Application Note

Optimizing Line and Load Regulation in Automotive, 48-V Battery and eBike Applications

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ABSTRACT

Higher voltage batteries are becoming more prevalent in automotive and eBike applications. The extended V_{IN} range is causing designers to examine more closely the line regulation of the pre-regulator. Furthermore, the pre-regulator might need to support a no load to full load condition, so load regulation is also of high importance. This application note reviews line and load regulation for 48-V battery and eBike, pre-regulators using *LM5013-Q1* as an example.

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1 Introduction

A common control topology employed in buck regulators is constant-on-time (COT). This control topology is being adopted in several 48-V battery and eBike, pre-regulators such as *LM5013-Q1*. This application note is an overview of how line and load regulation can be optimized with *LM5013-Q1* for wide-V_{IN} range applications, specifically, the 48 V battery and eBike applications.

2 Overview of COT

Figure 2-1 produces a regulated output voltage by using its feedback comparator to servo the output by comparing the sampled output voltage, V_{FB}, and the reference voltage, V_{REF}. The feedback comparator issues an on-time pulse, after it trips. This cycle continues at the programmed switching frequency for the set output voltage, dictated by the on-time (R_{RON}) and feedback (R_{FBT}, R_{FBB}) resistors. Equation 1 and Equation 2 illustrate the necessary calculations.

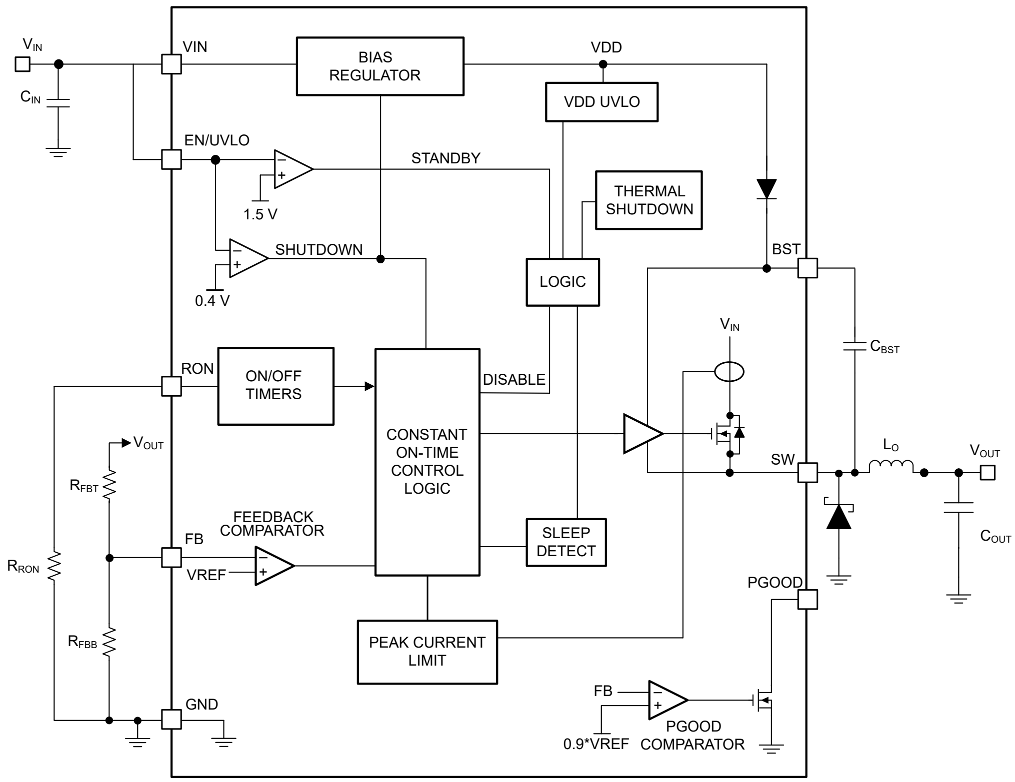

Figure 2-1. LM5013 Functional Block Diagram

$$R_{RON}(k\Omega) = \frac{V_{OUT}(V) \times 2500}{F_{SW}(kHz)} \tag{1}$$

$$R_{FBB} = \frac{V_{REF}}{V_{OUT} - V_{REF}} \times R_{FBT} \tag{2}$$

The feedback comparators terminal connected to the FB node must have sufficient ripple such that during the on-time, the FB node can be charged sufficiently above the reference voltage (V_{REF}). This outcome is achieved with example ripple injection circuit Figure 2-2.

