Providing a Constant Current for Powering LEDs Using the PRM and VTM

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Introduction

Light Emitting Diodes (LEDs) require a constant current for proper operation. The V•I Chip PRM Regulator and VTM Current Multiplier are designed to provide a regulated voltage using the Adaptive Loop Method of regulation (for further information please see www.vicorpower.com/fpa101/fpa101.pdf. In order to use the PRM and VTM to power an LED, it is therefore necessary to modify the operation of the PRM to provide a regulated current. This application note provides guidelines for implementing a constant current source using the PRM and VTM.

Using the PRM and VTM to provide a constant current provides several advantages over conventional approaches. The implementation of a VTM in a system provides point of load current multiplication. The output current of a VTM is proportional to its input current by the following equation:

$$I_{OUT} = \frac{I_{IN}}{K}$$

Equation 1

Thus in a controlled current application, the input current to the VTM can be sensed and regulated to control the output current. Sensing a lower current requires a smaller sensor which dissipates lower power and improves overall efficiency. Also the V•I Chips themselves provide high efficiency and high power density, making the overall LED system small and cool and maximizing the output in Lumens per watt of dissipation. The overall system architecture is illustrated in Figure 1.

A complete design example is covered in Appendix A, using the techniques outlined in this application note.

Some LEDs require a pulsed current in order to operate properly. Pulsed-current operation will be covered in a future application note, due to bandwidth limitations of the circuit configuration proposed here. Also most known LED types can be driven with a single PRM + VTM pair. Parallel operation of PRMs and VTMs to provide a regulated current is not addressed in this application note.

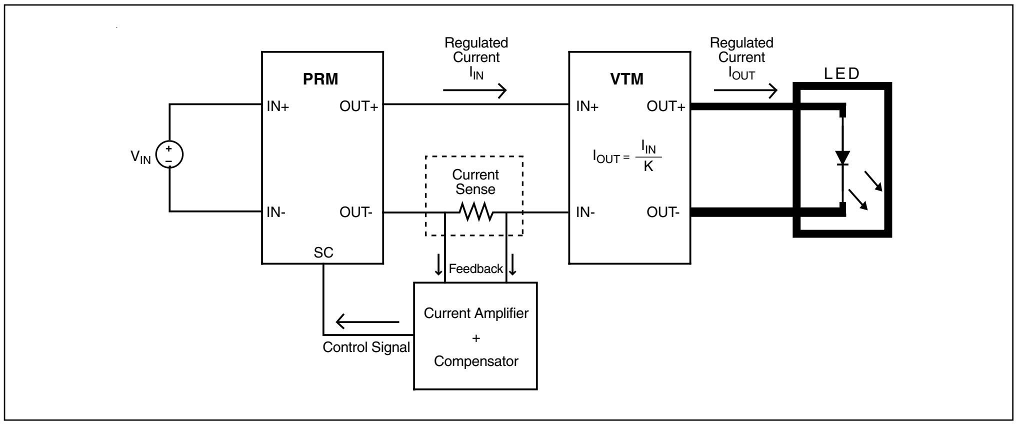


Figure 1
Regulated Current Source Basic Architecture

Background: Adaptive Loop Regulation

This application note requires a basic understanding of V•I Chips, and Factorized Power Architecture (FPA), including Adaptive Loop regulation. Please refer to the following link (www.vicorpower.com/fpa101/fpa101.pdf) for more information.

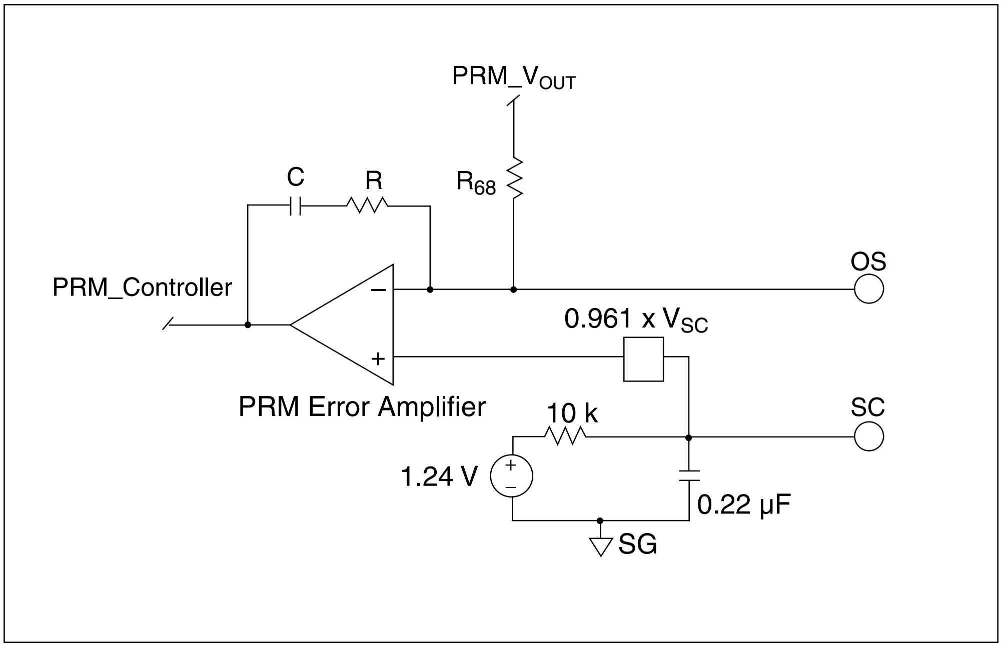
Before starting, the user should have a defined set of system design requirements. These requirements should include: output current set point, output voltage range, and current regulation accuracy. In most cases the specific data sheet of the LED or LED array will define many of the requirements for properly designing this circuit. It is important that the V-I characteristics of the end device (LED) are well understood to ensure that the circuit can provide the desired current within the voltage limitations of the PRM and VTM.

The PRM is pre-configured with an internal voltage loop that regulates the output voltage of the PRM to a set value.

The internal workings of the PRM should be well understood, as the external constant current circuit has been designed to work in conjunction with the internal voltage control loop, changing the PRM voltage reference in order to regulate the VTM output current.

A simplified block diagram of the PRM internal voltage control loop is shown in Figure 2.

Figure 2
Functional diagram of PRM Internal Error Amplifier



An internal reference is generated and connected to the SC port of the PRM through a 10 k resistor and a 0.22 µF capacitor, which provides a soft-start. The SC voltage can be adjusted by adding an external resistor, or by applying an external voltage. The applied voltage at the SC port should not exceed 6 Vdc.

The SC voltage is buffered and fed to the error amplifier through a resistive divider represented by the gain block of 0.961. R_{68} forms the top half of the voltage-sensing resistive divider. This resistor is fixed for each PRM. Please refer to table 1 for R_{68} values for each PRM. The bottom half of the divider is formed by adding a resistor from the OS pin to SG (R_{OS}). Equation 2 defines the PRM output as a function of V_{SC} and R_{OS}. From Equation 2, it is seen that for a given R_{OS} resistor, adjusting the SC voltage will determine the PRM output voltage. This is the method by which the external current control circuit will control the output.

Equation 2

$$PRM\_V_{OUT} = \frac{0.961 \times V_{SC} \times (R_{68} + R_{OS})}{R_{OS}}$$

Where:
V_{SC} is the voltage at the SC pin of the PRM.
R_{OS} is the resistance from OS to SG of the PRM.
R_{68} is the PRM internal resistor specified in Table 1.

