TI Designs

High Accuracy AC Current Measurement Reference Design Using PCB Rogowski Coil Sensor

Design Overview

The TIDA-01063 is a reference design for current sensing using a PCB Rogowski coil sensor to achieve very good linearity for wide measurement range at a very low system BOM cost. The PCB Rogowski sensor is advantageous for isolated current measurement due to its very high bandwidth of 20 MHz and fast settling time of 50 ns. The auto-zeroing, 12-nV/√Hz noise density of the INA188 makes it suitable to achieve a 12-bit system resolution for a full-scale current of 1000 A. Using a simple IIR digital integration algorithm and scalable sampling rate, it is possible to achieve better magnitude and phase response.

Design Resources

TIDA-01063	Design Folder
INA188	Product Folder
LP5907	Product Folder
LM2776	Product Folder
REF2025	Product Folder

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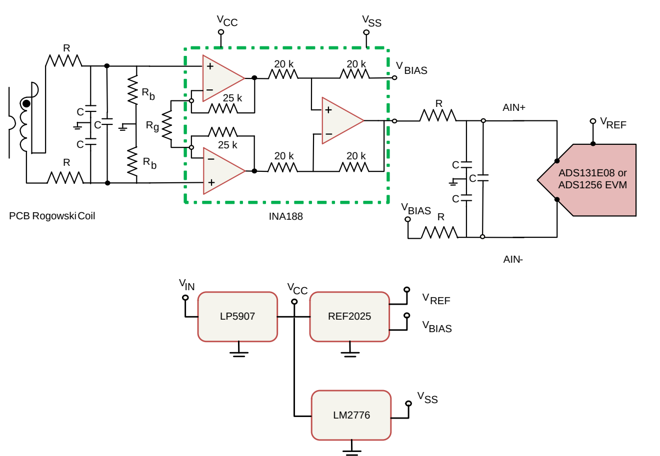
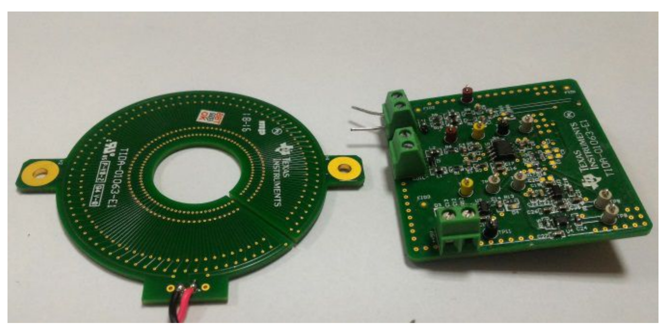
Design Features

- 0.058% Nonlinearity (Least Square Best Fit Straight Line)
- Very High Sensor Bandwidth of 20 MHz
- Uncalibrated Accuracy of 0.2%
- Theoretical Settling Time of 50 ns
- No Core Saturation
- Current Sensing for Multi-Conductor Using Single Sensor
- Low Footprint and BOM Cost

Featured Applications

- HVAC Systems: HVAC Motor Control
  - Compressor, Chiller, Blower
  - ID and FD Fan, Screw Feeder, Feed Pump, Steam Boiler
- Elevators and Escalators: Traction Inverter Motor Control





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1 Key System Specifications

Table 1. Key System Specifications

SYMBOL	PARAMETER	SPECIFICATION					DETAILS
		CONDITION	MIN	TYP	MAX	UNIT	
ELECTRICAL SPECIFICATION							
I_{IN}	Input primary current		(1) 1	—	100	A	—
f_{IN}	Input current frequency		(2) 45	50	60	Hz	—
I_Q	Quiescent current		—	—	5	mA	—
% E	Measured accuracy (RMS)	(Uncalibrated) Ambient temperature	–1	0.5	1	%	Section 4.2
Φ	Phase accuracy after integration	25°C	0.3	0.1	0.3	°	Section 4.3
V_{IN}	Input power supply (DC)		3.5	5	6.5	V	—
MECHANICAL SPECIFICATION							
ID	Inner diameter of coil		—	20	—	mm	Section 4.1.1
OD	Outer diameter of coil		—	60	—	mm	Section 4.1.1
a	Inner trace radius		—	12.5	—	mm	Section 4.1.2
b	Outer trace radius		—	27.7	—	mm	Section 4.1.2
θ	Angle between two trace		—	4.13	—	°	Section 4.1.2
N	No of turns		—	174	—		Section 4.1.2
ENVIRONMENTAL							
T	Operating temperature		–25	25	85	°C	—

(1) As per test equipment full scale current
(2) As per test equipment setting, sensor bandwidth up to 20 MHz

2 System Description

A three-phase AC induction motor drive system has a feedback sensor for current, speed, and rotation sensing, all integral parts for motor protection and motor drive systems.

For better system accuracy and stability, sensors need to be linear and highly accurate. Dynamic responses need to be fast enough to capture fault signals. Figure 1 shows a typical sensor interface for a motor starter or VFD drive system.

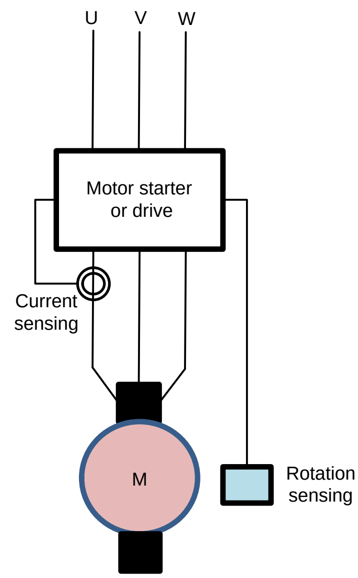

Figure 1. Typical Sensor Interface for Motor Drive System

Current sensing can be done using a simple resistor, current transformer, Hall-effect sensor, or Rogowski coil. For a wide range of dynamic current sensing for motor and short circuit detection, the current sensor needs to be linear with a wide bandwidth and fast response time.

The Rogowski coil is air core toroid, which measures EMF voltage generated by magnetic flux of a time-varying current signal. The air core offers very high linearity for a wide current range. The PCB Rogowski sensor can achieve very high signal bandwidth. A voltage isolation of 6 kV is possible using the Rogowski sensor.

The equivalent circuit per phase of a three-phase induction motor is as shown in Figure 2. There are two current components: I_1 is current due to magnetizing core, and I_2 is current due to mechanical load R on the rotor. The magnetizing current will be the no-load current upon which the minimum input resolution of the motor current can be computed.

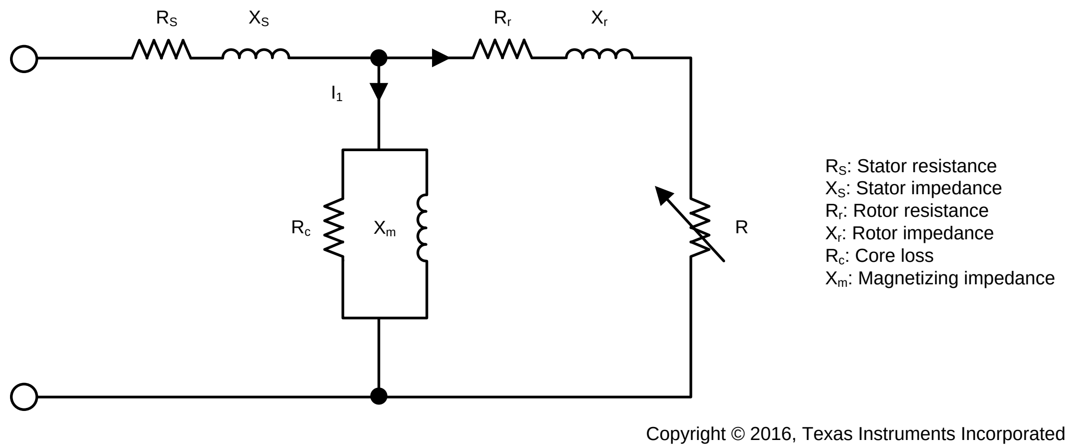

Figure 2. Equivalent Circuit of Per Phase of AC Motor

Due to the load change by load R, current amplitude I_2 will increase. In case of a short circuit fault in the rotor, the current is limited only by stator resistance, and current rise time is the ratio of stator inductance and stator resistance. Current flowing due to short circuit decides the maximum current measurement. For predicting motor failures, current amplitude, harmonics, phase angle, and motor waveform signatures must be known. Figure 3 shows that motor currents are typically 7 times the full-load current during stall mode.

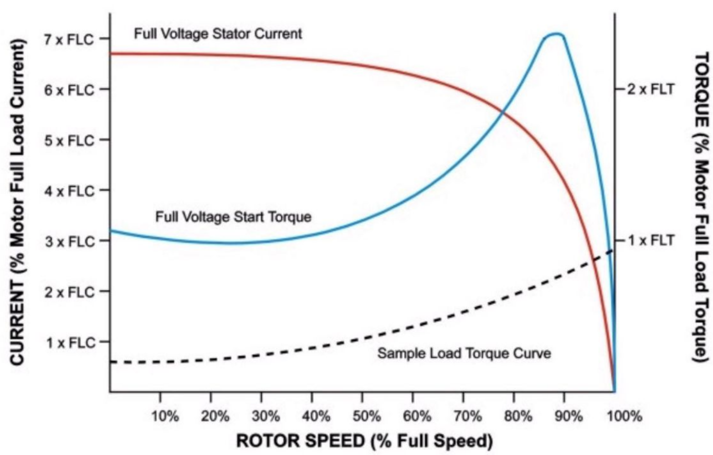

Figure 3. Typical Induction Motor Characteristic

3 Block Diagram

The TIDA-01063 design focuses on the design of the PCB Rogowski sensor and front-end design using a precision instrumentation amplifier and delta-sigma ADC.

