Design Guide: TIDA-010937

Isolated Low Delay High PWM Rejection Hall Current Sense Reference Design With Digital Interface

Description

This reference design demonstrates an accurate, reinforced, isolated bidirectional current sense system using the TMCS1123 precision Hall-effect current sensor for reliable phase current and DC-link current sensing in three phase inverters up to ±62A at 3.3V supply with less than 100ns overcurrent detection time. The overcurrent threshold is configurable up to 2.5-times the full-scale input current range. A small form factor 12-bit A/D converter with high-speed SPI or a delta-sigma modulator with up to 21MHz clock offer a high noise immunity 3.3V I/O digital interface. The interface connects to host processors like a C2000™ or Sitara™ MCU for easy performance evaluation of in-package hall-sensors with different A/D conversion technologies.

Resources

TIDA-010937	Design Folder
TMCS1123	Product Folder
AMC1035, ADS7043, REF2033	Product Folder
LAUNCHXL-F28379D	Tool Folder

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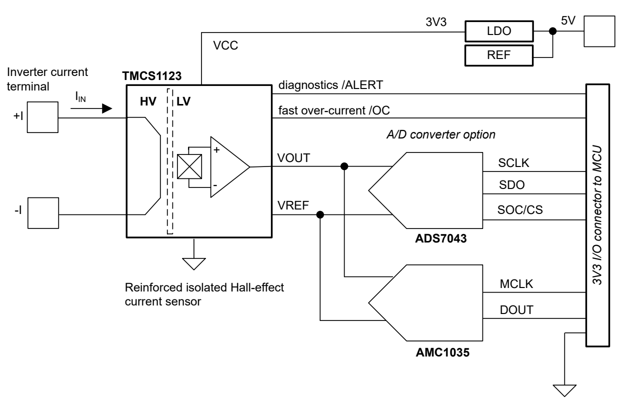
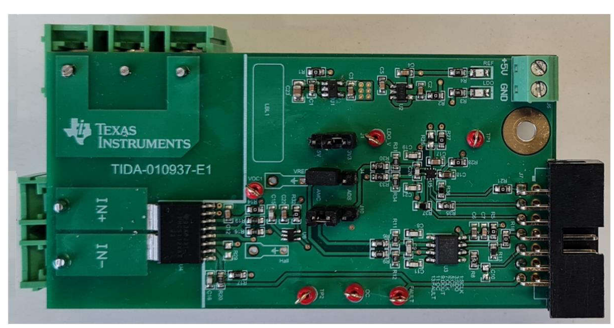


Features

- High linearity, low lifetime drift, low noise current sensor achieves 9.7 effective number of bits (ENOB) with modulator and Sinc3 OSR 64 filter over a range of ±62A
- Precision Hall-effect current sensor with ±1300V reinforced isolation working voltage and integrated overcurrent detection helps reduce system cost
- Low conductor resistance minimizes power loss and eases thermal dissipation requirements
- Very low analog propagation delay 0.6µs, helps achieve faster current loop and direct torque control
- Fast overcurrent response, less than 100ns, helps increase system reliability especially with fast switching GaN and SiC-FET inverters
- High common-mode transient immunity to reject PWM switching noise and high external magnetic field rejection helps increase system accuracy and reliability

Applications

- AC inverter and VF drives
- Single and multi-axis servo drives
- Industrial and collaborative robot
- DC-input BLDC motor drives
- Solar energy
- EV charging infrastructure



1 System Description

Isolated current sensing is vital in 110–690V_{AC} input 3-phase inverters for applications such as AC inverters and variable speed drives. The current is sensed in many subsystems, motor drive systems such as the motor phase currents, the DC-link current or the brake current as outlined in Figure 1-1. Accurate phase current sensing, for example, has a significant impact on the performance of vector-controlled three-phase inverters for industrial drives. The DC-link and brake currents are often measured to detect an overcurrent or short-circuit event due to a fault or miswiring in the system and a fast response is critical to turn off the related power switches and prevent further damage. Additional current sensing is important for diagnostics, monitoring, and predictive maintenance, such as analyzing the motor current harmonics for bearing deterioration or motor temperature estimation or input power monitoring.

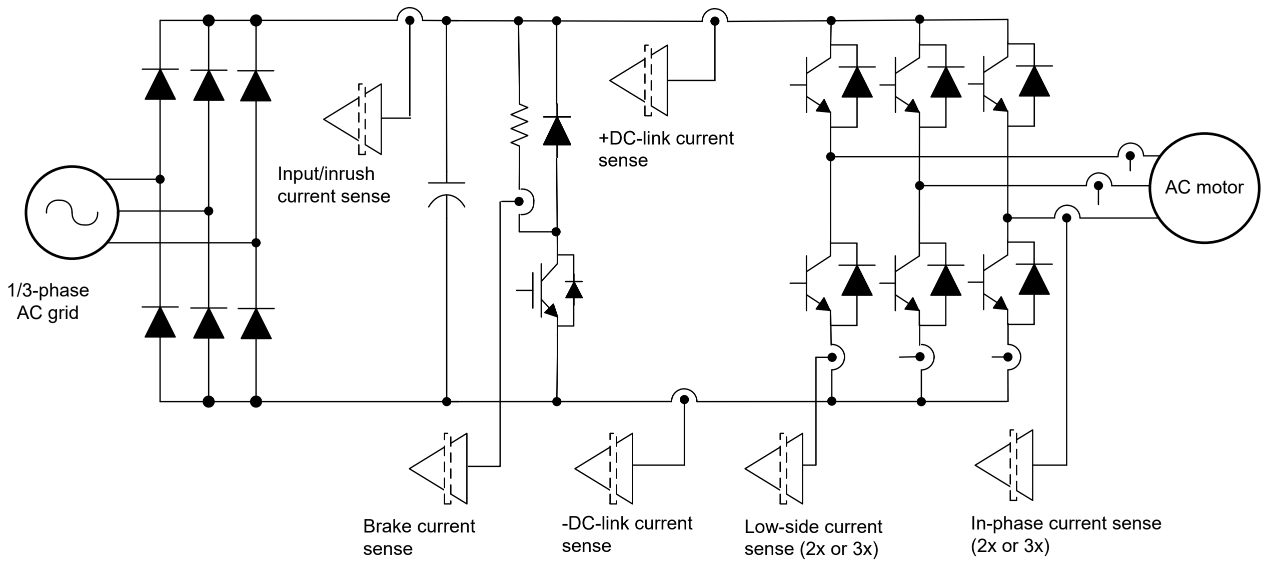


Figure 1-1. Current Sensing Options in 3-Phase Inverters

For current ranges up to around 100A, in-package Hall-effect current sensor ICs, like the TMCS1123 and shunt-based designs using either isolated amplifiers like AMC1300 and isolated modulators like AMC1306 are often used.

In-line shunt-based designs offer a highly-linear, highly-accurate, and ultra-low-noise option to measure the motor currents with three-phase inverters. However, these designs require a high-side floating supply, which is not always available in the system and the power losses of the shunt limit the maximum continuous current range.

In-package Hall-effect current sensors do not need a high-side floating supply and offer inherent isolation. These sensors have very low conductor resistance such as 0.67µΩ with the TMCS1123, an as well as inherent isolation. Often Hall-effect current sensors like the TMCS1123 provide low propagation delay and include a very fast overcurrent protection; therefore, offering a single-chip analog current sense option. Conversely, the signal-to-noise ratio and effective number of bits achievable in the system is typically lower with Hall-effect sensors than with shunt-based designs.

In all three-phase inverter systems where the high-side DC-link current needs to be measured and monitored for overcurrent, the TMCS1123 device does not need an additional isolated high-side supply referenced on top of the VDC voltage nor require a shunt. Hence, using this device solves system cost and fast overcurrent detection with an overcurrent range up to 2.5-times the full-scale input current range.

In applications such as AC inverters and variable speed drives, the TMCS1123 reinforced isolated in-package Hall sensors help reduce system cost for phase current sensing and overcurrent detection. The ultra-low propagation (600ns) of the TMCS1123 enables higher bandwidth current control algorithms with faster torque response such as direct torque control, hysteresis control and fast current loop (FCL) as shown in Figure 1-2. The fast current loop (FCL) reduces the total current control loop delay by a factor of 3 thus enabling a higher bandwidth closed-loop current control with faster response times.

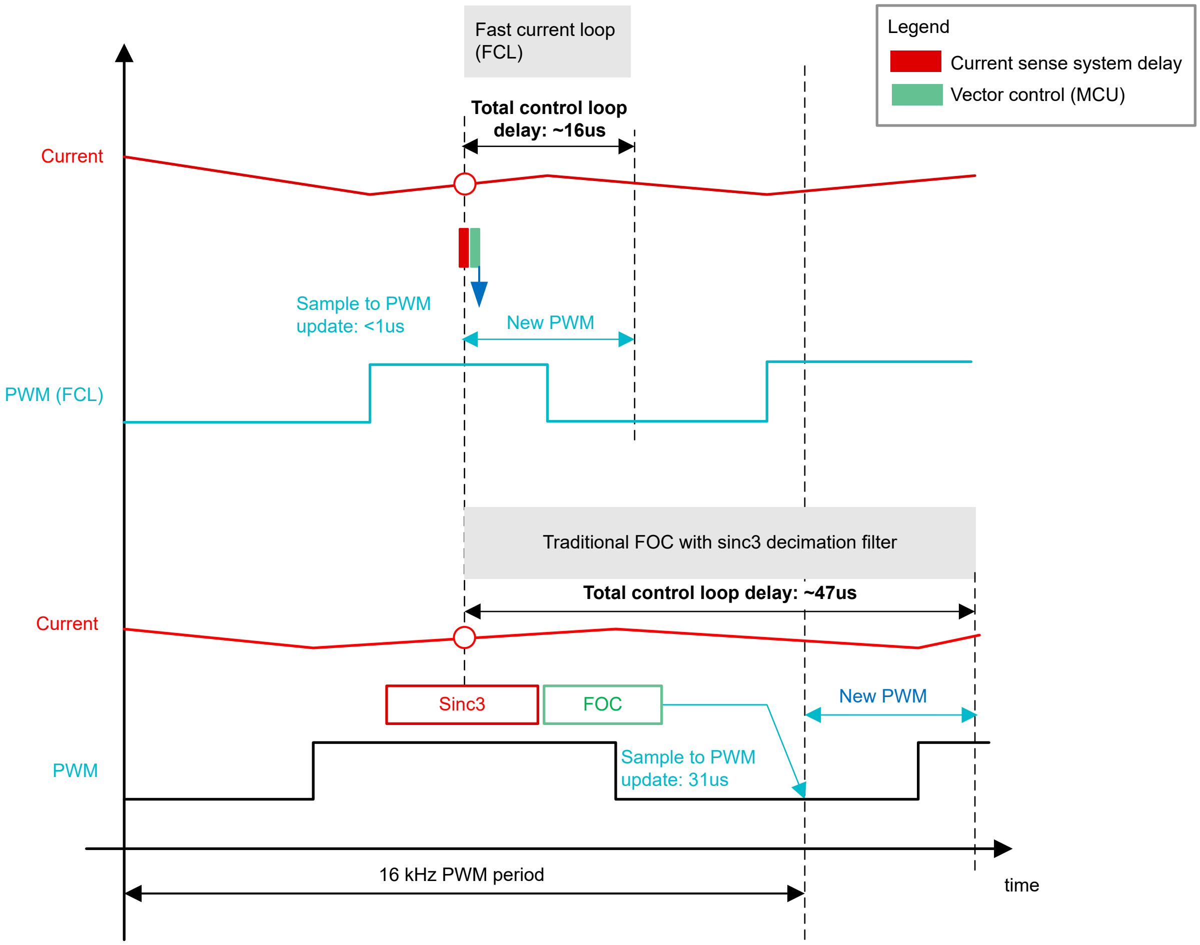


Figure 1-2. Fast Current Loop vs Traditional Current Loop Control With Double PWM Update

1.1 Key System Specifications

PARAMETER	SPECIFICATION	COMMENT
Full scale input current range (FSR)	±66A (MAX)	TMCS1123B1 at 3.3V
Effective number of bits	9 ENOB (TYP)	TMCS1123B1 and ADS7043
	9.7 ENOB (TYP)	TMCS1123B1 and AMC1035 with Sinc3 OSR64 filter
Propagation delay	0.6µs (TYP)	TMCS1123B1
	1.6µs (TYP)	Including A/D conversion and serial peripheral interface (SPI) transfer (ADS7043)
	5.5µs (TYP)	Including Sinc3 OSR64 filter (AMC1035)
OC threshold	2-times FSR	Configurable from 0 to 2.5-times FSR
OC response time	100ns (TYP)	
Isolation rating	Reinforced	
Maximum working voltage	±1300V (MAX)	Tested at $320V_{DC}$ working voltage
A/D converter options	12-bit SAR ADC (ADS7043) or delta-sigma modulator (AMC1035)	Selectable by jumper
MCU interface connector	2 × 10 header (2.54mm pitch), 3.3V I/O	
Logic supply	5V ±10%	
Temperature range (ambient)	–40°C to 125°C	Tested from 25°C to 85°C
PCB size	43.5mm × 86.34mm	1.71in × 3.4in (inch)
PCB layer stack	4 layer	2oz copper on top and bottom layers

2 System Overview

2.1 Block Diagram

Figure 2-1 shows the block diagram of this reference design.