Table 1
PRM Internal R_{68} Values

PRM	V_{IN}	P_{OUT}	R_{68}
P048-048-24AL	36 – 75 V	240 W	93.1 k
P048-048-12AL		120 W	
P048-048-12AL	38 – 55 V	320 W	
P045-048-17AL		170 W	
P024-048-12AL	18 – 36 V	120 W	
P036-048-12AL	18 – 60 V	120 W	
MP028F036M12AL	16 – 50 V	120 W	69.8 k

Current Control Circuit

Overview

The recommended current control circuit is shown below in Figure 3.

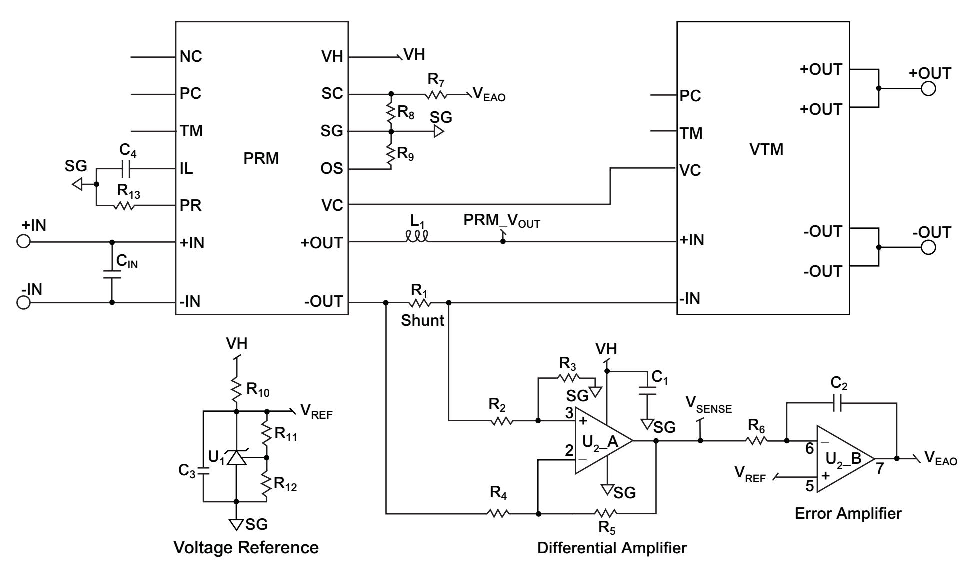


Figure 3
Constant Current Circuit

As the VTM is a current multiplier, the output current of the VTM can be regulated by its input current. The advantage of this approach is that the current can be sensed prior to the VTM current multiplication stage (at the higher voltage), reducing the I^2R power dissipation in the external shunt. In addition, the control circuitry remains on the primary (PRM) side, eliminating the need for isolating the feedback signal.

The circuit consists of a voltage reference, shunt resistor, differential amplifier, and error amplifier. Low-side sensing is implemented at the output of the PRM using an op amp configured as a differential amplifier. The voltage across the shunt resistor (R_1) is sensed and amplified with a gain determined by resistors R_2 through R_5. The reference voltage is generated using a precision adjustable shunt reference, and is tied to the non-inverting terminal of the error amplifier. This is the voltage to which the error amplifier will compare the differential amplifier output (V_{SENSE}). The output of the error amplifier (V_{EAO}) is tied to SC through resistors R_7 and R_8, allowing for the adjustment of the PRM output set point. The error amplifier will adjust the PRM output voltage until V_{SENSE} is equal to the reference voltage V_{REF}.
The recommended circuit components are shown in Table 2.

Table 2
Recommended Values

Ref Des	Value / Part Number	Manufacturer	Description	Link
R_1	CSM25120R010BXX	Vishay	Current Sense Resistor, 10 mΩ,1 W, 0.1%, 2512	CSM2512
R_2 R_4	1 k		Resistor, 0.1% 1k	
R_3 R_5	100 k		Resistor, 0.1%, 100 k	
R_6	16.2 k		Resistor, 1%, 16.2 k	
R_7	2.15 k		Resistor, 1%, 2.15 k	
R_8	1.24 k		Resistor, 1%, 1.24 k	
R_9*	4.99 k*		Resistor, 1%, 4.99 k*	
R_{10}	User Defined		Dependent on Reference Voltage	
R_{11}	User Defined		Dependent on Reference Voltage	
R_{12}	User Defined		Dependent on Reference Voltage	
R_{13}	10 k		Resistor, 1%, 10 k	
C_1	0.01 µF		Capacitor, Ceramic, 0.01 µF	
C_2	0.1 µF		Capacitor, 0.1 µF	
C_3	User Defined		Dependant on Startup	
C_4	0.01 µF		Capacitor,Ceramic, 0.01 µF	
U_1	TLV431B	TI	3 terminal, Adjustable, Precision Shunt Regulator	TLV431B
U_2	AD8667	Analog Devices	Low Noise, Precision, 16 V Dual Op amp	AD8667

*If using MP028F036M12AL use 4.12 k for R_9

The following are general guidelines to select the appropriate components for a straightforward, cost-effective solution with minimal component count. As there are many ways in which the circuit may be implemented, the recommended configuration may not be ideal for every application. This application note should contain enough detail for the end user to modify the circuit to fit their end application.

Some aspects of the circuit, such as startup timing, are difficult to predict and therefore must be tested and tuned to the individual application. It is up to the user to perform the necessary system testing and troubleshooting to successfully qualify the implementation of this circuit in their end application.

V•I Chip Selection (PRM, VTM)

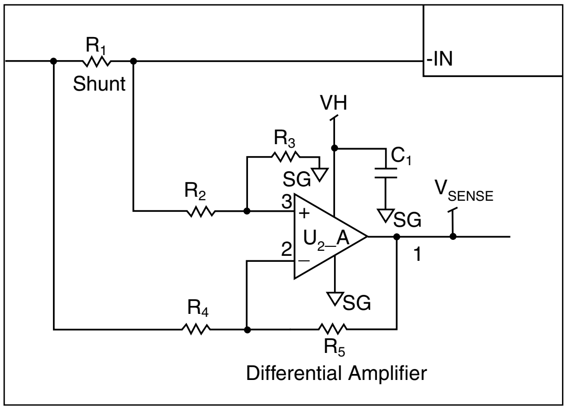
Select the PRM based on input voltage range and power level. Different load voltage requirements are addressed by appropriate VTM selection. To select a VTM, the following parameters must be known:

- Maximum output current.
- Minimum and maximum operating output voltage.

Refer to the web (vicorpower.com/cms/home/technical_resources/Data_Sheets) to determine if there is a VTM which will provide the desired current over the specified voltage range of the intended load device. Then, refer to the specific product data sheet for information on operation and performance.

Current Sensing Sub-circuit

Figure 4
Current Sense Components



Although there are other techniques, the recommended method of current sensing is low-side sensing using a differential amplifier.

Differential and Error Amplifier Selection (U_2)

The use of a dual op amp for the differential amplifier and error amplifier is recommended in order to minimize component count. Since the overall bandwidth of the system will be limited, the amplifier selection should optimize the current sensing accuracy. Critical parameters, which contribute directly to accuracy, are the input offset voltage and input offset current. These parameters should be kept as low as possible to minimize current sensing error. Amplifier current draw will also need to be considered when selecting a voltage supply.

The recommended amplifier is Analog Devices AD8667

The key parameters are summarized in Table 3. Refer to the manufacturer's data sheet for further information.

