AFE Design Guide and Fault Diagnostics With PGA411-Q1

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ABSTRACT

This report covers design calculations for the analog front-end (AFE) filter and discusses the fault diagnostics coverage and optimization for the AFE components for the PGA411-Q1 resolver sensor interface device. Project collateral discussed in this application report can be downloaded from the following URL: www.ti.com/lit/zip/SLAA710.

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1 Introduction

The PGA411-Q1 device includes AFE diagnostics to cover possible resolver-sensor failures or fault conditions. The major categories of fault conditions are resolver-coil mutual shorts, short to ground, short to battery, or open-coil conditions. Table 1 lists the diagnostics that are used for each condition:

Table 1. Diagnostic Coverage for Resolver Sensor Faults

Fault Condition	Fault Flag	Programmable Thresholds	Deglitch Timer
Resolver secondary coil open	FOSINOPH, FOSINOPL, FOCOSOPH, or FOCOSOPL	OOPENTHH and OOPENTHL	TOPEN
Resolver secondary coil mutual short	FOSHORT	OSHORTH and OSHORTL	TSHORT
Resolver secondary coil short to battery	FIZH1, FIZH2, FIZH3, FIZH4	OVIZH	IZTHL
Resolver secondary coil short to ground	FIZL1, FIZL2, FIZL3, FIZL4	OVIZL	IZTHL

The AFE diagnostics monitor the input and the output of the AFE for an out-of-range signal. Section 2 describes the various diagnostics, Appendix A provides the design equations used to select the AFE components and fault diagnostic thresholds, and Section 3 lists a design example.

Figure 1 shows the recommended AFE circuit for the PGA411-Q1 device. This circuit is similar to the AFE configuration used on the PGA411-Q1 EVM.
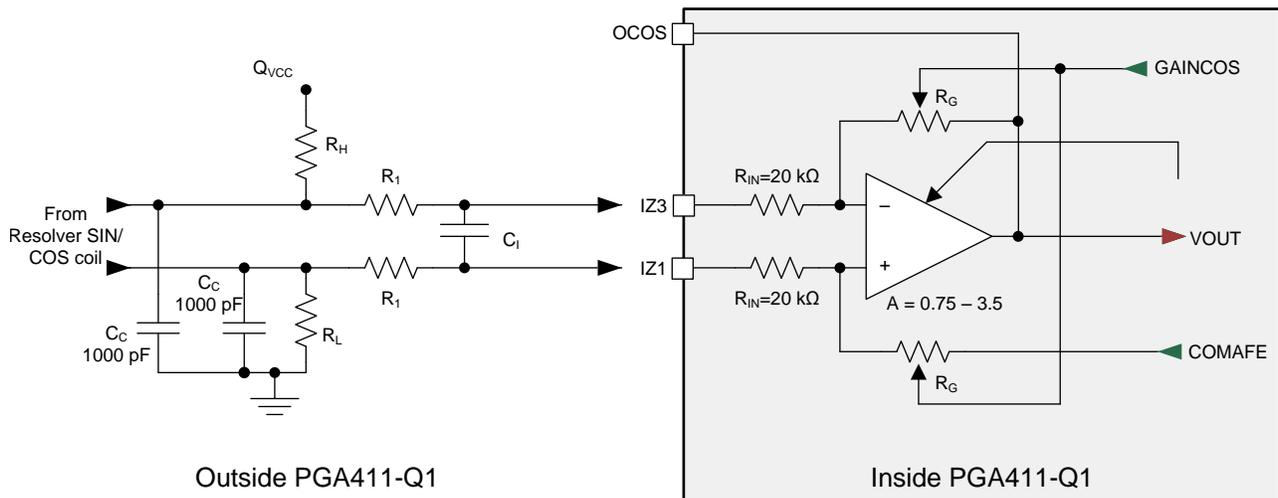

Figure 1. Recommended AFE Circuit of PGA411-Q1

2 AFE Diagnostics

2.1 Input Mutual Short Diagnostic

A mutually shorted secondary coil or an open primary coil on a resolver sensor both result in no signal being available at the input to the AFE. No signal at the input to the AFE means that the AFE input-pin voltages (IZx pins) will be within range, but the output of the AFE amplifier will be flat. The FOSHORT bit is flagged if the OSIN/OCOS outputs stay within the defined region set by the OSHORTH and OSHORTL thresholds for a time longer than the programmable deglitch time (TSHORT). Figure 2 shows the range of the programmable thresholds for OSHORTH and OSHORTL.
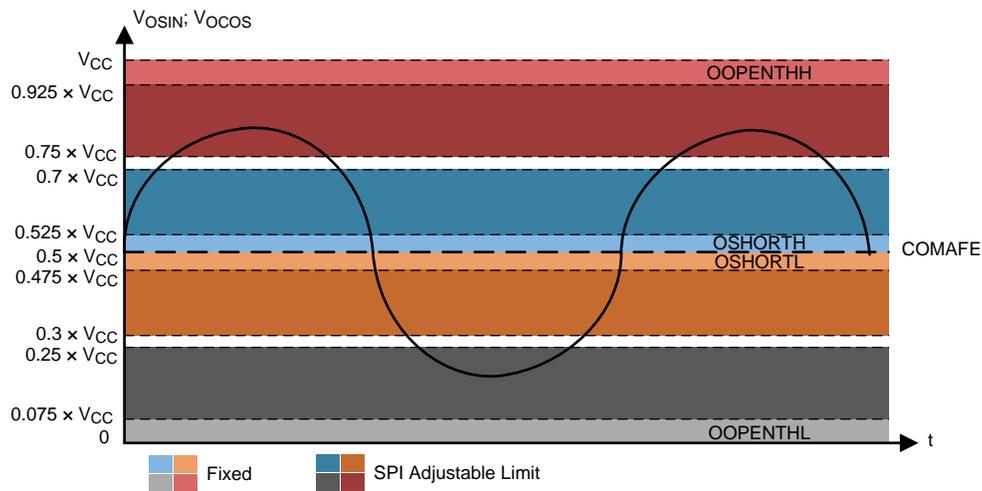
Figure 2. Programmable Threshold Levels for OSHORTH and OSHORTL

Either the sine or cosine outputs can be zero during the normal rotation of the resolver sensor at 0, 90, 180, and 270 degrees. During these regions, the input mutual short fault should not be flagged. See Figure 3 for an example of normal operating conditions.

The resolver is turned around the circle and faults are continuously monitored (example positions).

