

How to Design a Simple Constant-current/constant-power/constant-voltage-regulating Buck Converter



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Introduction

In a previous blog titled “[How to design a simple constant current/constant voltage buck converter](#),” I discussed how to design a constant current/constant voltage converter (CC/CV). With the addition of a simple modification, the functionality can be modified to regulate the output power and operate within a constant power (CP) limit as the output voltage varies in the CC mode of operation. This blog discusses the simple modification need to design a CC/CP/CV converter using the current monitor (CM) feature of the LM5117 buck controller.

Application Example

In the CC mode of operation, the output voltage increases as the load resistance increases, and as a result, the output power will increase linearly as the current is regulated into the load. However some applications require the output current to be reduced as output voltage increases thereby limiting the power delivered to the load. A relatively flat power limit over a wide output voltage range can be achieved with a simple modification to a CC/CV converter that uses the LM5117.

Method of Implementing CC/CP/CV

Figure 1 shows a typical discrete implementation of a CC/CP/CV converter. The difference between the CC/CV converter and the CC/CP/CV converter is the addition of a feedforward resistor (R_{ff}).

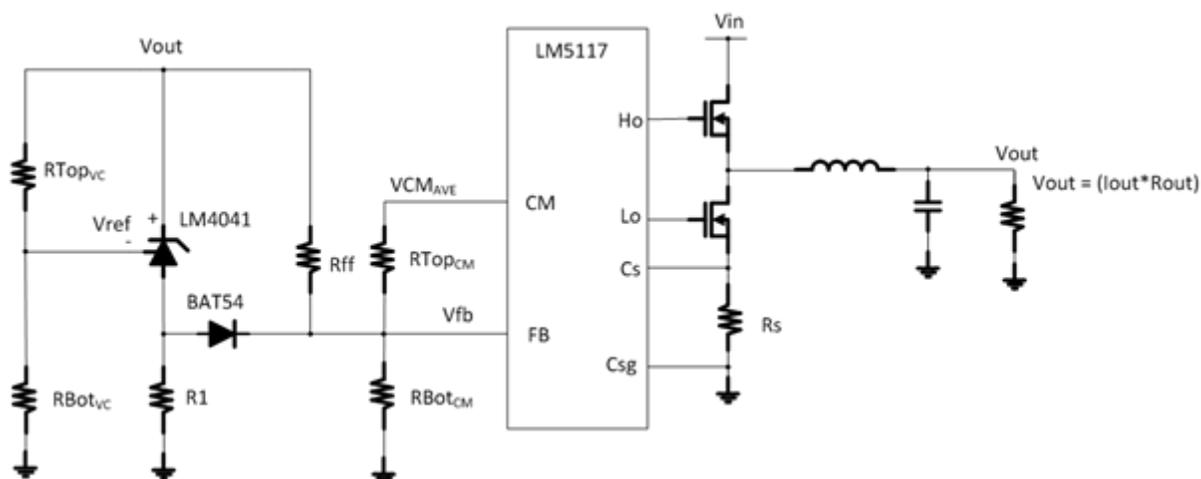


Figure 1. A Typical Discrete Implementation of a CC/CP/CV Converter

Output Current Regulation

The LM5117 has a CM pin. When the converter is operating in continuous conduction mode, the voltage on the CM pin ($V_{CM_{AVE}}$) is proportional to the output current. By using a resistor divider from the $V_{CM_{AVE}}$ to ground and connecting the divider tap point to the feedback node of the LM5117, you can control the output current. Equation 1 expresses the relationship between the voltage on the CM pin and the output current:

$$V_{CM_{AVE}} = 2 \cdot I_{out} \cdot R_s \cdot A_s \quad (1)$$

Where R_s is the current sense resistor and A_s is the internal current sense amplifier gain.

