

TI Designs: TIDA-01541

三相インバータ用の高帯域幅の位相電流およびDC-Link電圧センシングのリファレンス・デザイン

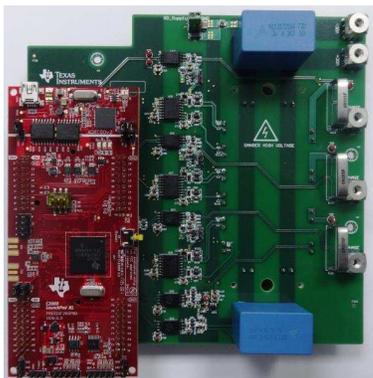


概要

このリファレンス・デザインは、三相インバータにおける絶縁位相電流およびDC-Link電圧測定のシステム・コストを低減し、小型の設計を可能にするとともに、高い帯域幅とセンシング精度を実現します。絶縁アンプの出力は、差動からシングルエンドへの変換回路を使用して、MCUの内部ADCに接続されます。絶縁アンプの使用により、MCU内でSAR ADCを使用できるため、電流センシングへのトレードオフなしでシステム・コストを低減できます。8ピンのパッケージにより、基板のフォーム・ファクタが小さくなります。絶縁アンプの帯域幅が高いため、3.5μs以内にIGBTを保護でき、高い性能仕様により高精度の電流および電圧測定が可能になります。DC-Linkの電圧測定は、高電圧の分圧器によるソースインピーダンスの影響を回避するため高い入力インピーダンスで行われ、精度が向上します。

リソース

TIDA-001541	デザイン・フォルダ
UCC21520	プロダクト・フォルダ
AMC1301	プロダクト・フォルダ
AMC1311	プロダクト・フォルダ
OPA320	プロダクト・フォルダ
TLC372	プロダクト・フォルダ
TLV1117	プロダクト・フォルダ
TLV704	プロダクト・フォルダ
REF2033	プロダクト・フォルダ
TL431B	プロダクト・フォルダ
SN74LVC1G10	プロダクト・フォルダ
TIDA-00366	ツール・フォルダ

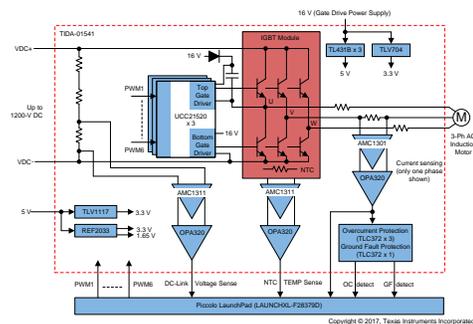


特長

- 強化された絶縁インバータで、定格10kWまでの400V~1200V DC-Linkドライブに適切
- 帯域幅の高い(200kHz超)強化された絶縁アンプにより、レイテンシの短い電流センシングが可能で、高速な過電流検出(3μs未満)により電力段を保護
- DC-Link電圧など高インピーダンスのノードの高精度センシングに最適化された、高インピーダンス入力の強化された絶縁アンプであり、0V~1026V DCのDC-Link電圧を誤差±1%の精度でセンシング
- 較正済みの電流測定誤差は±0.5%、±50Aを超えるFSR、温度範囲-25°C~+85°C
- 消費電力の低い、強化された絶縁アンプにより、ゲートドライバのブートストラップ・コンデンサの単純なLDOから電力を供給可能
- DCバスの低電圧、過電圧、過負荷、地絡、過熱に対する保護

アプリケーション

- ACインバータおよびVFドライブ
- サーボCNCおよびロボティクス
- 三相UPS
- 太陽光インバータ

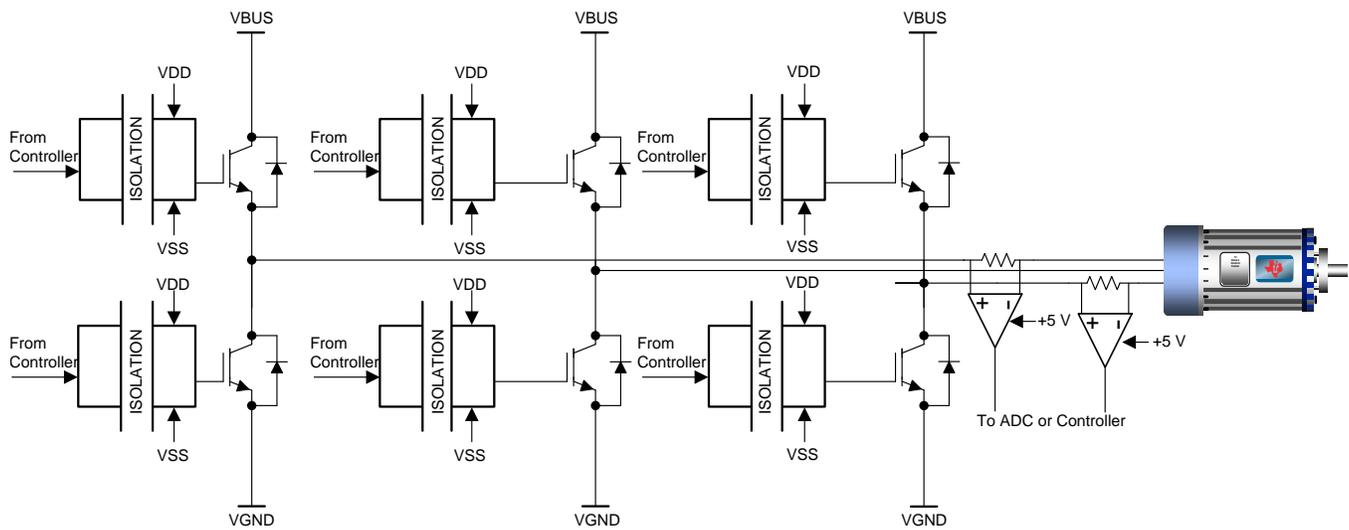




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1 System Description

Three-phase inverters have numerous applications like variable-frequency drives that control the speed of AC motors, uninterruptible power supply, solar inverters, and other similar inverter applications.  1 shows a typical application of a three-phase inverter using six isolated gate drivers. The system consists of isolated gate drivers for IGBTs, and the three-phase inverters include DC bus voltage sensing, inverter current sensing, IGBT protection (like overtemperature, overload, ground fault, and so on).



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図 1. Three-Phase Inverter With Isolated Gate Drive

There are many end applications such as HVAC, solar pumps, and appliances where cost is major concern without compromising the performance. High-end three-phase inverters use sigma-delta ($\Sigma\Delta$) modulators for current sensing, which also asks for using expensive controllers with built-in SINC filters. Using an isolated amplifier enables interfacing with a low-cost M4-core MCU or TI's Piccolo™ with a built-in SAR analog-to-digital converter (ADC). The overload protection can be implemented in external hardware, which reduces software complexity. The isolated gate drivers need different supplies for both high-side and low-side gate drivers. Instead of using expensive isolated supplies for powering the gate drivers, using a bootstrap power supply reduces BOM cost on the power supply and also reduces the board space.

DC-Link sensing is an important parameter in the motor control algorithm and is required to be sensed with an accuracy of 1%. The DC-link sensing circuits employ a high impedance voltage divider to scale the voltage to a lower level. However this cause DC-link feedback signals to have high source impedance. A high impedance source will affect the gain error and offset error if it is in the same range as the input impedance of isolated sensing amplifier. However this error can be mitigated by using AMC1311 which has very high input impedance in the giga ohm range. The high input impedance of AMC1311 makes the effect of source impedance negligible.

This reference design is based on the hardware of the TIDA-00366 design. The system design theory and test results relating to the power stage and current sensing are described in the design guide [Reference Design for Reinforced Isolation Three-Phase Inverter With Current, Voltage, and Temp Protection](#). This reference design looks at the sensing accuracy of the DC-Link voltage with the AMC1311 isolated amplifier for voltage sensing applications, self-heating with the isolated amplifiers AMC1301 and AMC1311, step response of the isolated amplifier, and short-circuit detection time.

