TI Designs: TIDA-01619

22-mm Diameter and Thermally Enhanced Three-Phase BLDC Motor Driver Reference Design

Description

The TIDA-01619 provides a three-phase brushless DC (BLDC) motor driver solution for systems with an operating range from 4.4 V to 18 V. This design features the DRV10974 motor driver with the ability to add MCU for closedloop speed control. The DRV10974 offers sensorless commutation with no need of hall sensors, only 6 external passive components allow for a low-cost solution and an 180° sinusoidal commutation system allows optimal efficiency and low acoustics. This reference design provides guidelines in 22-mm diameter board design and thermal enhancement with a double-layer layout and 2-oz copper thickness.

Resources

TIDA-01619	Design Folder
DRV10974	Product Folder

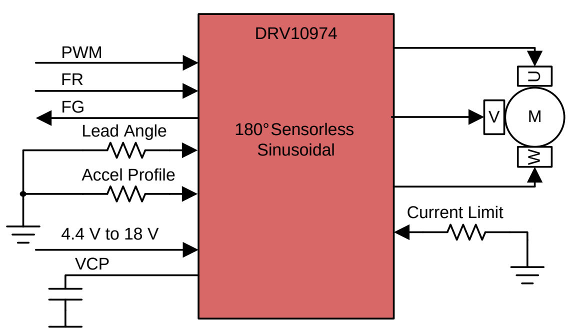
TI E2E™ Community — ASK Our E2E™ Experts

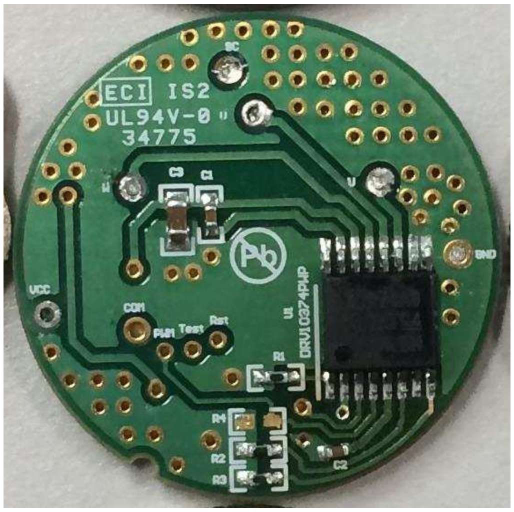
Applications

- Server Fans
- Desktop PC Fans
- BLDC Motor Drives

Features

- Thermally Enhanced: 2 Layers and 2-oz Copper Thickness
- Small Form Factor: 22-mm Diameter
- Input Voltage Range: 4.4 V to 18 V
- Phase Drive Current: 1-A Continuous (1.5-A Peak)
- 180° Sinusoidal Commutation for Optimal Acoustic Performance
- Lead Angle Configurable With External Resistor
- Soft Start and Resistor-Configurable Acceleration Profile
- Built-in Current Sense to Eliminate External Current-Sense Resistor
- No Motor Center Tap Required
- Simple User Interface:
  - One-Pin Configuration for Start-up
  - PWM Input Designates Magnitude of Voltage Applied to Motor
  - Open-Drain FG Output Provides Speed Feedback
  - Pin for Forward and Reverse Control
- Fully Protected:
  - Motor-Lock Detect and Restart
  - Overcurrent, Short-Circuit, Overtemperature, Undervoltage





An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

1 System Description

This reference design is a small, thermally enhanced, three-phase sensorless sinusoidal motor driver for brushless DC (BLDC) motors. The DRV10974 can support a range of voltage from 4.4 V to 18 V as input and a phase current of 1-A continuous and 1.5-A peak.

The PCB is designed for small space restriction and high temperature ambient areas. With a 22-mm diameter, the PCB is small to fit on server fans, desktop fans, and other small BLDC motors. The design also considers heat dissipation with a 2-oz copper thickness, double layers, and multiple vias for a thermally enhanced design.

The PWM pin in the DRV10974 allows to control speed by changing the duty cycle. The FG pin provides speed feedback and the FR pin for forward and reverse control. With resistors on pins CS, ADV, and RMP, one can configure current limit, lead angle, and acceleration profile, respectively.

