Buck Converter Stability checks using Richtek Fast Load Transient Tool

Richtek Field Application Engineering

December, 2016

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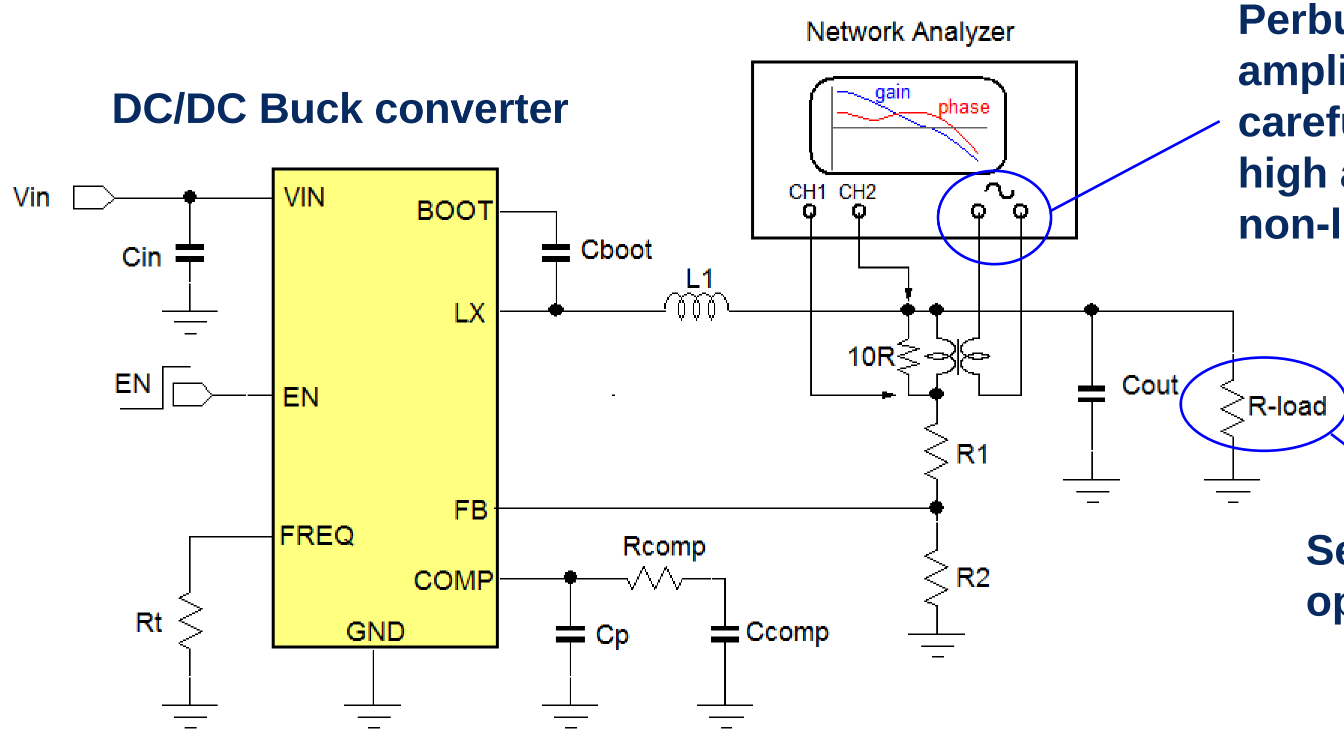
Converter stability check methods (I)

Frequency Domain Open Loop Gain-Phase Analysis



Perbutation signal amplitude needs careful adjustment: too high amplitude causes non-linear behavior.

Select for CCM operation

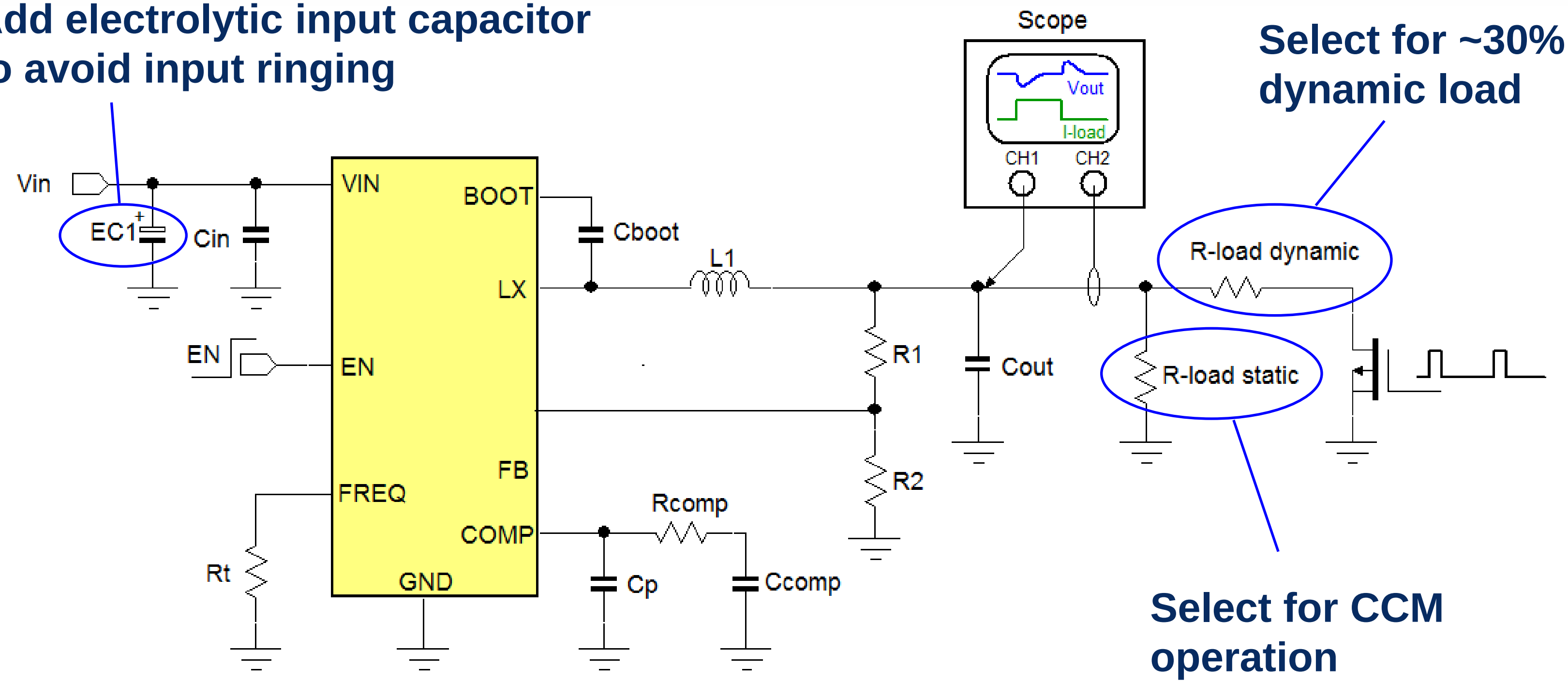
+ Good overview of critical loop parameters
- Complicated measurement
- Prone to noise pick-up and non-linear effects

Converter stability check methods (II)

Time Domain Fast Load Transient Analysis

Add electrolytic input capacitor to avoid input ringing

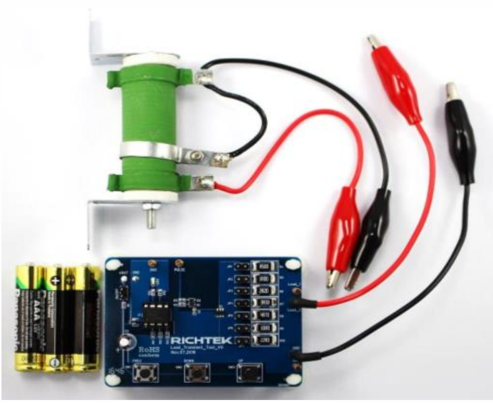
Select for ~30% dynamic load

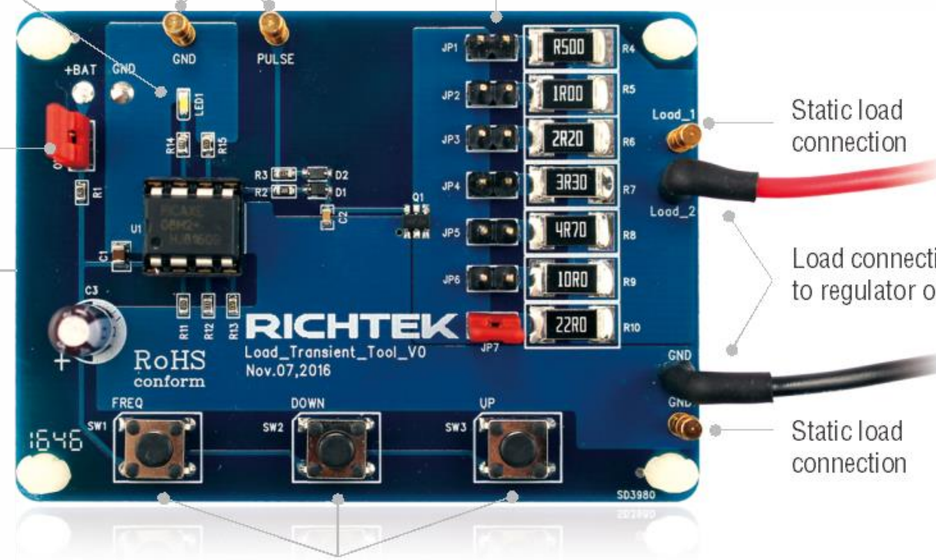


Select for CCM operation

+ Simple measurement
+ Can show various converter response effects
- Needs some skill to interprete the output waveform