1.1 Key System Specifications

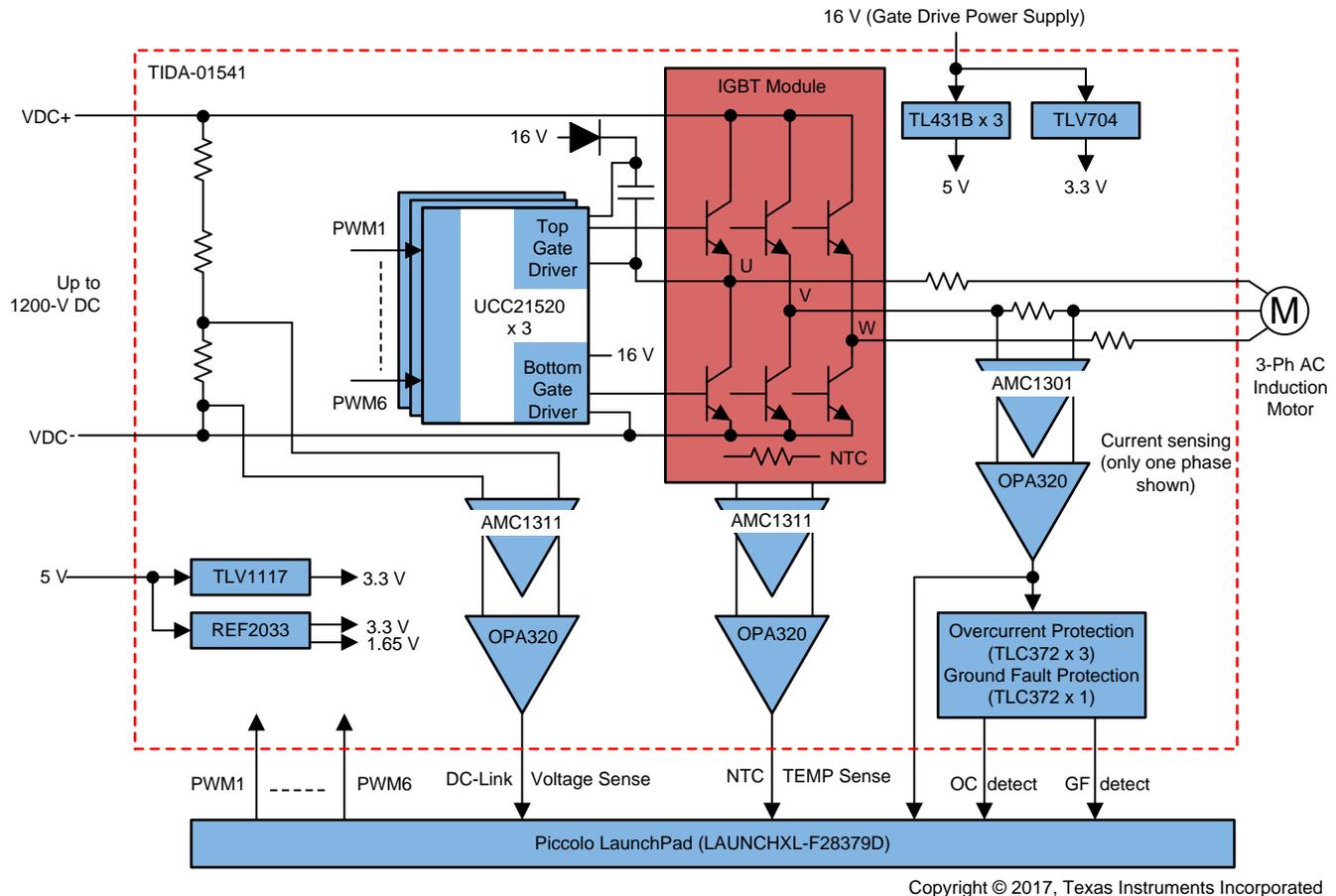
表 1. Key System Specifications

PARAMETER	SPECIFICATIONS
DC-Link input voltage	400 V to 1200 V
Gate driver supply voltage	16 V for low-side IGBT gate driver, 15 V (bootstrapped) for high-side IGBT gate driver
IGBT power module	Voltage rating: 1200 V, current rating: 50 A or more
Rated power capacity	10 kW
Inverter switching frequency	4 kHz (minimum) to 16 kHz; adjustable through software
Isolation	Reinforced (IEC 61800-5)
Microcontroller	TMS320F28379D
Operating ambient temperature	-25°C to +85°C
Motor	Three-phase, 400-V AC induction motor (ACIM)
Power supply specification for MCU	3.3V ± 5%
Feedbacks	Current sensing (±50 A), DC-Link bus voltage sensing (0 to 1026 V), IGBT module temperature sensing Interface for an external 3.3-V MCU with 3.3-V unipolar output input
Current sensing accuracy	±0.5%
DC-Link bus voltage sensing accuracy	±1%
OC detection latency	3.4 μs
Protections	Overload, overvoltage, undervoltage, ground fault, overtemperature
PCB	160 × 156 mm, four layers, 2-oz. copper

2 System Overview

2.1 Block Diagram

Figure 2 shows the system level block diagram for this reference design.



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Figure 2. System Level Block Diagram for TIDA-01541

This reference design assists a three-phase inverter rated up to 10 kW. As shown in Figure 2, the design uses three reinforced, isolated, dual-IGBT gate drivers (UCC21520) to drive six IGBTs. The IGBTs are integrated into a module along with a temperature sensor (NTC). The IGBTs inside the module are configured in half-bridge configurations. Each half-bridge is driven by two IGBT gate drivers—top (high side) and bottom (low side). The design is interfaced with TI's Piccolo LaunchPad™, LAUNCHXL-F28379D through two 20-pin connectors. The complementary PWM signals are generated from the LaunchPad. The three mid-points of IGBT half-bridges are connected. The board is designed to operate up to 1200-V DC for the inverter DC bus voltage.

Accurate phase current sensing with three-phase brushless motors is critical for motor drive performance, efficiency, and protection. This reference design uses in-phase current sensing using three 5-mΩ shunts and three reinforced isolated amplifiers (AMC1301). The benefits of using in-phase current sensing are:

1. Constant motor current flowing through the shunt, independent of IGBT switching
2. Easy detection of terminal-to-terminal short and terminal to GND short

The voltage generated across the shunt is amplified using the reinforced isolated amplifier, AMC1301. The output of the AMC1301 is signal conditioned and converted to a single-ended signal using the OPA320. Outputs of all the three channels are fed into the microcontroller (MCU).

The inverter protects against overload, short circuit, ground fault, DC bus undervoltage and overvoltage, and IGBT module over temperature. The DC bus voltage is dropped down using the resistor divider and fed to the AMC1311 for sensing. The under- and overvoltage are programmed in the MCU using the sensed signal. Similarly, the signal from NTC (integrated into IGBT module) is sensed using the AMC1311, and the sensed signal is fed to the MCU for overtemperature protection. The overload, short-circuit, and ground fault protections are implemented using comparators TLC372, which use the current sensed from the three shunts.

The board is powered through two external power supplies: one 16 V and the other 5 V. The low-side IGBT gate drivers are powered using 16 V, and high-side IGBT gate drivers are powered using a bootstrapped supply generated from 16 V. The MCU, op amps, and comparators are powered using 3.3 V generated from a 5-V supply using the TLV1117 (3.3 V). The design uses the TLV704 (3.3 V), TL431B, and REF2033 to generate other rails and references on the board.

Lower system cost is achieved by using the isolated amplifiers (AMC1301 and AMC1311) to measure motor current, DC-Link voltage, and NTC voltage. The signals are interfaced with an internal ADC of the MCU. The system cost is also reduced by using a bootstrap power supply configuration for IGBT gate drivers.

2.2 Highlighted Products

2.2.1 AMC1311

The AMC1311 device is a precision, high-impedance input isolated amplifier with an output separated from the input circuitry by an isolation barrier that is highly resistant to magnetic interference. This barrier is certified to provide reinforced galvanic isolation of up to 7 kV_{PEAK} according to VDE V 0884-11 and UL1577. Used in conjunction with isolated power supplies, this device prevents noise currents on a high common-mode voltage line from entering the local ground and interfering with or damaging sensitive circuitry. The high-impedance input of the AMC1311 device is optimized for connection to high-voltage resistive divider circuits or other voltage signal sources with high output resistance. The excellent performance of the device supports accurate voltage or temperature sensing and control in closed-loop systems. The integrated common-mode overvoltage and missing high-side supply voltage detection features of the AMC1311 device simplify system-level design and diagnostics.

- 2-V input voltage range optimized for isolated voltage measurement
- Low offset error and drift: ± 1.6 mV at 25°C, ± 21 μ V/°C
- Fixed gain: 1
- Very low gain error and drift: $\pm 0.3\%$ at 25°C, ± 60 ppm/°C
- Very low nonlinearity and drift: 0.05%, 1 ppm/°C

2.2.2 AMC1301

The AMC1301 is a precision isolation amplifier with an output separated from the input circuitry by an isolation barrier that is highly resistant to magnetic interference. The input of the AMC1301 is optimized for direct connection to shunt resistors or other low-voltage level signal sources. The excellent performance of the device supports accurate current control resulting in system-level power saving and, especially in motor control applications, lower torque ripple.

- ± 250 -mV input voltage range optimized for current measurement using shunt resistors
- Low offset error and drift: ± 200 μ V at 25°C, ± 3 μ V/°C
- Fixed gain: 8.2
- Very low gain error and drift: $\pm 0.3\%$ at 25°C, ± 50 ppm/°C
- Very low nonlinearity and drift: 0.03%, 1 ppm/°C

2.2.3 UCC21520

The UCC21520 is an isolated dual-channel gate driver with a 4-A source and 6-A sink peak current. The device is designed to drive power MOSFETs, IGBTs, and SiC MOSFETs up to 5 MHz with best-in-class propagation delay and pulse-width distortion. The input side is isolated from the two output drivers by a 5.7-kV_{RMS} reinforced isolation barrier with a minimum of 100-V/ns common-mode transient immunity (CMTI). Internal functional isolation between the two secondary-side drivers allows a working voltage of up to 1500-V DC. A disable pin shuts down both outputs simultaneously when it is set high and allows normal operation when left floating or grounded. The device accepts VDD supply voltages up to 25 V. A wide input VCCI range from 3 V to 18 V makes the driver suitable for interfacing with both analog and digital controllers.

2.2.4 OPA320

The OPA320 is precision, low-power, single-supply operational amplifier optimized for very low noise. Operated from a voltage range from 1.8 V to 5.5 V, the device is well-suited for driving ADCs. With a typical offset voltage of 40 μ V and very low drift over temperature (1.5 μ V/°C typical), it is very well suited for applications like control loop and current sensing in motor control.

2.2.5 TLC372 (Q-Version)

The TLC372 consists of two independent voltage comparators, each designed to operate from a single power supply (3-V to 16-V range). The outputs are open-drain configurations and can be connected to achieve positive-logic wired-AND relationships. The TLC372Q is characterized for operation from -40°C to $+125^{\circ}\text{C}$. The typical response time of comparators for the switching is 200 ns.