With full protection, an integrated BLDC motor driver, and an easy-to-use system, this reference design is best for small and thermal challenged applications.

1.1 Key System Specification

Table 1 lists the key system specification for this reference design.

Table 1. Key System Specification

PARAMETERS	SPECIFICATION
DC input voltage	4.4 V to 18 V
Current	1 A continuous / 1.5 A peak
Control method	Integrated 180° sinusoidal control
Protection circuits	Overcurrent, short-circuit, undervoltage, overtemperature
Operating ambient	–40°C to +120°C
Size	22-mm diameter

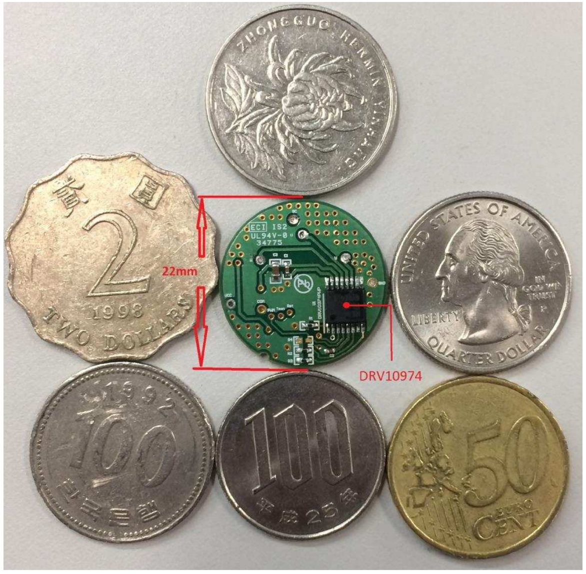


Figure 1. Reference Design Size Compared With World Currencies

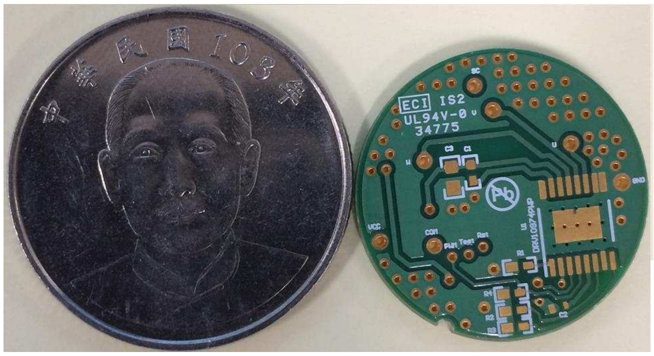


Figure 2. Reference Design Compared With Taiwan Currency

2 System Overview

2.1 Block Diagram

Figure 3 shows the block diagram for this reference design. This system outputs motor speed in hertz (FG pin) and three-phase motor control signals for U, V and W. System input pins are PWM, FR, lead angle, acceleration profile, VCC (4.4 V to 18 V), and current limit. For more information, see *DRV10974 12-V, Three-Phase, Sensorless BLDC Motor Driver*.

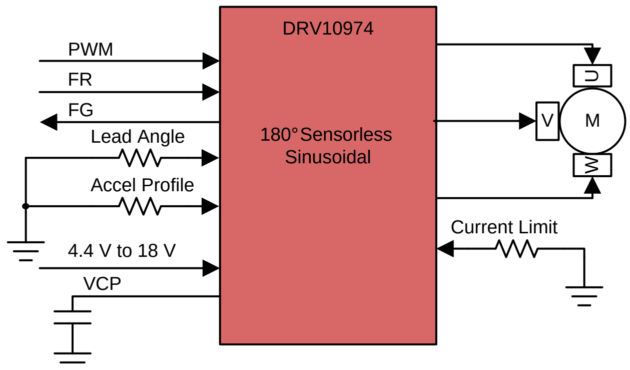


Figure 3. Block Diagram of TIDA-01619

2.2 Design Considerations

The following tables detail the external components recommended for the DRV10974 device to function and resistor configurations to set.