Table 3
AD8667 Parameters

Parameter	Symbol	Value	Units	Conditions
Offset Voltage Max	V_{OS}	450	mV	$-40<T_{AMB}<125$
Offset Current Max	I_{OS}	65	pA	$-40<T_{AMB}<125$
Bias Current Max	I_B	105	pA	$-40<T_{AMB}<125$
Supply Current per Amplifier Max	I_{SY}	325	µA	$-40<T_{AMB}<125$

Shunt (Current Sense) Resistor (R_1) Selection

As with the amplifier, the shunt resistor has a significant impact on the current sensing accuracy. If the expected resistance of the shunt varies by 5%, so too will the expected shunt voltage, resulting in an equivalent current sense error. It is, therefore, critical to select a shunt resistor within the desired tolerance of the current source accuracy. The magnitude of the shunt voltage should be large relative to the amplifier's input offset voltage to avoid further inaccuracy. In addition, the presence of the shunt contributes to additional power loss. Its value should be kept low to minimize power dissipation. The recommended shunt is the Vishay CSM25120R010B. This is a 10 mΩ, 0.1% tolerance, 1 W, 2512 metal foil, four-terminal resistor with Kelvin test points for voltage sensing. At 5 A, this part will dissipate approximately 250 mW of power.

Differential Amplifier Gain (R2 through R5)

For a given shunt value, the gain of the differential amplifier will determine the necessary reference voltage to achieve a desired output current. Assuming R_2 is equal to R_4, and R_3 is equal to R_5, the output of the differential amplifier is defined by Equation 3.

Equation 3

$$V_{SENSE} = V_{SHUNT} \cdot (\frac{R_3}{R_2})$$

Where:
V_{SENSE} is the differential amplifier output.
V_{SHUNT} is the voltage across the shunt (R_1).

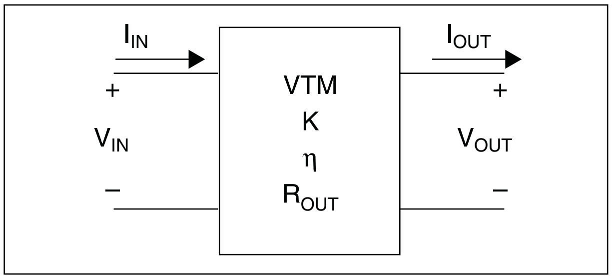
The recommended values equate to a gain of 100, resulting in a differential amplifier output of 1 V per Amp of PRM current when using a 10 mΩ shunt.

Voltage Reference (U1)

The VTM has the following input/output characteristics, illustrated in Figure 5:

1) $P_{IN} = V_{IN} \cdot I_{IN}$
2) $P_{OUT} = V_{OUT} \cdot I_{OUT}$
3) $V_{OUT} = V_{IN} \cdot K - I_{OUT} \cdot R_{OUT}$
4) $P_{OUT} = P_{IN} \cdot \eta$

Figure 5
VTM Operation



Based on the above relationships, Equation 4 can be solved for the necessary VTM input current when given output current, output voltage, VTM efficiency, and VTM output resistance. This is important since the PRM current control circuit will control the input current to the VTM.

Equation 4

$$VTM\_I_{IN} = PRM\_I_{OUT} = \frac{V_{OUT} \cdot I_{OUT} \cdot K}{\eta \cdot (V_{OUT} + I_{OUT} \cdot R_{OUT})}$$

Where:
I_{OUT} is the desired output current of the VTM.
V_{OUT} is the nominal output voltage of the VTM.
η is the nominal efficiency of the VTM at the given output.
R_{OUT} is the nominal output resistance of the VTM.
K is the transformation ratio of the VTM.

Based on the current sensing component selection, the required reference voltage can be determined by Equation 5.

Equation 5

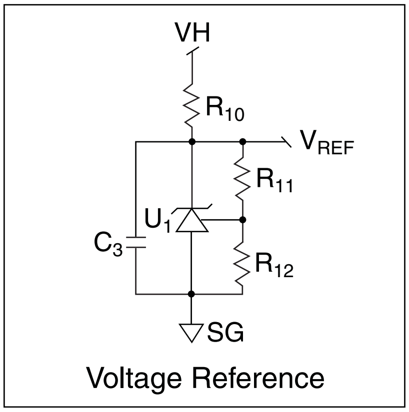
$$V_{REF} = PRM\_I_{OUT} \cdot R_1 \cdot (\frac{R_3}{R_2})$$

Where:
V_{REF} is the voltage reference.
PRM_I_{OUT} is the necessary PRM current from Equation 4.
R_1 is the shunt resistor.
R_3, and R_2 are the differential amplifier gain resistors.

For the values given in Table 2, $R_1 \cdot (\frac{R_3}{R_2}) = 1$ and therefore, $V_{REF} = PRM\_I_{OUT}$

There are multiple options available for generating the reference voltage.
One simple approach is to use an adjustable shunt regulator such as the TLV431B.

Figure 6
Reference Components



When selecting R_{10} and C_3, refer to the manufacturer's recommendations to ensure stability. Bear in mind that these components will also affect the startup timing, as described in a later section. Resistors R_{11} and R_{12} are used to adjust the output. The tolerance of these resistors will have a direct effect on accuracy; high precision resistors should be used. The current draw of the device should be kept below 1 mA for the recommended configuration to stay within the 5 mA limit of VH.

This approach assumes that the reference voltage will be adjusted to achieve the correct output current based on a given shunt and differential amplifier gain. An alternative approach would be to fix the reference and adjust the gain to obtain the desired output current.

In this case Equation 5 can be rearranged and the gain of the differential amplifier can be calculated for a given reference voltage, PRM output current and shunt.

Equation 6

$$(\frac{R_3}{R_2}) = \frac{V_{REF}}{PRM\_I_{OUT} \cdot R_1}$$

Voltage Limiting Sub-circuit

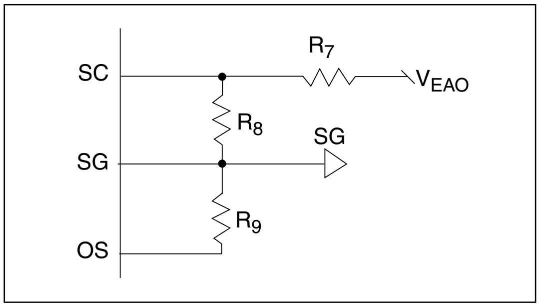


Figure 7
Voltage Limiting Components

The resistors R_7 and R_8 are required to limit the maximum voltage that appears on SC when the error amplifier is at its maximum. The resistor R_9 is selected to limit the maximum PRM output voltage during this condition.

The internal SC capacitor (0.22 µF) will create a pole with the equivalent resistance formed by the parallel combination of R_7, R_8, and the internal 10 kΩ resistor.

Equation 7

$$R_{EQ} = \frac{1}{\frac{1}{R_7} + \frac{1}{R_8} + \frac{1}{10\ k\Omega}}$$

Equation 8

$$F_{POLE} = \frac{1}{2 \cdot \pi \cdot R_{EQ} \cdot (0.22\ \mu F)}$$

This pole will limit the bandwidth of the error amplifier, as described in the next section. F_{POLE} can be increased by decreasing R_7 and R_8; however, this will also increase the amount of current necessary to drive SC. When using VH as the supply, F_{POLE} should be limited to 1 kHz maximum.

In order to select the appropriate components, the following should be defined:
1) The maximum output voltage of the error amplifier when saturated: $V_{EAO(MAX)}$.
2) The maximum SC voltage when the error amplifier is saturated: $V_{SC(MAX)}$.
3) The maximum PRM output voltage: $PRM\_V_{OUT(MAX)}$.
4) The SC pole frequency: F_{POLE}.