For highly accurate measurements, the front-end amplifier needs to have a very low offset, excellent linearity, and low-noise density over the bandwidth of measurement. For high accuracy measurements of the Rogowski coil output, the INA188 is used as the first stage amplification. See Figure 4 for an overview of the complete front-end interface.

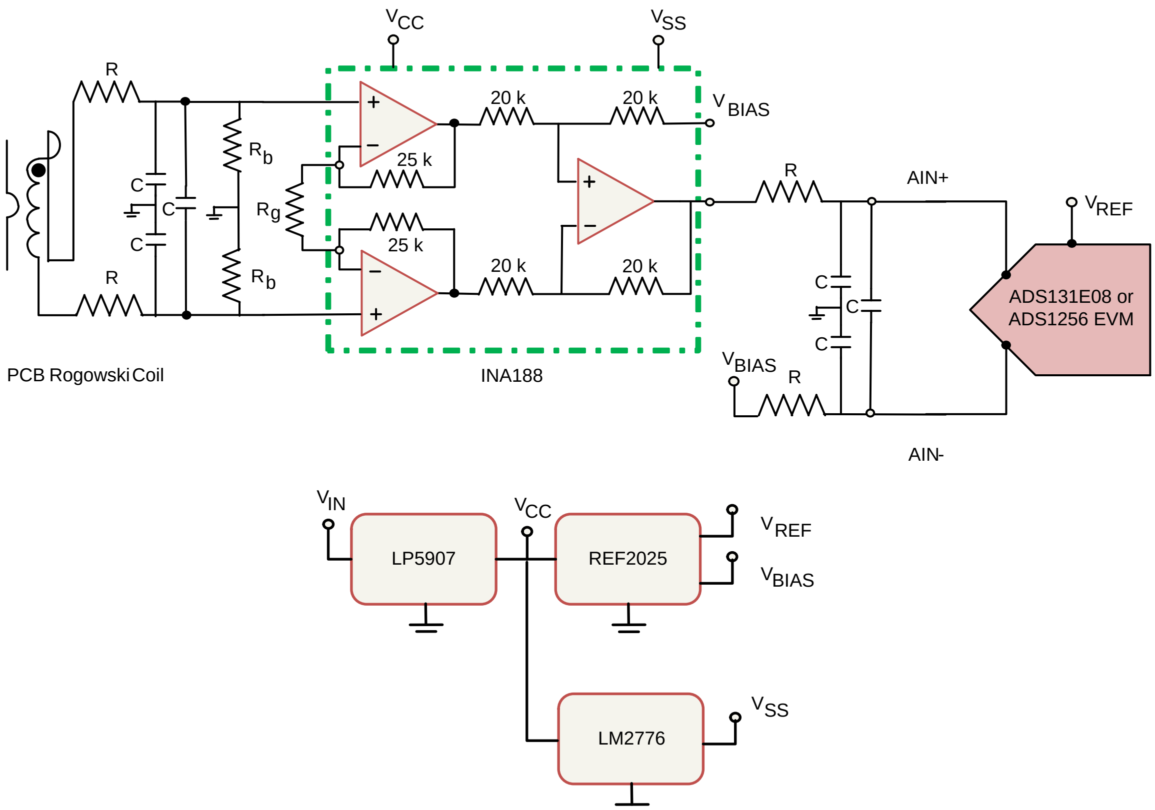

Figure 4. TIDA-01063 Block Diagram

3.1 Highlighted Products

3.1.1 INA188

The INA188 is a precision instrumentation amplifier that uses TI proprietary auto-zeroing techniques to achieve low offset voltage, near-zero offset and gain drift, excellent linearity, and exceptionally low-noise density (12 nV/√Hz) that extends down to DC.

The INA188 is optimized to provide excellent common-mode rejection of greater than 104 dB (G ≥ 10). Its superior common-mode and supply rejection supports high-resolution, precise measurement applications. The versatile three op-amp design offers a rail-to-rail output, low-voltage operation from a 4-V single supply as well as dual supplies up to ±18 V, and a wide, high-impedance input range. These specifications make the INA188 ideal for sensor conditioning.

3.1.2 LP5907

The LP5907 is a linear regulator capable of supplying a 250-mA output current. Designed to meet the requirements of analog circuits, the LP5907 provides low noise, high PSRR, low quiescent current, and low line or load transient response figures. The LP5907 offers class-leading noise performance without a noise bypass capacitor and the ability to place remote output capacitors.

3.1.3 LM2776

The LM2776 CMOS charge-pump voltage converter inverts a positive voltage in the range of 2.7 to 5.5 V to the corresponding negative voltage. The LM2776 uses three low-cost capacitors to provide 200 mA of output current without the cost, size, and electromagnetic interference (EMI) related to inductor-based converters.

With an operating current of only 100 µA and an operating efficiency greater than 90% at most loads, the LM2776 provides ideal performance for battery-powered systems requiring a high-power negative power supply.

3.1.4 REF2025

The REF2025 offers excellent temperature drift (8 ppm/°C, max) and initial accuracy (0.05%) on both the V_{REF} and V_{BIAS} outputs while operating at a quiescent current of less than 430 µA. In addition, the V_{REF} and V_{BIAS} outputs track each other with a precision of 6 ppm/°C (max) across a temperature range of –40°C to 85°C. All these features increase the precision of the signal chain and decrease board space while reducing the cost of the system as compared to a discrete solution.

4 System Design Theory

The TIDA-01063 is designed to meet wide AC current sensing using a low-cost current sensor.

4.1 Designing PCB Rogowski Coil

Rogowski coil current sensors are preferred due to its high linearity, wide current range measurement, and no magnetic saturation. Its excellent dynamic response makes the device suitable to sense high currents and detect short-circuit faults very quickly. Due to the extremely linear characteristics of the Rogowski coil, transfer characteristics of the sensor are quite simple as compared to an electromagnetic current transformer.

The commercially available Rogowski coils are limited to bandwidths in kHz. The bandwidth of the PCB Rogowski coil can be further improved up to GHz.

4.1.1 Rogowski Coil Magnetic Calculations

The Rogowski coil is air core toroid with N turns around it. Consider a trace with a finite length spatial located on a circular PCB as shown in Figure 5. Due to time varying current flowing through the conductor, a magnetic field is created around it.

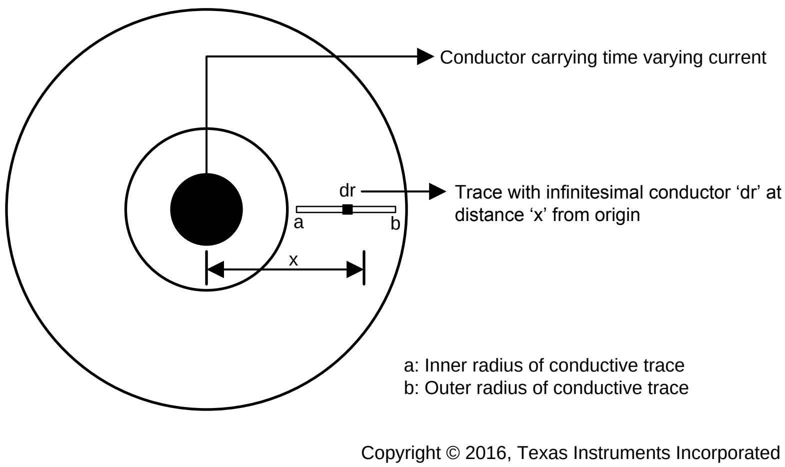

Figure 5. Rogowski Coil Design

Consider an infinitesimal conductive element 'dr' at a distance of x from the origin.

