Design Guide: TIDA-010276

36V, 50A 3-Phase GaN Inverter Reference Design for BLDC Motor Control

TEXAS INSTRUMENTS

Description

This design guide demonstrates a 36V, 50A Gallium nitride (GaN) field-effect transistor (FET) power stage for driving a three-phase brushless DC motor in cordless tools operating from a 5-cell Li-ion battery to a 10-cell battery pack. This reference design uses the LMG3100R017 GaN FET with integrated GaN-FET drive to improve the motor control system efficiency and performance. Additionally, the design offers a TI BoosterPack™ Plug-in Module compatible with 3.3V I/O interface that can connect to a C2000™ MCU LaunchPad™ development kit or MSPM0 MCU LaunchPad™ development kit for quick and easy performance evaluation of TI's GaN technology.

Resources

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TIDA-010276	Design Folder
LMG3100, LMR38010	Product Folder
TPS7B8150, OPA4323	Product Folder
LAUNCHXL-F2800137	Product Folder
LP-MSPM0G3507	Product Folder

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Features

- 6.50mm × 4.0mm LMG3100R017 GaN FET with integrated driver enables high power density and easy PCB layout
- High efficiency (> 99% peak) at 20kHz PWM enables operation at 25°C ambient up to 50A peak current without heat sink, 98.5% efficiency at 80kHz PWM in 50A peak current
- LMG3100R017 enables operation at higher PWM frequencies to help reduce DC-bus capacitor size and height by replacing electrolytic with ceramic capacitors
- Zero reverse recovery losses reduce switch node oscillations
- Low dead time of < 20ns minimizes phase voltage distortions
- Supports high-speed motor control with high PWM frequency
- Uses low-side current sampling, and adds phase voltage sampling to support verification of sensorless field-oriented control (FOC) or sensorless trapezoidal control
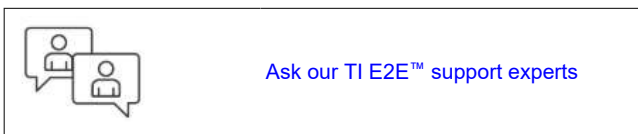
Applications

- Cordless handheld garden tool
- Cordless power tools
- Cordless vacuum cleaner
- Lawn mower
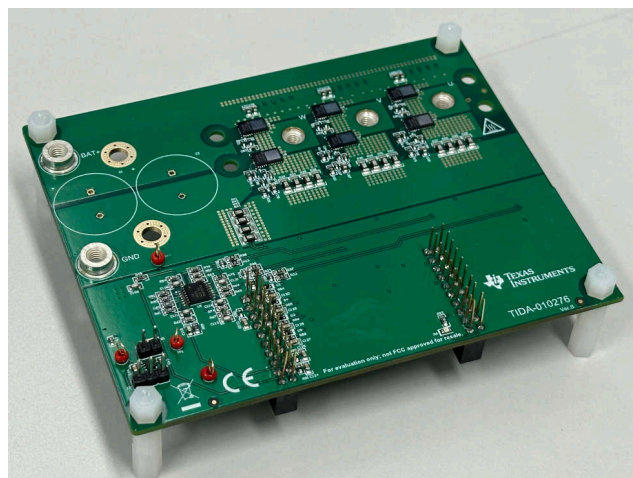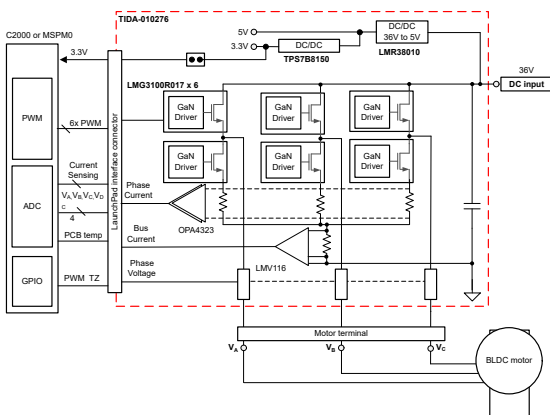
1 System Description

Power tools are used in various industrial and household applications such as drilling, grinding, cutting, polishing, driving fasteners, and so forth. The most common types of power tools use electric motors while some use internal combustion engines, steam engines, or compressed air. Power tools can be either corded or cordless (battery powered). Corded power tools use the mains power (the grid power) to power up the AC or DC motors.

Cordless tools use battery power to drive DC motors. Most cordless tools use lithium-ion batteries, the most advanced in the industry offering high energy density, low weight, and a longer lifetime. Power tools are available in different power levels and battery voltage levels. Power tools such as cordless chainsaws and circular saws and different garden tools like cordless wood and branch cutters require a very high torque and need a very high peak current.

Cordless tools use brushed or brushless DC (BLDC) motors. The BLDC motors are more efficient and have less maintenance, lower noise, and longer life. Power tools have requirements on form factor, efficiency, peak current, reliability, and thermal performance. Therefore, highly efficient power stages with a compact size are required to drive the power tool motor. The small form factor of the power stage enables flexible mounting, better PCB layout performance, and low-cost design. High efficiency provides maximum battery duration and reduces cooling efforts. The high-efficiency requirement, in turn, demands switching devices with a low drain-to-source resistance ($R_{DS(on)}$). The power stage must also make sure protections like motor stall or any high-current prevention are available.

This design features the use of GaN FETs, higher pulse-width modulation (PWM), and switching frequencies up to 100kHz to help reduce the DC-bus capacitor. These features reduce size and height by replacing electrolytic with ceramic capacitors, and higher efficiency can further reduce the area of the heat sink, which helps reduce the weight of the PCB. In addition, higher PWM switching frequencies are desired to reduce the current and thus reduce the torque ripple of the motor, especially with low-inductance brushless AC motors for more precise control.

The TIDA-010276 reference design uses a small size GaN-FET LMG3100R017 for a three-phase inverter. The LMG3100R017 integrates the driver and 80V GaN FET in a small 6.5mm × 4mm QFN package, optimized for extremely low gate loop and power loop impedance. The PCB offers mounting holes for an optional heat sink with the top-side cooled LMG3100R017 GaN-FET power modules. An integrated bootstrap diode helps further reduce space for the high-side GaN-FET bias supply. This design provides low-side current sampling and bus current sampling, and adds overcurrent protection for the bus current. In addition, the design also adds DC-bus voltage as well as the PWM filtered three-phase voltages to allow validation of advanced sensorless designs like InstaSPIN-FOC™ motors. The three-phase inverter operates from a wide input voltage range from 12V to 48V and offers onboard power management that provides a 5V rail to supply the LMG3100 gate driver and 3.3V for the current-sensing amplifiers and temperature sense. The TIDA-010276 offers a TI BoosterPack Plug-in Module compatible 3.3V I/O interface to connect to a C2000 MCU LaunchPad or MSPM0 LaunchPad for quick and easy performance evaluation.

1.1 Key System Specifications

Table 1-1 lists the key specifications of the TIDA-010276 small form factor three-phase GaN inverter reference design. The design can be directly connected to a C2000 MCU, MSPM0 LaunchPad development kit, 40-pin instance (J1–J3 and J4–J2). A jumper option is provided on the TIDA-010276 to the power the LaunchPad with 3.3V.

Table 1-1. Key System Specifications

PARAMETER	SPECIFICATIONS
Input voltage	36V DC (12V minimum to 48V maximum) – 10-cell Li-Ion
Rated output power	1800W
Current	50A
Phase current maximum range	±66A
Power FET type	GaN technology
Control method	Sensor-based, sensorless trapezoidal or Sensor-based, sensorless FOC
Inverter switching frequency	10kHz to 100kHz
Feedback signals	DC bus voltage, low-side bus current, low-side phase current, phase voltage, Hall sensor(connect to a LaunchPad development kit)
PCB layer stack	4-layer, 2oz copper
GaN-FET PCB area size	18mm × 58mm
Board specification	90mm × 112mm
Operating ambient	–20°C to 55°C

WARNING

TI intends this reference design to be operated in a lab environment only and does not consider the board to be a finished product for general consumer use.

TI Intends this reference design to be used only by qualified engineers and technicians familiar with the risks associated with handling high-voltage electrical and mechanical components, systems, and subsystems.

Hot surface! Contact can cause burns. **Do not touch!** Some components can reach high temperatures > 55°C when the board is powered on. Do not touch the board at any point during operation or immediately after operating, because high temperatures can be present.

CAUTION

Do not leave the design powered when unattended.

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2 System Overview

2.1 Block Diagram

Figure 2-1 shows the system block diagram of the three-phase GaN inverter with the TIDA-010276 indicated in the red dotted box.
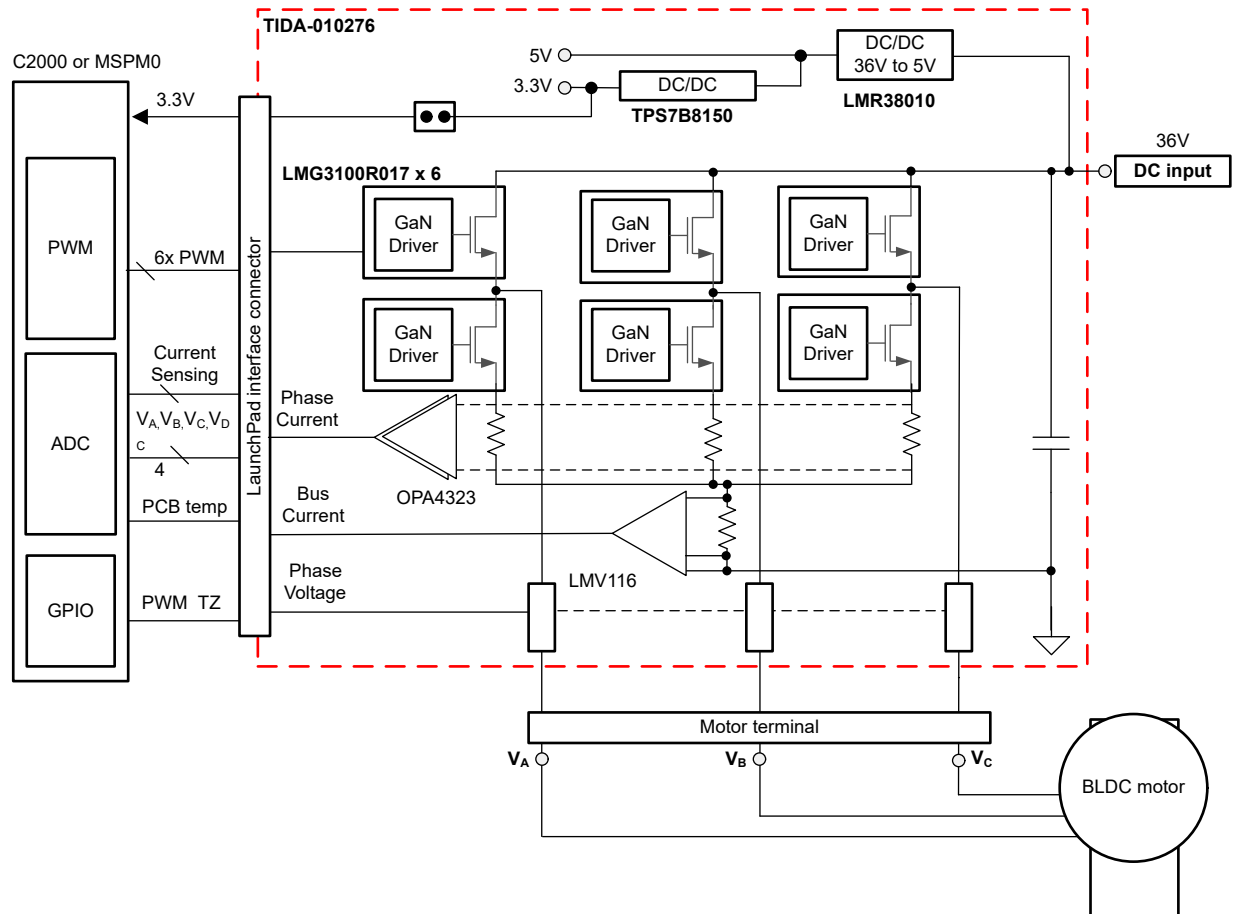

Figure 2-1. TIDA-010247 Block Diagram

2.2 System Overview

The reference design has the following subblocks:

- Three-phase power stage with GaN FET
- DC/DC converter LMR51606 generates the 5V rail to supply the GaN-FET power modules and the 3.3V LDO for current-sense amplifiers and temperature sensors
- DC bus voltage, low-side bus current, low-side phase current, phase voltage sensing
- MOSFET temperature sensing using onboard temperature sensor
- Host controller to implement the necessary motor control algorithms, sensing, and protections

2.3 Highlighted Products

The following highlighted products are used in this reference design. Key features for selecting the devices for this reference design are revealed in the following sections. Find more details of the highlighted devices in the respective product data sheet.

