February 1, 2012

LMP8646

Precision Current Limiter

General Description

The LMP8646 is a precision current limiter used to improve the current limit accuracy of any switching or linear regulator with an available feedback node.

The LMP8646 accepts input signals with a common mode voltage ranging from -2V to 76V. It has a variable gain which is used to adjust the sense current. The gain is configured with a single external resistor, R_G, providing a high level of flexibility and accuracy up to 2%. The adjustable bandwidth, which allows the device to be used with a variety of applications, is configurable with a single external capacitor in parallel with R_G. In addition, the output is buffered in order to provide a low output impedance.

The LMP8646 is an ideal choice for industrial, automotive, telecommunications, and consumer applications where circuit protection and improved precision systems are required. The LMP8646 is available in a 6-pin TSOT package and can operate at temperature range of –40°C to 125°C.

Applications

- High-side and low-side current limit
- Circuit fault protection
- Battery and supercap charging
- LED constant current drive
- Power management

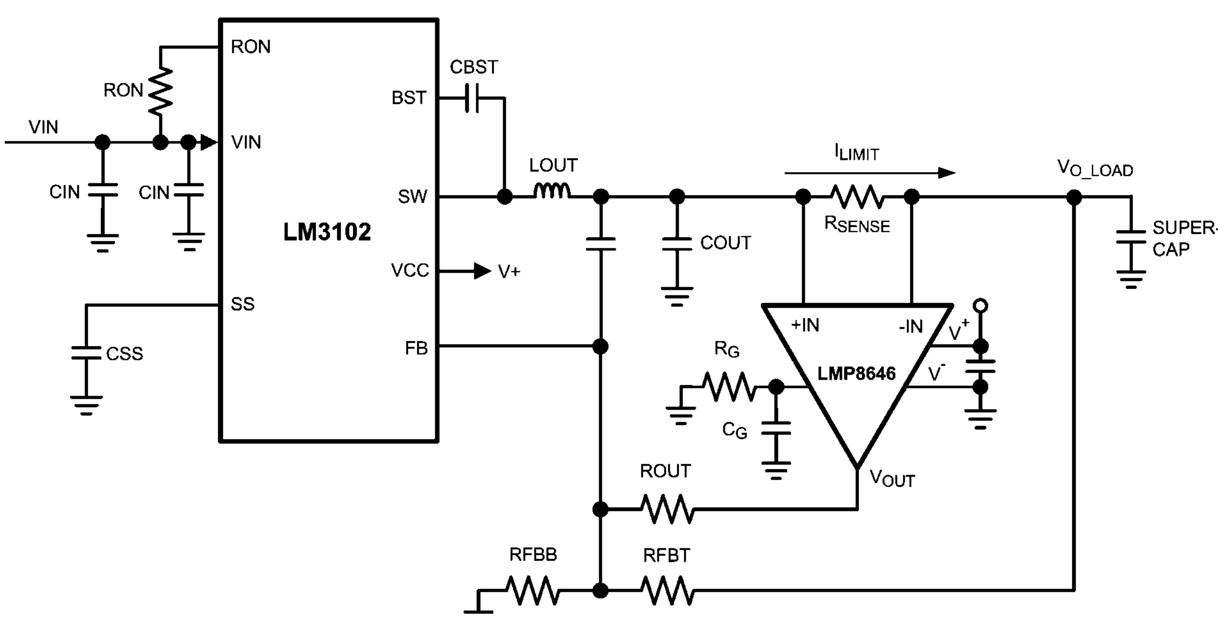
Features

- Provides circuit protection and current limiting
- Single supply operation
- -2V to +76V common mode voltage range
- Variable gain set by external resistor
- Adjustable bandwidth set by external capacitor
- Buffered output
- 3% output accuracy achievable at V_{SENSE} = 100 mV

Key Specifications

Supply voltage range	2.7V to 12V
Output current (source)	0 to 5 mA
Gain accuracy	2.0% (max)
Transconductance	200 µA/V
Offset	±1 mV (max)
Quiescent current	380 µA
Input bias	12 µA (typ)
PSRR	85 dB
CMRR	95 dB
Temperature range	–40°C to 125°C
6-Pin TSOT Package	

Typical Application



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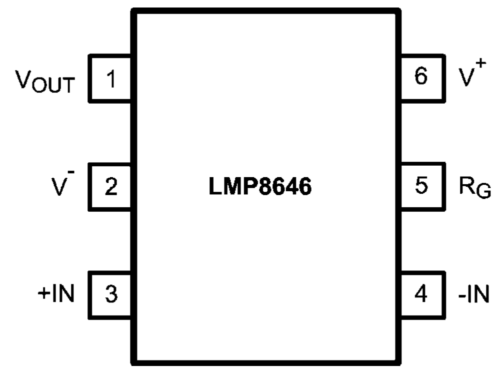
Ordering Information

Package	Part Number	Package Marking	Transport Media	NSC Drawing
6-Pin TSOT	LMP8646MK	AK7A	1k Units Tape and Reel	MK06A
	LMP8646MKX		3k Units Tape and Reel	
	LMP8646MKE		250 Units Tape and Reel	

Connection Diagram

6-Pin TSOT



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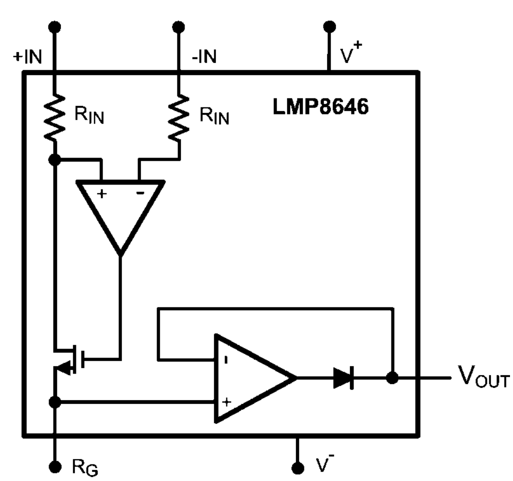
Top View

Pin Descriptions

Pin	Name	Description
1	V_{OUT}	Single-Ended Output Voltage
2	V-	Negative Supply Voltage. This pin should be connected to ground.
3	+IN	Positive Input
4	-IN	Negative Input
5	R_G	External Gain Resistor. An external capacitance (C_G) may be added in parallel with R_G to limit the bandwidth.
6	V+	Positive Supply Voltage

Block Diagram



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Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the Texas Instruments Sales Office/ Distributors for availability and specifications.

ESD Tolerance (Note 2)	
Human Body Model	
For input pins: +IN and -IN	±4000V
For all other pins	±2000V
Machine Model	200V
Charge device model	1250
Supply Voltage (V_S = V+ - V−)	13.2V
Differential voltage +IN- (-IN)	6V
Voltage at pins +IN, -IN	-6V to 80V
Voltage at R_G pin	13.2V
Voltage at OUT pin	V- to V+
Storage Temperature Range	-65°C to 150°C
Junction Temperature (Note 3)	150°C
For soldering specifications, see product folder at www.national.com and www.national.com/ms/MS/MS-SOLDERING.pdf	

Operating Ratings (Note 1)

Supply Voltage (V_S = V+ - V−)	2.7V to 12V
Temperature Range (Note 3)	-40°C to 125°C
Package Thermal Resistance(Note 3)	
TSOT-6	96°C/W

2.7V Electrical Characteristics (Note 4)

Unless otherwise specified, all limits guaranteed for at T_A = 25°C, V_S=(V+ – V-) = (2.7V - 0V) = 2.7 V, –2V < V_{CM} < 76V, R_G= 25kΩ, R_L = 10 kΩ. **Boldface** limits apply at the temperature extremes.

Symbol	Parameter	Condition	Min (Note 6)	Typ (Note 5)	Max (Note 6)	Units
V_{OFFSET}	Input Offset Voltage	V_{CM} = 2.1V	-1 **-1.7**		1 **1.7**	mV
TCV_{OS}	Input Offset Voltage Drift (Note 7, Note 9)	V_{CM} = 2.1V			7	μV/°C
I_B	Input Bias Current (Note 10)	V_{CM} = 2.1V		12	20	μA
e_{ni}	Input Voltage Noise (Note 9)	f > 10 kHz, R_G = 5 kΩ		120		$nV/\sqrt{Hz}$
V_{SENSE}	Max Input Sense Voltage (Note 9)	V_{CM} = 12V, R_G = 5 kΩ			600	mV
Gain A_V	Adjustable Gain Setting (Note 9)	V_{CM} = 12V	1		100	V/V
Gm	Transconductance = $1/R_{IN}$	V_{CM} = 2.1V		200		μA/V
	Accuracy	V_{CM} = 2.1V	-2 **-3.4**		2 **3.4**	%
	Gm drift (Note 9)	–40°C to 125°C, V_{CM}=2.1V			**140**	ppm /°C
PSRR	Power Supply Rejection Ratio	V_{CM} = 2.1V, 2.7V < V+ < 12V,	85			dB
CMRR	Common Mode Rejection Ratio	2.1V < V_{CM} < 76V	95			dB
		-2V < V_{CM} < 2.1V,	55			
SR	Slew Rate (Note 8, Note 9)	V_{CM} = 5V, C_G = 4 pF, V_{SENSE} from 25 mV to 175 mV, C_L = 30 pF, R_L = 1MΩ		0.5		V/μs
I_S	Supply Current	V_{CM} = 2.1V		380	610 **807**	uA
		V_{CM} = –2V		2000	2500 **2700**	
V_{OUT}	Maximum Output Voltage	V_{CM} = 2.1V, R_G = 500 kΩ	1.1			V
	Minimum Output Voltage	V_{CM} = 2.1V			20	mV
	Maximum Output Voltage	VS = V_{CM} = 3.3V, R_G = 500 kΩ	1.6			V
	Minimum Output Voltage	VS = V_{CM} = 3.3V, R_G = 500 kΩ			22	mV
I_{OUT}	Output current (Note 9)	Sourcing, V_{OUT}= 600mV, R_G = 150kΩ		5		mA
C_{LOAD}	Max Output Capacitance Load (Note 9)			30		pF

5V Electrical Characteristics (Note 4)

Unless otherwise specified, all limits guaranteed for at T_A = 25°C, V_S=V+-V-, V+ = 5V, V− = 0V, −2V < V_{CM} < 76V, R_g= 25kΩ, R_L = 10 kΩ. **Boldface** limits apply at the temperature extremes.