Richtek Load Transient Tool (I)

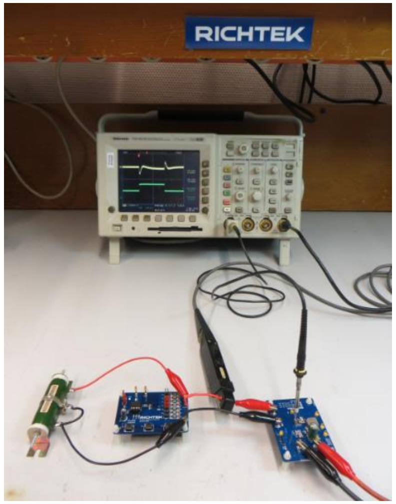


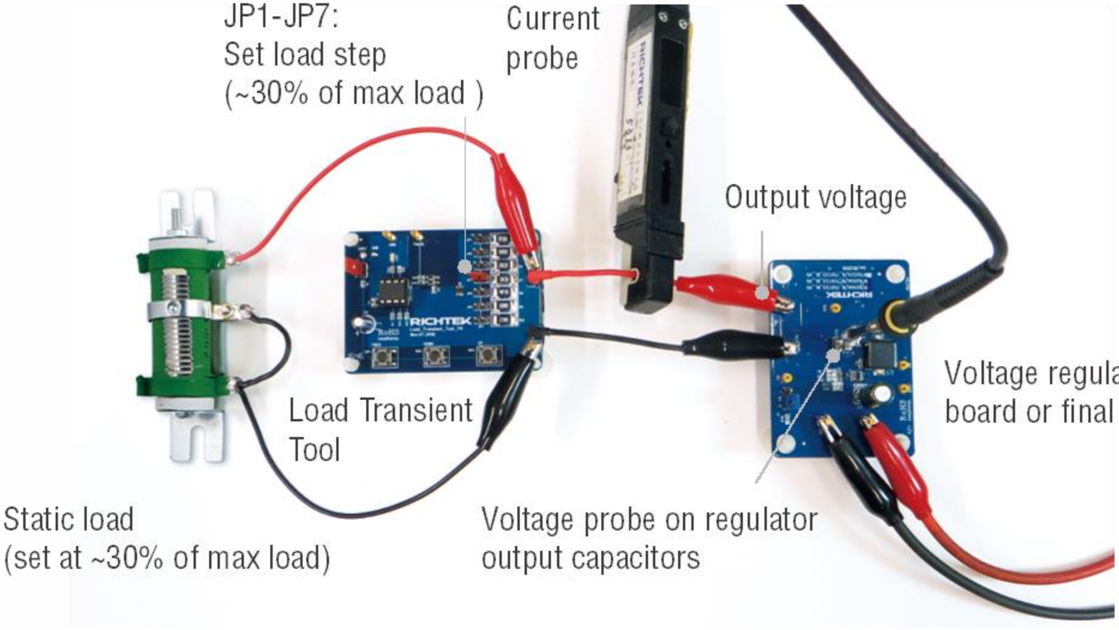


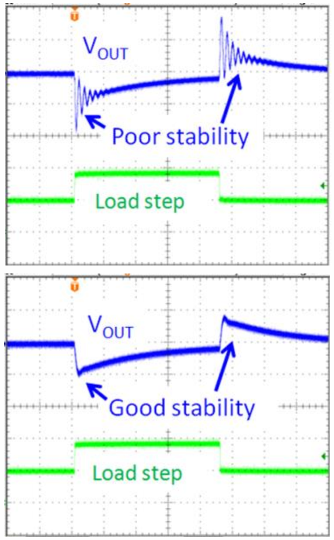
The Richtek Load Transient Tool contains a micro controller that switches a MOSFET on and off with a certain duty-cycle. By means of jumpers, 7 different pulse load resistors can be selected. The tool includes an adjustable 10Ω power resistor for setting the static load level. This tool can generate fast load steps (~500nsec rise/fall times), and the pulse load duty-cycle and frequency are adjustable by means of push buttons. The tool is battery powered, so it can easily be applied to any voltage regulator output in your system.

Richtek Load Transient Tool measurement setup

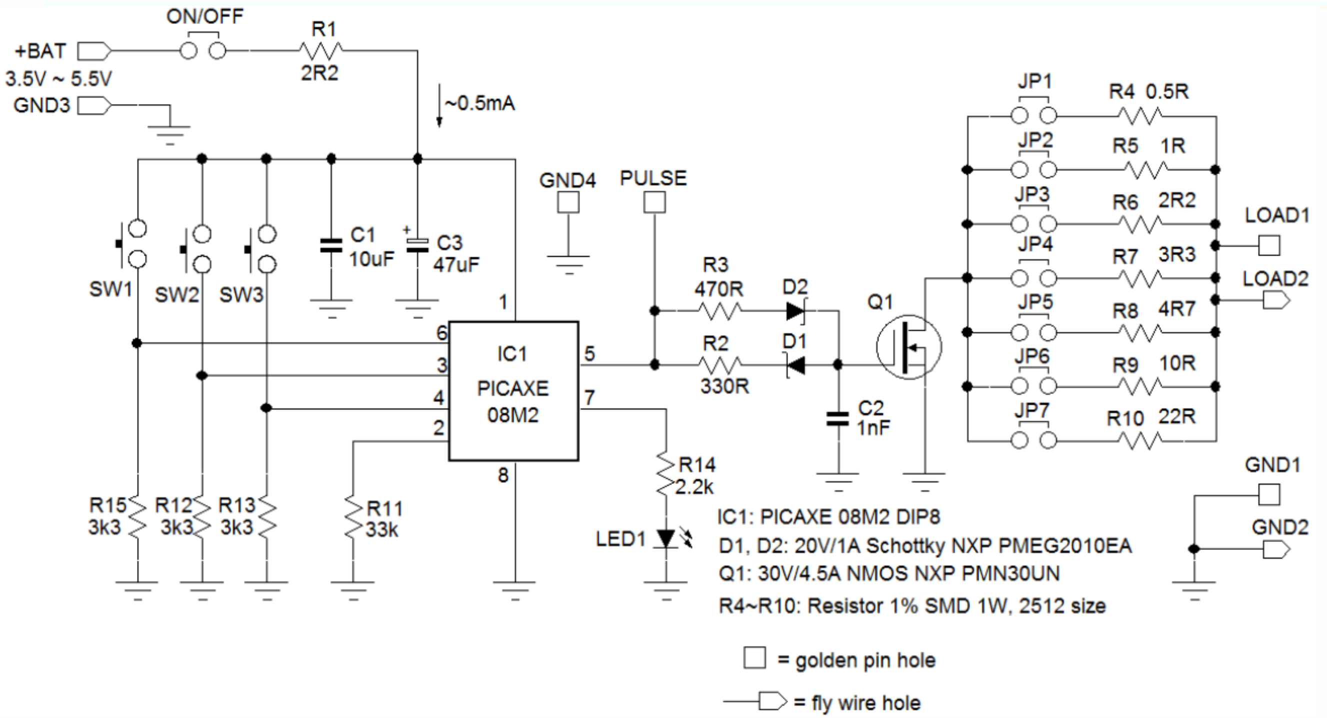
The Load transient tool is intended to be used for testing voltage regulators (buck, boost, LDO) with output voltage between 1V and 5V and maximum 5A current rating, but basically it can be used for testing any voltage regulator output. Just apply the pulse load leads to the converter output, adjust the static load resistor for CCM (continuous current mode) or ~ 30% of rated load, select the pulse load resistor for ~ 30% of rated load, measure the pulse current and the regulator output voltage across the output capacitors. Adjust the pulse load duty-cycle / frequency to see the full step load response.



