デッド・タイム挿入が組み込まれたゲート・ドライバを使用する三相インバータのリファレンス・デザイン

概要
このリファレンス・デザインは、強化され、絶縁された10kWの三相インバータのシステム・コスト低下と、小型の設計を実現します。単一のパッケージに格納されたデュアル・ゲート・ドライバを使用し、ブートストラップ構成によりゲート・ドライバの電源用にフローティング電圧を生成することで、システム・コストの低減と小型化を達成しています。デュアル・ゲート・ドライバUCC21520には、デッド・タイム挿入機能が搭載されており、抵抗オプションにより構成が可能です。この独自のデッド・タイム挿入により、入力PWM信号のオーバーラップに起因するシュートスルーから三相インバータが保護されます。過負荷、短絡、地絡、DCバスの低電圧と過電圧、およびハードウェアのIGBTモジュール過熱に対する保護により、システムの信頼性が向上します。

リソース
TIDA-01540 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
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200V〜690V AC駆動に適切
• 強化された絶縁ハーフ・ブリッジ・ゲート・ドライバは伝搬遅延マッチングが非常に優れており、デッド・タイムが短縮(低い歪みと低い電力損失)
• インターロック、デッド・タイム、挿入機能の搭載により、PWM入力信号のオーバーラップ時にIGBTを保護(デッド・タイムはプログラム可能)
• 一次側ロジック障害に対するSTOおよびフェイルセーフ対策を備え、IGBTへのゲート駆動出力をハイサイドとローサイドの両方同時にシャットダウンするディセーブル信号を使用することで、さらに高い信頼性を実現
• UCC21520はCMTIが高く(100kV/μs)、スイッチング過渡に対して高い堅牢性を実現
• UCC21520はIGBTの誤ったターンオンおよびターンオフを回避するため、5nsよりも短い入力パルスおよび過渡ノイズを除去

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
1 System Description

Insulated gate bipolar transistors (IGBTs) are mostly used in three-phase inverters that have numerous applications like variable-frequency drives that control the speed of AC motors, uninterruptible power supply, solar inverters, and other similar inverter applications. IGBTs have advantages such as high input impedance as the gate is insulated, a rapid response ability, good thermal stability, simple driving circuit, good ability to withstand high voltage, snubber-less operation, and controllability of switching behavior to provide reliable short-circuit protection. The IGBT is a voltage-controlled device, which gives it the ability to turn on and off very quickly.

图 1 shows atypical application of a three-phase inverter using six isolated gate drivers. Note that each phase uses a high-side and a low-side IGBT switch to apply positive and negative high-voltage DC pulses to the motor coils in an alternating mode. The output voltage to the motor is controlled by pulse width modulation (PWM). The output voltage is an average of the peak or maximum voltage and the amount of time the transistor is turned on or off.

Apart from isolated gate-drivers for IGBTs, the three-phase inverters include DC bus voltage sensing, inverter current sensing, and IGBT protection (like overtemperature, overload, ground fault, and so on).
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 ask for using expensive controllers with built-in SINC filters. Using an isolated amplifier enables interfacing with 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.

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 details a gate driver circuit for a three-phase inverter. The gate drive circuit comprises of three UCC21520 devices, which are dual IGBT gate drivers. The UCC21520 has many features to design a reliable three phase inverter.

The UCC21520 has a built-in dead-time insertion feature, which can insert a dead time into a complementary PWM for a half-bridge even if the PMWs overlap. The PWM overlap can be due to noise, damage of the connectors, wires connecting between the controller and gate diver, or a false PWM output. This feature is useful considering drives are trending to a more compact form factor. This new size can cause the PWM signals to have spacing and routing inside the drive if they are placed next to noise generators like high frequency signals, switching nodes, and so on. The simplest way to protect against IGBT shoot-through in this situation is to have interlock and dead band insertion.

The low propagation delay of the UCC21520 between the input and output contribute to reducing the deadband distortion in an inverter. In the reference design of the three-phase IGBT inverter, the deadband time is the sum of the time required for one IGBT to turn off and the other IGBT to turn on and the propagation delay. The low propagation delay allows the designer to use the minimum dead time possible for an IGBT module and reduce the related distortion in the current waveform.

The UCC21520 also has the single enable pin to disable the top and bottom IGBT, which can be used to implement safe torque of features in a motor drive.

