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APPLICATION NOTE 4798

How to Calculate the Operating Windows for a Remote Antenna Current-Sense Amplifier and Switch

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Abstract: This application note helps designers choose the correct external components to ensure that automobile antenna-detection circuitry meets performance objectives. A calculator details how to specify the critical external components for the MAX16913/MAX16913A remote antenna current-sense amplifiers and switches. The calculator also determines the device's operational windows and analog output voltage accuracy. An example calculation is given.

Introduction

The MAX16913/MAX16913A (**Figure 1**) are precision current-sense amplifiers (CSAs) and switches that provide phantom power to remote radio antennas in automotive applications. In addition, they provide short-circuit protection, current-limit protection, and open-load detection. To ensure that their antenna detection circuitry meets performance objectives, the design engineer must choose the correct external components for a design.

When working with CSAs and switches for antenna applications, the designer must often determine the operational windows for an open load, normal operation, a short circuit, and current limiting (**Figure 2**). In addition, the accuracy of the CSA's analog output voltage must also be verified.

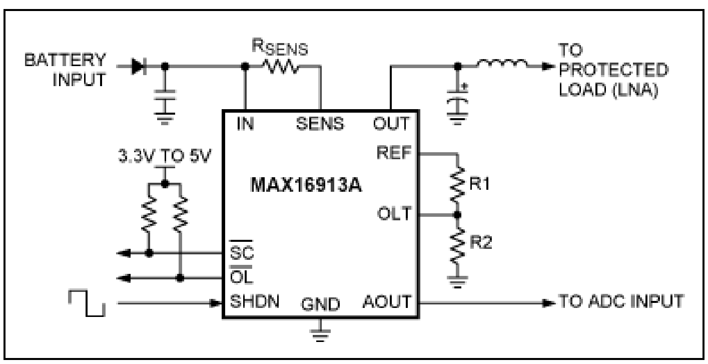

Figure 1. Typical operating circuit of the MAX16913A remote antenna CSA and switch.

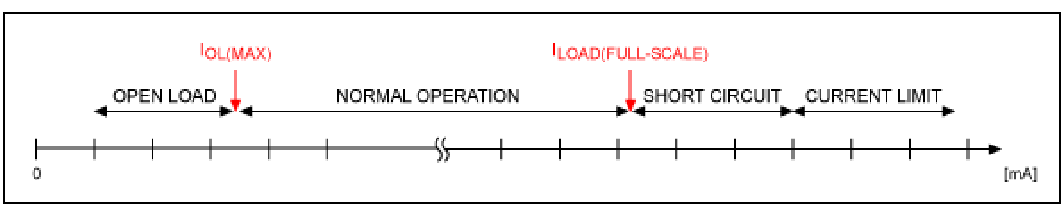

Figure 2. Operation ranges for these CSAs.

This application note presents a calculator that shows how to determine the proper sense resistor and the resistor-divider for setting the open-load threshold (detection range) tolerance. It considers the tolerances of both the external components and the MAX16913/MAX16913A, and then calculates the appropriate tolerance window ranges for optimal performance. The calculator is available here, and an example calculation follows.

Calculate the Required Sense Resistor

Ideally the maximum operating current develops the full-scale sense voltage across the current-sense resistor, R_{SENS} (Figure 1). Calculate the maximum value for R_{SENS} so that the differential voltage across IN and SENS does not exceed the minimum full-scale sense voltage (87mV)*:

$$R_{SENS(MAX)}(\Omega) = \frac{V_{DIFF(MIN)}(V)}{I_{LOAD(FULL-SCALE)}(A)}$$

Where $V_{DIFF(MIN)} = V_{IN} - V_{SENSE}$ = 87mV (min) at the maximum guaranteed output current, $I_{LOAD(FULL-SCALE)}$ (Figure 2).

However, resistors always have tolerances, so the actual resistor value can be higher by its tolerance rating, thus causing the device to detect a short circuit too early. After considering the resistor's tolerance rating, the nominal maximum resistor value can be calculated:

$$R_{SENS(MAX)(NOM)}(\Omega) = \frac{R_{SENS(MAX)}(\Omega)}{\left(\frac{R_{SENS\text{-}TOLERANCE}(\%)}{100} + 1\right)}$$

Where $R_{SENS(MAX)}$ is the maximum sense resistor calculated above, and $R_{SENS\text{-}TOLERANCE}$ is the tolerance rating of the resistor. Remember that exact values for the calculated sense resistor may not be available. If that is the case, choose the closest smaller value for $R_{SENS(MAX)(NOM)}$ and use that to calculate $R_{SENS\_P(NOM)}$. Alternatively serial or parallel combinations of standard resistors can be used to attain the optimal sense resistor.