Symbol	Parameter	Condition	Min (Note 6)	Typ (Note 5)	Max (Note 6)	Units
V_{OFFSET}	Input Offset Voltage	V_{CM} = 2.1V	-1 **-1.7**		1 **1.7**	mV
TCV_{OS}	Input Offset Voltage Drift (Note 7, Note 9)	V_{CM} = 2.1V			7	μV/°C
I_B	Input Bias Current (Note 10)	V_{CM} = 2.1V		12.5	22	µA
e_{ni}	Input Voltage Noise (Note 9)	f > 10 kHz, R_G = 5 kΩ		120		$nV/\sqrt{Hz}$
$V_{SENSE(MAX)}$	Max Input Sense Voltage (Note 9)	V_{CM} = 12V, R_G = 5 kΩ		600		mV
Gain A_V	Adjustable Gain Setting (Note 9)	V_{CM} = 12V	1		100	V/V
Gm	Transconductance = $1/R_{IN}$	V_{CM} = 2.1V		200		µA/V
	Accuracy	V_{CM} = 2.1V	-2 **-3.4**		2 **3.4**	%
	Gm drift (Note 9)	–40°C to 125°C, V_{CM}= 2.1V			140	ppm /°C
PSRR	Power Supply Rejection Ratio	V_{CM} = 2.1V, 2.7V < V+ < 12V,	85			dB
CMRR	Common Mode Rejection Ratio	2.1V <V_{CM} < 76V	95			dB
		-2V < V_{CM} < 2.1V	55			
SR	Slew Rate(Note 8, Note 9)	V_{CM} = 5V, C_G = 4 pF, V_{SENSE} from 100 mV to 500 mV, C_L = 30 pF, R_L= 1MΩ		0.5		V/µs
I_S	Supply Current	V_{CM} = 2.1V		450	660 **939**	uA
		V_{CM} = –2V		2100	2800 **3030**	
V_{OUT}	Maximum Output Voltage	V_{CM} =5V, R_G= 500 kΩ	3.3			V
	Minimum Output Voltage	V_{CM} =2.1V			22	mV
I_{OUT}	Output current (Note 9)	Sourcing, V_{OUT}= 1.65V, R_G = 150kΩ		5		mA
C_{LOAD}	Max Output Capacitance Load (Note 9)			30		pF

12V Electrical Characteristics (Note 4)

Unless otherwise specified, all limits guaranteed for at T_A = 25°C, V_S=V+-V-, V+ = 12V, V− = 0V, −2V < V_{CM} < 76V, R_g= 25kΩ, R_L = 10 kΩ. **Boldface** limits apply at the temperature extremes.

Symbol	Parameter	Condition	Min (Note 6)	Typ (Note 5)	Max (Note 6)	Units
V_{OFFSET}	Input Offset Voltage	V_{CM} = 2.1V	-1 **-1.7**		1 **1.7**	mV
TCV_{OS}	Input Offset Voltage Drift (Note 7, Note 9)	V_{CM} = 2.1V			7	μV/°C
I_B	Input Bias Current (Note 10)	V_{CM} = 2.1V		13	23	μA
e_{ni}	Input Voltage Noise (Note 9)	f > 10 kHz, R_G = 5 kΩ		120		$nV/\sqrt{Hz}$
$V_{SENSE(MAX)}$	Max Input Sense Voltage (Note 9)	V_{CM} =12V, R_G = 5 kΩ		600		mV
Gain A_V	Adjustable Gain Setting (Note 9)	V_{CM} = 12V	1		100	V/V
Gm	Transconductance = $1/R_{IN}$	V_{CM} = 2.1V		200		μA/V
	Accuracy	V_{CM} = 2.1V	-2 **-3.4**		2 **3.4**	%
	Gm drift (Note 9)	−40°C to 125°C, V_{CM} =2.1V			140	ppm /°C
PSRR	Power Supply Rejection Ratio	V_{CM} = 2.1V, 2.7V <V+ < 12V,	85			dB
CMRR	Common Mode Rejection Ratio	2.1V <V_{CM} < 76V	95			dB
		−2V <V_{CM} < 2.1V	55			
SR	Slew Rate (Note 8, Note 9)	V_{CM} = 5V, C_G = 4 pF, V_{SENSE} from 100 mV to 500 mV, C_L = 30 pF, R_L=1MΩ		0.6		V/μs
I_S	Supply Current	V_{CM} = 2.1V		555	845 **1123**	uA
		V_{CM} = −2V		2200	2900 **3110**	
V_{OUT}	Maximum Output Voltage	V_{CM} = 12V, R_G= 500kΩ,	10			V
	Minimum Output Voltage	V_{CM} = 2.1V			24	mV
I_{OUT}	Output current (Note 9)	Sourcing, V_{OUT}= 5.25V, R_G = 150kΩ		5		mA
C_{LOAD}	Max Output Capacitance Load (Note 9)			30		pF

Note 1: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is intended to be functional, but specific performance is not guaranteed. For guaranteed specifications and the test conditions, see the Electrical Characteristics Tables.

Note 2: Human Body Model, applicable std. MIL-STD-883, Method 3015.7. Machine Model, applicable std. JESD22-A115-A (ESD MM std. of JEDEC) Field-Induced Charge-Device Model, applicable std. JESD22-C101-C (ESD FICDM std. of JEDEC).

Note 3: The maximum power dissipation must be derated at elevated temperatures and is dictated by $T_{J(MAX)}$, θ_{JA}, and the ambient temperature, T_A. The maximum allowable power dissipation $P_{DMAX} = (T_{J(MAX)} - T_A)/\theta_{JA}$ or the number given in Absolute Maximum Ratings, whichever is lower.

Note 4: Electrical Table values apply only for factory testing conditions at the temperature indicated. Factory testing conditions result in very limited self-heating of the device such that $T_J = T_A$. No guarantee of parametric performance is indicated in the electrical tables under conditions of internal self-heating where $T_J > T_A$.

Note 5: Typical values represent the most likely parametric norm at the time of characterization. Actual typical values may vary over time and will also depend on the application and configuration. The typical values are not tested and are not guaranteed on shipped production material.

Note 6: All limits are guaranteed by testing, design, or statistical analysis.

Note 7: Offset voltage temperature drift is determined by dividing the change in V_{OS} at the temperature extremes by the total temperature change.

Note 8: The number specified is the average of rising and falling slew rates and measured at 90% to 10%.

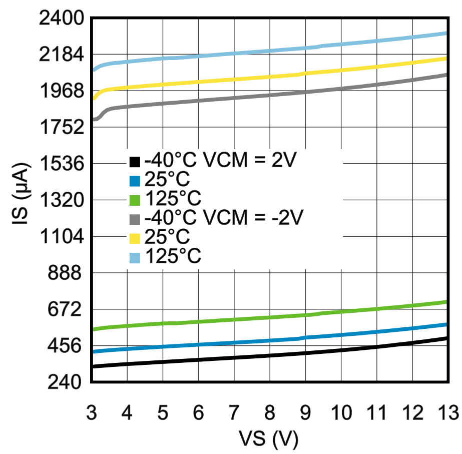
Note 9: This parameter is guaranteed by design and/or characterization and is not tested in production.

Note 10: Positive Bias Current corresponds to current flowing into the device.

Typical Performance Characteristics

Unless otherwise specified: T_A = 25°C, V_S=V+-V-, V_{SENSE}= +IN - (-IN), R_L = 10 kΩ.

Supply Curent vs. Supply Voltage for V_{CM} = 2V



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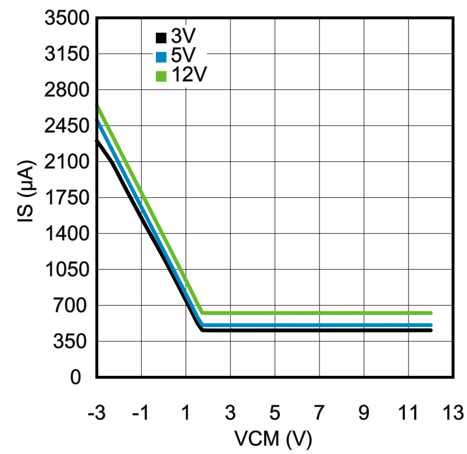
Supply Current vs. V_{CM}



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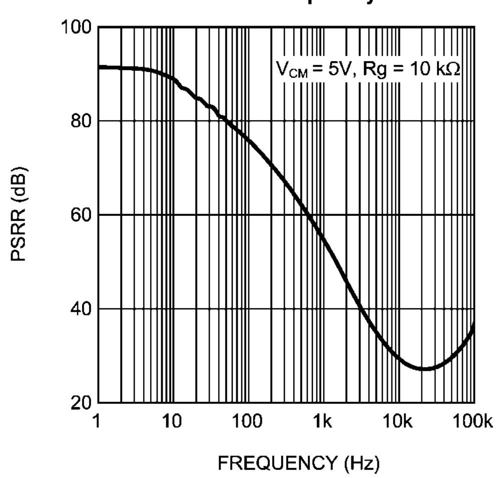
AC PSRR vs. Frequency



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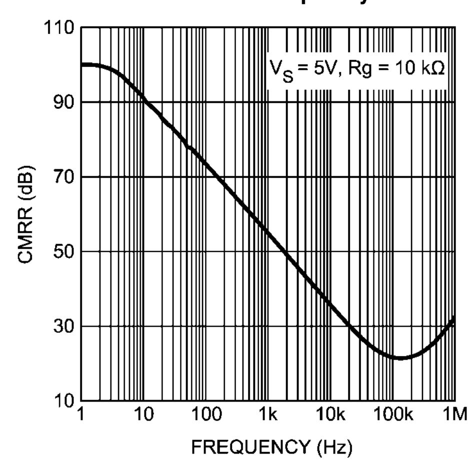
AC CMRR vs. Frequency