2.3.1 LMG3100

The LMG3100 device is a 100V, 97A Gallium Nitride (GaN) FET with integrated driver. The device consists of a 100V GaN FET driven by a high-frequency GaN-FET driver. Figure 2-2 shows the system block diagram. Table 2-1 details the key features and benefits for this design.
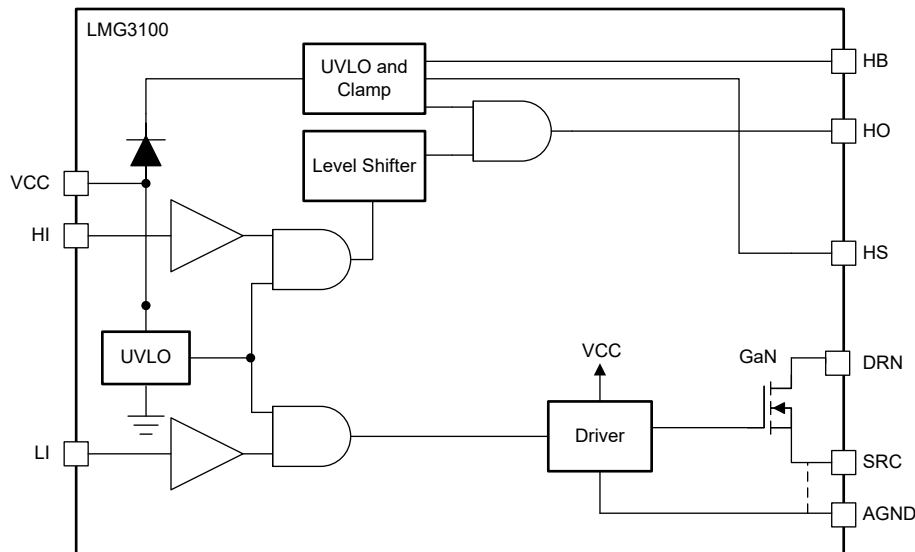

Figure 2-2. LMG3100 System Block Diagram

Table 2-1. Key Features and Benefits With LMG3100 in TIDA-010276

FEATURE	BENEFIT
Integrated 1.7mΩ, 90V GaN FET for 97A operation	Enables up to 60VDC, three-phase inverter with high current at 10kHz to 80KHz high-switching frequency for low inductance and high-speed drives
Integrated 90V, 1.7mΩ, GaN FETs and GaN driver	Minimized package parasitic elements enable ultra-fast switching for reduced switching losses to reduce or eliminate heat sink
GaN FETs have zero reverse recovery (3rd quadrant operation) and very small input capacitance CISS	Reduces or eliminates ringing in hard switching, like in inverters, to reduce EMI. Very low overshoot and undershoot allows higher nominal DC-link voltage than Si FET for same maximum rated voltage.
Excellent propagation delay (29.5ns typical) and matching (12ns typical)	Enables ultra-low dead band per half-bridge for major reduction of switching losses in three-phase inverter applications and elimination of dead-time distortions in the phase voltage
LMG3100 incorporates a high-side level shifter and bootstrap circuit	Two LMG3100 devices can be used to form a half bridge without needing an additional level shifter
Single 5V gate driver supply with bootstrap voltage clamping and undervoltage lockout	Easy power management. UVLO provides simultaneous shutdown of high-side and low-side GaN FET in case of gate driver undervoltage.
LMG3100 optimized pinout	Easy PCB layout with minimum inductance for reduced switching losses
Two exposed GaN dies on top (SW and PGND). Big PGND pad on bottom.	Realize lower top thermal resistance. Accepts both sides cooling.

2.3.2 LMR38010

The LMR38010 synchronous buck converter is designed to regulate over a wide input voltage range, minimizing the need for external surge suppression components. The LMR38010 operates during input voltage dips as low as 4.2V, at nearly 100% duty cycle if needed, making the device an excellent choice for wide input industrial applications and MHEV or EV systems.

The LMR38010 uses precision enable to provide flexibility by enabling a direct connection to the wide input voltage or precise control over device start-up and shutdown. The power-good flag, with built-in filtering and delay, offers a true indication of system status, eliminating the need for an external supervisor. The device

incorporates pseudorandom spread spectrum for minimal EMI and switching frequency can be configured between 200kHz and 2.2MHz to avoid noise-sensitive frequency bands. In addition, the frequency can be selected for improved efficiency at low operating frequency or smaller design size at high operating frequency.

The device has built-in protection features such as cycle-by-cycle current limit, hiccup mode short-circuit protection, and thermal shutdown in case of excessive power dissipation. The LMR38010 is available in an 8-pin HSOIC PowerPAD™ integrated circuit package.

2.3.3 TMP61

The TMP61 is a positive temperature coefficient (PTC) linear silicon thermistor. The device behaves as a temperature-dependent resistor, and can be configured in a variety of ways to monitor temperature based on the system-level requirements. The TMP61 has a nominal resistance at 25°C of 10kΩ with ±1% maximum tolerance, a maximum operating voltage of 5.5V, and maximum supply current of 400µA. The benefits of this device include no extra linearity circuitry, minimized calibration, less resistance toleration variation, larger sensitivity at high temperatures, and simplified conversion methods to save time and memory in the processor. This device can be used in a variety of applications to monitor temperature close to a heat source with the very small DEC package option compatible with the typical 0402 footprint.

2.3.4 TPS7B81

The TPS7B81 is a low-dropout (LDO) linear regulator that operates from input voltages up to 40V and can supply up to 150mA in current. With only 2.7µA of quiescent current at light loads, the device is an excellent choice for wide input supply designs and high cell-count battery applications that need very low standby power consumption. The 45V transient tolerance provides additional headroom for applications where inductive kickback can be present, thereby reducing external circuitry for voltage suppression.

With integrated short-circuit and overcurrent limiting, the TPS7B81 protects the system during fault conditions. In addition to the low standby power consumption, the very low dropout voltage in light load conditions helps maintain regulation even when powered by depleted batteries.

The TPS7B81 is available in thermally-enhanced, 8-pin HVSSOP and 6-pin WSON packages. Both packages offer high thermal conductivity, and the small size supports compact design, making them well designed for space-limited applications such as power tools or motor drive modules and battery packs.

2.3.5 OPA4323

The OPA4323 device is a low-voltage (1.7V to 5.5V), high-bandwidth (20MHz) amplifier (op amps) with a zero-crossover input stage and a rail-to-rail output stage. The zero-crossover input stage enables OPAx323 to achieve high linearity and low distortion for input signals with rail-to-rail swing that are typical in ADC driver applications. Gain-bandwidth of 20MHz provides a fast settling response for ADC sampling speeds from 0.5MSPS to 5MSPS, depending on the settling performance required. The OPA4323 is well-optimized for power savings as the device consumes just 1.6mA typical quiescent current.

The OPA4323 achieves a high slew-rate of 33V/µs allowing for fast detection of faults in motor current sensing applications. Unlike traditional amplifiers, the zero-crossover input stage allows for identical precision performance for both low- and high-side sensing applications, thus making OPA4323 the best choice for current sensing in a variety of end equipment such as the solar string inverters, power delivery, and high-speed motor control.

3 System Design Theory

3.1 Power Stage Design: Three-Phase Inverter

The nominal 36V DC input voltage is buffered with 2 × 1000µF electrolytic capacitors and 40 × 10µF ceramic capacitors to get a total of 2400µF DC-bus capacitance. The design can be tested with only ceramic capacitors or only electrolytic capacitors. The number of electrolytic capacitors or ceramic capacitors can be reduced, as needed, then the effect of higher switching frequency in reducing DC-bus capacitance can be evaluated. The PCB employs two separated ground planes: the power ground (PGND) and the logic or analog ground (GND). Both ground planes are connected through a net tie to minimize the crosstalk of high switching-frequency currents in the power ground plane into the logic plane. The PCB can optionally be tested with only ceramic capacitors or only electrolytic capacitors.
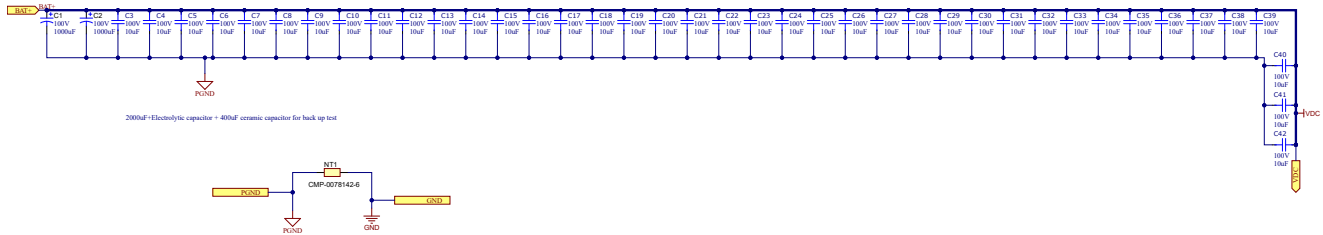
Figure 3-1. TIDA-010276 DC-Bus Decoupling and GND Scheme