1.1 Key System Specifications

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-Link input voltage</td>
<td>400 V to 1200 V</td>
</tr>
<tr>
<td>Gate driver supply voltage</td>
<td>16 V for low-side IGBT gate driver, 15 V (bootstrapped) for high-side IGBT gate driver</td>
</tr>
<tr>
<td>IGBT power module</td>
<td>Voltage rating: 1200 V, current rating: 50 A or more</td>
</tr>
<tr>
<td>Rated power capacity</td>
<td>10 kW</td>
</tr>
<tr>
<td>Inverter switching frequency</td>
<td>4 kHz (minimum) to 16 kHz: adjustable through software</td>
</tr>
<tr>
<td>Isolation</td>
<td>Reinforced (IEC 61800-5)</td>
</tr>
<tr>
<td>Gate drive</td>
<td>Unipolar 0 to 16 V, built-in PWM interlock and programable dead time insertion from 0 to 5 µs, input pulse rejection &lt; 5 ns</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>TMS320F28379D</td>
</tr>
<tr>
<td>Operating ambient temperature</td>
<td>–25°C to +85°C</td>
</tr>
<tr>
<td>Motor</td>
<td>Three-phase 400-V AC induction motor (ACIM)</td>
</tr>
</tbody>
</table>
### Table 1. Key System Specifications (continued)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supply specification for MCU</td>
<td>3.3 V ± 5%</td>
</tr>
<tr>
<td>Feedbacks</td>
<td>Current sensing (±50 A), DC-Link bus voltage sensing (0 to 1026 V), IGBT</td>
</tr>
<tr>
<td></td>
<td>module temperature sensing</td>
</tr>
<tr>
<td></td>
<td>Interface for an external 3.3-V MCU with 3.3-V unipolar output input</td>
</tr>
<tr>
<td>Protections</td>
<td>Overload, overvoltage, undervoltage, ground fault, overtemperature</td>
</tr>
<tr>
<td>PCB</td>
<td>160 × 156 mm, four layers, 2-oz copper</td>
</tr>
</tbody>
</table>
2 System Overview

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

This reference design implements a three-phase inverter rated up to 10 kW. As shown in 図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 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 a microcontroller (MCU).
The inverter protects against overload, short circuit, ground fault, DC bus undervoltage and overvoltage, and IGBT module overtemperature. 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 over-temperature 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.

### 2.1 Highlighted Products

#### 2.1.1 UCC21520

The UCC21520 is an isolated dual-channel gate driver with a 4-A source and 6-A sink peak current. This 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.

- Operating temperature range: –40 to +125°C
- Switching parameters:
  - 9-ns typical propagation delay
  - 10-ns minimum pulse width
  - 5-ns maximum delay matching
  - 5-ns maximum pulse-width distortion
- CMTI greater than 100 V/ns
- Programmable overlap and dead time
- Rejects input pulses and noise transients shorter than 5 ns
2.1.2 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\text{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 to connect 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: \pm 1.6 mV at 25°C, \pm 21 μV/°C
- Fixed gain: 1
- Very low gain error and drift: ±0.3% at 25°C, ± 60 ppm/°C
- Very low nonlinearity and drift: 0.05%, 1 ppm/°C

2.1.3 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 to connect directly 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 μV at 25°C, ± 3 μV/°C
- Fixed gain: 8.2
- Very low gain error and drift: ±0.3% at 25°C, ± 50 ppm/°C
- Very low nonlinearity and drift: 0.03%, 1 ppm/°C

2.1.4 OPA320

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

2.1.5 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 to operate from –40°C to +125°C. The typical response time of comparators for the switching is 200 ns.
2.1.6 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°C.
2.1.7 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.

2.1.8 REF2033

The REF2033 offers excellent temperature drift (8 ppm/°C, max) and initial accuracy (0.05%) on both the \(V_{\text{REF}}\) and \(V_{\text{BIAS}}\) outputs while operating at a quiescent current less than 430 \(\mu\text{A}\). In addition, the \(V_{\text{REF}}\) and \(V_{\text{BIAS}}\) 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. An extremely low dropout voltage of 10 mV allows this device to operate from very low input voltages.

2.1.8.1 TL431B (Q-Version)

The TL431 is a three-terminal adjustable shunt regulator with specified thermal stability over temperature ranges. The output voltage can be set to any value between \(V_{\text{REF}}\) (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.

2.1.8.2 SN74LVC1G10

The SN74LVC1G10 performs the Boolean function \(Y = \overline{(A \times B \times C)}\) or \(Y = \overline{A} + \overline{B} + \overline{C}\) 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 to operate from −40°C to +125°C.

2.2 System Design Theory

This reference design is based on the hardware of the TIDA-00366 design. The information on the IGBT inverter, IGBT gate driver, onboard power supply, and fault protection feature are given in the design guide Reference Design for Reinforced Isolation Three-Phase Inverter With Current, Voltage, and Temp Protection.