0 Degrees	45 Degrees	65 Degrees	90 Degrees

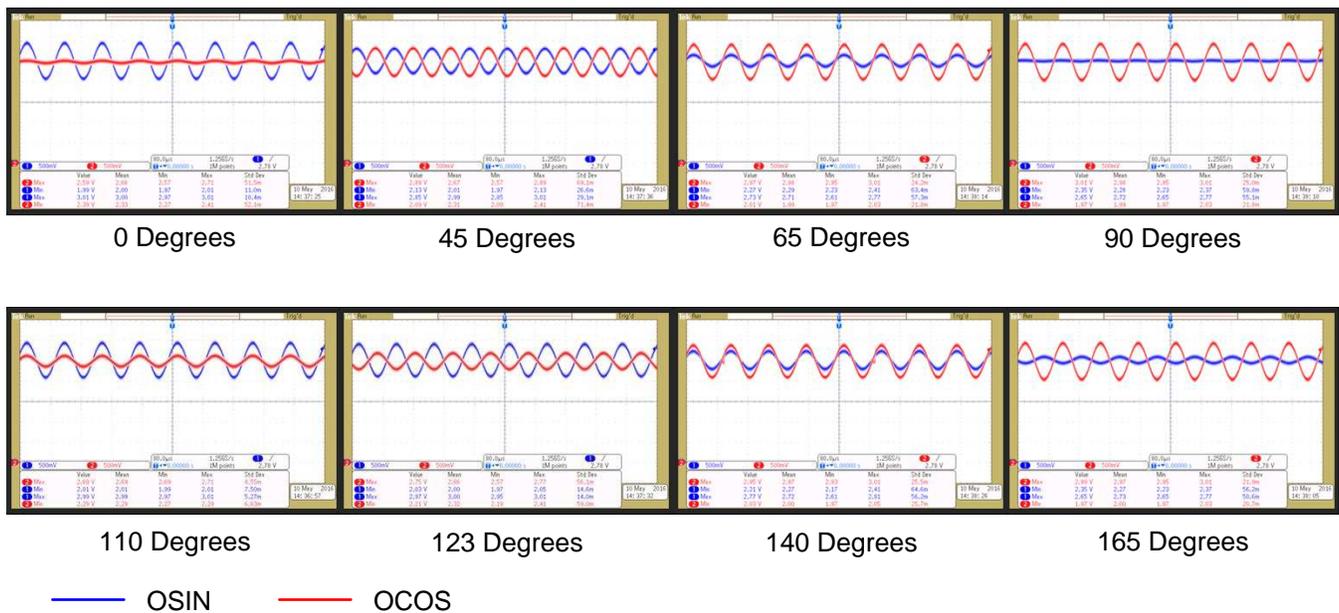| 110 Degrees	123 Degrees	140 Degrees	165 Degrees

—— OSIN   —— OCOS

Figure 3. Fault Threshold Levels

The FSHORT_CFG bit is configured when the FOSHORT fault is set as follows:
*   0: AND of sin, cos short fault condition sets FOSHORT
*   1: OR of sin, cos short fault condition sets FOSHORT

2.1.1 FSHORT_CFG Configured to 0 (AND)

Figure 4 shows the effect of the AND configuration. Both the OSIN and OCOS outputs must be below the OSHORTx thresholds to flag the FOSHORT fault. Therefore, if only one of the secondary coils is shorted, up to 180 degrees of revolution might have to occur for both OSIN and OCOS to be low at the same time. The deglitch time must be set so that even during maximum velocity, the OSIN or OCOS output would stay below the diagnostic threshold long enough to trigger the fault.

Figure 4. AND Configuration

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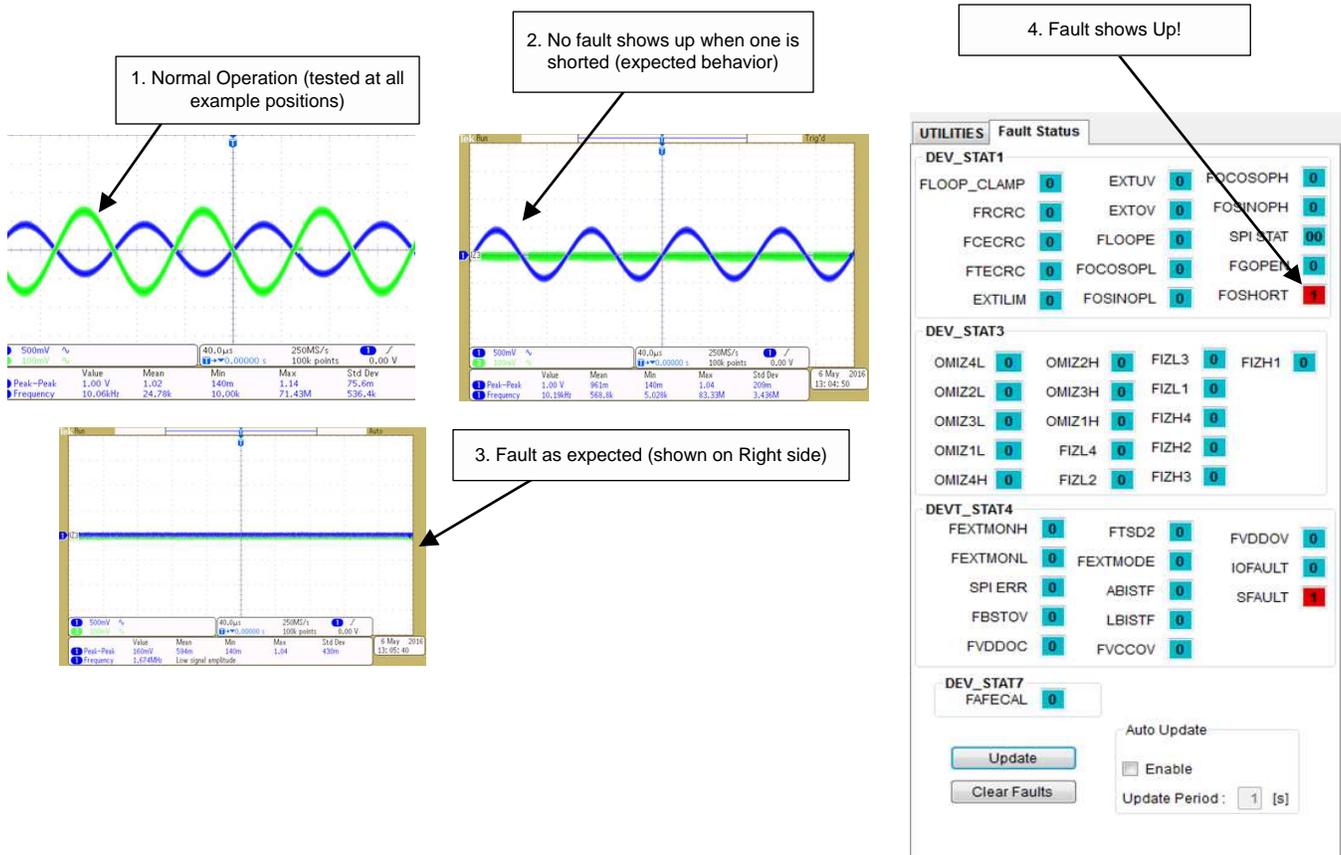
2.1.2   FSHORT_CFG Configured to 1 (OR)