The recommended value for $V_{SC(MAX)}$ is 3 V. The absolute maximum voltage rating for the PRM SC port is 6 V, and this value should be avoided with margin to prevent damage to internal components. R_7 and R_8 will be selected based on $V_{SC(MAX)}$, $V_{EAO(MAX)}$ and F_{POLE} using Equations 9 and 10:

Equation 9

$$R_7 = \frac{10\ k\Omega \cdot V_{EAO(MAX)}}{10\ k\Omega \cdot V_{SC(MAX)} \cdot 2\pi \cdot F_{POLE} \cdot 0.22\ \mu F - 1.24\ V}$$

Equation 10

$$R_8 = \frac{10\,k\Omega \cdot R_7 \cdot V_{SC(MAX)}}{10\,k\Omega \cdot V_{EAO(MAX)} + 1.24\,V \cdot R_7 - V_{SC(MAX)} \cdot (10\,k\Omega + R_7)}$$

Where:
$V_{EAO(MAX)}$ is the maximum error amplifier output voltage.
$V_{SC(MAX)}$ is the maximum SC voltage.
F_{POLE} is the SC pole frequency (Equation 7).

Once the maximum SC voltage has been defined, R_9 can be selected to limit the maximum PRM output voltage as defined in Equation 11:

Equation 11

$$R_9 = \left(\frac{R_{68} \cdot V_{SC(MAX)} \cdot 0.961}{PRM\_V_{OUT(MAX)} - V_{SC(MAX)} \cdot 0.961}\right)$$

The recommended components are designed to provide a maximum PRM output voltage that will not exceed its maximum rating. The parameters used for selecting these components are shown in Table 4.

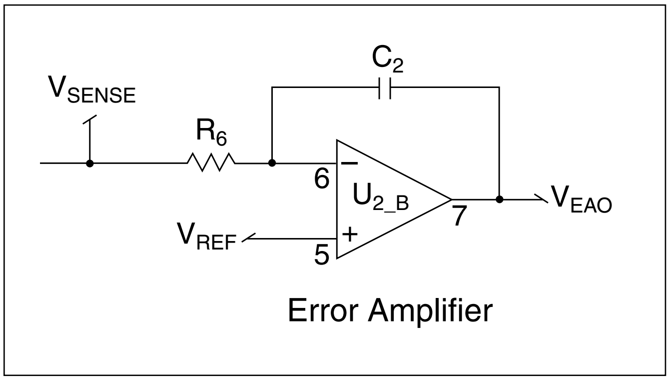
Table 4
Parameters

Parameter	Value
$V_{EAO(MAX)}$	8.6 V
$V_{SC(MAX)}$	3 V
F_{POLE}	1 kHz
$PRM\_V_{OUT(MAX)}$	*56 V

*51 V maximum for MP028F036M12AL

Compensation Components (R_6, C_2)

Figure 8
Error Amplifier Components



The compensation for this circuit consists of a single pole with the frequency response described by Equation 12 and shown in Figure 9. Starting at the origin (f = 0 Hz), the gain will decrease at a slope of -20 dB/decade when plotted vs. frequency on a log/linear scale. The crossover frequency (F_{CROSS}) of the error amplifier is determined by R_6 and C_2 as described in Equation 13.

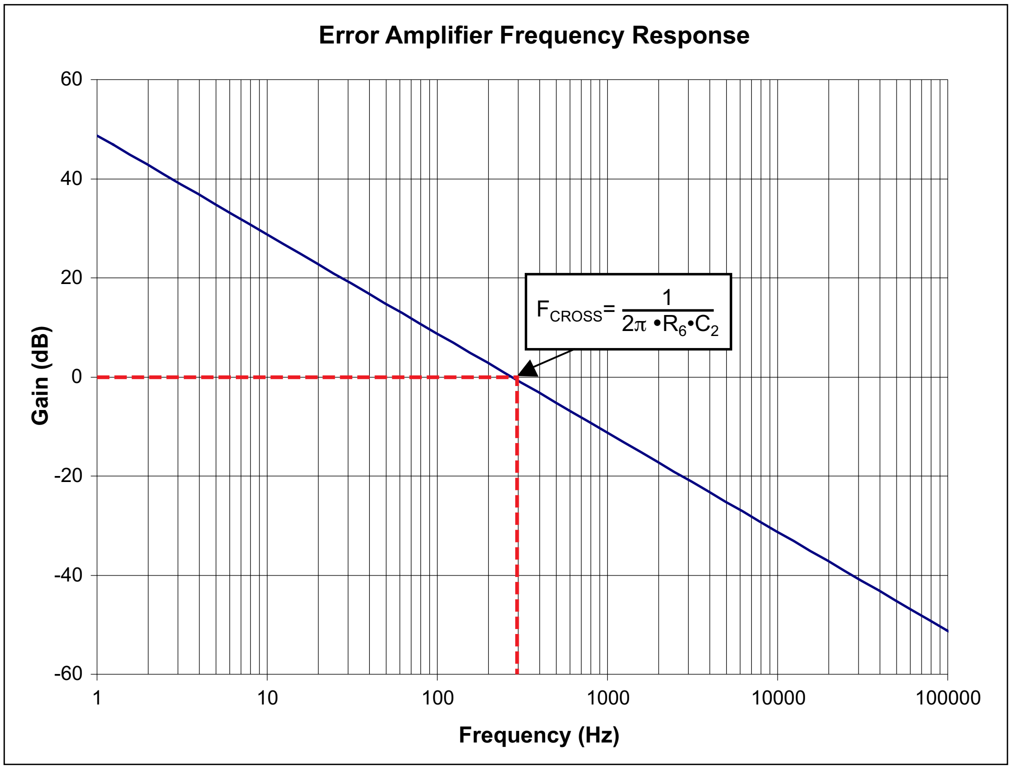
Equation 12

$$G(dB) = 20 \cdot log(\frac{1}{2\pi \cdot R_6 \cdot C_2 \cdot f})$$

Equation 13

$$F_{CROSS} = \frac{1}{2\pi \cdot R_6 \cdot C_2}$$

Figure 9
Error Amplifier Frequency Response



In order to insure stability, the error amplifier crossover frequency (F_{CROSS}) should be limited to a factor of 10 below the SC pole frequency.

Equation 14

$$F_{CROSS} = \frac{F_{POLE}}{10}$$

Rearranging the terms in Equation 13 allows for solving for the product of R_6 and C_2 to achieve the desired crossover frequency. The recommended values will provide a crossover frequency of approximately 100 Hz.

Equation 15

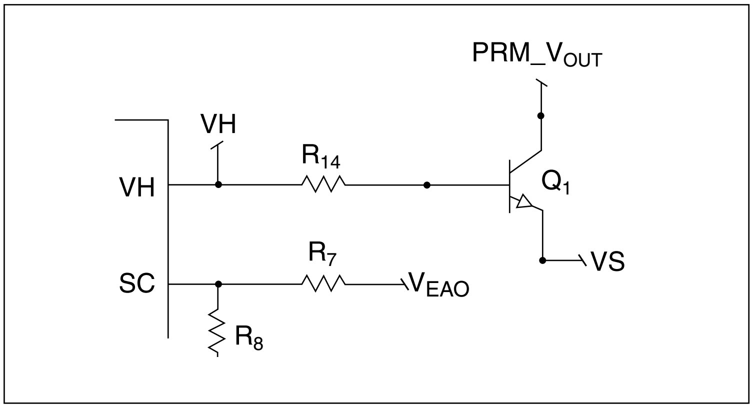
$$R_6 \cdot C_2 = \frac{1}{2\pi \cdot F_{CROSS}}$$

Voltage Supply (VH)

The recommended configuration is to power the op amp and reference using VH. VH is an auxiliary 9 V supply generated internally by the PRM. It is limited to 5 mA of current, and 0.1 µF of capacitance. If the recommended configuration has been changed, the maximum expected current draw should be determined to ensure that the 5 mA limit is not exceeded.