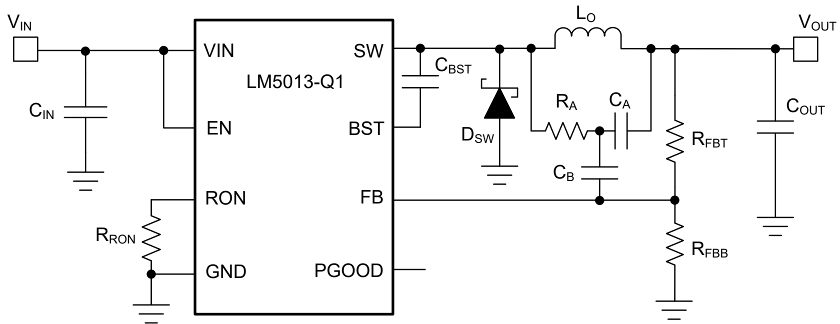

Figure 2-2. LM5013 Design With External Ripple Injection

The integrator (R_A, C_A) generates a voltage ramp , in-phase with the inductor current and is AC coupled with C_B. By following Equation 3, Equation 4, and Equation 5 sufficient ramp amplitude is applied to the feedback node for stability and transient performance is optimized. Note, the recommended minimum ramp amplitude, 12 mV in the case of LM5013, is advised for the device's given hysteresis, along with margin for reduced sensitivity to noise. Please refer to the *LM5013-Q1 Automotive 100-V Input, 3.5-A Non-Synchronous Buck DC/DC Converter with Ultra-low IQ* data sheet for the recommended value and further clarification of terms. Additional theory on this design is provide in the *Stability Analysis and Design of COT Type-3 Ripple Circuit* application note.

$$C_A \geq \frac{10}{F_{SW} \times (R_{FBT} || R_{FBB})} \tag{3}$$

$$V_{RAMP} = \frac{(V_{IN} - V_{OUT}) \times t_{ON}}{R_A C_A} \tag{4}$$

$$C_B \geq \frac{t_{TR}}{3 \times R_{FBT}} \tag{5}$$

3 Line Regulation

The injected ramp waveform leads to the average feedback voltage exceeding the reference voltage for which the output voltage was programmed with. Additionally, the waveform's peak (Equation 4) is directly proportional to the input voltage, leading to further variance as V_{IN} changes. This variance is gained up through the feedback divider, resulting in the output voltage varying from the set point. Figure 3-1 and Table 3-1 gives a conceptual and quantitative measure how higher, peak ramp amplitude results in an increase in average feedback voltage ($V_{FB(AVG)}$).

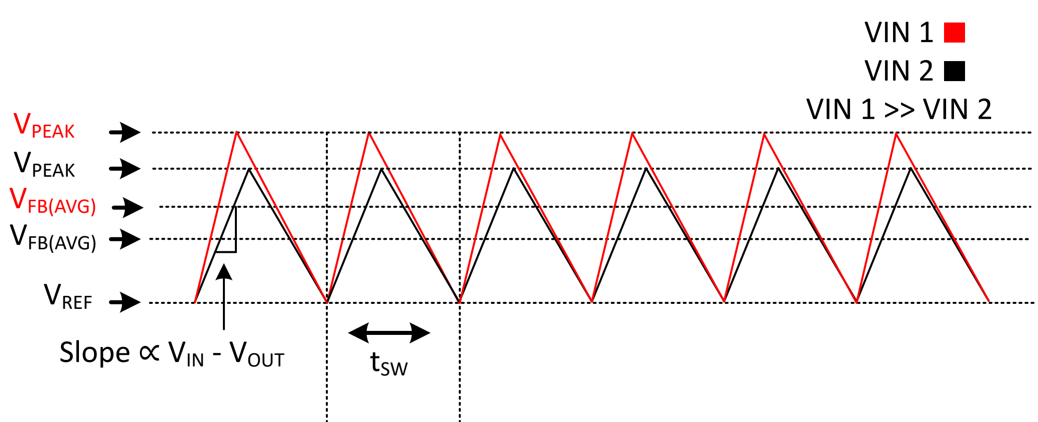

Figure 3-1. Peak Ramp Amplitude vs $V_{FB(AVG)}$

Table 3-1. Measured Peak Ramp Amplitude v. $V_{FB(AVG)}$

Ramp Amplitude, V_{PEAK} (mV)	$V_{FB(AVG)}$ (V)
13.488	1.204
15.437	1.206
20.342	1.212
23.353	1.217
23.945	1.216

4 Load Regulation

Load regulation is often a concern as well in buck regulators. Typically, regulators have a light-load mode to make sure the light load efficiency is optimized. The implementations can differ, though, in the case of LM5013 the switching frequency decreases with reduced loading. This point is illustrated in Figure 4-1. The reduced frequency leads to the average feedback voltage reducing. Similarly to the previous discussion, this leads to output variance. Figure 4-2 shows how a 12-V output decreases with reduced switching frequency.