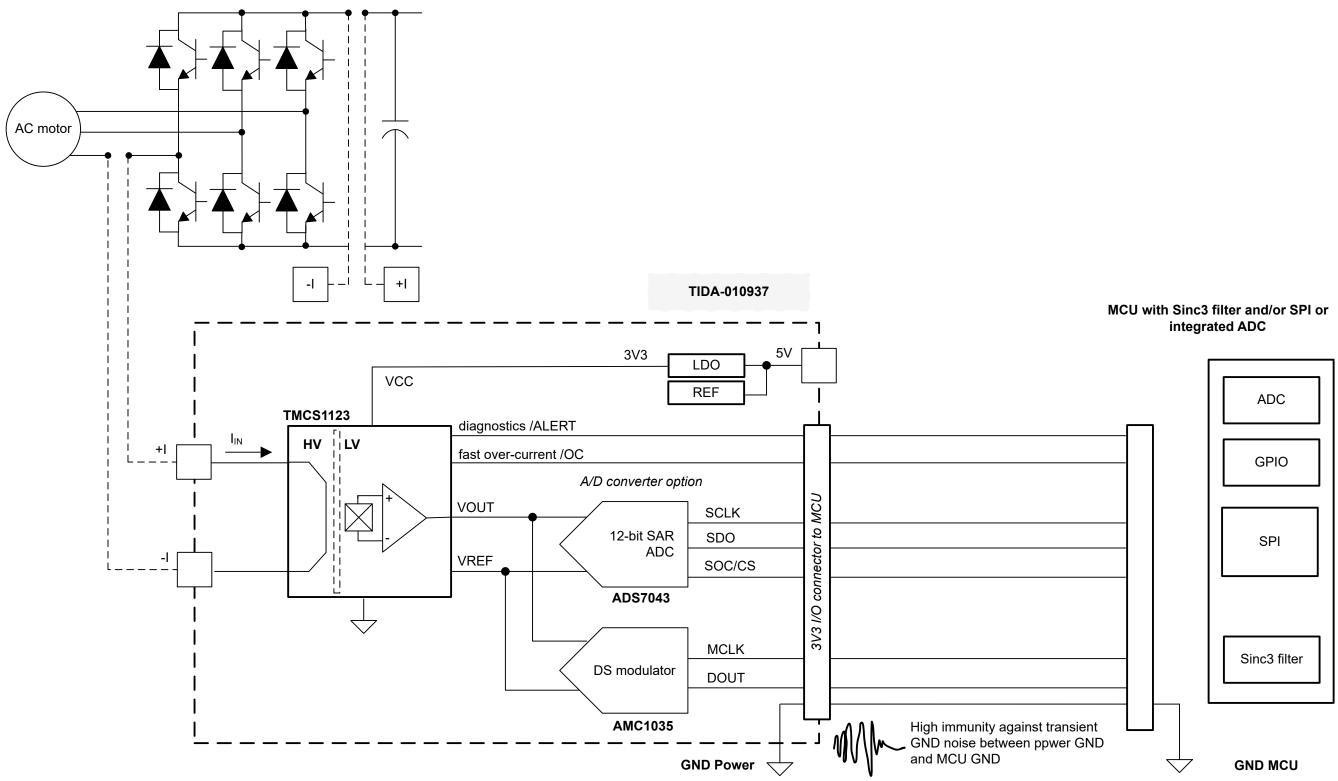


Figure 2-1. System Block Diagram

2.2 Design Consideration

This reference design can be used for both isolated bidirectional phase current sensing and isolated DC-link current sensing in 3-phase inverter applications such as AC inverters and variable frequency drives. The TMCS1123 or TMC1126 precision Hall-effect current sensors can be evaluated with various sensitivity options with up to ±62A linear and ±66A maximum full-scale range at 3.3V supply. The overcurrent threshold is configurable up to 2.5-times the full-scale input current range and an overcurrent signal with optional, configurable glitch filter is available for fast and reliable overcurrent detection. A small form factor 12-bit A/D converter with high-speed SPI or a delta-sigma modulator with up to 21MHz clock offer a high noise immunity 3.3V I/O digital interface. The interface connects to host processors like a C2000 or Sitara MCU for easy performance evaluation of in-package Hall-sensors with different A/D conversion technologies.

2.3 Highlighted Products

The TIDA-010937 reference design features the following key devices from Texas Instruments.

2.3.1 TMCS1123

The TMCS1123 is a high-accuracy, reinforced isolated Hall current sensor for in-phase or DC-bus current sensing and overcurrent detection:

- High accuracy, low drift (0.5% lifetime) with wide range of measurable current ranges from ±16A to ±96A
- Integrates overcurrent detection, fast OC response time and sensor fault diagnostics enhance system-level safety
- 5kV reinforced isolation and ±1300V reinforced working voltage
- Integrates V_{REF} for pseudo-differential sampling with A/D converter
- Fixed sensitivity allows the TMCS1123 to operate from a single 3V to 5.5V power supply, eliminates ratiometry errors, and improves supply noise rejection
- Extended industrial temperature range: –40°C to +125°C

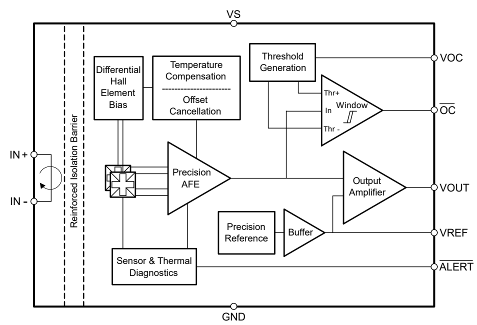


Figure 2-2. TMCS1123 Functional Block Diagram

2.3.2 ADS7043

The ADS7043 is a 1MSPS, 12-bit, analog-to-digital converter (ADC) with ultra-small package and is easy to use. The device complies with the JESD8-7A standard for normal DVDD range (1.65V to 1.95V).

- Supports pseudo-differential input and a wide differential analog input voltage range (±0.825V to ±1.8V)
- Wide digital supply range (1.65V to 3.6V)
- 1.5mm × 1.5mm QFN package supports space-constrained designs
- High-speed 16MHz SPI with < 1µs latency from start of conversion to SPI transfer complete

2.3.3 AMC1035

The AMC1035 is a precision delta-sigma (ΔΣ) modulator that operates from a single 3.0V to 5.5V supply and is optimized for voltage sensing:

- 16 bits of resolution with a dynamic range of 87dB at a data rate of 82kSPS can be achieved when used with a digital filter
- Selectable Manchester encoded or uncoded bitstream output
- Extended industrial temperature range: –40°C to +125°C

2.3.4 REF2033

The REF20xx is a precision voltage reference for ADC. The excellent temperature drift (8ppm/°C, maximum) and high initial accuracy (0.05%) increase the precision of signal chain. The key features for REF20xx are:

- Dual reference output pins to bias multiple device
- Low temperature drift 8ppm/°C increases the accuracy of the system
- Compact SOT23-5 package to reduce system board space

3 System Design Theory

Hall-effect current sensors like the TMCS1123 offer several advantages over shunt-based designs for reinforced isolated current sensing and overcurrent detection in 3-phase inverters. There is no need for a shunt or for an isolated bias supply, thus reducing system cost and PCB space. Another advantage is the very low analog signal propagation delay of 600ns (TMCS1123), and fast overcurrent detection (<0.5µs), where the overcurrent threshold can be up to 2.5-times the full-scale input current range.

Table 3-1. Brief Comparison of Isolated Semiconductor Current Sensing Designs

PARAMETER	TMCS1123	AMC1300	AMC1306M05	AMC23C11
Description	Hall-effect sensor	Isolated amplifier	Isolated modulator	Isolated comparator
ENOB (TYP)	≤ 10(1)	≤ 11	> 12(2)	N/A
Propagation delay	0.6µs	1.7µs	4.8µs(2)	N/A
Interface	Analog	Analog	Digital	Digital
Isolated supply required	No	Yes	Yes	Yes
OC response time	0.1µs	2.4µs	1.2µs(3)	300ns

(1) ENOB typically depends on the full-scale range, see Table 3-2
(2) With Sinc3 OSR 64 decimation filter
(3) With Sinc3 OSR 8 decimation filter

Other than shunt-based designs, the signal-to-noise ratio with in-package Hall-effect sensors scale with the full-scale current range of the Hall sensors, since the input referred noise density is independent of the device sensitivity and therefore, the input current range. Table 3-2 outlines the calculated ENOB over the full-scale range of the device with a 250kHz cutoff frequency, and a brick-wall factor of 1.22 to estimate the effective noise bandwidth.

Table 3-2. Estimated ENOB With TMCS1123 Device Variants

PARAMETER	TMCS1123B1A	TMCS1123B2A	TMCS1123B3A
Input Noise Density	170µA/√Hz	170µA/√Hz	170µA/√Hz
FSR (MAX)	±66A	±33A	±22A
SNR (DC)	57dB	51dB	47dB
ENOB (DC)	9.2	8.2	7.6

3.1 Hall-Effect Current Sensor Schematic Design

The TMCS1123 offers ±1300V reinforced working voltage with ≥ 8mm clearance and creepage. The zero-current output for TMCS1123Bx, when supplied with 3.3V is 1.65V so it is intended for bidirectional current sensing with a unipolar full-scale analog output from 0V to 3.3V. The TMCS1123Bx variants differ in sensitivity and support a wide current measurement range from ±10.3A to ±62A, with a 3.3V supply.

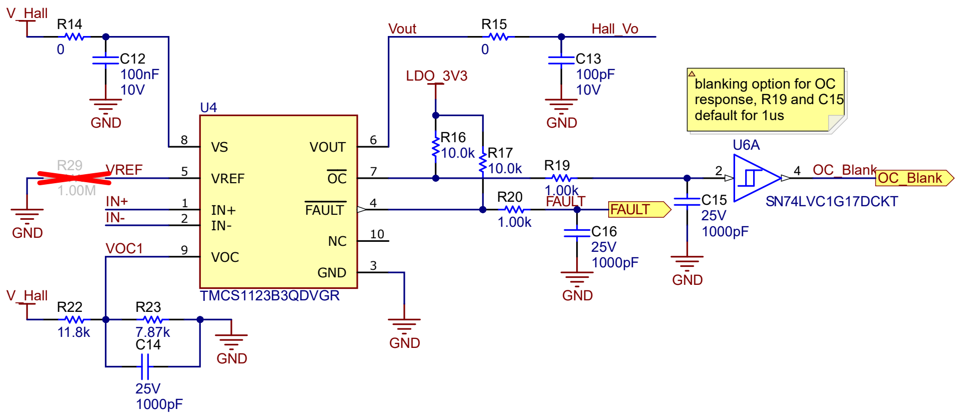


Figure 3-1. Hall Sensor TMCS1123 Schematic

In this reference design, TMCS1123B1 is used for DC and AC noise tests, the B3 version is used for noise immunity, overcurrent detection and latency tests. For the B1 version, the sensitivity is 25mV/A and the linear input current range is ±62A. For the B3 version, the sensitivity is 75mV/A and the linear input current range is ±20.7A. The V_{REF} pin outputs a constant 1.65V, and can be connected to the negative input of ADC and form a pseudo-differential input which helps improve the immunity to noise.

Both OC and FAULT pin are open-drain output, so a pullup resistor is needed. In this design, the OC pin and FAULT pin are connected to the 3.3V supply through a 10kΩ pullup resistor. For the OC pin the Schmitt trigger SN74LVC1G17 is used to filter out the noise and avoid a false trigger, R_{19} and C_{15} blank the noise and default delay t_d can be calculated using Equation 1:

$$t_d = R_{19}C_{15} = 1\mu s \quad (1)$$

V_{OC} is used for overcurrent detection threshold setting. V_{OC} can be calculated with Equation 2:

$$V_{OC} = \frac{S \times I_{OC}}{2.5} \quad (2)$$

where

- S is sensitivity of the Hall sensor. For TMCS1123B1, S = 25mV/A, For TMCS1123B3, S = 75mV/A
- I_{OC} is the overcurrent threshold.