If necessary, one method for increasing the capability of VH is shown in Figure 10.

Figure 10
Increasing VH source capability



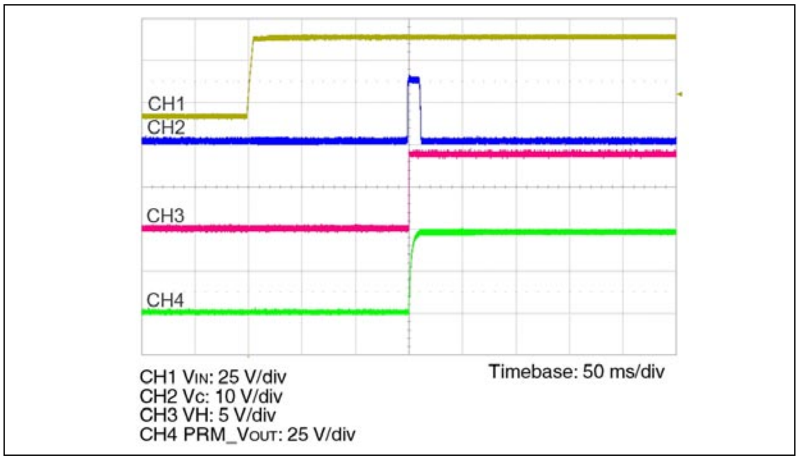
The transistor Q_1 is added as an emitter follower between the output and the supply rail (VS). R_{14} is sized to limit the maximum VH current draw. Since the majority of the power is now sourced through the PRM output, the limitation in supply current is determined by the transistor thermal limitations. The STMicro STN715 transistor allows for an 18 mA capability at an 85°C ambient temperature, and a 55 V PRM output voltage.

External supplies can be used if available, provided that the supply is primary referenced. Additional considerations for startup sequencing will need to be taken into account as described in the next section.

Startup Sequencing of the Current Regulation Circuit

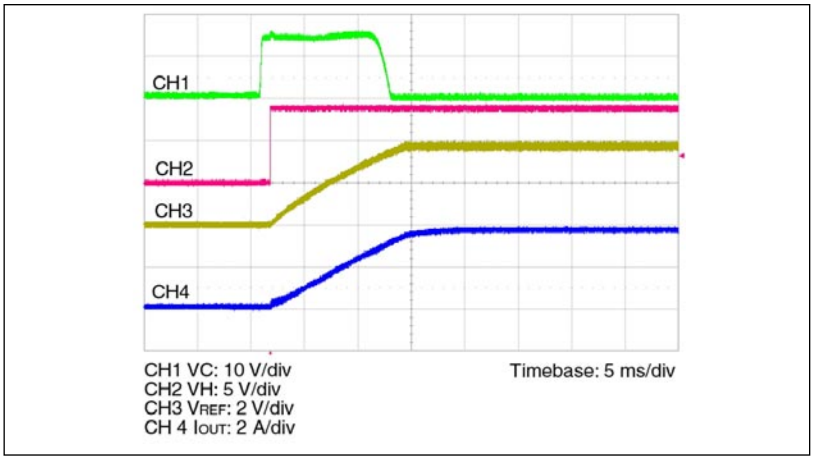
A typical PRM startup sequence is shown in Figure 11. From the application of input power, there is a delay prior to the PRM beginning to ramp its output voltage. At this time, VH and VC are generated. VC is a pulse of approximately 10 msec, which allows the VTM to temporarily operate below its minimum input of 26 V. With the VC pulse applied, the VTM output will track its input from 0 V, resulting in a soft start. The SC voltage directly controls the rate of rise of the PRM output. The same sequence would occur if enabling through the PC pin, the only difference being the delay time.

Figure 11
PRM Startup from Application of V_{IN}



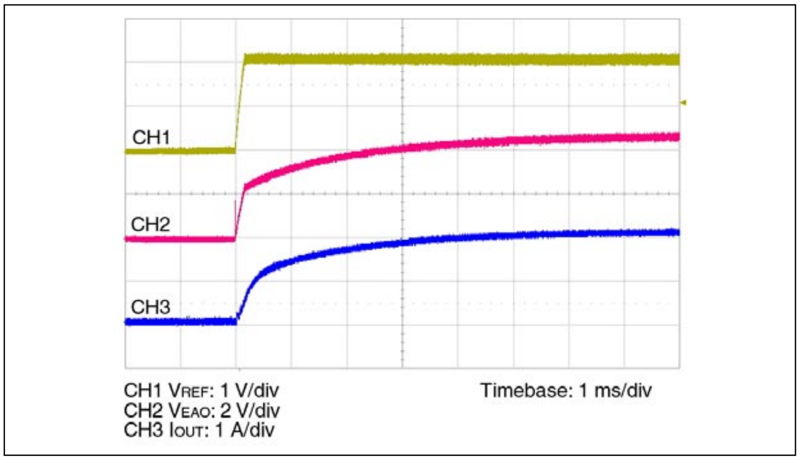
The startup timing for the constant current circuit is controlled not only by the rise time of V_{REF}, but also the magnitude of the reference voltage, and the error amplifier compensation components. The compensation components, R_6 and C_2, limit the maximum rate of rise of the error amplifier output, leading to two startup timing conditions. The first is illustrated in Figure 12, where the rate of rise of the reference is below the maximum rate of the error amplifier. In this case, the output of the error amplifier is able to track the reference; and the result is an output current rise that closely matches that of the reference voltage.

Figure 12
Constant Current Startup Condition 1



The second condition is where the rate of rise of V_{REF} exceeds the maximum rate of the error amplifier. In this case the error amplifier output will change its rate of rise in order force a current through C2 and R6 temporarily equalizing the voltages at pin 5 and pin 6. This is illustrated in Figure 13. As the output current increases during the startup sequence, the necessary slope decreases until output current feedback is able to satisfy the error amplifier.

Figure 13
Constant Current Startup Condition 2

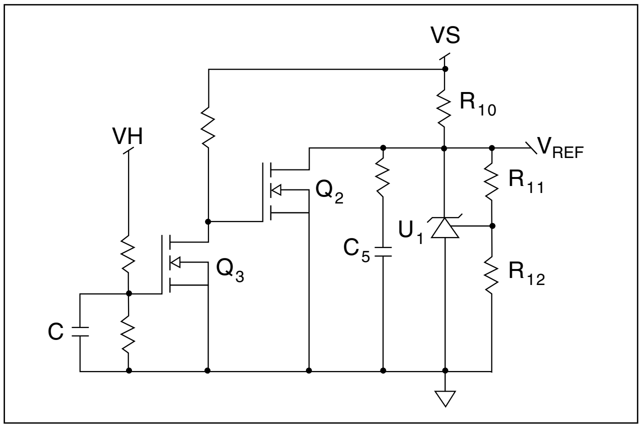


The startup timing for this condition is dependant on the magnitude of the reference voltage, and the characteristics of the load. Higher reference voltages will have a faster rise time, while lower reference voltages will have a slower rise time. To ensure a proper start-up, the VTM input voltage must reach 26 V within the 10 ms VC pulse duration. If the voltage is too low, the VTM will be unable to sustain its internal VCC when the VC voltage drops, and will subsiquently shut down. This puts a limitation on maximum rise time, and thus the minimum allowable reference voltage for a given C2 and R6. Low reference voltage set points may result in a condition where the output rise time is slower than the minimum 10msec to ensure a proper startup. In this case, the user should adjust the gain of the current sense amplifier to ensure that the reference voltage is high enough at the desired output current to ensure a proper start. Once running, the current can be trimmed down to a lower level without issue. An alternative solution would be to start at a higher output current and then trim down once the unit is up and running.