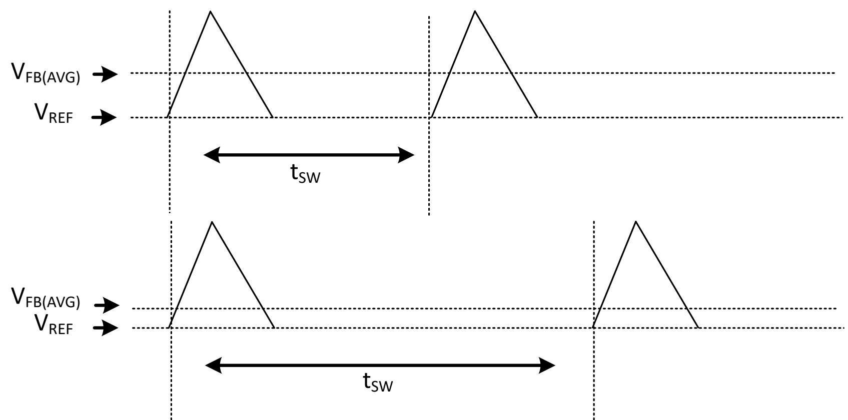

Figure 4-1. Light-load, Frequency Reduction Impact on $V_{FB(AVG)}$

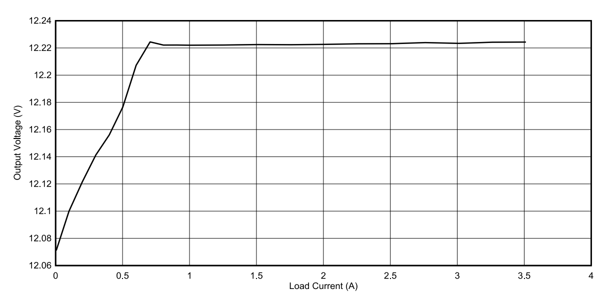

Figure 4-2. Light-load, Frequency Reduction Impact on V_{OUT} Regulation

This behavior can be avoided by changing the inductor so that the inductor current does not go discontinuous. The point at which the inductor current goes discontinuous is often the entry point for light-load mode in the case of LM5013. Alternatively, a minimum load can be applied at the output to make sure that the inductor current does not go discontinuous. Equation 6 demonstrates the minimum inductance (L_{OUT}) to make sure the inductor current does not go discontinuous at the application's minimum load current ($I_{OUT,min}$) with the consequence of (potential) reduced efficiency.

$$L_{OUT} \geq \frac{V_{OUT}}{2 \times I_{OUT,min} \times F_{SW}} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \tag{6}$$

If it is not possible to manipulate either the inductance, or application's minimum load current, then an alternative device with FPWM needs to be considered such as *LMR38020-Q1 4.2-V to 80-V, 2-A Automotive Synchronous SIMPLE SWITCHER® Power Converter with 40-μA IQ* data sheet. By operating in FPWM, the device's average feedback voltage will not be impacted as much by loading, as in the case of most devices who employ a light-load mode.

5 48 V_{IN} Design Example

This application note concludes with a typical design for LM5013-Q1, a 48 V to 12 V design. The LM5013-Q1 supports a load current up to 3 A. This design often requires the input to tolerate a V_{IN} range of 36 V to 60 V. The following calculations are presented for the ramp injection circuit selection to minimize V_{OUT} variation. Additionally, line and load regulation data is included, along with V_{OUT} transient waveform in the case V_{IN} falls below the designed minimum V_{IN} of 36 V, resulting in the injected ripple falling out of device specification.