**Note:** This reference design is designed for a three-phase inverter, but 2.2.1 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).
2.2.1 Isolated IGBT Gate Driver

A three-phase inverter application uses six power switches (IGBTs in this case). To drive these switches, six totally independent gate drivers are required. Also, with a high-voltage operation, it is necessary to have enough isolation between primary and secondary side of the gate driver. The UCC21520 is an isolated dual-channel gate driver with a 4-A source and a 6-A sink peak current. The device drives 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\textsubscript{RMS} reinforced isolation barrier with a minimum of 100-V/ns CMTI. Internal functional isolation between the two secondary-side drivers allows a working voltage of up to 1500-V DC. Figure 3 shows the internal structure of the UCC21520 gate driver.

![Functional Block Diagram of UCC21520](image)

This driver can be configured as two low-side drivers, two high-side drivers, or a half-bridge driver with programmable dead time (DT). A disable pin shuts down both outputs simultaneously when it is set high and allows normal operation when left floating or grounded. As a fail-safe measure, primary-side logic failures force both outputs low. 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. All the supply voltage pins have undervoltage lockout (UVLO) protection. With all these advanced features, the UCC21520 enables high efficiency, high power density, and robustness in a wide variety of power applications.
图 4 shows the circuit for the UCC21520 and associated components implemented for half-bridge configuration for a three-phase inverter.

2.2.1.1 Control Supply for Primary Side

VCCI pins (Pin 3 and Pin 8) are supplied with 3.3 V generated using the TLV1117 (3.3 V) (as explained in 2.1.6). C57 (4.7 µF) and C68 (0.1 µF) are used as local decoupling capacitors for VCCI pins.

2.2.1.2 Dead Time Control

The UCC21520 has a programmable dead time function using DT pin. Tying DT to VCCI allows the outputs to overlap. Leaving DT floating sets the dead time to < 15 ns. Placing a 500-Ω to 500-kΩ resistor between DT and GND adjusts dead time according to 式 1.

\[
DT \text{ (in ns)} = 10 \times R \cdot DT \text{ (in kΩ)}
\]  

A 130-kΩ resistor is connected between DT pin and GND pin, which sets the dead time to 1.3 µs as per 式 1. Select this resistor for a 1% tolerance to prevent any drift in the dead time. For this reference design, the dead time is controlled by the UCC21520 to ensure that there is always a minimum deadband. This deadband is useful in case a proper deadband is missing in the input PWM signal. C113 is a 2.2-nF capacitor used for filtering noise at the DT pin.

2.2.1.3 DISABLE Signal for Gate Drivers

The DISABLE pin is used to disable the gate drivers. The pin disables both driver outputs if asserted high and enables if set low or left open. This pin is pulled low internally if left open or floating. Tie this pin to ground if it is not used to achieve better noise immunity. For this reference design, the DISABLE pin is generated using a three-input NAND gate.
2.2.1.4 Supply for Low-Side Gate Drivers

The low-side gate drivers for all three channels are powered using 16V_GPS, which is supplied externally from connector J4 as shown in 图 5. VDBB is secondary-side power for driver B. It is supplied with 16V_GPS and locally decoupled to VSSB using low ESR and ESL capacitors C72 (0.1 μF) and C73 (4.7 μF), which are located as close to the device as possible. VSSB is ground for the secondary-side driver B and a ground reference for the secondary-side B channel.

2.2.1.5 Bootstrap Power Supply for High-Side Gate Drivers

One of the most widely used methods to supply power to the high-side drive circuitry of a gate driver is the bootstrap power supply. The bootstrap power supply consists of a bootstrap diode and a bootstrap capacitor (with an optional series resistor). This method has the advantage of being both simple and low cost. The maximum voltage that the bootstrap capacitor (V_BS) can reach is dependent on the elements of the bootstrap circuit. Consider the voltage drop across R_BOOT, V_F of the bootstrap diode, and the drop across the low-side switch (VCE(ON) or VFP, depending on the direction of current flow through the switch).

2.2.1.6 Selection of Bootstrap Capacitor (C_BOOT)

The bootstrap capacitor must be sized to have more than enough energy to drive the gate of the IGBT without depleting the bootstrap capacitor more than 10% and the AMC1301 used for current sensing. A good guideline is to size C_BOOT to be at least 10 times as large as the equivalent IGBT gate capacitance (Cg) and capacitance required to supply the AMC1301 with constant current for one PWM period. Calculate Cg based on the voltage driving the high-side gate of the IGBT (V_GE) and the gate charge of the IGBT (Qg). V_GE is approximately the bias voltage supplied to VDD after subtracting the forward voltage drop of the bootstrap diode D12 (V_DBOOT). In this design example, the estimated V_GE is approximately 15 V, as 式 2 shows.

\[
V_{GE} \approx V_{DD} - V_{DBOOT} = 16V - 1V = 15V
\]  \hspace{1cm} (2)

The IGBT module in this reference design has a specified Qg of 0.47 μC. The equivalent gate capacitance of the IGBT can be calculated as 式 3 shows.