3.2 LMG3100 GaN-FET Power Stage

The LMG3100 incorporates a high-side level shifter and bootstrap circuit, so that two LMG3100 devices can be used to form a half bridge without needing an additional level shifter. The PCB space is further reduced due to high integration and the fact that only a few additional passive components are required. Figure 3-2 shows the schematic of one half-bridge.
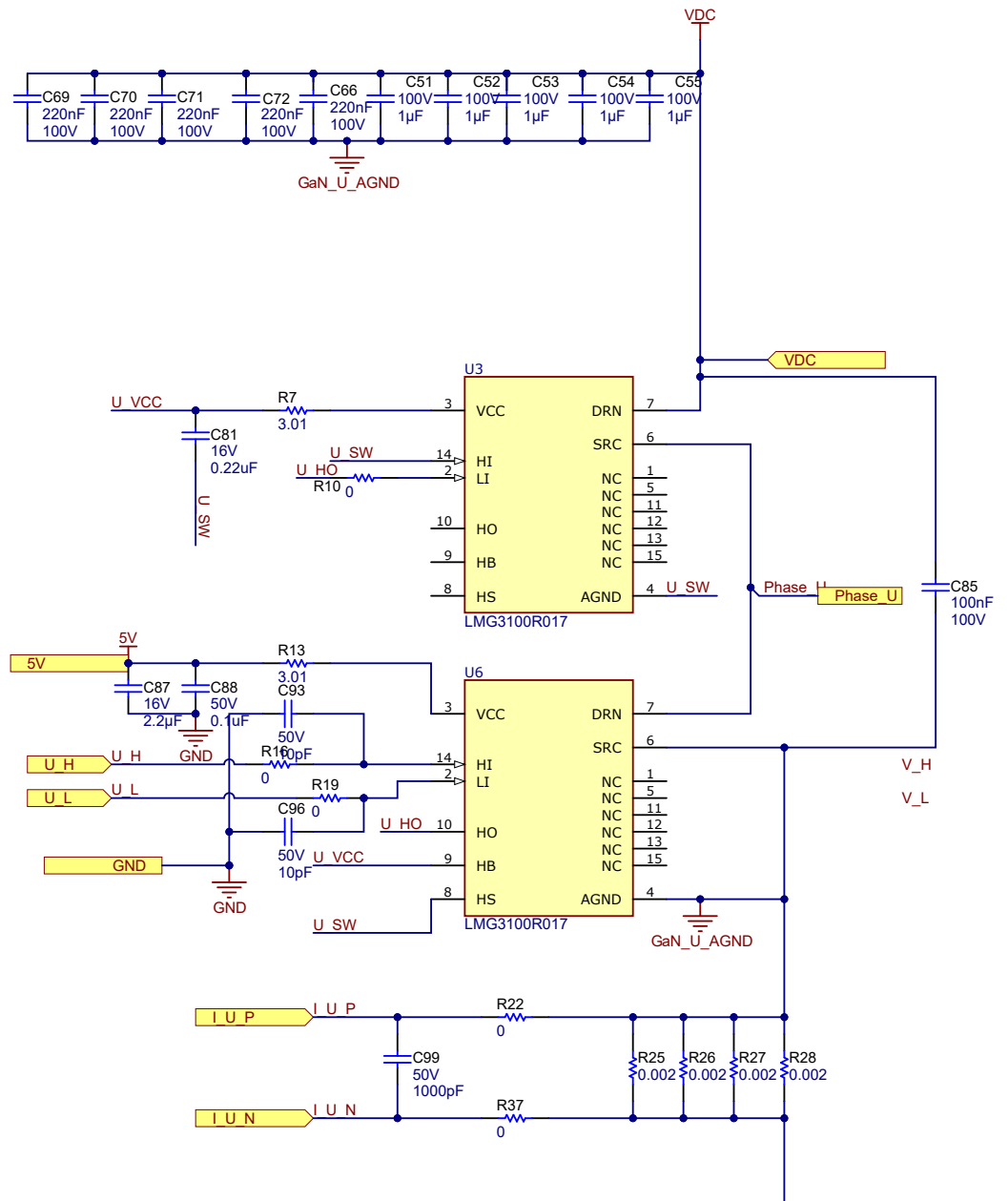
Figure 3-2. TIDA-010276 GaN Power Stage Schematic for Phase U

The 36V DC-link voltage is connected to the LMG3100 VIN pin and referenced to the power ground (PGND) pin. Local ceramic bypass capacitors *C51, C52, C53, C54,* and *C55* (1µF) and *C69, C70, C71, C72,* and *C66* (220nF) are placed in parallel, close between the VIN and AGND pins to minimize loop inductance. Capacitor *C85* is also added in half-bridge DRN and SRC to reduce the switch noise.

The LMG3100 integrated gate driver is supplied with 5V. A 1µF and 0.1µF ceramic bypass capacitor (C130, C86) are placed close to the VCC pin and AGND pin in the low-side GaN FET, as suggested in the data sheet. A 100nF ceramic bootstrap capacitor (C95) is placed close to the high-side gate-driver bootstrap rail and high-side GaN-FET source connection pins. R6 and R12 in the VCC path can limit the turn-on slew rate of the GaN FET. A 3Ω resistor was used for the tests in this design for R5 and R7. The complementary PWM signals for the high-side and low-side switch from the PWM buffer are low-pass filtered with R15, C89 and R18, C92 to reject high-frequency impulse noise and avoid false switching with a cutoff frequency of around 160MHz and a

propagation of around 1ns. Since this is a half-bridge application, connect the AGND of the high-side GaN FET to the low-side DRN pin. Because the low-side current sampling is used, connect AGND to the upper end of the sampling resistor and make sure that the voltage drop on the sampling resistor is as small as possible.

For layout, capacitors C55 *to* C69 need to be connected to the AGND network and make the connections as short as possible. Connect C85 as close as possible to the Phase_U network.

3.3 Power Management

Figure 3-3 shows the power-supply tree. A wide input voltage DC/DC buck converter is used to generate the 5V rail. A power module then generates 3.3V from 5V, which supplies 3.3V signal chain, such as OPA4323, and so forth. J1 or J2 can be used to disable LDO directly and supply 5V to GaN, OPA4323, and other circuits.
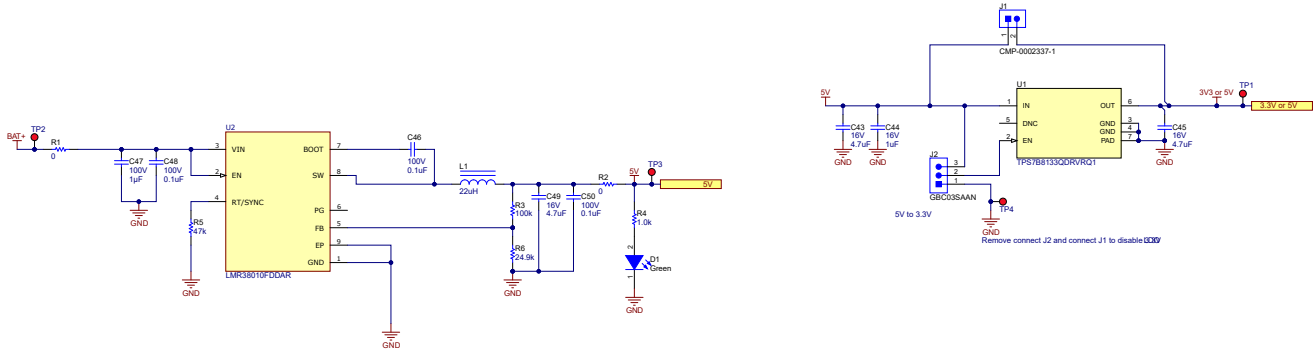
Figure 3-3. TIDA-010276 DC/DC and LDO

3.4 Current-Sensing Circuit

This reference design also supports bus current and low-side current sensing with an op amp. A 0.5mΩ sampling resistor is used by default, and a differential sampling is used in this design. The differential sampling gain can be changed by changing R54, R62, and R47. The default gain of this design is 51 and the current range is ±64.7A (for 3.3V), ±98A(for 5V), and the cutoff frequency is about 100kHz.
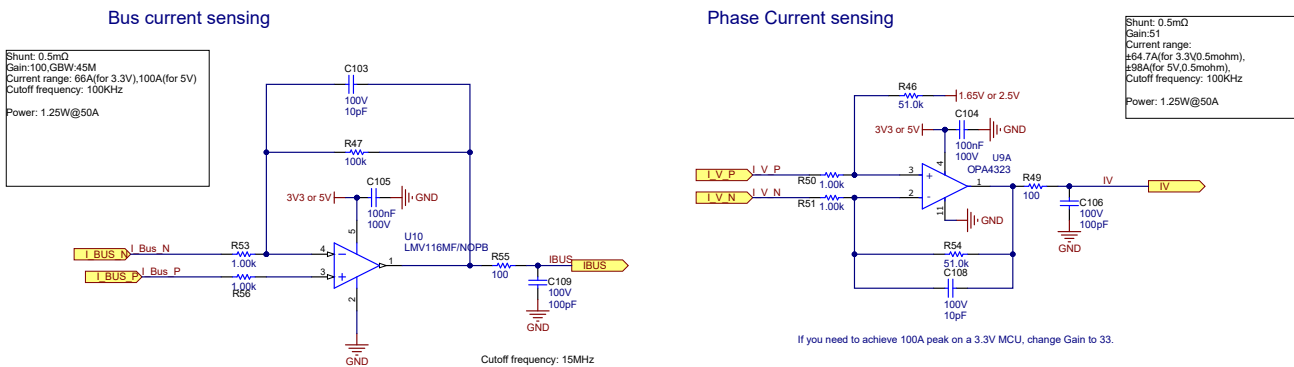
Figure 3-4. TIDA-010276 Current Sensing

3.5 Overcurrent Protection Circuit

TI designed the overcurrent protection hardware circuit. The LM393 is used as the comparator and the overcurrent protection threshold is set through R65 and R70. The default is 6A (for 3.3V), 9A (for 5V). After verifying that the hardware is normal, change R65 and R70 to 1kΩ and 10kΩ for testing.
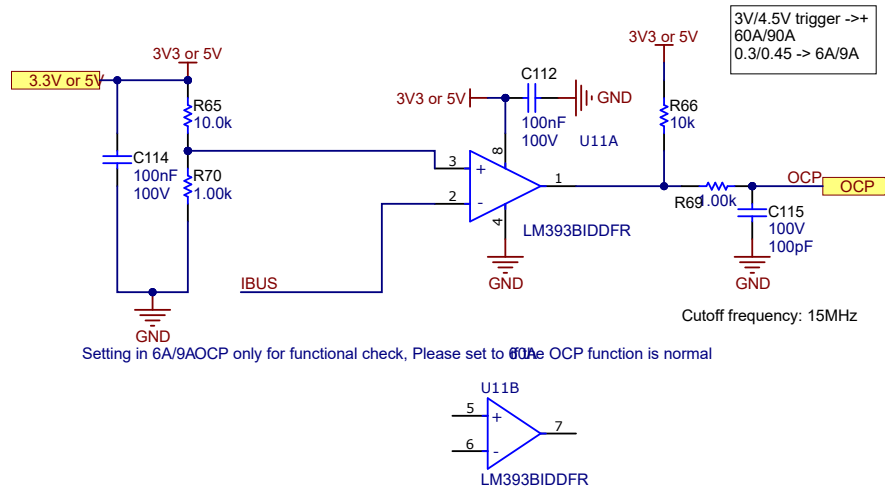
Figure 3-5. Overcurrent Protection Hardware Circuit

3.6 Phase Voltage and DC Input Voltage Sensing

The phase voltage for each phase and the DC link voltage, which is equal to the input voltage, are sensed through a resistor divider. Figure 3-6 shows an example of this for the DC-Link voltage (*R48*, *R52*) with a low-pass filter (*C107*) to attenuate the PWM carrier frequency. The phase voltage is scaled to 3.3V, assuming an absolute maximum voltage of 80V.
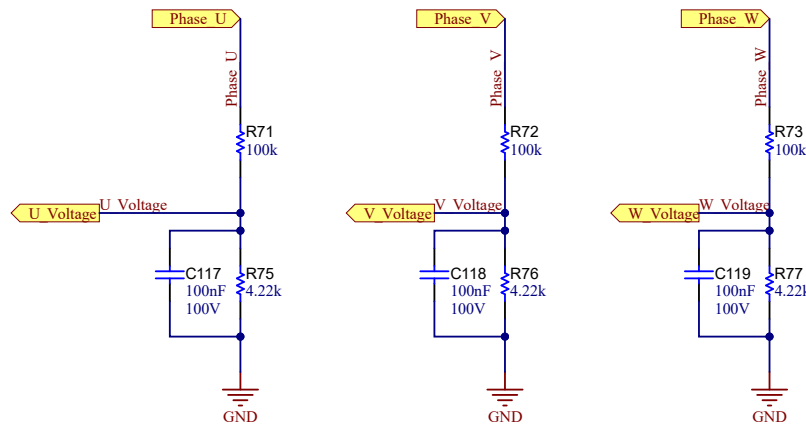
Figure 3-6. TIDA-010276 Phase Voltage and DC Input Voltage Sensing