If there is a minimum speed, then it can be deduced that the OSIN or OCOS signal will never stay low for long. The deglitch timing of this fault can then be adjusted so that the fault is flagged if OSIN or OCOS is shorted.
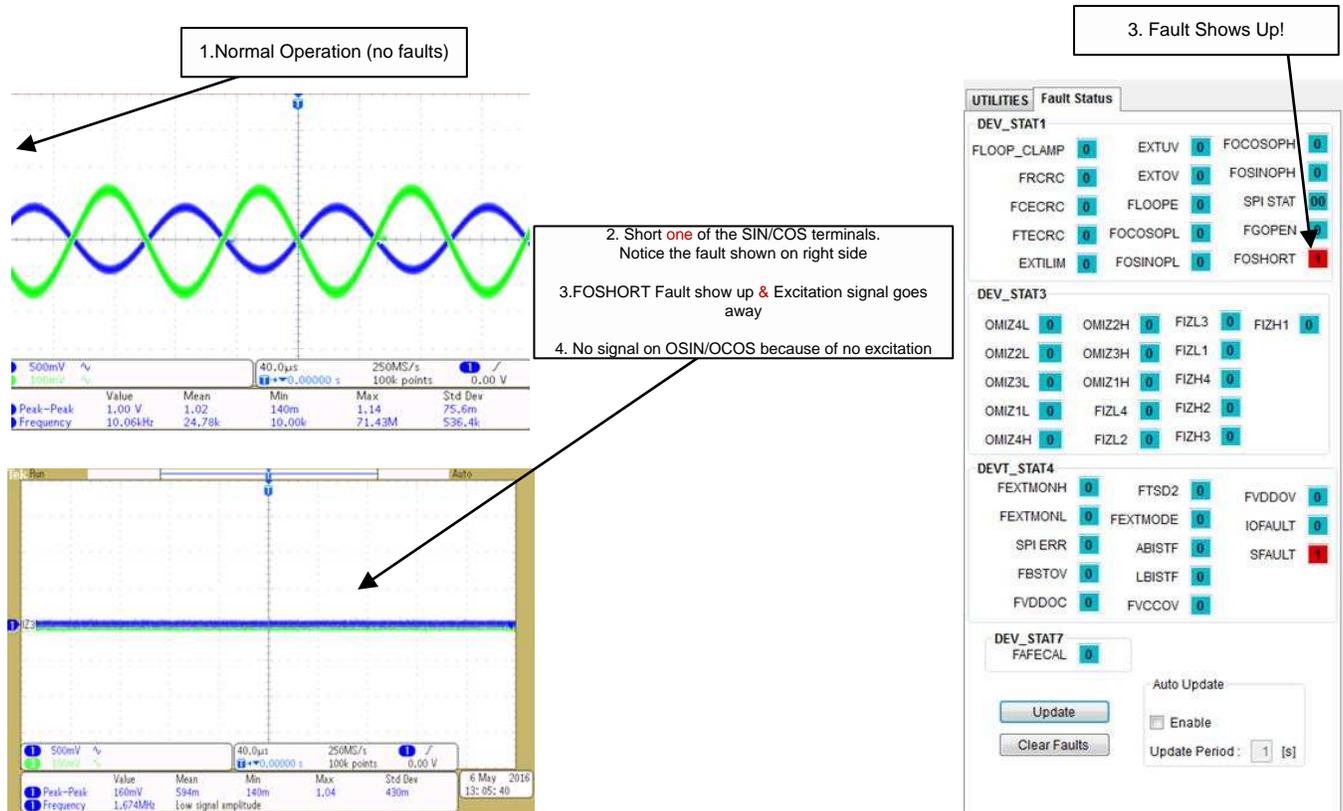

Figure 5. FSHORT_CFG Configuration

2.2 *Input Open-Coil Diagnostic*

If one of the secondary coils on the resolver sensor is disconnected, then no signal passes through to the AFE. For this case, pullup and pulldown resistors must be added to the circuit to pull the AFE inputs apart enough so that the OCOS or OSIN output is pulled out of range. When OCOS or OSIN crosses the programmed threshold (OOPENTHH or OOPENTHL) for longer than the deglitch time (TOPEN), then a fault flag is thrown (FOSINOPH, FOSINOPL, FOCOSOPH, or FOCOSOPL).