\[
C_{g} = Q_{g} / V_{GE} = (0.47 \mu C) / 15 = 0.0313 \mu F
\]  \hspace{1cm} (3)

The bootstrap capacitor also has to supply the AMC1301 on the high-voltage side with a maximum of 6.5 mA. Considering the lowest PWM frequency that needs to be supported is 4 kHz, this implies the bootstrap capacitor must hold this charge for one PWM period (that is, \(1/4 kHz = 250 \mu s\)). The total charge consumed is 250 μs × 6.5 mA = 1.625 μC. At 15 V, the capacitance required to store this charge is calculated using 式 4:

\[
C_{a} = Q_{a} / V_{GE} = (1.625 \mu C) / 15 = 0.1083 \mu F
\]  \hspace{1cm} (4)

After estimating the value for Cg, C_BOOT must be sized to at least 10 times larger than Cg, as 式 5 shows.

\[
C_{BOOT} \geq 10 \times (C_{g} + C_{a}) = 10 \times (0.0313 \mu F + 0.1083) = 1.396 \mu F
\]  \hspace{1cm} (5)

This reference design uses a parallel combination of 0.47-μF and 2.2-μF capacitors.
2.2.1.7 Selection of Bootstrap Diode

The voltage that the bootstrap diode encounters is the same as the full DC bus voltage (in this case, a maximum of 1200-V DC). The bootstrap diode voltage rating must be greater than the DC bus rail voltage. The bootstrap diode must be a fast recovery diode to minimize the recovery charge and thereby the charge that feeds from the bootstrap capacitor to the 16-V supply. The diode must be able to carry a pulsed peak current of 11.28 A (as per 式 6). However, the average current is much smaller and depends on the switching frequency and the gate charge requirement of the high-side IGBT. This reference design uses a 1300-V, 1-A, fast recovery diode BYG23T-M3.

The bootstrap diode power dissipation ($P_{\text{BOOT}}$) can be estimated based on the switching frequency, diode forward voltage drop, and the switching frequency of the PWM signal ($f_{\text{SW}}$). In this reference design, the switching frequency has been set to 16 kHz. 式 6 calculates the estimated power loss for the bootstrap diode.

$$P_{\text{BOOT}} = \frac{1}{2} \times Q_g \times f_{\text{sw}} \times V_{\text{DBOOT}} = \frac{1}{2} \times 0.47 \mu C \times 16 \text{ kHz} \times 1 \text{ V} = 3.76 \text{ mW} \quad (6)$$

2.2.1.8 Selection of Current Limiting Resistor for Bootstrap Diode

Considering that having a 1.5-V (p-p) ripple on the bootstrap capacitor, the charge on the 0.47-µF and 2.2-µF capacitors is:

$$Q = C \times V = (0.47 \mu + 2.2 \mu) \times 1.5 = 4 \mu C \quad (7)$$

For a capacitor charging period of 5 µs, the same charge is also represented as 式 8.

$$Q = 4 \mu C = I_{CH} \times 5 \mu s \quad (8)$$

This gives $I_{CH} = 0.8$ A.

With a voltage drop across diode being 1 V, the $R_{\text{BOOT}}$ is calculated as:

$$R_{\text{BOOT}} = \frac{V_{\text{DBOOT}}}{I_{CH}} = \frac{1}{0.8} = 1.25 \Omega \quad (9)$$

This reference design uses a $R_{\text{BOOT}}$ value of 1.33 Ω.

With $R_{\text{BOOT}} = 1.33 \Omega$, the bootstrap diode current is calculated as 式 10.

$$I_{DBOOT} (p k) = \frac{(V_{\text{DD}} - V_{\text{DBOOT}}) R_{\text{BOOT}}}{(16 - 1)} \times 1.33 = 11.28 \text{ A} \quad (10)$$

The power dissipation capability of the bootstrap resistor is important. The bootstrap resistor must be able to withstand the short period of high power dissipation during the initial charging sequence of the bootstrap capacitor.

2.2.1.9 Gate Resistors

The gate current and the appropriate power of the voltage supply depend on the operating frequency, bias control voltages, and total gate charge. The total gate charge is published in IGBT data sheets, depending on gate control voltage. The gate charge necessary for switching is very important to establish the switching performance of the IGBT. The lower the charge, the lower the gate drive current needed for a given switching time. The gate current can be controlled using an external gate resistor between driver output and gate of the IGBT. The value of the gate resistor determines the peak charge and discharge currents. The most classical way to influence the switching behavior of an IGBT is by selecting the gate resistors. The gate resistors can be different for the on and off switching process. In such cases, the turnon gate resistor is denominated with $R_{\text{Gon}}$ and for turning off with $R_{\text{Goff}}$ as shown in 図 6. The effective values of gate resistors become:

- Effective $R_{\text{Gon}} = R_{\text{Gon}}$
- Effective $R_{\text{Goff}} = R_{\text{Gon}} // R_{\text{Goff}}$
Depending on the gate resistor, both the voltage gradient (dv/dt) as well as the current gradient (di/dt) are modified. The higher the resistance of \( R_{\text{G(on)}} \), the softer the switching of the IGBT (and correspondingly, the turnoff of the free-wheeling diode). As a consequence, however, the turnon losses of the IGBT increase (and the recovery losses of free-wheeling diode decrease).