3.7 Power-Stage PCB Temperature Monitor

To sense the temperature of the PCB power stage, the TMP61 family of thermistors is selected because these devices offer ±1% from 0°C to +70°C with 0402 and 0603 package options. The TMP6131 device is placed close to the LMG3100. Based on the design tool, select a 10kΩ resistor as the pullup resistor. The analog output signal of the TMP6131 is low-pass filtered with R87 (20Ω) and C123 (2.2nF) and routed to connector J1-11 to connect to the C2000 MCU-integrated ADC. The signal can be used for real-time PCB temperature sensing and overtemperature protection through the C2000 MCU.
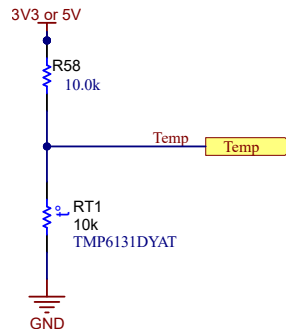
Figure 3-7. TIDA-010276 Temperature

3.8 Interface to Host MCU

The interface-to-host processor, such as the C2000 MCU, is compliant to a 3.3V I/O and provides all the required signals like the complementary PWM signals for phase U, V, and W; a PWM trip and disable signal; as well as accurate phase current, phase voltage, and DC-link voltage feedback to control the three-phase GaN inverter. The analog PCB temperature feedback (temp) further helps to protect the three-phase GaN power stage and adjust the safe operating area (SOA). Each analog feedback signal is low-pass filtered with an RC filter, for example $R90$ (20Ω) and $C125$ (2.2nF) before connecting to the MCU-integrated ADC. The 2.2nF capacitor is placed to drive the switched input capacitors of the ADC, which are typically in the range of 5pF to 15pF. The Schottky diodes D2 through D6 clamp the maximum phase voltages to around 3.6V in case the DC bus voltage exceeds the 80V (absolute maximum) value. The TIDA-010276 fits only upper headers of an 80-pin C2000 MCU LaunchPad, like the LAUNCHXL-F2800137. Additionally, the TIDA-010276 host interface offers the option to provide the 3.3V rail to power the C2000 LaunchPad. This option provides proper power-up sequencing of the entire system.
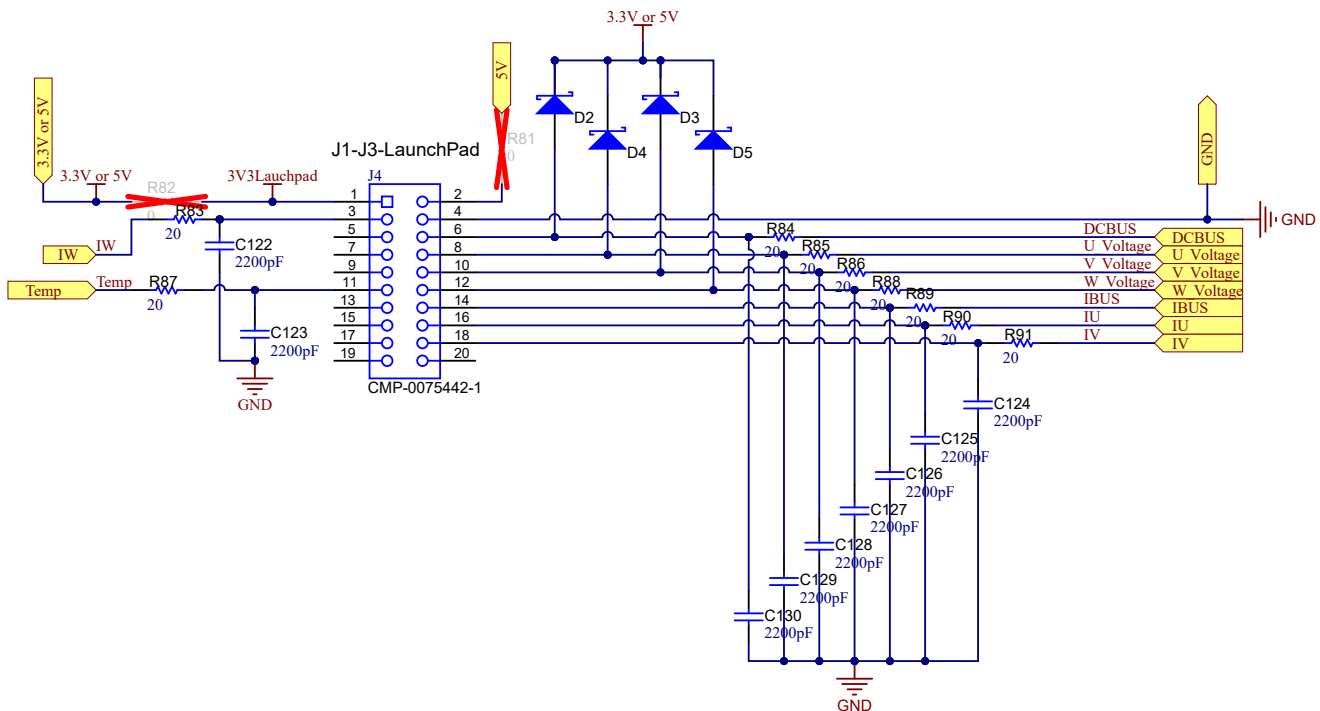
Figure 3-8. TIDA-010276 Interface

4 Hardware, Testing Requirements, and Test Results

4.1 Hardware Requirements

4.1.1 TIDA-010276 PCB Overview

Figure 4-1 and Figure 4-2 show labeled photos of the top and bottom of the PCB. Descriptions of these parts are provided in the following list:

- Two-terminal input for power supply: This pin is used to connect the input DC supply from the battery.
- Three-terminal output for motor winding connection: The phase output connections for connecting to the three-phase BLDC motor winding, marked as U, V, W
- 2-pin connector near BAT+/GND: Use to connect ceramic capacitor PCB
- Connector J1-J3, J4-J2: Use to connect MCU
- 2-pin connector J1: Can connect to bypass
- 3-pin connector J2: Use to enable or disable LDO
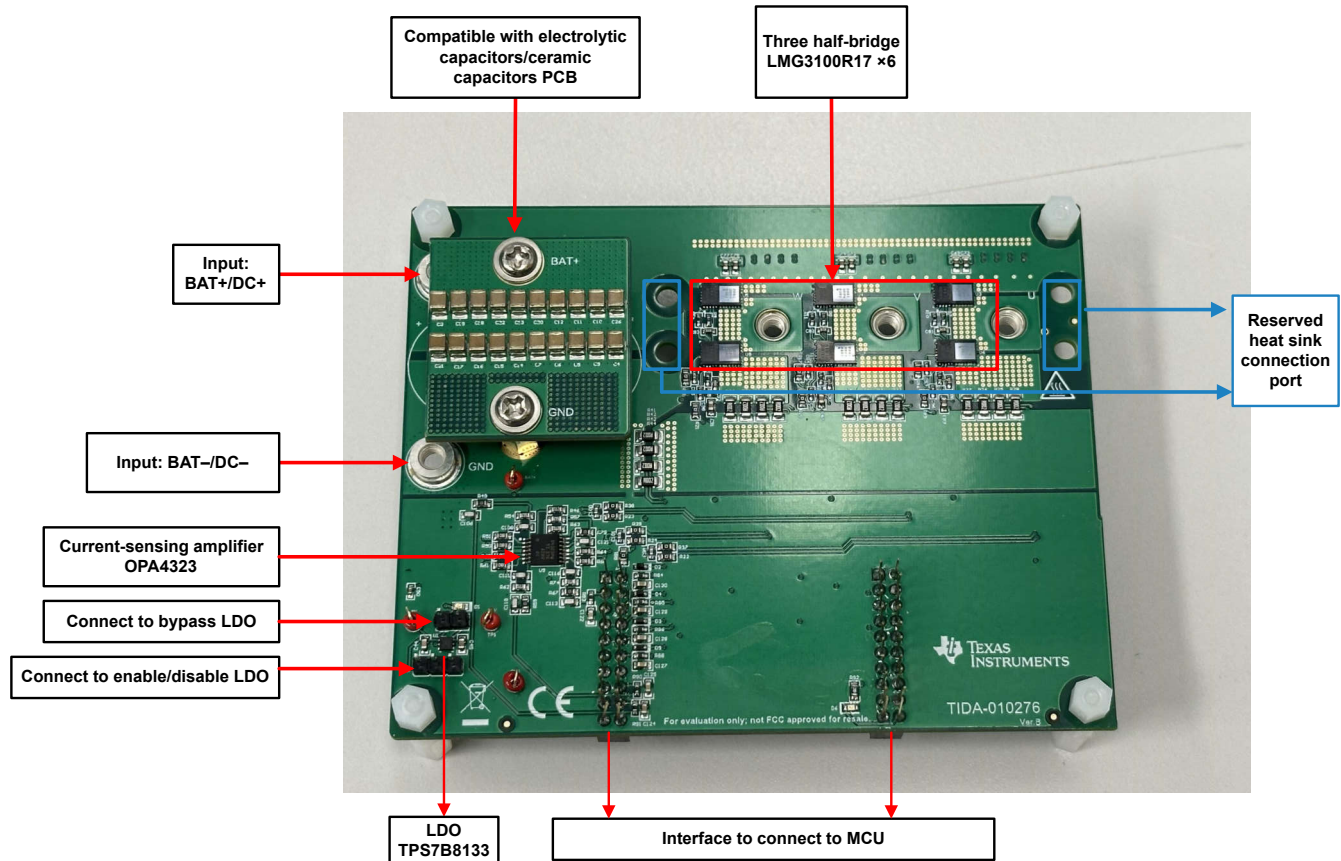
Figure 4-1. TIDA-010276 PCB Top View

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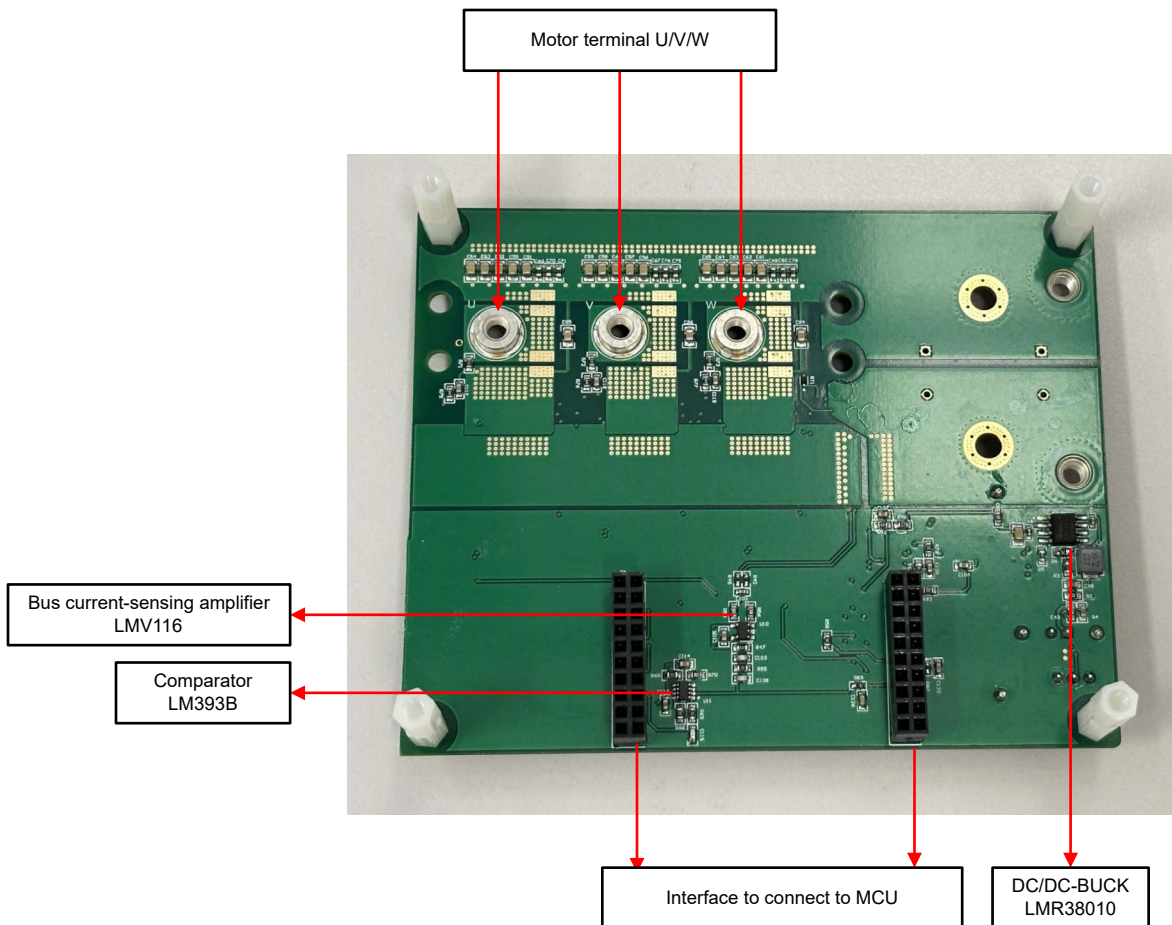
Figure 4-2. TIDA-010276 PCB Bottom View

4.1.2 TIDA-010276 Jumper Settings

Table 4-1 shows the four TIDA-010276 jumpers.