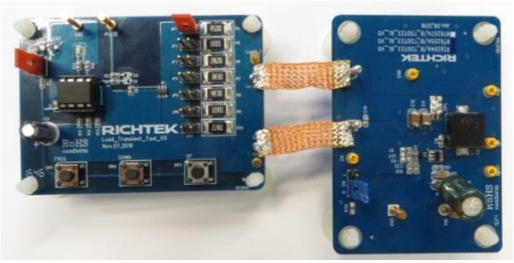




Richtek Load Transient Tool schematic



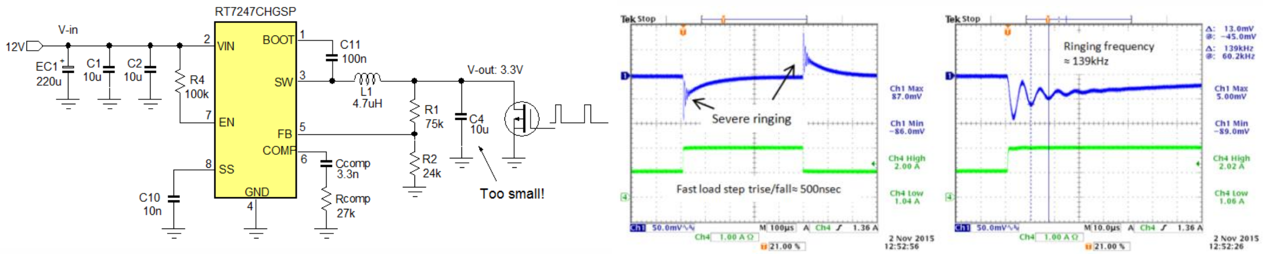
The above schematic shows the micro controller that drives the MOSFET switch. The MOSFET gate drive is designed to generate equal switching speeds with ~500nsec rise/fall times. Reducing or removing C2 can increase the switching speed, but the actual load current transient speed is mostly determined by the wiring inductance between the tool and the application. Especially when testing low voltage supplies (< 2V), it may be necessary to use short, thick wires between the tool and the application to minimize inductance.



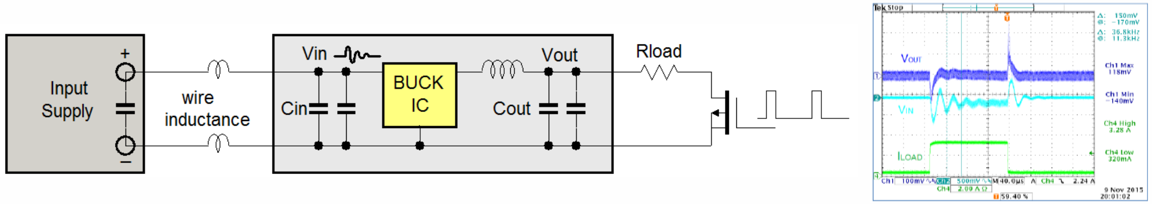
Low inductance connection

Richtek Load Transient Tool

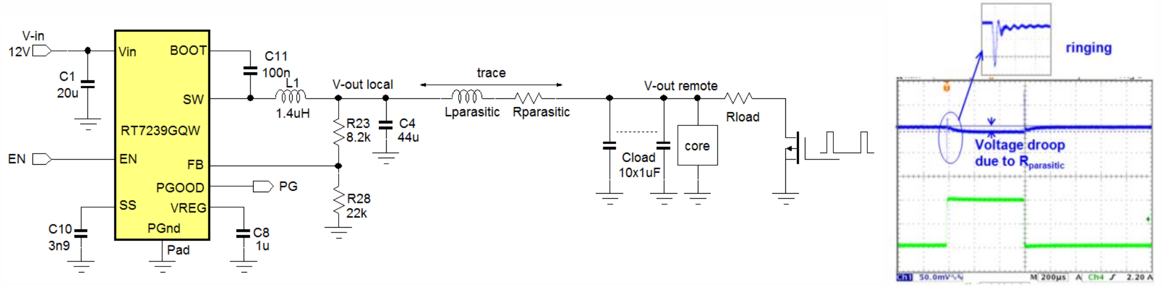
What can you do with the fast load transient tool?



Quickly check converter loop stability



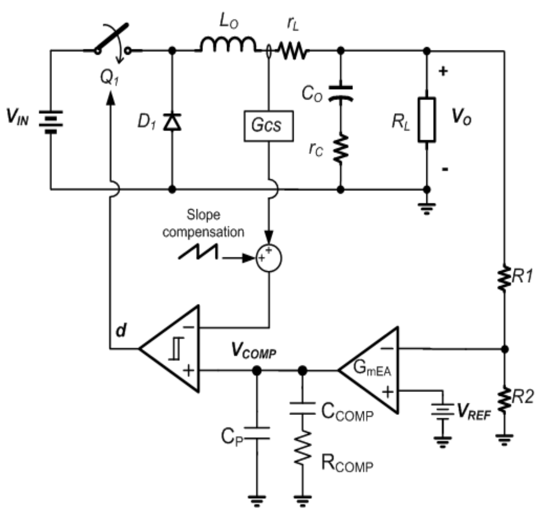
Check input supply stability

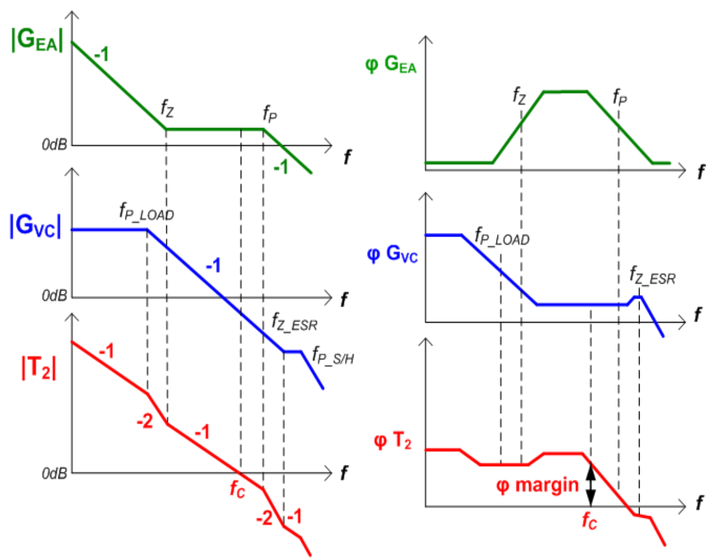


Check layout related problems

….and many more: Vout sag & soar, load regulation, slope compensation issues, estimate converter bandwidth, duty-cycle limits, check LDO, Boost, Flyback …..

Current Mode Buck converter control loop formula's





$$f_{P\_LOAD} = \frac{1}{2\pi C_{OUT} \cdot R_{LOAD}}$$

$$f_{Z\_ESR} = \frac{1}{2\pi C_{OUT} \cdot R_{ESR}}$$

$$f_Z = \frac{1}{2\pi C_{COMP} \cdot R_{COMP}}$$

$$f_P = \frac{1}{2\pi C_P \cdot R_{COMP}}$$

$$f_C = \frac{R_{COMP} \cdot G_{mEA} \cdot G_{CS}}{2\pi C_{OUT}} \cdot \frac{V_{REF}}{V_{OUT}}$$

Standard design values:

1.Set $F_{CONTROL}$ for ~ 1/10 of $F_{SWITCHING}$

$$R_{COMP} = \frac{2\pi C_{OUT} \cdot 0.1 F_{SW}}{G_{mEA} \cdot G_{CS}} \cdot \frac{V_{OUT}}{V_{REF}}$$