When powering the circuit from VH, the amplifier supply voltage and reference will not be generated until VH is present. This is the instant at which the PRM is able to respond to a control signal. If the supply and reference were present prior to this instant, the circuit would not have a controlled start. The error amplifier would rail in an unsuccessful attempt to bring the current up to the appropriate value. This is an undesirable situation. Once the PRM is enabled, the control signal would be at a maximum, forcing the PRM to its maximum voltage with no control over the rate of rise.

The rise of the voltage reference must be synchronized to the VH signal to ensure that the error amplifier voltage remains low until the PRM is ready to respond to a control signal. The circuit shown in Figure 14 is one example of a modification of the circuit shown in Figure 6 which enables operation with an external supply.

Figure 14
Reference Sequencing Circuit



**VS is an external supply*

Current Regulation Accuracy

The fact that the current control is done at the VTM input adds additional complexity as variations in the VTM parameters and load voltage will lead to errors in the current set point. The contributing factors to the overall accuracy are the current sensing accuracy, reference accuracy, and variation in the VTM efficiency, VTM R_{OUT}, and V_{OUT}.

The current sensing accuracy is mostly determined by the magnitude of the input offset voltage of the AD8667 with respect to the shunt voltage. The offset error can be approximated by Equation 16.

Equation 16

$$Offset\_\%Error = \left(\frac{V_{OFFSET}}{V_{SHUNT}}\right) \cdot 100$$

Where:
V_{OFFSET} is the specified offset voltage of the op amp.
V_{SHUNT} is the shunt voltage at the operating current.

Since the shunt voltage is a function of load the offset error will vary with load current and will be worse at lighter loads. If the maximum current is consistently low, consider increasing the shunt value for improved accuracy.

The other contributing factors to the accuracy are the expected variation in the load voltage, VTM Rout and VTM efficiency. When using the values for efficiency given in the data sheet, the expected variation is ±1%. This percentage error caries over to the overall accuracy.

The effect of R_{OUT} and V_{OUT} variation is dependent on nominal operating conditions and can be predicted by Equation 17 and Equation 18:

Equation 17

$$Voltage\_\%Error = \frac{V\%}{\left(1 - \frac{K \cdot V_{OUT} \cdot (1 + V\%)}{I_{IN} \cdot R_{OUT} \cdot \eta}\right)} \cdot 100$$

Equation 18

$$R_{OUT}\_\%Error = \frac{R\%}{\left(\frac{K \cdot V_{OUT}}{I_{IN} \cdot R_{OUT} \cdot \eta} - (1 + R\%)\right)} \cdot 100$$

Where:
I_{IN} is the set VTM input current
V_{OUT} is the nominal output voltage of the load device
V% is the % variation of the load voltage
R_{OUT} is the nominal output resistance of the VTM
R% is the percent variation in R_{OUT} (from data sheet)
K is the VTM input to output ratio
η is the nominal efficiency (from data sheet)

Table 5 summarizes the contributing factors to the overall error.

Table 5
Current Source Error

Error Source	**Error (%)**	**Comments**
Shunt Tolerance	±0.1	0.1% Tolerance Shunt
Differential Amplifier Offset	$Offset\_\%Error = (\frac{V_{OFFSET}}{V_{SHUNT}}) \cdot 100$	Load Dependent
Differential Amplifier Gain	±0.2	0.1% Tolerance Resistors
TLV431B Reference	±0.5	
TLV431 Divider	±0.2	0.1% Tolerance Resistors
VTM Efficiency	±1	
VTM R_{OUT}	$R_{OUT}\_\%Error = \frac{R\%}{(\frac{K \cdot V_{OUT}}{I \cdot R \cdot \eta} - (1 + R\%)} \cdot 100$	Equation 18
V_{OUT}	$Voltage\_\%Error = \frac{V\%}{(1 - \frac{K \cdot V_{OUT} \cdot (1 + V\%)}{I_{IN} \cdot R_{OUT} \cdot \eta})} \cdot 100$	Equation 17

If the overall accuracy is not acceptable, the current sensing stage can be moved to the output of the VTM. As the VTM is an isolated device, this will require the addition of an opto coupler to transfer the feedback signal to the primary side. The implementation of this additional stage is beyond the scope of this document. Please contact Vicor applications engineering for additional information if required.

Layout Considerations

Application Note AN:005 details board layout using V•I Chip components. Additional consideration must be given to the external current control circuit components.

The shunt voltage is on the millivolt level and is highly sensitive to noise. As such, current sensing circuitry should be located close to the shunt to avoid routing the sense signal over any distance. A 4 terminal Kelvin contact shunt is recommended for best results, eliminating error caused by solder resistance from the shunt to the current carrying connection on the PCB.

The control signal from the sense circuit to the PRM should be shielded. Avoid routing this signal directly underneath the PRM if possible. Components that tie directly to the PRM should be located close to their respective pins. It is also critical that all components be referenced to SG, and that SG not be tied to any other ground in the system, including –IN and –OUT of the PRM.

Ensure that there is no unintentional bypass path which effectively shorts the shunt resistor.

Conclusion

The high power density and high efficiency of V•I Chips can be used to power LEDs and other loads requiring regulated current operation by using the circuit and guidelines discussed in this document. Appendix A covers a complete design example using the Constant Current LED Driver Demonstration board.

For additional assistance, circuit, schematic, or board layout review please contact Vicor Applications Engineering at:

Tel: 800-735-6200
Customer Service: custserv@vicorpower.com
Technical Support: apps@vicorpower.com

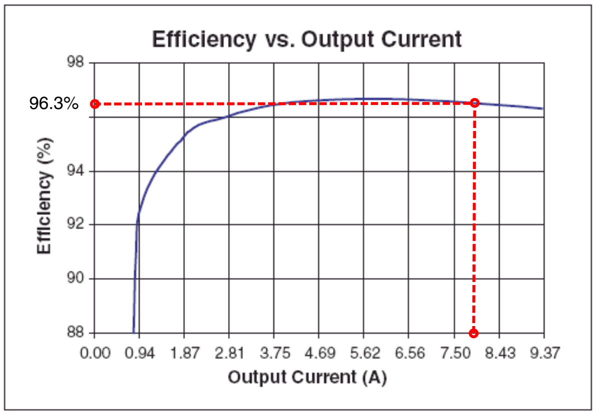
Appendix A - Design Example

An application requires that eight, 1 A Opto-Semiconductor LED strings be placed in parallel for appropriate luminance intensity. The current control accuracy required is ±5%. The forward voltage of the cells in question ranges from 20 V to 30 V and is nominally 25 V. The input voltage is 48V ±10%. The maximum ambient temperature is 50°C.

1) Select the appropriate VTM from the product listing:
V048F320T009 is chosen due to its operating voltage range of 17.3 V to 36.7 V, and a maximum output current of 9 A. This voltage and current range fall within the specification of the LED string.