As per the Biot Savart Law, the magnetic field strength at distance x is given by Equation 1:

$$dH = \frac{I_{PRIMARY}}{2 \times \pi \times x} \quad (1)$$

The magnetic flux density at point 'dr' is found using Equation 2:

$$dB = \mu \times dH \quad (2)$$

where

- μ is the permeability of free space

Substituting Equation 1 in Equation 2, the magnetic flux density due to current flowing through conductor is

$$dB = \mu \times \frac{I_{PRIMARY}}{2 \times \pi \times x} \quad (3)$$

The magnetic flux across the conductive trace is given as

$$\phi = \int_a^b dB \times dA \quad (4)$$

Equation 5 substitutes 'dA', which is rectangular cross section area for element 'dr' with PCB height 'h' in Equation 4.

$$\phi = \int_a^b \left(\left(\mu \times \frac{I_{PRIMARY}}{2 \times \pi \times x} \right) \times (dr \times h) \right) \tag{5}$$

So, the total flux across the conductive trace is

$$\phi = \frac{\mu \times I_{PRIMARY} \times h}{2 \times \pi} \times \ln \frac{b}{a} \tag{6}$$

As per Lenz's law, the voltage induced due to N turns is

$$V = N \times \frac{d\phi}{dt} \tag{7}$$

Substituting flux from Equation 6, the voltage induced due to time-varying current is

$$V = N \times \frac{\mu \times h}{2 \times \pi} \times \ln \frac{b}{a} \times \frac{dI_{PRIMARY}}{dt} \tag{8}$$

So, the mutual inductance (M) for the Rogowski coil is

$$M = N \times \frac{\mu \times h}{2 \times \pi} \times \ln \frac{b}{a} \tag{9}$$

Assume the sinusoidal current of amplitude 'I_m' and frequency 'f_{IN}' is flowing through conductor located at center of coil. So, the voltage induced is given as

$$V = M \times \frac{dI_m \sin(2 \times \pi \times f_{IN} \times t)}{dt} \tag{10}$$

Solving the derivative gets

$$V = M \times 2 \times f_{IN} \times \pi \times I_m \times \cos(2 \times \pi \times f_{IN} \times t) \tag{11}$$

At time t = 0, the cosine term is 1. So, the peak induced voltage is

$$V_{PEAK} = M \times 2 \times f_{IN} \times \pi \times I_m \tag{12}$$

Substituting RMS current (I_{RMS}) which is (I_m / 1.414) in Equation 12:

$$V_{RMS} = M \times 4.44 \times f_{IN} \times I_{RMS} \tag{13}$$

So, induced voltage is proportional to RMS primary current flowing through the conductor and frequency of primary current flowing through the conductor.

4.1.2 PCB Rogowski Coil Winding Turns Limitation

The number of turns in the PCB coil is limited by its inner radius and via size fabrication. The distance between two via sizes needs to be at least 3 times the pad width for easy PCB fabrication.

As shown in Figure 6, let 'v_h' be the via hole diameter and 'v_p' be the via pad diameter.

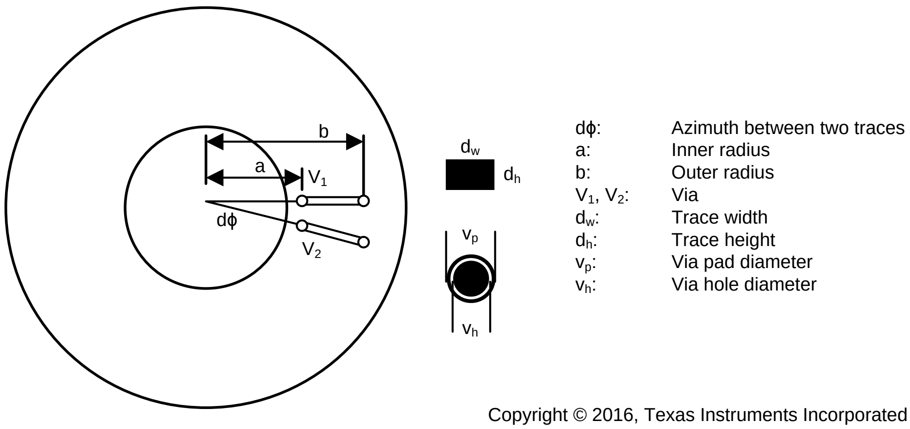

Figure 6. Turns Calculation

The linear distance between via V_1 and V_2 is

$$d = a \times \sin d\phi \tag{14}$$

The distance between two via d's must be at least

$$d = 3 \times \left(v_h - v_p\right) \tag{15}$$

Substituting Equation 15 in Equation 14, the angle between two trace is

$$d\phi = \sin^{-1}\left(\frac{3 \times \left(v_h - v_p\right)}{a}\right) \tag{16}$$

So, the total number of turns on one PCB Rogowski coil is

$$N = \frac{360}{d\phi} \tag{17}$$

With a known inner radius and via size, the number of turns N can be calculated. Using N in Equation 8, the mutual inductance can be computed. For a higher mutual inductance, the PCB coil can be cascaded in series.

4.1.3 PCB Rogowski Coil Transfer Function

Because the PCB Rogowski coil does not have a magnetic core, modeling the sensor is quite simple. Figure 7 shows a model of the PCB sensor for N turns. The inter-capacitance shown is a combination of both the lumped and distributed capacitance.

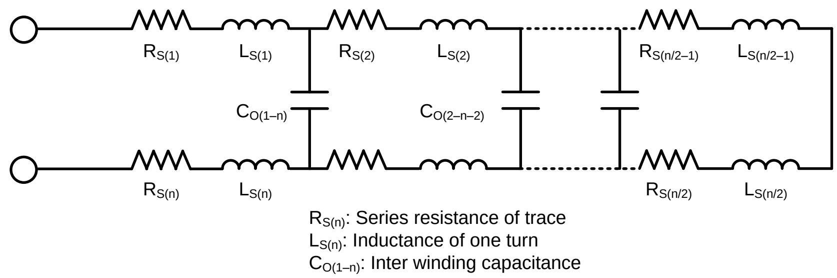

Figure 7. PCB Rogowski Coil Equivalent Circuit

The model is similar to an equivalent circuit in the transmission line with one end shorted. Computing the inter-winding capacitance is not simple. Therefore, the sensor can be modeled as a simple RLC circuit up to the first resonance as shown in Figure 8.

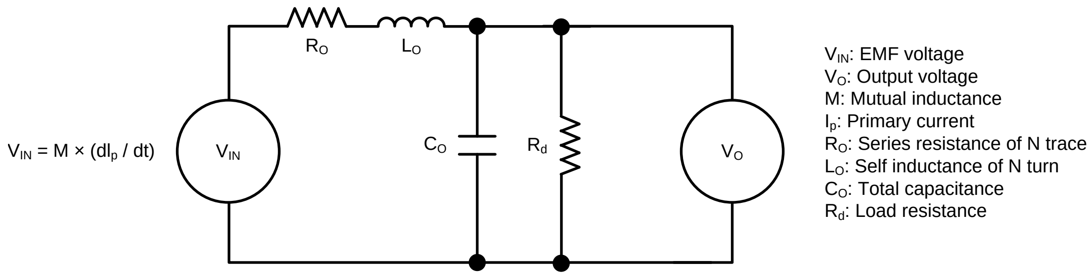

Figure 8. Simplified PCB Rogowski Coil Equivalent Circuit

The voltage induced due to current flowing through the conductor is modeled as the voltage source. The self-inductance, coil resistance, and total parasitic inter-winding capacitance is modeled to understand the dynamic performance of the sensor.

The transfer function for the RLC circuit in an s domain circuit is as per Equation 18:

$$\frac{V_O(s)}{V_{IN}(s)} = \frac{1}{L_O \times C_O \times \left(s^2 + s \times \frac{1}{L_O \times C_O} \times \left(\frac{L_O}{R_d} + C_O \times R_O\right) + \frac{1}{L_O \times C_O} \times \frac{R_d + R_O}{R_d}\right)} \tag{18}$$

Comparing the denominator with a standard second-order equation, the angular frequency and damping factor can be derived with Equation 19.

$$\frac{d^2x}{dt^2} + 2 \times \zeta \times \omega_O \times \frac{dx}{dt} + \omega_O{}^2 x = 0 \tag{19}$$

So, the angular frequency for the RLC circuit is

$$\omega_O = \frac{1}{\sqrt{L_O \times C_O}} \times \sqrt{\frac{R_d + R_O}{R_d}} \tag{20}$$

When $R_d \gg R_o$, the angular frequency depends only upon self-inductance and equivalent capacitance.

$$\omega_O = \frac{1}{\sqrt{L_O \times C_O}} \tag{21}$$

The damping factor for the RLC circuit is

$$\zeta = \frac{1}{2 \times \sqrt{L_O \times C_O}} \times \sqrt{\frac{R_d}{R_d + R_O}} \times \left(\frac{L_O}{R_d} + C_O \times R_O \right) \tag{22}$$

To get the fastest rise time without oscillation, the circuit must be critically damped. Assuming $\zeta = 0.707$ for a quality factor of 0.707 for known values of the RLC circuit, load resistance for the circuit can be computed.

The total resistance of coil is the sum of N turns resistance and via resistance. Resistance of N turns is the sum of the resistance of N single turn. The standard equation of resistance at ambient temperature is shown in Equation 23.

$$R = P \times \frac{l}{A} \tag{23}$$

Where l is length of conductor, A is cross-sectional area, and P is resistivity of copper. The cross-sectional area of a trace of finite length is equal to the area of a rectangle. So, resistance for one turn with trace length 'd_l', trace width 'd_w', and trace thickness 'd_h' is

$$R_1 = 2 \times \left(P \times \frac{d_l}{d_w \times d_h} \right) \tag{24}$$

The total resistance for N turns is given by Equation 25.

$$R_n = N \times 2 \times \left(P \times \frac{d_l}{d_w \times d_h} \right) \tag{25}$$

The self-inductance of the Rogowski coil can be calculated by using the standard inductance equation of toroid with a rectangular cross section. See Equation 26 to calculate the self-Inductance of the coil.

$$L = N^2 \times \frac{\mu \times h}{2 \times \pi} \times \ln \frac{b}{a} \tag{26}$$

Determine total capacitance by knowing the first resonant frequency of the circuit. To find out the resonant frequency, use a vector signal analyzer. Set the analyzer on the S11 parameter, which gives the coefficient of the input voltage reflection. The frequency at which the first dip in gain margin occurs is the resonant frequency of the circuit. For the designed PCB Rogowski, the observed resonant frequency is at 20 MHz as shown in Figure 9.