2.F_Z to be just below F_{P_LOAD}

$$C_{COMP} \geq \frac{C_{LOAD} \cdot R_{LOAD}}{R_{COMP}}$$

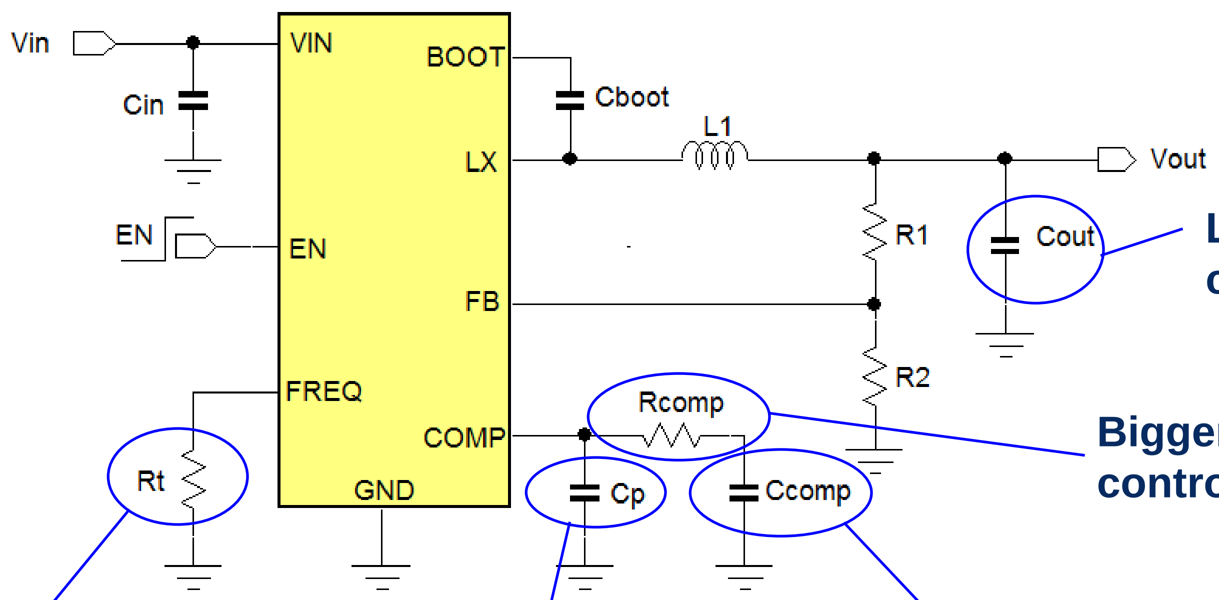
3.F_P to be close to F_{Z_ESR}

$$C_P = \frac{C_{OUT} \cdot R_{ESR}}{R_{COMP}}$$

(in noisy application with MLCC Cout, F_P can be set between 0.5 ~ 1* $F_{SWITCHING}$)

Current Mode Buck converter

Components that influence Current Mode Buck converter loop stability



Lower Cout increases control bandwidth

Bigger R_{COMP} increases control bandwidth

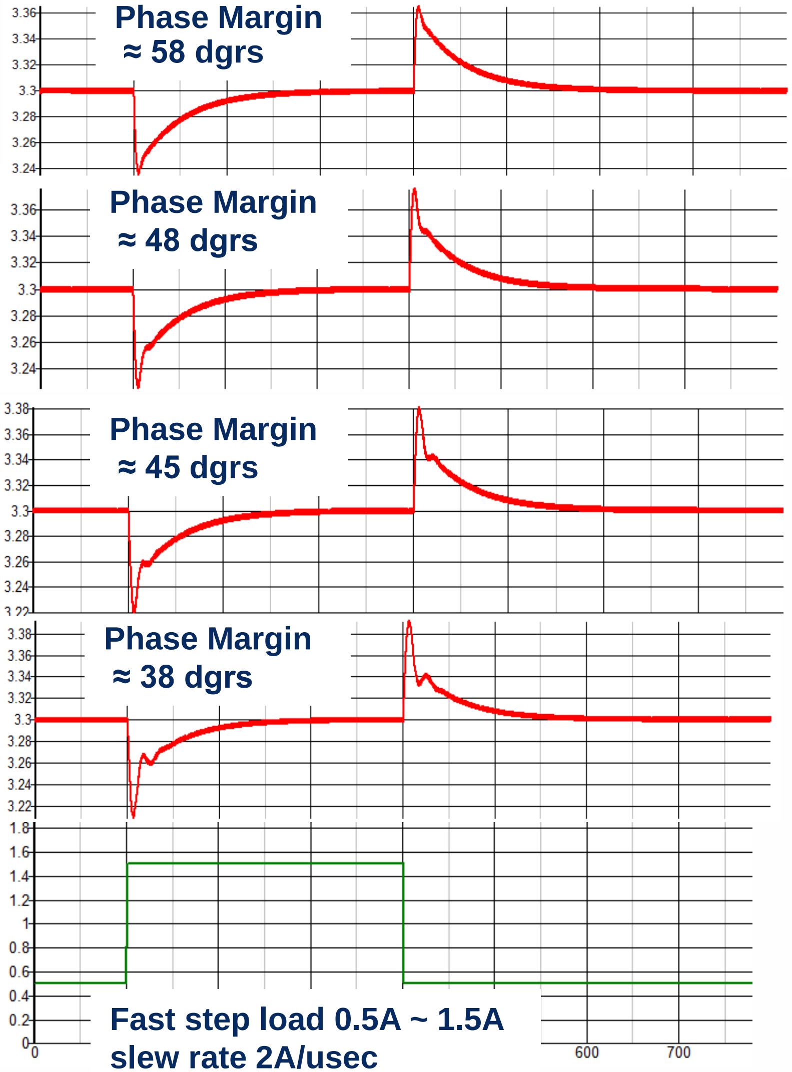
Higher switching frequency normally requires:
- **Lower L1**
- **Higher R_{COMP}**
- **Lower C_{COMP}**
- **Lower C_P**

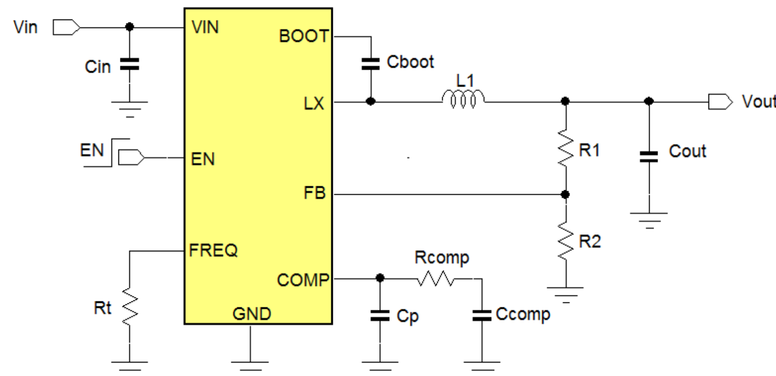
Too small C_{COMP} can result in lower phase margin

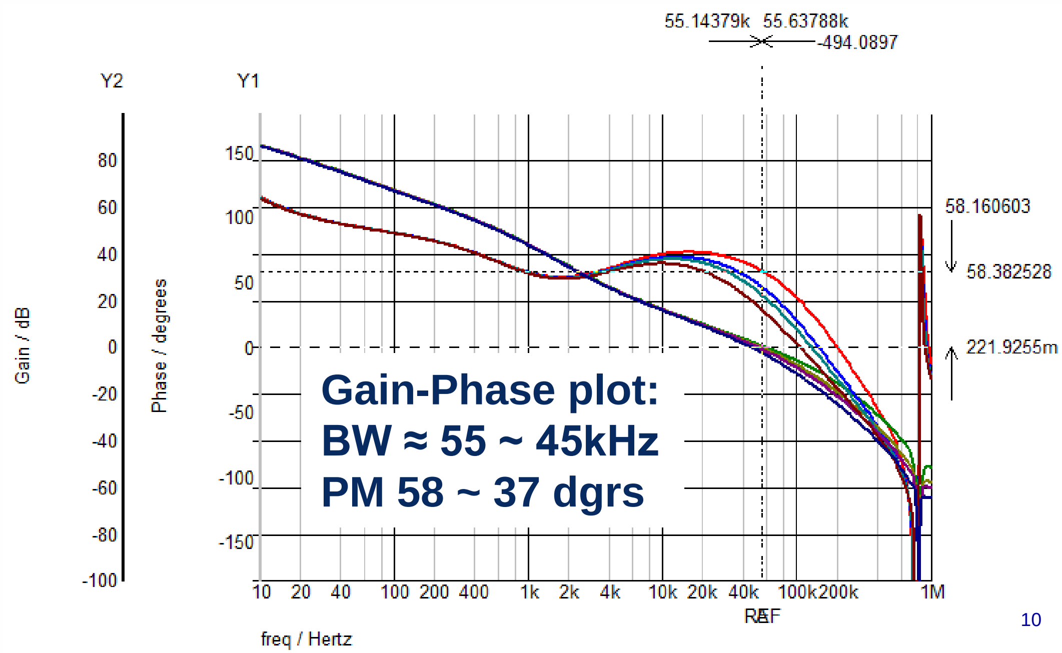
Too big C_P can result in lower phase margin

