Setting the Shunt Voltage on an Adjustable Shunt Regulator

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ABSTRACT

The ability to set the shunt voltage, $V_{KA}$, to any voltage between $V_{REF}$ and the maximum rated voltage for the shunt regulator provides a lot of flexibility. It takes two resistors to set the shunt voltage. In an ideal common anode shunt regulator, the shunt voltage would be $V_{REF} \times (R_1/R_2 + 1)$. A few shunt regulators have a common cathode where the feedback voltage is relative to the cathode and are not covered in this document. The TL430, TL431, TL432, TLV431, TLVH431, TLVH432, and TL1431 are covered.

However real world shunt regulators have limited gain, non-zero reference input current, and suffer from cathode voltage modulation. This application report derives comprehensive formulas that accurately represent the relationship between the shunt voltage and feedback resistors. It also shows a practical example.

Shunt Regulator Limitations

Real world shunt regulators have three parameters that should be taken into account.

1. Dynamic impedance, $Z_{KA}$
2. Reference pin current, $I_{REF}$
3. Ratio of change in reference voltage to the change in cathode voltage, $\Delta V_{REF}/\Delta V_{KA}$.

The first parameter will cause a $V_{REF}$ shift for all $V_{KA}$ values and the last two only apply when $V_{KA}$ is set greater than $V_{REF}$.

$Z_{KA}$ offsets the $V_{REF}$ in direct proportion to the cathode current. The data sheet generally specifies $V_{REF}$ at a specific current. At any other current $Z_{KA}$ impacts $V_{REF}$.

$I_{REF}$ causes an inequality in the feedback resistor currents which changes the effective DC feedback ratio. This factor is often included in data sheet formulas.

$\Delta V_{REF}/\Delta V_{KA}$ specifies how much the $V_{REF}$ voltage changes when the cathode voltage changes. This is a frequently ignored factor although the effect can be significant.
General Design Example

To calculate the values for resistors \( R_1 \) and \( R_2 \), it is required that the feedback current, \( I_{FB} \), cathode current, \( I_{KA} \), and desired shunt voltage, \( V_{KA} \), are known.

![Circuit Diagram](https://www.ti.com/lit/ds/slaa773/slaa773.pdf)

**electrical characteristics over recommended operating conditions, \( T_A = 25^\circ C \) (unless otherwise noted)**

<table>
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<tr>
<th>PARAMETER</th>
<th>TEST CONDITIONS</th>
<th>TL431C, TL432C (UNIT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{ref} ) Reference voltage</td>
<td>( V_{KA} = V_{REF}, I_{KA} = 10 \text{ mA} )</td>
<td>MIN: 2440</td>
</tr>
<tr>
<td>( V_{(dev)} ) Deviation of reference voltage over full temperature range</td>
<td>( V_{KA} = V_{REF}, I_{KA} = 10 \text{ mA}, T_A = 0^\circ C \text{ to } 70^\circ C )</td>
<td>SOT23-3 and TL432 devices MIN: 6</td>
</tr>
<tr>
<td>( \Delta V_{ref} ) Deviation of reference current over full temperature range</td>
<td>( I_{KA} = 10 \text{ mA} )</td>
<td>All other devices MIN: 4</td>
</tr>
<tr>
<td>( I_{off} ) Reference input current</td>
<td>( I_{KA} = 10 \text{ mA}, R_1 = 10 \text{ k\Omega}, R_2 = \infty )</td>
<td>MIN: 0.1</td>
</tr>
<tr>
<td>( I_{(dev)} ) Deviation of reference input current over full temperature range</td>
<td>( I_{KA} = 10 \text{ mA}, R_1 = 10 \text{ k\Omega}, R_2 = \infty, T_A = 0^\circ C \text{ to } 70^\circ C )</td>
<td>MIN: 0.4</td>
</tr>
<tr>
<td>( I_{min} ) Minimum cathode current for regulation</td>
<td>( V_{KA} = V_{REF} )</td>
<td>MIN: 0.4</td>
</tr>
<tr>
<td>( I_{off} ) Off-state cathode current</td>
<td>( V_{KA} = 36 \text{ V}, V_{REF} = 0 )</td>
<td>MIN: 0.1</td>
</tr>
<tr>
<td>(</td>
<td>Z_{KA}</td>
<td>) Dynamic impedance</td>
</tr>
</tbody>
</table>

The table specifies when \( V_{KA} = V_{REF} \) and \( I_{KA} \) is 10 mA the nominal \( V_{REF} \) (labeled \( V_{NOM} \)) is 2.495 V. The reference voltage varies with cathode voltage at two different rates; it is \(-1.4 \text{ mV/V} \) from \( V_{REF} \) to 10 V then \(-1 \text{ mV/V} \) above 10 V. The reference pin current is 2 \( \mu A \).