For this reference design, \( R_{\text{G(on)}} = 16.5 \Omega \) and \( R_{\text{G(off)}} = 0 \Omega \).

With the internal gate resistance of \( 4 \Omega \), the gate currents are calculated as:

- Source current = \( 16 \text{ V} / (16.5 + 4) \Omega = 780 \text{ mA} \)
- Sink current = \( 16 \text{ V} / 4 \Omega \approx 4 \text{ A} \) (considering zero on-resistance of diode)

Another important point to highlight is that 图6 shows 10-kΩ resistors across the gate and emitter terminals of the IGBTs. These resistors are a safety precaution and are placed across these nodes to ensure that the IGBTs are not turned on if the UCC21520 device is not in place or not properly soldered on the circuit board.

### 2.2.1.10 Power Dissipation in Gate Driver

This section explains the calculation power dissipated in the gate driver related to this reference design. For more information on the power loss, see [UCC21520 4-A, 6-A, 5.7-kV\(_{\text{RMS}}\) Isolated Dual-Channel Gate Driver](http://www-s.ti.com/sc/techlit/TIDUDJ9).

\[
P_{\text{GDQ}} = V_{\text{VCCI}} \times I_{\text{VCCI}} + V_{\text{DDA}} \times I_{\text{DDA}} + V_{\text{DDB}} \times I_{\text{DDB}} \tag{11}
\]

Where

- \( V_{\text{VCCI}} \) and \( I_{\text{VCCI}} \) are the low-voltage sides bias voltage and quiescent current, 5 V and 2.5 mA respectively
- \( V_{\text{DDA}} \) and \( V_{\text{DDB}} \) are gate drive supply voltage for top and bottom gate drivers, which is 16 V
- \( I_{\text{DDA}} \) and \( I_{\text{DDB}} \) are the quiescent current taken from the gate drive power supply
- \( P_{\text{GDQ}} \) is calculated to be 60.5 mW

The power dissipation due to switching of the gate driver is given in 式12:

\[
P_{\text{GSW}} = 2 \times V_{\text{DD}} \times Q_{\text{G}} \times f_{\text{SW}} \tag{12}
\]

Where

- \( V_{\text{DD}} \) is gate drive supply voltage of 16 V
- \( Q_{\text{G}} \) is the IGBT gate charge, which is 0.47 µF
• $f_{SW}$ is the PWM switching frequency of 16 kHz

$P_{GSW}$ is calculated to be 240.64 mW

The power dissipation in gate driver due to this switching is given in 式13:

$$P_{GDO} = P_{GSW} \times (R_{OH} | | R_{NMOS} | | R_{ON} + R_{GFET\_INT} + R_{OFF} | | R_{ON} + R_{GFET\_INT})$$

(13)

Where

• $R_{OH}$, $R_{NMOS}$, and $R_{OL}$ is from the UCC21520 data sheet; values are 5 $\Omega$, 1.47 $\Omega$, and 0.55 $\Omega$, respectively

• $R_{ON}$ is the turnon gate resistance which is 16.5 $\Omega$

• $R_{OFF}$ is the turnoff gate resistance which is 0 for TIDA-01540

• $R_{GFET}$ is the IGBT internal resistance, which is 4$\Omega$

• $P_{GDO}$ is calculated to be 41.72 mW

The total power dissipation is $P_G = P_{GDO} + P_{GSW} = 102.22$ mW. Considering the UCC21520 has a junction to ambient thermal resistance of $R_{\Theta JC} = 11.1^\circ$C/W, the temperature rise due to this is calculated as $R_{\Theta JA} \times P_G = 102.22$ mW $\times 11.1^\circ$C/W $= 1.13^\circ$C.

2.2.2 Connectors to Connect C2000™ Piccolo™ LaunchPad™

表2 shows the pinout for C2000 Piccolo LaunchPad. The highlighted pins are used for connecting the reference design board.

