Application Report
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Step-Down Converter with Cable Voltage Drop Compensation

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ABSTRACT

Output voltages of DCDC converters typically are precisely regulated at the location the feedback divider is connected. In case of longer connections to the load which, for example, is not on the same PCB the precision of the regulation suffers from the way the connection is established. If weight and connection count is critical, using sense wires or traces from the converter to the load is not an option. The weight also restricts the cross section of the wires which can be used. This means voltage drop which depends on the load current must be expected. Since this voltage drop cannot be fed back to the converter, compensation can only be done by adjusting the output voltage of the converter to match the voltage drop along the cables. This application report describes a circuit which addresses this problem at the output of a low voltage, highly efficient and small step-down converter which is typically used in such environments. The document also details the design and selection of the key components and provides measurement results showing the performance of the circuit.

1 Overview

In this example, the power circuit is implemented based on the TPS62130, a highly efficient synchronous step-down converter. To sense the load current, a current sense amplifier is designed based on the instrumentation amplifier, INA213. The complete circuit is shown in Figure 1.

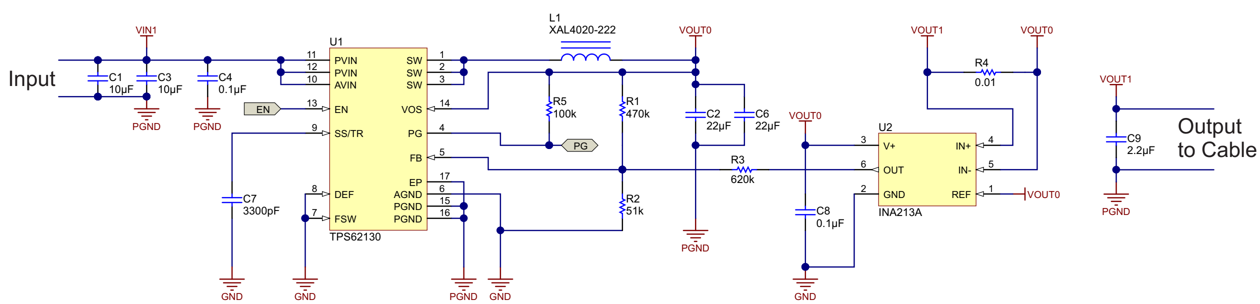

Figure 1. Circuit Schematic

The objective of the circuit is to provide an accurate 5-V supply at the end of the cable for a load which can vary between 0 A and 2 A. The cable connection in this example is 5 meters long (2 x 2.5 m) with a cross section of 0.5 mm^2. This circuit typically can be used to power a remote USB plug in a car which can be used for USB communication to the media hub and in addition to charge a USB device with 2 A of charge current. An example of an implementation is found in the TI reference designs library.

DCS-Control is a trademark of Texas Instruments.

2 Detailed Description

2.1 Current Feedback System

To measure the output current accurately, a current sense resistor is used. The voltage drop across the current sense resistor is measured by an instrumentation amplifier (INA213). The instrumentation amplifier generates an output voltage proportional to the output current of the DCDC converter (TPS62130). The output voltage of the instrumentation amplifier is connected as an offset voltage into the voltage feedback divider of the TPS62130 and changes the divider in a way that at increasing output current, the output voltage of the TPS62130 is increased. Knowing the voltage drop across the cable for a certain current or knowing the resistance of the cable connecting the load is required to derive the values for the resistors in the feedback network and the current sense resistor.

The minimum value for the resistance of the current sense resistor $\boldsymbol{R_{SHmin}}$ can be calculated using Equation 1.

$$R_{SH\,\min} = \frac{R_C}{G_{CS} - 1} \tag{1}$$

$\boldsymbol{R_C}$ is the resistance of the cable connected to the output of the TPS62130 and $\boldsymbol{G_{CS}}$ is the gain of the instrumentation amplifier.