Figure 6. Fault Diagnostics Threshold Levels
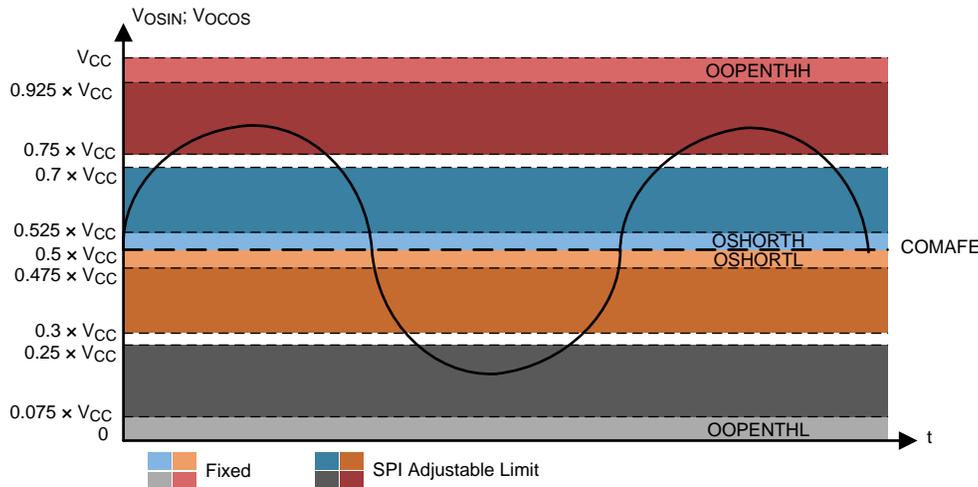
Figure 7 and Figure 8 show the OSIN and OCOS signals during normal operation, and then during an open fault condition where they are pulled out of range for longer than the deglitch time.
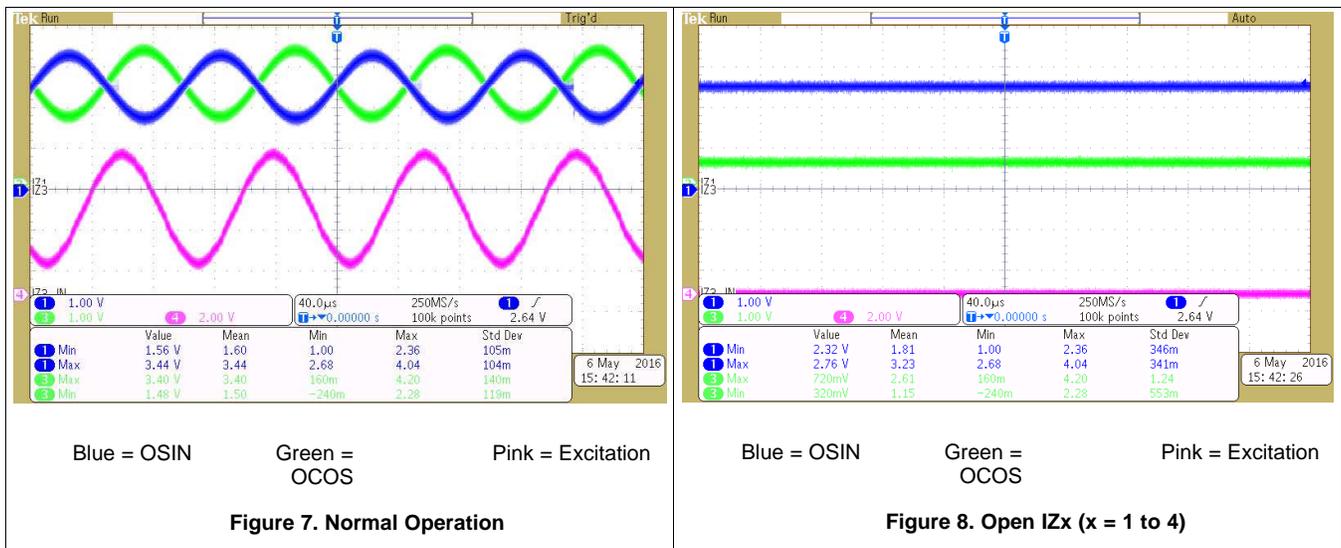

Blue = OSIN   Green = OCOS   Pink = Excitation

Figure 7. Normal Operation

Blue = OSIN   Green = OCOS   Pink = Excitation

Figure 8. Open IZx (x = 1 to 4)

2.3 Short to Ground or Battery

When one of the secondary resolver coils is shorted to ground or battery, the voltage at the AFE input pins (IZx pins) is pulled out of range. When the voltage at the IZx pins exceeds the range defined by the OVIZH and OVIZL thresholds for at least the deglitch time (IZTHL bits), the FIZHx or FIZLx fault is flagged.
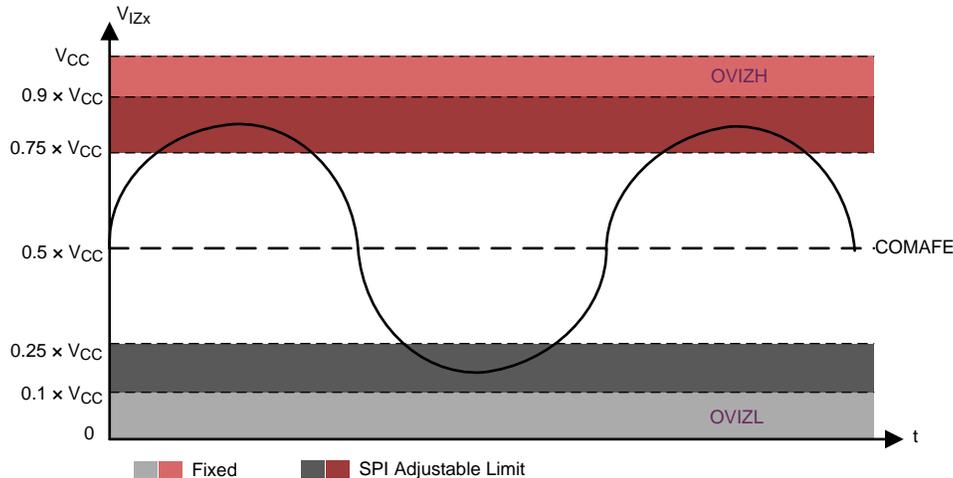