The relationship between the voltage on the CM pin ($V_{CM_{AVE}}$) and the voltage at the feedback node of the LM5117 (V_{fb}) is set by the resistor divider network and is expressed in [Equation 2](#).

$$V_{CM_{AVE}} = \left(\frac{R_{top_{CM}}}{R_{bot_{CM}}} + 1 \right) V_{fb} \quad (2)$$

Combining [Equation 1](#) and [Equation 2](#) and rearranging for output current we can see how the output current is controlled by the feedback resistors from the CM to V_{fb} . This is shown in [Equation 3](#).

$$I_{out} = \frac{\left(\frac{R_{top_{CM}}}{R_{bot_{CM}}} + 1 \right) V_{fb}}{2 \cdot A_v \cdot R_s} \quad (3)$$

CP Programming

R_{ff} is used to offset $V_{CM_{AVE}}$ as V_{out} varies by injecting a current into V_{fb} . At higher output voltages, more current is injected into V_{fb} through R_{ff} which reduces $V_{CM_{AVE}}$. As can be seen in [Equation 1](#), $V_{CM_{AVE}}$ controls the output current (I_{out}) and by reducing $V_{CM_{AVE}}$, we reduce the regulated output current as the output voltage increases. [Equation 4](#) calculates the voltage reduction ($V_{off_{CM}}$) at $V_{CM_{AVE}}$:

$$V_{off_{CM}} = \frac{V_{out} - V_{fb}}{R_{ff}} \cdot R_{Top_{CM}} \quad (4)$$

R_{ff} has a linear relationship with the output voltage and the output voltage has a linear relationship with I_{out} . Because we are in effect summing into V_{fb} , the power limit over a given output voltage range will be nonlinear.

As an example, given the requirements of a 60W power limit and an output voltage range of 6V to 12V, we can calculate the power stage components. It is suggested the power stage components be selected for the highest I_{out} of 10A corresponding to the lowest output voltage of 6V with a power limit of 60W. From our calculations, we determine $R_s = 12m\Omega$ and $A_s = 8.5$. Note that the A_s of the LM5117 is reduced by external 200 Ω series resistors at CS and CSG. Refer to the LM5117 datasheet for more details on how series resistors connected to these pins reduces the current sense gain.

As a starting point, select values for $R_{Top_{CM}}$ and $R_{Bot_{CM}}$ that will yield a maximum regulated output current 1.4 times greater than the specified regulated current of 10A, which occurs at the minimum output voltage. This suggestion is based on the fact that R_{ff} will reduce $V_{CM_{AVE}}$ as described earlier and therefore reduce I_{out} .

For example, for a 60 W power limit at a 6 V output, multiply 10 A by 1.4, which yields 14 A of regulated output current. Select 10 k Ω for $R_{Bot_{CM}}$ and rearrange [Equation 3](#) to calculate ~25 k Ω for $R_{top_{CM}}$. Select a standard value of 25.5 k Ω for $R_{top_{CM}}$.

[Equation 5](#) calculates the amount of error introduced at the minimum V_{out} and serves as a good starting value for R_{ff} :

$$V_{CM_error} = 0.8 \cdot I_{out} \cdot R_s \cdot A_s \quad (5)$$

With the addition of R_{ff} at the minimum V_{out} , you need to ensure that this error is subtracted from $V_{CM_{AVE}}$ by making sure that the V_{CM_error} is equal to the $V_{CM_{AVE}}$. Make Equation 5 equal to Equation 4 and rearrange for R_{ff} , as shown in Equation 6:

$$R_{ff} = \frac{(V_{out} - V_{ref}) 1.25 \cdot R_{top_CM}}{A_s \cdot I_{out} \cdot R_s} \quad (6)$$

Evaluating Equation 6 yields an $R_{ff} = 167k\Omega$. Select a standard value of $155k\Omega$ for R_{ff} . Using Equation 4, calculate $V_{off_{CM}} = 0.855V$ at a 6V output.

Equation 7 shows the resulting $V_{CM_{AVE}}$, which is determined by subtracting Equation 4 from Equation 2:

$$V_{CM_{AVE}} = \left[\left(\frac{R_{top_{CM}}}{R_{bot_{CM}}} + 1 \right) V_{fb} \right] - V_{off_{CM}} \quad (7)$$

For the given example here, $V_{CM_{AVE}} = 1.985V$

$V_{CM_{AVE}}$ controls the output current and this voltage decreases as the output voltage increases. Equation 8 shows the relationship between the regulated output current (I_{out_adj}), $V_{CM_{AVE}}$ and $V_{off_{CM}}$.

$$I_{out_adj} = \frac{\left[\left(\frac{R_{top_{CM}}}{R_{bot_{CM}}} + 1 \right) V_{fb} \right] - V_{off_{CM}}}{2 \cdot A_V \cdot R_s} \quad (8)$$

Evaluating Equation 8 yields an $I_{out_adj} = 10.053$ at a 6V output.