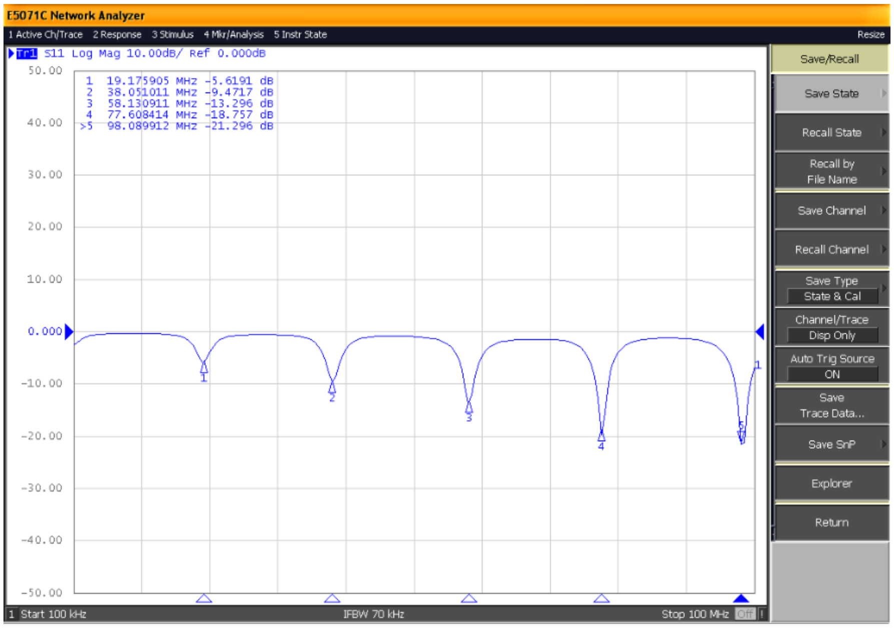

Figure 9. Two-Port Analysis

So the equivalent capacitance for the designed PCB Rogowski coil of self-inductance of 8.34 µH is 7.58 pF. The total resistance of the PCB coil is 0.77 Ω.

Time constant for the RLC circuit is given by Equation 27.

$$\tau = \frac{2 \times L_o \times C_o}{\left(\frac{L_o}{R_d} + C_o \times R_o \right)} \quad (27)$$

Settling time t_s of circuit is 4 times the time constant.

$$t_s = 4 \times \tau \quad (28)$$

The settling time of a circuit decides the sampling rate of ADC. Settling time must be much less than the sampling period to measure stable data from the sensor. Simulating the step response gives a greater understanding on the dynamic characteristics of the RLC circuit. An equivalent circuit for a designed sensor is shown in Figure 10.

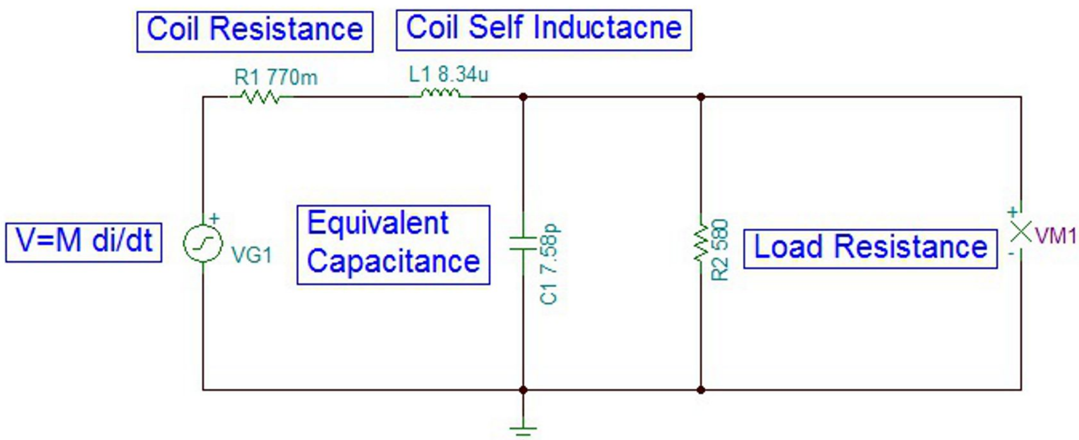

Figure 10. Circuit Model of Simplified PCB Rogowski Coil

Simulating these values for a step response of time 150 ns shows that the output settles before 50 ns without any oscillations.

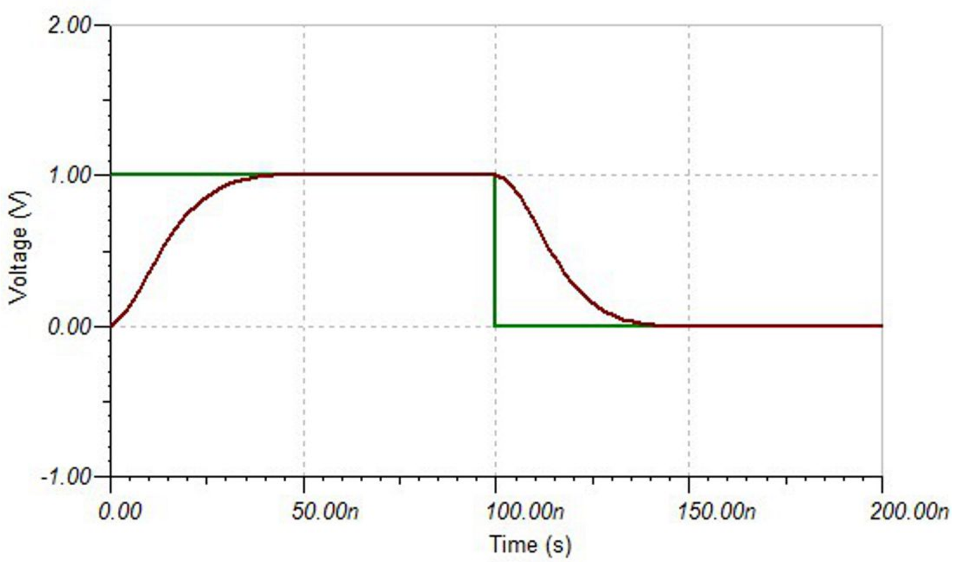

Figure 11. Step Response

4.2 INA188 Amplifier—Error Budgeting

The PCB Rogowski coil output (RMS) voltage is in microvolts. Because the signal amplitude is almost the same as the step size of the delta-sigma ADC, input resolution will be limited if the sensor is interfaced directly with the ADC. An external amplifier would improve the input resolution. This amplifier needs to be a zero drift series with very low noise voltage for the signal measurement bandwidth. Gain error and gain nonlinearity affect the AC performance. The INA188 instrumentation amplifier is from a precision family with excellent linearity due to its auto-zeroing technique. The device's high input impedance, 5-ppm gain drift, and very low noise density of 12 nV/√Hz make it ideal for sensor signal conditioning. For computing resolution error, assume a full-scale current of 1000 A and the parameters mentioned in Table 2.

Table 2. Input Parameters

PARAMETER	VALUE	UNIT	SYMBOL
Rogowski mutual inductance	0.000000048	H	M
Max primary current	1000	A	I
Signal frequency	50	—	—
Full scale voltage	0.010656	V	V_{DIFF}
Series R_{sh+}	0	Ω	R_{sh+}
Series R_{sh-}	0	Ω	R_{sh-}
Bias resistor R_{bias+} (0.1% 25 ppm)	100000	Ω	R_{b+}
Bias resistor R_{bias-} (0.1% 25 ppm)	100000	Ω	R_{b-}
Gain	100	V/V	G
Max temperature	85	°C	T_{MAX}
Min temperature	–25	°C	T_{MIN}
Common mode voltage	0.005328	V	V_{CM}

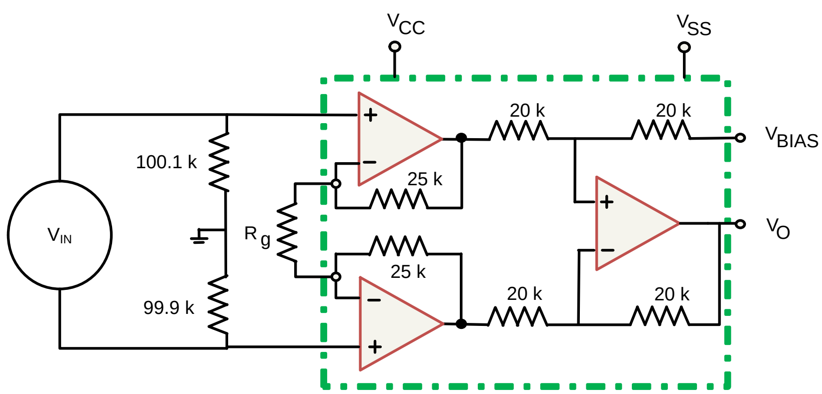

Figure 12. INA188 Instrumentation Amplifier

To achieve a 1% accuracy for full-scale current of 1000 A, the maximum resolution error of the operational amplifier needs to be less than the voltage output of the Rogowski coil at 10 A. The output of the Rogowski coil for a 50-Hz sine wave current signal with a 10-A amplitude is 107 µV. The worst case resolution error must be less than 107 µV.