Too high control bandwidth can cause too low phase margin

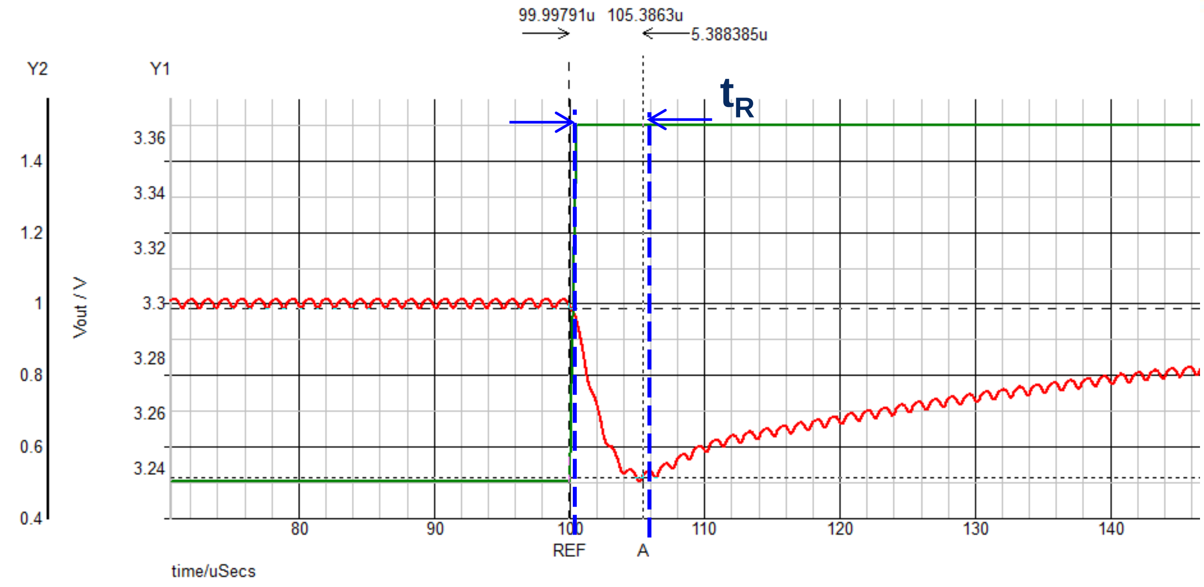
Example of Fast Transient response vs. Phase Margin







What else can you learn from Fast Transient response?



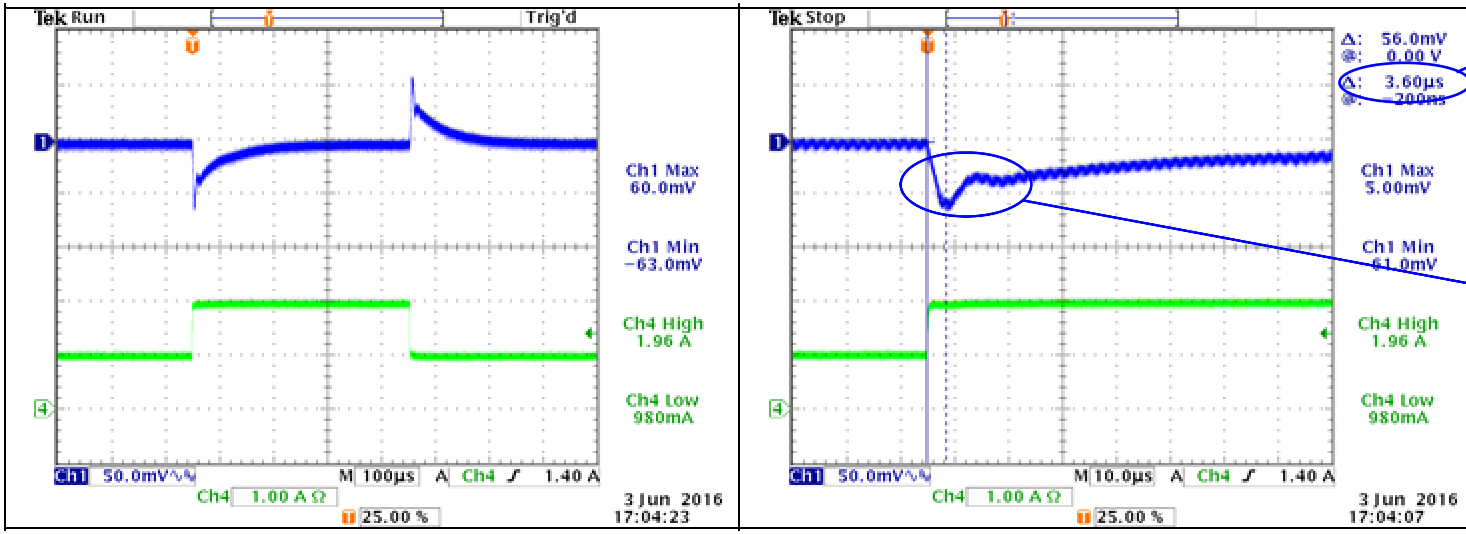
Response time t_R is a rough indication of the control bandwidth:

For most current mode buck converters:
Bandwidth BW ≈ 0.3 / t_R

In this example:
t_R = 5.3usec: → BW ≈ 0.3/5.3usec = 57kHz

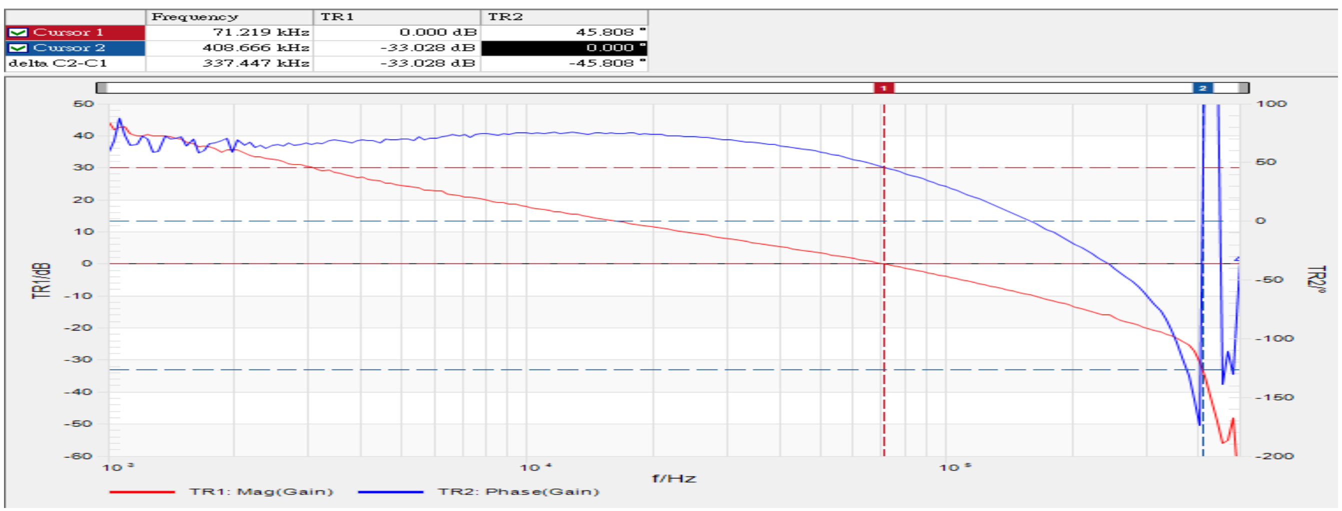
Note: Load step rise time must be << than 1/F_C.
→ Choose load step rise time around 500nsec

Actual measurement example



t_R = 3.6usec: → BW ≈ 0.3/3.6usec = 83kHz

Single bump: → PM ≈ 45 dgs



Actual Gain-Phase measurement:

Measured BW = 72kHz
Measured PM = 45.8 dgs

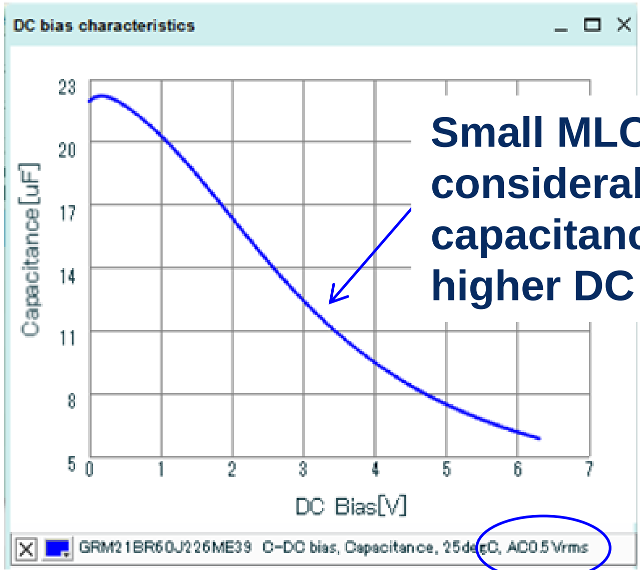
Output capacitor value is critical for loop stability!