Table 4-1. TIDA-010276 Jumper Settings

JUMPER	FUNCTION	POPULATED	NOT POPULATED
J1	LDO Setting	Bypass LDO set the output to 5V	Default
J2	LDO Setting	Connect 1-2 disable LDO, Connect 2-3 enable LDO	Connect 2-3 enable LDO
J1-J3, J2-J4	Control Connection	Connect with C2000 LaunchPad	Not Control signal
R82, R81	3.3V or 5V for LaunchPad	Supply LaunchPad	Not populated (default) LaunchPad uses own USB power

CAUTION

Do not populate R82 and R81 at the same time. When R82 or R81 are populated, make sure the C2000 LaunchPad is not powered through USB. To accomplish this setup, remove the power supply jumpers on the F2800137 LaunchPad.

The TIDA-010276 interface specification is compliant to the TI BoosterPack plug-in module standard. The TIDA-010276 board can be connected to the C2000 LaunchPad headers J1–J4. Figure 4-3 shows the TIDA-010276 connected to the F2800137 LaunchPad headers J1–J4. The TIDA-010276 does not power the LaunchPad.

Connect the DC power supply (12V to 48V, 36V nominal) to the DC input voltage connector (MP1, MP3) and the three-phase motor to the three-phase output voltage connector (MP2, MP4, and MP5). Validate that the three-phase motor can handle the high slew rates of the phase voltages during PWM switching.
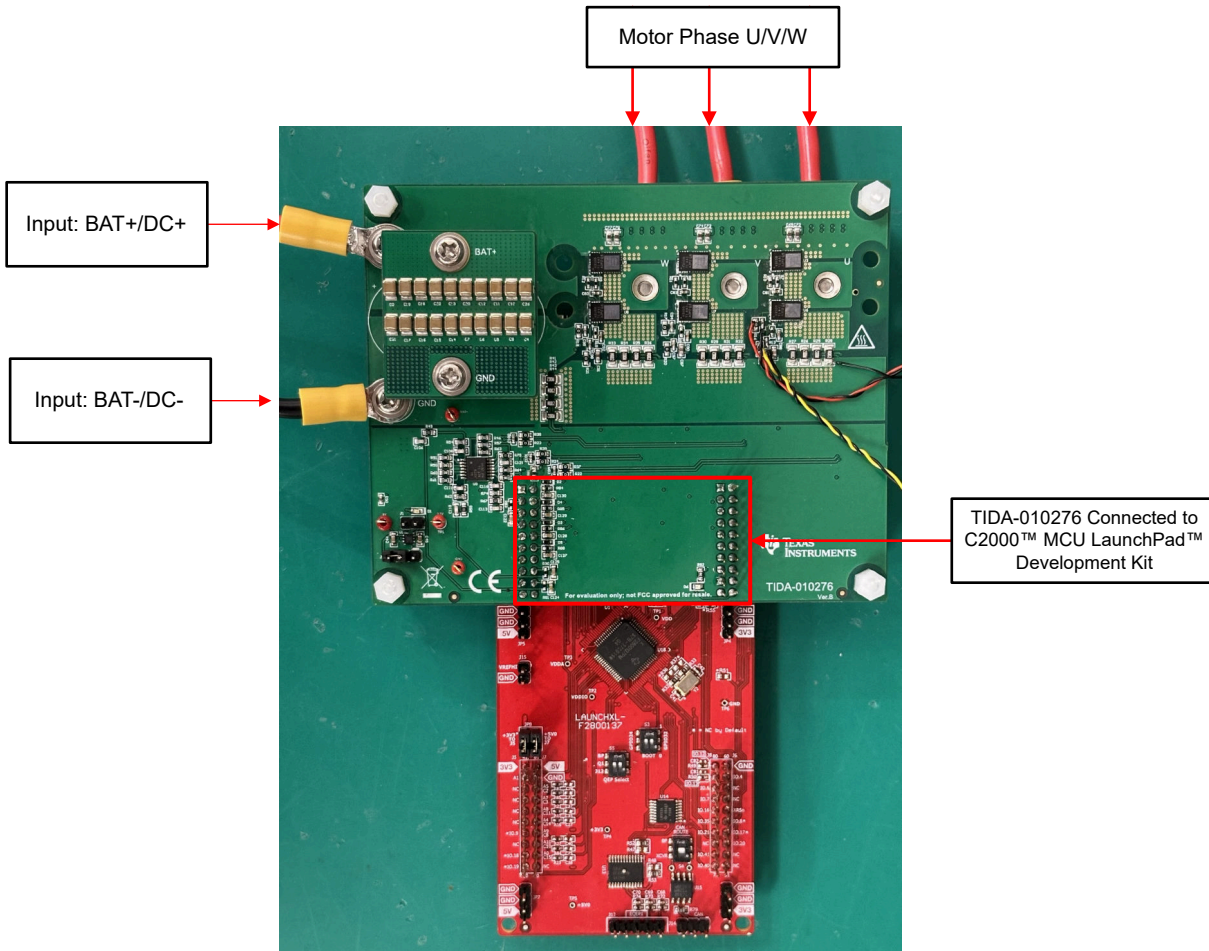
Figure 4-3. TIDA-010276 PCB Connections to C2000 LaunchPad™

4.2 Test Setup

lists the key test equipment. Descriptions and pictures of the test setup for specific tests are provided in the corresponding test results sections.

Table 4-2. Key Test Equipment

DESCRIPTION	PART NUMBER
High-speed oscilloscope	Tektronix MSO4104B
Single-ended probes	Tektronix P6139B
Power analyzer	HIOKI PW6001
Isolated current probe	CYBERTEK CP8030H, HIOKI CT6872
Dynamometer	MAGTROL DSP6000
Multimeter	Fluke 17B+
Thermal camera	FOTRIC
Adjustable power supply (10A)	ITECH IT6724H
Adjustable power supply (20A)	ITECH M3902C
C2000 MCU LaunchPad Development Kit	Texas Instruments LAUNCHXL-F2800137

- Remove the motor connections from the board, and power on the input DC supply. Make sure that a minimum of a 15V$_{DC}$ input is applied and the 3.3V is generated in the board.
- Program the MCU as detailed
- Remove the programmer, and switch off the DC input supply
- Connect the inverter output to the motor winding terminals
- Disconnect the J1 to disable bypass LDO
- Connect J2 (1-2 pin) to enable LDO
- Use a DC power supply with current-limit protection and apply 36V$_{DC}$ to the board
- Use MCU and debug tools to run the motor

4.3 Test Results

The following sections show the test data. The test results are divided into multiple sections that cover the steady state performance and data, functional performance waveforms, and transient performance waveforms of a BLDC motor.

4.3.1 Power Management and System Power Up and Power Down

The focus of this test was to validate the onboard 5V and 3.3V power supplies and measure the typical current consumption of the 3.3V and 5V rail. For these tests, the C2000 MCU LaunchPad development kit was not powered from the TIDA-010276. Due to the high step-down ratio 36:5 (36V input to 5V output), the voltage ripple at the 5V rail was validated too.
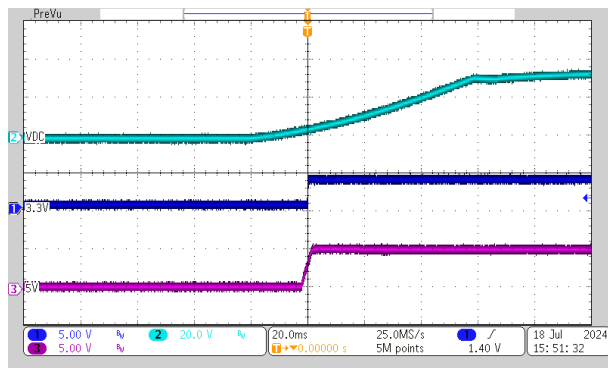
Figure 4-4. TIDA-010276 Power Up
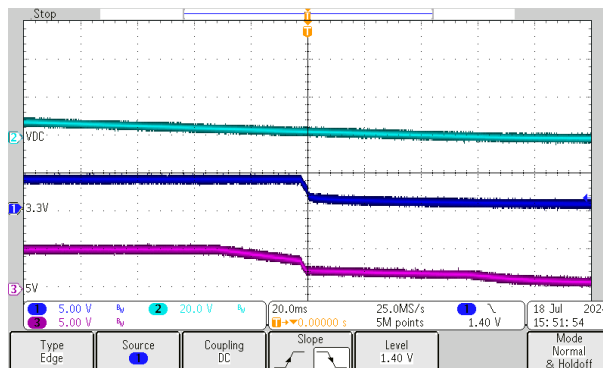
Figure 4-5. TIDA-010276 Power Down

For the power-down stage, when the bus voltage drops to about 5V, the output of the LMR38010 drops along with the bus voltage. When the bus is lower than 3.3V, the 3.3V rail also starts to drop. The AC ripple of the 5V rail remains well below 10mV$_{PP}$ in light load. The frequency of ripple is 574kHz, which matches the buck converter switching frequency. The offset of the 5V rail is about 5.03V.
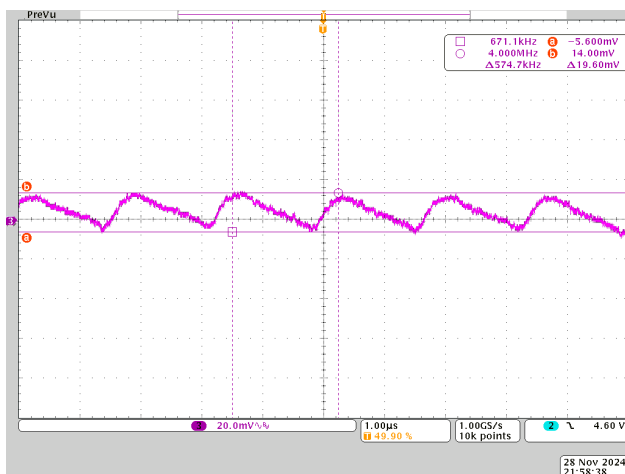

Figure 4-6. TIDA-010276 Output Ripple at Nominal Load (20mA)