From Table 3 through Table 6, the worst case resolution error for the INA188 at a bandwidth of 1.5 kHz is 2.92 µV, which is less than expected value.

Table 3. INA188 Absolute Error Budget

SR NO	PARAMETER	EQUATION	SPECIFICATION	UNIT	ERROR (PPM)	ERROR (VOLTAGE)
1	Input offset voltage	$\left(\frac{V_{OS}}{V_{DIFF}}\right) \times 10^6$	0.000065	V	6099	—
2	Output offset voltage	$\left(\frac{\left(\frac{V_{o\_os}}{G}\right)}{V_{DIFF}}\right) \times 10^6$	0.00018	V	168	—
3	CMRR	$\left(\frac{\left(\frac{V_{CM}}{10^{(CMRR/20)}}\right)}{V_{DIFF}}\right) \times 10^6$	118	dB	0.62	—
4	Gain error	Gain error (%) × 10^4	0.5	%	5000	—
5	Input offset current	I_{OS}	1.70E-10	A	—	—
6	Input bias current	I_b	5.60E-10	A	—	—
7	Input bias + current	$I_{b+} = \frac{((2 \times I_b) + I_{OS})}{2}$	6.45E-10	A	—	—
8	Input bias – current	$I_{b-} = I_{b+} - I_{OS}$	4.75E-10	A	—	—
9	Input bias + current error	$V_{b+} = (I_{b+} + x (R_{sh+} + R_{b+})$	6.46E-05	V	—	—
10	Input bias – current error	$V_{b-} = (I_{b-} x (R_{sh-} + R_{b-})$	4.75E-05	V	—	—
11	Bias current error	$\left(\frac{(V_{b+} - V_{b-})}{V_{DIFF}}\right) \times 10^6$	1.71E-05	V	1606	—
Best case absolute error (A)					3600	38.3 µV
Worst case absolute error (A)					11269	120 µV

Table 4. INA188 Drift Error Budget

SR NO	PARAMETER	EQUATION	SPECIFICATION	UNIT	ERROR (PPM)	ERROR (VOLTAGE)
12	Gain drift	(Gain drift ppm/°C) × (T_{MAX} – 25)	50	—	3000	—
13	Input offset voltage drift	$\left(\frac{\left(V_{IN\_OS\_DRIFT} \times \left(T_{MAX} - 25\right)\right)}{V_{DIFF}}\right) \times 10^{6}$	0.0000002	V/°C	1126	—
14	Output offset voltage drift	$\left(\frac{\left(\left(\frac{V_{O\_OS\_DRIFT}}{Gain}\right) \times \left(T_{MAX} - 25\right)\right)}{V_{DIFF}}\right) \times 10^{6}$	0.00000035	V/°C	19	—
17	Maximum input offset current	$I_{O\_MAX} = I_{OS} + I_{OS\_DRIFT}$	3.40E-10	A	—	—
18	Maximum input bias current	$I_{B\_MAX} = I_b + I_{b\_DRIFT}$	0.000000001	A	—	—
19	I_{b+} drift current	$I_{bm(+)} = \frac{\left(\left(2 \times I_{b\_MAX}\right) + I_{O\_MAX}\right)}{2}$	1.17E-09	A	—	—
20	I_{b-} drift current	$I_{bm(-)} = I_{bm(+)} - I_{O\_MAX}$	8.30E-10	A	—	—
21	I_{b+} drift current error	$V_{bm+} = (I_{bm(+)} + x\ (R_{sh+(85)} + R_{b+(85)})$	0.000117294	V	—	—
22	I_{b-} current error	$V_{bm-} = (I_{bm(-)} \times (R_{sh-(85)} + R_{b-(85)})$	8.28E-05	V	—	—
23	Bias current drift voltage	$V_b = V_{bm+} - V_{bm-}$	3.45E-05	V	—	—
24	Bias current drift error	$\left(\frac{V_b}{V_{DIFF}}\right) \times 10^{6}$	—	V	1631	—
Best case drift error (B)					1798	19.1 µV
Worst case drift error (B)					5777	6.15 µV

Table 5. INA188 Resolution Error Budget

SR NO	PARAMETER	EQUATION	SPECIFICATION	UNIT	ERROR (PPM)	ERROR (VOLTAGE)
25	Gain nonlinearity	—	0.8	ppm	0.8	—
26	Input nosie voltage	Eni (RMS)	1.25E-08	V	—	—
27	Output noise voltage	Eno (RMS)	0.000000118	V	—	—
28	Bandwidth	BW	1500	Hz	—	—
29	Noise bandwidth voltage	$\left(\frac{\left(\sqrt{BW} \times \sqrt{Eni^2 + \left(\frac{Eno}{G}\right)^2} \times 6\right)}{V_{DIFF}}\right) \times 10^6$	—	—	273	—
Best case resolution error (C)					194	2 µV
Worst case resolution error (C)					275	2.92 µV

Table 6. INA188 Total Error (Absolute + Drift + Resolution) Budget

ERROR	ERROR (PPM)	ERROR (VOLTAGE)
Best case error	5592	59.5 µV
Worst case error	17321	184 µV

4.3 Digital Integration

The output voltage of the Rogowski coil is the differentiation of the primary current. To get the actual waveform of the primary current, the output voltage needs to be integrated in either an analog or digital domain. Integrating in a digital domain is simple and advantageous over analog due to its better magnitude and phase response. The time constant of the integrator can also be changed easily in digital integration by changing sampling rate.

Integrating in digital domain can be implemented using simple first-order IIR function as shown in Equation 29.

$$y(n) = y(n-1) + (T \times x(n)) \tag{29}$$

where

- y(n) is the present sample output
- y(n – 1) is the previous sample output
- x(n) is the present sample input.

The first-order IIR filter is forward rectangular window integration. To have an approximate area of the curve, the rectangular windows must be very small. Hence, the sampling rate must be much higher than the input signal frequency to get better curve fitting. The Z transform of the first-order IIR filter is

$$\frac{Y(z)}{X(z)} = \frac{T}{1 - z^{-1}} \tag{30}$$

At DC input z^{-1} is 1, which gives infinite scaling of the output. So, the output will saturate for the DC input. To avoid output saturation, all DC components need to be filtered out before integrating the function. A high pass filter needs to be implemented before integration. A simple way of removing the DC component is subtracting the average of input samples for each cycle from each sample. An alternate way is to redefine the IIR filter with constant B as shown in Equation 31.

$$y(n) = (B \times y(n-1)) + (T \times x(n)) \tag{31}$$

The value of B can vary from 0.95 to 0.99. Z transformed for modified IIR filter is

$$\frac{Y(z)}{X(z)} = \frac{T}{1 - Bz^{-1}} \tag{32}$$

So, the DC component will be some constant value, which can be subtracted from each sample. Integration will add an offset value after each sample. To correct the offset, subtract the DC component from each computed output. The simplest way is to subtract the average of output samples for one cycle for each sample.

The algorithm needs to have two high pass filters, one before and one after integration for offset correction. Figure 13 gives the complete flow of the digital integration concept.

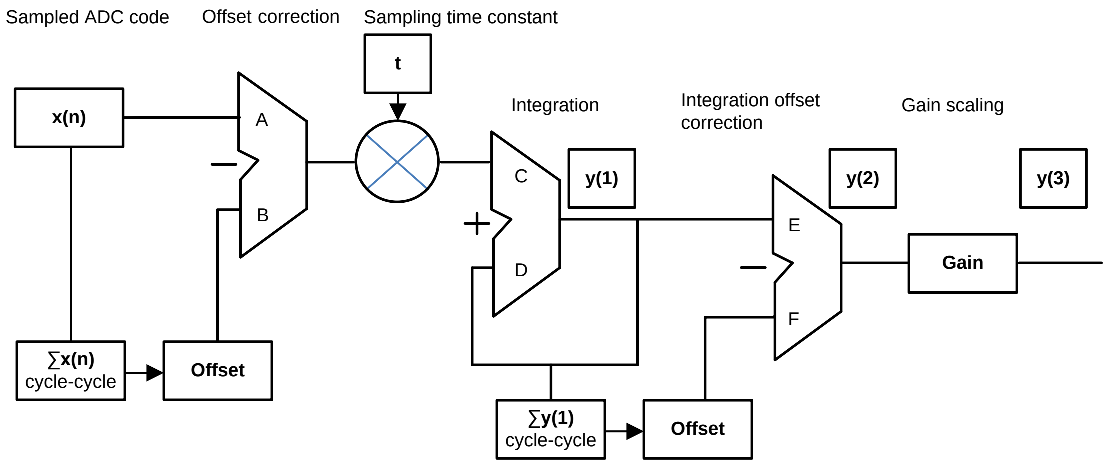

Figure 13. Digital Integration Logic

To get better curve fitting at a lower sampling rate, trapezoidal window integration can be implemented using Equation 33.

$$y(n) = y(n-1) + \left(\left(\frac{T}{2}\right) \times \left(x(n) + x(n-1)\right)\right) \quad (33)$$

5 Getting Started Hardware

The TIDA-01063 TI Design can be interfaced easily to the ADS1256 EVM or ADS131E08 EVM. There are two PCBs as shown in Figure 14. The circular PCB is the Rogowski sensor and the square PCB is the interface board for the sensor.