Calculate the Short-Circuit Current-Detection Window

The nominal sense resistor has been chosen. Now the typical current through the sense resistor, when a short circuit is detected, can be calculated as follows:

$$I_{SC(TYP)}(A) = \frac{V_{SC(TYP)}(V)}{R_{SENS\_P(NOM)}(\Omega)}$$

Where $V_{SC(TYP)}$ is the typical value of the short-circuit voltage threshold (100mV)* and $R_{SENS\_P(NOM)}$ is the sense resistor selected above.

However, as V_{SC} and R_{SENS} have uncorrelated tolerances (i.e., have minimum and maximum values that vary independently of each other), an additional error has to be considered. So the worst-case short-circuit, current-detection window is:

$$I_{SC(MIN)}(A) = \frac{V_{SC(MIN)}(V)}{R_{SENS\_P(MAX)}(\Omega)}$$

And

$$I_{SC(MAX)}(A) = \frac{V_{SC(MAX)}(V)}{R_{SENS\_P(MIN)}(\Omega)}$$

Where $V_{SC(MIN)}$ is the minimum value of the short-circuit voltage threshold (87mV)* and $V_{SC(MAX)}$ is the maximum value (110mV).* Therefore:

$R_{SENS\_P(MAX)}$ = $R_{SENS\_P(NOM)}$ + its tolerance rating + $R_{SENS\_P(MIN)}$
= $R_{SENS\_P(NOM)}$ - its tolerance rating

The short-circuit flag (active-low SC) will thus go low when the current is in the range between $I_{SC(MIN)}$ and $I_{SC(MAX)}$.

Calculate the Current-Limit Range

Analogous to the short-circuit current-detection window, the current-limit range is typically:

$$I_{LIM(TYP)}(A) = \frac{V_{LIM(TYP)}(V)}{R_{SENS\_P(NOM)}(\Omega)}$$

Where $V_{LIM(TYP)}$ is the typical value of the current-limit threshold voltage between IN and SENS (200mV),* and $R_{SENS\_P(NOM)}$ is the sense resistor selected.

Considering that V_{LIM} and R_{SENS} have uncorrelated tolerances, the worst-case current-limit range through the sense resistor can be calculated:

$$I_{LIM(MIN)}(A) = \frac{V_{LIM(MIN)}(V)}{R_{SENS\_P(MAX)}(\Omega)}$$

And

$$I_{LIM(MAX)}(A) = \frac{V_{LIM(MAX)}(V)}{R_{SENS\_P(MIN)}(\Omega)}$$

Where $V_{LIM(MIN)}$ is the minimum value of the voltage between IN and SENS (173mV),* and $V_{LIM(MAX)}$ is the maximum value (225mV).*

Calculate the Open-Load Detection Window

This procedure differs for the MAX16913 and MAX16913A.

For the MAX16913

The open-load detection threshold (active-low OL) for the MAX16913 is set internally to V_{OLT} = 0.66V.* The associated current range using a 1Ω resistor is specified in the data sheet as 10mA (min), 20mA (typ), and 30mA (max). These values include the tolerance of the open-load comparator, the gain amplifier, and the external sense resistor (1Ω).

To determine the open-load detection window using a different sense resistor, first the given current levels must be converted to a voltage:

$$V_{OLT(MIN)} = \frac{10mA}{1\Omega} = 10mV$$
$$V_{OLT(TYP)} = \frac{20mA}{1\Omega} = 20mV$$
$$V_{OLT(MAX)} = \frac{30mA}{1\Omega} = 30mV$$

Then using the values calculated above, the typical value of the open-load current detection threshold calculates to:

$$I_{OL(TYP)}(A) = \frac{V_{OLT(TYP)}(V)}{R_{SENS\_P(NOM)}(\Omega)}$$

Where $V_{OLT(TYP)}$ is the typical value of the open-load detection-threshold voltage calculated above, and $R_{SENS\_P(NOM)}$ is the sense resistor selected.