Figure 9. Programmable Threshold Levels for OVIZH and OVIZL

Normally, the common mode voltage will shift, but the full signal across the resolver coil will still be sensed. In Figure 10, which shows a short to 5-V condition, a short occurs on one side of a secondary coil even though the OCOS output does not change. The DC-bias point at the AFE input pins shifts up, pushing the IZx voltage across the diagnostic threshold. The deglitch timing for this diagnostic is shorter than the other fault conditions so that the change in DC-bias voltage can be detected.
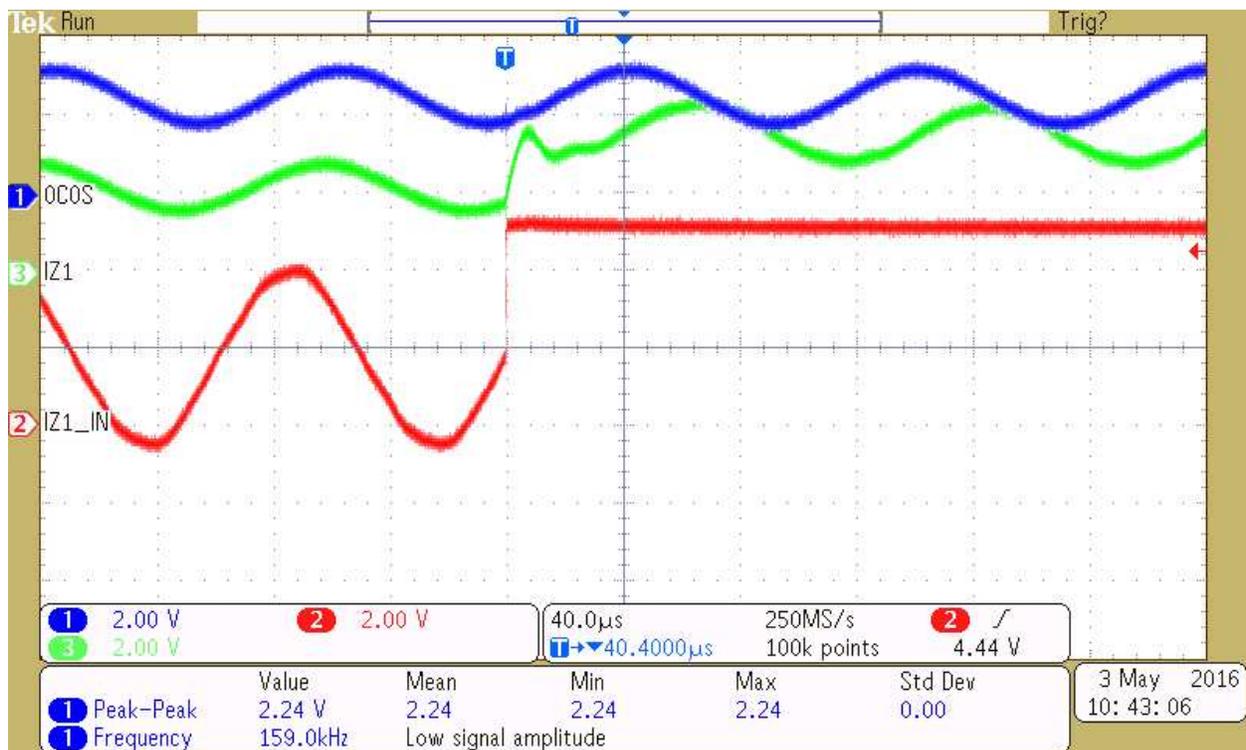

Figure 10. Short to 5 V on Resolver Cosine Coil

2.4 *Special Case: Large Voltage Across Secondary Coils of Resolver Sensor*

The AFE design depends on the maximum signal on the secondary side of the SIN and COS coils of the resolver sensor. In the case where the maximum peak-to-peak signal across the secondary coil is greater than about 3.3 V_{PP}, the short-to-ground condition of the resolver coil will become more difficult to detect.

Normally, the DC bias at the IZx pins during the short condition is assumed to be below the short-to-ground threshold. With a larger input voltage, keeping the DC bias below the threshold becomes difficult while maintaining all of the other system requirements when considering component tolerances.

The carrier signal still causes the signal to go out of range, but up to 90 degrees of revolution might have to occur before the fault is caught. This delay should not be an issue because a usable angle is still output from the PGA411-Q1 device during this type of fault condition.
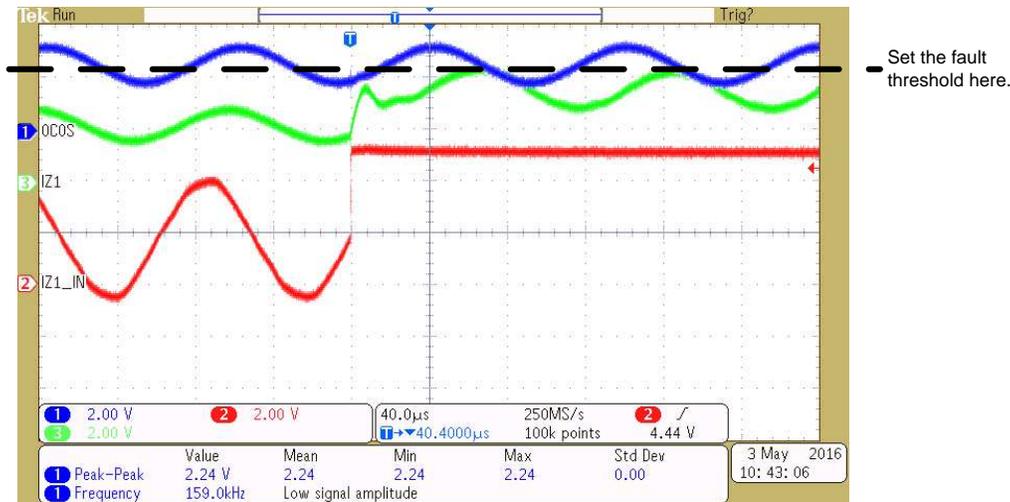

Figure 11. Short to 5 V on Resolver Cosine Coil with Example Threshold

3 Design Example

The PGA411-Q1 AFE calculator provides a convenient method for checking the AFE components and diagnostic-threshold register settings. The calculator includes component and PGA411-Q1 diagnostic tolerances to examine the worst case scenario for each fault case. The nominal equations that describe the AFE behavior are examined in Appendix A, and the AFE equations considering component tolerances are explained in Appendix B.

For most applications, the AFE component and threshold settings in Table 2 allow for correct fault diagnostics during fault conditions.

Table 2. Recommended Threshold Settings

Mode	Gain Setting	External Resistors		Diagnostic Thresholds			
	R_G	R1	RH/RL	OVIZH	OVIZL	OOPENTHH	OOPENTHL
4-V_{RMS} Mode	20 kΩ	8.5 kΩ	25 kΩ	90%	15%	75%	25%
7-V_{RMS} Mode	20 kΩ	20 kΩ	15 kΩ	90%	15%	75%	25%

3.1 *Using the Excel Calculator*

The PGA411-Q1 AFE Excel calculator is available to calculate the effects of the AFE components on the input signal and the interaction between the various fault conditions and the threshold settings. To use the calculator, follow these steps which correspond to the numbers in Figure 12:

1. Modify the input fields. These fields include the PGA411-Q1 exciter amplifier output amplitude, resolver-sensor transformation ratio, and supply voltages. The AFE resistors must also be chosen here. In addition, tolerances expressed in percentages must be entered which affects the worst-case

condition for each fault condition.

2. Modify the diagnostic threshold settings. The fields highlighted in yellow can be changed by selecting an option from the drop down list.

3. Examine the outputs. The typical and worst case value is calculated for normal operation and for each fault case. The diagnostic levels are checked against the typical and worst case values. The cells will be highlighted in red in two cases: if a diagnostic would not be flagged when it should be, or if a diagnostic could be flagged incorrectly.

