Application Note

End of Line Calibration Using the TMCS2100-Q1 Current Sensor for Three-Phase Systems

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ABSTRACT

The TMCS2100-Q1 is an ambient magnetic field sensor that measures the combined magnetic field from currents in three-phase systems. Devices are pre-programmed by the user with values tuned to a specific bus bar geometry during characterization. Manufacturing tolerances in the final assembly can shift the sensor position relative to the bus bars, introducing amplitude errors in the sensor output that can be addressed on the manufacturing line. This application note describes end-of-line (EOL) calibration procedures for measuring the per-unit error in a manufacturing flow, as well as how to correct these per-unit errors by adjusting the Gain 2 and frequency compensation register values.

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1 Introduction

The TMCS2100-Q1 is an ambient magnetic field sensor designed for isolated bus bar current measurement. In a three-phase automotive inverter, one sensor pair is mounted near each phase bus bar. Because the sensor is sensitive to all ambient magnetic fields — not just the field from the target bus bar — each sensor also picks up a fraction of the field produced by the two neighboring bus bars. This neighboring bus bar contribution is called crosstalk.

Before the inverter reaches end-of-line (EOL) test, each TMCS2100-Q1 device has already been programmed with characterized gain values (Gain 1, Gain 2, and polarity register values) derived from a reference mechanical assembly. These values are tuned to the intended bus bar geometry to minimize crosstalk, phase, and amplitude errors over frequency. However, manufacturing tolerances, including small variations in sensor placement, bus bar position, and sensor gain, cause the actual magnetic coupling to differ slightly from the characterized reference unit. The result is an amplitude error: the sensor output during three-phase operation can be slightly higher or lower than preferred.

EOL calibration measures this error on each unit and corrects the error by trimming the device Gain 2 registers. The goal is to minimize the amplitude error of the combined-field output (the signal seen by the sensor when all three phases carry current) rather than the single bus bar response. This reflects the true operating condition of the system, including any crosstalk still present in the signal chain.

This document does not address the subject of DC offset calibration. DC calibration cannot be addressed at a sensor level but must be addressed through system design or digital calibration.

2 Error Measurement

2.1 Overview

Three different approaches are presented here for measuring the complete sensor error that can be expected in the application (Figure 2-1). The first method, described in the Balanced Three-Phase Calibration section, tests the sensor under the normal operating conditions directly by replicating the input current waveform and calculating the error to a reference. The second method, found in the Crosstalk Matrix Calibration section, calculates the combined signal that is seen in operation by linearly combining the component signals using a crosstalk matrix. The third method, outlined in the Paired-Phase Injection Calibration section, calculates the combined signal by measuring a current signal flowing down one leg of the three-phase system and returning on another; based on these measurements the combined signal can be calculated. A summary comparison of all three methods is found in the Method Comparison section.

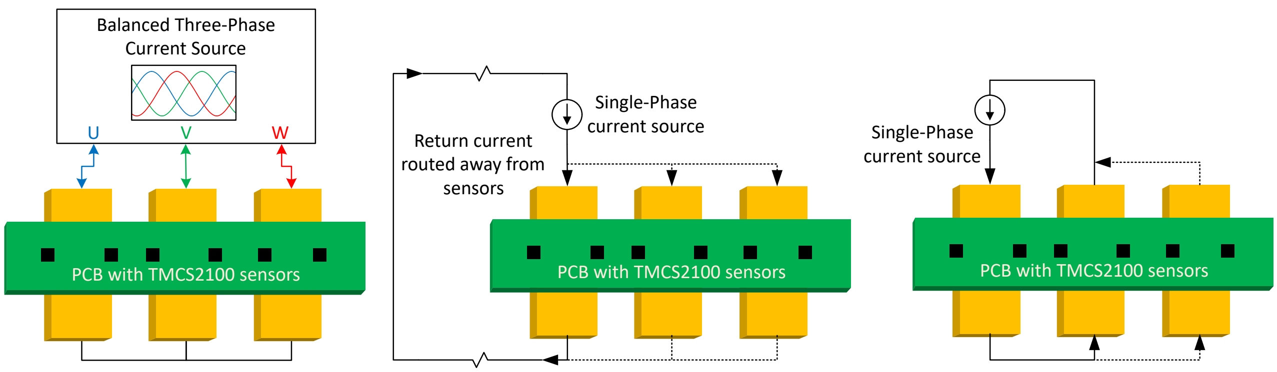


Figure 2-1. Overview of Different Error Measurement Methods

2.1.1 Measurement Accuracy

The accuracy of the measurements used during calibration limits the accuracy of the calibration, so proper measurement techniques must be used during the measurement of both the input current and device outputs. A full discussion of measurement accuracy is beyond the scope of this document, but a selection of relevant best practices are presented here.

2.1.1.1 Offset Cancellation

Sensor offset must be canceled in the measurement to make sure that the gain calibration is not inadvertently correcting offset errors, causing higher gain error. Offset can be canceled digitally by measuring the offset and saving the value to later subtract from the measured calibration value. Alternatively, measurements can be made in a way that inherently rejects offset, such as measuring the peak-to-peak signal or applying a Fourier transform and inspecting the magnitude of the input signal frequency.

2.1.1.2 Signal Magnitude

To present a large enough signal to the TMCS2100-Q1 to overcome noise and residual offset effects, TI recommends using a calibration signal that is at least 10% of the full-scale range (FSR) of the output of the device. Larger currents give more accuracy. In addition, designs that use a low full-scale range in operation can need to provide larger currents to improve SNR.