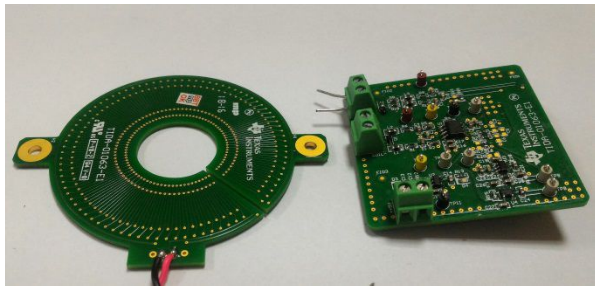

Figure 14. TIDA-01063 Boards

The board consists of two analog input channels, one for reference voltage signal and another for the PCB Rogowski sensor input. The voltage reference signal is to compute phase error only. An AC voltage of 1.5 to 2.5 V needs to be applied externally.

5.1 Connectors

The interface board has four connectors as described in Table 7:

Table 7. Interface Board Connector

CONNECTOR	DESCRIPTION	VOLTAGE
J1	PCB Rogowski coil input	10.7 µV to 1.07 mV
J3	AC reference voltage	1.5 to 2.5 V (RMS)
J4	DC power supply	5 V
J2	Interface connector for EVM board	—

For pinout and software installation of the ADS1256 EVM or ADS131E08 EVM, see the following product pages:

- ADS1256 EVM
- ADS131E08 EVM

This section describes the respective pinouts and locations for the connectors on the interface board.

5.1.1 Power Supply

The board is powered up through the J4 connector; a maximum DC voltage of 6.5 V can be applied to it. The board can be powered up using the ADC EVM supply or by an external DC source. For the external DC supply, both the EVM and the interface board must have common ground. See Figure 15 for pinout details.

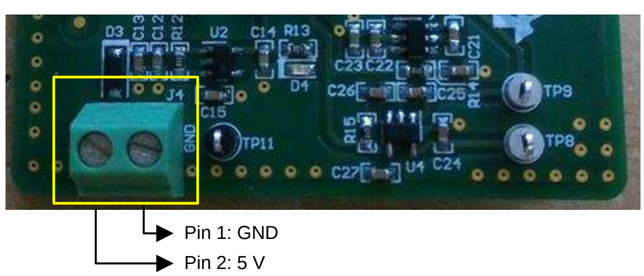

Figure 15. Power Supply

5.1.2 ADC EVM Interface Connector

The 20-pin connector J2 is for easy interface to connector J1 of the ADS1256 EVM. Connector J1 can also be used to connect the ADS131E08 EVM. See Figure 16 for a detailed pinout schematic.

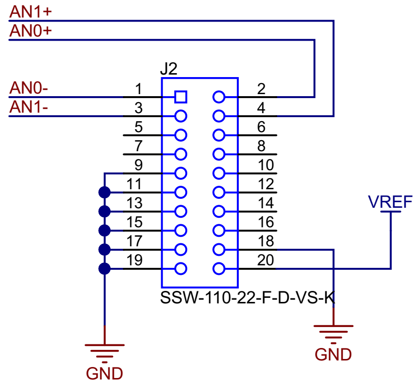

Figure 16. EVM Connector

5.1.3 PCB Rogowski Coil Input

The PCB Rogowski coil has four pads as shown in Figure 17. The coil output is connected to Pad 2 and Pad 3. The shield for the coil can be connected to Pad 1 or Pad 4.

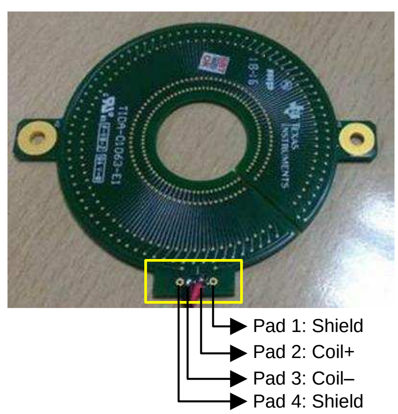

Figure 17. Rogowski Coil Connection

The output of the PCB Rogowski coil can be connected to connector J1 of the interface board as shown in Figure 18.

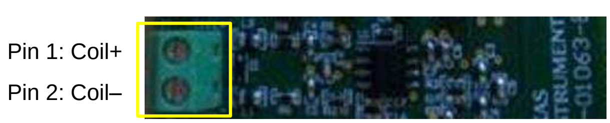

Figure 18. Rogowski Coil Connector

5.1.4 Reference Voltage

For the phase error computation phase, synchronous AC voltage must be connected to connector J3. The legend for positive signal wiring has been printed on the board. See Figure 19 for field wiring.

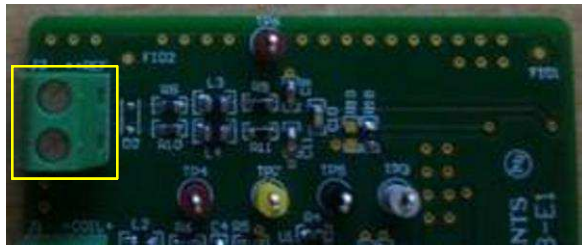

Figure 19. Reference Voltage Connector

5.2 Test Point

The required test point has been populated on the interface board to measure signals. See Table 8 for more details.

Table 8. Test Point

TEST POINT NO	DESCRIPTION	VOLTAGE RANGE
TP10	V_{CC}	3.3 V
TP1	V_{SS}	–3.3 V
TP8	V_{REF}	2.5 V
TP9	V_{BIAS}	1.25 V
TP6 – TP7	Reference voltage (after voltage divider)	0.227 V (AC Voltage for a 2.5-V input) AC coupling
TP4 – TP2	Rogowski coil voltage	0 to 1.07 mV (RMS) (100 A FS) AC coupling
TP3 – TP5	INA188 output	0 to 0.5328 mV (RMS) AC coupling
TP11	GND	0 V

5.3 Connecting to the ADS131E08 EVM

Connect the interface board to connector J10 of the MMB0 motherboard. To power up the interface board, connect two wires from Pin 3 and Pin 5 of connector J9 on the MMB0 motherboard to connector J4. Connect test points TP6 and TP7 of the interface board to connector J10 of the ADS131E08 EVM to capture a reference voltage signal. Connect test points TP3 and TP9 of the interface board to connector J11 of the ADS131E08 EVM for capturing Rogowski Coil signal. See Figure 20 for connecting the interface board to the ADS131E08 EVM.

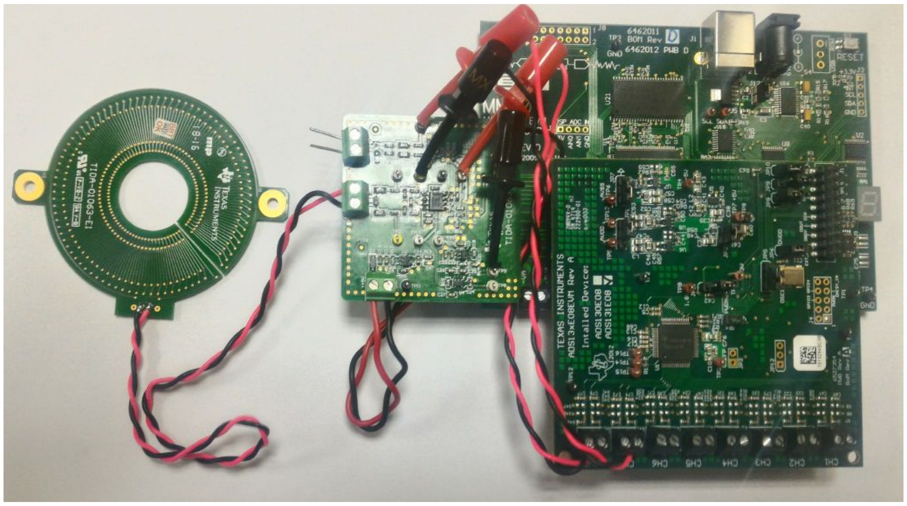

Figure 20. Connecting TIDA-01063 to ADS131E08 EVM

5.4 Connecting to the ADS1256 EVM

Before connecting the interface board to the ADS1256 EVM, check the default jumper settings as per the ADS1256 EVM user's guide (SBAU090). Change switches S1, S2, and S3 to external mode. After inserting the interface board on connector J1, connect the power supply from Pin 3 and Pin 6 of connector J3 of the ADS1256 EVM as shown in Figure 21.

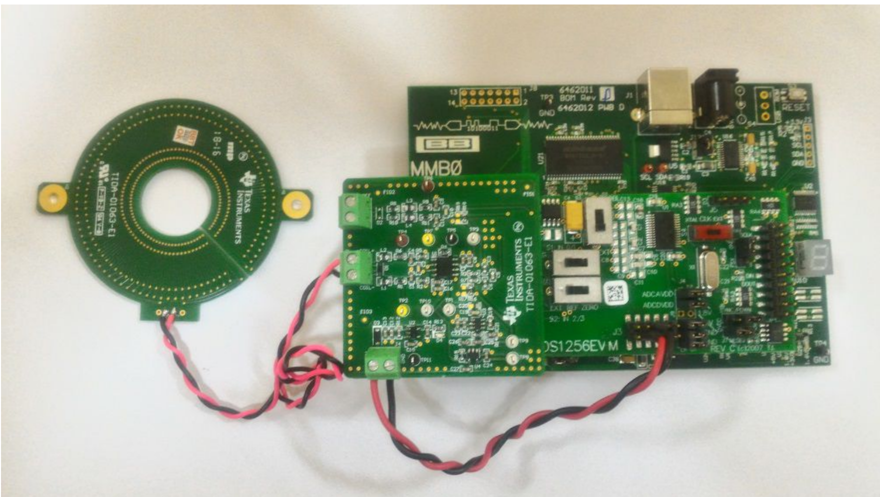

Figure 21. Connecting TIDA-01063 Boards to ADS1256 EVM

5.5 Computing Phase Error Using Digital Integration Tool

Configure the ADS131E08 EVM GUI to a data rate of 4 ksps and set the samples/CH to 400 as shown in Figure 22.