4.3.2 GaN Inverter Switch Node Voltage

The focus on this test was to validate the transient response of the switch node voltage of the GaN inverter at 36V. The other aim of the test was to validate the capacity or amount of local bypass capacitors at each of the LMG3100 GaN power modules. The C2000 MCU was configured to generate a three-phase space vector with complementary PWM with 16.6ns dead band. The PWM duty cycle per phase was configured to drive the corresponding phase current IA with IB = IC = –0.5 IA. Figure 4-7 shows the LMG3100 switch node voltage being measured at the LMG3100 SW pin referenced to the PGND.
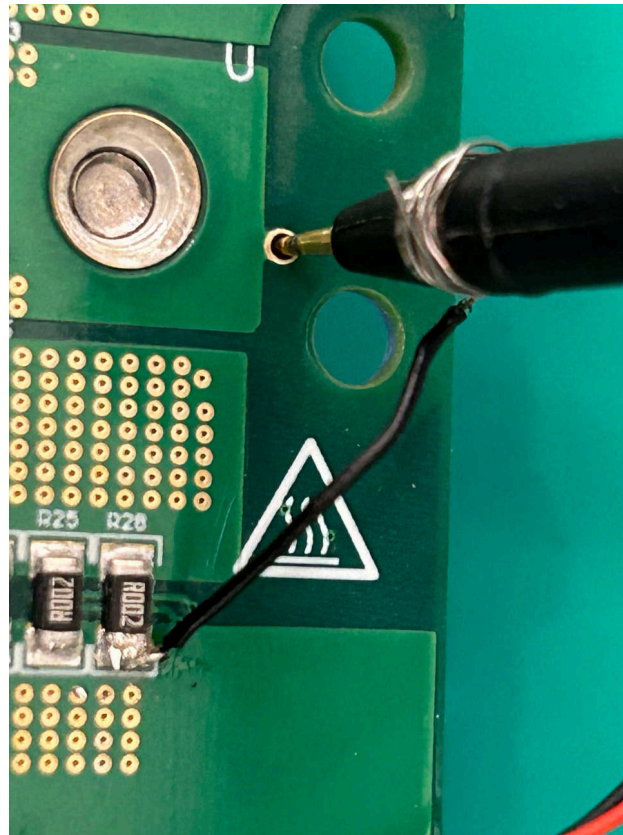
Figure 4-7. Test Setup for LMG3100 Switch-Node

Figure 4-8 and Figure 4-9 show that the PWM input has a dead time of 16.6ns between the upper and lower bridge.
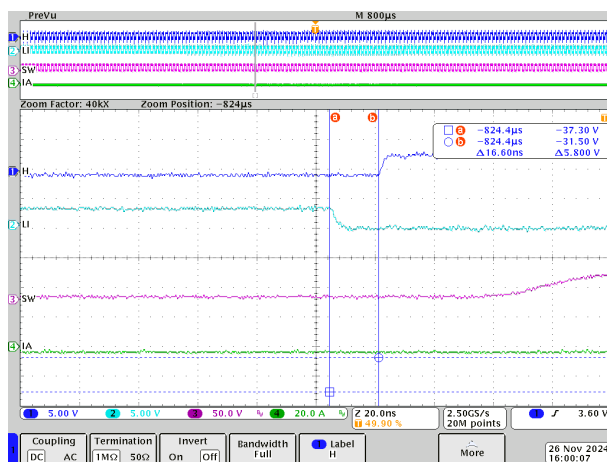
Figure 4-8. Rising Edge PWM U (H and L)
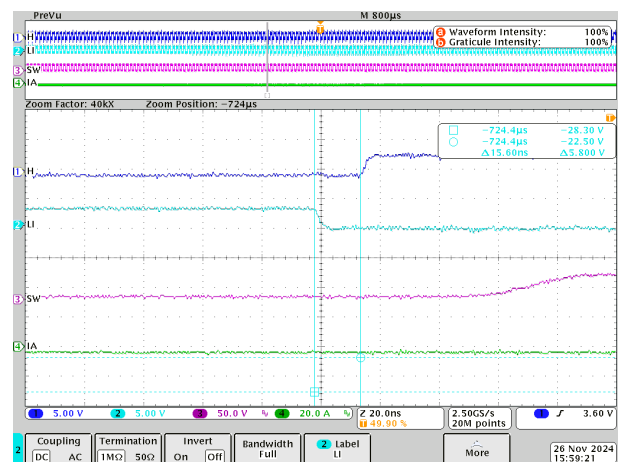
Figure 4-9. Falling Edge PWM U (H and L)

4.3.3 Switch Node Voltage Transient Response

Figure 4-10 through Figure 4-13 outline the SW transient voltage at hard-switching and soft-switching. PWM frequency (20kHz), LMG3100 propagation delay, as well as the 16.6ns PWM dead band can be well identified. Due to the low phase current there is hard-switching and a combination of soft- and hard-switching as shown in the following waveforms. The turn-on and turn-off slew rate (20% to 80%) of the GaN FETs was configured to around 10V/ns to 15V/ns.
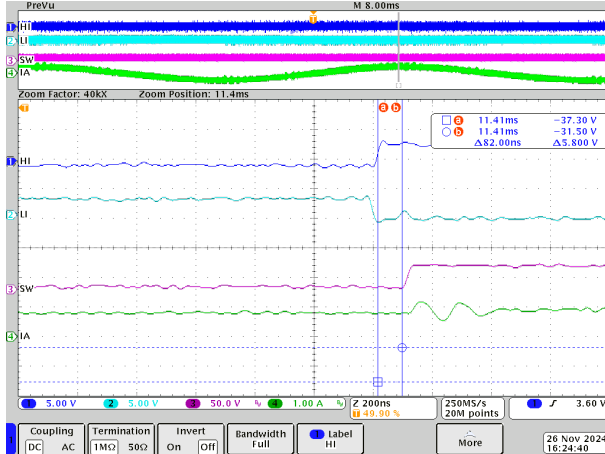

Figure 4-10. Phase U Rising SW, Phase Current 36V, 1A
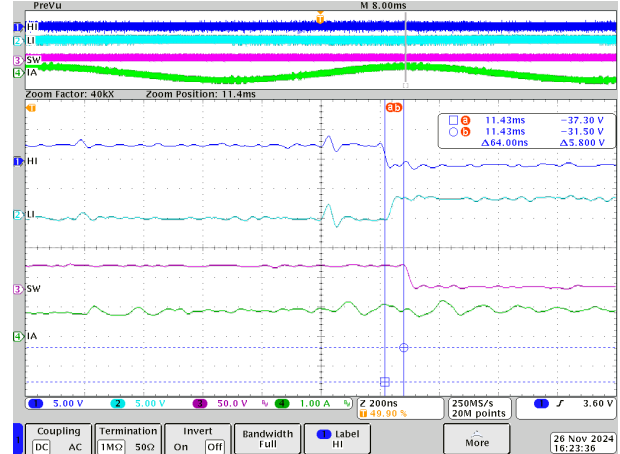
Figure 4-11. Phase U Falling SW, Phase Current 36V, 1A
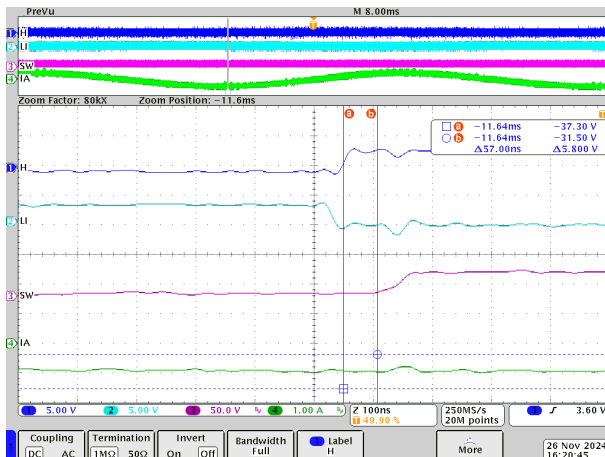
Figure 4-12. Phase U Rising SW, Phase Current 36V, –1A
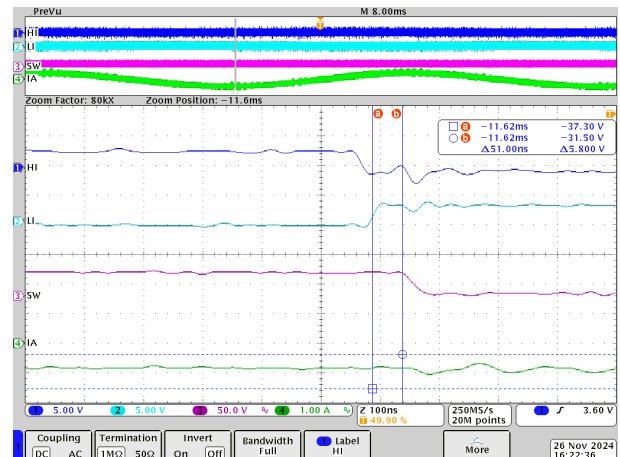
Figure 4-13. Phase U Falling SW, Phase Current 36V, –1A

Figure 4-14 through Figure 4-17 show the test result of PWM input to GaN-FET propagation delay, tested in output of 1A and 20A. Propagation delay is small enough for a motor control system.
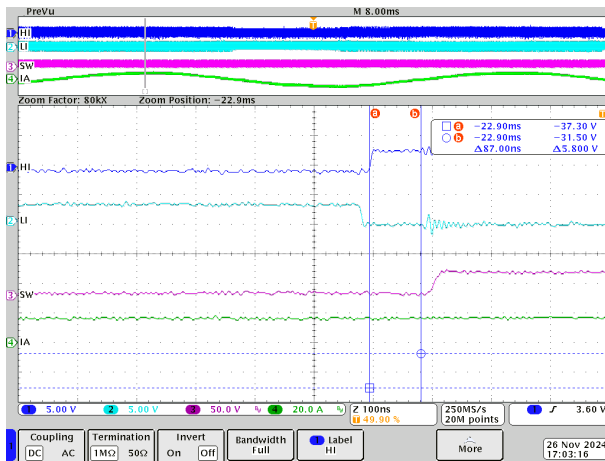

Figure 4-14. Phase U Rising SW, Phase Current 36V, 20A

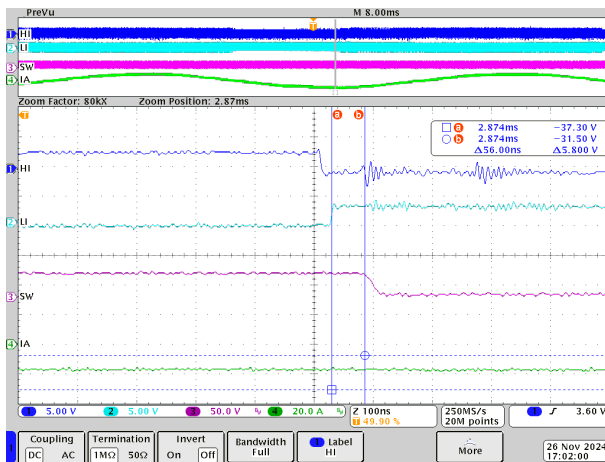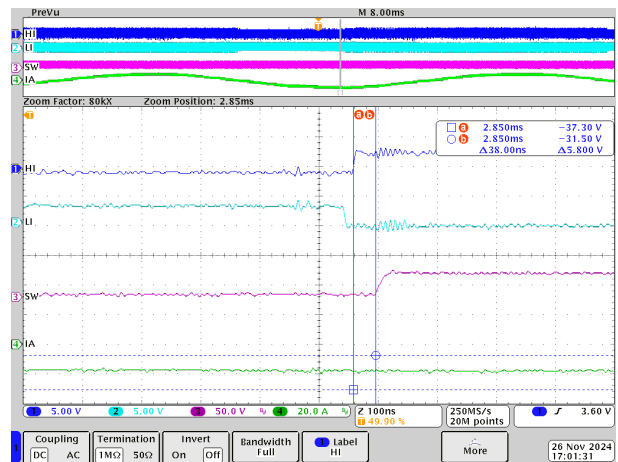**Figure 4-15. Phase U Falling SW, Phase Current 36V, 20A**

Figure 4-16. Phase U Rising SW, Phase Current 36V, –20A

Figure 4-17. Phase U Falling SW, Phase Current 36V, –20A

4.3.4 Impact of PWM Frequency to DC-Bus Voltage Ripple

The key function of the bus capacitor is to smooth the bus voltages and provide a transition current in the switch to keep the bus voltage ripple small enough to change the FET time becoming shorter, the amount of command required by the capacitor becomes smaller, so using a higher PWM switching frequency can reduce the required bus capacitance value. Typically, bus capacitors are placed as electrolytic capacitors. The following test attempts to replace electrolytic capacitors with ceramic capacitors, increasing the frequency of PWM ripple electrolytic capacitors and ceramic capacitors at different frequencies.