2.2.6 TLV1117 (I-Version)

The TLV1117 device is a positive low-dropout voltage regulator designed to provide up to 800 mA of output current. The internal circuitry is designed to operate down to 1-V input-to-output differential. Dropout voltage is specified at a maximum of 1.3 V at 800 mA, decreasing at lower load currents. With excellent line and load regulations, the device is available in multiple packages and works for a temperature range from -40°C to $+125^{\circ}\text{C}$.

2.2.7 TLV704

The TLV704 is a 3.3-V LDO with ultra-low quiescent current and operates over a wide operating input voltage of 2.5 V to 24 V. The device is an excellent choice for industrial applications that undergo large line transients. The TLV704 is available in a 3-mm × 3-mm SOT23-5 package, which is ideal for cost-effective board manufacturing.

2.2.8 REF2033

The REF2033 offers excellent temperature drift (8 ppm/°C, max) and initial accuracy (0.05%) on both the VREF and VBIAS outputs while operating at a quiescent current less than 430 μA. In addition, the VREF and VBIAS outputs track each other with a precision of 6 ppm/°C (max) across the 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. Extremely low dropout voltage of only 10 mV allows operation from very low input voltages.

2.2.8.1 TL431B (Q-Version)

The TL431 is a three-terminal adjustable shunt regulator with specified thermal stability overtemperature ranges. The output voltage can be set to any value between Vref (approximately 2.5 V) and 36 V with two external resistors. Active output circuitry provides a very sharp turnon characteristic, making these devices excellent replacements for Zener diodes in many applications. The "B-grade" version comes with initial tolerances (at 25°C) of 0.5% and TL431BQ devices are characterized for operation from –40°C to +125°C.

2.2.8.2 SN74LVC1G10

The SN74LVC1G10 performs the Boolean function $Y = !(A \times B \times C)$ or $Y = !A + !B + !C$ in positive logic. With a supply range from 1.65 V to 5.5 V and availability in multiple packages, this NAND gate is characterized for operation from –40°C to +125°C.

2.3 System Design Theory

This reference design is based on the hardware of the TIDA-00366 design. Only the important system design theory related to current sensing, voltage sensing, and relevant changes are given in this section. For information on the IGBT inverter, IGBT gate driver, onboard power supply, and fault protection feature, see [Reference Design for Reinforced Isolation Three-Phase Inverter With Current, Voltage, and Temp Protection](#).

注: This reference design is designed for a three-phase Inverter, but [2.3.1](#) explains the circuits and components for one channel (U-Phase) only. The same explanation is applicable to other two channels (V-Phase and W-Phase).

2.3.1 Isolated Current Sensing Circuit

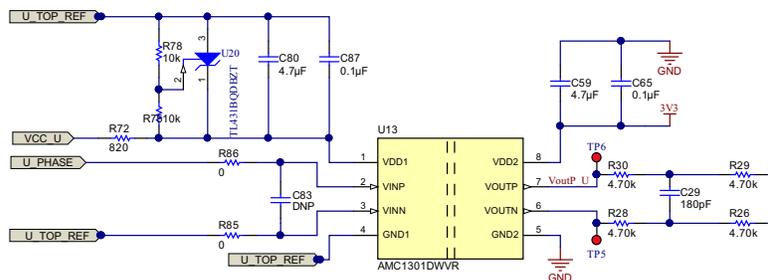
2.3.1.1 Selecting a Shunt Resistor for the Inverter

The peak winding current can go up to 51 A for a 10-kW drive for the selected IGBT module. Considering 50 A as the peak current (with some margin), the shunt value can be calculated as given in [式 1](#).

$$R_{SHUNT} = \left(\frac{\pm 250 \text{ mV}}{\pm 50 \text{ A}} \right) = 5 \text{ m}\Omega \quad (1)$$

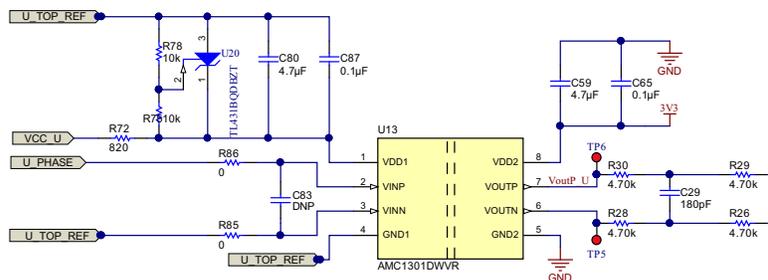
Where ±250 mV is the input voltage range for the AMC1301.

2.3.1.2 Reinforced Isolated Amplifier AMC1301

The AMC1301 is a precision isolation amplifier with an output separated from the input circuitry by an isolation barrier that is highly resistant to magnetic interference. The input of the AMC1301 is optimized for direct connection to shunt resistors.  shows the circuit and components related to the AMC1301.

VDD1 is power supply and GND1 is ground for the hot side of the circuit where the inputs VINP and VINN are coming directly from the 5-mΩ shunt resistor. VDD1 generated from the bootstrap supply. GND1 is connected to the "U_TOP_REF" terminal, which is the mid-point of the connection between the top and bottom IGBT of the half-bridge. The capacitors C80 (4.7 μF) and C87 (0.1 μF) are used for decoupling of the VDD1 supply and must be kept very close to the VDD1 pin of the AMC1301 in the layout. For any noise filtering required by the user, use a differential RC filter (R86, R85, and C83). To test this reference design, do not use filtering (R85 = R86 = 0 Ω and C83 = DNP).

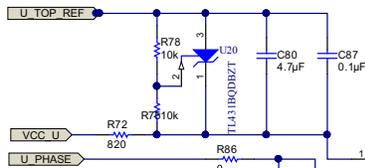
On the cold side, VDD2 is generated from an LDO TLV1117 (3.3 V). The capacitors C59 (4.7 μF) and C65 (0.1 μF) are used for decoupling of VDD2 supply and must be kept very close to the VDD2 pin of the AMC1301 in the layout. The output of the AMC1301 is available on pins VOUTP and VOUTN. A differential filter with a cutoff frequency of 95 kHz is connected at the output using R30 (4.7 kΩ), R28 (4.7 kΩ) and C29 (180 pF).

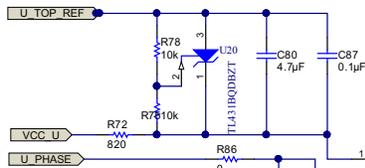


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 3. Reinforced Isolated Amplifier AMC1301

2.3.1.3 Primary-Side Supply Generation Using TL431B

The power supply for the high-side gate driver is generated using a bootstrap circuit. The reference point for the high-side IGBT gate driver and related circuitry is "U_TOP_REF". The same reference is used for the current sensing circuit, which is why the power supply for VDD1 for the AMC1301 must also be generated from the same bootstrap supply.  shows the power supply generation for VDD1 of the AMC1301 using the TL431B shunt regulator. The internal reference value for the TL431B is 2.5 V, which helps in deciding the output voltage.



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 4. Power Supply Generation Using TL431B

2.3.1.4 Differential-to-Single-Ended Conversion Using OPA320 for Current Sensing

The output of the AMC1301 is differential and has a common-mode voltage of 1.4 V. To interface it with MCU, the output of the AMC1301 must be converted to a single-ended form and must range between a 0- to 3.3-V range (because of the limitations from MCU power supply).

2.3.1.4.1 Selection of Op Amp

The op amp selection is important as it is integral part of the signal chain for measuring the current, DC-Link voltage, and IGBT module temperature. For the op amp, consider the following parameters:

- Offset voltage: The offset voltage specification for op-amp adds into the overall measurement accuracy so lowest offset voltage is preferred for the op-amp.
- Offset voltage drift: The signal chain accuracy is measured from a temperature range of -25°C to 85°C. The offset voltage drift should be low so as to get lowest error through the specified temperature range. Zero drift op-amps are preferred, if available.
- Rail-to-rail input and output: The input and output of op-amp should go to both the rails so as to use the full range of 1.65V on both positive and negative cycles (when the output is interfaced with MCU)
- Input common-mode range: The input of op-amp should be able to take a common-mode voltage of $V_{DD}/2$ which equals 1.65V for this application.
- Common-mode rejection ratio (CMRR): The switching frequency of typical 3-phase industrial inverter goes up to 16-20 kHz. The CMRR of greater than 80dB at 100 kHz (approximately 5 times the switching frequency of inverter) is generally preferred for such applications.

With all the above mentioned specifications, the cost of the op-amp should be as low as possible. This design uses OPA320 with the specifications shown in 表 2.

表 2. Key Specifications for OPA320

PARAMETER	VALUE
Supply voltage (V)	1.8 to 5.5 V
I _q /GBW > ratio	1.2 mA/20 MHz 60 μA/MHz
Noise at 1 kHz (nV/√Hz)	8 nV/√Hz
Rail-to-rail	RRIO input extend ± 100 mV beyond rail; V _{OUT} to ± 10 mV
Zero-crossover	Yes
Input bias max (pA)	1 pA max
Offset voltage (mV)	100 μV, max
Offset drift	0.5 μV/°C
Packaging	SOT23-5, SOT23-6

Note that five single op-amps are used so as to simplify the component placement in PCB layout. Use of OPA320 assures high precision and excellent signal linearity over the entire input common mode range, making it ideal for driving sampling ADCs.

2.3.1.4.2 Calculation of Gain for Amplifier

The data sheet of the AMC1301 has a "Specified linear full-scale range (VINP – VINN)" of –250 mV to 250 mV. With a nominal gain of 8.2, the V_{OUT} range is –2.05 V to 2.05 V. So V_{OUT(P-P)} for the AMC1301 is 4.10 V.