Multiplying Equation 8 with the output voltage calculates the output power, shown in Equation 9:

$$P_{out} = I_{out_adj} \cdot V_{out} \quad (9)$$

Where

$$V_{out} = I_{out_adj} \cdot R_{load} \quad (10)$$

Evaluating Equation 10 calculates a $P_{out} = 60.13W$.

I recommend using Equation 7, Equation 8 and Equation 9 to check the power limit for a given output-voltage range to ensure that the power-limit profile suits the needs of your particular application. You can adjust R_{ff} and $R_{Top_{CM}}$ to modify the power-limit profile for a given output-voltage range.

Figure 2 shows a plot of the power limit as voltage increases using the values from the example. As previously stated, the CP regulation is not precisely constant, but the power variation in this example is less than $\pm 7\%$ over the full operating range.

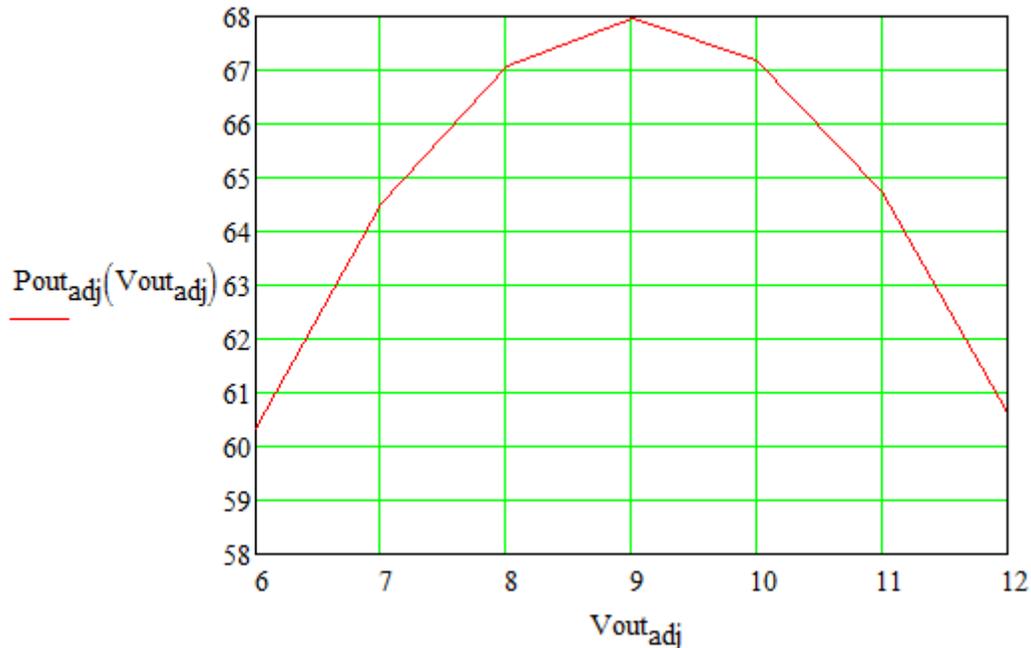


Figure 2. Power-limit Curve as a Function of Output Voltage

CV Programming

Looking at Figure 1, the voltage-clamp circuit uses the LM4041 voltage reference. The LM4041 is unique when compared to other references in that its reference voltage V_{fb} is set between the LM4041's cathode and reference pin as opposed to the anode and reference pin (cathode-referenced and anode-referenced voltage references, respectively). This is advantageous for this particular application because it minimizes the interaction between R_{ff} and R_1 during transition from CP to CV control.

Being cathode-referenced, the LM4041 allows the voltage reference to turn on without introducing errors during the transition. By using the LM4041, the end result is a small change in the output voltage as the converter changes from CP to CV regulation, which is solely based on the values selected for $R_{Top_{VC}}$ and $R_{Bot_{VC}}$.