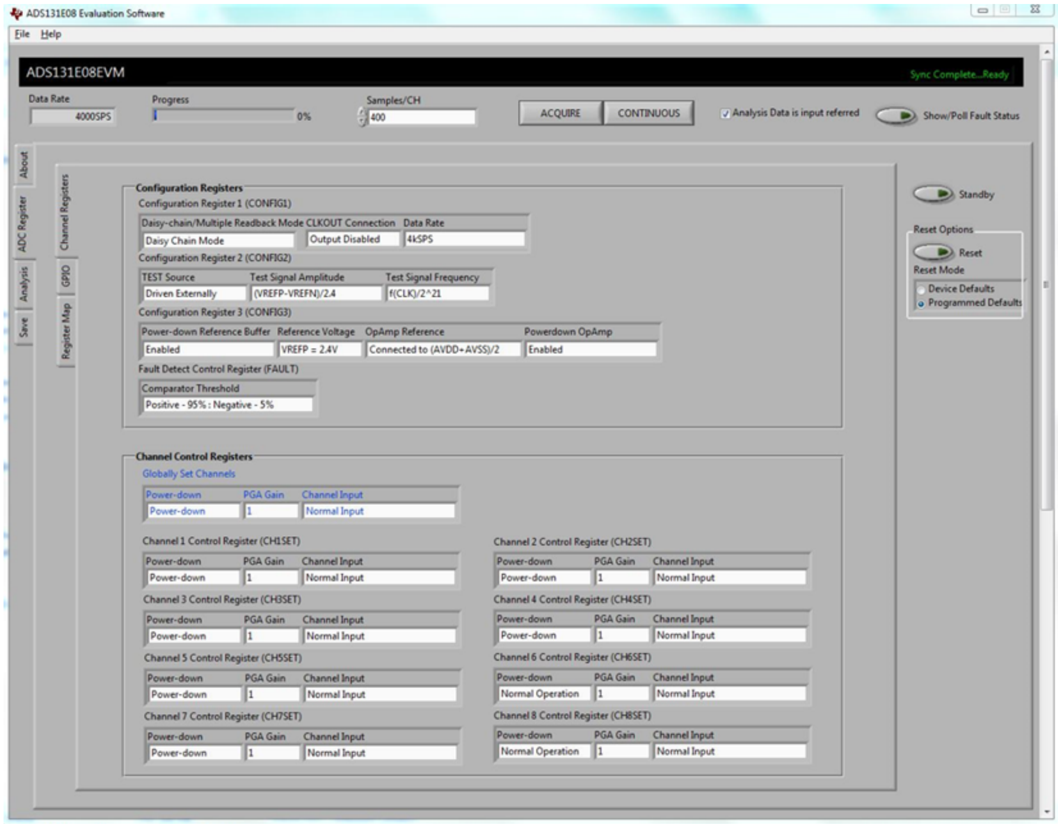

Figure 22. ADS131E08 EVM Settings

Click on "Analysis", select "CH8" and then inject current through the Rogowski coil from the AC power source. Also apply a reference voltage from the AC power source with zero phase lag. Click on the "Acquire" button and export data to Microsoft® Excel® as shown in Figure 23.

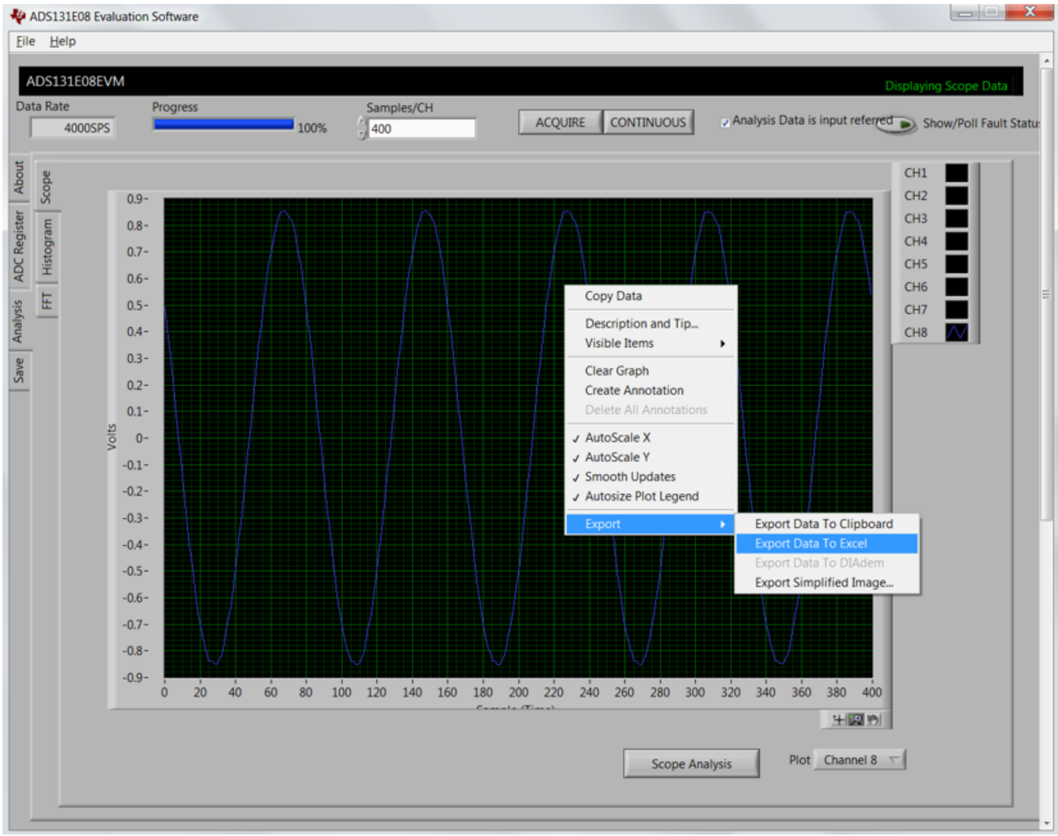

Figure 23. Exporting Samples From GUI

Copy the sample data of channel 7 and channel 8 from the exported Excel file and paste its values into columns C26 through C425 (AIN1) for the reference voltage and D26 through D425 (AIN2) for the Rogowski coil. Go to the sheet "Plot & RMS calculator" to check the RMS error and plots of the Rogowski coil signal after integration.

5.5.1 Computing Phase Error

To get the phase error, enter in cell M11 the time at which the signal of plot 1 is zero in the first cycle as shown in Figure 24.

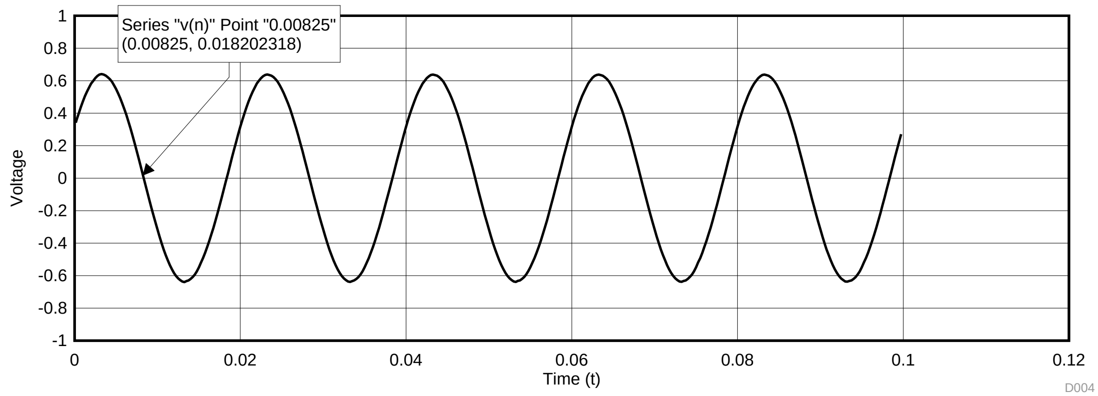

Figure 24. Zero Crossing for Plot 1

Enter in cell M12 the time at which the signal of plot 2 is zero in the first cycle, as shown in Figure 25.