2.2 Balanced Three-Phase Calibration

This method applies balanced (zero-sum) three-phase sinusoidal currents to the bus bar system under test and directly measures the TMCS2100-Q1 amplitude error under that condition (Figure 2-2). Because the sensor experiences exactly the intended operating environment during measurement, the result directly represents the error to be corrected. This approach is practical for production stations where a three-phase current source is available, and test time must be minimized.

The frequency compensation in the TMCS2100-Q1 works to make the amplitude response flat over frequency, so the frequency of the input current can theoretically be any frequency in the operating range without affecting the effectiveness of the calibration. However, since mechanical variations can have a second-order effect on the amplitude over frequency, TI recommends to measure the error in the center of the operating range.

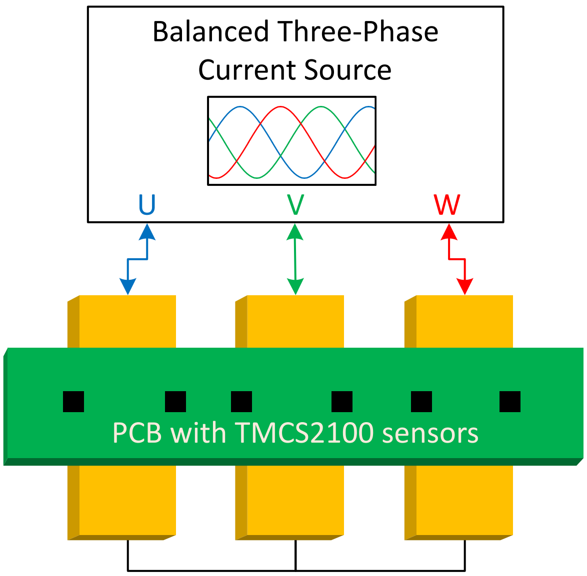


Figure 2-2. Balanced Three-Phase Current Connection Diagram

2.2.1 Equipment Requirements

Note

If the inverter drive hardware is available and controllable at EOL, the inverter can serve as the three-phase current source, eliminating the need for external excitation equipment.

Item	Requirement
Three-phase current source	Balanced sinusoidal output when connected to appropriate load
Balanced load	Three-phase resistive or RL load matched to source power inputs; alternatively synchronized electronic loads
Reference current sensors	One per phase; accuracy ≤ 0.1 %
TMCS2100-Q1 programming interface	I^2C access to all TMCS2100-Q1 devices

2.2.2 Test Configuration

1. Connect the three-phase source to the inverter bus bar system through the balanced load.
2. Place one reference current sensor measuring each phase conductor, clear of the TMCS2100-Q1 sensors.
3. Connect the TMCS2100-Q1 programming interface and program the initial register values to all sensors, including any frequency compensation values.
4. Set source parameters:

Parameter	Value
Phase	Current phase angles must match the end application phase angles using the same phase commutation order
Frequency	Center of nominal operating range
Amplitude	Minimum of 10% of FSR

2.2.3 Calibration Procedure

1. Acquire amplitude data: With balanced three-phase excitation active at the nominal test current, capture simultaneous data from the TMCS2100-Q1 differential outputs and the reference current sensors.

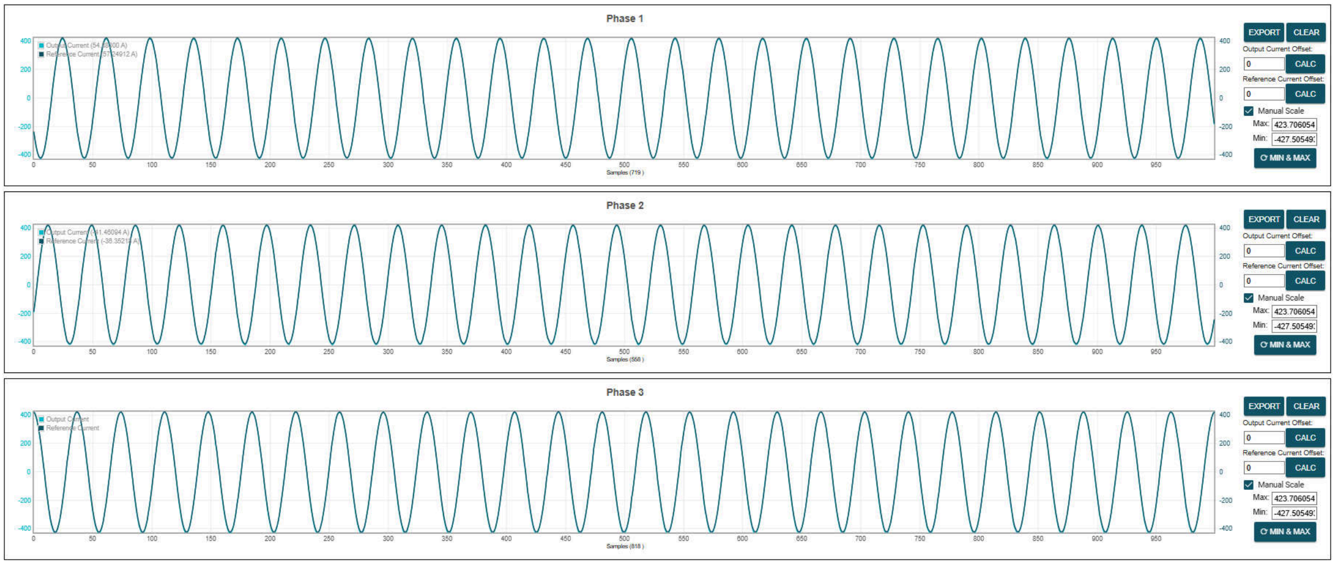


Figure 2-3. Three-Phase Data Capture Using TMCS2100 Characterization Board GUI

2. Calculate expected output and calculate the amplitude error:

$$V_{expected} = I_{ref} \times S_{ideal} \tag{1}$$

Where S_{Ideal} is the characterized or nominal sensitivity (V/A) established during characterization.

$$\text{Error}(\%) = \frac{V_{measured} - V_{expected}}{V_{expected}} \times 100 \tag{2}$$

A positive value indicates sensitivity higher than nominal; negative indicates sensitivity is lower than nominal.