Table 2. Recommended External Components

NODE 1	NODE 2	COMPONENT
VCC	GND	10-µF, 25-V ceramic capacitor tied from VCC to ground
VCP	VCC	100-nF, 10-V ceramic capacitor tied from VCP to VCC
V1P8	GND	1-µF, 6.3-V ceramic capacitor tied from V1P8 to ground
RMP	GND	1%, 1/8 watt resistor tied from RMP to ground to set the desired acceleration profile
CS	GND	1%, 1/8 watt resistor tied from CS to ground to set the desired current limit
ADV	GND	1% 1/8 watt resistor tied from ADV to ground to set the desired lead angle (time)

Table 3. Acceleration Profile Settings

RMP SELECTION	R_{RMP} (kΩ)	Accel2 (Hz/s^2)	Accel1 (Hz/s)	CLOSED-LOOP ACCELERATION (s)	CLOSED-LOOP DECELERATION (s)
0	7.32	0.22	4.6	2.7	44
1	10.7	1.65	9.2	2.7	22
2	14.3	1.65	15	1	22
3	17.8	3.3	25	1	11
4	22.1	7	25	0.2	44
5	28	7	35	0.2	22
6	34	14	50	0.2	22
7	41.2	27	75	0.2	11
8	49.9	27	75	5.4	11
9	59	14	50	8	22
10	71.5	7	35	11	22
11	86.6	7	25	22	44

Table 3. Acceleration Profile Settings (continued)

RMP SELECTION	R_{RMP} (kΩ)	Accel2 (Hz/s^2)	Accel1 (Hz/s)	CLOSED-LOOP ACCELERATION (s)	CLOSED-LOOP DECELERATION (s)
12	105	3.3	25	5.4	11
13	124	1.65	15	8	22
14	150	1.65	9.2	11	22
15	182	0.22	4.6	22	44

Table 4. Soft and Start-up Current Limit

$R_{(CS)}$ (kΩ)	$I_{(LIMIT)}$ (mA)
7.32	200
16.2	400
25.5	600
38.3	800
54.9	1000
80.6	1200
115	1400
182	1600 (1500 for align)

Table 5. Lead Time Selection

R_{ADV} (kΩ)	LEAD TIME (µs)
10.7	10
14.3	25
17.8	50
22.1	100
28	150
34	200
41.2	250
49.9	300
59	400
71.5	500
86.6	600
105	700
124	800
150	900
182	1000

Figure 4 shows the schematic of the simple, low external components of this reference design. Figure 5 shows different PCB layouts.