表 2. C2000™ LaunchPad™ Pinout

<table>
<thead>
<tr>
<th>SIGNAL NAME ON TIDA-01540</th>
<th>MUX VALUE</th>
<th>J1 PIN</th>
<th>J3 PIN</th>
<th>SIGNAL NAME ON TIDA-01540</th>
</tr>
</thead>
<tbody>
<tr>
<td>X 2 1 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3V</td>
<td>1</td>
<td>1</td>
<td>5V</td>
<td></td>
</tr>
<tr>
<td>GPIO32</td>
<td>2</td>
<td>2</td>
<td>GND</td>
<td></td>
</tr>
<tr>
<td>SCIIRQDB</td>
<td>GPIO19</td>
<td>3</td>
<td>3</td>
<td>ADCIN14 CMPIN4P 1V65_REF</td>
</tr>
<tr>
<td>SCIITXDB</td>
<td>GPIO18</td>
<td>4</td>
<td>4</td>
<td>ADCINC3 CMPIN5N L_U V_DC</td>
</tr>
<tr>
<td>GPIO67</td>
<td>5</td>
<td>5</td>
<td>ADCIN63 CMPIN6N I_U</td>
<td></td>
</tr>
<tr>
<td>GPIO111</td>
<td>6</td>
<td>6</td>
<td>ADCIN3 CMPIN1N 3V3_REF</td>
<td></td>
</tr>
<tr>
<td>SPICLK4</td>
<td>GPIO60</td>
<td>7</td>
<td>7</td>
<td>ADCINC2 CMPIN6P I_V</td>
</tr>
<tr>
<td>GPIO22</td>
<td>8</td>
<td>8</td>
<td>ADCIN82 CMPIN3P I_W</td>
<td></td>
</tr>
<tr>
<td>SCLA</td>
<td>GPIO105</td>
<td>9</td>
<td>9</td>
<td>ADCIN2 CMPIN1P V_DC</td>
</tr>
<tr>
<td>SDAA</td>
<td>GPIO104</td>
<td>10</td>
<td>10</td>
<td>ADCIN0 DACOUTA MODULE_T_EMP</td>
</tr>
<tr>
<td>PWM_U_T OP</td>
<td>EPWM1A</td>
<td>GPIO0</td>
<td>1</td>
<td>GND</td>
</tr>
<tr>
<td>PWM_U_B OT</td>
<td>EPWM1B</td>
<td>GPIO1</td>
<td>2</td>
<td>GND</td>
</tr>
<tr>
<td>PWM_V_T OP</td>
<td>EPWM2A</td>
<td>GPIO2</td>
<td>3</td>
<td>GND</td>
</tr>
<tr>
<td>PWM_V_B OT</td>
<td>EPWM2B</td>
<td>GPIO3</td>
<td>4</td>
<td>GND</td>
</tr>
<tr>
<td>PWM_W_T OP</td>
<td>EPWM3A</td>
<td>GPIO4</td>
<td>5</td>
<td>GND</td>
</tr>
<tr>
<td>PWM_W_B OT</td>
<td>EPWM3B</td>
<td>GPIO5</td>
<td>6</td>
<td>GND</td>
</tr>
<tr>
<td>OUTPUTXB AR1</td>
<td>GPIO24</td>
<td>7</td>
<td>7</td>
<td>GND</td>
</tr>
<tr>
<td>OUTPUTXB AR7</td>
<td>GPIO16</td>
<td>8</td>
<td>8</td>
<td>GND</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SIGNAL NAME ON TIDA-01540</th>
<th>MUX VALUE</th>
<th>J4 PIN</th>
<th>J2 PIN</th>
<th>SIGNAL NAME ON TIDA-01540</th>
</tr>
</thead>
<tbody>
<tr>
<td>X 2 1 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PWM_U_T OP</td>
<td>EPWM1A</td>
<td>GPIO0</td>
<td>1</td>
<td>GND</td>
</tr>
<tr>
<td>PWM_U_B OT</td>
<td>EPWM1B</td>
<td>GPIO1</td>
<td>2</td>
<td>GND</td>
</tr>
<tr>
<td>PWM_V_T OP</td>
<td>EPWM2A</td>
<td>GPIO2</td>
<td>3</td>
<td>GND</td>
</tr>
<tr>
<td>PWM_V_B OT</td>
<td>EPWM2B</td>
<td>GPIO3</td>
<td>4</td>
<td>GND</td>
</tr>
<tr>
<td>PWM_W_T OP</td>
<td>EPWM3A</td>
<td>GPIO4</td>
<td>5</td>
<td>GND</td>
</tr>
<tr>
<td>PWM_W_B OT</td>
<td>EPWM3B</td>
<td>GPIO5</td>
<td>6</td>
<td>GND</td>
</tr>
<tr>
<td>OUTPUTXB AR1</td>
<td>GPIO24</td>
<td>7</td>
<td>7</td>
<td>GND</td>
</tr>
<tr>
<td>OUTPUTXB AR7</td>
<td>GPIO16</td>
<td>8</td>
<td>8</td>
<td>GND</td>
</tr>
</tbody>
</table>
表 2. C2000™ LaunchPad™ Pinout (continued)