Considering also the tolerances of the open-load current threshold and the tolerance of the sense resistor, then the current range for open-load detection calculates to:

$$I_{OL(MIN)}(A) = \frac{V_{OLT(MIN)}(V)}{R_{SENS\_P(MAX)}(\Omega)}$$

And

$$I_{OL(MAX)}(A) = \frac{V_{OLT(MAX)}(V)}{R_{SENS\_P(MIN)}(\Omega)}$$

Where $V_{OLT(MIN)}$ and $V_{OLT(MAX)}$ are the minimum and maximum values of the open-load detection-threshold voltage; $R_{SENS\_P(MIN)}$ and $R_{SENS\_P(MAX)}$ are the minimum and maximum values of the sense resistor calculated above.

The worst-case open-load detection window lies between $I_{OL(MIN)}$ and $I_{OL(MAX)}$.

For the MAX16913A

The open-load threshold for the MAX16913A can be adjusted externally with a resistor-divider between REF, OLT, and GND. Therefore, the first task is to specify the external resistor-divider.

Specify the External Resistor-Divider

To begin, choose the voltage needed on the OLT pin to set the desired nominal OL threshold (at the OLT pin, Figure 1) using the following formula:

$$V_{OLT}(V) = I_{OLT}(A) \times R_{SENS}(\Omega) \times A_V(V/V) + 0.133 \times V_{REF}$$

Where AV is the (V_{IN} - V_{SENS}) to V_{AOUT} gain (13V/V) and V_{REF} is the REF pin voltage (3V).* The ratio of the external resistors on the OLT pin can then be calculated using the following equation:

$$R_2/R_1 = V_{OLT}/(V_{REF} \times (1 - V_{OLT}/V_{REF}))$$

Where V_{REF} is the voltage on the REF pin (3V). An arbitrary standard value can now be chosen for R_1 or R_2, and the other resistor value can then be calculated (Figure 1). However, ensure that the impedance of the resistor-divider does not load the internal reference voltage excessively.

Determine the Open-Load Threshold-Voltage Range

The standard resistor values for R1 and R2 have now been defined. Next, considering the uncorrelated tolerances of V_{REF} and the resistors R1 and R2, the worst-case voltage range for the open-load pin, V_{OLTw}, can be calculated:

$$V_{OLTw(MIN)}(V) = \frac{R_{2(MIN)}(\Omega) \times V_{REF(MIN)}(V)}{R_{1(MAX)}(\Omega) + R_{2(MIN)}(\Omega)}$$

And

$$V_{OLTw(MAX)}(V) = \frac{R_{2(MIN)}(\Omega) \times V_{REF(MAX)}(V)}{R_{1(MIN)}(\Omega) + R_{2(MIN)}(\Omega)}$$

Where $R_{2(MIN)}$ is the nominal value of R_2 minus its tolerance value. This can be restated as $R_{2(MIN)} = R_2 - (R_2 \times (R_{2TOL}[\%]/100\%))$ and $R_{1(MAX)}$ is the nominal value of R_1 plus the tolerance.

Determine the Worst-Case, Open-Load Current-Detection Window

At this point $V_{OLTw(MIN)}$ and $V_{OLTw(MAX)}$ have been calculated. Now taking into consideration the tolerances of the REF output voltage, V_{REF}, the sense resistor, $R_{SENS\_P(NOM)}$, and the gain, AV, the worst-case current window when open load is detected (active-low OL) can be calculated:

$$I_{OL(MIN)}(A) = \frac{V_{OLTw(MIN)}(V) - 0.134 \times V_{REF(MAX)}(V)}{A_{V(MAX)}(V/V) \times R_{SENS\_P(MAX)}(\Omega)}$$

And

$$I_{OL(MAX)}(A) = \frac{V_{OLTw(MAX)}(V) - 0.132 \times V_{REF(MIN)}(V)}{A_{V(MIN)}(V/V) \times R_{SENS\_P(MIN)}(\Omega)}$$

Where $V_{OLTw(MIN)}$, $V_{OLTw(MAX)}$, $R_{SENS\_P(MIN)}$, and $R_{SENS\_P(MAX)}$ have been calculated above; A_V is the (V_{IN} - V_{SENS}) to V_{AOUT} gain which has minimum and maximum values of 12.87 and 13.13, respectively*; and $V_{REF(MIN)}$ and $V_{REF(MAX)}$ are the minimum and maximum values of the REF pin voltage (2.7V and 3.3V).*