Equation 11 sets the voltage clamp set point:

$$V_{clamp} = \frac{V_{ref} \cdot (R_{Bot_{VC}} + R_{Top_{VC}})}{R_{Bot_{VC}}} \quad (11)$$

CC/CP/CV Design of the LM5117

The design approach for the power stage of a CC/CP/CV converter using the LM5117 is the same as it is for a basic buck converter. I suggest carrying out the design at the highest output power level using either [WEBENCH® Designer](#) or the [LM5117 Quick Start Calculator](#). You can also look at the LM5117 data sheet for guidance on the design of the buck power stage.

Example Schematic

Figure 3 shows a 48V input, 60W power limit LM5117 from 6V to 12V, with an output voltage limiter (V_{clamp}) set to engage at 12.5V.

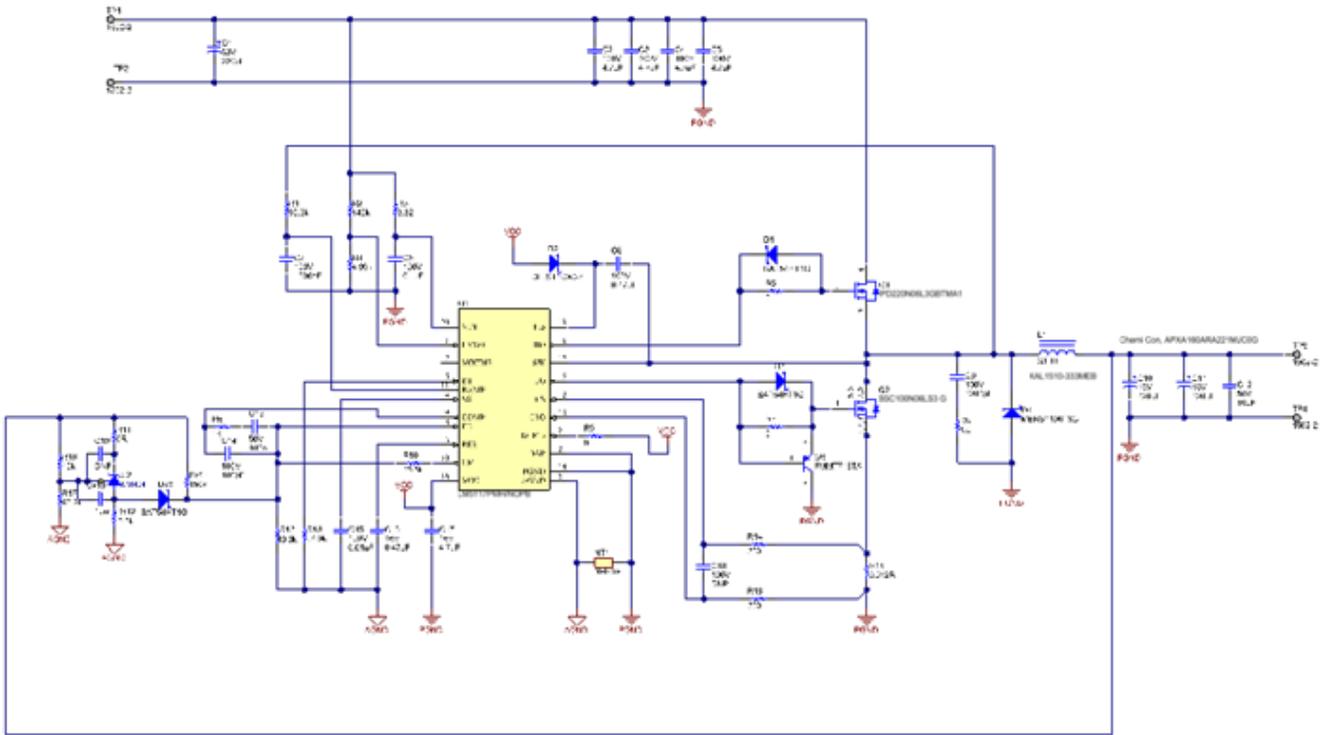


Figure 3. Example Schematic for a 5V to 12V Power Limit of 60W and a Voltage Clamp Set at 12.5V

Figure 4 shows the measured efficiency as a function of I_{out}.