3. Apply gain correction:
   a. Calculate C_{new} for the primary and secondary sensors using Section 3.1.
   b. Calculate updated frequency compensation codes for both sensors using Section 3.3.
   c. Program the TMCS2100-Q1 sensors with the new device values.

2.3 Crosstalk Matrix Calibration

This method characterizes each bus bar individually by energizing one phase at a time and measuring all three TMCS2100-Q1 sensor responses (\). The nine measured sensitivities form a *crosstalk matrix* from which the amplitude error under balanced three-phase operation is calculated mathematically, without ever applying all three phases simultaneously. This approach is practical for production stations where only a single-phase DC current source is available, and also yields detailed per-phase diagnostic information that applying a simultaneous three-phase signal does not. Additionally, the crosstalk matrix produced by this method can be used in application firmware to remove residual crosstalk at run time, providing higher accuracy than Gain 2 calibration alone (see Section 2.3.5).

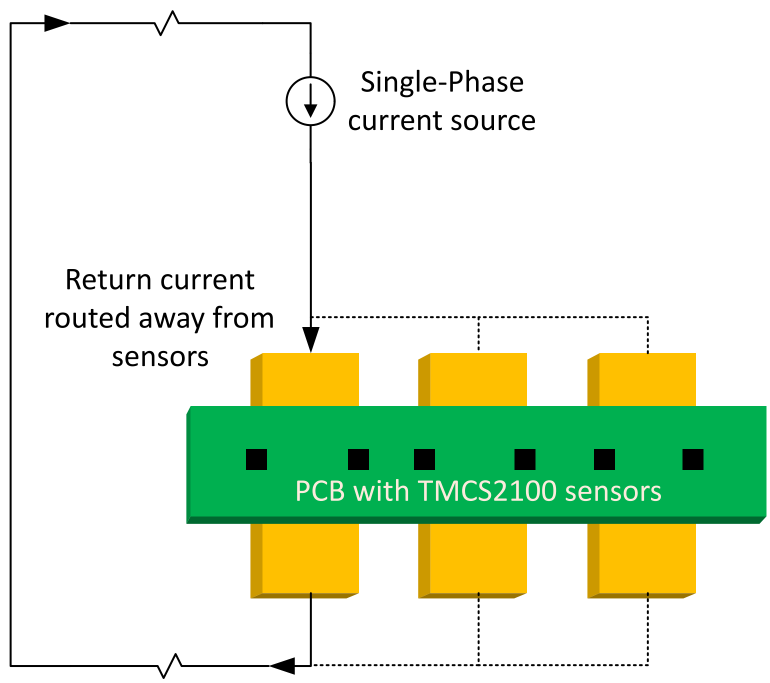


Figure 2-4. Single-Phase Connection Diagram for Extracting Crosstalk Matrix

2.3.1 Theoretical Foundation

This section establishes the mathematical relationship between the single-phase sensitivity measurements and the combined-field amplitude error, forming the basis for error calculations.

2.3.1.1 Crosstalk Model

Each sensor output is a linear superposition of the three phase fields:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_{AA} & S_{AB} & S_{AC} \\ S_{BA} & S_{BB} & S_{BC} \\ S_{CA} & S_{CB} & S_{CC} \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad (3)$$

Each matrix element S_{XY} is the measured sensitivity in V/A, defined as:

$$S_{XY} = \frac{V_X}{I_Y} \quad (4)$$

That is, the ratio of sensor X output to the current in bus bar Y when only bus bar Y carries current. The diagonal elements S_{AA}, S_{BB}, and S_{CC} are the direct sensitivities; off-diagonal elements represent crosstalk sensitivities. Off-diagonal elements can be positive or negative depending on geometry.

2.3.1.2 Matrix Population by Single-Phase Excitation

Energizing one bus bar at a time and measuring all three sensor responses yields one column of [*S*] per test:

Table 2-1.

Energized phase	Measurements	Sensitivities determined
A only	V_A, V_B, V_C at current I_A	$S_{AA} = V_A/I_A$ $S_{BA} = V_B/I_A$ $S_{CA} = V_C/I_A$

Table 2-1. (continued)

Energized phase	Measurements	Sensitivities determined
B only	V_A, V_B, V_C at current I_B	$S_{AB} = V_A / I_B$ $S_{BB} = V_B / I_B$ $S_{CB} = V_C / I_B$
C only	V_A, V_B, V_C at current I_C	$S_{AC} = V_A / I_C$ $S_{BC} = V_B / I_C$ $S_{CC} = V_C / I_C$

2.3.1.3 Combined-Field Amplitude Under Balanced Operation

For balanced three-phase currents with amplitude I_0, the combined-field sensitivity at each sensor is calculated from the measured component sensitivities as follows.