After selecting an appropriate value for the current sense resistor, the maximum compensation voltage $\boldsymbol{\Delta V_{COMPmax}}$ the instrumentation amplifier can generate in the feedback divider can be calculated using Equation 2. $\boldsymbol{R_{SH}}$ is the resistance of the selected current sense resistor and $\boldsymbol{I_{OUTmax}}$ is the maximum output current the converter needs to provide.

$$\Delta V_{COMP\,\max} = R_{SH} \cdot G_{CS} \cdot I_{OUT\,\max} \tag{2}$$

Equation 3 shows how to calculate the maximum voltage change $\boldsymbol{\Delta V_{OUTmax}}$ at the output of the TPS62130. This voltage is adding to the nominal output voltage. The sum of this voltage and the nominal output voltage must not exceed the maximum output voltage rating of the TPS62130.

$$\Delta V_{OUT\,\max} = \left(R_C + R_{SH}\right) \cdot I_{OUT\,\max} \tag{3}$$

2.2 Voltage Feedback Network

For no output current the resistors in the feedback network can be calculated using the information in the TPS62130 datasheet. To define the order of magnitude of the resistance values, the resistor $\boldsymbol{R_2}$ needs to be defined. The TPS62130 datasheet gives guidance for that. With the value of $\boldsymbol{R_2}$, knowing the output voltage $\boldsymbol{V_{OUT0}}$ which needs to be regulated at the load and the feedback voltage of the TPS62130 $\boldsymbol{V_{FB}}$, the value of $\boldsymbol{R_{13}}$, the resistance of the resistor network with $\boldsymbol{R_1}$ and $\boldsymbol{R_3}$ in parallel can be calculated using Equation 4.

$$R_{13} = R_2 \cdot \left(\frac{V_{OUT\,0}}{V_{FB}} - 1 \right) \tag{4}$$

Using $\boldsymbol{R_{13}}$, the resistance of $\boldsymbol{R_1}$ and $\boldsymbol{R_3}$ in parallel, together with the gain of the instrumentation amplifier $\boldsymbol{G_{CS}}$, the resistance values of the cable connection $\boldsymbol{R_C}$ and the current sense resistor $\boldsymbol{R_{SH}}$, $\boldsymbol{R_3}$ can be calculated using Equation 5.

$$R_3 = R_{13} \cdot \left(\frac{G_{CS} \cdot R_{SH}}{R_C + R_{SH}} \right) \tag{5}$$

Since the value for $\boldsymbol{R_3}$ and the parallel resistance of $\boldsymbol{R_3}$ and $\boldsymbol{R_1}$ is known, $\boldsymbol{R_1}$ can now be calculated using Equation 6.

$$R_1 = \frac{R_{13} \cdot R_3}{R_3 - R_{13}} \tag{6}$$

3 Example

In the current example, an output voltage V_{OUT0} of 5.0 V should be regulated at a maximum output current I_{OUTmax} of 2.0 A. The resistance of the cable and the connecting headers R_C is calculated to be 0.20 Ω. The current amplifier is based on INA213. It has a fixed gain G_{CS} of 50.

Using Equation 1, the minimum resistance of the current sense resistor R_{SHmin} is calculated to be 4 mΩ. So, using a 10-mΩ current sense resistor for R_{SH} works properly.

With the cable resistance R_C and the maximum output current I_{OUTmax} the maximum voltage change ΔV_{OUTmax} at the output of the TPS62130 is calculated using Equation 3 to be 0.42 V. The maximum output voltage of TPS62130 is 6 V. So the calculated maximum voltage of 5.42 V at the output is well within TPS62130's recommended operating range.

Using the given values for R_{SH}, G_{CS}, and I_{OUTmax} in Equation 2 the maximum output voltage change $\Delta V_{COMPmax}$, the current feedback system can control is calculated to be 1 V.

Selecting 51 kΩ for R_2, taking the feedback voltage V_{FB} of 800 mV from the TPS62130 datasheet and using all calculated parameters from above allows calculating R_{13} (268 kΩ, Equation 4), R_3 (620 kΩ, Equation 5), and R_1 (470 kΩ, Equation 6).

The resistors finally selected may not perfectly match the calculation results. To determine the error in the output voltage at different output currents I_{OUT} caused by the nonmatching resistors in the feedback network, Equation 7 and Equation 8 can be used with the selected resistor values.

$$R_{13} = \frac{R_1 \cdot R_3}{R_1 + R_3} \tag{7}$$

$$V_{OUT} = V_{FB} \cdot \left(\frac{R_{13}}{R_2} + 1 \right) + I_{OUT} \cdot \left[R_{SH} \left(\frac{R_{13} \cdot G_{CS}}{R_3} - 1 \right) - R_C \right] \tag{8}$$

Using the 470 kΩ for R_1, 51 kΩ for R_2, and 620 kΩ for R_3 in the example results in an output voltage of 4.994 V at 0-A output current and 4.993 V at 2-A output current.