To set a 40A threshold, V_{OC} needs to be 1.2V.

The resistor divider R_{22} and R_{23} can be calculated with Equation 3:

$$\frac{R_{23}}{R_{22} + R_{23}} = \frac{V_{OC}}{V_s} \quad (3)$$

Select 7.87kΩ as R23, R22 needs to be 13.77kΩ.

3.2 Analog-to-Digital Converter

For the A/D conversion, this design uses a SAR ADC ADS7043 and a delta-sigma modulator AMC1035 and compares the performance with the TMCS1123 between the two conversion methods. 0Ω resistors and jumpers are used to select which of the two ADCs are active and connected the output of the TMCS1123 Hall-effect sensor.

Jumpers J_4 and J_{10} are used for signal path selection. J_4 is used for the V_{REF} path selection of the TMCS1123; J_{10} is used for the output voltage path selection of the TMCS1123. Both for J_4 and J_{10}, connecting J_1 and J_2 connects the signal to AMC1035, connecting J_2 and J_3 connects the signal to ADS7043.

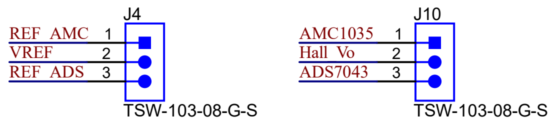


Figure 3-2. Signal Path Selection Jumper

3.2.1 Delta-Sigma Modulator

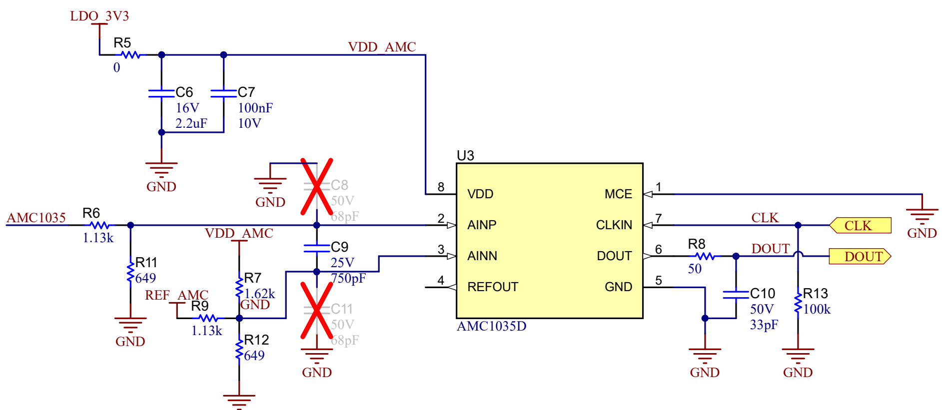


Figure 3-3. AMC1035 Schematic

3.2.1.1 Common-Mode Voltage Limit

When the output of the TMCS1123 is connected directly to the ADC input, the common mode input voltage range of the corresponding ADCs needs to be met, to not impact the performance of the ADC.

For the AMC1035, the common input voltage range is –0.8V to 0.9V and differential input voltage range is –1V to 1V. An additional resistor divider is needed. IN+ and IN- are the input voltages of resistor divider, K is resistor divider ratio. K range can be calculated using Equation 4 and Equation 5:

$$-1V < K \times (IN_+ - IN_-) < 1V \tag{4}$$

$$-0.8V < \frac{K \times (IN_+ - IN_-)}{2} < 0.9V \tag{5}$$

The differential voltage (IN_+ – IN_-) is in the range of –1.65V to 1.65V, and common mode voltage (IN_+ + IN_-)/2 is in the range of 0.825V to 2.475V, so K needs to be less than 0.364. Make K equal to 0.36 and select 649Ω as R_{11}, R_{12}, thus R_6 and R_9 need to be 1.13kΩ.

3.2.1.2 Input Filter

To further reduce the high-frequency noise of the system, use an external anti-aliasing input filter.

R_6, R_{11}, R_9, R_{12}, and C_9 form the input filter for the AMC1035. Choose 500kHz as the filter bandwidth to provide 26dB attenuation at 10MHz. The resistors and capacitors can be calculated through Equation 6:

$$\frac{1}{2\pi(R_6 /\!\!/ R_{11} + R_9 /\!\!/ R_{12})C_9} = BW \quad (6)$$

R_6, R_9, R_{11}, and R_{12} are calculated in Section 3.2.1.1, put these values in Equation 6 and C_9 calculates to be 750pF.

3.2.1.3 Interface to MCU

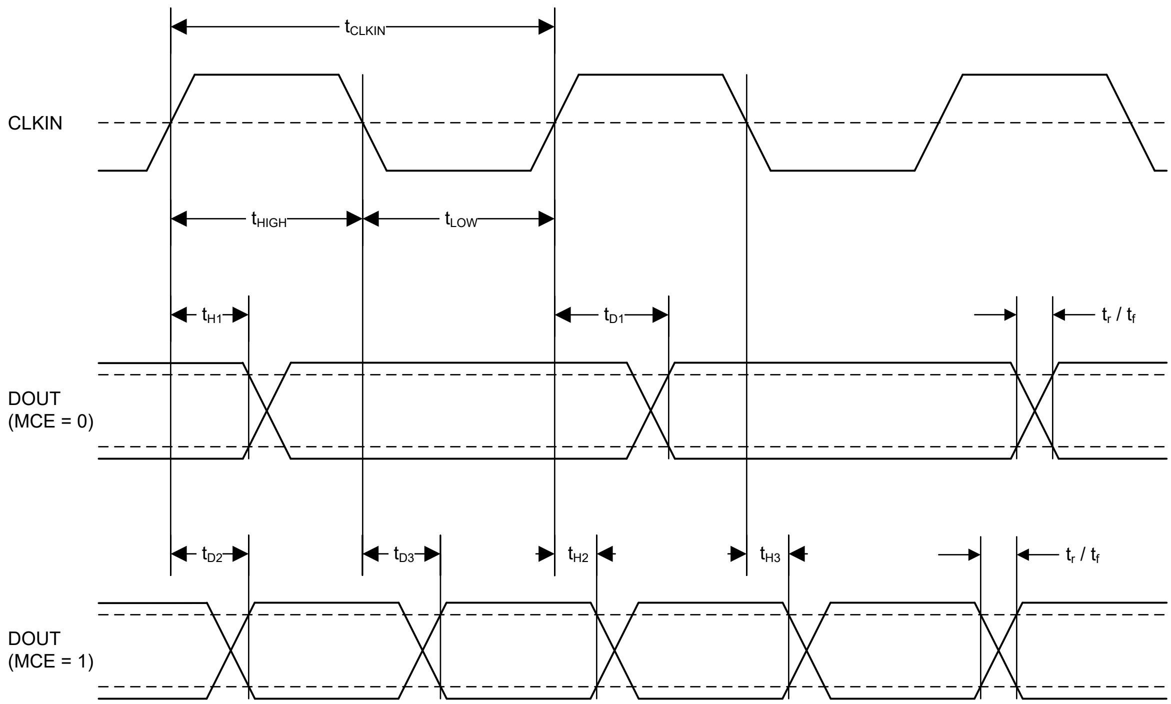


Figure 3-4. AMC1035 Digital Interface

AMC1035 is connected to the SDFM module of the F28379D, CLK is the input pin for the AMC1035 and is connected to ground through a 100kΩ pulldown resistor. DOUT is the output pin, R8 is a 50Ω line-termination resistor and C10 is an optional capacitor to control the signal slew rate.

3.2.2 12-bit SAR ADC

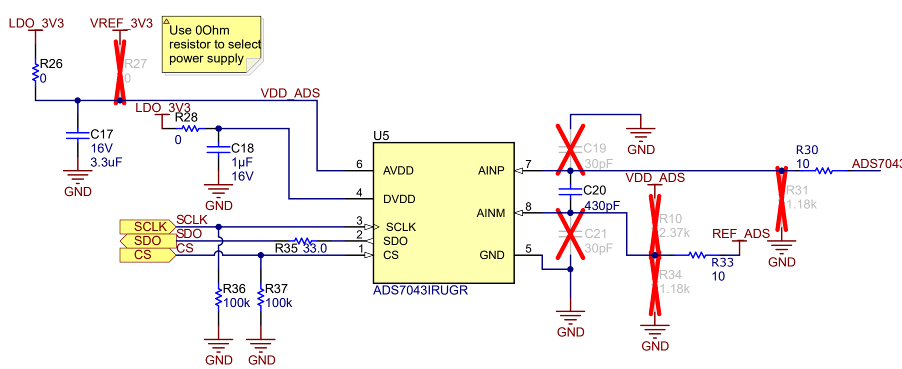


Figure 3-5. ADS7043 Schematic

3.2.2.1 Common-Mode Voltage Limit

The ADS7043 is a pseudo-differential input ADC, the negative input range is 1.55V to 1.75V (3.3V supply), the positive input range is –0.1V to 3.4V. The 1.65V V_{REF} and 0V–3V V_{OUT} of the TMCS1123 are acceptable for ADS7043 and no additional resistor divider is needed.

R_{10} and R_{34} form an optional resistor divider when the V_{REF} is not available, R_{30} and R_{31} form an optional resistor divider when the higher output range Hall sensor is connected to the ADC. R_{10}, R31 and R_{34} are not soldered on the board by default.

3.2.2.2 Input Filter

The anti-aliasing input filter is also needed for ADS7043. In Figure 3-4, R_{30}, R_{33}, and C_{20} form the input filter. Likewise with the AMC1035, the resistors and capacitors can be calculated using Equation 7:

$$\frac{1}{2\pi(R_{30} + R_{33})C_{20}} = BW \tag{7}$$

Choose 500kHz as filter bandwidth and a 430pF differential capacitor as C_{20}, R_{30} and R_{33} need to be 10Ω.

3.2.2.3 Interface to MCU

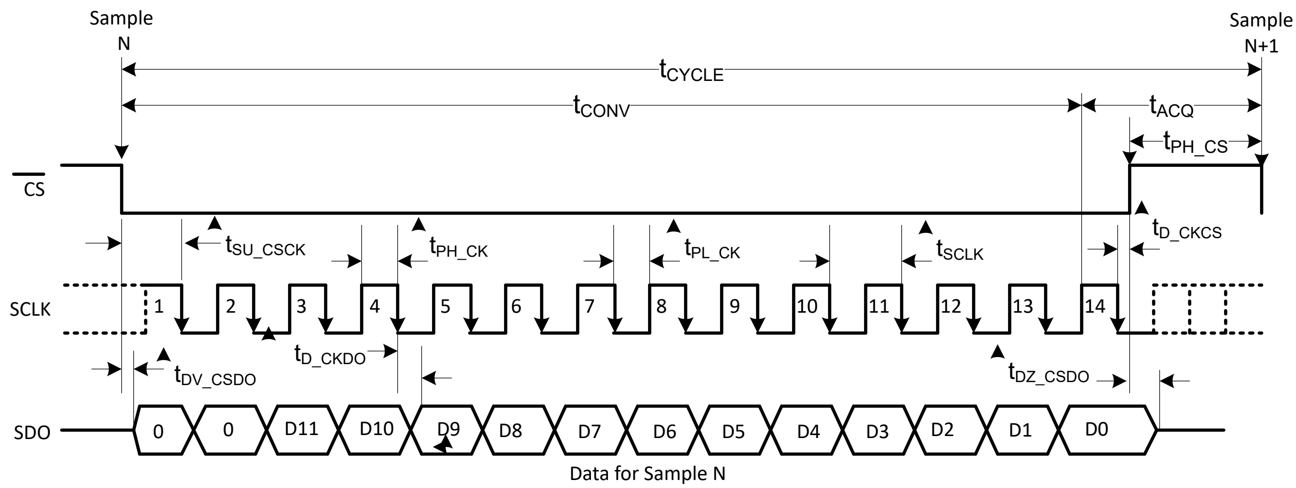


Figure 3-6. ADS7043 SPI

ADS7043 is connected to F28379D through the SPI. The SCLK and CS pins make up the output port for ADS7043, so 100kΩ pulldown resistors R_{36} and R_{37} are used to avoid floating and getting invalid data. SDO is the output pin for ADS7043, a 33Ω terminating resistor is placed to provide the signal integrity.

Figure 3-6 shows the ADS7043 SPI waveform. During the SPI transmission, CS is pulled down first and the transmission starts. SDO outputs the digital signal with the first two bits set to 0, followed by 12 bits of the conversion result. Then CS is pulled up and the transmission stops.