The following tests were taken on a working 400μF ceramic capacitor, compared with 1000μF electrolytic capacitor data.
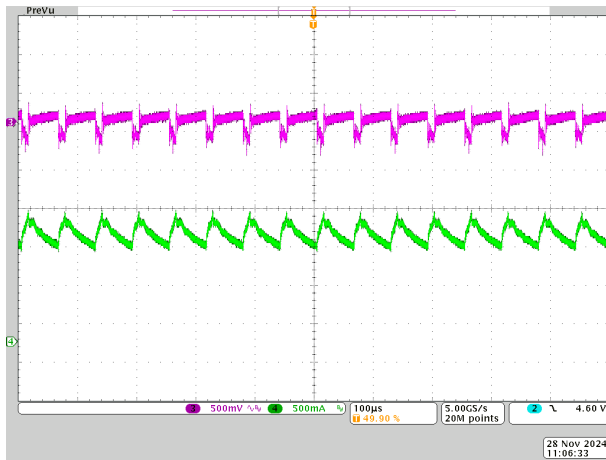

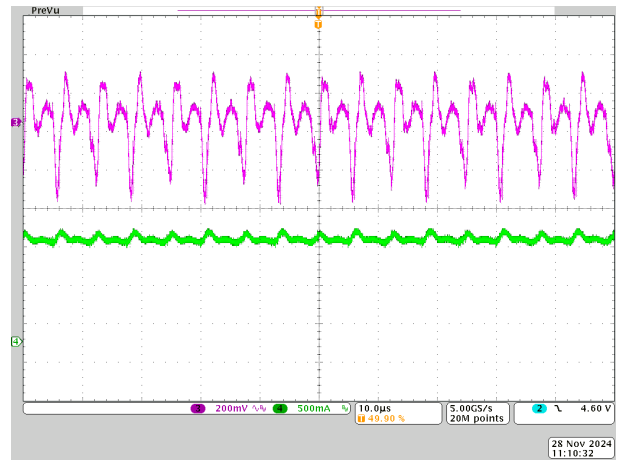**Figure 4-18. Electrolytic Capacitors Ripple Current and Ripple Voltage at 8kHz PWM, 10A**

Figure 4-19. Electrolytic Capacitors Ripple Current and Ripple Voltage at 80kHz PWM, 10A
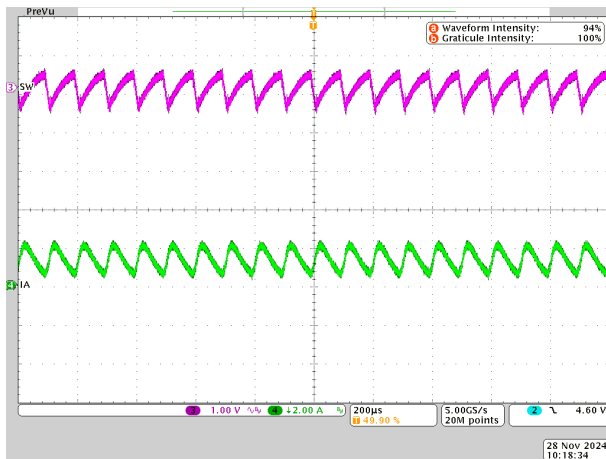

Figure 4-20. Ceramic Capacitors Ripple Current and Ripple Voltage at 8kHz PWM, 10A
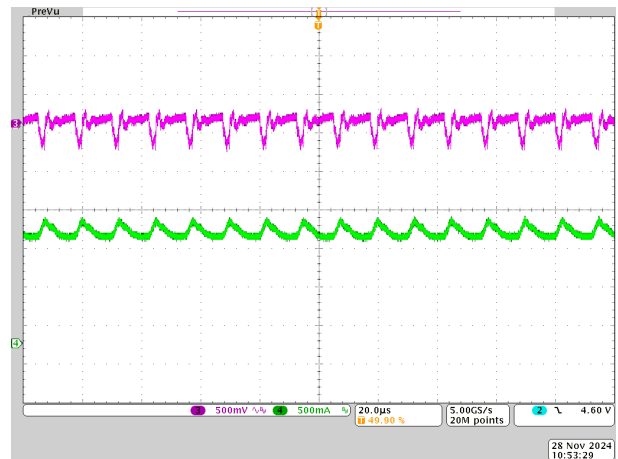

Figure 4-21. Ceramic Capacitors Ripple Current and Ripple Voltage at 80kHz PWM, 10A

As the results show, as the frequency increases, the ripple on the bus decreases, so capacitors with smaller capacitance can be used. But ceramic capacitors have significantly larger voltage ripple at low frequencies. Because the actual capacitance of this 10μF ceramic capacitor is only 4μF at a voltage of 36V (from the GRM32EC72A106KE05 data sheet), the actual effective capacitances corresponding to the 400μF ceramic capacitors is 160μF. When the PWM frequency increases to 80kHz, the voltage ripple of a 400μF ceramic capacitor (160μF effective capacitances) and an 1000μF electrolytic capacitor is similar. Therefore, the ultra-low switching loss of GaN can be used to increase the PWM frequency to 80kHz. At the same time, the electrolytic capacitor can be replaced with a ceramic capacitor of the same capacity to achieve a smaller size.
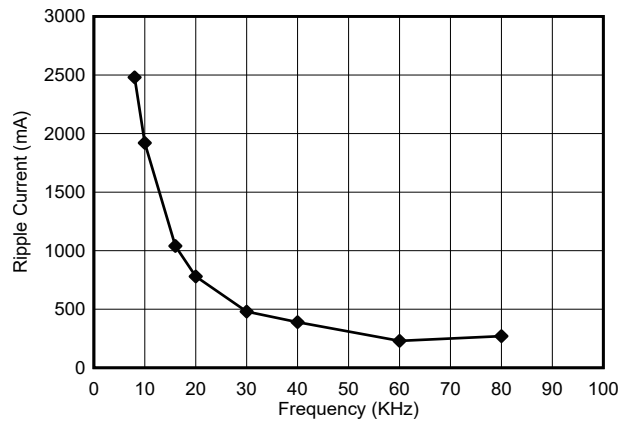
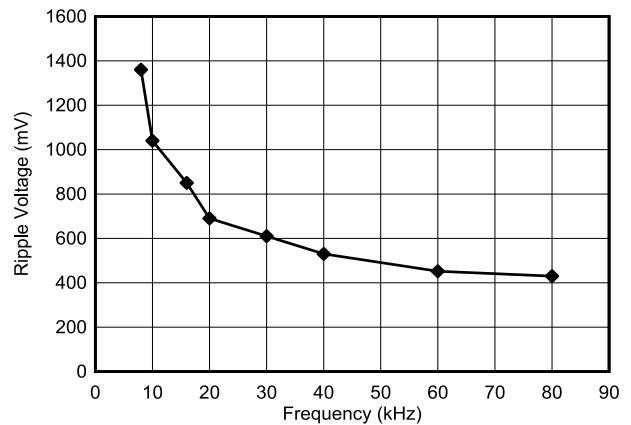**Figure 4-22. Ceramic Capacitors Ripple Current Change From 8kHz to 10kHz**

Figure 4-23. Ceramic Capacitors Ripple Voltage Change From 8kHz to 10kHz

4.3.5 Efficiency Measurements

The efficiency testing was done at a 27°C lab temperature using a HIOKI® PW6001 power analyzer and HIOKI® CT6872 current transformer. The PWM carrier frequency was set from 20Hz to 80kHz. The voltage is 36V and the motor speed is 600rpm, with the motor running in current mode to test the power loss. Figure 4-24 shows a picture of the test setup. For all of these tests neither a heat sink nor a fan were used, hence only natural convection of the TIDA-010276 PCB is applied.
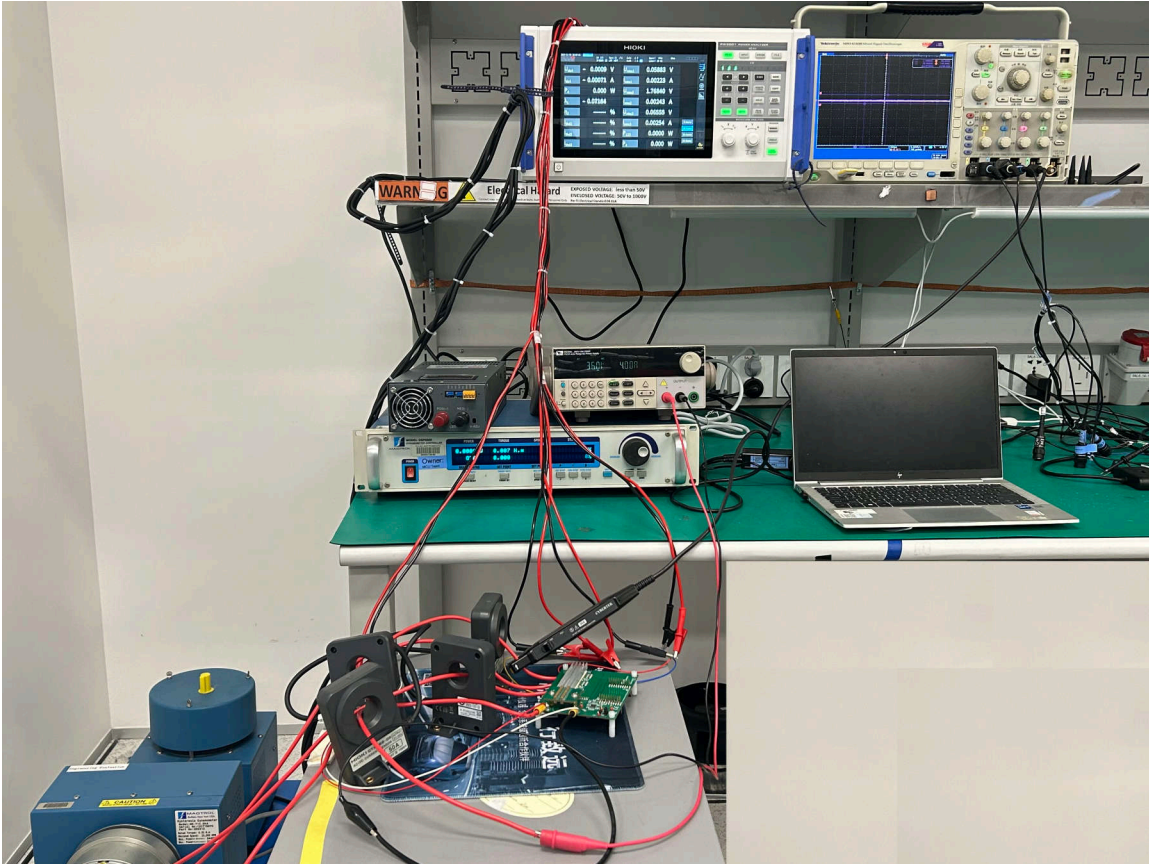

Figure 4-24. Test Setup for Inverter Efficiency Analysis

Figure 4-25 shows the TIDA-010276 power losses versus the three-phase motor load current in A_{RMS}. These numbers do not include the power losses of the C2000 MCU LaunchPad development kit.
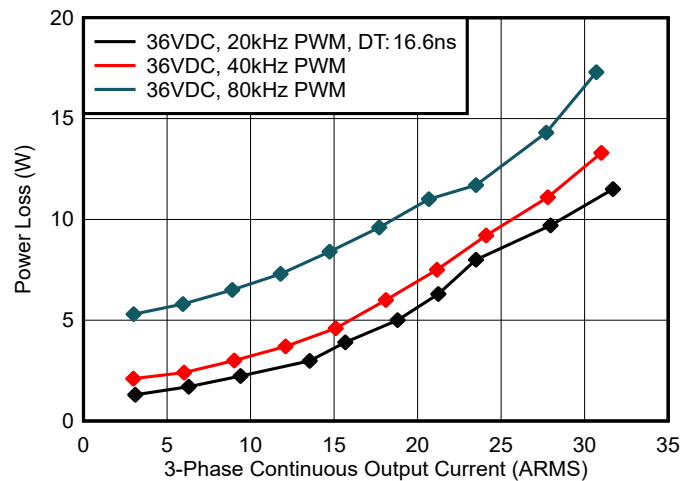

Figure 4-25. TIDA-010276 Board Losses at 36V Input vs 3-Phase Output Current

The TIDA-010276 power losses are dominated by the losses in the GaN FETs (LMG3100) and the losses in the 0.5mΩ bus current shunt resistor and three 0.5mΩ low-side FET shunt resistors. The theoretical maximum peak efficiency at 36VDC with a maximum phase-to-phase voltage of 14.69V$_{RMS}$ (Space Vector PWM with 3rd harmonics) and a power factor of 0.9 is 99.16% at 20kHz PWM, 99.01% at 40Hz PWM, 98.58% in 80kHz, according to the calculation results shown in Figure 4-26.