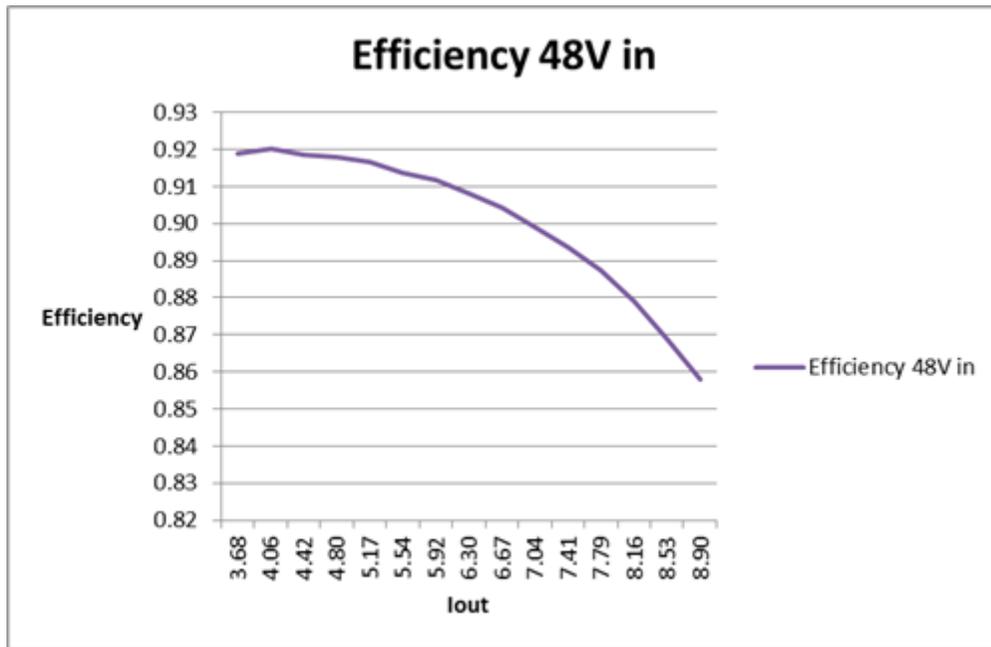


Figure 4. Efficiency of the Buck Converter Based on Figure 3

Figure 5 shows the measured power-limit profile as a function of the output voltage.

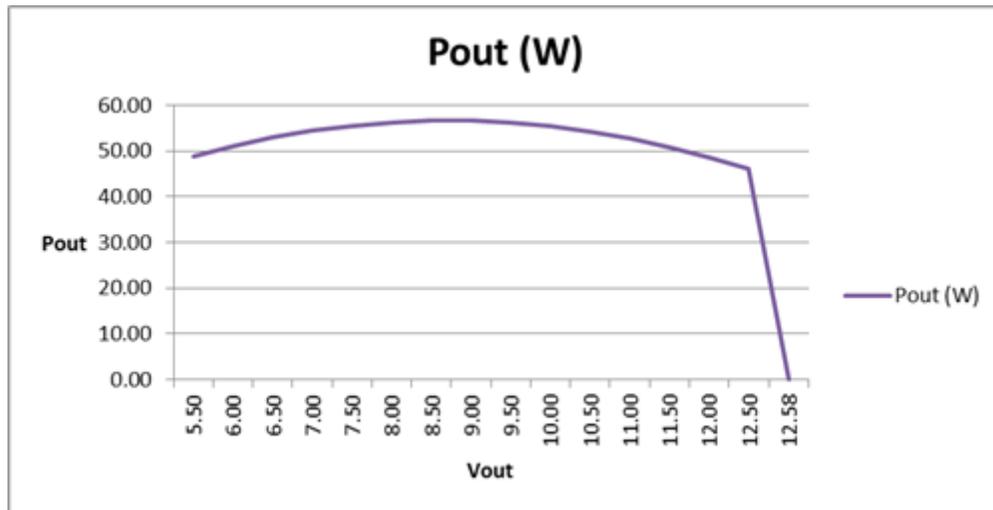


Figure 5. Power-limit Profile

(I further reduced Rff to keep the power limit below 60W, selecting a final value of 150kΩ for Rff.)