3.3 Power Supply and Reference Voltage

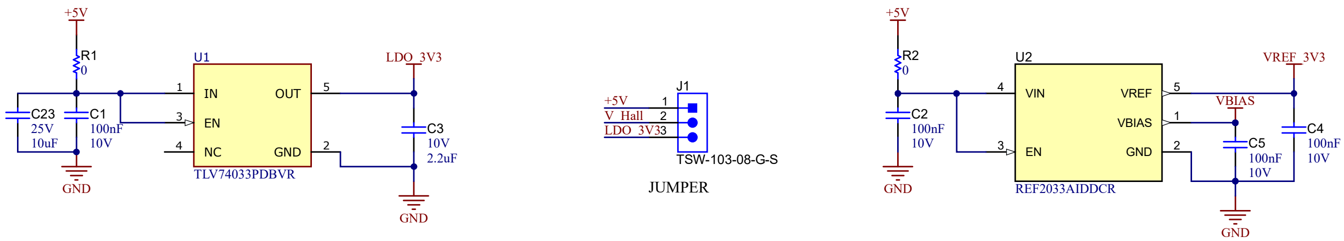


Figure 3-7. Power Supply Schematic

TLV74033 and REF2033 are used in this design to power the devices on the board. For TLV74033, the device accepts up to 5.5V input voltage and generates a 3.3V rail for TMCS1123, ADS7043, and AMC1035 supply. Two parallel capacitors C_{23} (10µF) and C_1 (100nF) are needed for noise decoupling, an output capacitor C3 (2.2µF) is needed for stable operation.

For REF2033, the device is powered by an external 5V supply and generates precise 3.3V output. This method can be an option to power the ADS7043 and perform as the reference of the ADC; conversely, the device can be connected to ADS7043 and to the negative input pin of the AMC1035 to form a pseudo-differential input in case the Hall sensor does not provide the reference output. Similarly with the TLV74033, C_2 (100nF) is needed for decoupling and C_4 and C_5 (100nF) are used for stable operation.

The TMCS1123 can accept 3V to 5.5V supply voltage. In this design, the external 5V and the 3.3V output of the TLV74033 is designed for the supply source of the sensor. J_1 is used for the power supply selection of the Hall sensor.

4 Hardware, Software, Testing Requirements, and Test Results

4.1 Hardware Requirements

Figure 4-1 and Figure 4-2 outline the printed-circuit-board (PCB) top view and bottom view with the key devices, input current, and I/O connectors to interface to an MCU and the jumpers to configure the design.

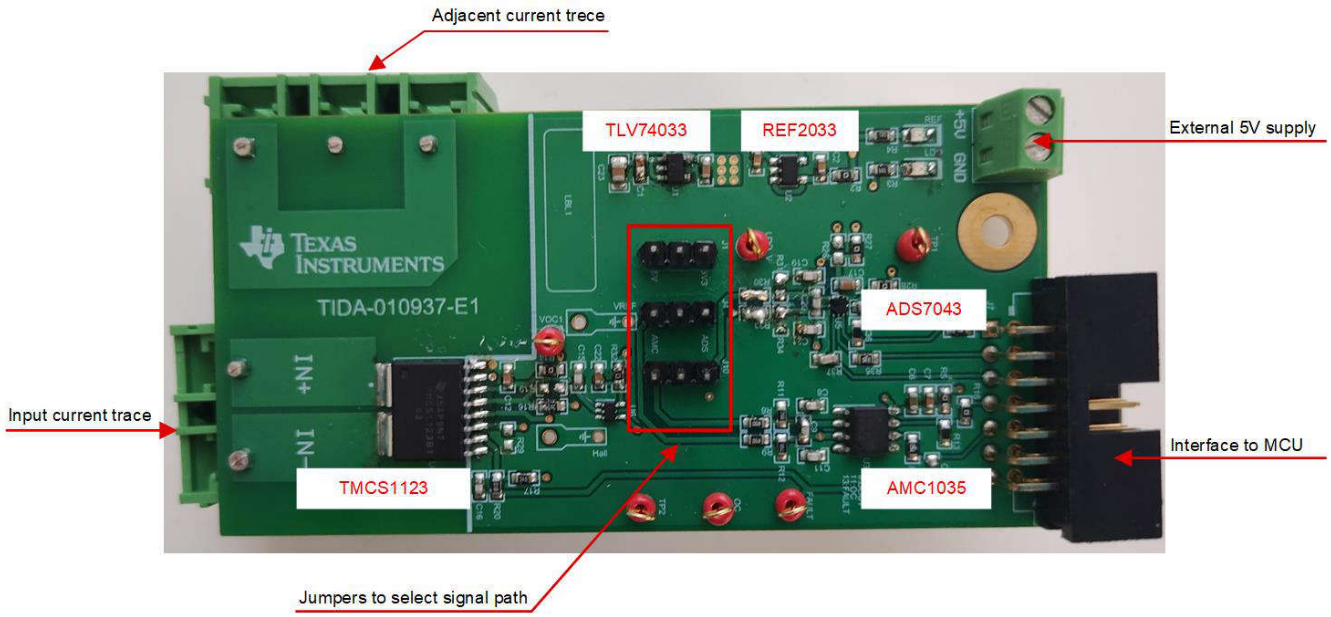


Figure 4-1. TIDA-010937 PCB Top View

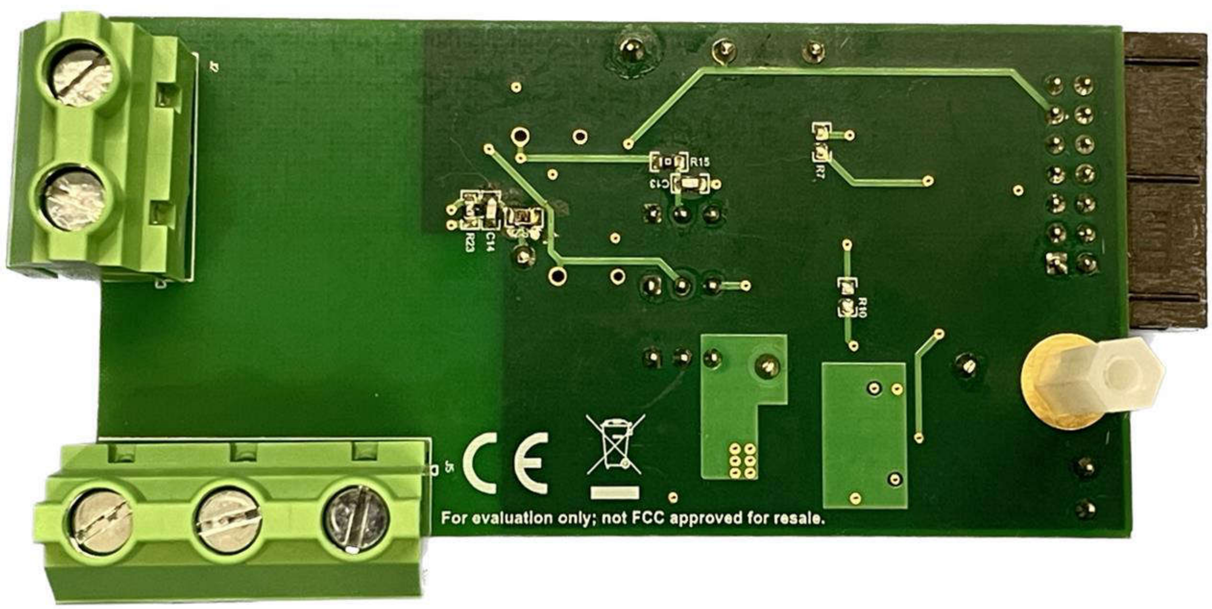


Figure 4-2. TIDA-010937 PCB Bottom View

The headers and default jumper settings are explained in Table 4-1 and Table 4-2.

Table 4-1. Default Resistor and Jumper Settings

HEADER, RESISTOR	JUMPER, RESISTOR SETTING
J1	Connect to 3.3V power supply
J4	Connect to ADS7043
J10	Connect to ADS7043
R26, R27	Populate R27 to choose 3.3V supply from REF2033

Table 4-2. Host MCU Interface J7

HEADER	SIGNAL	I/O
J7-1	SCLK for ADS7043	3.3V input
J7-3	SDO from ADS7043	3.3V output
J7-5	CS for ADS7043	3.3V input
J7-7	CLK for AMC1035	3.3V input
J7-9	DOUT from AMC1035	3.3V output
J7-11	OC from TMCS1123	3.3V output
J7-13	FAULT from TMCS1123	3.3V output

4.2 Software Requirements

TI internal test software was developed to validate the TIDA-010937 design for the TMS320F28379D device. The corresponding LaunchPad™ Development Kit was used. This software is not available for public use. For C2000 software support, see the MotorControl software development kit (SDK) for C2000™ and the TI E2E™ design support forum for C2000™ microcontrollers.

4.3 Test Setup

Table 4-3 lists the test equipment used to test this reference design. Figure 4-3 illustrates the test setup.

Table 4-3. Test Equipment

TEST EQUIPMENT	PART NUMBER
High-speed oscilloscope	MSO4104B
Single-ended probes	P2220
Current probe	CP8030H
DC source	GPS-4303C
High voltage DC source	6260-600
DC electronic load	IT8501
Signal generator	AFG3252
Multimeter	34401A
Thermal chamber	VT4002
Thermal imager	TIS55

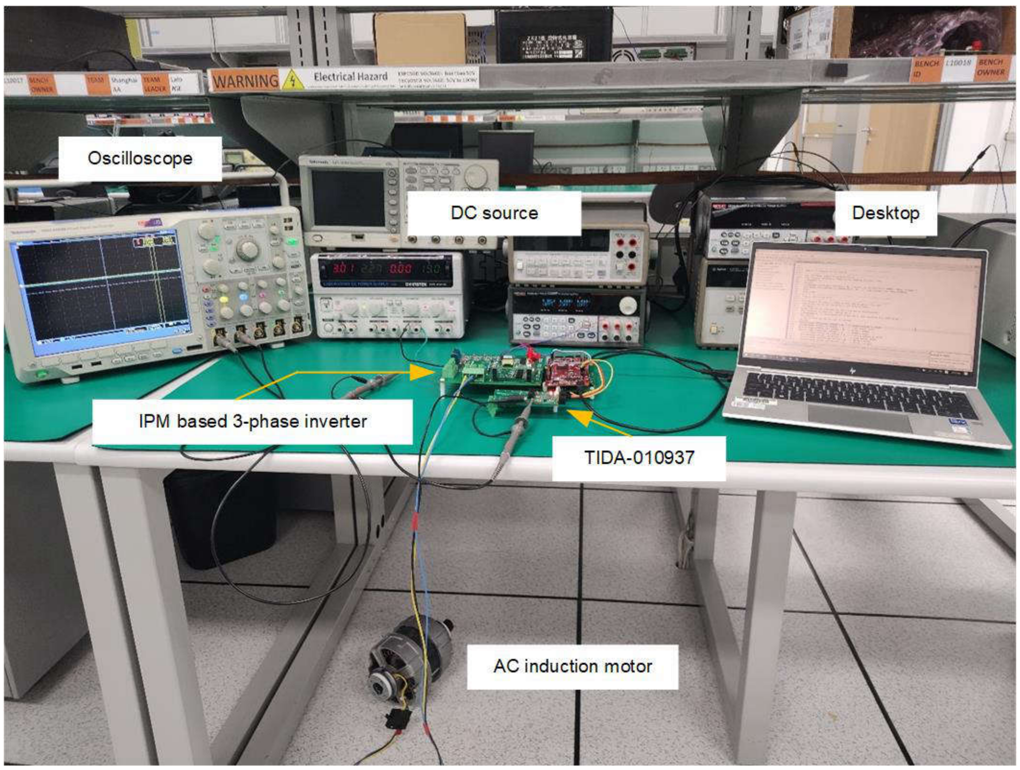


Figure 4-3. Test Setup

4.3.1 Precautions

This reference design is a reinforced isolated in-phase current sensing using the TMCS1123 for a 3-phase inverter. The input common mode voltage can be up to 600V_{DC} (MAX); therefore, the PCB is exposed to voltages above 60V_{DC} and 25V_{AC} so extreme care must be exercised while testing.

This reference design is meant for exploring TI's technology in a lab space only and to be used by professional engineers, who are qualified to work with high voltage. Users must make sure proper high-voltage safety precautions are observed before and while testing. Do not directly handle any exposed terminals (high voltage or otherwise) while the power is turned on. All connections must be done while the reference design is de-energized and not powered-up. Even during operation at room temperature around 25°C, some components and parts of the PCB surface can reach temperatures higher than 100°C. A high temperature warning symbol is added to the PCB. Do not touch the PCB as contact can cause burns. After removing power from the PCB, let the PCB cool down for some time before handling the board again.

