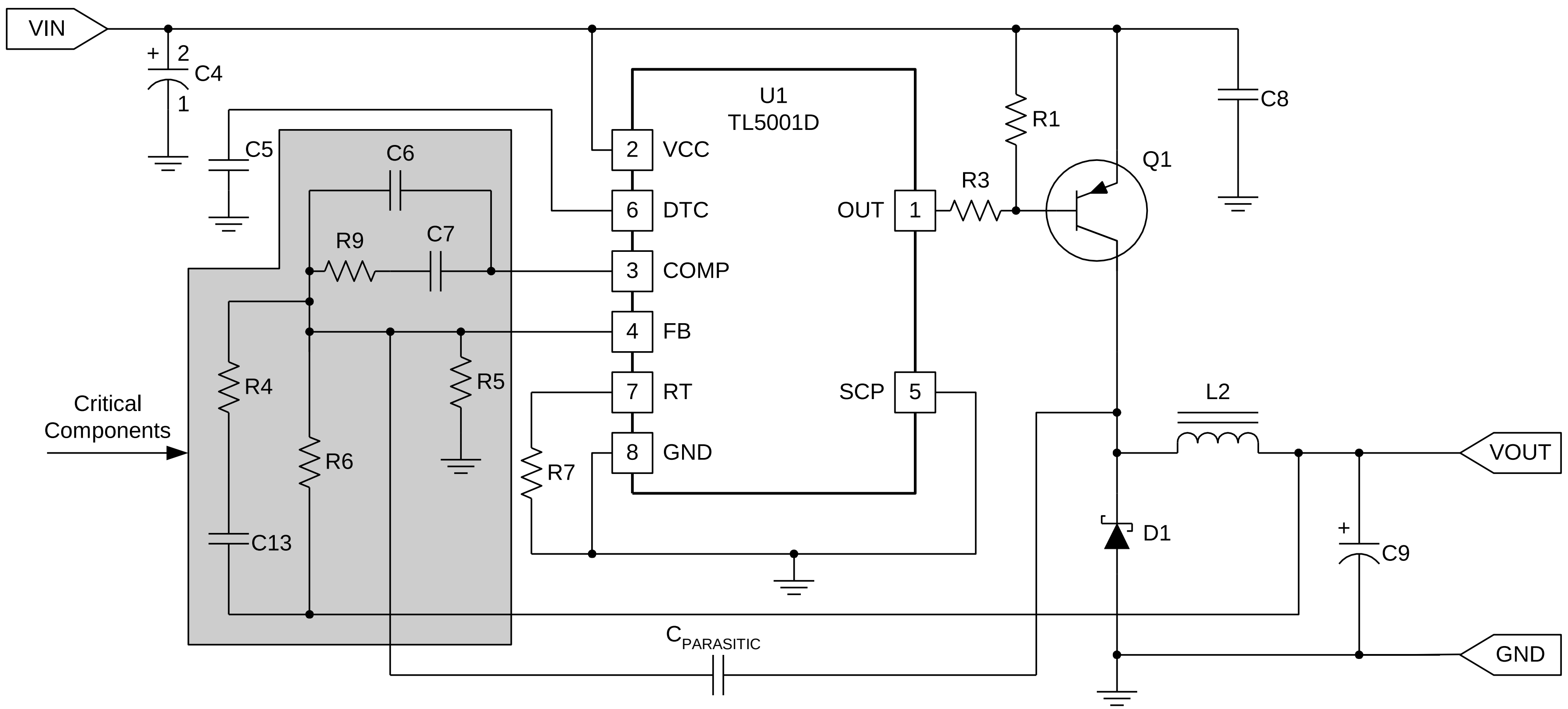


Reduce Gain

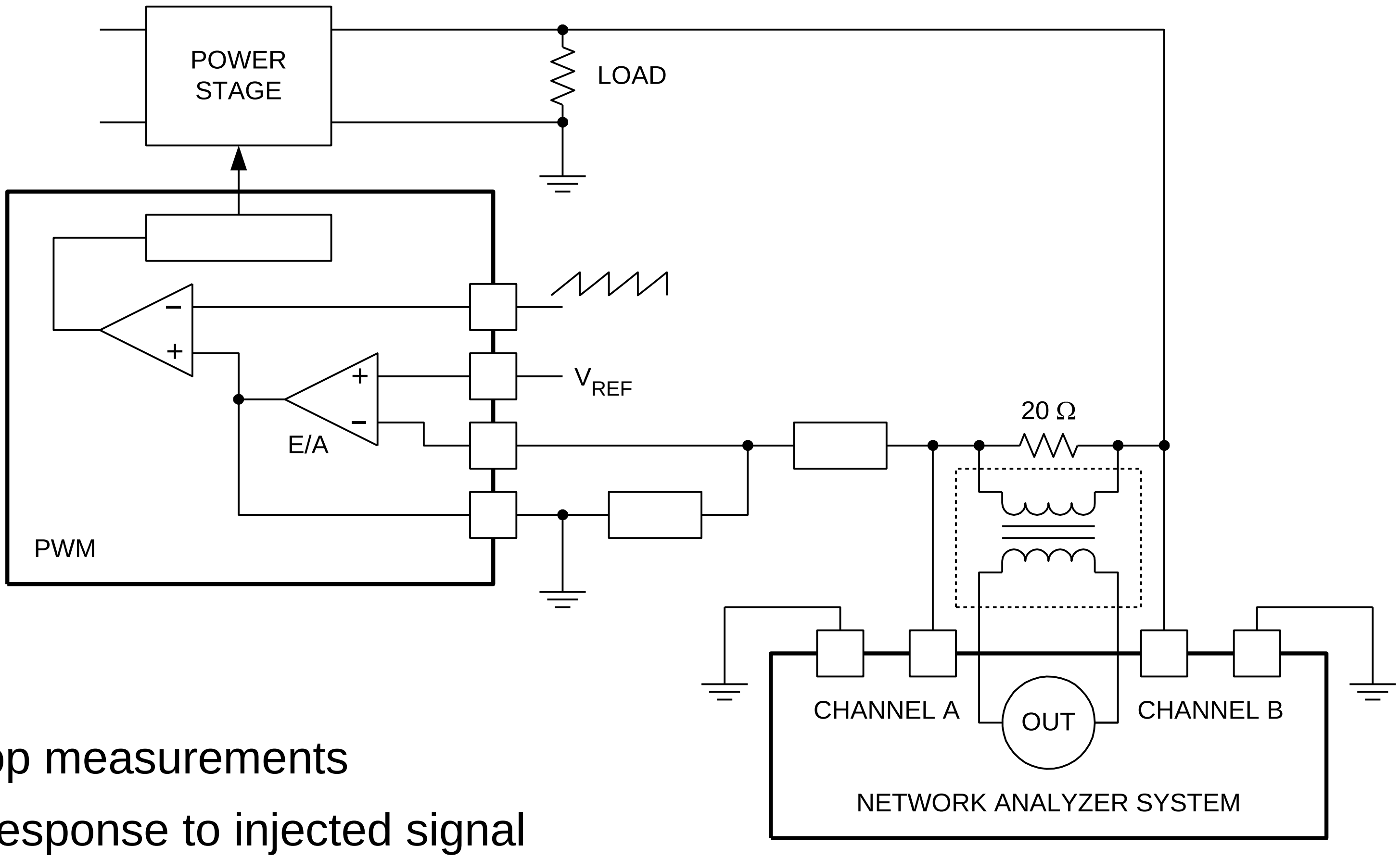
SwitcherPro Demo

Chaos Created by Noise Injection

- Compensation network should be placed close to error amplifier
- Place resistors so they connect to inverting input of E/A