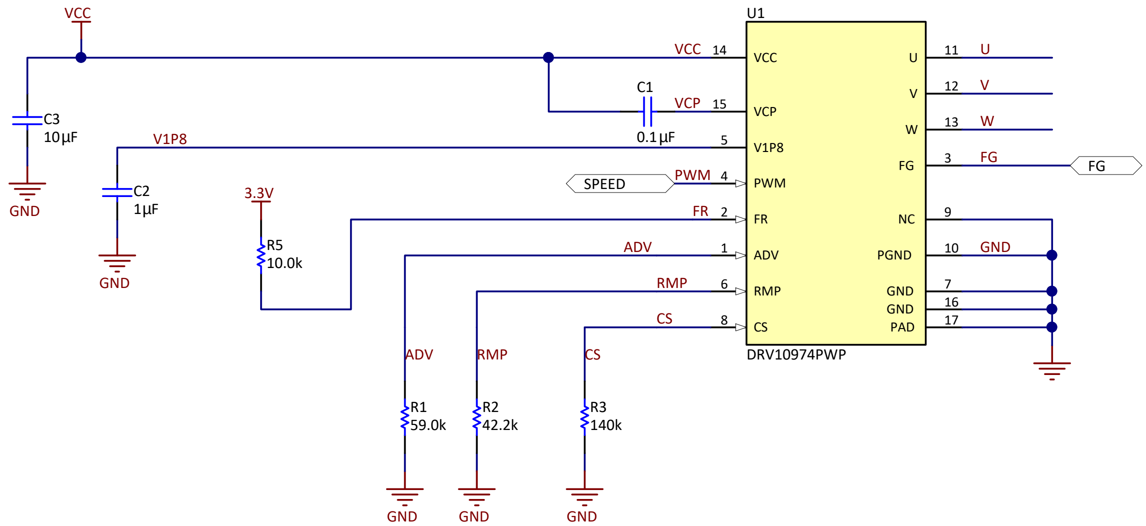


Figure 4. Reference Design Schematic

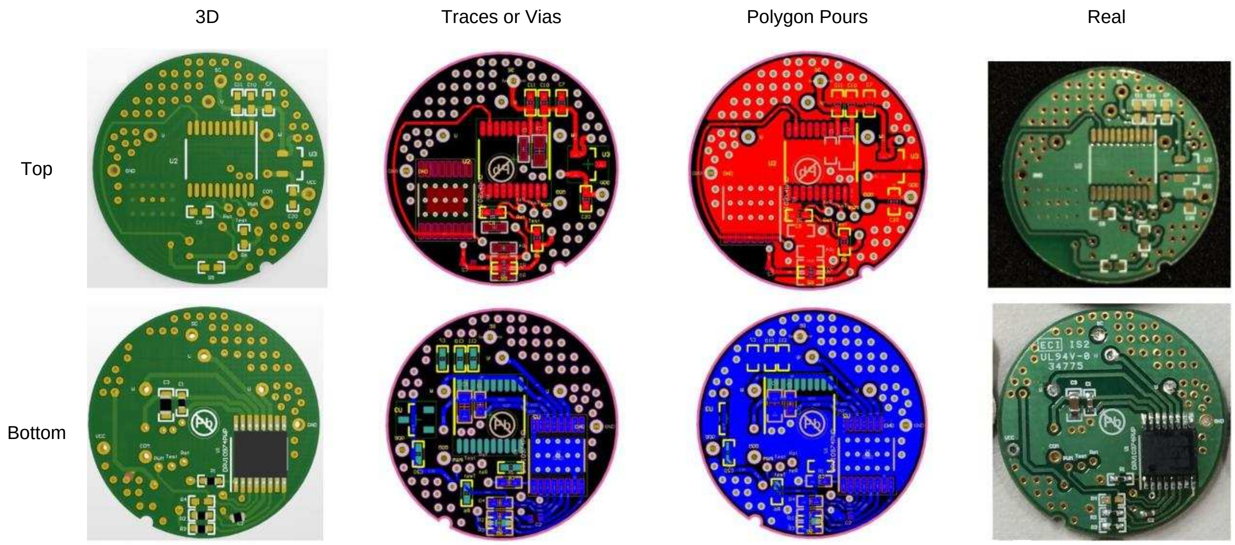


Figure 5. Reference Design PCB Layouts

2.3 Highlighted Products

2.3.1 DRV10974

The DRV10974 device is a three-phase, sensorless motor driver with integrated power MOSFETs, which provide drive-current capability up to 1 A continuous (RMS). The device is specifically designed for low-noise, low external-component count, 12-V motor drive applications. The 180° commutation requires no configuration beyond setting the peak current, the lead angle, and the acceleration profile, each of which is configured by an external resistor. The 180° sensorless-control scheme provides sinusoidal output voltages to the motor phases.

Interfacing to the DRV10974 device is simple and intuitive. The DRV10974 device receives a PWM input that it uses to control the speed of the motor. The duty cycle of the PWM input is used to determine the magnitude of the voltage applied to the motor. The resulting motor speed can be monitored on the FG pin. The FR pin is used to control the direction of rotation for the motor. The acceleration ramp rate is controlled by the RMP pin. The current limit is controlled by a resistor on the CS pin. The lead angle is controlled by a resistor on the ADV pin. When the motor is not spinning, a low-power mode turns off unused circuits to conserve power.

The DRV10974 device features extensive protection and fault-detect mechanisms to ensure reliable operation. The device provides overcurrent protection without the requirement for an external current-sense resistor. Rotorlock detect uses several methods to reliably determine when the rotor stops spinning unexpectedly. The device provides additional protection for undervoltage lockout (UVLO), for thermal shutdown, and for phase short circuit (phase to phase, phase to ground, phase to supply).