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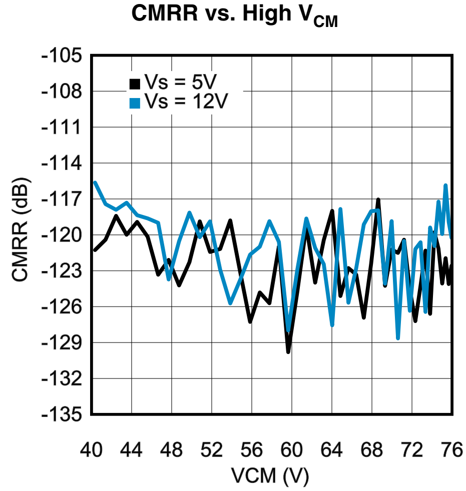
CMRR vs. High V_{CM}



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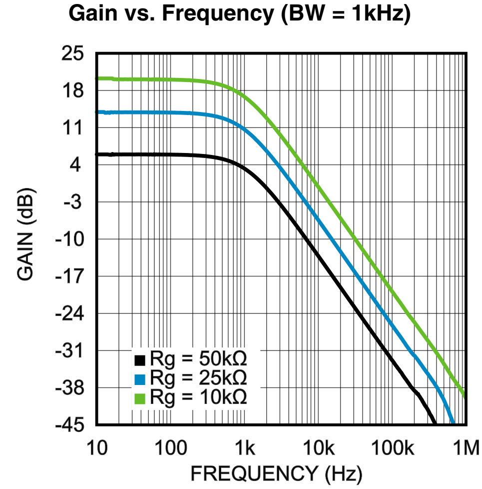
Gain vs. Frequency (BW = 1kHz)



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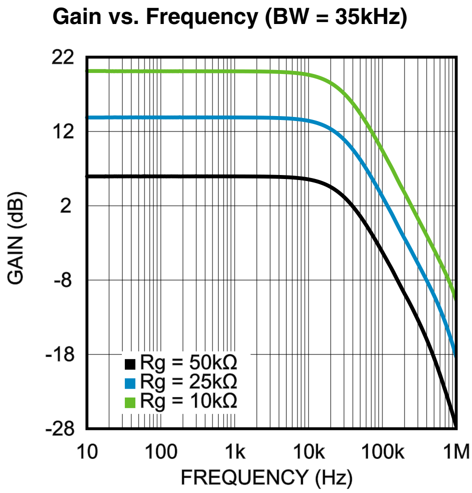

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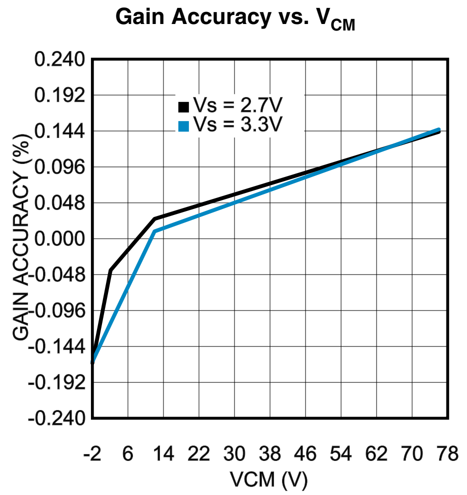

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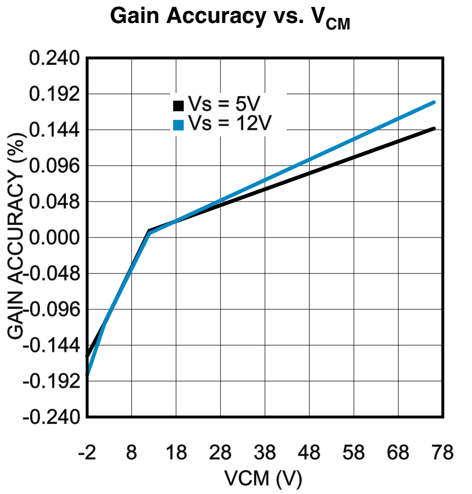

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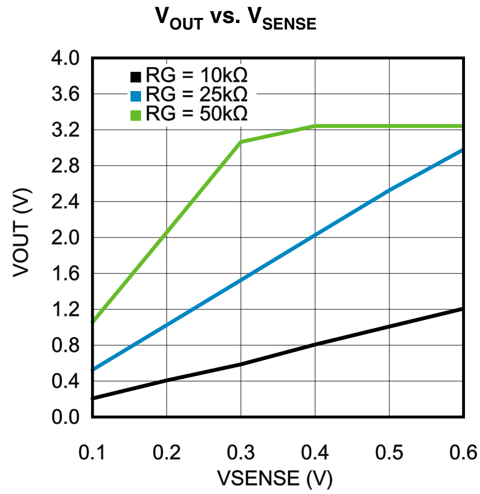

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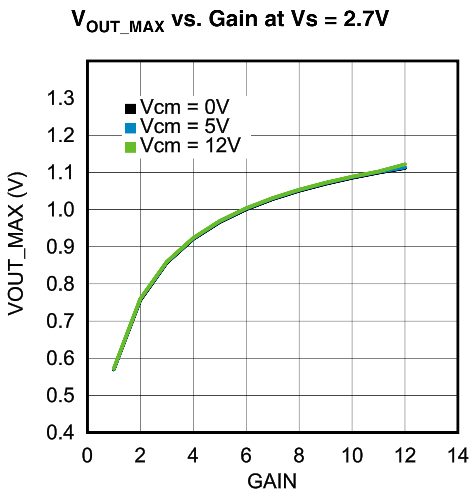

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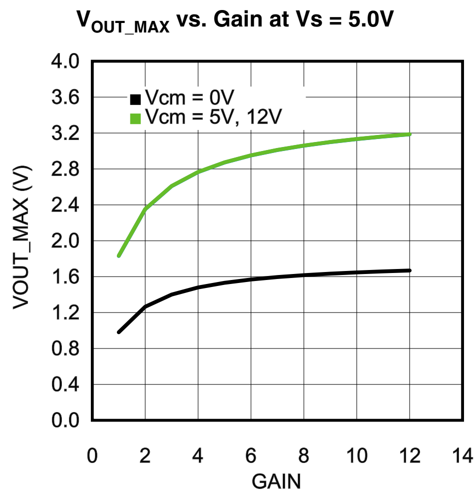

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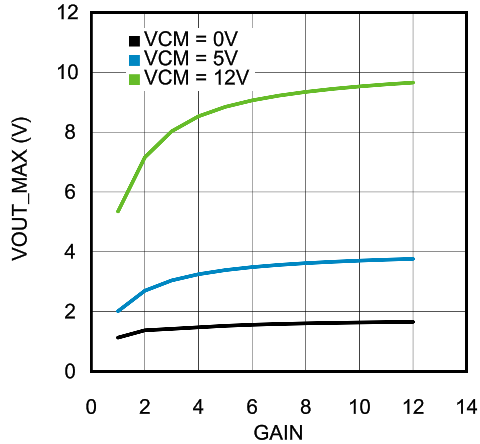
V_{OUT_MAX} vs. Gain at Vs = 12V



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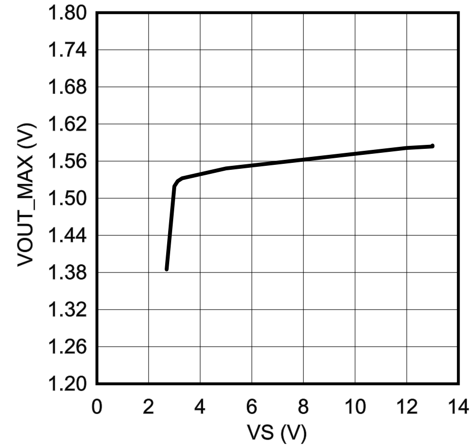
V_{OUT_MAX} vs. V_S at V_{CM} = -2V



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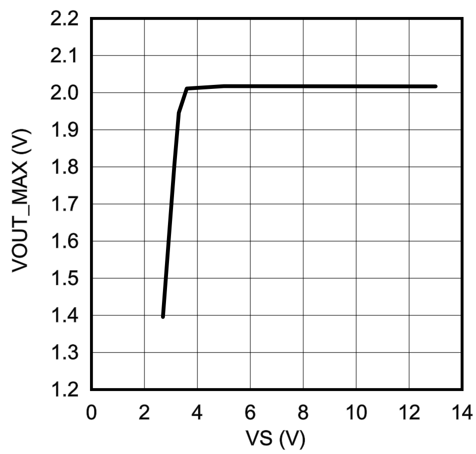
V_{OUT_MAX} vs. V_S at V_{CM} = 2.1V



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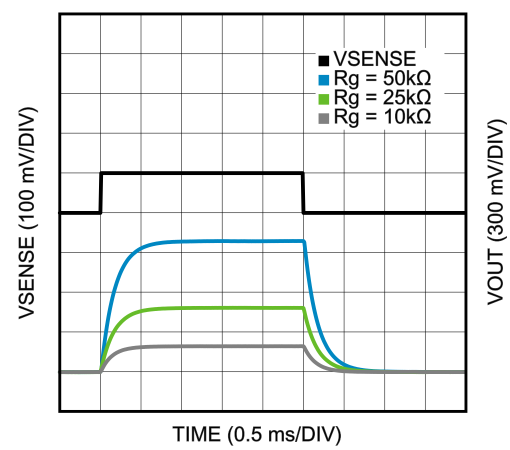
Large Step Response at BW = 1kHz



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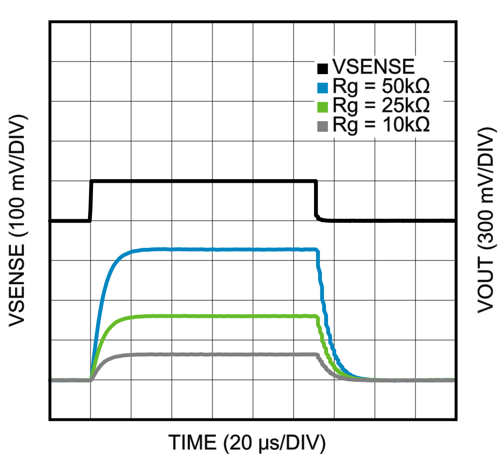
Large Step Response at BW = 35 kHz