<table>
<thead>
<tr>
<th>SIGNAL NAME ON TIDA-01540</th>
<th>MUX VALUE</th>
<th>J1 PIN</th>
<th>J3 PIN</th>
<th>MUX VALUE</th>
<th>SIGNAL NAME ON TIDA-01540</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DAC1/ GPIO20</td>
<td>9</td>
<td>9</td>
<td>GPIO125</td>
<td>SD1_C2</td>
<td></td>
</tr>
<tr>
<td>DAC2/ GPIO21</td>
<td>10</td>
<td>10</td>
<td>GPIO29</td>
<td>OUTPUTXB_ARG</td>
<td></td>
</tr>
</tbody>
</table>

On reference design board, two 20-pin connectors are used to connect with the C2000 LaunchPad as shown in 図 7. The PWM signals for 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 = 10 Ω and C = 10 pF. This filter corresponds to a cutoff frequency of 159 MHz and an RC time delay of 1 ns. GND_FAULT and OVERLOAD signals are generated from the respective comparators connected to the MCU on GPIOs and also connected to a three-input NAND gate as explained in 2.2.1.3 to generate the DISABLE signal 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.

The 3.3-V supply generated using the TLV1117 is provided as a supply to the LaunchPad as shown in 図 8. 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.
図8. 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 PCB for this reference design. This section also explains the power supply requirement and connectors used to connect the external world.

3.1.1 TIDA-01541 PCB Overview

图 9 shows the top view of the PCB. The three phases (U, V, and W) have current sensing circuit and dual channel gate drivers as highlighted in the figure.

图 9. Top View of PCB for TIDA-01540

图 10 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.
3.1.2 Connector

Table 3 shows the connectors used on the reference design PCB and their purposes.

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

3.2.1 Test Setup

The following subsections provide descriptions and pictures of the test setup. 表 4 lists the key test equipment used in the subsequent tests.

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>TEST EQUIPMENT PART NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2000 F28379D LaunchPad</td>
<td>Texas Instruments LAUNCHXL-F28379D</td>
</tr>
<tr>
<td>Adjustable power supply</td>
<td>Keithley 2230G-30-1 (two power supplies are used to ensure isolation between 16-V and 5-V rails)</td>
</tr>
<tr>
<td>High-voltage power supply</td>
<td>Keysight N5751A (300 V and 2.5 A)</td>
</tr>
<tr>
<td>Load motor</td>
<td>ACIM, three-phase AC, 415 V (L-N, delta connected), 8.4 A_{RMS} (max), 3.7-kW rated, 50 Hz, 1460 RPM</td>
</tr>
<tr>
<td>Oscilloscope</td>
<td>Tektronix MDO3024</td>
</tr>
<tr>
<td>High-voltage differential probes</td>
<td>Tektronix THDP0200</td>
</tr>
<tr>
<td>Low-voltage probes</td>
<td>Tektronix TPP0200</td>
</tr>
</tbody>
</table>

図 11 shows the test setup used. The board is powered from three power supplies: 0 V 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 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.
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

图 12 is the thermal image of the board. For this test, the board is supplied with 3.3 V to the LaunchPad and the 5-V power rail of this reference design, and the gate drive power supply is 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 UCC2150 on the high-voltage side. Because the DC-Link is turned off, the thermal image captures temperatures due to the self-heating of the UCC21520 and not the power dissipation of the IGBT module. The temperature of the UCC21520 is 27.6°C, which is a temperature rise of 4.8°C from the ambient temperature of 22.8°C.

图 12. UCC21520 Surface Temperature
3.2.2.1.1 Propagation Delay of UCC21520

The propagation delay for the gate driver is obtained with the DC-Link disconnected. The half bridge of the inverter is driven with a complementary PWM of 50%. The motor is disconnected in this test. 图13 is an oscilloscope capture of the input PWM signal and output gate drive of the UCC21520. 图14 and 图15 are the propagation delays for the rising and falling edge for the gate signal of the top IGBT in the half bridge. Similarly, 图16 and 图17 are the propagation delays for the rising and falling edge for the gate signal of the bottom IGBT in the half bridge.