WARNING

Danger! High Voltage. Electric shock is possible when connecting the board to live wire. The board must be handled with care only by a professional person, qualified to work with high voltage. For safety, use of isolated test equipment with overvoltage and overcurrent protection is highly recommended.

WARNING

Hot surface! Contact can cause burns. Do not touch!

WARNING

Do not leave the board powered when unattended.

4.4 Test Results

4.4.1 DC Performance

DC performance testing focuses on effective output noise performance with either SAR ADC ADS7043 or delta-sigma modulator AMC1035 using a Sinc^3 OSR64 filter with the 2000 MCU. In this test, the effective output noise of both the TMCS1123B1 and TMCS1123B3 versions after the A/D conversion were measured and the ENOB is calculated. For TMCS1123B1, the full-scale range is ±66A; for TMCS1123B3, the full-scale range is ±22A.

4.4.1.1 Output Voltage Noise and ENOB After A/D Conversion

The DC noise measurement was conducted at 0A current, using ADS7043 and AMC1035 to sample the output voltage of the TMCS1123 at 10kHz, and then scale the sampled voltage to the effective input current. Figure 4-4 to Figure 4-7 show the effective output noise with TMCS1123 after A/D conversion. The effective output noise with the delta-sigma modulator AMC1035 is lower since the Sinc^3 OSR 64 filter has a 80kHz cut-off frequency and hence reduce the noise floor versus the SAR ADC.

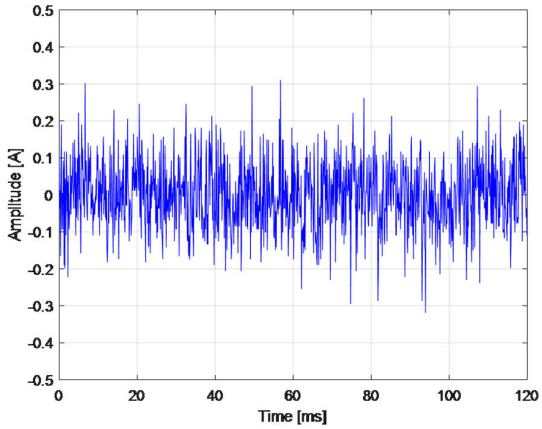


Figure 4-4. TMCS1123B3 Effective Noise at 0A Input After A/D Conversion (ADS7043)

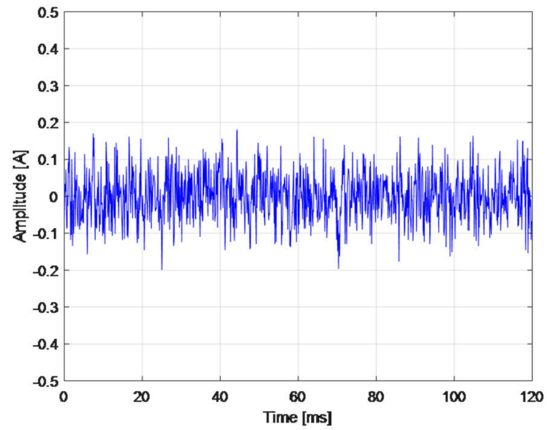


Figure 4-5. TMCS1123B3 Effective Noise at 0A Input After A/D Conversion (AMC1035, $Sinc^3$ OSR64)

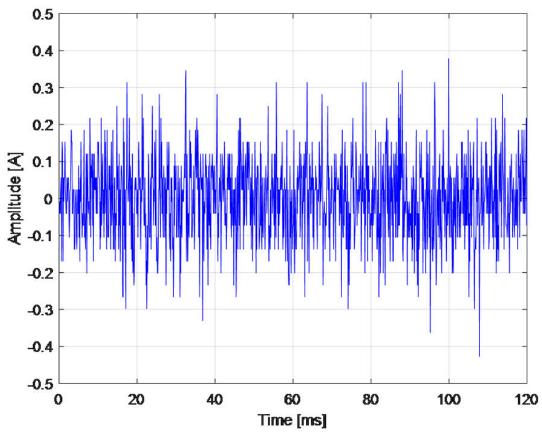


Figure 4-6. TMCS1123B1 Effective Noise at 0A Input After A/D Conversion (ADS7043)

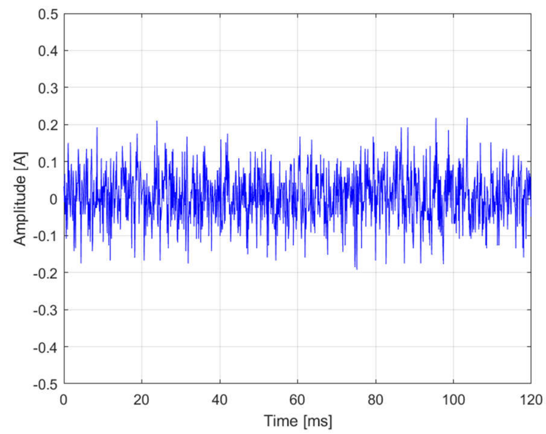


Figure 4-7. TMCS1123B1 Effective Noise at 0A Input After A/D Conversion (AMC1035, $Sinc^3$ OSR64)

Calculate the ENOB according to the noise root mean square (RMS) value, the results are listed in Table 4-4.

Compare the noise results of the TMCS1123B3 and TMCS1123B1 devices, when ADS7043 is used. The input noise RMS for the B1 version is 110.13mA, 20% larger than the B3 version, but the full-scale range of the B1 version is 3 times larger, so ENOB for B1 is 8.93 bits, 1.4 bits higher than the B3 version.

Compare the results of the ADS7043 and AMC1035 devices. Using the Sinc filter can significantly help to reduce the noise for both the B1 and B3 versions. When using TMCS1123B1 and AMC1035, 64 times OSR $Sinc^3$ filter helps reduce 38% noise and gains 0.7 bits ENOB compared with the results of the ADS7043.

Table 4-4. ENOB Test Results

DEVICE	TMCS1123B3 (±22A)		TMCS1123B1 (±66A)	
ADC	ADS7043	AMC1035 $Sinc^3$ OSR = 64	ADS7043	AMC1035 $Sinc^3$ OSR = 64
Output noise RMS/mA	91	64	105	68
SNR /dB	48	51	56	60
ENOB (DC)/bit	7.6	8.1	9.0	9.7

4.4.1.2 Linearity and Temperature Drift

In real systems, the ambient temperature usually changes significantly. The gain and offset of the sensor also changes with temperature, resulting in increased measurement errors. Calibration is necessary to improve test accuracy. In this section, the drift test is done under 25°C and 85°C, calibration is only done based on test data under 25°C.

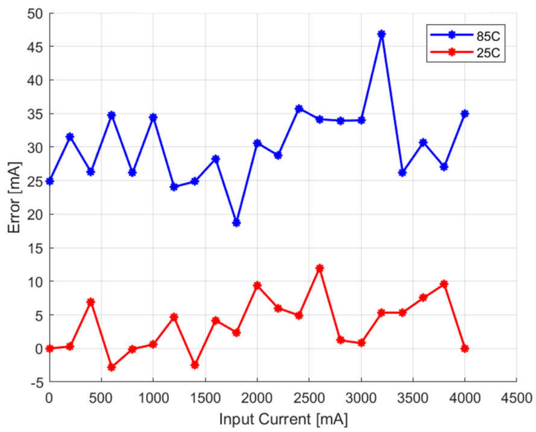


Figure 4-8. Linearity Error With Calibration at 25°C

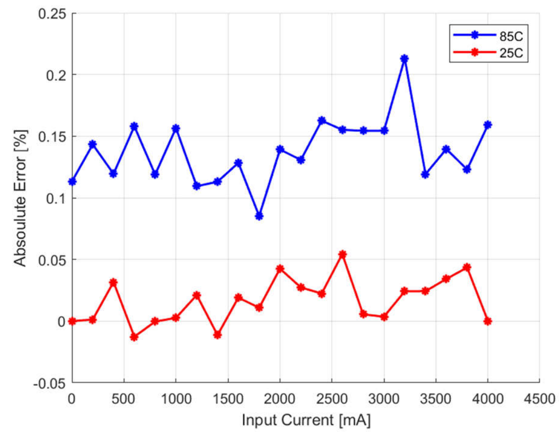


Figure 4-9. Absolute Error With Calibration at 25°C

At each test point, 1200 samples are records and averaging is done to filter out the noise influence. Under 25°C, after the calibration the maximum linearity error is 12mA which means 0.058% absolute error. When the temperature rises to 85°C, offset rises to 27mA. After calibration, the maximum error is 46.9mA which means 0.23% absolute error. The offset drift can be calculated using Equation 8:

$$\text{offset drift} = \frac{\Delta \text{offset}}{\Delta \text{T}} = \frac{27\text{mA} \times 75\text{mV/A}}{60°\text{C}} = 33.7\mu\text{V/°C} \tag{8}$$

Offset drift is close to the maximum value of the data sheet (35µV/°C), this is because the chip under test is an engineering sample, which is single-temperature-point trimmed. The mass-produced devices are multi-temperature point trimmed, which helps greatly improve the drift performance.

4.4.2 AC Performance

The AC performance test is mainly focused on the SNR at small input current and latency between input current and output voltage. To test these items, a voltage-to-current converter using OPA541 is built to generate a current wave with a signal generator. For SNR test, a 50Hz, 1.5A peak sinusoidal current is generated; for the latency test, a 10kHz, 3A peak square wave current is generated. Figure 4-10 shows the block diagram of the test setup.

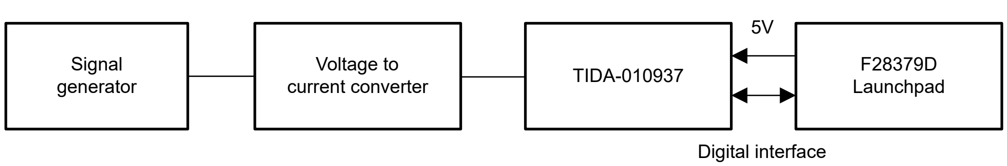


Figure 4-10. AC Performance Test Setup

4.4.2.1 SNR Measurement

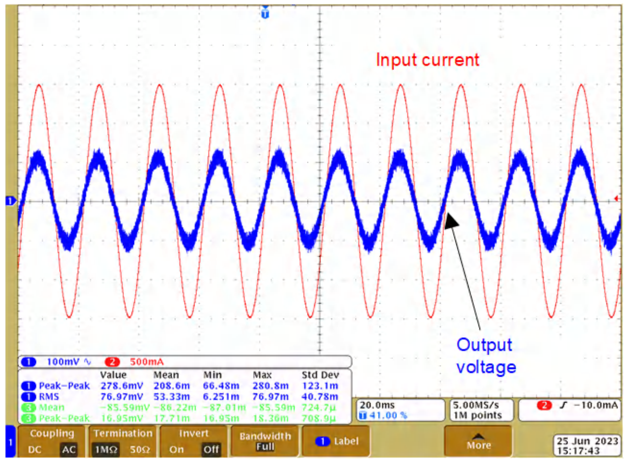


Figure 4-11. Input Current and Output Voltage Waveform (B3 version)

By adjusting the output of the signal generator, the power amplifier board outputs 1.5A, 50Hz sinusoidal current and injects the current into the TMCS1123. In Figure 4-11, the red curve shows the waveform of the input current and the blue curve shows the output voltage of TMCS1123.

At a 1.5A sinusoidal input current, the effective signal-to-noise ratio was measured around 23.6dB. Considering the entire full-scale range ±22A, the SNR is around 47dB and the ENOB is 7.5 bits. The measurement with the AMC1035 and a Sinc^3 OSR 64 filter (80kHz cut-off frequency) shows a 2.6dB higher SNR and 0.4-bit higher ENOB than the results with the SAR ADS7043. The B1 version shows 1.1-bit higher ENOB than the B3 version due to the higher full-scale range, while the TMCS1123 input noise density is almost the same.

Table 4-5. SNR and ENOB Test Under Low-Input Current

DEVICE	TMCS1123B3 (±22A)		TMCS1123B1 (±66A)	
ADC	ADS7043	AMC1035 Sinc^3 OSR=64	ADS7043	AMC1035 Sinc3 OSR=64
SNR at 1.5A/dB	23.6	26.3	20.5	24.1
SNR at FSR/dB	47.0	49.6	53.4	57.0
ENOB (AC)/bit	7.5	7.9	8.6	9.2

4.4.2.2 Latency Test

Latency is an important parameter in a drive system, the delay between the real phase current and sampled current affects the bandwidth of the current loop which further affects the response time and stability of the system. To better show the input current and output voltage of the TMCS1123, a 10kHz, 3A square wave current is injected into TIDA-010937. Use the persistence mode of the oscilloscope to capture delay between 50% input and 50% output.