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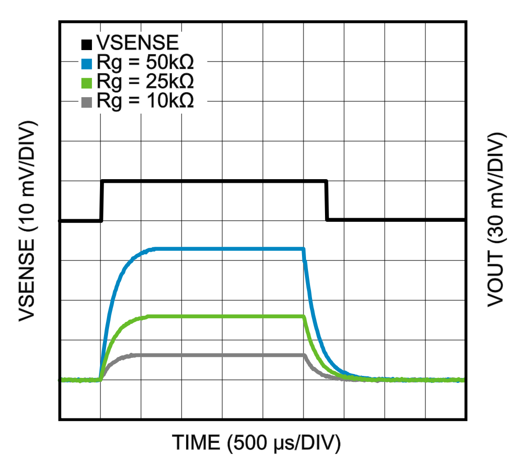
Small Step Response at BW = 1 kHz



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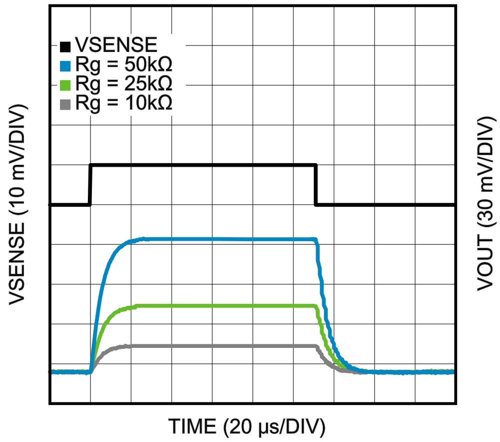
Small Step Response at BW = 35 kHz



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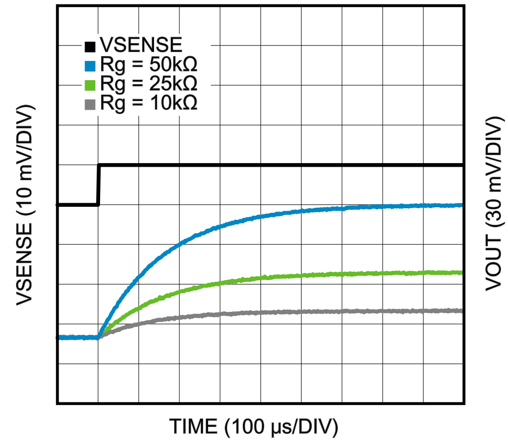
Settling Time (Rise) at 1kHz



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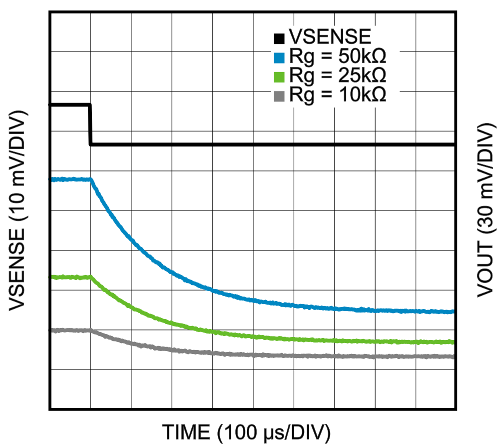
Settling Time (Fall) at 1kHz



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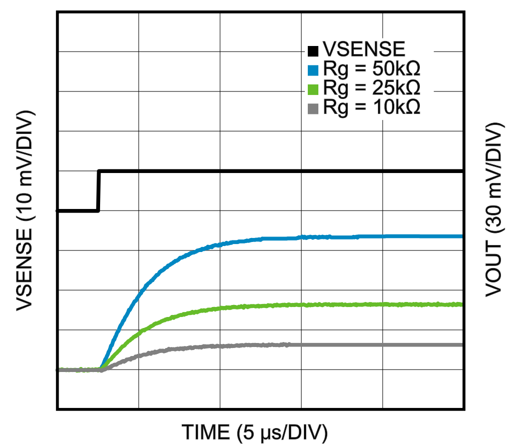
Settling Time (Rise) at 35kHz



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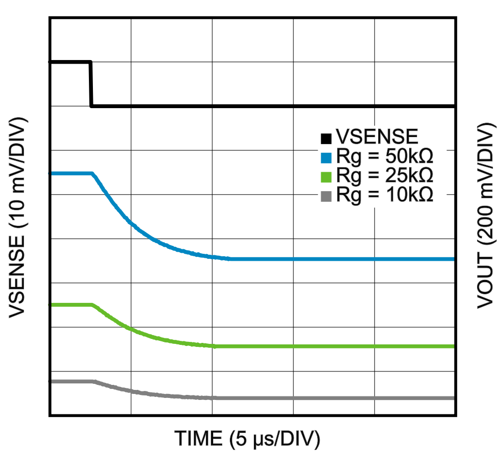
Settling Time (Fall) at 35kHz



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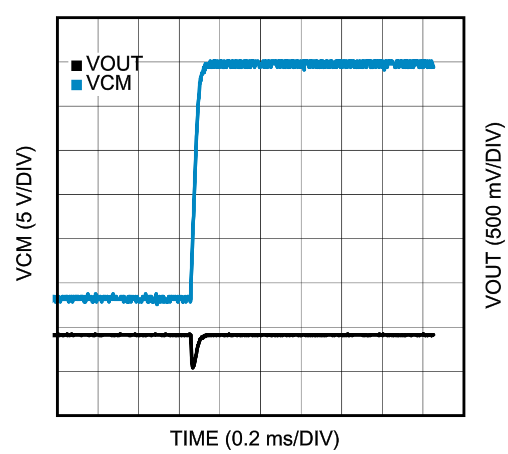
Common Mode Step Response (Rise) at 35 kHz



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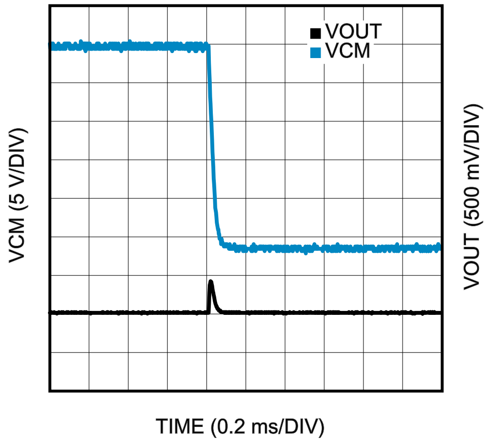
Common Mode Step Response (Fall) at 35 kHz



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FUNCTIONAL DESCRIPTION

GENERAL

The LMP8646 is a single supply precision current limiter with variable gain selected through an external resistor (R_G) and a variable bandwidth selected through an external capacitor (C_G) in parallel with R_G. Its common-mode of operation is -2V to +76V, and the LMP8646 has an buffered output to provide a low output impedance. More details of the LMP8646's functional description can be seen in the following subsections.

THEORY OF OPERATION

As seen from *Figure 1*, the sense current flowing through R_{SENSE} develops a voltage drop equal to V_{SENSE}. The high impedance inputs of the amplifier does not conduct this current and the high open loop gain of the sense amplifier forces its non-inverting input to the same voltage as the inverting input. In this way the voltage drop across R_{IN} matches V_{SENSE}. The current I_{IN} flowing through R_{IN} has the following equation:

$$I_{IN} = V_{SENSE}/ R_{IN} = R_{SENSE}{*}I_{SENSE}/R_{IN}$$

$$\text{where } R_{IN} = 1/Gm = 1/(200\ \mu A/V) = 5\ kOhm$$

I_{IN} flows entirely across the external gain resistor R_G to develop a voltage drop equal to:

$$V_{RG} = I_{IN}{*}R_G = (V_{SENSE}/R_{IN})\ {*}R_G = [(R_{SENSE}{*}I_{SENSE}) / R_{IN}]{*}R_G$$

This voltage is buffered and showed at the output with a very low impedance allowing a very easy interface of the LMP8646 with the feedback of many voltage regulators. This output voltage has the following equation:

$$V_{OUT} = V_{RG} = [(R_{SENSE}{*}I_{SENSE}) / R_{IN}]{*}R_G$$

$$V_{OUT} = V_{SENSE}{*}\ R_G/R_{IN}$$

$$V_{OUT} = V_{SENSE}{*}\ R_G/(5\ kOhm)$$

$$V_{OUT} = V_{SENSE}{*}\ \text{Gain, where Gain} = R_G/R_{IN}$$

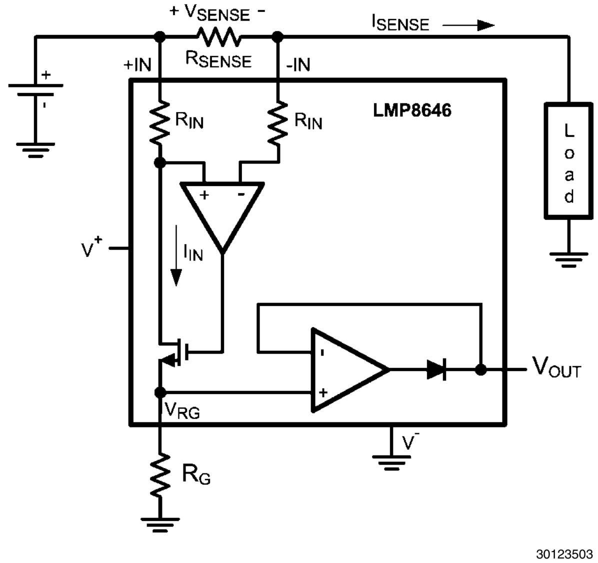


FIGURE 1. Current monitor

MAXIMUM OUTPUT VOLTAGE, V_{OUT_MAX}

The maximum output voltage, V_{OUT_MAX}, depends on the supply voltage, $V_S = V^+ - V^-$, and on the common mode voltage, $V_{CM} = (+IN + -IN) / 2$.

The following subsections show three cases to calculate for V_{OUT_MAX}.

Case 1: $-2V < V_{CM} < 1.8V$, and $V_S > 2.7V$

If $V_S \geq 5$ V,
then $V_{OUT\_MAX} = 1.3V$.
Else if Vs = 2.7V,
then $V_{OUT\_MAX} = 1.1V$.

Case 2: $1.8V < V_{CM} < V_S$, and $V_S > 3.3V$

In this case, V_X is a fixed value that depends on the supply voltage. V_X has the following values:

If $V_S = 12V$, then $V_X = 10V$.
Else if $V_S = 5V$, then $V_X = 3.3V$.
Else if $V_S = 2.7V$, then $V_X = 1.1V$.