Phase A:

$$S_{Total,A} = \frac{|V_A|}{I_0} = \sqrt{\left(S_{AA} - \frac{1}{2}S_{AB} - \frac{1}{2}S_{AC}\right)^2 + \frac{3}{4}\left(S_{AB} - S_{AC}\right)^2} \quad (5)$$

Phase B:

$$S_{Total,B} = \frac{|V_B|}{I_0} = \sqrt{\left(S_{BB} - \frac{1}{2}S_{BA} - \frac{1}{2}S_{BC}\right)^2 + \frac{3}{4}\left(S_{BA} - S_{BC}\right)^2} \quad (6)$$

Phase C:

$$S_{Total,C} = \frac{|V_C|}{I_0} = \sqrt{\left(S_{CC} - \frac{1}{2}S_{CA} - \frac{1}{2}S_{CB}\right)^2 + \frac{3}{4}\left(S_{CA} - S_{CB}\right)^2} \quad (7)$$

Note

Derivation note: These expressions result from phasor addition of the three sinusoidal components.

The amplitude error for phase X is:

$$Error_X(\%) = \frac{S_{Total,X} - S_{ideal,X}}{S_{ideal,X}} \times 100 \quad (8)$$

Where $S_{ideal,X}$ (in V/A) is the ideal sensitivity for phase X.

2.3.2 Equipment Requirements

Item	Requirement
Single-phase current source	Adjustable AC or DC current source capable of producing current at least 10% of the FSR
Phase-switching fixture	Relay matrix or manual patch panel to route current to each bus bar in sequence; non-energized phases must be open during each test
Reference current sensor	One sensor used in series with the source; measurement accuracy ≤ 0.1 %
TMCS2100-Q1 programming interface	I²C access to all TMCS2100-Q1 devices

2.3.3 Calibration Procedure

1. Energize Phase A: measure matrix column 1
   a. Route test current through Phase A bus bar. Phases B and C must be open with no current.
   b. Simultaneously acquire all three TMCS2100-Q1 differential outputs: V_A, V_B, and V_C.
   c. Record the reference current: I_A.
   d. Calculate the different device sensitivities: $S_{AA} = V_A / I_A$, $S_{BA} = V_B / I_A$, $S_{CA} = V_C / I_A$
2. Repeat step one for phases B and C.

3. Calculate combined-field amplitude errors: apply the formulas from Section 2.3.1.3 to compute the S_{Total} values and compare S_{Total} to S_{Ideal} for each phase.
4. Apply gain correction
   a. Calculate C_{new} for the primary and secondary sensors using Section 3.1.
   b. Calculate updated frequency compensation codes for both sensors using Section 3.3.
   c. Program the TMCS2100-Q1 sensors with the new device values

2.3.4 Worked Example

Setup: Test current I_{test} = 50A; characterized sensitivity S_{Ideal} = 0.0500V/A for all phases.

Measured matrix elements (each $S_{XY} = V_X / I_Y$, in V/A):

Table 2-2.

	Bus bar A current	Bus bar B current	Bus bar C current
Sensor A	$S_{AA} = 0.0490$	$S_{AB} = 0.0024$	$S_{AC} = -0.0036$
Sensor B	$S_{BA} = 0.0030$	$S_{BB} = 0.0504$	$S_{BC} = 0.0040$
Sensor C	$S_{CA} = -0.0040$	$S_{CB} = 0.0036$	$S_{CC} = 0.0496$

Phase A combined-field gain:

$$|V_A|/I_0 = \sqrt{(0.0490 - 0.0012 + 0.0018)^2 + 0.75 \times (0.0024 + 0.0036)^2} = \sqrt{(0.0496)^2 + 0.75 \times (0.0060)^2} = \sqrt{0.002460 + 0.000027} = 0.04987\text{V/A} \quad (9)$$

Phase A error:

$$\text{Error}_A = \frac{0.04987 - 0.0500}{0.0500} \times 100 = -0.26\% \quad (10)$$

The same calculation applied to Phases B and C use the respective diagonal and off-diagonal elements from [*S*]. Once errors are determined for all three phases, the Gain 2 correction formula from Section 3.1 is applied to the primary and secondary sensors of each sensor, and the matrix measurement is optionally repeated to verify the result.

2.3.5 Runtime Crosstalk Cancellation

Because the crosstalk matrix calibration method characterizes the coupling between each bus bar and the sensors on each bus bar, the crosstalk matrix [*S*] can be used to implement software-based crosstalk compensation at run time, providing higher accuracy at the cost of processing time.

Section 2.3.1.1 gives:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = [S] \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad (11)$$

Inverting this relationship recovers the true phase currents from the sensor outputs:

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = [S]^{-1} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (12)$$

Where $[S]^{-1}$ is the matrix inverse of the measured crosstalk matrix. Given simultaneous measurements from all three sensor outputs, this operation yields the three phase currents with crosstalk mitigated.

2.3.5.1 Implementation

1. Adjust [*S*] for the calibrated values: After EOL calibration is complete, the sensor sensitivities in [*S*] must be adjusted to match the new calibrated sensor sensitivities. For each row of [*S*], the sensor sensitivities must be reduced by the amount of error measured for the corresponding bus bar.
2. Precompute $[S]^{-1}$: After adjusting [*S*] for the calibrated values, compute the matrix inverse of [*S*] on the test station host. This is a one-time calculation per unit.
3. Store the nine coefficients: Program the elements of $[S]^{-1}$ into memory on the microcontroller. These are unit-specific crosstalk cancellation values.
4. Apply at runtime: For each measurement cycle, multiply the three sensor outputs by $[S]^{-1}$ to obtain compensated phase currents. This requires nine multiply-accumulate operations per cycle using all three sensor outputs.