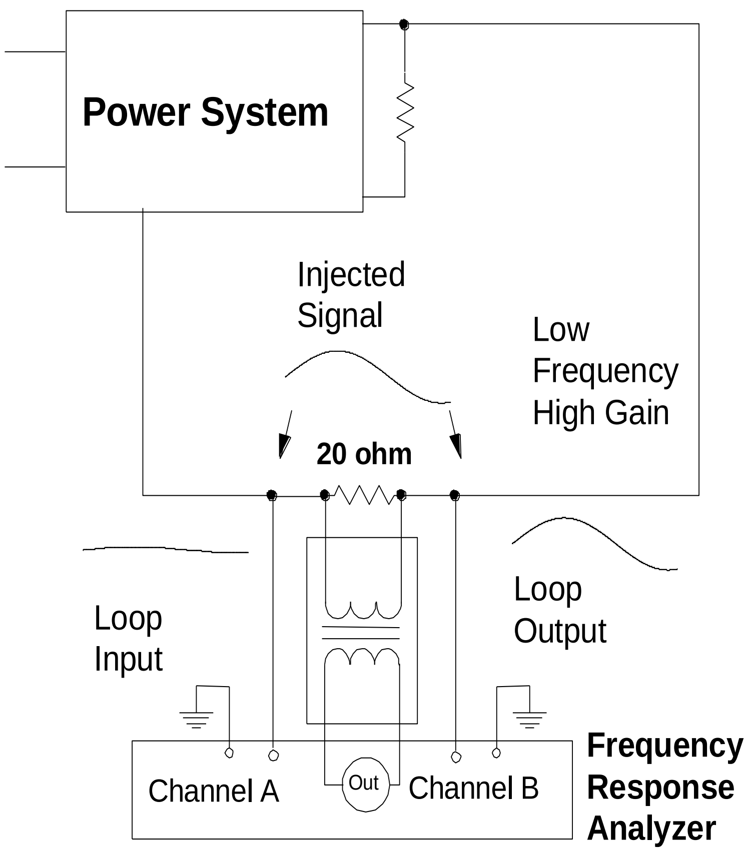


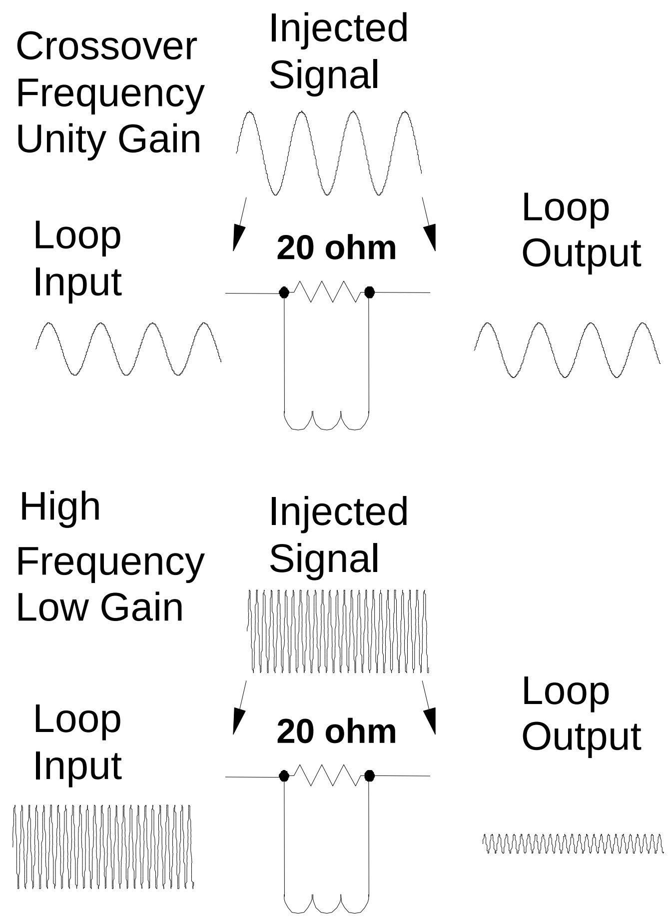
Measuring Loop Response



- Closed loop measurements
- Measure response to injected signal
- Measurement must not affect operation
- Direct measurement of gain/phase margins

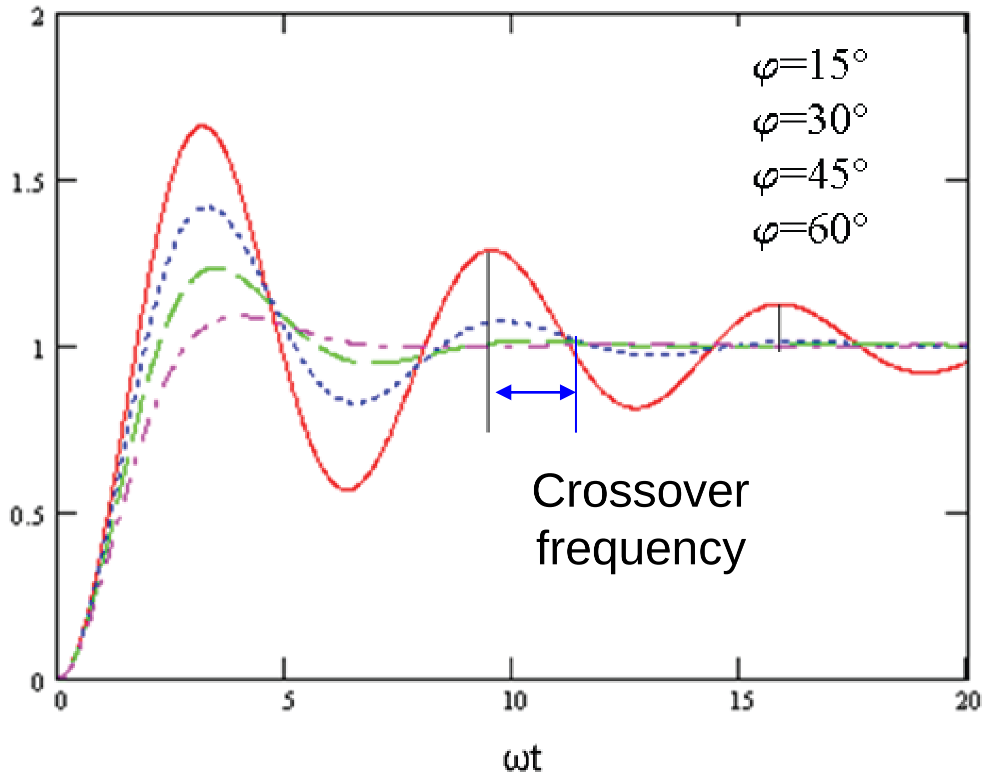
Freq. Measurements w/Constant Injected Signal





Loop Measurement from Transient Response

The important thing to look for is the ringing on the output immediately following the application of the load step. The frequency of the ringing indicates the control loop's crossover frequency, and the number of periods occurring before the ringing dies out indicates the phase margin.



Thank you!