If $V_X \leq (V_{CM} - V_{SENSE} - 0.25)$,
then $V_{OUT\_MAX} = V_X$.
Else,
$V_{OUT\_MAX} = (V_{CM} - V_{SENSE} - 0.25)$.

For example, if $V_{CM} = 4V$, $V_S = 5V$ (and thus $V_X = 3.3V$), $V_{SENSE} = 0.1$ V, then $V_{OUT\_MAX} = 3.3V$ because $3.3V \leq (4 - 0.1 - 0.25)$.

Case 3: $V_{CM} > V_S$, and $V_S > 2.7V$

If $V_S = 12V$, then $V_{OUT\_MAX} = 10V$.
Else if $V_S = 5V$, then $V_{OUT\_MAX} = 3.3V$.
Else if $V_S = 2.7V$, then $V_{OUT\_MAX} = 1.1V$.

APPLICATIONS INFORMATION

OUTPUT ACCURACY

The output accuracy is the device error contributed by the LMP8646 based on its offset and gain errors. The LMP8646 output accuracy has the following equations:

$$\text{Output Accuracy} = \left|\frac{V_{OUT\_THEO} - V_{OUT\_CAL}}{V_{OUT\_THEO}}\right| \times 100(\%)$$

$$\text{where } V_{OUT\_THEO} = (V_{SENSE}) \times \frac{R_G}{1/Gm}$$

$$\text{and } V_{OUT\_CALC} = \frac{(V_{SENSE} + V_{OFFSET}) \times R_G}{1/[Gm\ (1 + Gm\_Accuracy)]}$$

30123538

FIGURE 2. Output Accuracy Equations

For example, assume V_{SENSE} = 100 mV, R_G = 10 kOhm, and it is known that V_{OFFSET} = 1 mV and Gm_Accuracy = 2% (Electrical Characteristics Table), then the output accuracy can be calculated as:

$$V_{OUT\_THEO} = (100\text{ mV}) \times \frac{10\text{ k}\Omega}{1/(200\mu)} = 0.2\text{V}$$

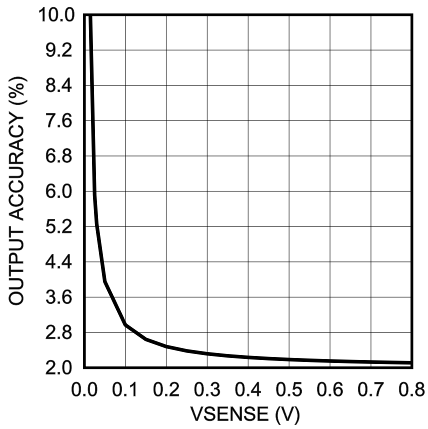
$$V_{OUT\_CALC} = \frac{(100\text{ mV} + 1\text{ mV}) \times 10\text{ k}\Omega}{1/[200\mu\ (1 + 2/100)]} = 0.20604\text{V}$$

$$\text{Output Accuracy} = \left|\frac{0.2\text{V} - 0.20604\text{V}}{0.2\text{V}}\right| \times 100 = 3.02\%$$

30123539

FIGURE 3. Output Accuracy Example

In fact, as V_{SENSE} decreases, the output accuracy worsens as seen in *Figure 4*. These equations provide a valuable tool to estimate how the LMP8646 affects the overall system performance. Knowing this information allows the system designer to pick the appropriate external resistances (R_{SENSE} and R_G) to adjust for the tolerable system error. Examples of this tolerable system error can be seen in the next sections.



30123570

FIGURE 4. Output Accuracy vs. V_{SENSE}

SELECTION OF THE SENSE RESISTOR, R_{SENSE}

The accuracy of the current measurement also depends on the value of the shunt resistor R_{SENSE}. Its value depends on the application and is a compromise between small-signal accuracy and maximum permissible voltage loss in the load line.

R_{SENSE} is directly proportional to V_{SENSE} through the equation $R_{SENSE} = (V_{SENSE}) / (I_{SENSE})$. If V_{SENSE} is small, then there is a smaller voltage loss in the load line, but the output accuracy is worse because the LMP8646 offset error will contribute more. Therefore, high values of R_{SENSE} provide better output accuracy by minimizing the effects of offset, while low values of R_{SENSE} minimize the voltage loss in the load line. For most applications, best performance is obtained with an R_{SENSE} value that provides a V_{SENSE} of 100 mV to 200 mV.

R_{SENSE} Consideration for System Error

The output accuracy described in the previous section talks about the error contributed just by the LMP8646. The system error, however, consists of the errors contributed by the LMP8646 as well as other external resistors such as R_{SENSE} and R_G. Let's rewrite the output accuracy equation for the system error assuming that R_{SENSE} is non-ideal and R_G is ideal. This equation can be seen as:

$$\text{System Error} = \left|\frac{V_{OUT\_THEO} - V_{OUT\_CAL}}{V_{OUT\_THEO}}\right| \times 100(\%)$$

$$\text{where } V_{OUT\_THEO} = (R_{SENSE} \times I_{SENSE}) \times \frac{R_G}{1/Gm}$$

$$\text{and } V_{OUT\_CALC} = \frac{[R_{SENSE}\ (1+\text{Tolerance}) \times I_{SENSE} + V_{OFFSET}] \times R_G}{1/[Gm\ (1 + Gm\_Accuracy)]}$$

30123554

FIGURE 5. System Error Equation Assuming R_{SENSE} is Non-ideal and R_G is Ideal

Continuing from the previous output accuracy example, we can calculate for the system error assuming that R_{SENSE} = 100 mOhm (with 1% tolerance), I_{SENSE} = 1A, and R_G = 10 kOhm. From the Electrical Characteristics Table, it is also known that V_{OFFSET} = 1 mV and Gm_Accuracy = 2%.

$$V_{OUT\_THEO} = (100\text{ m}\Omega \times 1\text{A}) \times \frac{10\text{ k}\Omega}{1/(200\mu)} = 0.2\text{V}$$

$$V_{OUT\_CALC} = \frac{[100\text{ m}\Omega\ (1+1/100) \times 1\text{A} + 1\text{mV}] \times 10\text{ k}\Omega}{1/[200\mu\ (1 + 2/100)]} = 0.20808\text{V}$$

$$\text{System Error} = \left|\frac{0.2\text{V} - 0.20808\text{V}}{0.2\text{V}}\right| \times 100 = 4.04\%$$

30123555

FIGURE 6. System Error Example Assuming R_{SENSE} is Non-ideal and R_G is Ideal

Because an R_{SENSE} tolerance will increase the system error, we recommend selecting an R_{SENSE} resistor with low tolerance.

SELECTION OF THE GAIN RESISTOR, R_G

For the LMP8646, the gain is selected through an external resistor connected to the R_G pin. The voltage at this R_G pin is equal to V_{OUT}, which has the equation $V_{OUT} = V_{RG} = V_{SENSE} * R_G/(5\ kOhm)$.

In fact, R_G must be chosen such that the V_{OUT} does not exceed its maximum ratings (V_{OUT_MAX}) as described in the *MAXIMUM OUTPUT VOLTAGE, V_{OUT_MAX}* section. Using this V_{OUT_MAX} and the equation $R_{G\_MAX} = (V_{OUT\_MAX} * 5kOhm) / (V_{SENSE})$, a plot of R_{G_MAX} vs. V_{SENSE} can be seen for three cases below. Use these plots to help select the appropriate R_G value so that V_{SENSE} and V_{OUT} stay within the recommended operating ratings. Since these plots are for R_{G_MAX}, all of the combinations of R_G below the curve are allowed.

Case 1: $-2V < V_{CM} < 1.8V$, and $V_S > 3.3V$

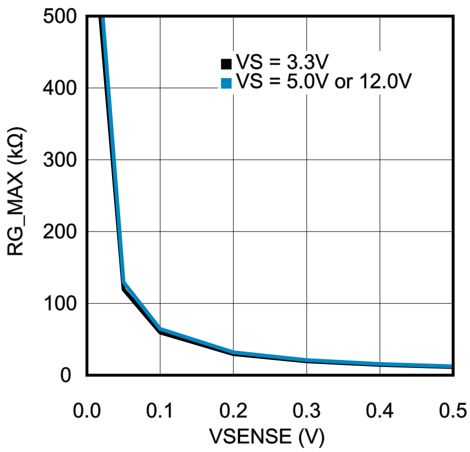


FIGURE 7. Allowed R_G for CASE 1

Case 2: $1.8V < V_{CM} < V_S$, and $V_S > 3.3V$

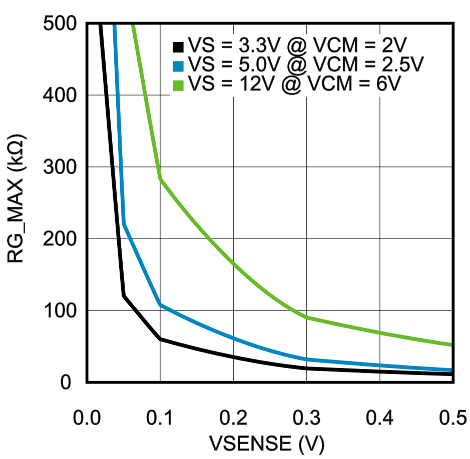


FIGURE 8. Allowed R_G for CASE 2

Case 3: $V_{CM} > V_S$, and $V_S > 3.3V$

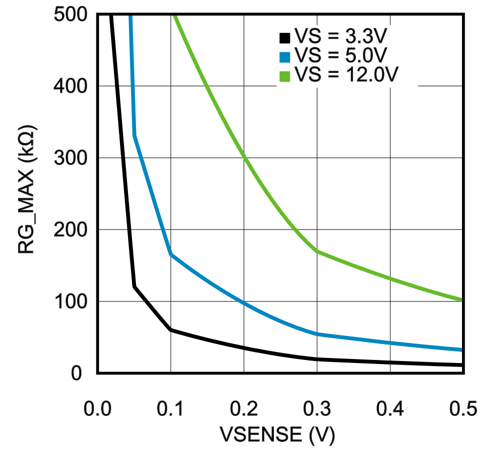


FIGURE 9. Allowed R_G for CASE 3

R_G Consideration for System Error

The previous section discussed the system error assuming that R_{SENSE} is non-ideal and R_G is ideal. This section expands the system error equation by assuming that both R_{SENSE} and R_G are non-ideal. This system error equation can be rewritten as:

$$\text{System Error} = \left|\frac{V_{OUT\_THEO} - V_{OUT\_CAL}}{V_{OUT\_THEO}}\right| \times 100(\%)$$

$$\text{where } V_{OUT\_THEO} = (R_{SENSE} \times I_{SENSE}) \times \frac{R_G}{1/Gm}$$

$$\text{and } V_{OUT\_CALC} = \frac{[R_{SENSE}\,(1+\text{Tolerance}) \times I_{SENSE} + V_{OFFSET}] \times R_G\,(1+\text{Tolerance})}{1/[Gm\,(1 + Gm\_Accuracy)]}$$