$$f_C = \frac{R_{COMP}\cdot G_{mEA}\cdot G_{CS}}{2\pi C_{OUT}}\cdot\frac{V_{REF}}{V_{OUT}}$$

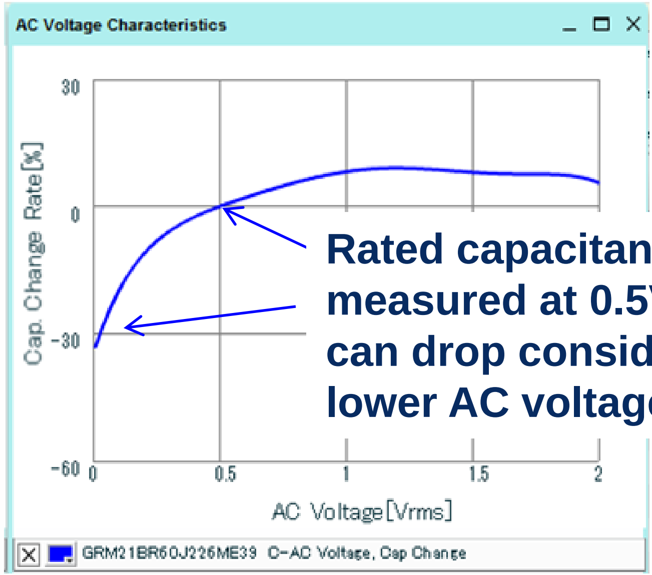
Smaller output capacitor increases BW!

Source: http://ds.murata.com/software/simsurfing/en-us/

Be aware of MLCC capacitor DC bias and AC ripple characteristics:



Small MLCC has considerable capacitance drop at higher DC bias

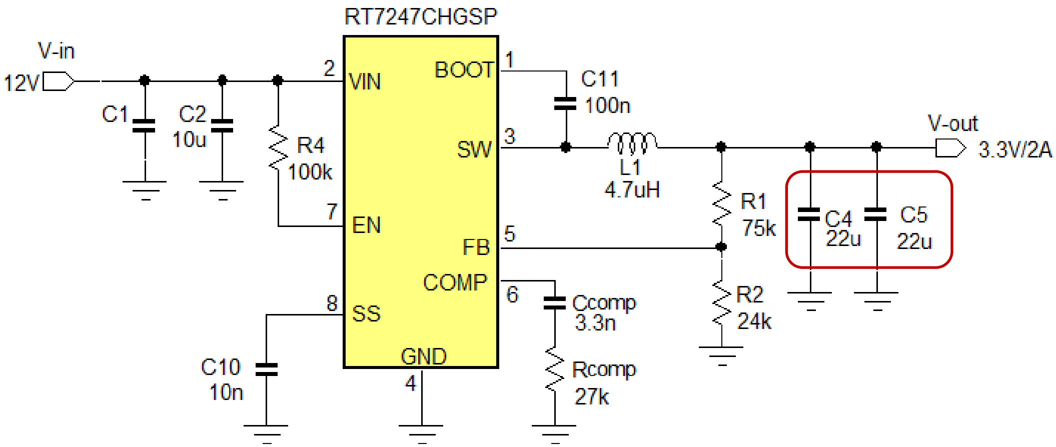


Rated capacitance is measured at 0.5Vac, but can drop considerably at lower AC voltage

(if DC bias or AC voltage effect is not specified for your capactor type, ask for it)

→ Always use actual capacitance when designing the control loop!

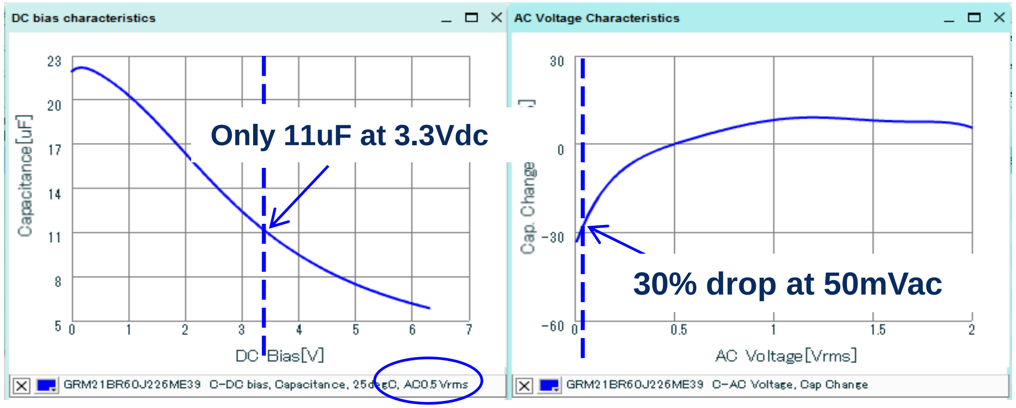
Practical example on output capacitor influence (I)



800kHz converter designed for 2x22uF output capacitance in 3.3V output application.

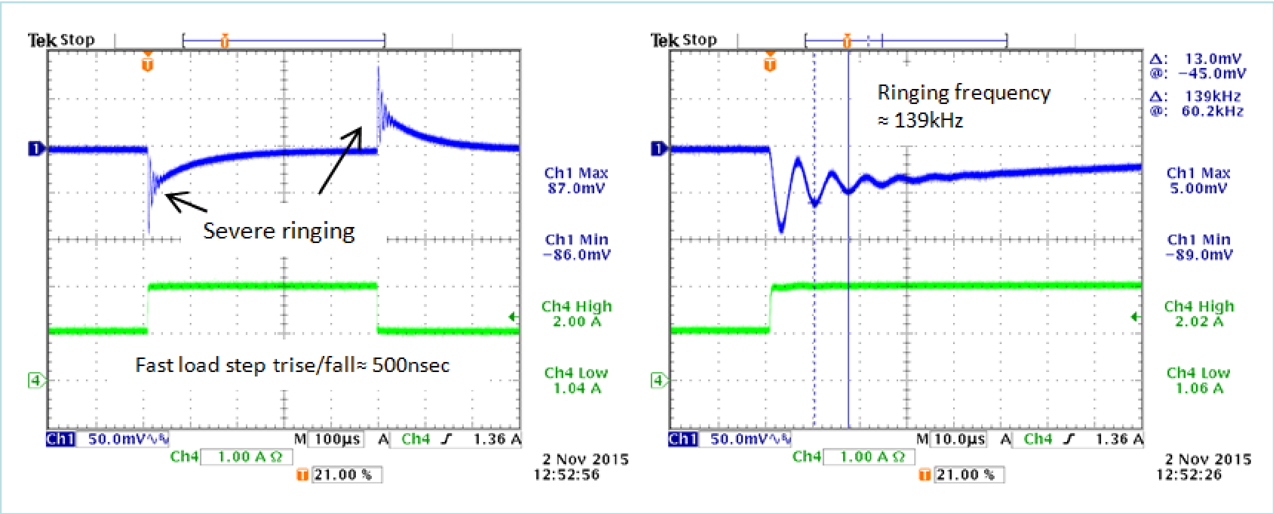
Circuit was designed for BW = 69kHz and PM = 59dgs

Designer selects 2x 22µF / 6.3V 0805 MLCC: GRM21BR60J226ME39L



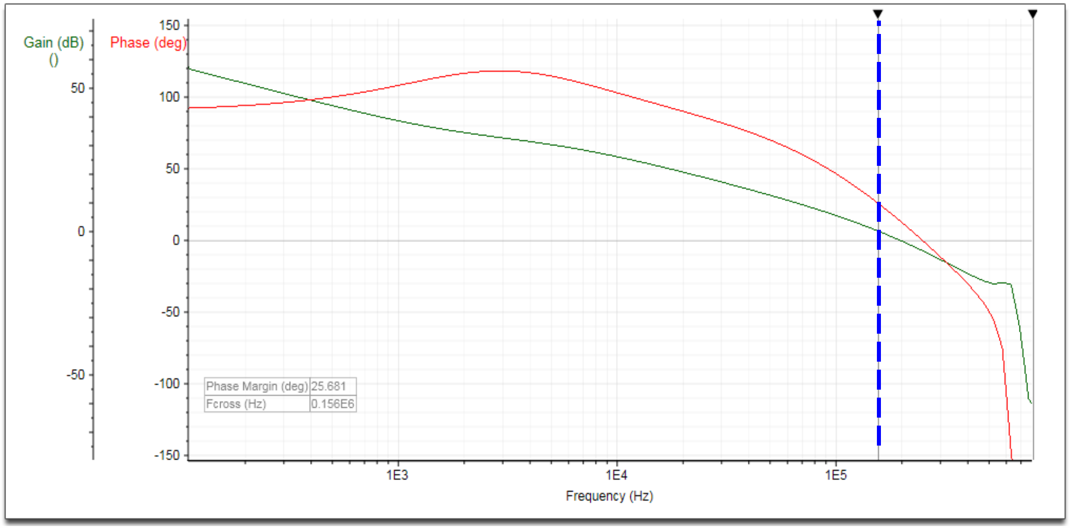
Actual capacitance is 11uF * 0.7 = 8uF: total output capacitance 16uF instead of 44uF
Converter Bandwidth will become 44/16 = 2.75 times higher than design value.