1. The frequency is selected to be 300 kHz and the R_{RON} resistor is calculated for the output voltage of 12 V.
2. The corresponding feedback resistances are calculated for for the output voltage of 12 V and selected RFBT = 453 kΩ.
3. The ramp capacitor (C_A) can be calculated with the previously selected components.
4. The ramp resistor (R_A) is calculated for the minimum, input voltage (largest t_{ON}), and LM5013's minimum recommended ramp voltage of 12 mV.
5. The ramp coupling cap (C_B) is determined by the arbitrarily selected transient settling time of 50 us.
6. The output capacitance of 44 µF is selected for typical load transient requirements which often supersedes the capacitance requirements for steady state/stability. A calculation wasn't necessarily followed.
7. C_{IN} and C_{BST} are selected per the minimum *LM5013-Q1 Automotive 100-V Input, 3.5-A Non-Synchronous Buck DC/DC Converter with Ultra-low IQ* data sheet recommendation. D_{SW} is selected to be a Schottky diode with a DC rating of 100 V and current rating of 3 A.

$$R_{RON}(k\Omega) = \frac{V_{OUT}(V) \times 2500}{F_{SW}(kHz)} = \frac{12 \times 2500}{300} = 100\ k\Omega \tag{7}$$

$$R_{FBB} = \frac{V_{REF}}{V_{OUT} - V_{REF}} \times R_{FBT} = \frac{1.2}{12 - 1.2} \times 453\ k\Omega\ = 50.33 k\Omega;\ R_{FBB} = 49.9\ \ k\Omega \tag{8}$$

$$C_A \geq \frac{10}{F_{SW} \times (R_{FBT}||R_{FBB})} = \frac{10}{300\ kHz \times (44.95\ k\Omega)} = 741 pF;\ C_A =\ 3.3nF \tag{9}$$

$$R_A = \frac{\left(V_{IN,\,MIN} - V_{OUT}\right) \times\ t_{ON,\,MAX}}{V_{RAMP,\,MIN} \times C_A} = \frac{(36 - 12) \times \frac{100\ k\Omega}{36 \times 2.5} \times 10^{-6}}{12\ mV \times 3.3\ nF} = 673\ k\Omega \tag{10}$$

$$C_B \geq \frac{t_{TR}}{3 \times R_{FBT}} = \frac{50\ us}{3{*}453\ k\Omega} = 36\ pF; C_B = 56\ pF \tag{11}$$

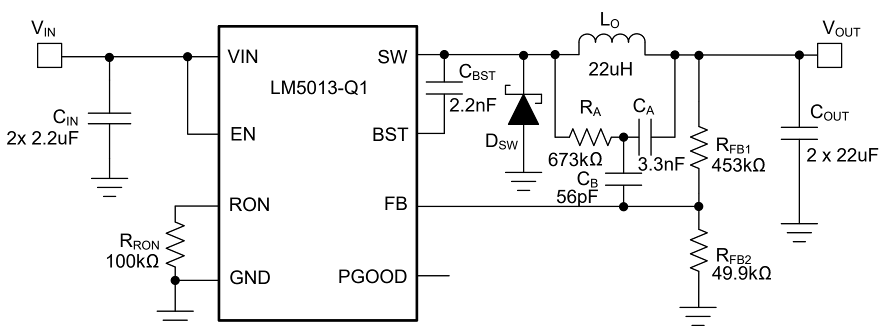

Figure 5-1. 48 V to 12 V, LM5013-Q1 Design

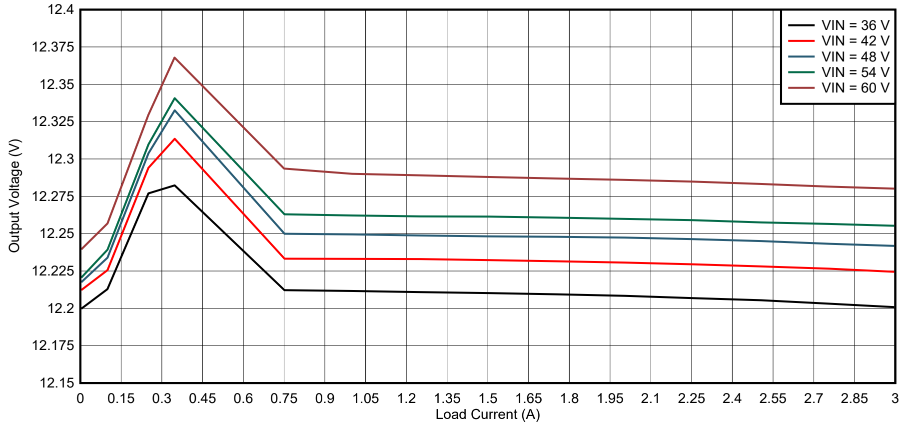

Figure 5-2. Load and Line Regulation

The load and line regulation data above was taken at V_{IN} = 36 V, 42 V, 48 V, 54 V, and 60 V. The load current was varied from 0 A to 3 A.