Figure 6 shows the measured output voltage as a function of Iout. The converter's sense resistor (Rs) sets the maximum current at the right side of the graph. Note that the value of Rs will affect the power-regulation variation.

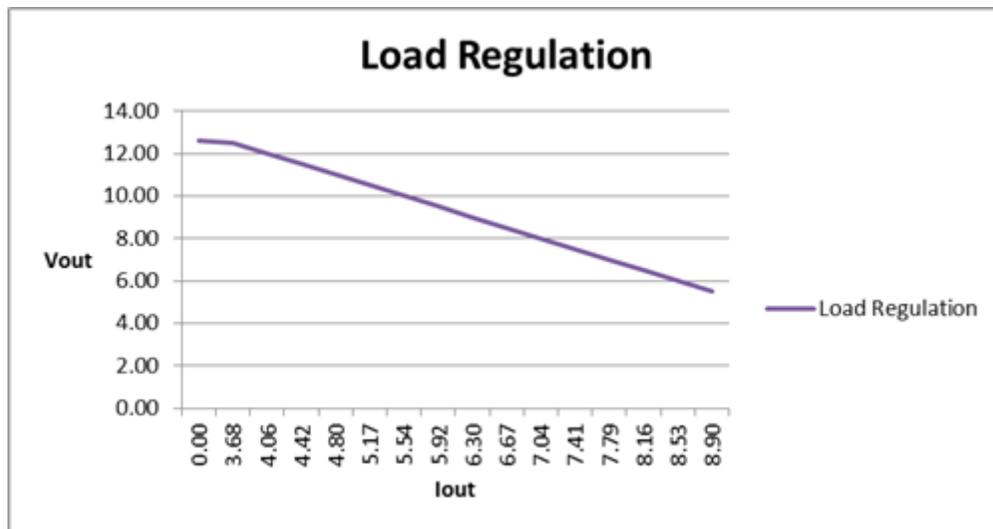


Figure 6. Output-voltage Variation as a Function of Iout

Figure 7 shows the measured switch node (CH3), Vout ripple (CH1) and output current (CH4) at 48Vin, 6.6Vout at Iout > 8A.