Practical example on output capacitor influence (II)



Step load shows severe ringing with ringing frequency of 139kHz

(Ringing frequency indicates Fc value)



Circuit simulation using online Richtek Designer tool and using 16uF output capacitance confirms the step load result:

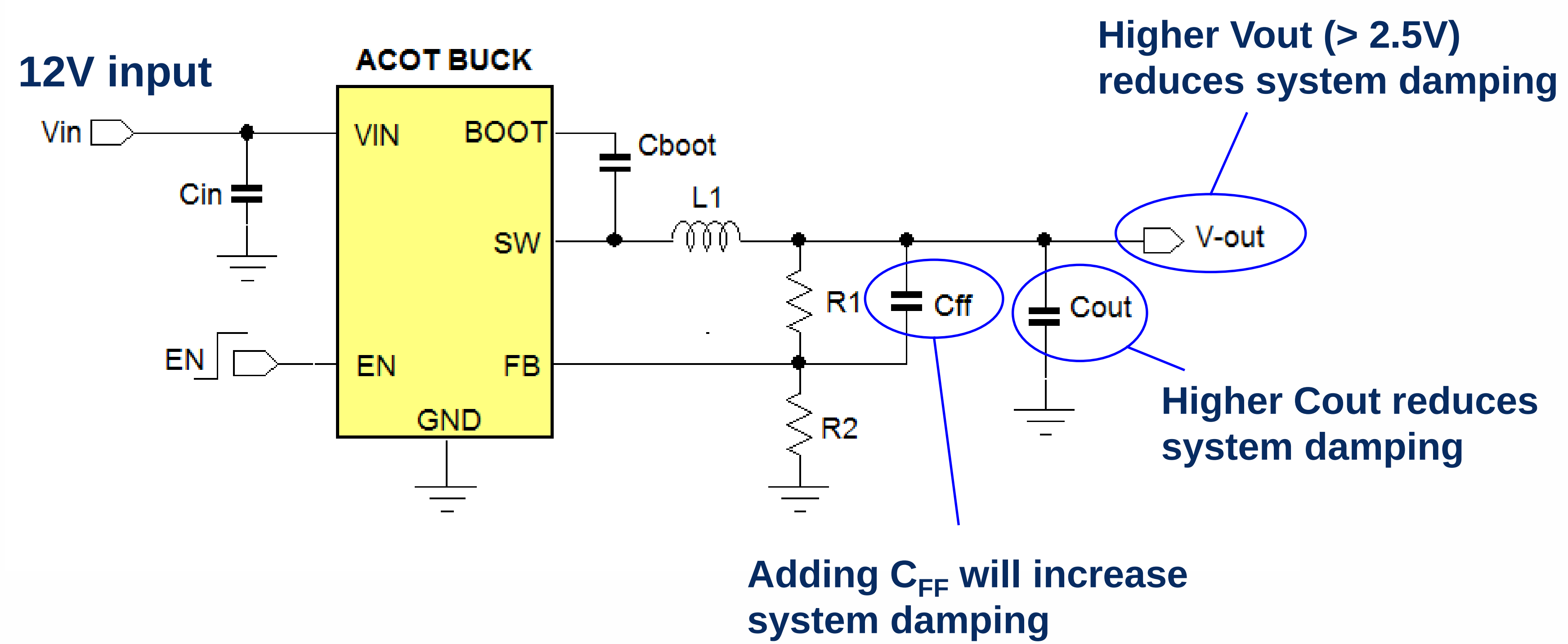
BW = 156kHz and PM = 26dgs

→ You can reduce R_{COMP} to reduce the BW to original design value for better PM.

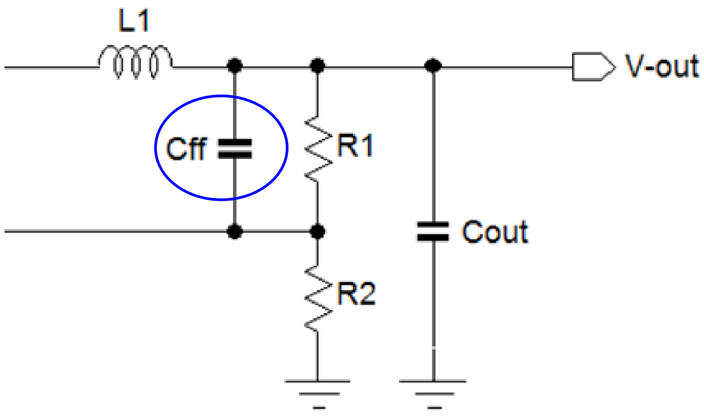
ACOT™ Buck converter stability

ACOT buck converters are much less critical in stability compared to current mode buck converters.

Normally applications with higher duty-cycle (> 20%) or large value output capacitors need to add some C_{FF} to increase system damping.

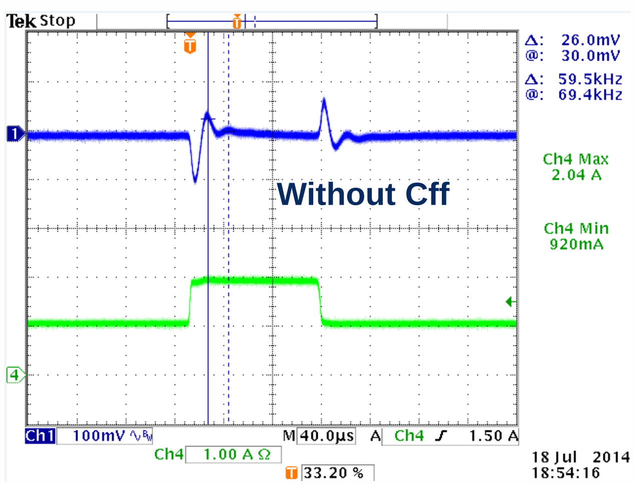


ACOT converter stability: How to tune Cff



The feed-forward capacitor plays a role in the damping of the ACOT control loop, especially at higher duty-cycle applications like 12V → 5V. For low duty-cycle applications like 12V → 1V it is normally not needed. The value of Cff for a specific ACOT converter depends on duty-cycle, C_{OUT} value, inductor value and R1 value.

Practical method to find Cff value:



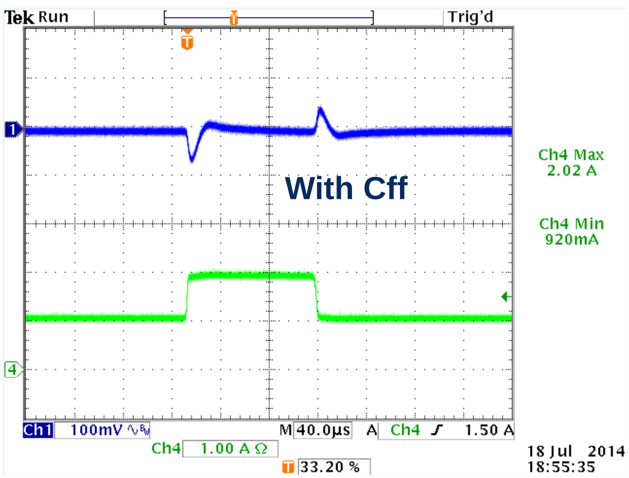
1. Apply a fast step load and if it shows ringing, measure the ringing frequency
In this 12V → 5V example: f_{RING}=59.5kHz

2. Calculate Cff by the formula:

$$C_{FF} = \frac{1}{2\pi \cdot R1 \cdot f_{RING} \cdot 0.8}$$

In this example: (R1 = 120k)

$$\frac{1}{2\pi \cdot 120k \cdot 59.5k \cdot 0.8} = 27.9pF$$



After adding Cff = 27pF: well-damped step response

Relevant Richtek application note

AN038: Fast Load Transient Testing

Richtek Application AN038

Practical hints and tips on converter stability testing using fast load transients

Let's show this with the below example where a RT7294CGJ6F, a low cost 18V/2.5A ACOT buck IC in SOT-23-6 is used to make a 1V core supply rail:

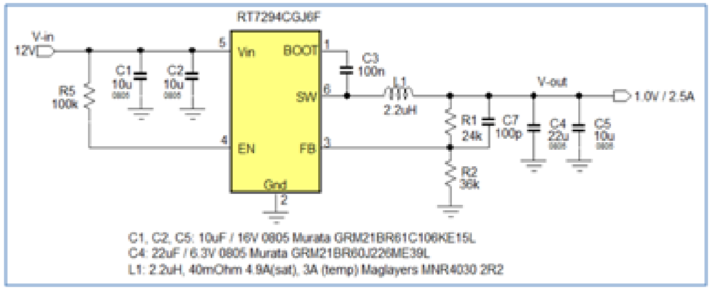


FIGURE 41

ACOT converters have a fixed ON time and a variable OFF time and can react ve... The converter maximum duty-cycle is limited by the ON ... converter can achieve. ACOT converters ... low load step occurs, the ACOT converte... current down as fast as possible, temporari...