4. Examine the visual representation. This shows the typical V_{PP} values of the IZx and OSIN/OCOS pins.
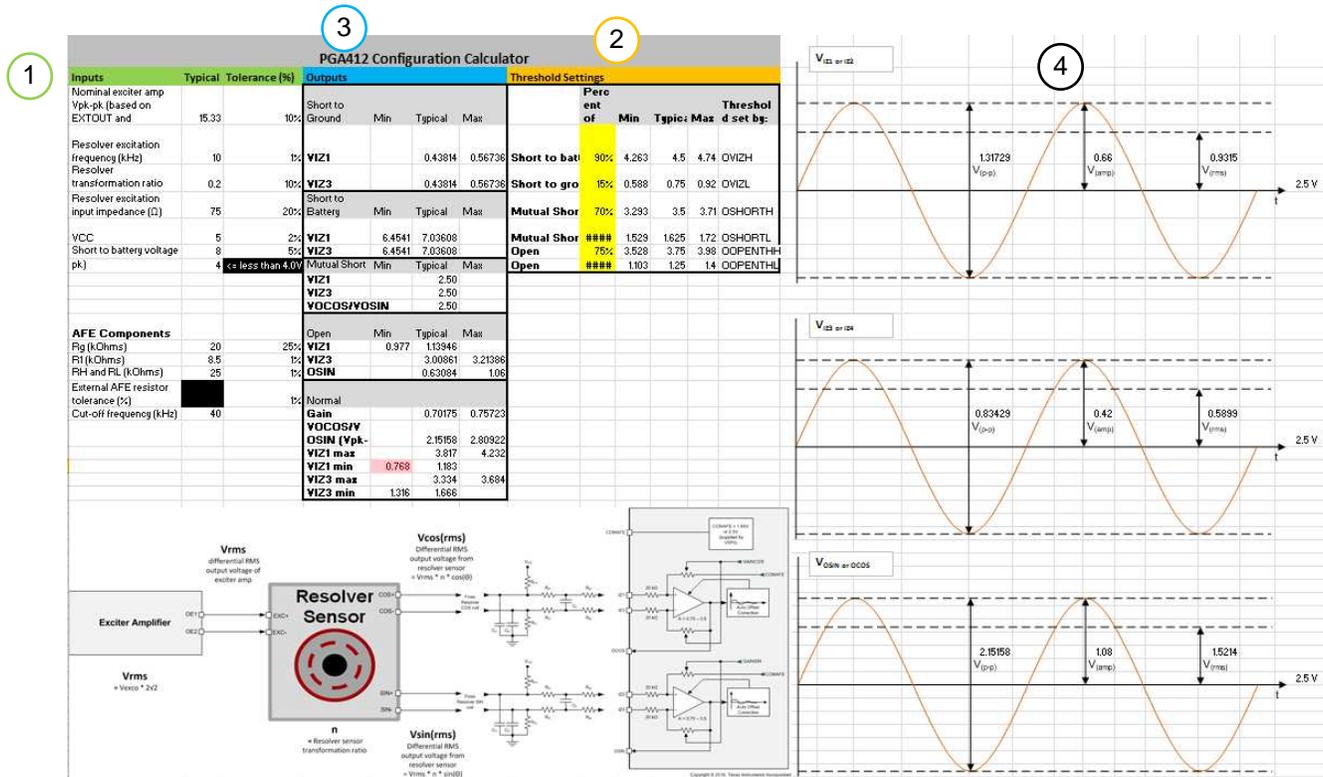

Figure 12. PGA411-Q1 AFE Calculator

The AFE calculator can be used to find solutions for specific use cases. Follow this procedure to find the solutions:

1. Identify the maximum gain of the AFE. This gain will be based on the maximum peak-to-peak input voltage at the sine and cosine coils, which will be related to the maximum excitation signal with the maximum resolver transformation ratio.

2. Select the maximum R_H that will still satisfy the system requirements.

    This step ensures that offset error is kept to a minimum.

3. Start with the lowest R_G setting (15 kΩ) and search for a value for R1 that will satisfy requirements.

4. Modify the diagnostic thresholds as necessary to find a solution while searching through R1 values.

5. With a larger peak-to-peak voltage on the resolver sensor sine or cosine coils, the short-to-ground condition might have to depend on the carrier signal at the IZx pins to trigger the fault. In this case, use the VIZ1 maximum and VIZ3 maxium values to determine if the fault will be triggered.

Nominal Design Equations

This section contains the design equations to describe the behavior of the AFE under various fault conditions. These equations should be used to decide on the diagnostic thresholds.

A.1 Design Procedure

The sine and cosine signal paths should be designed in the same way, therefore, for ease of explanation, only the cosine signal path is discussed. Use the steps that follow:

1. Select the gain of the overall AFE.

   The maximum input at the resolver SIN or COS coil must be scaled down to the input range of the IZx pins and the output range of the OSIN and OCOS signals. The maximum output value for OSIN/OCOS is 3 V_{PP}.

2. Next, the AFE must be designed so that faults only occur when they are supposed to. Four possible faults must be considered on the AFE which can all be detected and identified by the PGA411-Q1 diagnostics if the external AFE circuit and internal fault thresholds are set appropriately. These faults are listed as follows:

   1. Resolver sensor open circuit

   2. Resolver sensor mutual short

   3. Resolver sensor shorted to battery

   4. Resolver sensor shorted to ground

A.1.1 Normal Operation

Normal operation should achieve the maximum signal-to-noise ratio without triggering any faults. The differential voltage between IZ1 and IZ3 must be less than 3 V_{PP}. The output of the amplifier should always be less than 4 V_{PP}. This signal is observable on the OCOS pin.