2.4 System Design Theory

2.4.1 Thermal Design

The system design consists of only the DRV10974. The board is designed to maximize the heat dissipation of the device. The PCB is designed with a 2-oz copper thickness and two layers. The board also uses thermal vias to effectively connect the GND planes and transfer heat between the layers.

Equation 1 shows how to calculate θ_{JA}, which is the constant the board tries to minimize through good layout techniques and thicker copper layers.

$$\theta_{JA} = T_{junction} - \left(T_{ambient} \times \text{Power Dissipation}\right) \tag{1}$$

Figure 6 shows the thermal resistance model for a typical PCB. This reference design is designed to minimize these resistances in this module by using 2-oz copper as well as thermal vias. Another way to minimize these thermal resistances is to make sure traces are parallel to the flow of heat as to not block the flow of heat. Heat flows radially from the heat source. The heat source of this reference design is the pins and power pad of the DRV10974. Traces from the pins should go in the same direction as the pins and not make sharp turns. The power pad should have thermal vias underneath that flow through the layers of board.

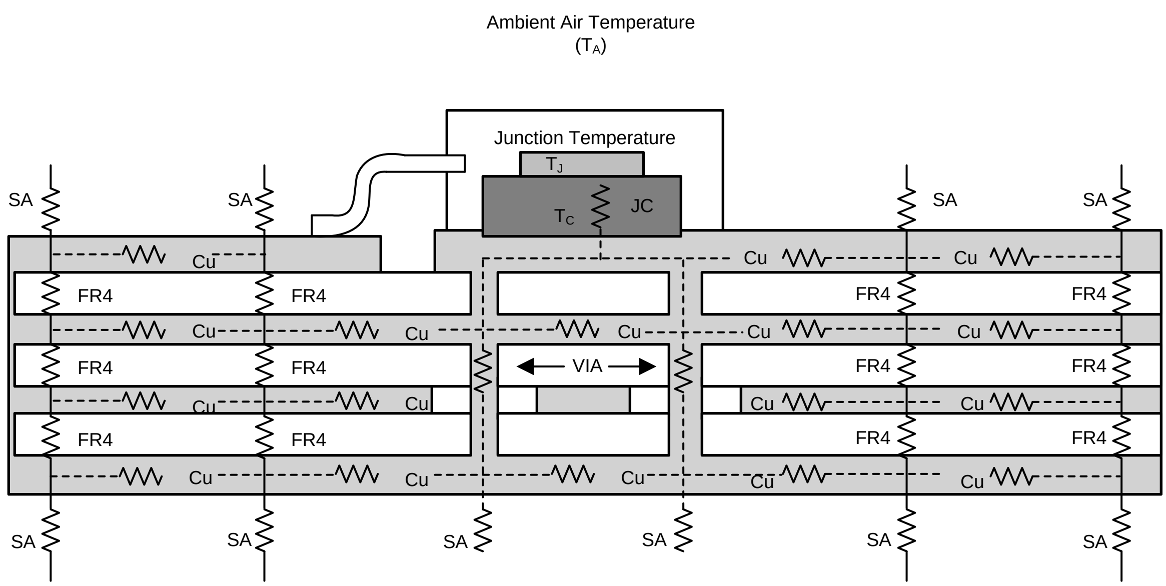


Figure 6. Thermal Model

[Figure 7](#) shows examples of three different PCBs with either no breaks in the thermal path, traces cut perpendicular to the heat flow, or traces cut parallel to the heat flow. If there are no breaks in the thermal path, the PCB has a more even heat distribution, leading to a better heat dissipation than the other two PCBs. If the traces are cut perpendicular to the heat flow, the PCB has a less even heat distribution than the first case, leading to a reduced heat dissipation. If the traces are cut parallel to the flow of heat, the PCB has worse heat distribution than the first example but better than the second example, leading to heat dissipation that falls between the two. This reference design uses thermal vias to allow paths around traces that run perpendicular to the flow of heat. For more information, see *How to Design a Thermally-Efficient Integrated BLDC Motor Drive PCB*.