Evaluate the Current Through R_{SENS} by Measuring Voltage on A_{OUT}

A_{OUT} Accuracy

With a given sense resistor, R_{SENS}, and a defined current through it, I_{SENS}, then the worst-case range of voltage values measured at the current-sense amplifier's output, A_{OUT} (e.g., a microcontroller's analog-to-digital converter (ADC)), can now be calculated. Consider also the uncorrelated tolerances of A_{OUT_Z} and the sense resistor, R_{SENS}. Therefore:

$$V_{AOUT(MIN)}(V) = A_{OUT\_Z(MIN)}(V) + A_{V(MIN)}(V/V) \times R_{SENS(MIN)}(\Omega) \times I_{SENS}(A)$$

And

$$V_{AOUT(MAX)}(V) = A_{OUT\_Z(MAX)}(V) + A_{V(MAX)}(V/V) \times R_{SENS(MAX)}(\Omega) \times I_{SENS}(A)$$

Where $A_{V(MIN)}$ is 12.87V and $A_{V(MAX)}$ is 13.13V;* and $A_{OUT\_Z(MIN)}$ and $A_{OUT\_Z(MAX)}$ are the minimum and maximum values of the A_{OUT} zero-current output voltage (340mV)* (460mV);* and $R_{SENS(MIN)}$ and $R_{SENS(MAX)}$ are the sense resistor plus/minus its tolerance.

Stated in other words, the sensed current produces a worst-case A_{OUT} voltage variation between $V_{AOUT(MIN)}$ and $V_{AOUT(MAX)}$.

Taking the above worst-case voltage levels and using a microcontroller's software to calculate those voltages back to a current, one can calculate:

$$I_{EVALUATED(MIN)}(A) = \frac{V_{AOUT(MIN)}(V) - AOUT\_Z_{(TYP)}(V)}{A_V(V/V) \times R_{SENS}(\Omega)}$$

And

$$I_{EVALUATED(MAX)}(A) = \frac{V_{AOUT(MAX)}(V) - AOUT\_Z_{(TYP)}(V)}{A_V(V/V) \times R_{SENS}(\Omega)}$$

Where $V_{AOUT(MIN)}$ and $V_{AOUT(MAX)}$ have been calculated above; AV is the (V_{IN} - V_{SENS}) to V_{AOUT} gain (13V/V);* $A_{OUT\_Z(TYP)}$ is the typical value of the A_{OUT} zero-current output voltage (400mV);* and R_{SENS} is the nominal value of the sense resistor.

Thus when the analog output voltage is used to measure a certain current through the sense resistor, the microcontroller's ADC gives a current value between $I_{EVALUATED(MIN)}$ and $I_{EVALUATED(MAX)}$.

The current measurement tolerance, I_{TOL}, is:

$$I_{TOL}(\%) = \frac{I_{SENS}(A) - I_{EVALUATED(MIN)}(A)}{I_{SENS}(A)} \times 100\%$$

Example Calculations

For these example calculations we assume an antenna phantom supply application where the upper end of the normal operation window ($I_{LOAD(FULL\text{-}SCALE)}$) is at 100mA. Then the maximum value of the sense resistor required is:

$$R_{SENS(MAX)}(\Omega) = \frac{V_{DIFF(MIN)}(V)}{I_{LOAD(FULL-SCALE)}(A)} = \frac{87mV}{100mA} = 0.87\Omega$$

When using a resistor with a 1% tolerance, the maximum sense resistor that can be selected is:

$$R_{SENS(MAX)(NOM)}(\Omega) = \frac{R_{SENS(MAX)}(\Omega)}{\left(\frac{R_{SENS\text{-}TOLERANCE}(\%)}{100} + 1\right)} = \frac{0.87\Omega}{\left(\frac{1\%}{100} + 1\right)} = 0.861\Omega$$

As a 0.861Ω resistor is not available as a standard value, we select the next smaller value from the E96 series for $R_{SENS\text{-}P(NOM)}$ = 0.845Ω. We use this value for our subsequent calculations.

Next, the typical current value for short-circuit detection can be calculated:

$$I_{SC(TYP)}(A) = \frac{V_{SC(TYP)}(V)}{R_{SENS\_P(NOM)}(\Omega)} = \frac{0.1V}{0.845\Omega} = 118.3mA$$

As previously shown, the minimum and maximum values for the short-circuit current-detection window lie between $I_{SC(MIN)}$ and $I_{SC(MAX)}$. To calculate these values, we first need the minimum and maximum values of the selected sense resistor.