Figure 4-12 shows the latency between 50% input current and 50% output voltage, which shows a value of 300ns. The mismatch bandwidth of the current probe and the voltage probe also offsets around 200ns latency, so the total latency of TMCS1123 is around 500ns.

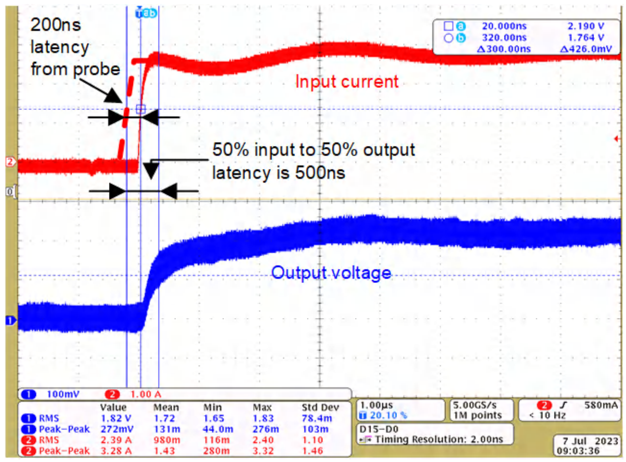


Figure 4-12. TMCS1123 Input Current and Corresponding Output Voltage

4.4.3 PWM Rejection

During PWM switching, the phase current suffers large common-mode voltage transients of up to 10kV/µs with an IGBT based 3-phase inverter, which can affect the accuracy of current sensor. Therefore the PWM rejection, also called common-mode transient immunity (CMTI) is an important parameter to provide accurate current measurement. To test the PWM rejection of the TMCS1123, a 3-phase inverter with $320V_{DC}$ bus (TIDA-010025) and an AC motor were used. The TMCS1123 on the TIDA-010937 was connected to the phase U of the 3-phase inverter and the software on the C200 MCU was configured to sample the phase current with the ADS7043 data converter over 1200 PWM periods, while continuously changing the start of conversion time of the ADC from the beginning of the PWM cycle to the end of the PWM cycle increasing the system-on-chip (SoC) in 60ns steps every new PWM cycle. This results in an equivalent 16MHz sampled current measurement over one PWM period. To make sure the current does not change over the 1200 PWM periods (10kHz PWM period), the current was impressed to 3A DC. The test setup is shown in Figure 4-13.

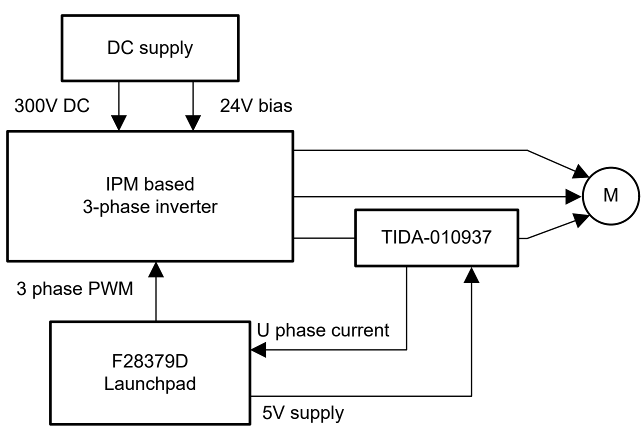


Figure 4-13. TMCS1123 PWM Rejection Test Setup

In Figure 4-14, the blue curve is the oscilloscope waveform of the output voltage and the red curve is the input current of the TMCS1123 measured with a current probe. The TIDA-010025 outputs a 3A average DC current. The small transient noise spikes are due to the oscilloscope being sensitive to the IGBT inverter PWM switching.

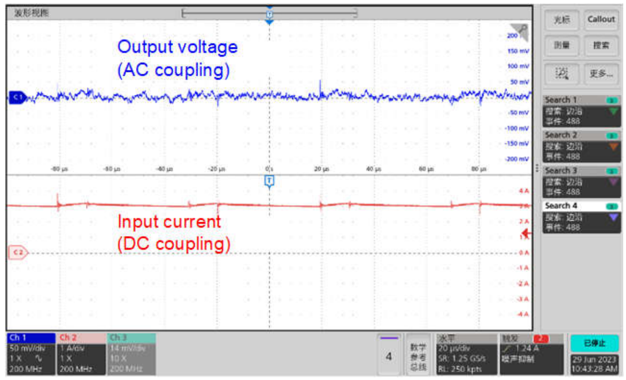


Figure 4-14. Oscilloscope Measurement of Output Voltage and Input Current of TMCS1123

Figure 4-15 shows the phase-current measurement (blue using the ADS7043 SAR ADC as explained earlier). The blue curve is the waveform of the U phase current measured with the time triggered ADS7043, as described earlier (16MHz equivalent sample rate) and the red curve is U phase voltage waveform. There is no ringing during PWM switching on the TMCS1123 output; therefore, the TMCS1123 also retains high accuracy during the PWM switching.

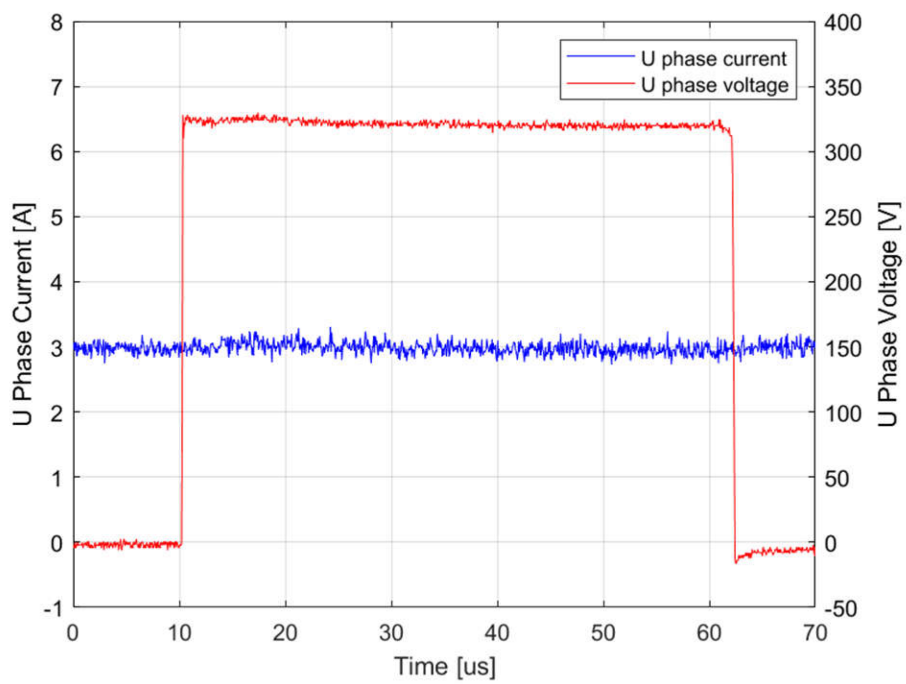


Figure 4-15. TMCS1123 Current Over One PWM Cycle Samples With Time Triggered ADS7043 ADC

4.4.4 Overcurrent Response

To generate a high-current pulse, a GaN-based half-bridge circuit LMG3422EVM is used. A top-level representation of the test setup is shown in Figure 4-16.

The LMG3422EVM features two LMG3422 600V GaN field-effect transistors (FET) with an integrated driver and protection in a half-bridge configuration with all the required bias circuits and logic or power level shifting. The GaN half-bridge generates a high slew rate output voltage pulse and a current limit resistor is used to set the peak value of the output current.

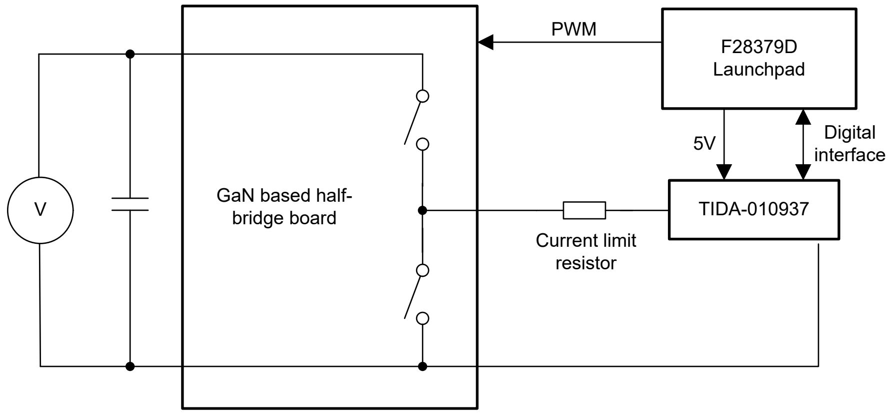


Figure 4-16. Overcurrent Response Test Setup

To validate the OC threshold, the DC bus voltage is adjusted to get the desired peak current injected into the TMCS1123. The results are shown in Figure 4-17 and Figure 4-18. The signal V_{OUT} is the analog output voltage of the TMCS1123 Hall sensor. V_{OC} is the analog input, which sets the overcurrent threshold to 37A. OC is an active low digital output, which goes low when an overcurrent is detected. When the peak current is 36.8A, OC is not triggered and when the current is increased to 37.2A, OC is triggered, so the threshold is around 37A.

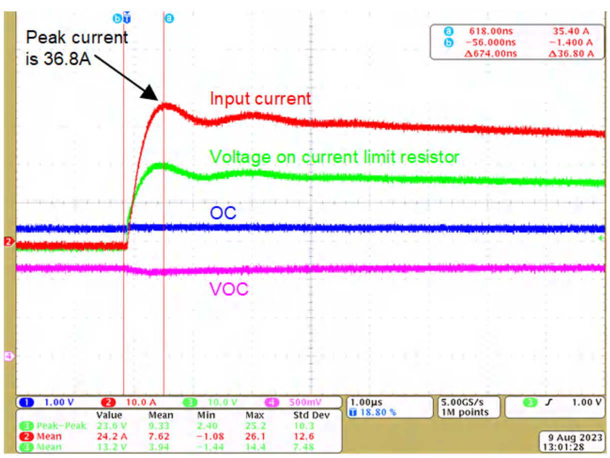


Figure 4-17. OC Threshold Check (Peak Current = 36.8A)

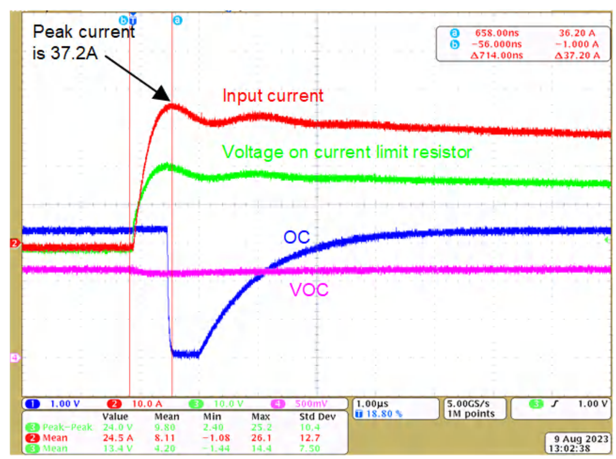


Figure 4-18. OC Threshold Check (Peak Current = 37.2A)

Next, continually increase the peak current and observe the OC waveform. In Figure 4-19, the peak current is 37.2A and OC is triggered when the current reaches to 36.8A. In Figure 4-20, the peak current is 57.6A and OC is triggered when current reaches to 37.2A. During current rise, there is slight drop in V_{OC}, which drops from 1.2V to 1.16V, meaning the theoretical threshold drops from 40A to 38.7A. The real threshold is 37A and is within the threshold tolerance in the data sheet. This test shows that the overcurrent response time of TMCS1123 is very fast, OC is triggered as soon as the current reaches the threshold.