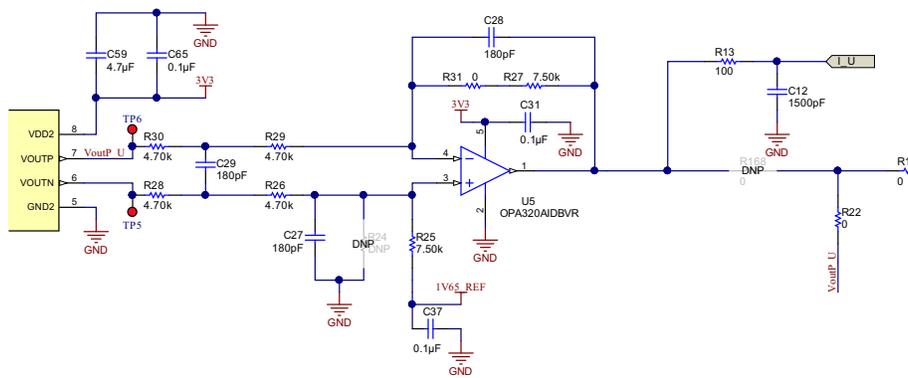
The $V_{OUT(P-P)}$ required from the OPA320 = 3 V (the voltage output swing can go up to 30 mV, close to both the rails). The op amp must have a gain of 0.731, calculated as $Opam\ Gain = 3/4.10 = 0.731\ V/V$.

2.3.1.4.3 Component Selections

The output of the AMC1301 is filtered using a differential filter (combination of R30, R28, and C29) with a cutoff frequency of approximately 94 kHz. The gain for the differential amplifier is calculated in 式 2.

$$Differential\ Amplifier\ Gain = \frac{R_f}{R_{in}} = \frac{7.5\ k\Omega}{4.7\ k\Omega + 4.7\ k\Omega} = 0.7978\ V/V \quad (2)$$

図 5 shows the circuit for the differential amplifier to convert a differential output of the AMC1301 to single-ended to feed into the MCU. The output of differential amplifier is routed through two paths: one going to the MCU pin (I_U) with an RC filter (cutoff frequency > 1 MHz and time delay of 150 ns) and other going to the comparator for overload protection.



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図 5. Differential-to-Single-Ended Signal Conversion

2.3.2 DC-Link Voltage Sensing Circuit

The design implements undervoltage and overvoltage protections on DC Bus by measuring DC-Link voltage. The DC bus input voltage is scaled down and fed to the MCU using the AMC1311 reinforced isolation amplifier, and the op amp OPA320. The output of the OPA320 can directly drive an ADC input or can be further filtered before processed by the ADC.

To scale down the DC-Link voltage, a resistor divider network is chosen considering the maximum voltage for the MCU ADC input as 3 V and the maximum DC-Link voltage to be measured as 1026 V.

To achieve better linearity and the noise performance of the device, the allowable input voltage is from 0 to 2 V. The voltage divider resistor is selected such that input voltage to the amplifier is less than 2 V at maximum DC bus condition. 図 6 shows six 1-MΩ resistors and an 11-kΩ resistor used to drop the VDC signal.

注: The undervoltage for this design can be set at 400-V DC. In that case, use two 200-V Zener diodes (currently DNP) connected in parallel with two 1-MΩ resistors. The spacing for the resistors and Zener diodes are important due to its high-voltage operation.

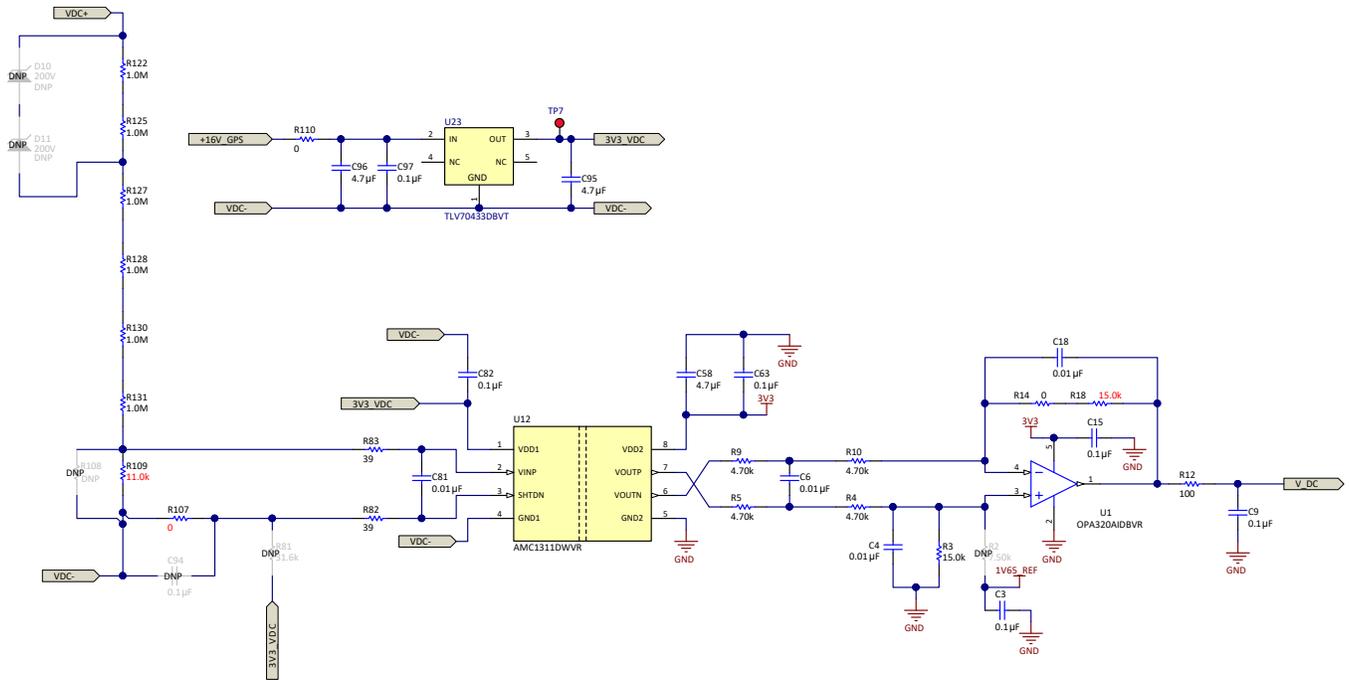


図 6. DC-Link Voltage Sensing Circuit

2.3.2.1 Calculation of Gain for Differential-to-Single-Ended Conversion for Voltage Sensing

The AMC1311 data sheet has a "Specified linear full-scale range" of 0 V to 2 V. With a nominal gain of 1, the V_{OUT} range is 0 V to 2 V. So $V_{OUT(P-P)}$ for the AMC1311 is 2 V.

$V_{OUT(P-P)}$ required from the OPA320 is 3 V (the voltage output swing can go up to 30 mV close to both the rails). The op amp must have a gain of 1.5, calculated as Opam Gain = $3/2 = 1.5$ V/V.

2.3.2.2 Component Selections

The output of the AMC1311 is filtered using a differential filter (a combination of R9, R5, and C6) with a cutoff frequency of approximately 94 kHz. The gain for the differential amplifier is calculated in 式 3.

$$\text{Differential Amplifier Gain} = \frac{R_f}{R_{in}} = \frac{15 \text{ k}\Omega}{(4.7 \text{ k}\Omega + 4.7 \text{ k}\Omega)} = 1.5957 \text{ V/V} \quad (3)$$

2.3.3 NTC Temperature Sensing Circuit

The IGBT module used in this reference design has an integrated NTC thermistor. 図 7 shows the characteristics of this NTC thermistor.

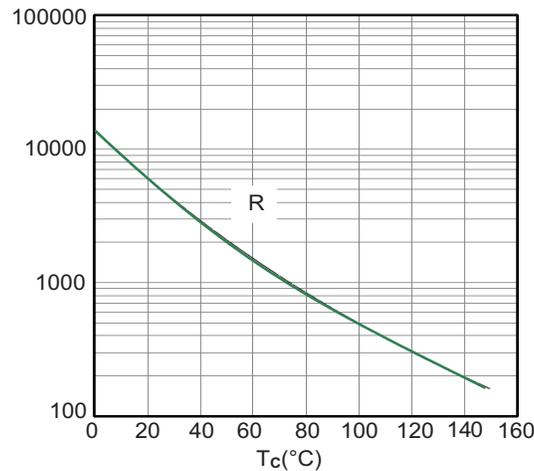


図 7. NTC Characteristics

The design implements overtemperature protection by sensing the NTC voltage and providing the signal to the MCU for shutting off the PWMs. The NTC is biased using one resistor R106 (15.0 kΩ) as shown in 図 8. The biased signal is given to the VINP pin of the AMC1311. The sensed signal is filtered using an RC filter at the input of AMC1311. The differential output of the AMC1311 is filtered and converted to a single-ended signal by the OPA320 with the gain of 1.5. The output of the OPA320 is filtered using an RC filter (cutoff frequency = 16 kHz and RC delay = 10 μs) and fed to the MCU as a "MODULE_TEMP" signal.