2.4 Paired-Phase Injection Calibration

This method uses a more common line-to-line injection scheme (Figure 2-5). DC test current is driven down one phase bus bar and returned through a second, with the third bus bar left open. Repeating this across the phase pairs — each in both current directions for offset cancellation — provides enough information to compute the combined-field amplitude error under a nominal three-phase operation condition.

Like the method described in Section 2.3, this method calculates the balanced error analytically and requires only a single-phase DC source; unlike in Section 2.3, the current flows through the inverter without requiring an external return path. The tradeoff is that the individual crosstalk matrix elements cannot be recovered from paired-phase data, so runtime compensation like in Section 2.3.5 is not possible.

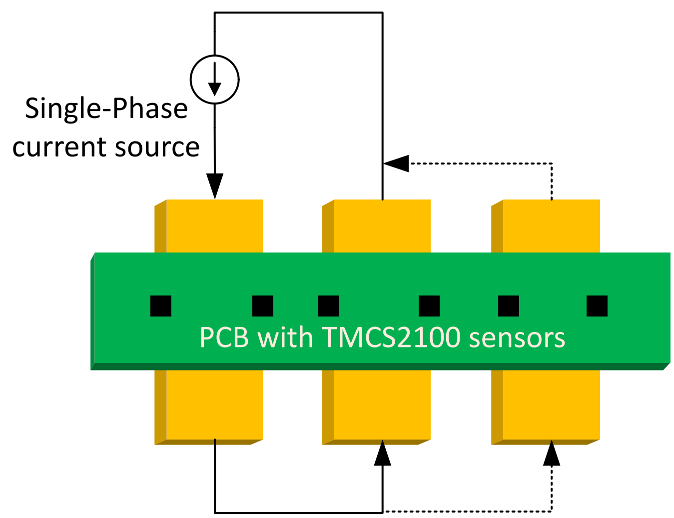


Figure 2-5. Paired-Phase Current Injection

2.4.1 Theoretical Foundation

Each line-to-line injection drives equal and opposite current *I* in two bus bars. Measuring the voltage produced by this signal can be represented by the following equation, using phases A and B as the example forward and return currents respectively:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_{AA} & S_{AB} & S_{AC} \\ S_{BA} & S_{BB} & S_{BC} \\ S_{CA} & S_{CB} & S_{CC} \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} S_{AA} & S_{AB} & S_{AC} \\ S_{BA} & S_{BB} & S_{BC} \\ S_{CA} & S_{CB} & S_{CC} \end{bmatrix} \begin{bmatrix} I \\ -I \\ 0 \end{bmatrix} = I \begin{bmatrix} S_{AA} - S_{AB} \\ S_{BA} - S_{BB} \\ S_{CA} - S_{CB} \end{bmatrix} \quad (13)$$

This allows us to calculate the sensitivity of each bus bar sensor to current flowing from one bus bar to another (denoted $s_{A,A\rightarrow B}$ for the sensitivity of bus bar A to current flowing from A to B):

$$\begin{bmatrix} s_{A,A\rightarrow B} \\ s_{B,A\rightarrow B} \\ s_{C,A\rightarrow B} \end{bmatrix} = \begin{bmatrix} V_{A,A\rightarrow B} \\ V_{B,A\rightarrow B} \\ V_{C,A\rightarrow B} \end{bmatrix} \div I_{A\rightarrow B} = \begin{bmatrix} S_{AA} - S_{AB} \\ S_{BA} - S_{BB} \\ S_{CA} - S_{CB} \end{bmatrix} \quad (14)$$

And equivalently for current flowing for the other two connections:

$$\begin{bmatrix} s_{A,A\rightarrow C} \\ s_{B,A\rightarrow C} \\ s_{C,A\rightarrow C} \end{bmatrix} = \begin{bmatrix} S_{AA} - S_{AC} \\ S_{BA} - S_{BC} \\ S_{CA} - S_{CC} \end{bmatrix} \quad (15)$$

$$\begin{bmatrix} s_{A,B\rightarrow C} \\ s_{B,B\rightarrow C} \\ s_{C,B\rightarrow C} \end{bmatrix} = \begin{bmatrix} S_{AB} - S_{AC} \\ S_{BB} - S_{BC} \\ S_{CB} - S_{CC} \end{bmatrix} \quad (16)$$

Now recall the equation from Section 2.3.1.3 for estimating the total sensitivity of a bus bar to a balanced three-phase current:

$$S_{Total,A} = \sqrt{\left(S_{AA} - \tfrac{1}{2}S_{AB} - \tfrac{1}{2}S_{AC}\right)^2 + \tfrac{3}{4}\left(S_{AB} - S_{AC}\right)^2} \quad (17)$$

Using the measured $s_{A,A\rightarrow B}$, $s_{A,A\rightarrow C}$, and $s_{A,B\rightarrow C}$, the equation can be rewritten as:

$$S_{Total,A} = \sqrt{\left(\frac{s_{A,A\rightarrow B} + s_{A,A\rightarrow C}}{2}\right)^2 + \tfrac{3}{4}\left(s_{A,B\rightarrow C}\right)^2} \quad (18)$$

Meaning that the total sensitivity of a sensor to a balanced three-phase signal can be calculated.