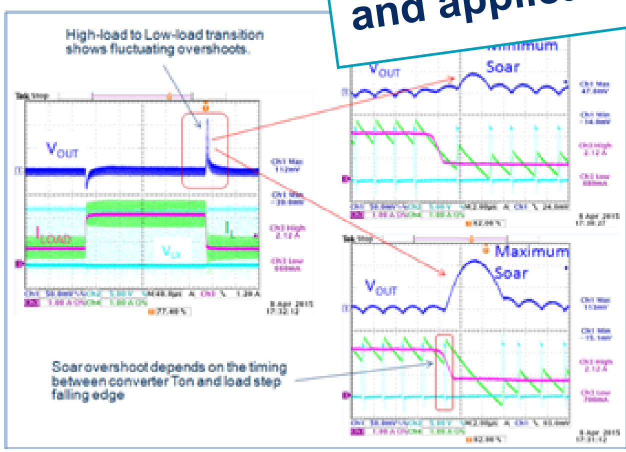
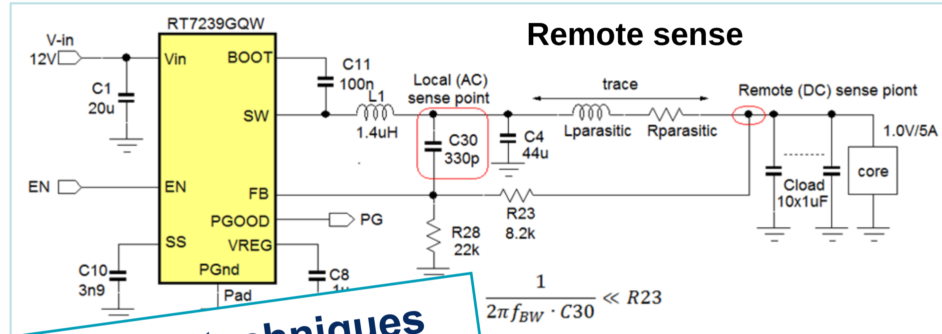
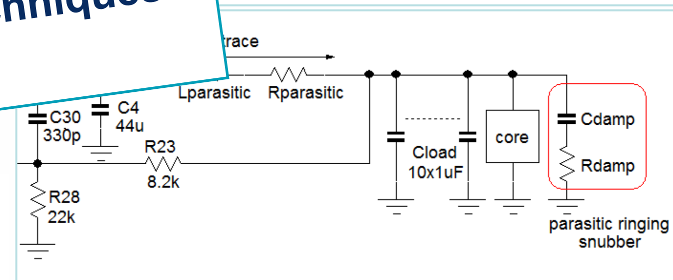


FIGURE 42

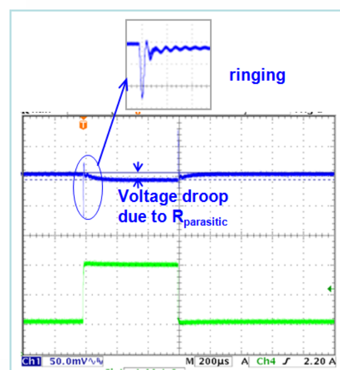


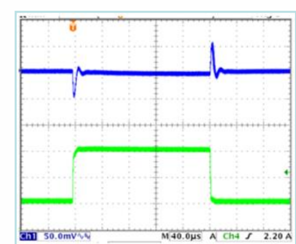
Technical explanation, measurement techniques and application examples



$$R_{SNUBBER} = \sqrt{\frac{L_{PARASITIC}}{C_{LOAD}}} \approx \sqrt{\frac{30nH}{10uF}} = 55m\Omega$$

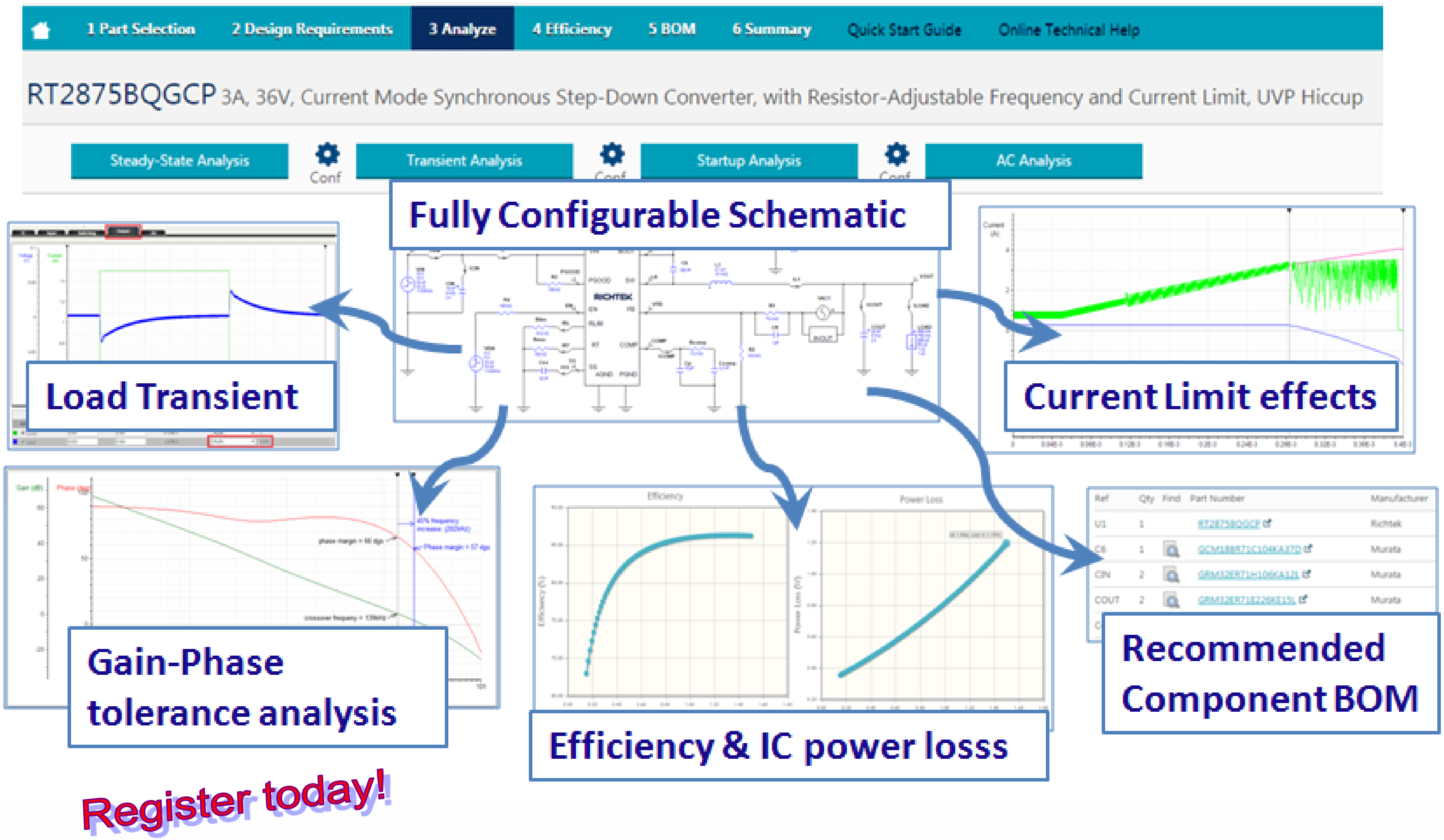
$$C_{SNUBBER} = \frac{2\pi\sqrt{L_{PARASITIC}\cdot C_{LOAD}}}{R_{SNUBBER}} \approx \frac{2\pi\sqrt{30nH\cdot 10\mu F}}{55m\Omega} = 62uF$$





Richtek Designer online tool

Full simulation of application circuit



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