4 Test Results

Unless the test did require a different setup, all the following tests are performed with an 8-V input voltage supply for the circuit. The load is represented by an electronic load, connected with a 5-m cable connection (2 x 2.5 m). In parallel to the load at the end of the cable, a 10-µF capacitor is used to represent the input capacitor of the load circuit.

4.1 Load Regulation

Figure 2 shows the output voltage at the output of the TPS62130 which is increasing linearly with the load current and the regulated voltage at the load which is staying constant at 5 V. The relative error is shown in Figure 3.

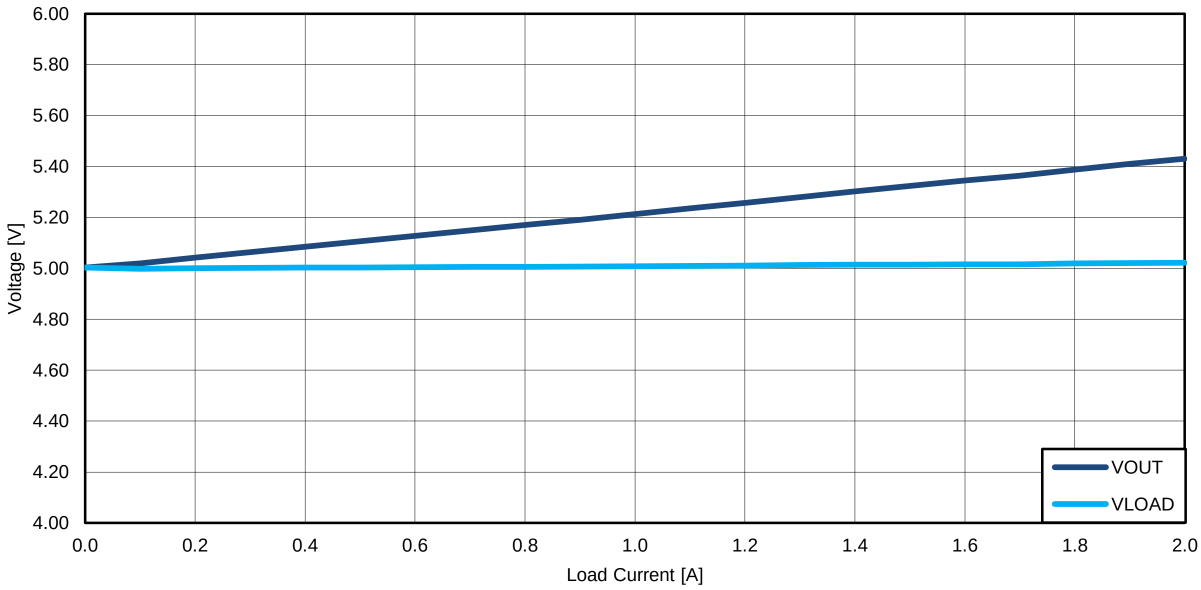

Figure 2. Converter Output Voltage and Regulated Voltage at the Load

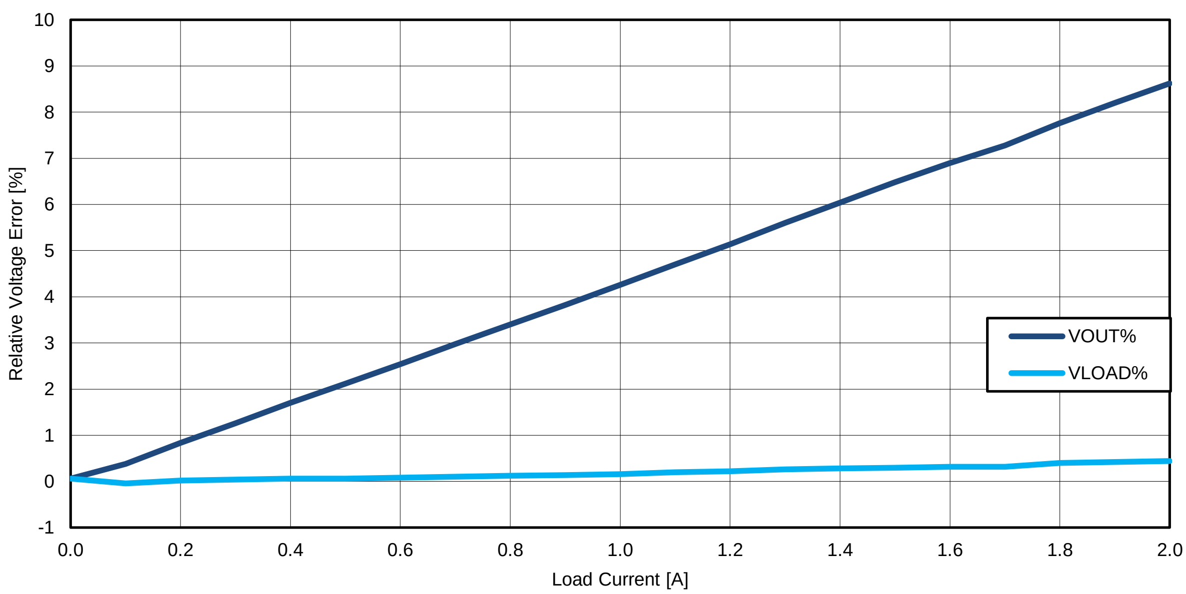

Figure 3. Error of the Converter Output Voltage and Regulated Voltage at the Load