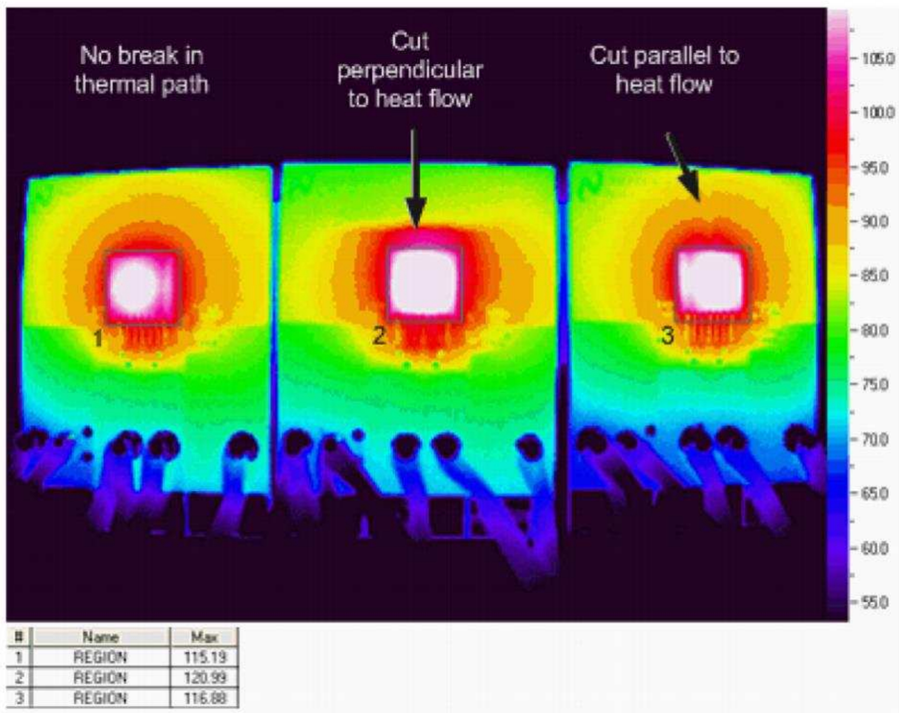


Figure 7. Effects of Blocked Thermal Path

2.4.2 Variant Design

This reference design has a second variant that allows users to add speed loop control or speed regulation to the design. To add speed regulation to this reference design, add a microcontroller (MCU) with software and a low dropout regulator (LDO) to the system. The LDO powers the MCU, and the MCU stores and performs the speed regulation given by the software. Figure 8 shows the variant schematic.

Referring to the top row and 3D column in Figure 5, there are no components populated. These are placeholders for the MCU, LDO, and external components.

Recommended components include the following:

- MCU: MSP430G2553IPW20
- LDO: TLV76033DBZR
- Figure 8 shows recommended external components