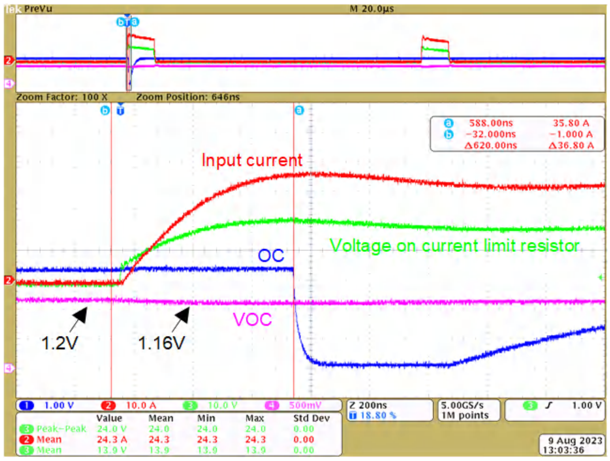


Figure 4-19. OC Response Test (Peak Current = 37.2A)

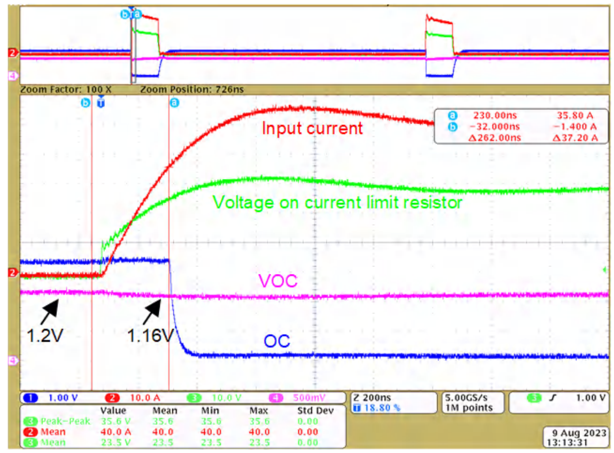


Figure 4-20. OC Response Test (Peak Current = 57.6A)

Observe the TMCS1123 output voltage behavior after the OC event, results are shown in Figure 4-21. V_{OUT} begins to fall 68ns after the OC event.

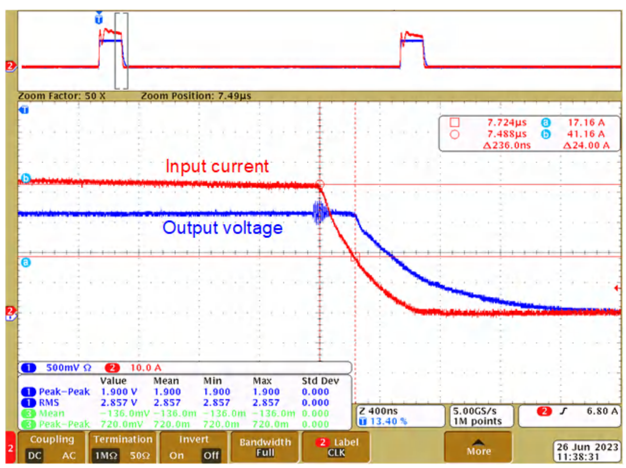


Figure 4-21. V_{OUT} Recovery Time After OC Event

4.4.5 Adjacent Current Rejection

For the adjacent current rejection test, the test setup is similar with OC response test. Please refer to Section 4.4.4 for details. The only difference is that the 40A current pulse is injected to the adjacent trace shown in Figure 4-22 to simulate the magnetic field interference.

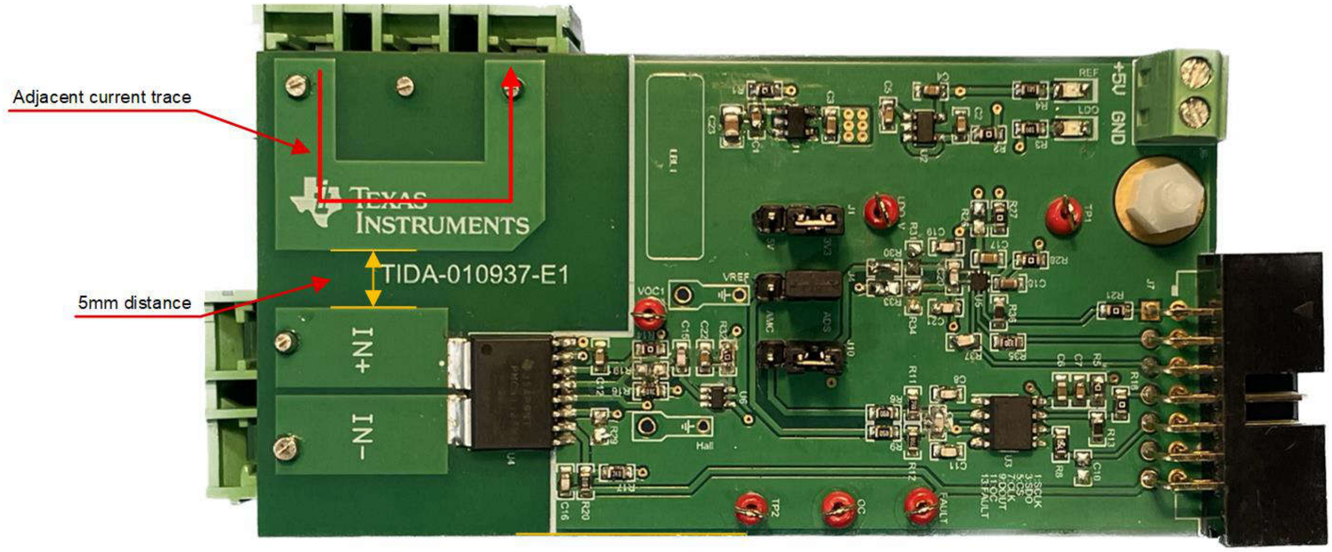


Figure 4-22. Adjacent Current Trace

From Figure 4-23, the 40A peak input adjacent current has no influence on the output voltage. There is no significant disturbance on output voltage at the adjacent current rising and falling edge. The output voltage is dominated by the output noise of the TMCS1123.

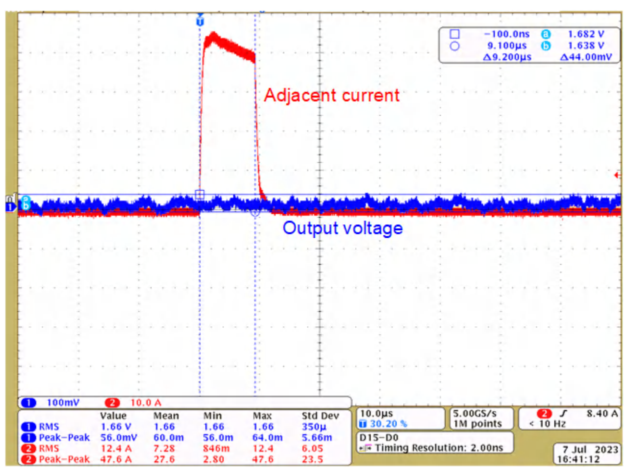


Figure 4-23. Adjacent Current and Output Voltage

4.4.6 Power Supply Rejection Ratio

Power supply noise usually adds extra noise on the output voltage of the Hall sensor, which reduces the accuracy of the sensor. Power supply rejection ration (PSRR) is an important parameter for Hall sensors. In PSRR tests, a 300mV, 100kHz peak-to-peak ripple is injected to the TMCS1123 supply voltage. The output voltage ripple of the TMCS1123 shows the ability to reject the power supply ripple. In this test, a DC power supply and signal generator are used to generate this ripple. The block diagram is shown as Figure 4-24.

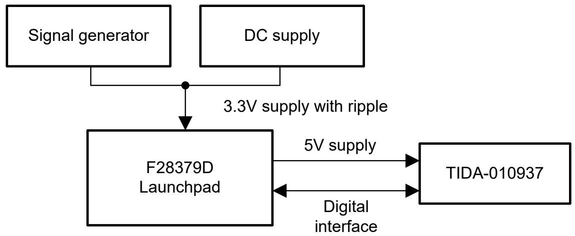


Figure 4-24. PSRR Test Setup

In Figure 4-25, the purple curve is the injected voltage ripple with a 320mV peak-to-peak value and 100kHz frequency. The scope plot shows the both the reference voltage V_{REF} and output voltage V_{OUT} of TMCS1123 have the same frequency ripple. Record the V_{REF} and V_{OUT} in 100ms, measure the peak-to-peak value of the waveform in 100ms and compare the value with the results under no power-supply ripple.

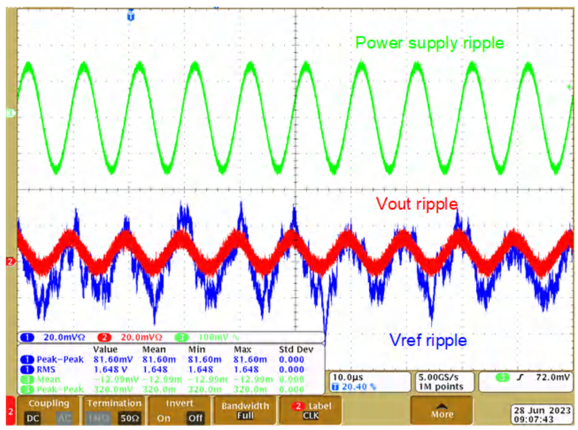


Figure 4-25. Power Supply Ripple, Reference Voltage, Output Voltage Waveform

The results are shown in Figure 4-26 and Figure 4-27.

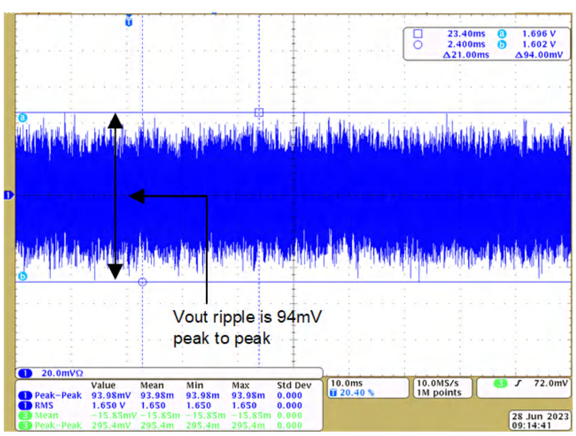


Figure 4-26. TMCS1123 Output Voltage vs GND at High Supply Voltage Ripple

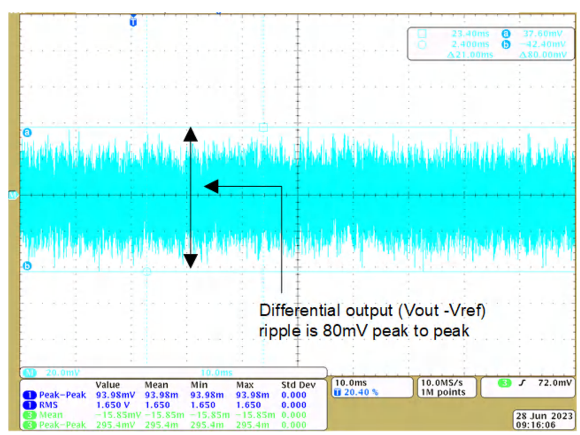


Figure 4-27. TMCS1123 Output Voltage vs V_{REF} High-Supply Voltage Ripple

When the power supply ripple is added, the ripple of V_{OUT} is $94mV_{PP}$ and differential output voltage ripple of $V_{OUT} – V_{REF}$ is 80mV, the differential output helps TMCS1123 to reduce output noise brought by power supply ripple and improve the measurement accuracy.

Plot the sampling data of the ADS7043 and AMC1035, which is shown in Figure 4-28 to Figure 4-31.