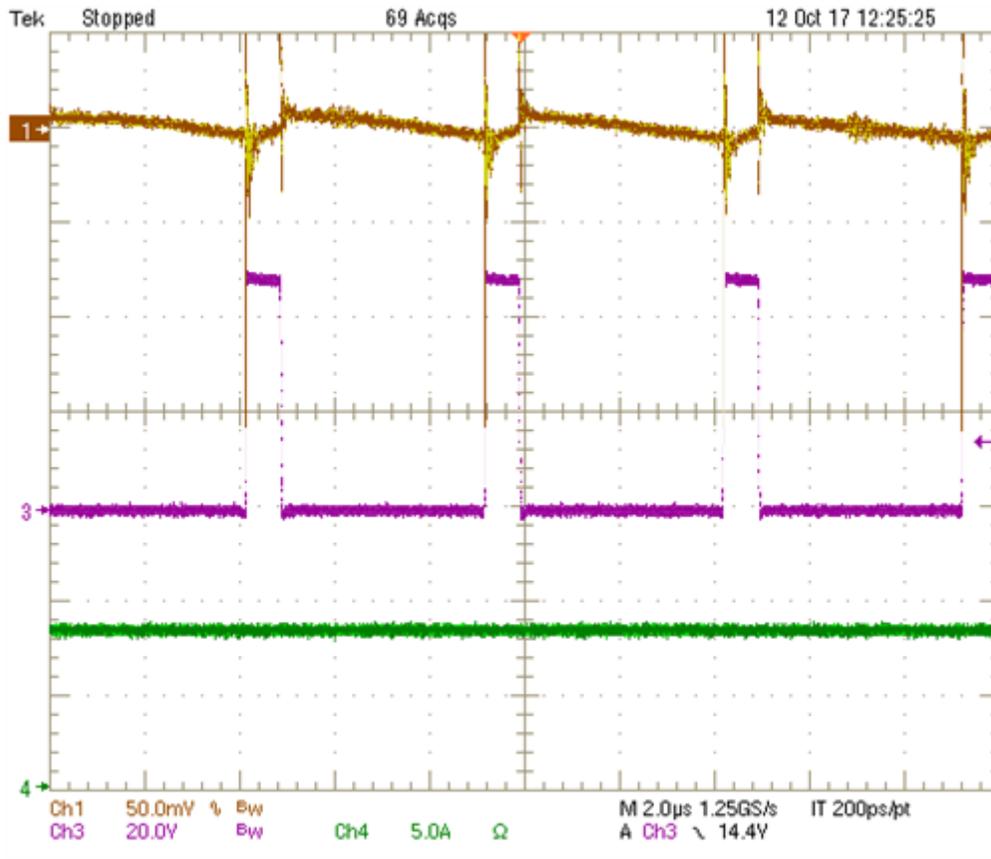


Figure 7. Steady-state Scope Shots

Figure 8 shows the measured transient response at a 48V input voltage, with Vout (CH1), Iout (CH4) and a load step from 3.8A to 5.7A (0.1A/µs).

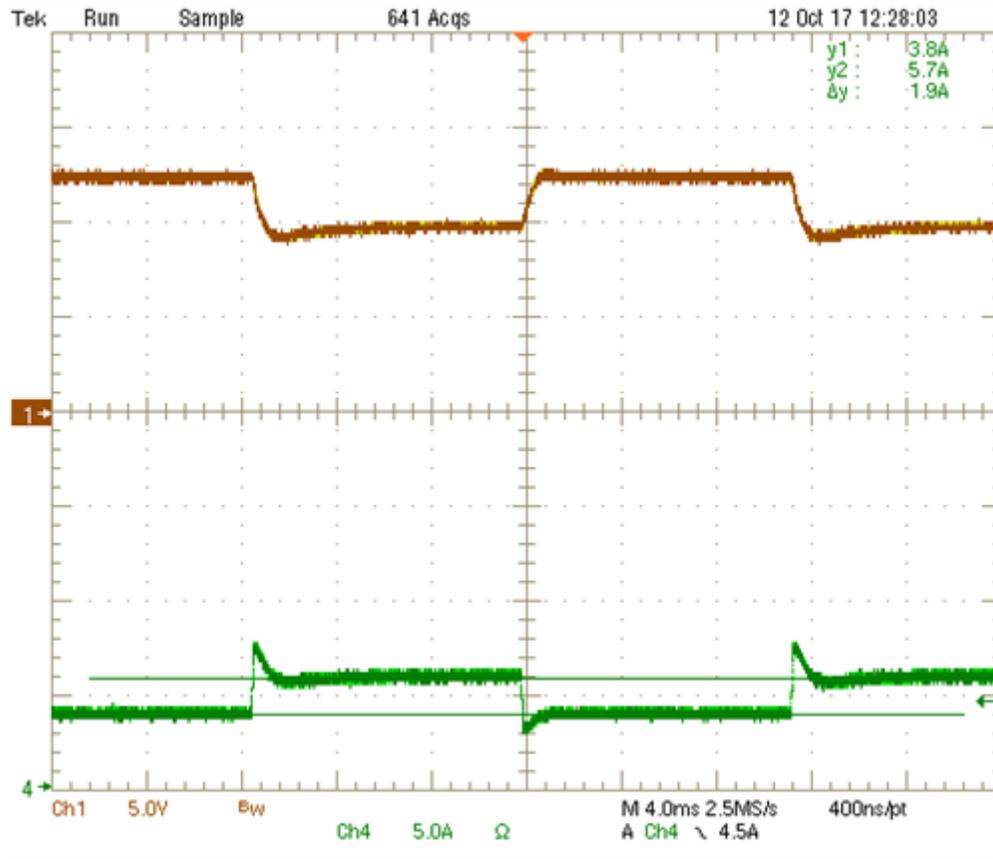


Figure 8. Transient Response Scope Shots

Conclusion

The LM5117 configured as a CC/CP/CV converter provides a power-limit profile for an output-voltage range with the addition of an R_{ff} resistor to a CC/CV converter. This design approach is relatively simple and provides advantages of reduced size, cost and power losses.

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