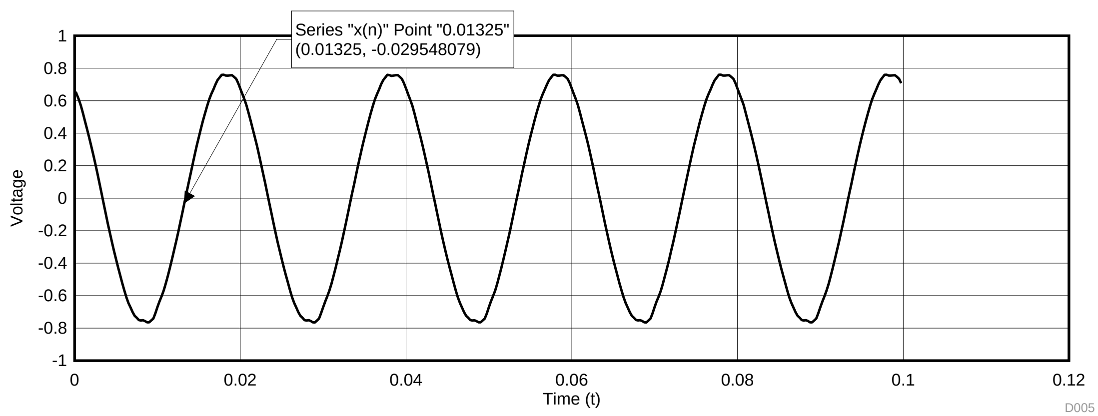

Figure 25. Zero Crossing for Plot 2

Enter in cell M15 the time at which the signal of plot 3 is zero in the first cycle as shown in Figure 26.

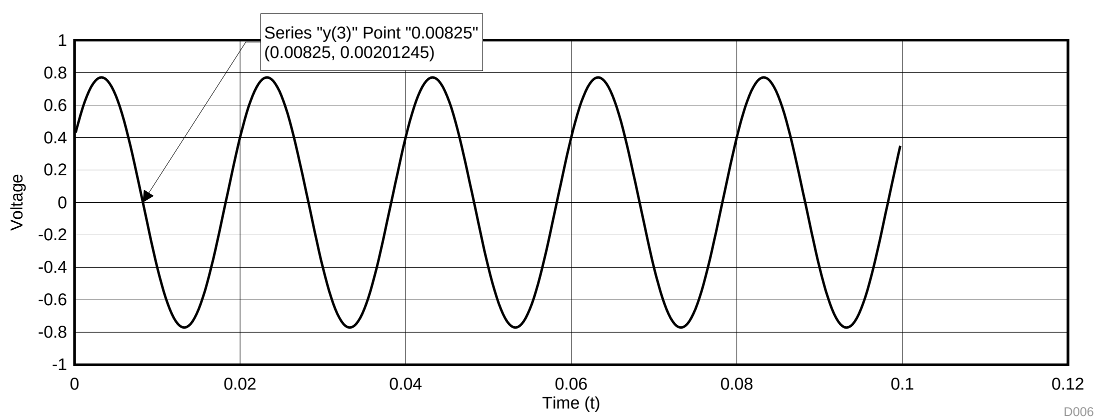

Figure 26. Zero Crossing for Plot 3

After entering the observed zero crossing time in its respective cells, the tool computes the phase error of 90° for the Rogowski coil input and phase error of 0° after integration.

6 Test Setup

The test setup consists of the boards that make up the TIDA-01063, the MTE current source, and the ADS131E08 EVM as shown in Figure 27.

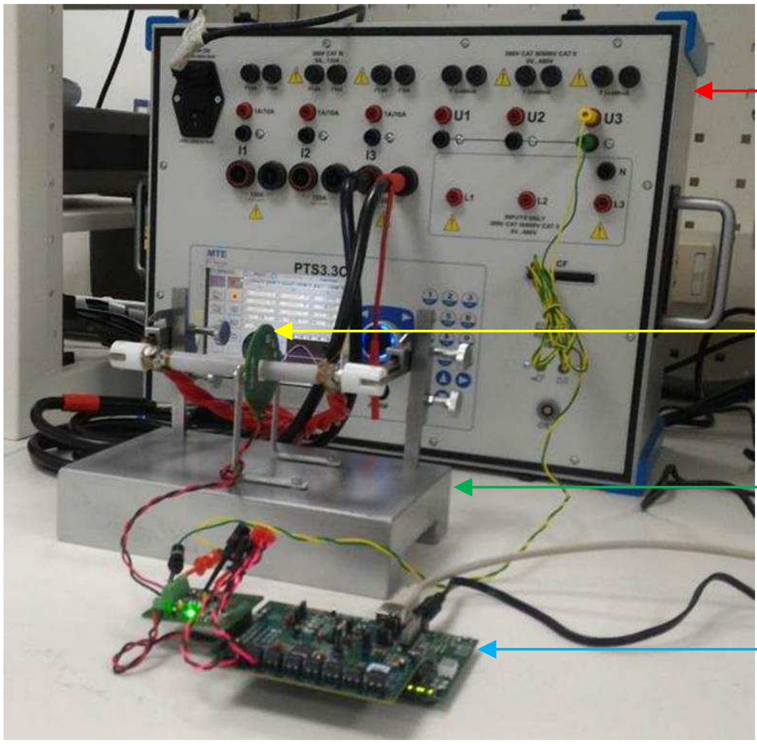

Figure 27. TIDA-01063 Test Setup

This design is tested to compute the RMS error using the ADS131E08 EVM and the phase error using the Rogowski coil tool. In order to RMS error, gather samples for 1 min and compute RMS using scope analysis of the ADS131E08 EVM.

7 Test Results

7.1 Linearity

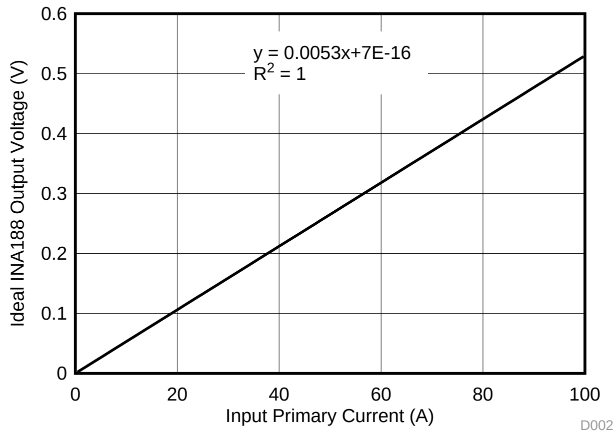

Figure 28. Ideal Linearity

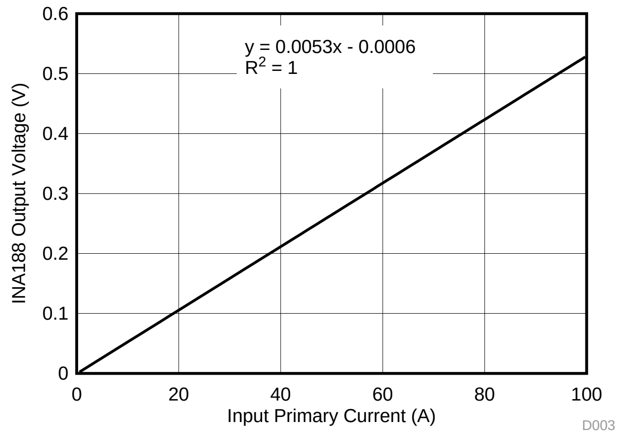

Figure 29. Observed Linearity at 25°C

7.2 Uncalibrated Error

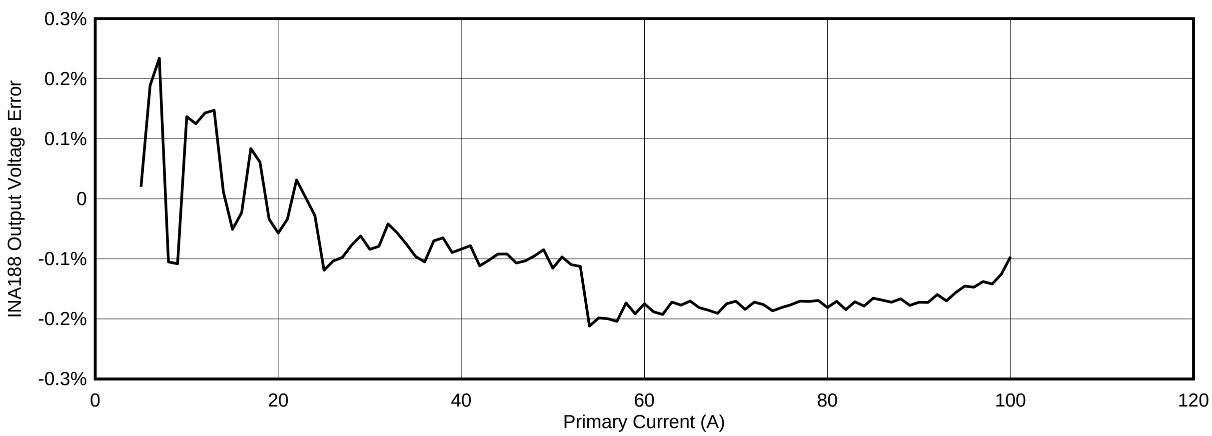

Figure 30. Uncalibrated Error at 25°C

8 Design Files

8.1 Schematics

To download the schematics, see the design files at TIDA-01063.

8.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01063.

8.3 Altium Project

To download the Altium project files, see the design files at TIDA-01063.

8.4 Gerber Files

To download the Gerber files, see the design files at TIDA-01063.

9 References

1. Helix Technologies (http://www.helixtech.com.au/Images/Delta-T6_Dyn_Motor_StartingDOL.jpg)

10 About the Authors

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Revision A History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (June 2016) to A Revision	Page
• Changed from preview page	1

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