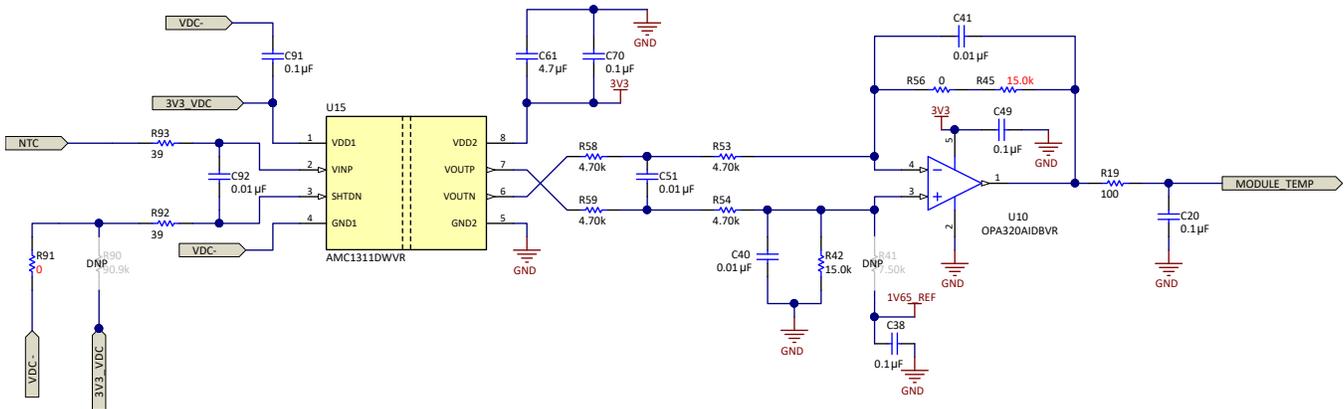


図 8. NTC Temperature Sensing Circuit

2.3.4 Overload (or Overcurrent) Protection

2.3.4.1 Selection of Comparators

A typical industrial drive needs to have overload protection to operate within 300 to 500 ns. To reach this goal, this reference design use the TLC372, a very low-cost and dual-channel comparator. The device operates from a supply range from 3 V to 16 V and has typical response time of 200 ns.

2.3.4.2 Calculation of Threshold Levels

Considering $50 A_{PEAK}$ as the threshold for ground fault conditions (which is > 200% of rated current), 表 3 shows the calculations used to select the resistors for setting the threshold on the comparators.

- $I_{SENSE(RMS)} = 35.4 A$
- $I_{SENSE(PEAK)} = 50 A$
- $R_{SHUNT} = 5 m\Omega$

表 3. Calculations of Threshold Levels for Overload Protection

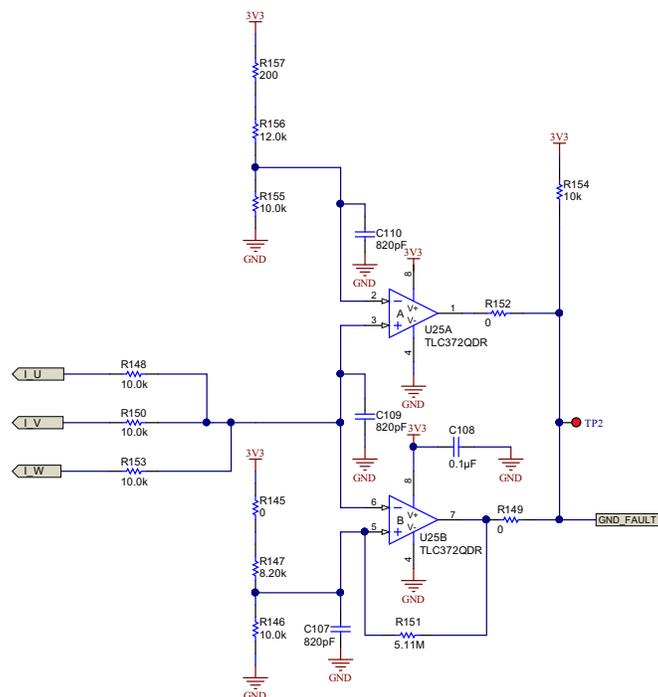
PARAMETER	EQUATION	CALCULATED VALUE	UNIT
Input to AMC1301 (peak)	$I_{sense(peak)} \times R_{shunt}$	250	mV
Output of AMC1301 at VOUTP pin for 250-mV input	$1.44 + \text{input to AMC1301} \times 4.1$	2.465	V
Output of AMC1301 at VOUTN pin for -250-mV input	$1.44 + \text{input to AMC1301} \times 4.1$	0.415	V

2.3.4.3 Calculation of Resistors for Setting the Threshold

The high threshold is set by resistors R20 and R23, whereas the low threshold is set by resistors R23 and R21 as shown in 9. Assuming R21 = 1.5 kΩ, R23 and R20 are calculated as: R23 = 10.7 kΩ, R20 = 3 kΩ.

9 shows the input signal for the comparators (which is compared with threshold) coming from the output of the op amp stage. The TLC372 is an open-drain output comparator that needs a pullup resistor at the output. R11 serves that purpose. C13 (0.1 μF) is used as a decoupling capacitor for the TLC372 comparator. C23 (0.1 μF) is used as local decoupling for the threshold to generate the resistor divider network.

The OVERLOAD signal generated from all the three channels is combined together. This signal is given to the MCU as well as to the DISABLE logic gate input for further processing.



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9. Overload Protection Circuit

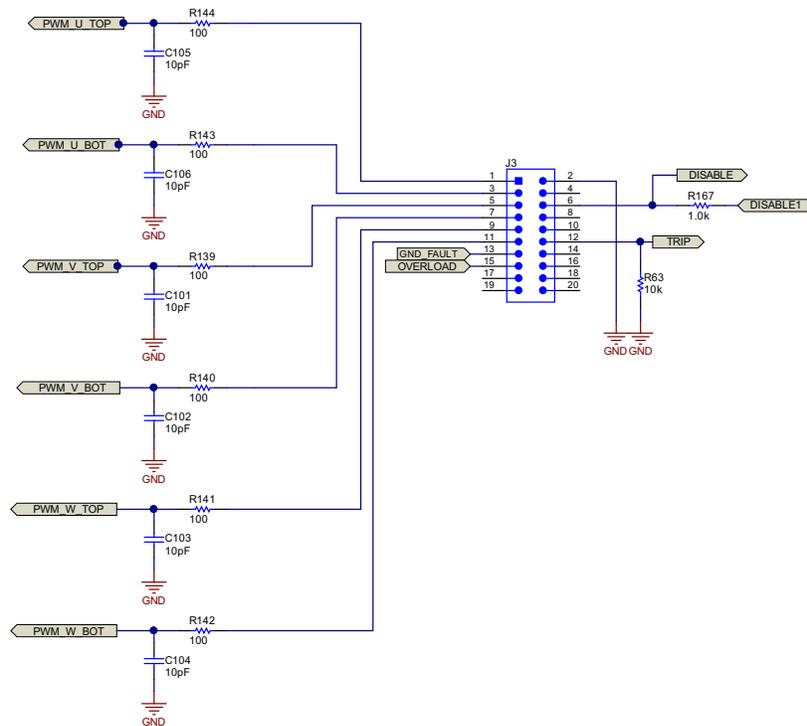
2.3.4.4 Connectors to Connect C2000™ Piccolo™ LaunchPad™

表 4 shows the pinout for the C2000 Piccolo LaunchPad. The highlighted pins are used for connecting the reference design board.

表 4. C2000™ LaunchPad™ Pinout

SIGNAL NAME ON TIDA-01541	MUX VALUE				J1 PIN	J3 PIN	MUX VALUE				SIGNAL NAME ON TIDA-01541
	X	2	1	0			0	ALT FUNCTION	2	X	
				3.3V	1	1	5V				
				GPIO32	2	2	GND				GND
		SCIRXDB		GPIO19	3	3	ADCIN14	CMPIN4P			1V65_REF
		SCITXDB		GPIO18	4	4	ADCINC3	CMPIN6N			I_U/ V_DC
				GPIO67	5	5	ADCINB3	CMPIN3N			I_U
				GPIO111	6	6	ADCINA3	CMPIN1N			3V3_REF
	SPICLK_A			GPIO60	7	7	ADCINC2	CMPIN6P			I_V
				GPIO22	8	8	ADCINB2	CMPIN3P			I_W
			SCLA	GPIO105	9	9	ADCINA2	CMPIN1P			V_DC
			SDAA	GPIO104	10	10	ADCINA0	DACOUTA			MODULE_TEMP
SIGNAL NAME ON TIDA-01541	MUX VALUE				J4 PIN	J2 PIN	MUX VALUE				SIGNAL NAME ON TIDA-01541
	X	2	1	0			0	1	2	X	
PWM_U_T OP			EPWM1A	GPIO0	1	1	GND				GND
PWM_U_B OT			EPWM1B	GPIO1	2	2	GPIO61				
PWM_V_T OP			EPWM2A	GPIO2	3	3	GPIO123			D1_C1	DISABLE
PWM_V_B OT			EPWM2B	GPIO3	4	4	GPIO122			D1_D1	
PWM_W_T OP			EPWM3A	GPIO4	5	5	RST				
PWM_W_B OT			EPWM3B	GPIO5	6	6	GPIO58			SPISIMOA	TRIP
			OUTPUTXB AR1	GPIO24	7	7	GPIO59			SPISOMIA	
	OUTPUTXB AR7			GPIO16	8	8	GPIO124			SD1_D2	
				DAC1/ GPIO20	9	9	GPIO125			SD1_C2	
				DAC2/ GPIO21	10	10	GPIO29			OUTPUTXB AR6	

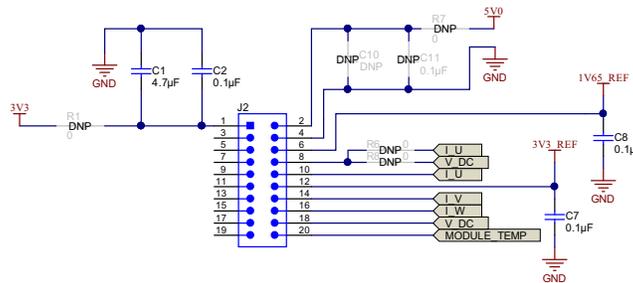
On the design board, two 20-pin connectors are used to connect with the C2000 LaunchPad as shown in  10. The PWM signals for the inverter are generated using the LAUNCHXL-F28027 board. The PWM signals generated from the MCU are filtered using an RC filter with values of R = 100 Ω and C = 10 pF, which corresponds to a cut-off frequency of 159 MHz and an RC time delay of 1 ns. GND_FAULT and OVERLOAD signals are generated from their respective comparators. These signals are connected to the MCU on GPIOs and to a three-input NAND gate to generate the DISABLE for gate drivers. The TRIP signal is generated from the MCU in case the user wants to interrupt the PWM signals or if the GND_FAULT and OVERLOAD signals need to be latched.