4.2 Load Transient

Figure 4 shows the load transient behavior of the converter. The output voltage of the TPS62130 and the voltage regulated at the load are shown. Since in this circuit there is no direct feedback of the voltage error at the load, the voltage drop during load transients can be significant. In this example, the voltage variation during load transients is up to ±10%.

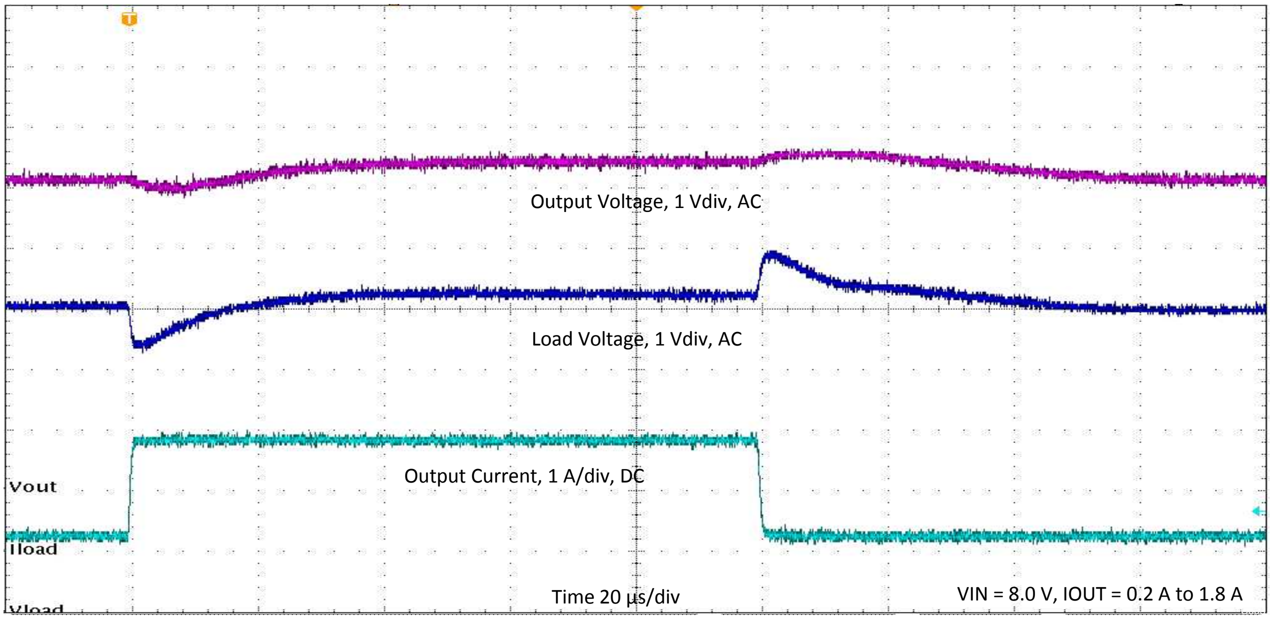

Figure 4. Load Transient

4.3 Line Transient

Figure 5 shows the line transient behavior of the converter. The control topology implemented in the TPS62130 (DCS-Control™), allows maintaining a well-regulated load voltage at the output of the TPS62130 and at the load. The supply voltage change is almost not visible in the curves of the output and load voltage.