$$R_{SENS\_P(MIN)}(\Omega) = R_{SENS\_P(NOM)}(\Omega) - \frac{R_{SENS\_P(NOM)}(\Omega) \times R_{SENS\text{-}TOLERANCE}(\%)}{100\%} = 0.845\Omega - \frac{0.845\Omega \times 1\%}{100\%} = 0.837\Omega$$

$$R_{SENS\_P(MAX)}(\Omega) = R_{SENS\_P(NOM)}(\Omega) + \frac{R_{SENS\_P(NOM)}(\Omega) \times R_{SENS\text{-}TOLERANCE}(\%)}{100\%} = 0.845\Omega + \frac{0.845\Omega \times 1\%}{100\%} = 0.853\Omega$$

This allows us to derive the limits of the short-circuit current-detection window:

$$I_{SC(MIN)}(A) = \frac{V_{SC(MIN)}(V)}{R_{SENS\_P(MAX)}(\Omega)} = \frac{87mV}{0.853\Omega} = 102mA$$

And

$$I_{SC(MAX)}(A) = \frac{V_{SC(MAX)}(V)}{R_{SENS\_P(MIN)}(\Omega)} = \frac{110mV}{0.837\Omega} = 131mA$$

Analogous to the short-circuit current-detection window, the typical value of the current-limit range is:

$$I_{LIM(TYP)}(A) = \frac{V_{LIM(TYP)}(V)}{R_{SENS\_P(NOM)}(\Omega)} = \frac{200mV}{0.845\Omega} = 237mA$$

Considering the tolerances, the minimum and maximum values for the current-limit range lie between $I_{LIM(MIN)}$ and $I_{LIM(MAX)}$:

$$I_{LIM(MIN)}(A) = \frac{V_{LIM(MIN)}(V)}{R_{SENS\_P(MAX)}(\Omega)} = \frac{173mV}{0.853\Omega} = 203mA$$

And

$$I_{LIM(MAX)}(A) = \frac{V_{LIM(MAX)}(V)}{R_{SENS\_P(MIN)}(\Omega)} = \frac{225mV}{0.837\Omega} = 269mA$$

Now for the MAX16913, the typical value for the open-load detection threshold is:

$$I_{OL(TYP)}(A) = \frac{V_{OLT(TYP)}(V)}{R_{SENS\_P(NOM)}(\Omega)} = \frac{20mV}{0.845\Omega} = 24mA$$

Including the tolerances, the minimum and maximum values are:

$$I_{OL(MIN)}(A) = \frac{V_{OLT(MIN)}(V)}{R_{SENS\_P(MAX)}(\Omega)} = \frac{10mV}{0.853\Omega} = 11.7mA$$

And

$$I_{OL(MAX)}(A) = \frac{V_{OLT(MAX)}(V)}{R_{SENS\_P(MIN)}(\Omega)} = \frac{30mV}{0.837\Omega} = 35.8mA$$

Turning now to the MAX16913A, we assume an application where the maximum current value of the open-load detection window is at 30mA. Therefore, the maximum voltage value for the center point of the resistor-divider is:

$$V_{OLT(MAX)}(V) = I_{OL(MAX)}(A) \times R_{SENS\_P(MAX)}(\Omega) \times A_V(V/V) + 0.134 \times V_{REF(MAX)}(V)$$
$$= 30mA \times 0.853\Omega \times 13.13(V/V) + 442mV = 0.778V$$

Next we pick a standard resistor for R2 from the E96 series, 90.9kΩ (1%), and calculate its maximum value:

$$R_{2(MAX)}(\Omega) = R_2(\Omega) + \frac{R_2(\Omega) \times R_{2TOL}(\%)}{100\%} = 90.9k\Omega + \frac{90.9k\Omega \times 1\%}{100\%} = 91.81k\Omega$$

The minimum resistor value for the upper resistor of the divider is then:

$$R_{1(MIN)}(\Omega) = \frac{R_{2(MAX)}(\Omega) \times V_{REF(MAX)}(V)}{V_{OLT(MAX)}(V)} - R_{2(MAX)}(\Omega) = \frac{91.81k\Omega \times 3.3V}{0.778V} - 91.81k\Omega = 389.43k\Omega$$

The nominal value, assuming also a 1% tolerance, is:

$$R_{1(NOM)}(\Omega) = \frac{R_{1(MIN)}(\Omega) \times 100}{100 - R_{1TOL}(\%)} = \frac{389.43k\Omega \times 100\%}{100\% - 1\%} = 393.36k\Omega$$