Observe that while the PWM switching frequency increases, the power losses of the board do not increase significantly. This also reflects the very low switching losses of the LMG3100R17 GaN FETs to help to achieve very high efficiency even at higher PWM switching frequencies.
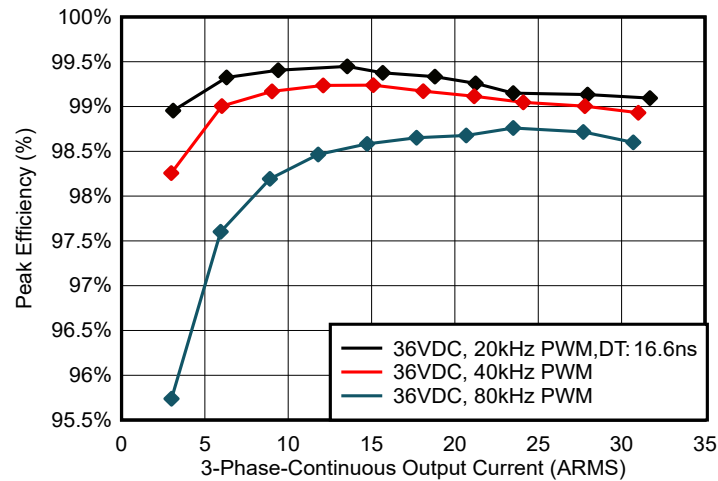

Figure 4-26. Calculated Maximum Peak Efficiency at 36VDC and 40kHz, 60kHz, and 80kHz PWM

The TIDA-010276 design and an e-bike motor were used for system testing. Testing determined that increasing the switching frequency also improves the overall efficiency of the motor drive. Table 4-3 details the TIDA-010276 motor system efficiency test results.

Table 4-3. TIDA-010276 Motor System Efficiency Test Results

PARAMETER	20kHz (DEAD TIME 1µs)	80kHz (DEAD TIME 16.6ns)
P$_{IN}$	49.8W	48.2W
P$_{OUT}$(Inverter)	49.2W	47.5W
η (Inverter)	98.70%	98.50%
Speed	480rpm	480rpm
Torque	0.68Nm	0.68Nm
P$_{mech}$	34.178W	34.178W
η (motor)	68.63%	70.90%
η (total)	67.7%	69.9%

4.3.6 Thermal Analysis

The thermal analysis of the design was done at 27°C lab temperature with 36V$_{DC}$ input with 20kHz, 40kHz, and 80kHz with the high-power motor driven. The motor is run for about 10 minutes before capturing the temperature. For this test, neither a heat sink or a fan were used.
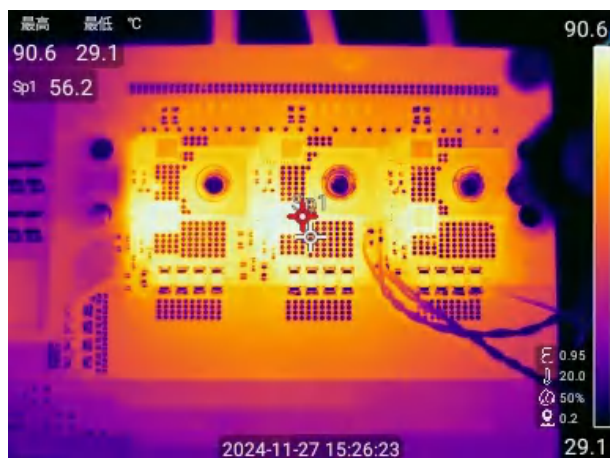

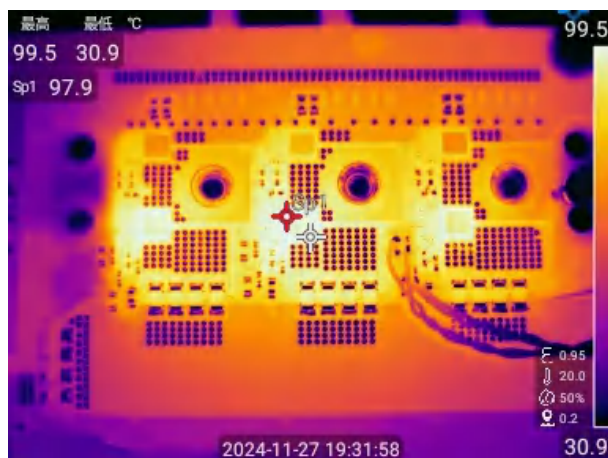**Figure 4-27. Thermal Image of TIDA-010276 at 50A Peak, 20kHz PWM**

Figure 4-28. Thermal Image of TIDA-010276 at 50A Peak, 40kHz PWM
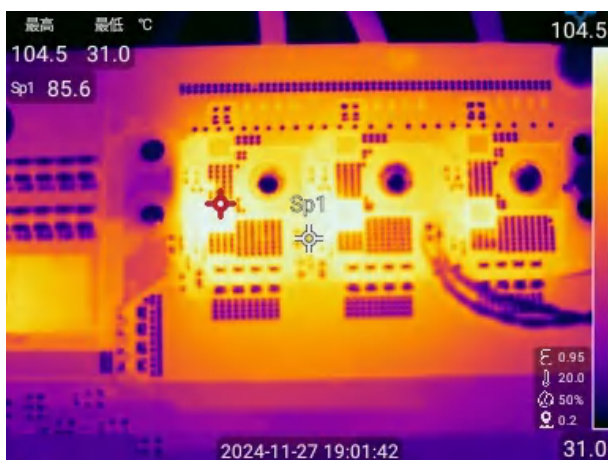

Figure 4-29. Thermal Image of TIDA-010276 at 50A Peak, 80kHz PWM

Since LMG3100 has exposed dies on top, the case temperature of LMG3100 can be very close to the temperature of the die. The maximum junction temperature is up to 175°C. In this test some margin is still in the junction temperature.

A small heat sink was used to test the TIDA-010276, run the motor in 80kHz, 50A peak (27°C lab temperature). Figure 4-30 shows the design with a small heat sink and Figure 4-31 shows the resulting thermal image. If using the TIDA-010276 to run at a higher power, choose a larger heat sink to meet the thermal requirements.
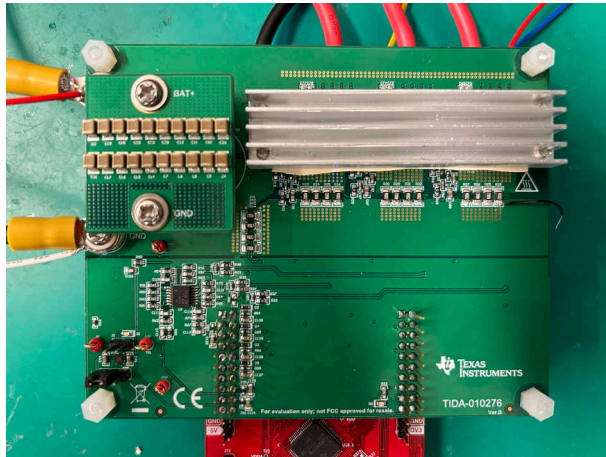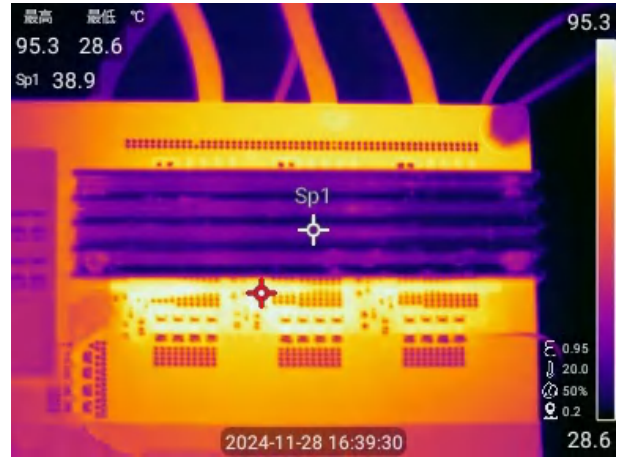

Figure 4-30. TIDA-010276 With Small Heat Sink

Figure 4-31. Thermal Image of TIDA-010276 at 50A Peak, 80kHz PWM

5 Design and Documentation Support

5.1 Design Files

5.1.1 Schematics

To download the schematics, see the design files at TIDA-010276.

5.1.2 BOM

To download the bill of materials (BOM), see the design files at TIDA-010276.

5.2 Tools and Software

Tools

CCSTUDIO	Code Composer Studio is an integrated development environment (IDE) for TI's microcontrollers and processors. The IDE comprises a suite of tools used to develop and debug embedded applications. Code Composer Studio is available for download across Microsoft® Windows®, Linux®, and macOS® desktops. The software can also be used in the cloud by visiting the TI developer zone.
TMS320F2800137 LaunchPad™ development kit for C2000™ real-time MCU	LAUNCHXL-F2800137 is a development board for TI C2000™ real-time microcontrollers series of F280013x devices. This kit is an excellent choice for initial evaluation and prototyping, and provides a standardized and easy-to-use platform to develop the next application. This extended version LaunchPad™ development kit offers extra pins for development and supports the connection of two BoosterPack™ plug-in modules. As part of the vast TI MCU LaunchPad ecosystem, this tool is also cross-compatible with a broad range of plug-in modules.

Software

MotorControl Software Development Kit (SDK) for C2000™ MCU	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.

5.3 Documentation Support

1. Texas Instruments, *LMG3100R017 100V, 97A GaN FET With Integrated Driver Data Sheet*
2. Texas Instruments, *LMR38010 4.2-V to 80-V, 1-A, Synchronous SIMPLE SWITCHER® Power Converter with 40-µA I_Q Data Sheet*
3. Texas Instruments, *TPS7B81 150-mA, 40-V, Ultra-Low-I_Q, Low-Dropout Regulator Data Sheet*
4. Texas Instruments, *TMP61 ±1% 10-kΩ Linear Thermistor With 0402 and 0603 Package Options Data Sheet*
5. Texas Instruments, *OPAx323 20MHz High Bandwidth, 114dB CMRR, Low Voltage (1.7V to 5.5V), RRIO Zero-Cross Operational Amplifier Data Sheet*

5.4 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 About the Author

JENSON FANG is a System Engineer at Texas Instruments where he is responsible for developing appliance system related Motor control and BMS Solutions, and so on.

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