If the line transient goes down to voltages lower than the programmed output voltage at the output of the TPS62130, as shown in Figure 6, the output voltage and the load voltage follow the curve of the input voltage with TPS62130 in a 100% duty cycle mode. As soon as the input voltage is again high enough to regulate the output voltage, the control of TPS62130 recovers smoothly.

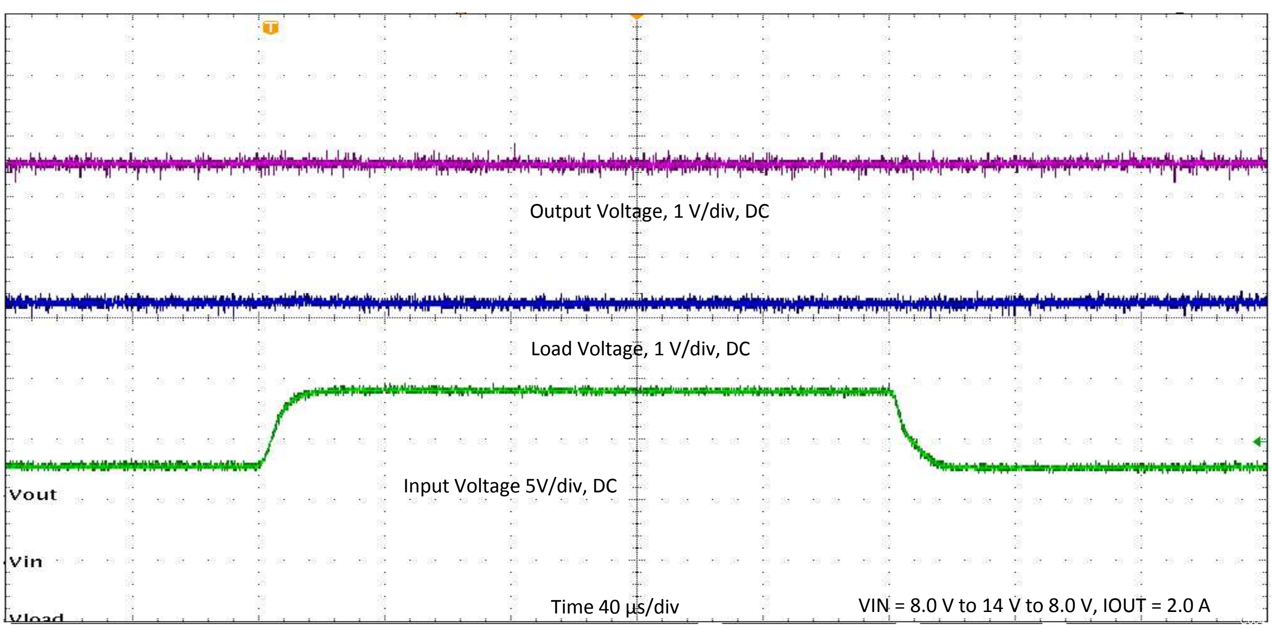

Figure 5. Line Transient

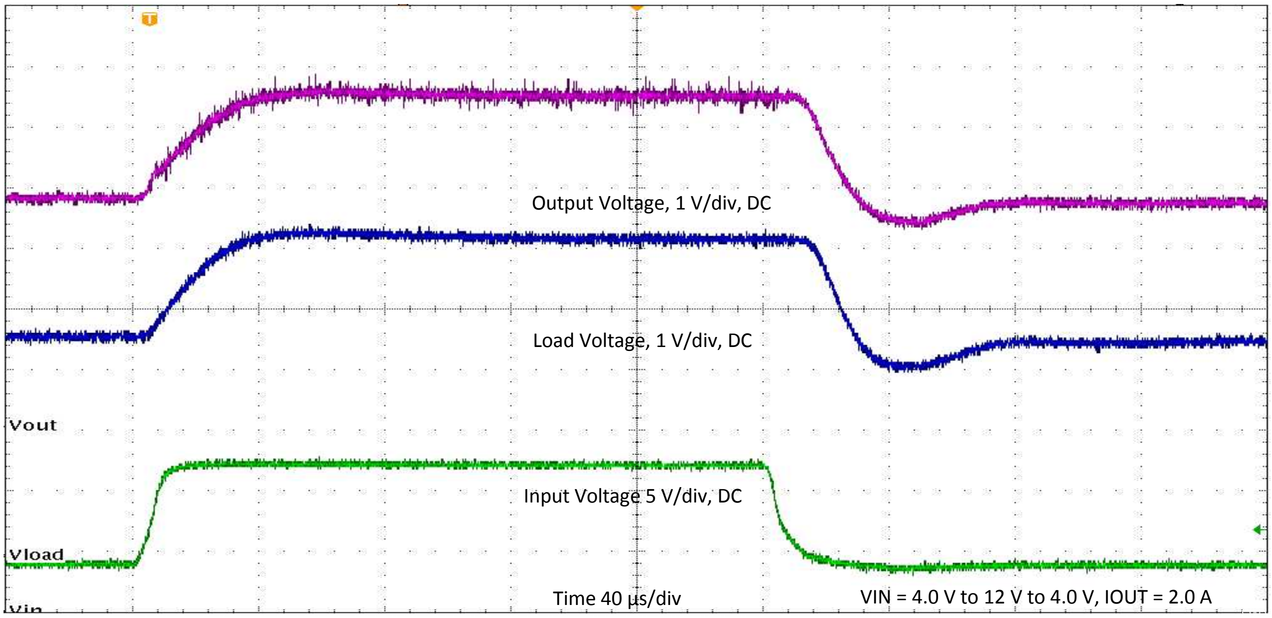

Figure 6. Line Transient into Undervoltage

4.4 Startup