The closest higher standard value to be selected with the same tolerance is R1 = 392kΩ. Considering also its tolerance, we calculate:

$$R_{1(MIN)}(\Omega) = \frac{R_1(\Omega)}{100\% + R_{1TOL}(\%)} = \frac{392k\Omega}{101\%} = 388.12k\Omega$$
$$R_{1(MAX)}(\Omega) = \frac{R_1(\Omega)}{100\% - R_{1TOL}(\%)} = \frac{392k\Omega}{99\%} = 395.96k\Omega$$

And the minimum value for R2 is:

$$R_{2(MIN)}(\Omega) = R_2(\Omega) - \frac{R_2(\Omega) \times R_{2TOL}(\%)}{100\%} = 90.9k\Omega - \frac{90.9k\Omega \times 1\%}{100\%} = 89.99k\Omega$$

Continuing with these values, the open-load threshold-voltage range is:

$$V_{OLTw(MIN)}(V) = \frac{R_{2(MIN)}(\Omega) \times V_{REF(MIN)}(V)}{R_{1(MAX)}(\Omega) + R_{2(MIN)}(\Omega)} = \frac{89.99k\Omega \times 2.7V}{395.96k\Omega + 89.99k\Omega} = 0.499V$$

And

$$V_{OLTw(MAX)}(V) = \frac{R_{2(MIN)}(\Omega) \times V_{REF(MAX)}(V)}{R_{1(MIN)}(\Omega) + R_{2(MIN)}(\Omega)} = \frac{89.99k\Omega \times 3.3V}{388.12k\Omega + 89.99k\Omega} = 0.621V$$

Then the worst-case current window for the open-load detection of the MAX16913A is:

$$I_{OL(MIN)}(A) = \frac{V_{OLTw(MIN)}(V) - 0.134 \times V_{REF(MAX)}(V)}{A_{V(MAX)}(V/V) \times R_{SENS\_P(MAX)}(\Omega)} = \frac{0.499V - 442mV}{13.13(V/V) \times 0.853\Omega} = 5.09mA$$

And

$$I_{OL(MAX)}(A) = \frac{V_{OLTw(MAX)}(V) - 0.132 \times V_{REF(MIN)}(V)}{A_{V(MIN)}(V/V) \times R_{SENS\_P(MIN)}(\Omega)} = \frac{0.621V - 356mV}{12.87(V/V) \times 0.837\Omega} = 24.5mA$$

To evaluate the analog output, A_{OUT}, accuracy, we assume the same sense resistor selected above (0.845Ω) and evaluate the accuracy at a load current of 100mA. At this current, the minimum and maximum values of the A_{OUT} voltage are between:

$$V_{AOUT(MIN)}(V) = A_{OUT\_Z(MIN)}(V) + A_{V(MIN)}(V/V) \times R_{SENS(MIN)}(\Omega) \times I_{SENS}(A) = 340mV + 12.87(V/V) \times 0.837\Omega \times 100mA = 1.417V$$

And

$V_{AOUT(MAX)}(V) = A_{OUT\_Z(MAX)}(V) + A_{V(MAX)}(V/V) \times R_{SENS(MAX)}(\Omega) \times I_{SENS}(A) = 460mV + 13.13(V/V) \times 0.853\Omega \times 100mA = 1.58V$

Taking these voltages and calculating back as the microcontroller's software would do (i.e., taking the typical values from the data sheet), we derive an evaluated current between:

$$I_{EVALUATED(MIN)}(A) = \frac{V_{AOUT(MIN)}(V) - AOUT\_Z_{(TYP)}(V)}{A_V(V/V) \times R_{SENS}(\Omega)} = \frac{1.417V - 400mV}{13(V/V) \times 0.845\Omega} = 92.6mA$$

And

$$I_{EVALUATED(MAX)}(A) = \frac{V_{AOUT(MAX)}(V) - AOUT\_Z_{(TYP)}(V)}{A_V(V/V) \times R_{SENS}(\Omega)} = \frac{1.58V - 400mV}{13(V/V) \times 0.845\Omega} = 107.4mA$$

The worst-case tolerance of the measured current can then be up to:

$$I_{TOL}(\%) = \frac{I_{SENS}(A) - I_{EVALUATED(MIN)}(A)}{I_{SENS}(A)} \times 100\% = \frac{100mA - 92.6mA}{100mA} \times 100\% = 7.4\%$$

*For more details on these calculations, see the data sheet for the MAX16913/MAX16913A.

Related Parts		
MAX16913	Remote Antenna Current-Sense Amplifier and Switches	Free Samples
MAX16913A	Remote Antenna Current-Sense Amplifier and Switches	Free Samples

More Information
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