30123556

FIGURE 10. System Error Equation Assuming R_{SENSE} and R_G are Non-ideal

Continuing from the previous system error equation, we can recalculate for the system error assuming that R_G has a 1% tolerance.

$$V_{OUT\_THEO} = (100\ m\Omega\ \times 1A) \times \frac{10\ k\Omega}{1/(200\mu)} = 0.2V$$

$$V_{OUT\_CALC} = \frac{[100\ m\Omega\,(1+1/100) \times 1A + 1mV] \times 10\ k\Omega\,(1+1/100)}{1/[200\mu\,(1 + 2/100)]} = 0.21016V$$

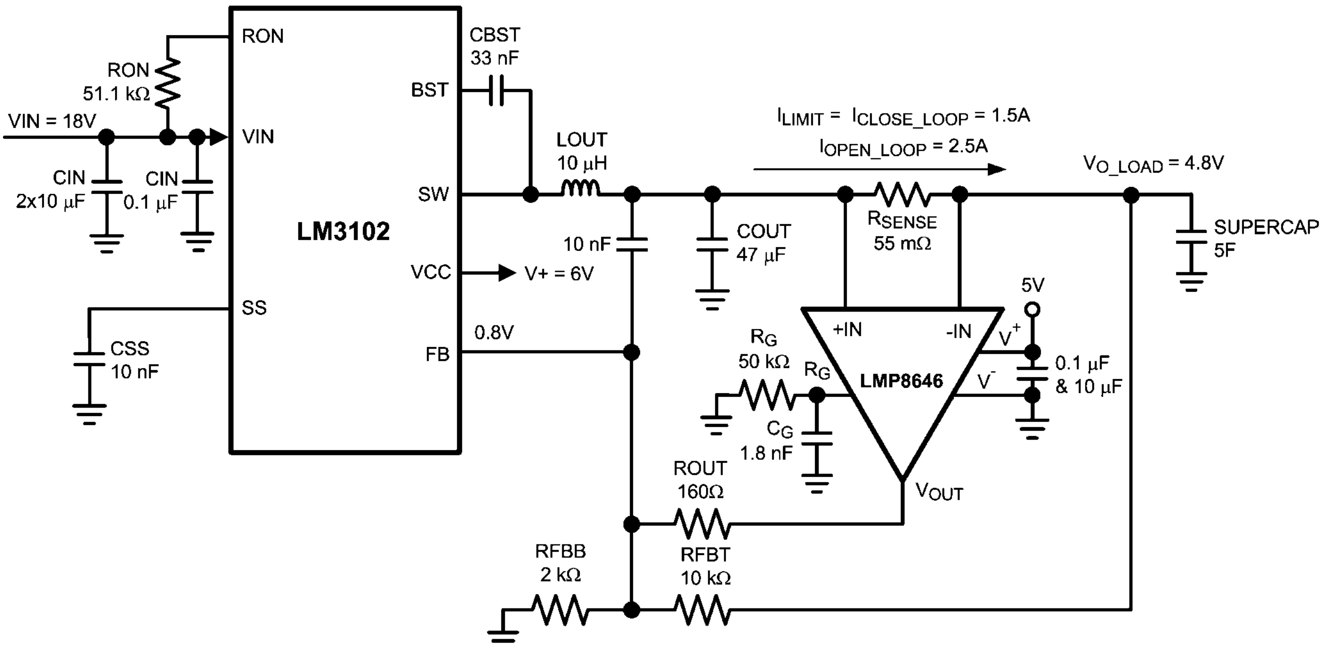
$$\text{System Error} = \left|\frac{0.2V - 0.21016V}{0.2V}\right| \times 100 = 5.08\%$$

30123557

FIGURE 11. System Error Example Assuming R_{SENSE} and R_G are Non-ideal

Because an R_G tolerance will increase the system error, we recommend selecting an R_G resistor with low tolerance.

APPLICATION #1: CURRENT LIMITER WITH A CAPACITIVE LOAD



30123531

FIGURE 12. SuperCap Application with LM3102 Regulator

A supercap application requires a very high capacitive load to be charged. This example assumes the output capacitor is 5F with a limited sense current at 1.5A. The LM3102 will provide the current to charge the supercap, and the LMP8646 will monitor this current to make sure it does not exceed the desired 1.5A value.

This is done by connecting the LMP8646 output to the feedback pin of the LM3102, as shown in *Figure 12*. This feedback voltage at the FB pin is compared to a 0.8V internal reference. Any voltage above this 0.8V means the output current is above the desired value of 1.5A, and the LM3102 will reduce its output current to maintain the desired 0.8V at the FB pin.

The following steps show the design procedures for this supercap application. In summary, the steps consist of selecting the components for the voltage regulator, integrating the LMP8646 and selecting the proper values for its gain, bandwidth, and output resistor, and adjusting these components to yield the desired performance.

Step 1: Choose the components for the Regulator.

Refer to the LM3102 evaluation board application note (AN-1646) to select the appropriate components for the LM3102 voltage regulator.

Step 2: Choose the sense resistor, R_{SENSE}

R_{SENSE} sets the voltage V_{SENSE} between +IN and -IN and has the following equation:

$$R_{SENSE} = V_{OUT} / [(I_{LIMIT}) * (R_G / 5kOhm)]$$

In general, R_{SENSE} depends on the output voltage, limit current, and gain. Refer to section *SELECTION OF THE SENSE RESISTOR, R_{SENSE}* to choose the appropriate R_{SENSE} value; this example uses 55 mOhm.

Step 3: Choose the gain resistor, R_G, for LMP8646

R_G is chosen from the limited sense current. As stated, V_{OUT} = (R_{SENSE} * I_{LIMIT}) * (R_G / 5kOhm). Since V_{OUT} = V_{FB} = 0.8V, the limited sense current is 1.5A, and R_{SENSE} is 55 mOhm, R_G can be calculated as:

$$R_G = (V_{OUT} * 5\ kOhm) / (R_{SENSE} * I_{LIMIT})$$

$$R_G = (0.8 * 5\ kOhm) / (55\ mOhm * 1.5A) = 50\ kOhm$$

(approximate)

Step 4: Choose the Bandwidth Capacitance, C_G.

The product of C_G and R_G determines the bandwidth for the LMP8646. Refer to the Typical Performance Characteristics plots to see the range for the LMP8646 bandwidth and gain. Since each application is very unique, the LMP8646 bandwidth capacitance, C_G, needs to be adjusted to fit the appropriate application.

Bench data has been collected for the supercap application with the LM3102 regulator, and we found that this application works best for a bandwidth of 500 Hz to 3 kHz. Operating outside of this recommended bandwidth range might create an undesirable load current ringing. We recommend choosing a bandwidth that is in the middle of this range and using the equation C_G = 1/(2*pi*R_G*Bandwidth) to find C_G. For example, if the bandwidth is 1.75 kHz and R_G is 50 kOhm, then C_G is approximately 1.8 nF. After this selection, capture the plot for I_{LIMIT} and adjust C_G until a desired load current plot is obtained.

Step 5: Calculate the Output Accuracy and Tolerable System Error

Since the LMP8646 is a precision current limiter, the output current accuracy is extremely important. This accuracy is affected by the system error contributed by the LMP8646 device error and other errors contributed by external resistances, such as R_{SENSE} and R_G.

In this application, $V_{SENSE} = I_{LIMIT} * R_{SENSE}$ = 1.5A * 55 mOhm = 0.0825V, and R_G = 50 kOhm. From the Electrical Characteristics Table, it is known that V_{OFFSET} = 1 mV and Gm_Accuracy = 2%. Using the equations shown in *Figure 2*, the output accuracy can be calculated as 3.24%.

After figuring out the LMP8646 output accuracy, choose a tolerable system error or the output current accuracy that is bigger than the LMP8646 output accuracy. This tolerable system error will be labeled as I_{ERROR}, and it has the equation $I_{ERROR} = (I_{MAX} - I_{LIMIT})/I_{MAX}$ (%). In this example, we will choose an I_{ERROR} of 5%, which will be used to calculate for ROUT shown in the next step.

Step 6: Choose the output resistor, ROUT

At startup, the capacitor is not charged yet and thus the output voltage of the LM3102 is very small. Therefore, at startup, the output current is at its maximum (I_{MAX}). When the output voltage is at its nominal, then the output current will settle to the desired limited value. Because a large current error is not desired, ROUT needs to be chosen to stabilize the loop with minimal initial startup current error. Follow the equations and example below to choose the appropriate value for ROUT to minimize this initial error.

As discussed in step 4, the allowable I_{ERROR} is 5%, where $I_{ERROR} = (I_{MAX} - I_{LIMIT})/I_{MAX}$ (%). Therefore, the maximum allowable current is calculated as: $I_{MAX} = I_{LIMIT} (1+ I_{ERROR})$ = 1.5A * (1 + 5/100) = 1.575 A.

Next, use the formula below to calculate for ROUT:

$$ROUT = \frac{(I_{MAX} * R_{SENSE} * Gain - V_{FB})}{\frac{V_{FB}}{RFBB} - \frac{(V_{O\_REG\_MIN} - V_{FB})}{RFBT}}$$

30123533

FIGURE 13. ROUT Equation

For example, assume the minimum LM3102 output voltage, $V_{O\_REG\_MIN}$, is 0.6V, then ROUT can be calculated as ROUT = [1.575A * 55 mOhm * (49.9k / 5k) - 0.8] / [(0.8 / 2k) - (0.6 - 0.8) / 10k] = 153.6 Ohm.