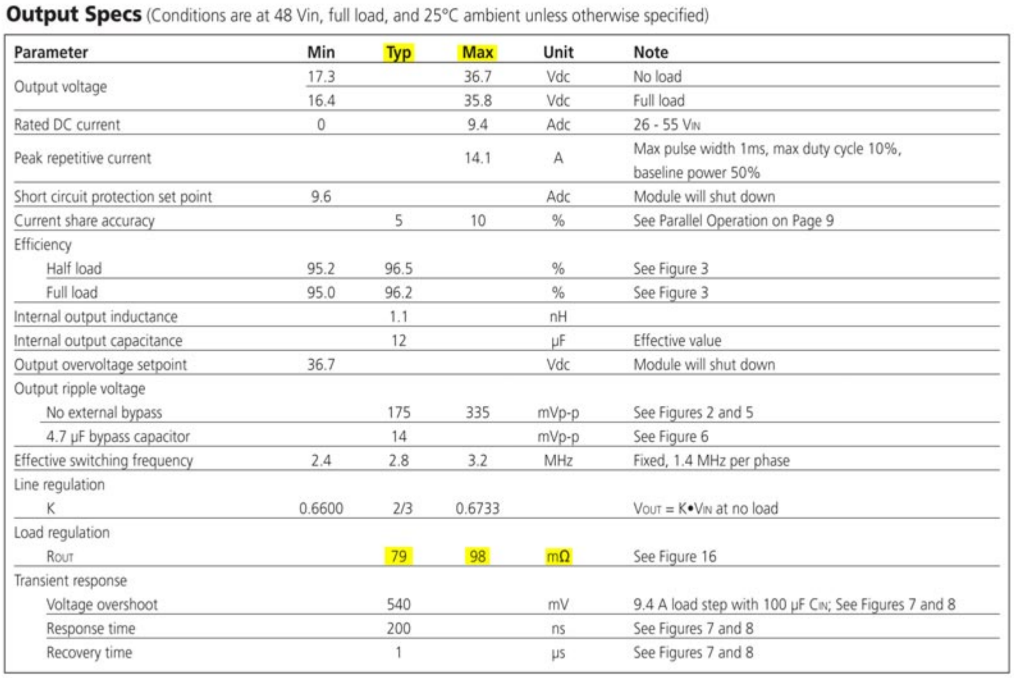
2) Find the required PRM output current:
The efficiency plot of the V048F320T009 is located on the data sheet (Figure 3, pg. 3) and used to determine the VTM efficiency, which is approximately 96.3% at 8 A.

Figure A1
V048F320T009 Efficiency vs. Load Graph



The nominal value for R_{OUT} is found to be 79 mΩ from the output specifications table on pg. 2 of the data sheet.

Figure A2
V048F320T009 Output Specifications Table



Output Specs (Conditions are at 48 Vin, full load, and 25°C ambient unless otherwise specified)

Parameter	Min	Typ	Max	Unit	Note
Output voltage	17.3		36.7	Vdc	No load
	16.4		35.8	Vdc	Full load
Rated DC current	0		9.4	Adc	26 - 55 V_{IN}
Peak repetitive current			14.1	A	Max pulse width 1ms, max duty cycle 10%, baseline power 50%
Short circuit protection set point	9.6			Adc	Module will shut down
Current share accuracy		5	10	%	See Parallel Operation on Page 9
Efficiency					
Half load	95.2	96.5		%	See Figure 3
Full load	95.0	96.2		%	See Figure 3
Internal output inductance		1.1		nH	
Internal output capacitance		12		µF	Effective value
Output overvoltage setpoint	36.7			Vdc	Module will shut down
Output ripple voltage					
No external bypass		175	335	mVp-p	See Figures 2 and 5
4.7 µF bypass capacitor		14		mVp-p	See Figure 6
Effective switching frequency	2.4	2.8	3.2	MHz	Fixed, 1.4 MHz per phase
Line regulation					
K	0.6600	2/3	0.6733		$V_{OUT} = K \bullet V_{IN}$ at no load
Load regulation					
R_{OUT}		79	98	mΩ	See Figure 16
Transient response					
Voltage overshoot		540		mV	9.4 A load step with 100 µF C_{IN}; See Figures 7 and 8
Response time		200		ns	See Figures 7 and 8
Recovery time		1		µs	See Figures 7 and 8

Using these numbers, and the nominal output voltage of the LED string (25 V), the necessary PRM output current is calculated for a VTM output current of 8 A using Equation 4 from the Application Note.

$$VTM\_I_{IN} = PRM\_I_{OUT} = \frac{V_{OUT} \cdot I_{OUT} \ \ K}{\eta \cdot (V_{OUT} + I_{OUT} \cdot R_{OUT})} = \frac{25\ V \cdot 8\ A \cdot 2/3}{0.963 \cdot (25\ V + 8\ A \cdot 0.079\ \Omega)} = 5.4\ A$$

The P045F048T32AL is selected for its 6.67 A output current capability and 38 V - 55 V input voltage range.

3) Find the necessary reference voltage:
The recommended values for the shunt resistor, and gain resistors are used. Equation 5 is used to determine the necessary reference voltage for a 5.4 A PRM output current.

$$V_{REF} = PRM\_I_{OUT} \cdot R_1 \cdot \left(\frac{R_3}{R_2}\right) = 5.4\ A \cdot 10\ m\Omega \cdot \left(\frac{100\ k\Omega}{1\ k\Omega}\right) = 5.4\ V$$

Using a TLV431B shunt regulator, R_{11}, and R_{12} are selected to provide a 5.4 V output using 0.1% tolerance resistors. R_{10} is selected to limit the current to 1 mA.

$$R_{10} = \frac{VH - V_{REF}}{1\ mA} = \frac{9\ V - 5.4\ V}{1\ mA} = 36\ k\Omega$$

The closest standard 1% value is selected as 35.7 KΩ.

4) Determine the maximum PRM output voltage:

The maximum PRM output voltage is selected to ensure that the PRM and VTM can provide the maximum operating voltage of 30 V taking into account the maximum output resistance ($R_{OUT(MAX)}$) of the VTM. For additional margin, the maximum output voltage is increased by 1 V.

$$PRM\_V_{OUT(MAX)} = \frac{(V_{OUT(MAX)} + I_{OUT} \cdot R_{OUT(MAX)})}{K} = \frac{31\ V + 8\ A \cdot (98\ m\Omega)}{2/3} = 47.7\ V$$

5) Find R_7, R_8 and R_9:

The recommended parameters are used for the maximum SC voltage ($V_{SC(MAX)}$ = 3 V) and SC pole frequency (F_{POLE} = 1 kHz) defined in Table 4. The maximum error amplifier output voltage ($V_{EAO(MAX)}$) is determined from the AD8667 data sheet which specifies the output dropout voltage as a function of temperature on page 8 (www.analog.com/UploadedFiles/Data_Sheets/AD8663_AD8667_AD8669.pdf). At 50°C, the dropout voltage is 250 mV, resulting in a $V_{EAO(MAX)}$ of 8.75 V.