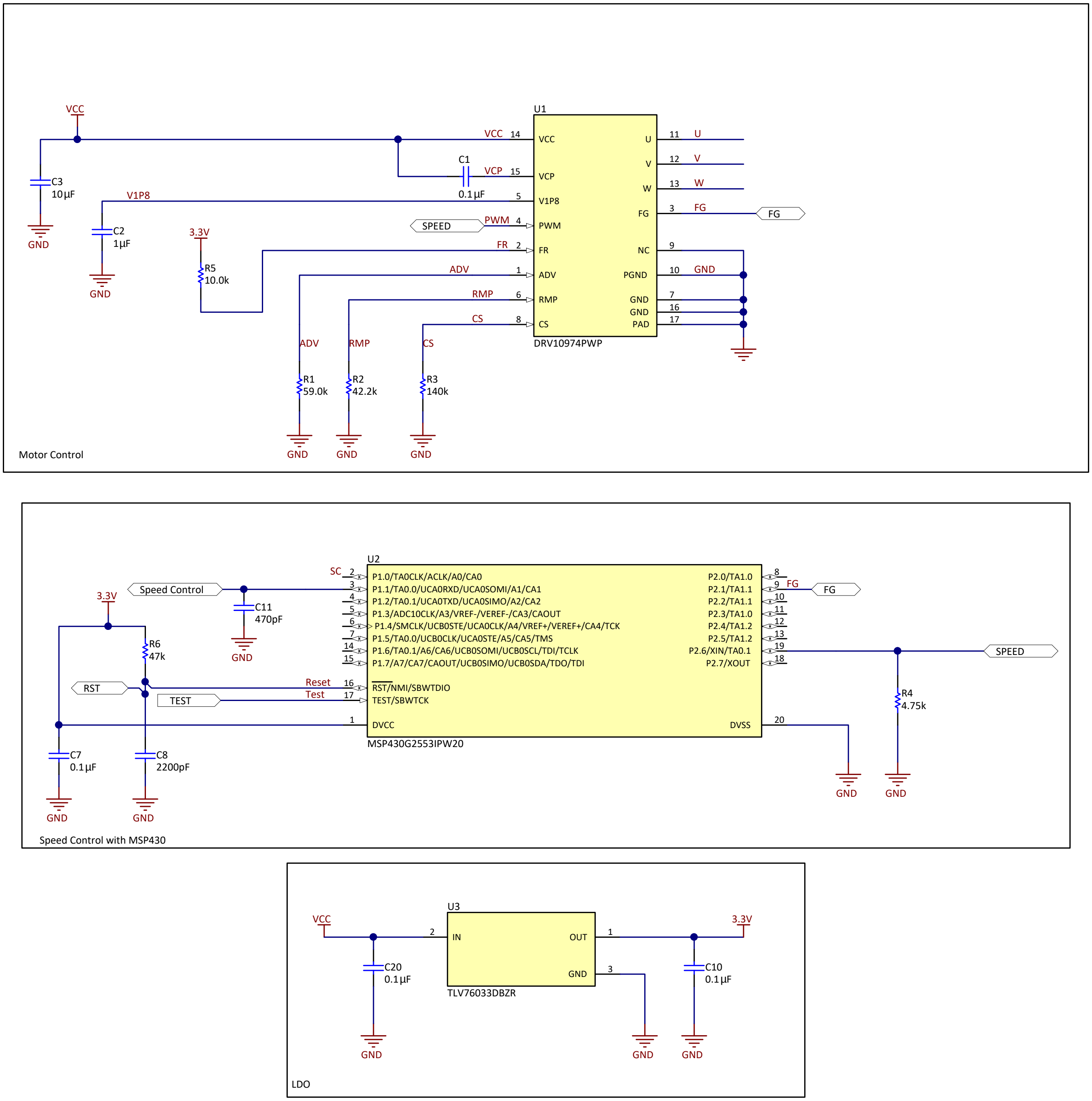


Figure 8. Variants for DRV10974, MCU, and LDO

3 Hardware, Testing Requirements, and Test Results

3.1 Required Hardware

This reference design is powered through the VCC input via and controlled using a frequency generator connected to PWM pin. The BLDC motor is connected through U, V, and W phase vias.

To set up the system, first connect the U, V, and W vias to motor U, V, and W phase winding. Then connect the frequency generator to PWM via. For the motor to spin, the PWM duty cycle must be > 15%. For more information, see *DRV10974 12-V, Three-Phase, Sensorless BLDC Motor Driver*. Lastly, connect the DC power supply to VCC (4.4 V to 18 V) ground (GND) vias.

3.1.1 Testing Requirements

Test equipment needed to test design include the following:

- Oscilloscope: Connect to VCC, PWM, FG, U, V, or W
- DC voltage source: Connect to VCC and GND
- Thermal camera: To take thermal images
- Frequency generator: Connect to PWM
- Three-phase BLDC motor: Connect U, V, and W
- Thermal chamber: To simulate test ambient temperatures

Figure 9 provides a via reference.