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図 10. 20-Pin Connector to Connect With Connectors J1 and J3 on LAUNCHXL-F28379D

The 3.3-V supply generated using the TLV1117 (3.3 V) is provided as a supply to the LaunchPad as shown in 図 11. The supply can also power the MCU from an external 5 V by populating onboard components R7, C10, and C11. The sensed signals I_U, I_V, I_W, V_DC, and MODULE_TEMP are connected to ADC input pins after the RC filtering (for aliasing). 1V65_REF and 3V3_REF are also provided to ADCs for any ratiometric measurements.



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図 11. 20-Pin Connector to Connect With Connectors J4 and J2 on LAUNCHXL-F28379D

3 Hardware, Testing Requirements, and Test Results

3.1 Hardware

This section explains the top and bottom views of the reference design PCB. This section also explains the power supply requirement and connectors used to connect the external world.

3.1.1 TIDA-01541 PCB Overview

Figure 12 shows the top view of the PCB. The three phases (U, V and W) have a current sensing circuit and dual channel gate drivers as highlighted in the figure.

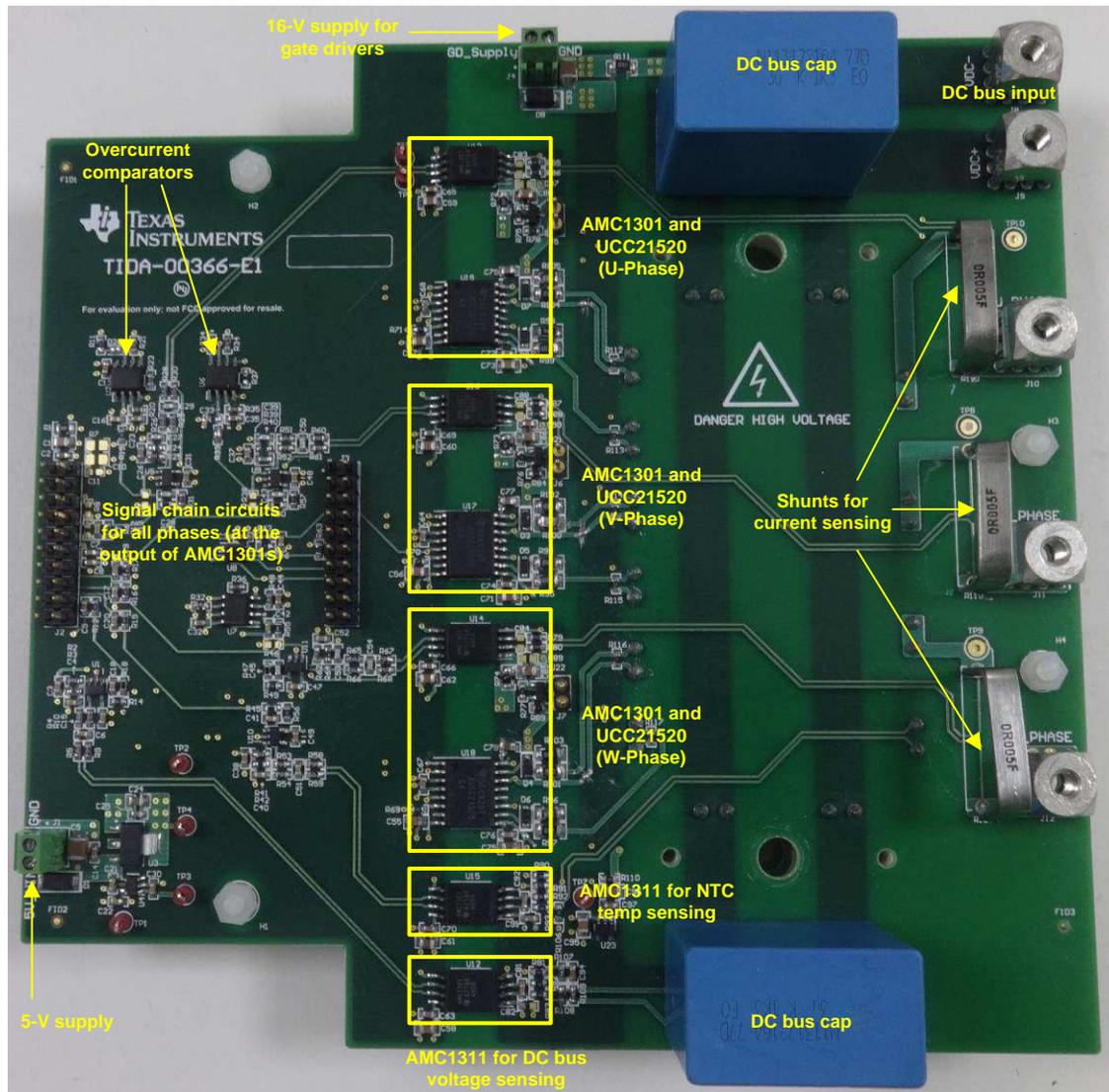


Figure 12. Top View of PCB for TIDA-01541

Figure 13 shows the bottom view of the PCB. The IGBT module is mounted on the bottom layer so that the heat sink can be connected to it as required by the output power levels.

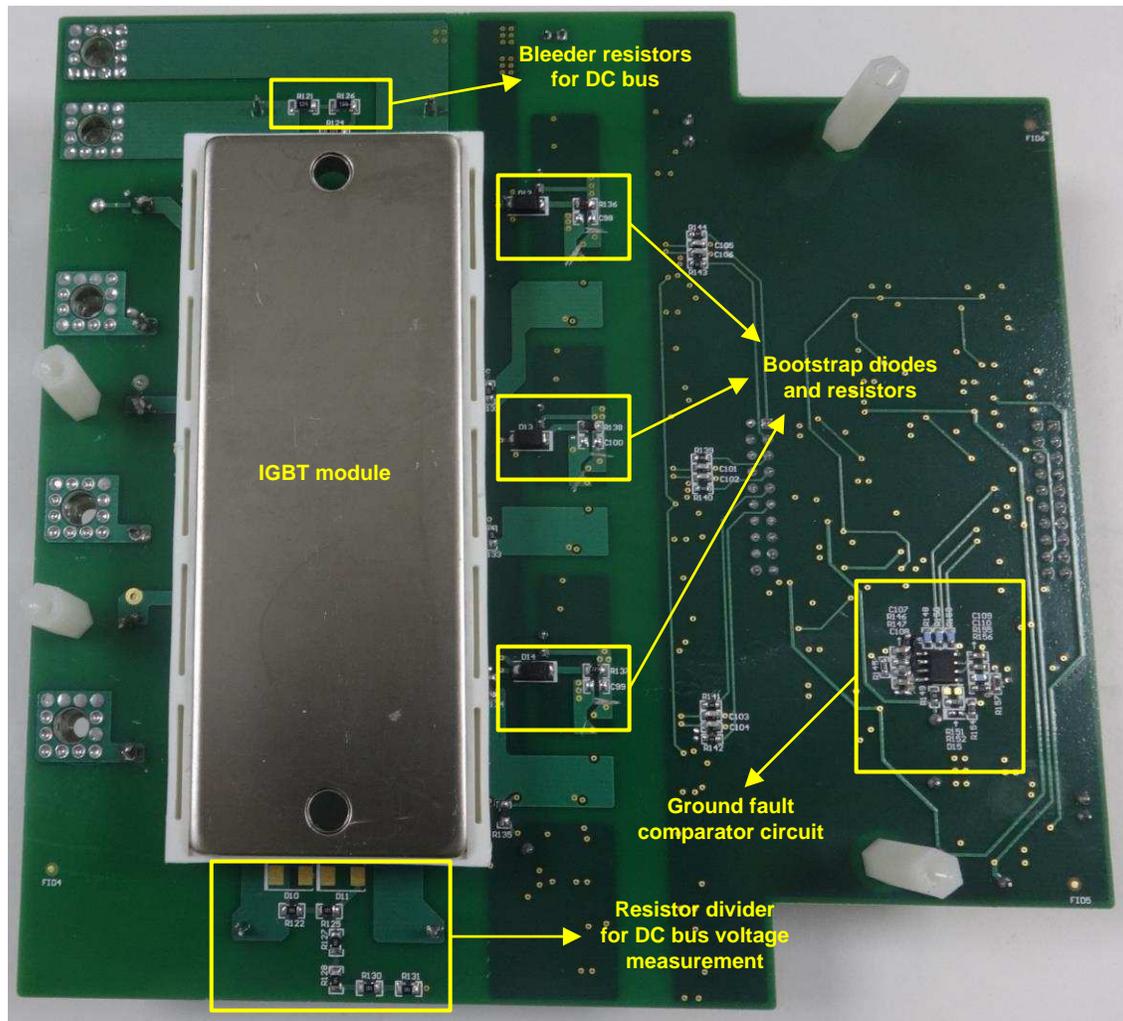


図 13. Bottom View of PCB for TIDA-01541

3.1.2 Connector

表 5 shows the connectors used on the reference design PCB and their purposes.