Using Equation 9, R_7 is calculated:

$$R_7 = \frac{10\ k\Omega \cdot V_{EAO(MAX)}}{10\ k\Omega \cdot V_{SC(MAX)} \cdot 2\pi \cdot F_{POLE} \cdot 0.22\ \mu F - 1.24\ V} = \frac{10\ k\Omega \cdot 8.75\ V}{10\ k\Omega \cdot 3\ V \cdot 2\pi \cdot 1\ kHz \cdot 0.22\ \mu F - 1.24\ V} = 2.4\ K\Omega$$

The closest standard 1% value is selected as 2.37 kΩ

Using Equation 10, R_8 is selected:

$$R_8 = \frac{10\ k\Omega\ R_7 \cdot V_{SC(MAX)}}{10\ k\Omega \cdot V_{EAO(MAX)} + 1.24\ \text{V} \cdot R_7 - V_{SC(MAX)} \cdot (10\ k\Omega + R_7)} = \frac{10\ k\Omega \cdot 2.37\ k\Omega \cdot 3\ V}{10\ k\Omega \cdot 8.75\ V + 1.24\ V \cdot 2.37\ k\Omega - 3\ V \cdot (10\ k\Omega + 2.37\ k\Omega)} = 1.33\ k\Omega$$

The closest standard 1% value is selected as 1.33 kΩ.

Using Equation 11, R_9 is selected based on $V_{SC(MAX)}$, $PRM\_V_{OUT(MAX)}$, and the R_{68} value from Table 1:

$$R_9 = \left(\frac{R_{68} \cdot V_{SC(MAX)} \cdot 0.961}{PRM\_V_{OUT(MAX)} - V_{SC(MAX)} \cdot 0.961}\right) = \left(\frac{93.1\ k\Omega \cdot 3\ V \cdot 0.961}{47.7\ V - 3\ V\ \cdot\ 0.961}\right) = 5.99\ k\Omega$$

The closest standard 1% value is selected as 6.04 kΩ.

6) Determine the compensation components R_6 and C_2

The crossover frequency is selected as 100 Hz which is a factor of 10 below the SC pole frequency of 1 kHz.

C_2 is fixed at a standard value of 0.1 µF, and R_6 is calculated using Equation 15:

$$R_6 = \frac{1}{C_2 \cdot 2\pi \cdot F_{CROSS}} = \frac{1}{0.1\ \mu F \cdot 2\pi \cdot 100\ Hz} = 15.9\ k\Omega$$

The closest standard 1% value is selected as 16 kΩ.

7) Determine the overall accuracy:

The sources of error are specified in Table 5. These factors are added up to determine the overall % error.

The shunt error is 0.1%.

The offset error is calculated using Equation 16, assuming a maximum input offset voltage of 300 µV for the AD8667 at 50°C.

$$Offset\_\%Error = \left(\frac{V_{OFFSET}}{V_{SHUNT}}\right) \cdot 100 = \left(\frac{300\ \mu V}{5.4\ A \cdot 10\ m\Omega}\right) \cdot 100 = .55\%$$

The error due to the gain resistors is .2%
The error due to the voltage reference and resistors is .7%
The error due to variation in efficiency is 1%

In order to calculate the error due to output voltage variation, the percent variation in the load voltage from the nominal is calculated based on the specifications.

$$V\% = \frac{V_{MAX} - V_{NOM}}{V_{NOM}} = \frac{30\,V - 25\,V}{25\,V} = 20\% = 0.2$$

The maximum percent error due to this voltage variation is predicted using Equation 17.

$$Voltage\_\%Error = \frac{V\%}{(1 - \frac{K \cdot V_{OUT} \cdot (1 + V\%)}{I_{IN} \cdot R_{OUT} \cdot \eta})} \cdot 100 = \frac{0.2}{(1 - \frac{\frac{2}{3} \cdot 25V \cdot (1 + 0.2)}{5.4\,A \cdot 79\;m\Omega \cdot .963})} \cdot 100 = 0.4\%$$

In order to calculate the error due to variation in R_{OUT}, the percent variation in R_{OUT} from the nominal is calculated based on the data sheet specifications.

$$R\% = \frac{R_{OUT(MAX)} - R_{OUT(NOM)}}{R_{OUT(NOM)}} = \frac{98\;m\Omega - 79\;m\Omega}{79\;m\Omega} = 24\% = 0.24$$

The maximum percent error due to this variation is predicted from Equation 17.

$$R_{OUT}\_\%Error = \frac{R\%}{(\frac{K \cdot V_{OUT}}{I_{IN} \cdot R_{OUT} \cdot \eta} - (1 + R\%))} x100 = \frac{0.24}{\frac{\frac{2}{3} \cdot 25\,V}{5.4\,A \cdot 79\;m\Omega \cdot 0.963} - (1 + .24)} x100 = 0.61\%$$

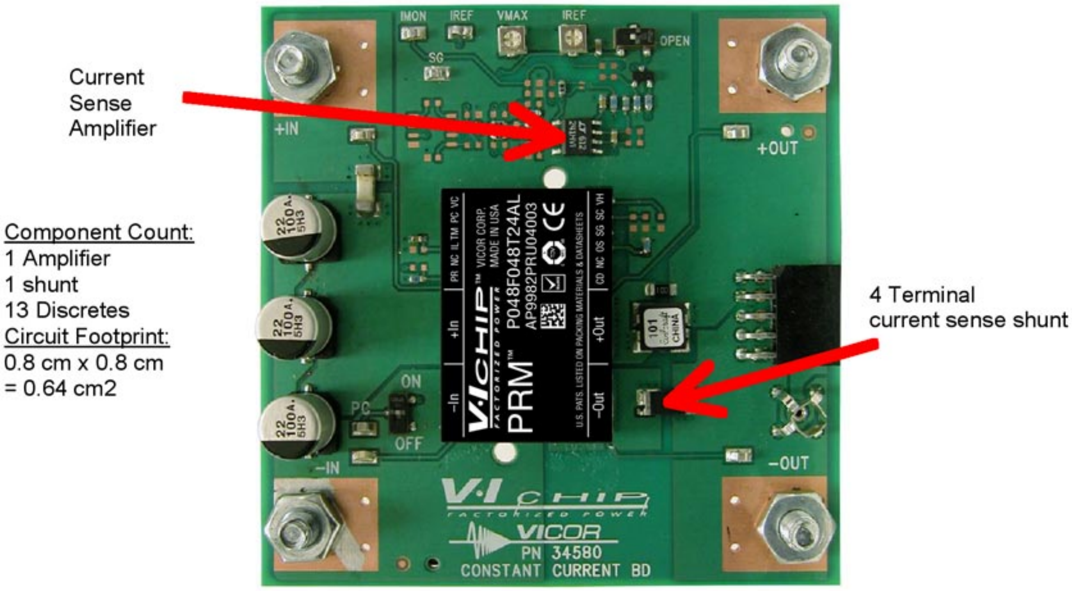
The total error is the sum of all the errors.

$$Total\_\%Error = Shunt\_\%Error + Offset\_\%Error + Gain\_\%Error + Reference\_\%Error$$
$$+ Efficiency\_\%Error + V_{OUT}\_\%Error + R_{OUT}\_\%Error$$

$$Total\_\%Error = 0.1\% + 0.55\% + 0.2\% + 0.7\% + 1.0\% + 0.4\% + 0.6\% = 3.6\%$$

Designing an LED driver circuit can be a challenging task due to the design variabilities and unknowns which may occur during the process. A Constant Current LED Driver Demonstration Board is available to assist in the design process. The board contains the basic circuit outlined in AN:018 along with the ability to adjust the output voltage and current settings and match the PRM with any standard VTM. For further information please consult the User's Guide (UG:007 vicorpower.com/cms/home/technical_resources/manuals-and-design-guides).

Figure A3
Constant Current LED Driver Demonstration Board



Current Sense Amplifier

Component Count:
1 Amplifier
1 shunt
13 Discretes
Circuit Footprint:
0.8 cm x 0.8 cm
= 0.64 cm2

4 Terminal current sense shunt