表5. Propagation Delay Measurement for UCC21520

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>PROPAGATION DELAY (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top IGBT gate driver rising edge propagation delay</td>
<td>30.44</td>
</tr>
<tr>
<td>Top IGBT gate driver rising edge propagation delay</td>
<td>29.64</td>
</tr>
<tr>
<td>Top IGBT gate driver rising edge propagation delay</td>
<td>20.84</td>
</tr>
<tr>
<td>Top IGBT gate driver rising edge propagation delay</td>
<td>24.84</td>
</tr>
</tbody>
</table>

图13. UCC21520 Half-Bridge Input and Output PWMs
図14. Top IGBT Gate Driver Rising Edge Propagation Delay

図15. Top IGBT Gate Driver Falling Edge Propagation Delay
The consequence of the propagation delay for a three-phase inverter is that the dead time between the top and bottom IGBT must be increased to accommodate the propagation delay time. The IGBT module on this reference design uses a dead time of 1.3 µs. The dead time must be adjusted by 60 ns (30 ns each for the top and bottom IGBT gate driver). The effect of the dead time is to increase the distortion on the current waveform. To demonstrate the effect of the dead band, an ACIM motor is connected and the inverter run in open loop at 10 Hz. The DC-Link is supplied with 600 V and a three-phase current of 1.5 \( A_{\text{RMS}} \) is injected into the motor.
图18 shows one motor line current waveform with the dead time set to 1.3 µs. 图19 shows is for a dead time of 1.8 µs, which would be the dead time if using an optocoupler-based gate driver with a propagation delay of 250 ns. Notice the waveform becomes more non-sinusoidal as the dead time increases.
3.2.2.1.2 Deadband Insertion and Interlock

The deadband and interlock feature of the UCC21520 are tested by driving the inverter with a complementary PWM of 50%; however, the PWM inputs to the UCC21520 are made to overlap by 2 µs. Figure 20 is the oscilloscope capture of the input PWM signal and output gate drive signals of the UCC21520. Figure 21 and Figure 22 are the zoomed-in waveforms for the switch node turnon and at switch node turnoff. Notice when the input PWMs overlap the interlock is active, hence both IGBTs are kept off. In an off state period, the interlock is active. After the end of the overlap, a time period of 1.3 µs elapses before the IGBT is turned on. This period corresponds to the deadband insertion of 1.3 µs.

This test simulates an overlap to check the interlock and dead time insertion; however, the overlap could be due to an software fault, damage to the gate drive signal connectors, or an EFT condition picked up on the input PWM signal. Without the interlock feature, this overlap would have caused the top and bottom IGBTs of the gate driver to turn on and cause a shoot-through condition that would damage the inverter.

![Figure 20: Dead Time Insertion for Overlapping PWMs](image1)

![Figure 21: Dead Time Insertion for Overlapping PWMs for Switch Node Turnon](image2)
图 22. Dead Time Insertion for Overlapping PWMs for Switch Node Turnoff
3.2.2.1.3 Bootstrap Power Supply Ripple

图 23 and 图 24 show the voltage rail and ripple for the bootstrap supply for the high-side gate driver, respectively. The PWM frequency is 4 kHz for this test. The top IGBT is turned on for 90% of the time and the bottom IGBT is turned on for the remaining 10%. The motor is disconnected in this test. 图 23 shows the bootstrap supply voltage and the ripple when the DC-Link power supply is disconnected. 图 24 shows the bootstrap supply voltage and the ripple when the DC-Link is powered with 600-V DC.

图 23. Bootstrap Power Supply Voltage and Ripple With DC-Link at 0 V

图 24. Bootstrap Power Supply Voltage and Ripple With DC-Link at 600 V
4 Design Files

4.1 Schematics
To download the schematics, see the design files at TIDA-01540.

4.2 Bill of Materials
To download the bill of materials (BOM), see the design files at TIDA-01540.

4.3 PCB Layout Recommendations
The hardware for this reference design is based on the TIDA-00366 design. For PCB layout recommendations, refer to 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-01540.

4.4 Altium Project
To download the Altium project files, see the design files at TIDA-01540.

4.5 Gerber Files
To download the Gerber files, see the design files at TIDA-01540.

4.6 Assembly Drawings
To download the assembly drawings, see the design files at TIDA-01540.

5 Related Documentation
1. Texas Instruments, LAUNCHXL-F28379D Overview User’s Guide
2. Texas Instruments, TIDA-01541 High-Bandwidth Phase Current and DC-Link Voltage Sensing Reference Design for Three-Phase Inverters

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

NELSON ALEXANDER is a systems engineer at Texas Instruments, where he is responsible for developing subsystem design solutions for the Industrial Motor Drive segment. Nelson has been with TI since 2011, has been involved in designing embedded systems, and has experiences in microcontrollers, isolation, analog signal chains, and IGBT gate drivers. Nelson earned his bachelor of engineering in electrical and electronics engineering at MSRIT, Bangalore.

N. NAVANEETH KUMAR is a systems architect at Texas Instruments, where he is responsible for developing subsystem solutions for motor controls within Industrial Systems. N. Navaneeth brings to this role his extensive experience in power electronics, EMC, analog, and mixed signal designs. He has system-level product design experience in drives, solar inverters, UPS, and protection relays. N. Navaneeth earned his bachelor of electronics and communication engineering from Bharathiar University, India and his master of science in electronic product development from Bolton University, UK.
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