Populate ROUT with a resistor that is as close as possible to 153.6 Ohm (this application uses 160 Ohm). If the limited sense current has a gain error and is not 1.5A at any point in time, then adjust this ROUT value to obtain the desired limit current.

We recommend that the value for ROUT is at least 50 Ohm.

Step 7: Adjusting Components

Capture the output current and output voltage plots and adjust the components as necessary. The most common components to adjust are C_G to decrease the current ripple and ROUT to get a low current error. An example output current and voltage plot can be seen in *Figure 14* .

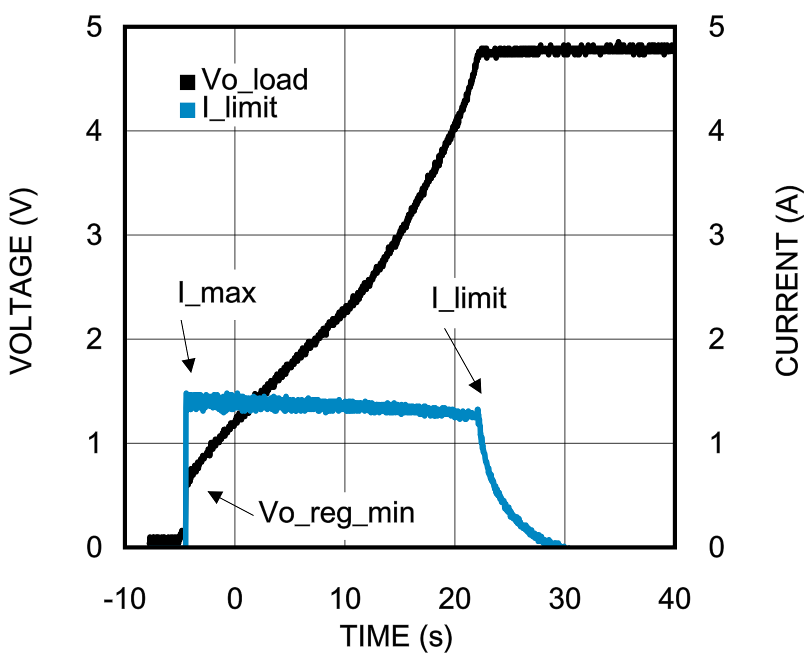


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FIGURE 14. SuperCap Application with LM3102 Regulator Plot

APPLICATION #2: CURRENT LIMITER WITH A RESISTIVE LOAD

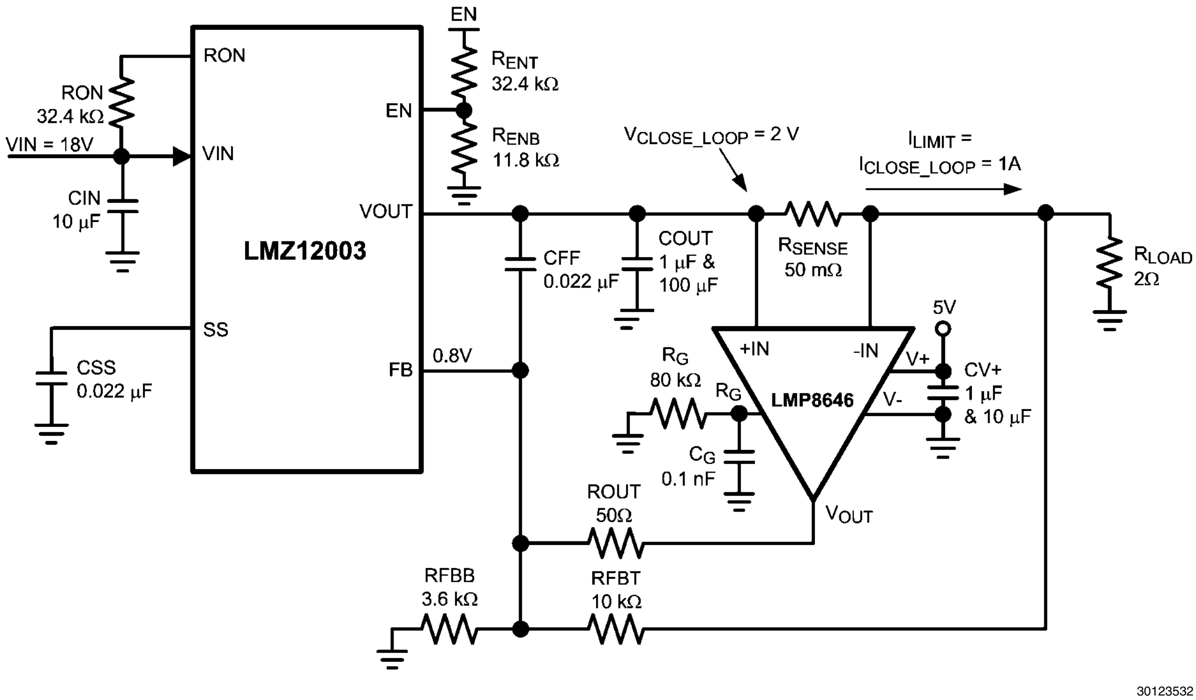


FIGURE 15. Resistive Load Application with LMZ12003 Regulator

This subsection describes the design process for a resistive load application with the LMZ12003 voltage regulator as seen in *Figure 15*. To see the current limiting capability of the LMP8646, the open-loop current must be greater than the close-loop current. An open-loop occurs when the LMP8646 output is not connected the LMZ12003's feedback pin. For this example, we will let the open-loop current to be 1.5A and the close-loop current, I_{LIMIT}, to be 1A.

Step 1: Choose the components for the Regulator.

Refer to the LMZ12003 application note (AN-2031) to select the appropriate components for the LMZ12003.

Step 2: Choose the sense resistor, R_{SENSE}

R_{SENSE} sets the voltage V_{SENSE} between +IN and -IN and has the following equation:

$$R_{SENSE} = V_{OUT} / [(I_{LIMIT}) * (R_G / 5kOhm)]$$

In general, R_{SENSE} depends on the output voltage, limit current, and gain. Refer to section *SELECTION OF THE SENSE RESISTOR, R_{SENSE}* to choose the appropriate R_{SENSE} value; this example uses 50 mOhm.

Step 3: Choose the gain resistor, R_G, for LMP8646

R_G is chosen from I_{LIMIT}. As stated, $V_{OUT} = (R_{SENSE} * I_{LIMIT}) * (R_G / 5kOhm)$. Since $V_{OUT} = V_{FB} = 0.8V$, $I_{LIMIT} = 1A$, and $R_{SENSE} = 50$ mOhm , R_G can be calculated as:

$$R_G = (V_{OUT} * 5 \text{ kOhm}) / (R_{SENSE} * I_{LIMIT})$$

$$R_G = (0.8 * 5 \text{ kOhm}) / (50 \text{ mOhm} * 1A) = 80 \text{ kOhm}$$

Step 4: Choose the Bandwidth Capacitance, C_G.

The product of C_G and R_G determines the bandwidth for the LMP8646. Refer to the Typical Performance Characteristics plots to see the range for the LMP8646 bandwidth and gain. Since each application is very unique, the LMP8646 bandwidth capacitance, C_G, needs to be adjusted to fit the appropriate application.

Bench data has been collected for this resistive load application with the LMZ12003 regulator, and we found that this application works best for a bandwidth of 2 kHz to 30 kHz. Operating anything less than this recommended bandwidth might prevent the LMP8646 from quickly limiting the current. We recommend choosing a bandwidth that is in the middle of this range and using the equation: $C_G = 1/(2*pi*R_G*Bandwidth)$ to find C_G (this example uses a C_G value of 0.1nF). After this selection, capture the load current plot and adjust C_G until a desired output current plot is obtained.

Step 5: Choose the output resistor, ROUT, for the LMP8646

ROUT plays a very small role in the overall system performance for the resistive load application. ROUT was important in the supercap application because it affects the initial current error. Because current is directly proportional to voltage for a resistive load, the output current is not large at startup. The bigger the ROUT, the longer it takes for the output voltage to reach its final value. We recommend that the value for ROUT is at least 50 Ohm, which is the chosen value for this example.

Step 6: Adjusting Components

Capture the output current and output voltage plots and adjust the components as necessary. The most common component to adjust is C_G for the bandwidth. An example of the output current and voltage plot can be seen in *Figure 16*.