Table 3. Important Device Specifications for Normal Operation

Parameter		Test Conditions	Minimum	Typical	Maximum	Unit
V_{IZx}	Differential IZx input voltage range (pk-pk)	S_{GAIN} = 0.75; C_{GAIN} = 0.75 COMAFE=2.5 V			3	V
$V_{OS}(V_{OC})$	Output voltage range	OSIN pin; OCOS pin; I_{OUT} = 10 µA	0.5		4.5	V

Using the signal from the resolver cosine coil, use Equation 1 to calculate the gain.

$$Gain = \frac{R_G}{R_{IN} + R1}$$

where

- R_{IN} is the internal input impedance, fixed at 20 kΩ
- R_G is the internal feedback resistor, four programmable values of 15 kΩ, 20 kΩ, 30 kΩ, or 70 kΩ
- R1 is the external resistance, used to attenuate the signal further if necessary   (1)

For normal operation, use the equations that follow:

$$V_O = \frac{(R1 + R_{IN}) \times V_{COM} - R_G \times V_{AC}}{R1 + R_{IN}}$$

(2)

$$V_{IZ1} = V_{COM} + V_{AC}\left(\frac{(R_{IN} + R_G) \times (R_G + R_H)}{2 \times (R1 + R_{IN}) \times (R1 + R_{IN} + R_G + R_H)} \right)$$

(3)

$$V_{IZ3} = V_{COM} + V_{AC}\left(\frac{R_G \times (R_G + R_H) - R_{IN} \times (R_H + 2 \times R1 + 2 \times R_{IN} + R_G)}{2 \times (R1 + R_{IN}) \times (R1 + R_{IN} + R_G + R_H)} \right)$$

(4)

A.1.2   Short-to-Ground DC Equations

A short to ground on one of the resolver coils causes a DC shift in the AFE signals. With one side of a coil shorted, the full differential signal still occurs across the IZx pins; however, the controller should be warned that an error occurred in the system.

In systems that require attenuation between the resolver coils and the IZx pins, the IZx pins will not be pulled completely to ground. To ensure that a fault is triggered during this condition, the bias point of the IZx pins must be pulled below the short-to-ground threshold set by the OVIZL bits.

The following equations show the new DC-bias points during a short-to-ground condition. The series impedance of the resolver coil is relatively low, so these equations assume that a short on either terminal of a resolver coil results in pulling both DC-bias points of the terminal to ground.

$$V_O = V_{COM}$$

(5)

$$V1 = V3 = \frac{V_{COMAFE} \times R1}{R1 + R_G + R_{IN}}$$

(6)

A.1.3   Short-to-Battery DC Equations

A short-to-battery condition works the same way as a short to ground. The output of the AFE amplifier still outputs the correct value, but the DC-bias points of the IZx pins are shifted. To ensure that a fault is triggered during this condition, the bias point of the IZx pins must be pulled above the short-to-battery threshold set by the OVIZH bits.

The following equations show the new DC bias points during a short-to-power condition. The series impedance of the resolver coil is relatively low, so these equations assume that a short on either terminal of a resolver coil results in pulling both DC-bias points of the terminals to battery.

$$V_O = V_{COM}$$

(7)

$$V1 = V2 = V_{COM} + \frac{(R_{IN} + R_G) \times (V_{CC} - V_{COM})}{R1 + R_G + R_{IN}}$$

(8)

A.1.4 Open Equations

If a terminal of a resolver coil is disconnected, then each node floats to a bias point with no AC signal on top of it. Pullup and pulldown resistors are typically added to the external AFE circuit to ensure that the IZx inputs are pulled apart, causing the AFE amplifier output to be pulled outside of the normal range.

The amplifier output must be pulled to outside of the range of the thresholds programmed in the OOPENTHH and OOPENTHL bits to set the open input diagnostic flag. The IZx bias points must be set so that they do not cross above or below the short-to-ground or short-to-battery thresholds.

$$V_O = V_C - \frac{R_G \times V_{CC}}{R1 + R_H + R_{IN}}$$

(9)

$$V1 = V_C \times \frac{R1 + R_H}{R1 + R_G + R_H + R_{IN}}$$

(10)

$$V3 = \frac{R_{IN} \times V_{CC}}{R1 + R_H + R_{IN}} + \frac{V_C \times (R1 + R_H)}{R1 + R_G + R_H + R_{IN}}$$

(11)

Design Equations With Tolerances

Each of the design equations previously discussed do not include component tolerances, which makes the balancing of the various requirements more difficult. This section explains how to consider component tolerances to ensure robust diagnostic performance during AFE fault events.

B.1 Gain

The PGA411-Q1 specification shows that the internal gain (set by R_G and R_{IN}) will vary less than ±2%.

Table 4. SIN and COS Input Gain Amplifier (IZ1, IZ3), (IZ2, IZ4), (OSIN, OCOS)

Parameter		Test Conditions	Minimum	Typical	Maximum	Unit
$S_{GAIN}(C_{GAIN})$	SIN and COS amplifier gain	COMAFE = 2.5 V; GAINCOS = GAINSIN = 0x00	0.735	0.75	0.765	V/V
		COMAFE = 2.5 V; GAINCOS = GAINSIN = 0x01	0.98	1	1.02	
		COMAFE = 2.5 V; GAINCOS = GAINSIN = 0x02	2.205	2.25	2.295	
		COMAFE = 2.5 V; GAINCOS = GAINSIN = 0x03	3.43	3.5	3.57	

$$G_{internal} = \frac{R_G}{R_{IN}}$$

(12)

However, the input impedance (R_{IN}) can vary ±25%.

Table 5. IZx Input Resistence

Parameter		Test Conditions	Minimum	Typical	Maximum	Unit
R_{IZx}	IZx input resistance (internal)		15	20	25	kΩ

This variance means that the R_G and R_{IN} resistors can each vary ±25%; however, the matching between them will always be within ±2%. If more attenuation is needed, then an external resistor must be used, and this resistor will not be matched with the internal resistors.

For this analysis, only the maximum gain must be considered because the AFE amplifier differential output must stay below a certain level. Because the internal resistors are matched, they will drift together and stay within at least 2% of each other. To keep the analysis clear when considering equations with tolerances, the following table shows the notation used for R_G and R_{IN}.