2.4.2 Equipment Requirements

Item	Requirement
Single-phase current source	DC source capable of at least 10% of the TMCS2100-Q1 full-scale
Line-to-line routing fixture	Means to connect the source across a selected pair of bus bars (current down one, return through the other) with the third bus bar open.
Reference current sensor	One sensor in series with the source; accuracy ≤ 0.1 %
TMCS2100-Q1 programming interface	I^2C access to all TMCS2100-Q1 devices

2.4.3 Calibration Procedure

Offset can be rejected by driving each pair in both current directions and subtracting the two measurements. Note that the same three current flow paths are read on *all three* sensor channels; each injection contributes one term to the error calculation of every sensor.

1. Route calibration current from phase A to phase B; read all sensors.
   a. Drive I_{test} down bus bar A and return through bus bar B, with bus bar C open.
   b. Simultaneously measure all three TMCS2100-Q1 differential outputs: $V_{A,A\rightarrow B}$, $V_{B,A\rightarrow B}$, $V_{C,A\rightarrow B}$, and the reference current $I_{A\rightarrow B}$.
   c. Reverse the polarity (I_{test} down B, return through A) and measure $V_{A,B\rightarrow A}$, $V_{B,B\rightarrow A}$, $V_{C,B\rightarrow A}$, and $I_{B\rightarrow A}$.
   d. For each sensor X, compute the offset-canceled response:

$$s_{X,A\rightarrow B} = \frac{V_{X,A\rightarrow B} - V_{X,B\rightarrow A}}{I_{A\rightarrow B} + I_{B\rightarrow A}} \quad (19)$$

2. Repeat step one for bus bar currents $I_{A\rightarrow C}$ and $I_{B\rightarrow C}$ until all sensitivity values $s_{X,X\rightarrow X}$ have been measured.

3. Consistency check (optional): Confirm $s_{X,A\rightarrow B} \cong s_{X,A\rightarrow C} - s_{X,B\rightarrow C}$ for each sensor. A large discrepancy indicates a measurement, routing, leakage, or linearity problem.
4. Calculate combined-field amplitude errors: For each phase, apply Equation 18 to obtain S_{Total} and compare to S_{Ideal} for that phase to obtain the error percentage using Equation 8.
5. Apply gain correction. For each phase:
   a. Calculate C_{new} for the primary and secondary sensors using Section 3.1.
   b. Calculate updated frequency compensation codes for both sensors using Section 3.3.
   c. Program the TMCS2100-Q1 sensors with the new device values

2.5 Method Comparison

The choice between methods depends primarily on the test equipment available at the EOL station. Table 2-3 summarizes the key differences.

Table 2-3. Comparison of Measurement Methods

Criterion	Balanced Three-Phase Calibration	Crosstalk Matrix Calibration	Paired-Phase Injection Calibration
Source equipment	Three-phase source required (recommended to use the inverter) load and source together must present balanced current signal	Single-phase AC/DC current source sufficient	Single-phase AC/DC current source sufficient
Reference measurements per unit	One per phase (3 total)	Only one reference measurement required if other phases are open	Only one reference measurement required if current does not flow through open phase
Error type	Direct measurement; immune to nonlinear behavior	Calculated from matrix; assumes linearity	Calculated from pair responses; assumes linearity
Runtime crosstalk compensation	Not available; individual coupling coefficients not measured	$[S]^{-1}$ can be computed and applied in firmware for full crosstalk removal (Section 2.3.5)	Not available; matrix cannot be isolated from paired data
Recommended when	Three-phase load/source available; throughput priority	Single-phase or DC load used; extremely low crosstalk required; or per-phase diagnostics needed	Single-phase station where single-bus bar isolation is not physically possible

3 Sensitivity Adjustment Procedure

The TMCS2100-Q1 sensitivity is controlled by four programmable register values: Gain 1, Gain 2, and the Polarity bits. During EOL calibration, only Gain 2 is adjusted; Gain 1 and the Polarity bits are not modified. Each phase uses a primary and secondary TMCS2100-Q1 sensor. During calibration, both devices must update the respective Gain 2 values. Applying the calibration to only one device distorts the sensor characterization, failing to properly calibrate the device.

8.2.2 MEM1 Register (Address = 0x11)

The Memory Register 1 is show below.

Table 8-12. MEM1 Register Field Descriptions

Bit	Field	Type	Description
15-14	$\overline{\text{OC}}$_CONFIG	R/W	Register used to select the sensor channel for comparison or to disable the comparator for Over Current Detection Overcurrent Detection Configuration. 00b = Enable Sensor 1 01b = Enable Sensor 2 10b = Disable Comparator and Output 11b = Disable Comparator and Output
13-0	GAIN2	R/W	Gain Value for Gain 2

Figure 3-1. Gain 2 Register Value From Datasheet

3.1 Formula

Once the amplitude error has been determined using one of the methods in Section 2, the new Gain 2 value is calculated as follows:

$$C_{new} = C_{original} + 0.01 \times \left(C_{original} - 18687.13\right) \times \text{Error} \tag{20}$$

Symbol	Definition
C_{new}	New Gain 2 value to program to the device (unsigned integer, rounded to nearest whole number)
$C_{original}$	Current Gain 2 code before this adjustment
Error	Signed amplitude error in percent (for example, −5 for sensitivity 5% lower than nominal, +3 for sensitivity 3% higher than nominal)

The value 18687.13 is a device constant related to the internal gain of the device.

3.2 Calculation Example

Given the pre-programmed characterization codes: Primary Gain 2 = 6062, Secondary Gain 2 = 3160.