表 5. Connectors

CONNECTOR	PURPOSE
J1	5V_VIN power supply to power MCU, op amps, low side of AMC1301, low side of AMC1311, and comparators
J2	To connect to J1–J5 of LAUNCHXL-F28379D
J3	To connect to J6–J2 of LAUNCHXL-F28379D
J4	16-V GD_Supply to power low-side gate drivers
J5	To supply external isolated 16 V for U-Phase low-side gate driver if bootstrap configuration is not used
J6	To supply external isolated 16 V for V-Phase low-side gate driver if bootstrap configuration is not used
J7	To supply external isolated 16 V for W-Phase low-side gate driver if bootstrap configuration is not used
J13	VDC input
J14	Output for connecting to motor

3.2 Testing and Results

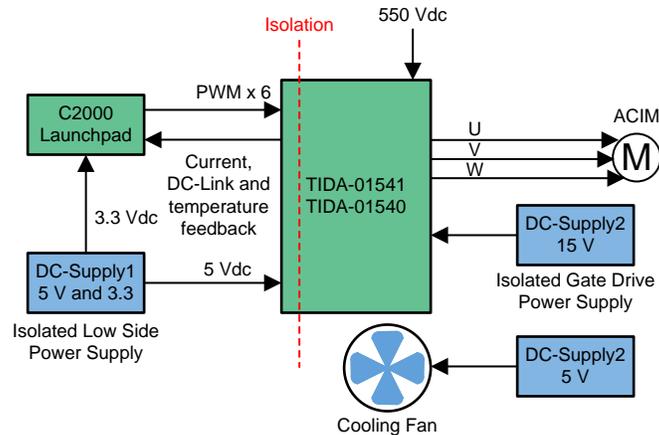
3.2.1 Test Setup

The following subsections provide descriptions and pictures of the test setup. 表 6 lists the key test equipment used in the subsequent tests.

表 6. Key Test Equipment

DESCRIPTION	TEST EQUIPMENT PART NUMBER
C2000 F28379D LaunchPad	Texas Instruments LAUNCHXL-F28379D
Adjustable power supply	Keithley 2230G-30-1 (two power supplies to ensure isolation between 16-V and 5-V rails)
High-voltage power supply	Sorensen SGI 1000/5
Load motor	ACIM, three-phase AC, 415 V (L-N, delta connected), 8.4 A _{RMS} (max) , 3.7-kW rated, 50 Hz, 1460 RPM
Oscilloscope	Tektronix MSO2024B
Oscilloscope	Tektronix MDO3024
High-voltage differential probes	Tektronix THDP0200
Low-voltage probes	Tektronix TPP0200

図 14 shows the test setup used. The board is powered from three power supplies: 0 to 1000 V for the DC-Link, 16 V for the power supply of the gate drive, and 5 V for the low-voltage side bias. The C2000 LaunchPad is powered from a 3.3-V power supply. The 1000-V power supply and the power supply of the gate drive are isolated from each other and also isolated from the 3.3-V and 5-V power supply.



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図 14. TIDA-01541 Test Setup

3.2.2 Test Results

This section shows the test results relating to the DC-Link accuracy, current and voltage sensing histogram, step response of the AMC1301, and short-circuit response time.

3.2.2.1 Thermal Image

Figure 15 is the thermal image of the board. For this test, the board is supplied with low voltage bias of 3.3 V and 5 V, and the gate drive power supply is given 16 V; however, the DC-Link turned off. All three half-bridges of the inverter are driven with a complementary PWM of 50%. This PWM is required to generate the bootstrap power supply, which supplies the AMC1301 on the high-voltage side. Because the DC-Link is turned off, the thermal image captures temperatures due to the self-heating of the AMC1301 and AMC1311 and not the power dissipation of the IGBT module. The temperature of the AMC1301 and AMC1311 boards is 30.2°C, which is a temperature rise of 7.4°C from the ambient temperature.

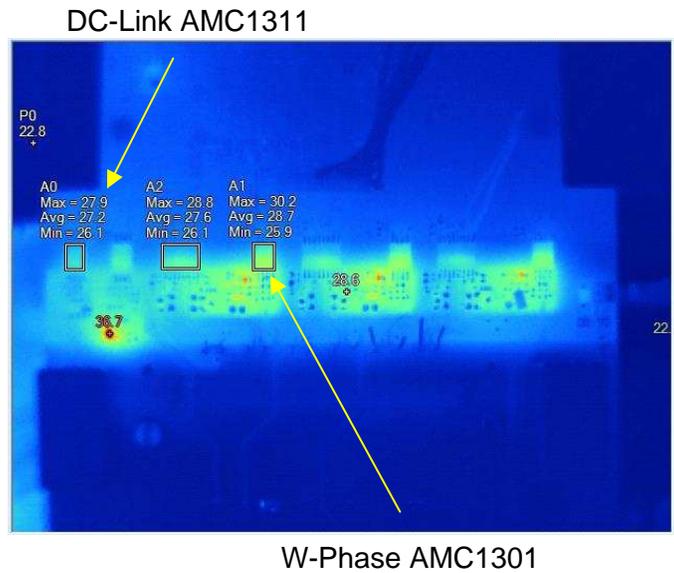


Figure 15. AMC1301 and AMC1311 Surface Temperature

3.2.2.2 DC-Link Voltage Measurement Accuracy

Figure 16 shows the measurement accuracy of the DC-Link voltage, which is a graph of the percentage full-scale error versus DC-Link voltage measurement. The full scale that can be measured is 1026 V. The measurement is done by applying a DC-Link voltage between 50 V to 1000 V. During this test, the inverter is running and the motor is disconnected, which brings a switching frequency of 16 kHz. The uncalibrated error is observed to be $\pm 1\%$ throughout the measurement range.

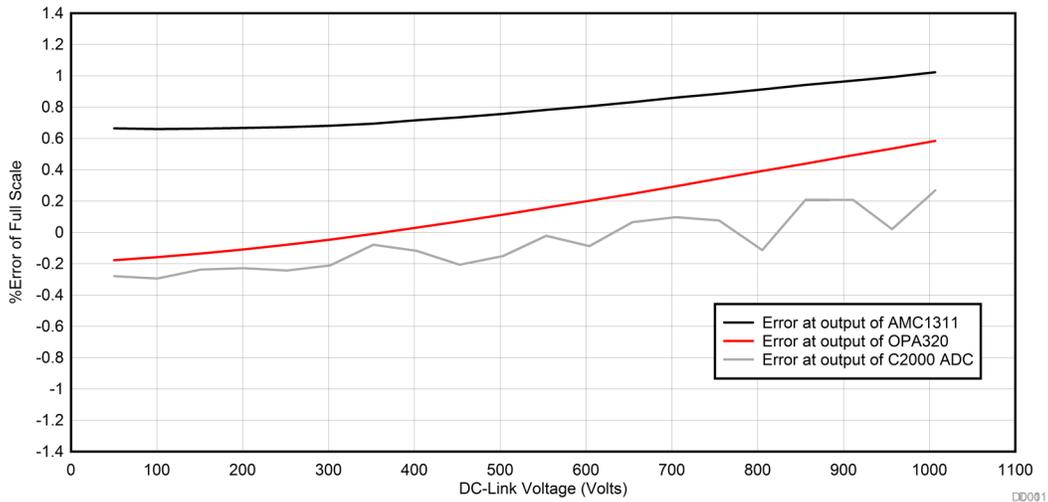


Figure 16. Uncalibrated Percentage Full-Scale Error vs DC-Link Voltage at No Load

Figure 17 shows the measurement accuracy of the DC-Link voltage when there is current in the motor. The error is measured at the output of the C2000 ADC. The test is done for a no-load current, and a current of 3 A_{RMS} and 5 A_{RMS} is sourced by the inverter into the AC induction motor. Note that the accuracy remains relatively the same throughout the range when there is a current of 3 A_{RMS}. The voltage measurement with 5 A_{RMS} into the motor is done for one reading at 600 V.

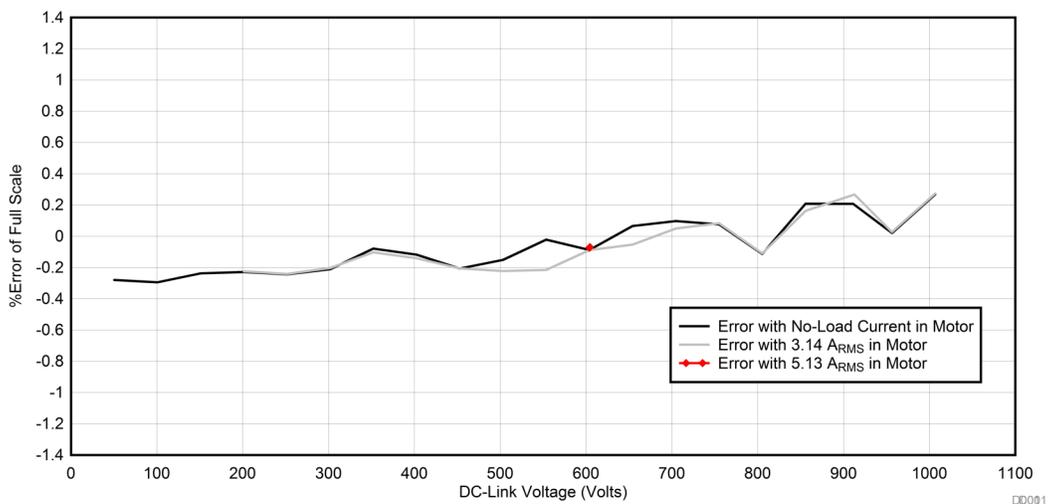
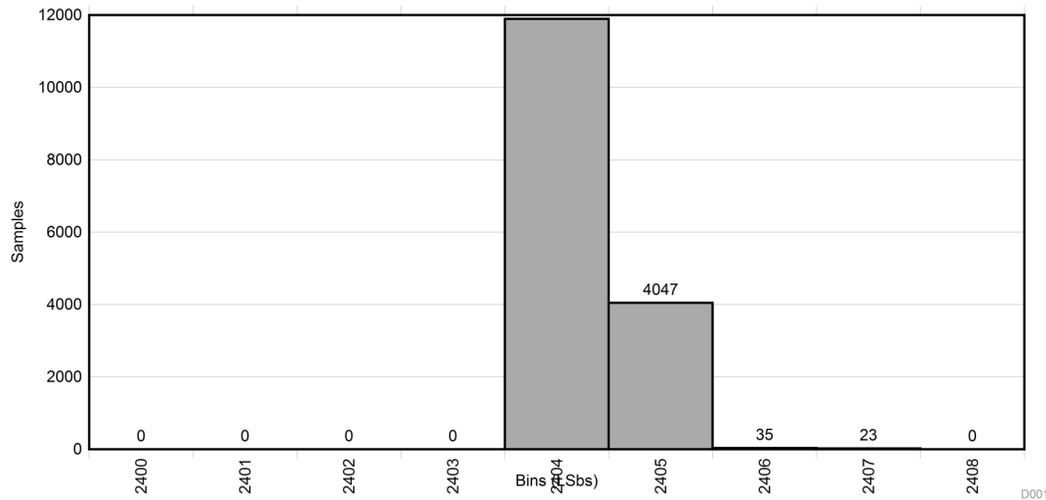