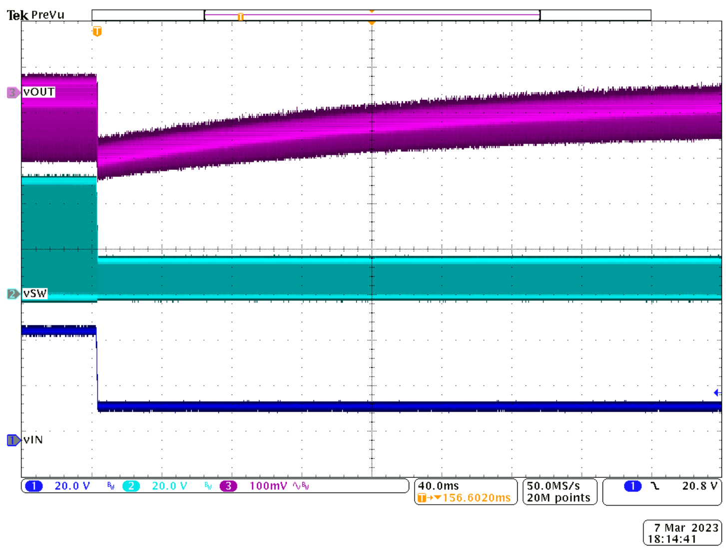

Figure 5-3. Line Transient (48 V to 15 V), Outside of Design Specification

A line transient below the design's V_{IN} range was applied and recorded was the V_{OUT} transient. The converter matained regulation after the transient, with the net effect being reduced, peak-to-peak ripple and the DC output voltage falling. The ripple and DC output voltage fell as a result of the decreased inductor current ripple and average feedback voltage reducing, respectfully.

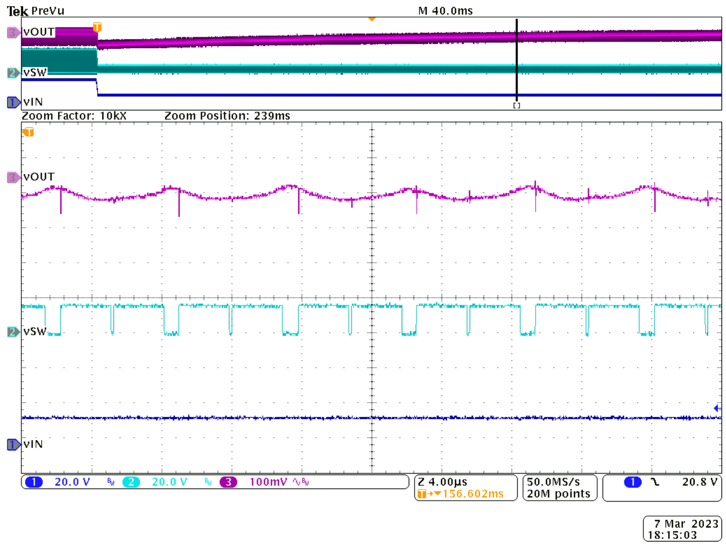

Figure 5-4. Line Transient (48 V to 15 V), Zoom-in of Double Pulsing on V_{SW} as a Result of Insufficient Ramp Injection

A zoom-in of the V_{SW} and V_{OUT} was taken to highlight the effect of insufficient ramp injection. The injected ramp voltage falling much below 12 mV caused false triggering of PWM comparator used in the COT architecture. It can be seen that the switching behavior becomes less periodic as a result of the double pulses on V_{SW} (small, then large).

6 Summary

48 V_{IN} applications larger V_{IN} and load current range puts a bigger focus on line and load regulation for the pre-regulator in those designs. LM5013-Q1, a popular 48 V_{IN} pre-regulator uses a COT topology, which by nature, is controlled by feedback voltage variation. Increasing line and load ranges do not create worry by following the steps outlined in this article to minimize the output variation. The concepts covered in this article need to be used in your future design to make sure best practices are being followed and the highest performance can be achieved.

7 References

- Texas Instruments, *Stability Analysis and Design of COT Type-3 Ripple Circuit*, application note.
- Texas Instruments, *Selecting an Ideal Ripple Generation Network for Your COT Buck Converter*, application note.