Measured amplitude error: −0.895%

Primary sensor:

$$C_{new} = 6062 + 0.01 \times (6062 - 18687.13) \times (-0.895) = 6062 + 113 = 6175 \tag{21}$$

Secondary sensor:

$$C_{new} = 3160 + 0.01 \times (3160 - 18687.13) \times (-0.895) = 3160 + 139 = 3299 \tag{22}$$

Programming these two values corrects the 0.895% undershoot.

3.3 Frequency Compensation Values Adjustment

The TMCS2100-Q1 contains two frequency compensation values, *FREQ_SLP1* and *FREQ_SLP2*, that apply gain corrections at specific frequency points to flatten the frequency response of the sensor. The codes stored in these registers are delta code values (the second term from Equation 20) originally computed using the characterized Gain 2 code. Because the codes are expressed relative to that original Gain 2 value, the codes must be recomputed whenever Gain 2 is adjusted as a part of EOL calibration.

3.3.1 Step 1: Convert Frequency Compensation Codes to Error Percentages

For each frequency compensation register, recover the error percentage the register encodes using the pre-calibration Gain 2 code $C_{original}$:

$$\mathrm{Error}_{FS1} = \frac{\mathrm{FREQ\_SLP1}_{original}}{0.01 \times \left(C_{original} - 18687.13\right)} \tag{23}$$

For the error associated with *FREQ_SLP2*, the equation becomes:

$$\mathrm{Error}_{FS2} = \frac{\mathrm{FREQ\_SLP2}_{original}}{0.01 \times \left(C_{original} + \mathrm{FREQ\_SLP1}_{original} - 18687.13\right)} \tag{24}$$

3.3.2 Step 2: Compute New Frequency Compensation Codes

Substitute the new Gain 2 code C_{new} to obtain the updated frequency compensation codes:

$$\mathrm{FREQ\_SLP1}_{new} = 0.01 \times (C_{new} - 18687.13) \times \mathrm{Error}_{FS1} \tag{25}$$

$$\mathrm{FREQ\_SLP2}_{new} = 0.01 \times (C_{new} + \mathrm{FREQ\_SLP1}_{new} - 18687.13) \times \mathrm{Error}_{FS2} \tag{26}$$

Round $FREQ\_SLPx_{new}$ to the nearest integer before programming.

3.3.3 Calculation Example (Continued for Frequency Compensation)

Given that $C_{original}$ = 6062, C_{new} = 6175, $FREQ\_SLP1_{original}$ = -92, and $FREQSLP2_{original}$ = -374, begin by calculating the original error percentage used in frequency compensation:

$$\mathrm{Error}_{FS1} = \frac{-92}{0.01 \times (6062 - 18687.13)} = 0.729\% \tag{27}$$

$$\mathrm{Error}_{FS2} = \frac{-374}{0.01 \times (6062 - 92 - 18687.13)} = 2.94\% \tag{28}$$

Then use those percentages to calculate the new frequency compensation register values:

$$\mathrm{FREQ}_{\mathrm{SLP1}_{new}} = 0.01 \times (6175 - 18687.13) \times 0.729\% = -91 \tag{29}$$

$$\mathrm{FREQ}_{\mathrm{SLP2}_{new}} = 0.01 \times (6175 - 91 - 18687.13) \times 2.94 = -371 \tag{30}$$

The same calculations are repeated for the secondary sensor using the original register values.

3.4 GUI Calculator

These calculations are fully implemented in the TMCS2100 Characterization GUI, which can be used to measure error and perform example calculations. The error measurement uses the data capture from the TMCS2100 Characterization EVM and performs an FFT on the data to extract the amplitude and phase error at the dominant frequency:

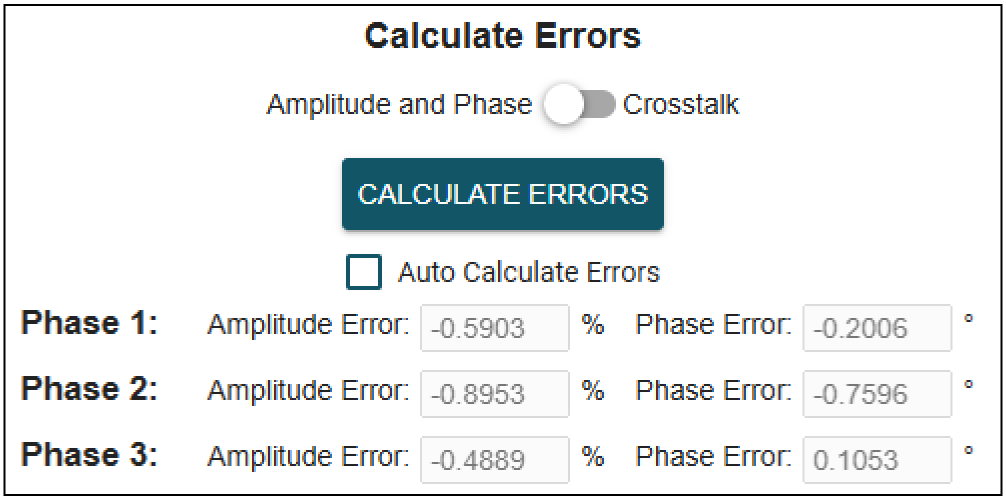


Figure 3-2. Example GUI Error Calculation

If the error has been measured externally, check the *manual amplitude errors* box to override the error values used for calibration:

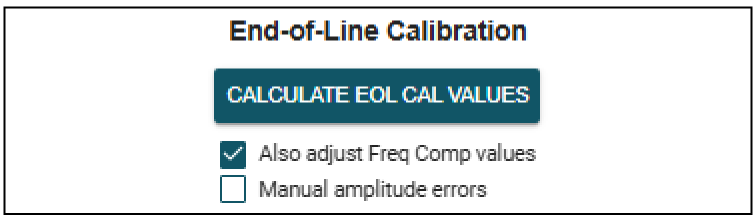
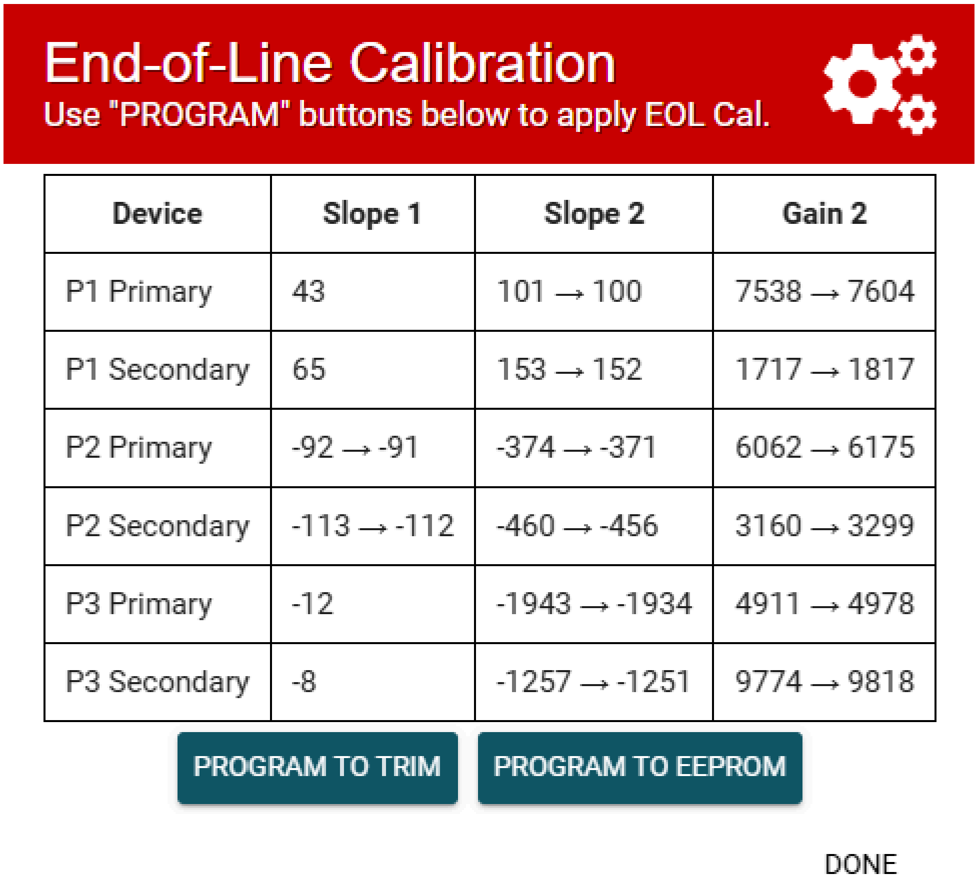


Figure 3-3. EOL Calibration Options

If the "Also adjust Freq Comp values" box is checked, the GUI also performs the required calculations to adjust the *FREQ_SLP* values:



Device	Slope 1	Slope 2	Gain 2
P1 Primary	43	101 → 100	7538 → 7604
P1 Secondary	65	153 → 152	1717 → 1817
P2 Primary	-92 → -91	-374 → -371	6062 → 6175
P2 Secondary	-113 → -112	-460 → -456	3160 → 3299
P3 Primary	-12	-1943 → -1934	4911 → 4978
P3 Secondary	-8	-1257 → -1251	9774 → 9818

Figure 3-4. GUI EOL Register Calculations

4 Troubleshooting

If crosstalk performance in a system deteriorates after applying EOL calibration, this indicates that the calibration values are not being applied correctly to both devices. Some possible causes include:

- The memory control bit has not been set before programming
- Memory register 0 is being overwritten
- One of the Gain 2 values is saturating the register field
- A communication or calculation error is corrupting the Gain 2 register codes

To correct this, fix any I2C communication errors. If the modified Gain 2 value is saturating, do not simply clamp the Gain 2 value. Instead, the Gain values for both TMCS2100-Q1 devices must be changed by the same amount. Using the equations in Section 3.1, calculate the maximum error correction possible in percent and apply this correction instead of the calculated correction. A Gain 2 value that is saturating or close to saturating indicates that the FSR used in characterization is too small. Generally, a Gain 2 value less than 16128 is recommended after characterization.

5 Summary

End of line calibration of the TMCS2100-Q1 magnetic current sensor is best achieved using the total signal that the sensor experiences during operation. This can be achieved in multiple ways, three of which are presented here. Directly measuring the magnetic field while the inverter is operating is the simplest option conceptually, but requires more measurement hardware and the ability to control a large current for measurement. Another method involves computing the total signal from individual signal components, measured individually by isolating the signals from each bus bar. Finally, the third method presented offers an alternate way of computing the combined signal with minimal equipment requirements. All methods arrive at the same result but have different requirements at the end of the line. The choice of method ultimately depends on what is feasible in production for a given manufacturing flow.

6 References

1. Texas Instruments, TMCS2100-Q1 Coreless Multi-Sensor Hall-Effect Current Sensor, datasheet.

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