Figure 17. Uncalibrated Percentage Full-Scale Error vs DC-Link Voltage at No Load With Current

3.2.2.3 DC-Link Voltage Measurement Histogram

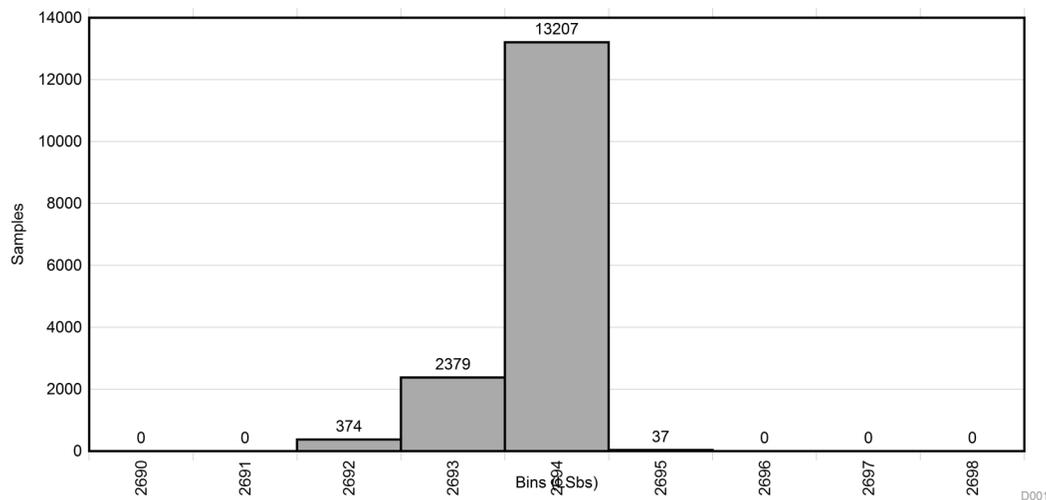
The histogram of the DC-Link voltage feedback signal is obtained using the 12-bit ADC of the C2000 and buffering the sample for 1 s at a sampling rate of 16 kHz.  18 shows the histogram of the DC-Link feedback when the DC-Link is powered with 600 V and the invert is driving a three-phase sinusoidal current of 3 A_{RMS} into the motor. The samples differ from the center by 4 LSBs that equal to 0.1% of the full-scale range.



 18. Histogram of DC-Link Sensing Measuring 600 V With 3 A_{RMS} in Motor

3.2.2.4 Phase Current Sensing Histogram

The histogram of the phase current feedback signal is obtained using the 12-bit ADC of the C2000 and buffering the sample for 1 s at a sampling rate of 16 kHz.  19 shows the histogram of the phase current feedback, which is obtained with a 600-V DC-Link and the invert is driving a DC current into the motor. This test is done by fixing the PWM duty in three phases such that the U-Phase has 3-A DC and the V and W phase have -1.5-A DC each. The samples are spread across 4 LSBs, which is equal to 0.1% of the full-scale range.



 19. Histogram of Phase Current Feedback Signal Sensing Measuring 3-A DC Into Motor and 600-V DC-Link

3.2.2.5 Step Response and Overcurrent Detection Latency

The propagation delay for the current measurement is captured by applying a 250-mV step-input to the input of the AMC1301 (after de-soldering the 5-mΩ shunt from the PCB).

Figure 20 shows the response of AMC1301 output and the window comparator when an input to the AMC1301 is a step voltage from 0 V to 250 mV. Similarly, Figure 21 is the response for a step input from 0 V to -250 mV. Table 7 shows the summary of measured delays.

表 7. Summary of Measured Delays

PARAMETER	PROPAGATION DELAY
Positive step input of propagation delay from input to output of AMC1301	1.8 μs
Positive step input of propagation delay from AMC1301 input to comparator TLC372 output	3.2 μs
Negative step input of propagation delay from input to output of AMC1301	1.8 μs
Negative step input of propagation delay from AMC1301 input to comparator TLC372 output	3.3 μs

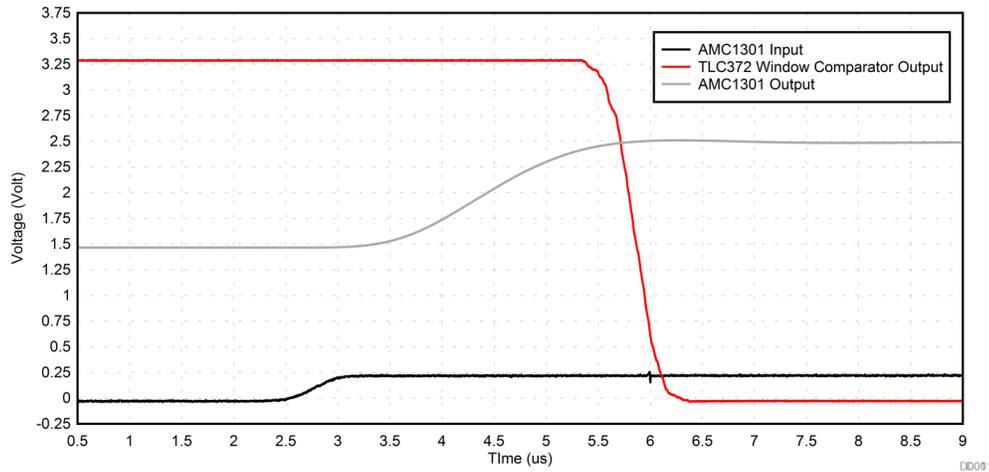


Figure 20. Positive 250-mV Step Input Response

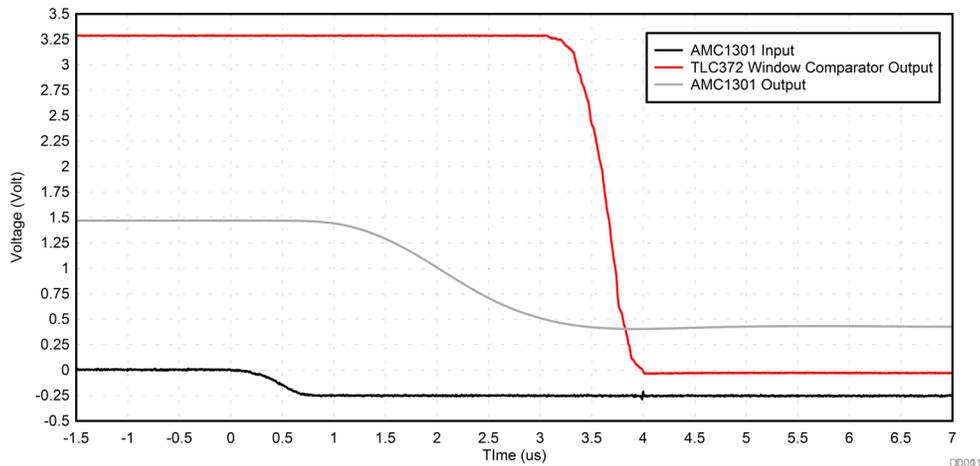


Figure 21. Negative 250-mV Step Input Response

4 Design Files

4.1 Schematics

To download the schematics, see the design files at [TIDA-01541](#).

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-01541](#).

4.3 PCB Layout Recommendations

The hardware for this reference design is based on the TIDA-00366 reference design. For the PCB layout recommendation, see [Reference Design for Reinforced Isolation Three-Phase Inverter With Current, Voltage, and Temp Protection](#).

4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-01541](#).

4.4 Altium Project

To download the Altium project files, see the design files at [TIDA-01541](#).

4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-01541](#).

4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-01541](#).

5 Related Documentation

1. Texas Instruments, [LAUNCHXL-F28379D Overview User's Guide](#)

5.1 商標

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6 Terminology

PWM— Pulse width modulation

MCU— Microcontroller unit

IGBT— Insulated bipolar gate transistor

RPM— Rotation per minute

RMS— Root mean square

NTC— Negative temperature coefficient thermistor

7 About the Authors

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改訂履歴

資料番号末尾の英字は改訂を表しています。その改訂履歴は英語版に準じています。

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