The \( Z_{KA} \) parameter offsets \( V_{REF} \) by \((I_{KA} - I_{NOM}) \times Z_{KA}\)

In addition, the \( \Delta V_{REF}/\Delta V_{KA} \) parameter offsets \( V_{REF} \) by either \(-1.4 \text{ mV} \times (V_{KA} - 2.5 \text{ V}) \) if \( V_{KA} \leq 10 \text{ V} \) or \(-10.5 \text{ mV/V} \times (V_{KA} - 10 \text{ V}) \) if \( V_{KA} > 10 \text{ V} \). The "-10.5 \text{ mV/V}" constant is the \( V_{REF} \) offset as \( V_{KA} \) changes from \( V_{NOM} \) to 10 V, \((10 \text{ V} - 2.495 \text{ V}) \times -1.4 \text{ mV/V} \).

Therefore:

**If \( V_{KA} \leq 10 \text{ V} \) then:**

\[
V_{REF} = V_{NOM} + (I_{KA} - I_{NOM}) \times Z_{KA} + (V_{KA} - V_{NOM}) \times -1.4 \text{ mV/V}
\]

**If \( V_{KA} > 10 \text{ V} \) then:**

\[
V_{REF} = V_{NOM} + (I_{KA} - I_{NOM}) \times Z_{KA} + (V_{KA} - 10 \text{ V}) \times -1 \text{ mV/V} -10.5 \text{ mV/V}
\]

Now that \( V_{REF} \) is solved, \( R_1 \) and \( R_2 \) can be determined.

\[
R_1 = \frac{(V_{KA} - V_{REF})}{I_{FB}}
\]

\[
R_2 = \frac{V_{REF}}{(I_{FB} - I_{REF})} \text{; Note that } R_2 \text{ has less current than } R_1
\]
Practical Example

Design goal; TL431 cathode set to 12 V, cathode current 2 mA, and feedback current 0.2 mA.

Using the formula derived in the general example for $V_{KA} > 10 \text{ V}$.

$$V_{RF} = V_{NOM} + (I_{KA} - I_{NOM}) \times Z_{KA} + (V_{KA} - 10 \text{ V}) \times -1 \text{ mV} - 10.5 \text{ mV}$$

$$V_{RF} = 2.495 \text{ V} + (2 \text{ mA} - 10 \text{ mA}) \times 0.2 \Omega + (12 \text{ V} - 10 \text{ V}) \times -1 \text{ mV} - 10.5 \text{ mV}$$

$$V_{RF} = 2.4809 \text{ V}$$

$$R_1 = \frac{(V_{KA} - V_{RF})}{I_{FB}}$$

$$R_1 = \frac{(12\text{ V} - 2.4809 \text{ V})}{0.2 \text{ mA}}$$

$$R_1 = 47.596 \text{ k}\Omega$$

$$R_2 = \frac{V_{RF}}{(I_{FB} - I_{REF})}$$

$$R_2 = \frac{2.4809 \text{ V}}{(0.2 \text{ mA} - 2 \text{ }\mu\text{A})}$$

$$R_2 = 12.530 \text{ k}\Omega$$

Simulation using TI-TINA agrees with the solution.

The closest standard 1% resistor values are $R_1 = 47.5 \text{ k}\Omega$ and $R_2 = 12.4 \text{ k}\Omega$. This results in a shunt voltage of 12.08 V which is a 0.66% error. Other resistor combinations may provide a shunt voltage that is centered better. A formula to test for $R_1$ values that may be closer to standard values using standard $R_2$ resistors is $R_1 = (V_{KA} - V_{REF})/(V_{REF}/R_2 + I_{REF})$. Moving $R_2$ up and down the resistor table five values revealed the best resistor pair was $R_1 = 43.2 \text{ k}\Omega$ and $R_2 = 11.33k\Omega$. This produced a more centered shunt voltage of 12.05 V and $I_{FB}$ marginally increased to $(V_{KA} - V_{REF})/R_1 = 0.22 \text{ mA}$.
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