Table 6. Notation of Tolerances of R_G and R_{IN}

	Notation			
	Max-Max	Max-Min	Min-Max	Min-Min
Effect on R_G and R_{IN}	1.25 × nominal	1.23 × nominal	0.77 × nominal	0.75 × nominal

$$G_{Max} = \frac{R_{G(Max\text{-}Max)}}{R_{IN(Max\text{-}Min)} + R1_{Min}}$$

(13)

$$G_{Max} = \frac{1.25 \times R_G}{1.23 \times R_{IN} + R1_{Min}}$$

(14)

The voltages at the IZx pins must also stay within a range so that they do not trip the short to battery or short to ground fault. The maximum and minimum of both IZx pins must be considered.

$$V_{IZ1(Max)} = V_{COM(Max)} + V_{AC(Max)} \times \left(\frac{\left(R_{IN(Max-Min)} + R_{G(Max-Max)}\right) \times \left(R_{G(Max-Max)} + R_{H(Max)}\right)}{\left(R1_{(Min)} + R_{IN(Max-Min)}\right) \times \left(R1_{(Min)} + R_{IN(Max-Min)} + R_{G(Max-Max)} + R_{H(Max)}\right)} \right)$$
(15)

$$V_{IZ1(Min)} = V_{COM(Min)} - V_{AC(Max)} \times \left(\frac{\left(R_{IN(Max-Min)} + R_{G(Max-Max)}\right) \times \left(R_{G(Max-Max)} + R_{H(Max)}\right)}{\left(R1_{(Min)} + R_{IN(Max-Min)}\right) \times \left(R1_{(Min)} + R_{IN(Max-Min)} + R_{G(Max-Max)} + R_{H(Max)}\right)} \right)$$
(16)

$$V_{IZ3(Max)} = V_{COM(Max)} + V_{AC(Max)} \times \left(\frac{R_{G(Max-Min)} \times \left(R_{G(Max-Min)} + R_{H(Min)}\right) - R_{IN(Max-Max)} \times \left(R_{H(Min)} + 2 \times R1_{(Min)} + 2 \times R_{IN(Max-Max)} + R_{G(Max-Min)}\right)}{\left(R1_{(Min)} + R_{IN(Max-Max)}\right) \times \left(R1_{(Min)} + R_{IN(Max-Max)} + R_{G(Max-Min)} + R_{H(Min)}\right)} \right)$$
(17)

$$V_{IZ3(Min)} = V_{COM(Min)} - V_{AC(Max)} \times \left(\frac{R_{G(Max-Min)} \times \left(R_{G(Max-Min)} + R_{H(Min)}\right) - R_{IN(Max-Max)} \times \left(R_{H(Min)} + 2 \times R1_{(Min)} + 2 \times R_{IN(Max-Max)} + R_{G(Max-Min)}\right)}{\left(R1_{(Min)} + R_{IN(Max-Max)}\right) \times \left(R1_{(Min)} + R_{IN(Max-Max)} + R_{G(Max-Min)} + R_{H(Min)}\right)} \right)$$
(18)

$$V_{AC} = \frac{\left(V_{PP(ExciterOutput)} \times T_{transformationRatio}\right)}{2}$$
(19)

B.2   *Short-to-Ground DC Equations*

When considering the worst case short to ground, the voltage at the IZx pins must be below the short-to-ground threshold, so the maximum voltage at the IZx pins must be considered.

$$V_{IZ1(Max)} = V_{IZ3(Max)} = \left(\frac{V_{COM(Max)} \times R1_{(Max)}}{R1_{(Max)} + R_{IN(Min-Max)} + R_{G(Min-Min)}} \right)$$
(20)

$$V_{IZ1(Max)} = V_{IZ3(Max)} = \left(\frac{2.625 \text{ V} \times R1_{(Max)}}{R1_{(Max)} + 0.75 + R_{IN} + 0.75 + R_{G}} \right)$$
(21)

B.3   *Short-to-Battery DC Equations*

When considering the worst case short to battery, the voltage at the IZx pins must be above the short-to-ground threshold, so the minimum voltage at the IZx pins must be considered.

$$V_{IZ1(Min)} = V_{IZ3(Min)} = V_{COM(min)} + \left(\frac{\left(R_{IN(Min-Min)} + R_{G(Min-Min)}\right) \times \left(V_{SHORT(Min)} - V_{COM(Min)}\right)}{R1_{(Max)} + R_{G(Min-Min)} + R_{IN(Min-Min)}} \right)$$
(22)

$$V_{IZ1(Min)} = V_{IZ3(Min)} = 2.375 \text{ V} + \left(\frac{\left(0.75 \times R_{IN} + 0.75 \times R_{G}\right) \times \left(V_{SHORT(Min)} - 2.375 \text{ V}\right)}{R1_{(Max)} + 0.75 \times R_{G} + 0.75 \times R_{IN}} \right)$$
(23)

B.4   Open Equations

The recommended external-AFE circuit pulls the IZx pins when the resolver coil is disconnected so that the AFE amplifier output voltage is pulled low. The V_O voltage must be pulled below the OOPENTHL threshold, so for worst case, the maximum V_O must be considered. At the same time, VIZ1 and VIZ3 must not exceed the short-to-battery or short-to-ground thresholds. The IZ1 pin is pulled low and the IZ3 pin is pulled high during an open fault, so the minimum IZ1 voltage and the maximum IZ3 voltage must be considered for the worst case analysis.

$$V_{O(Max)} = V_{COM(Max)} - \left(\frac{R_{G(Min-Min)} \times V_{CC(Min)}}{R1_{(Max)} + R_{H(Max)} + R_{IN(Min-Max)}} \right) \tag{24}$$

$$V_{O(Max)} = 2.625\ V - \left(\frac{0.75 \times R_G \times V_{CC(Min)}}{R1_{(Max)} + R_{H(Max)} + 0.77 \times R_{IN}} \right) \tag{25}$$

$$V_{IZ1(Min)} = V_{COM(Min)} \times \left(\frac{R1_{(Min)} + R_{H(Min)}}{R1_{(Min)} + R_{G(Max-Max)} + R_{H(Min)} + R_{IN(Max-Max)}} \right) \tag{26}$$

$$V_{IZ1(Min)} = 2.375\ V \times \left(\frac{R1_{(Min)} + R_{H(Min)}}{R1_{(Min)} + 1.25 \times R_G + R_{H(Min)} + 1.25 \times R_{IN}} \right) \tag{27}$$

$$V_{IZ3(Max)} = \frac{R_{IN(Max-Max)} \times V_{CC(Max)}}{R1_{(Min)} + R_{H(Min)} + R_{IN(Max-Max)}} + \frac{V_{COM(Max)} \times \left(R1_{(Min)} + R_{H(Min)} \right)}{R1_{(Min)} + R_{G(Max-Min)} + R_{H(Min)} + R_{IN(Max-Max)}} \tag{28}$$

$$V_{IZ3(Max)} = \frac{1.25 \times R_{IN} \times V_{CC(Max)}}{R1_{(Min)} + R_{H(Min)} + 1.25 \times R_{IN}} + \frac{V_{COM(Max)} \times \left(R1_{(Min)} + R_{H(Min)} \right)}{R1_{(Min)} + 1.23 \times R_G + R_{H(Min)} + 1.25 \times R_{IN}} \tag{29}$$