Figure 7 shows the startup behavior of the proposed circuit. The voltage at EN is directly following the input voltage which is just turned on in this measurement. This means the converter starts operating as soon as the input voltage is higher than its undervoltage threshold. The output voltage and the load voltage are ramped up smoothly to the programmed voltage levels. When removing the input voltage, the converter stops operating and actively discharges the output.

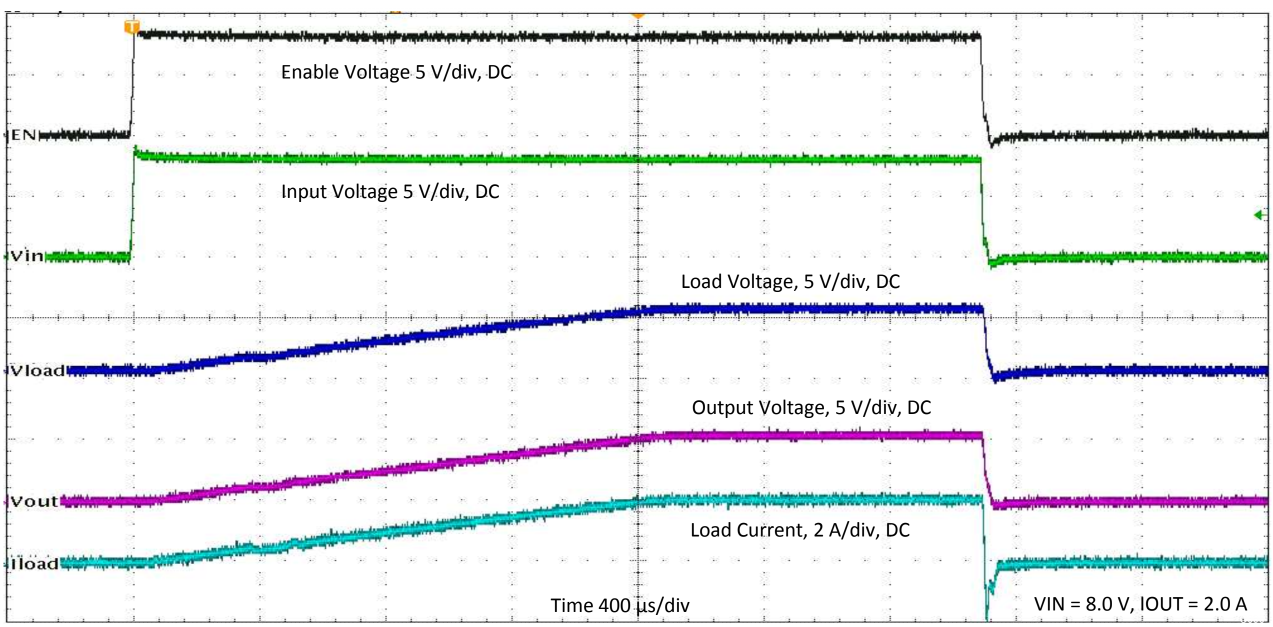

Figure 7. Startup

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