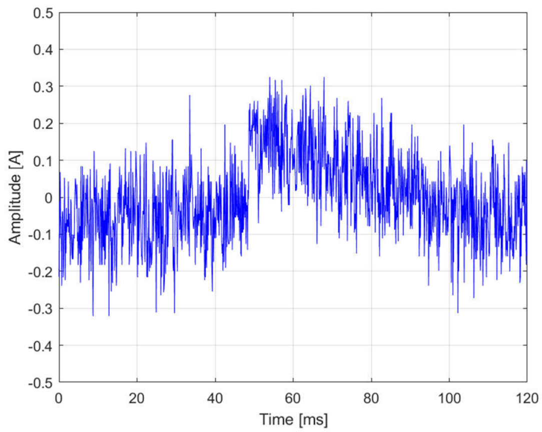


Figure 4-28. Output Noise With Supply Voltage Ripple (Sampled With ADS7043 at 10kHz)

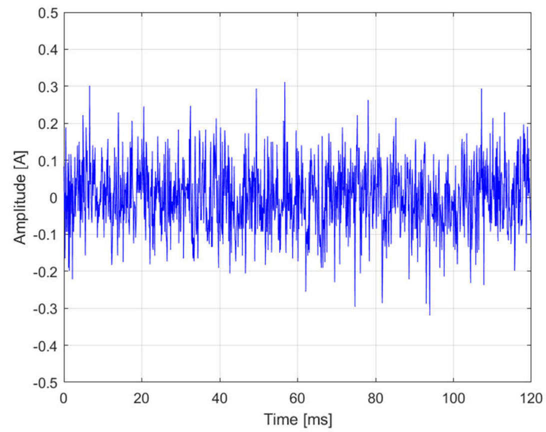


Figure 4-29. Output Noise no Supply Voltage Ripple (Sampled With ADS7043 at 10kHz)

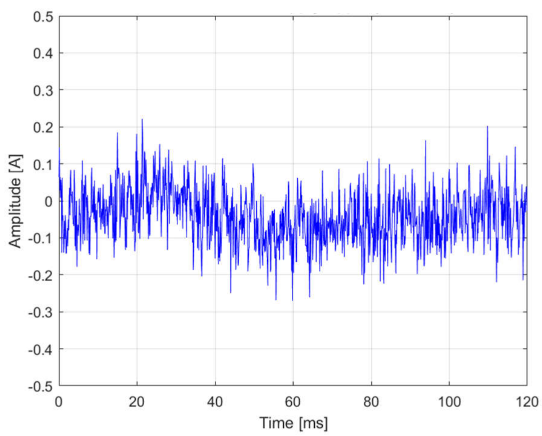


Figure 4-30. Output Noise With Supply Voltage Ripple (Sampled With AMC1035 at 10kHz)

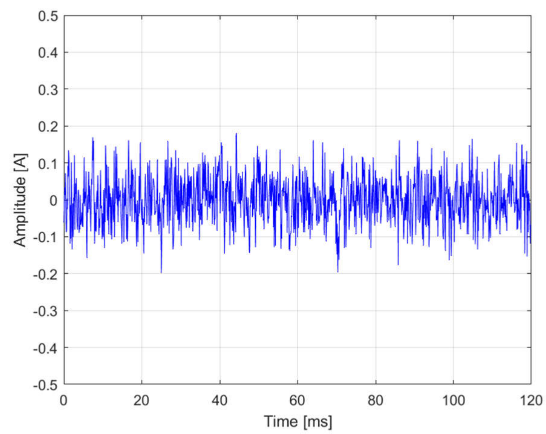


Figure 4-31. Output Noise With no Supply Voltage Ripple (Sampled With AMC1035 at 10kHz)

For ADS7043, the peak-to-peak noise is around 600mA and for AMC1035, the value is around 450mA. These results are consistent with DC noise test results in Section 4.4.1.1. Using Delta-Sigma modulators can further reduce the influence from the power supply ripple.

The results show spectral aliasing due to higher signal frequency (100kHz) than sampling frequency (10kHz).

4.4.7 Digital Interface

For ADS7043, SPI protocol is used for data transferring. The digital interface waveform is shown in Figure 4-32. When CS is pulled down, a frame transferring starts. A 10MHz clock signal is generated by MCU. Then ADS743 starts with 2 bits zero and then sends 12 bit conversion results. All the signals are measured on the output connector of the TIDA-010937.

Figure 4-32. ADS7043 Digital Interface Timing

Figure 4-33 shows the AMC1035 digital interface waveform. In this reference design, F28379D provides a continuous 20MHz clock signal. Under a 0V differential input signal condition, the AMC1035 outputs a stream of ones and zeros that are high 50% of the time and low 50% of the time. All the signals are measured on the output connector J7 of the TIDA-010937.

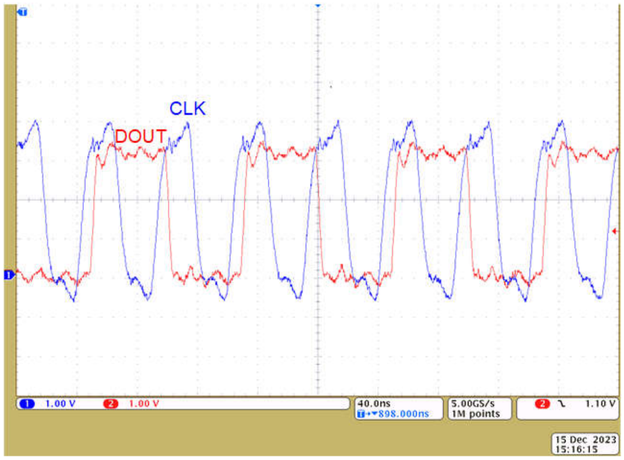


Figure 4-33. AMC1035 Digital Interface Timing

5 Performance Comparison with Competitor's Device

Based on the TIDA-010937 board, a competitor's Hall-sensor current was analyzed. The competitor's device is a pin-compatible device with the TMCS1123B3, however the bandwidth is only 120kHz and the linear measurement range is ±15A. This section details analysis of the performance between these two devices.

5.1 Effective Number of Bits

For the noise test details, see Section 4.4.1.1. For DC ENOB, the equivalent input current noise under 0A input is tested and ENOB is calculated. By recording the conversion results of the ADC, SNR and ENOB can be calculated. The test results are shown in Table 5-1.

Table 5-1. Noise and DC/AC ENOB Comparison

DEVICE		TMCS1123B3		COMPETITOR'S DEVICE	
Bandwidth		250kHz		120kHz	
Full-Scale Range		±22A		±18A	
ADC		ADS7043	AMC1035 Sinc^3 64OSR	ADS7043	AMC1035 Sinc^3 64OSR
DC Performance	RMS /mA	91	64	89	66
	SNR/dB	48	51	46	49
	ENOB /bits	7.6	8.1	7.3	7.8

The linear measurement range of the TMCS1123B3 is ±20.7A and the full-scale range is ±22A. The linear range takes up to 94.1% of the full-scale range, the linear measurement range of the competitor's device is ±15A and the full-scale range is ±18A. The linear range takes up to 83.3% of the full-scale range.

Even the bandwidth of the TMCS1123 (250kHz) is higher than competitor's device (120kHz), the input current noise is almost the same which means TMCS1123 has lower noise density than competitor's device. Adding an extra filter circuit can further improve the accuracy of the TMCS1123.

5.2 Latency

For the latency test details, see Section 4.4.2.2. Inject a 10kHz, 3A peak square wave current into TIDA-010937 and measure the latency between 50% input and 50% output. The test results are shown in Figure 5-1 and Figure 5-2

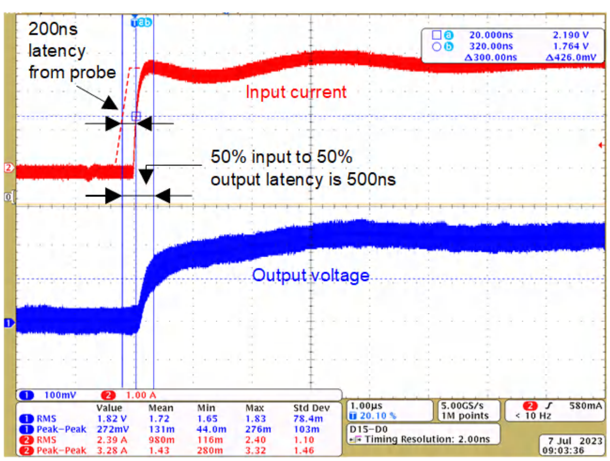


Figure 5-1. Latency Test (TMCS1123B3)

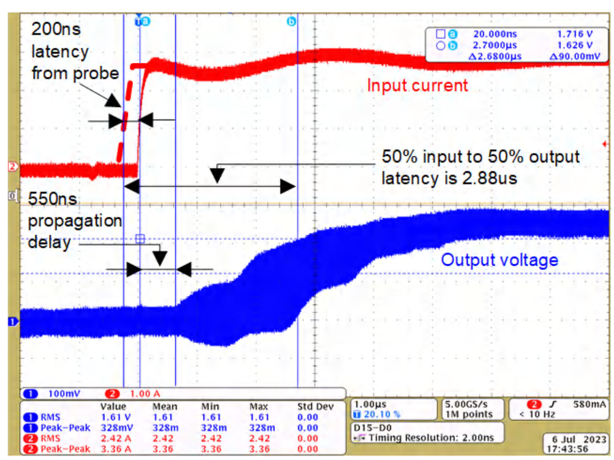


Figure 5-2. Latency Test (Competitor's Device)

Figure 5-1 shows TMCS1123 has a significant advantage on latency. The latency as low as 300ns provides the higher frequency current sensing and does not influence the system control bandwidth. For the competitor's device, the latency consists of two parts: one is up to 550ns propagation delay, the other is zero to 50% latency which is around 2.1µs.

Also, the persistence mode of the scope shows that there is large ringing during the rising edge of the input current on competitor's device, while the output voltage of the TMCS1123 is smoother and is designed for high di/dt applications.

5.3 PWM Rejection

For the PWM rejection test details, see Section 4.4.3. The output voltage of the current sensor during one PWM cycle is recorded by continuously increasing the ADC sampling point position. The test results are shown in Figure 5-3 and Figure 5-4.

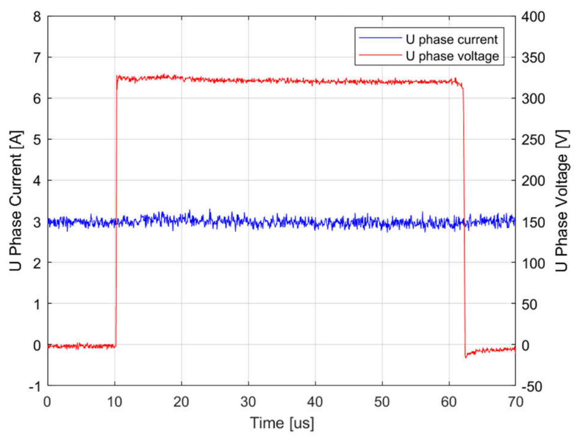


Figure 5-3. PWM Rejection Test (TMCS1123B1)

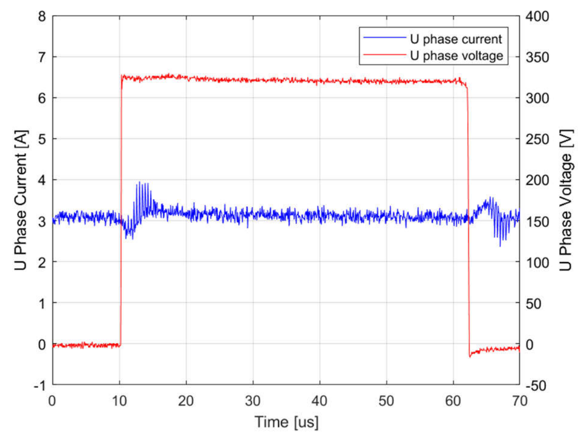


Figure 5-4. PWM Rejection Test (Competitor's Device)

During the switching, the competitor's device outputs large spike noise which is up to 1A if converted to equivalent input current, while TMCS1123 shows great immunity to the common-mode transient. Higher CMTI provides an accurate sampling result especially in a small duty cycle.

6 Design and Documentation Support

6.1 Design Files

6.1.1 Schematics

To download the schematics, see the design files at TIDA-010937.

6.1.2 BOM

To download the bill of materials (BOM), see the design files at TIDA-010937.

6.1.3 PCB Layout Recommendations

For layout recommendations, see the *TMCS1123 Precision 250kHz Hall-Effect Current Sensor With ±1.3kV Reinforced Isolation Working Voltage, Overcurrent Detection and Ambient Field Rejection* data sheet.

6.1.3.1 Layout Prints

To download the layout prints, see the design files at TIDA-010937.

6.2 Tools and Software

Tools

F28379D LaunchPad™ development kit for C2000™Delfino™ MCU	LAUNCHXL-F28379D is a low-cost evaluation and development tool for the TMS320F2837xD, TMS320F2837xS, and TMS320F2807x products in the TI MCU LaunchPad™ development kit ecosystem which is compatible with various plug-on BoosterPack Plug-in Module. This extended version of the LaunchPad development kit supports the connection of two BoosterPacks. The LaunchPad development kit provides a standardized and easy-to-use platform to use while developing your next application.

Software

MotorControl software development kit (SDK) for C2000™	MotorControl SDK for C2000™ microcontrollers (MCU) is a cohesive set of software infrastructure, tools, and documentation designed to minimize C2000 real-time controller based motor control system development time targeted for various three-phase motor control applications. The software includes firmware that runs on C2000 motor control evaluation modules (EVMs) and TI reference designs which are targeted for industrial drives, robotics, appliances, and automotive applications. MotorControl SDK provides all the needed resources at every stage of development and evaluation for high performance motor control applications.

6.3 Documentation Support

1. Texas Instruments, *TMCS1123 Precision 250kHz Hall-Effect Current Sensor With ±1.3kV Reinforced Isolation Working Voltage, Overcurrent Detection and Ambient Field Rejection Data Sheet*

6.4 Support Resources

TI E2E™ support forums are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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6.5 Trademarks

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