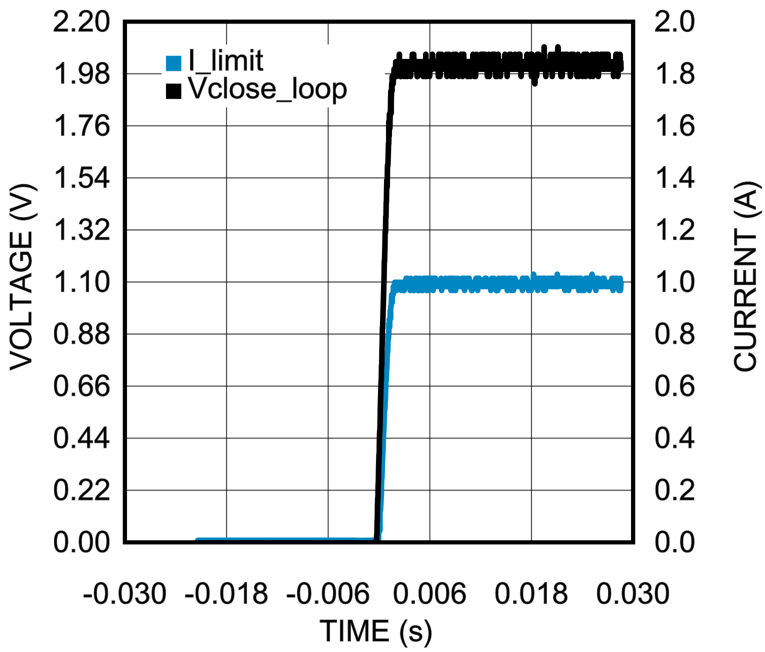


FIGURE 16. Plot for the Resistive Load Application with LMZ12003 Regulator Plot

APPLICATION #3: CURRENT LIMITER WITH A LOW-DROPOUT REGULATOR AND RESISTIVE LOAD

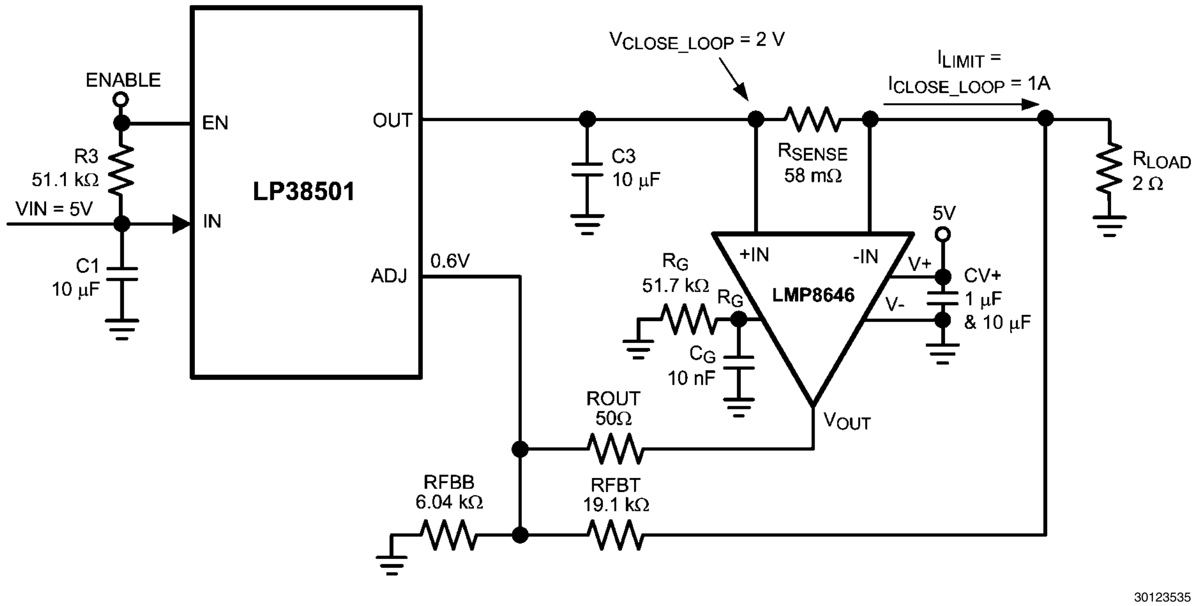


FIGURE 17. Resistive Load Application with LP38501 Regulator

This next example is the same as the last example, except that the regulator is now a low-dropout regulator, the LP38501, as seen in *Figure 17*. For this example, we will let the open-loop current to be 1.25A and the close-loop current, I_{LIMIT}, to be 1A.

Step 1: Choose the components for the Regulator.

Refer to the LP38501 application note (AN-1830) to select the appropriate components for the LP38501.

Step 2: Choose the sense resistor, R_{SENSE}

R_{SENSE} sets the voltage V_{SENSE} between +IN and -IN and has the following equation:

$$R_{SENSE} = V_{OUT} / [(I_{LIMIT}) * (R_G / 5kOhm)]$$

In general, R_{SENSE} depends on the output voltage, limit current, and gain. Refer to section *SELECTION OF THE SENSE RESISTOR, R_{SENSE}* to choose the appropriate R_{SENSE} value; this example uses 58 mOhm.

Step 3: Choose the gain resistor, R_G, for LMP8646

R_G is chosen from I_{LIMIT}. As stated, $V_{OUT} = (R_{SENSE} * I_{LIMIT}) * (R_G / 5kOhm)$. Since V_{OUT} = ADJ = 0.6V, I_{LIMIT} = 1A, and R_{SENSE} = 58 mOhm , R_G can be calculated as:

$$R_G = (V_{OUT} * 5\ kOhm) / (R_{SENSE} * I_{LIMIT})$$

$$R_G = (0.6 * 5\ kOhm) / (58\ mOhm * 1A) = 51.7\ kOhm$$

Step 4: Choose the Bandwidth Capacitance, C_G.

The product of C_G and R_G determines the bandwidth for the LMP8646. Refer to the Typical Performance Characteristics plots to see the range for the LMP8646 bandwidth and gain.

Since each application is very unique, the LMP8646 bandwidth capacitance, C_G, needs to be adjusted to fit the appropriate application.

Bench data has been collected for this resistive load application with the LP38501 regulator, and we found that this application works best for a bandwidth of 50 Hz to 300 Hz. Operating anything larger than this recommended bandwidth might prevent the LMP8646 from quickly limiting the current. We recommend choosing a bandwidth that is in the middle of this range and using the equation: $C_G = 1/(2*pi*R_G*Bandwidth)$ to find C_G (this example uses a C_G value of 10 nF). After this selection, capture the plot for I_{SENSE} and adjust C_G until a desired sense current plot is obtained.

Step 5: Choose the output resistor, ROUT, for the LMP8646

ROUT plays a very small role in the overall system performance for the resistive load application. ROUT was important in the supercap application because it affects the initial current error. Because current is directly proportional to voltage for a resistive load, the output current is not large at startup. The bigger the ROUT, the longer it takes for the output voltage to reach its final value. We recommend that the value for ROUT is at least 50 Ohm, which is the value we used for this example.

Step 6: Adjusting Components

Capture the output current and output voltage plots and adjust the components as necessary. The most common component to adjust is C_G for the bandwidth. An example plot of the output current and voltage can be seen in *Figure 18*.

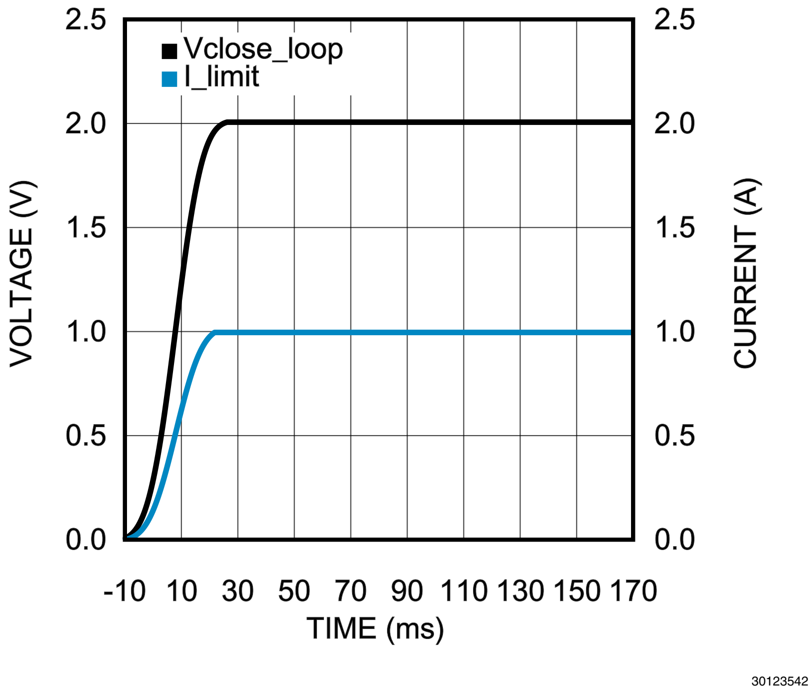
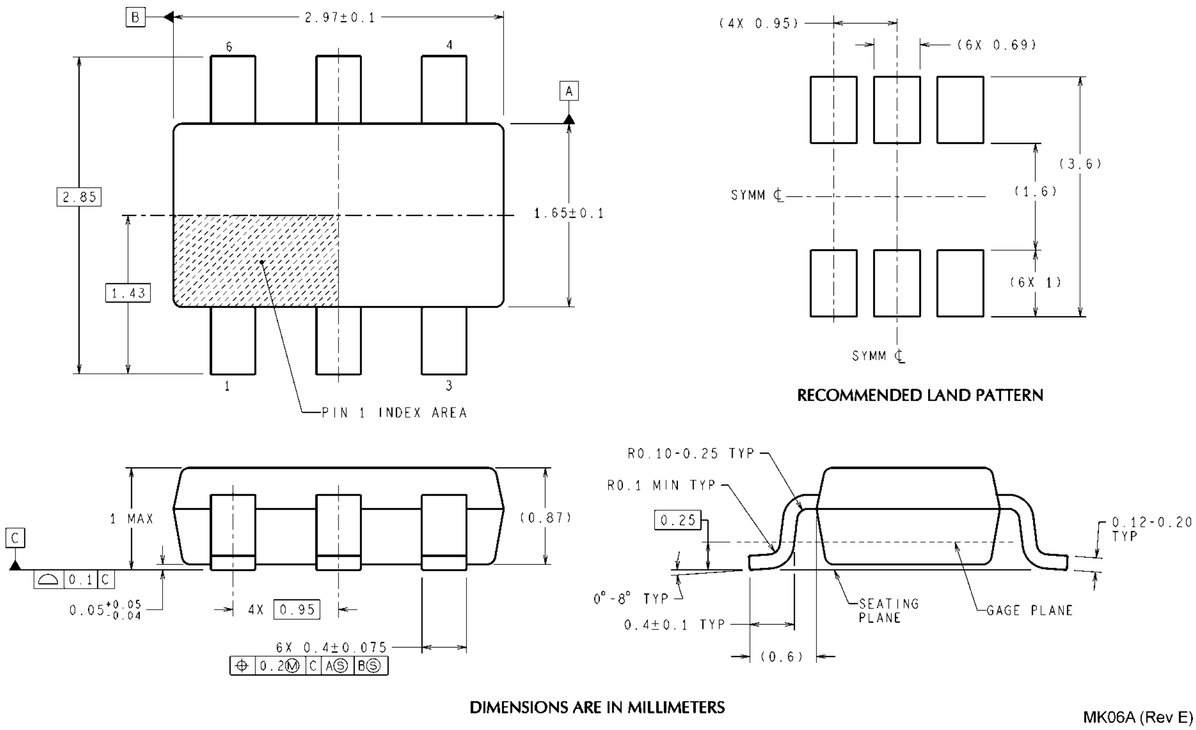


FIGURE 18. Plot for the Resistive Load Application with the LP38501 LDO Regulator

Physical Dimensions inches (millimeters) unless otherwise noted



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Notes

Notes

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Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
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