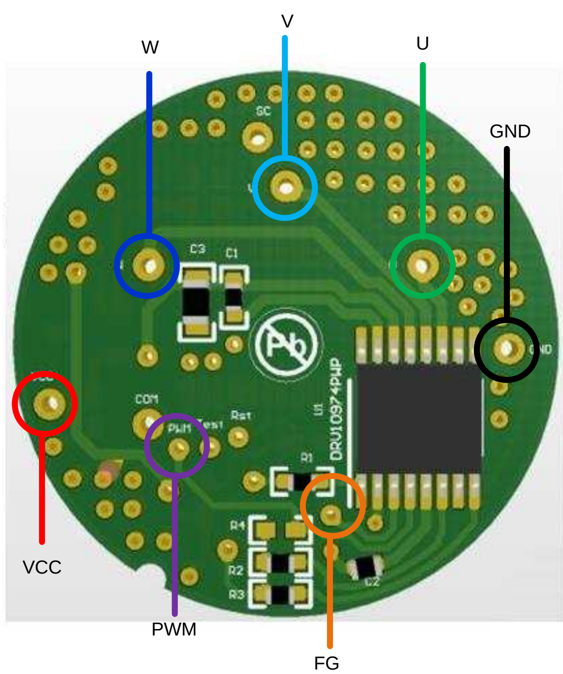


Figure 9. Reference Design Vias Highlighted

3.2 Testing and Results

3.2.1 Test Setup

- Functional test: Test the system at 25°C ambient temperature; evaluate temperature at top of case.
- Thermal test: Test the system at 70°C, 90°C, 110°C, 120°C, and 130°C ambient temperature; evaluate temperature at top of case.

3.2.2 Test Results

3.2.2.1 Functional Test at 25°C Ambient Temperature

A functional test shows the reference design performance at an ambient temperature of approximately 25°C. In Figure 10, the top waveform is supply current (C3), the middle waveform is FG (C2), and the bottom waveform is Phase U current (C4). Figure 10 also shows the supply current RMS (P1), FG frequency (P2) and phase U current frequency (P4), RMS (P5), and peak to peak (P6, neglect amplitude naming in image). Table 6 shows the data collected from all tests.

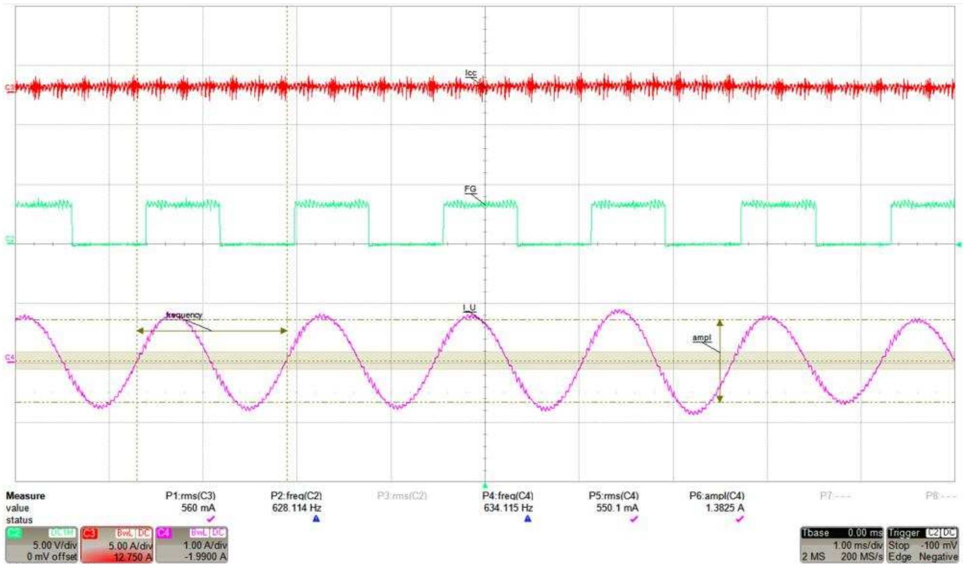


Figure 10. Phase U Current Waveform at 25°C Ambient Temperature

Figure 11 shows the reference design thermal image at a 25°C ambient temperature. The top-of-case temperature is 59.4°C, located at the right side of image. The test was done inside a thermal chamber and set at 25°C ambient temperature. The PCB was enclosed in a foam cylinder with 4 inches of length and 3 inches diameter for minimum air circulation on the IC.

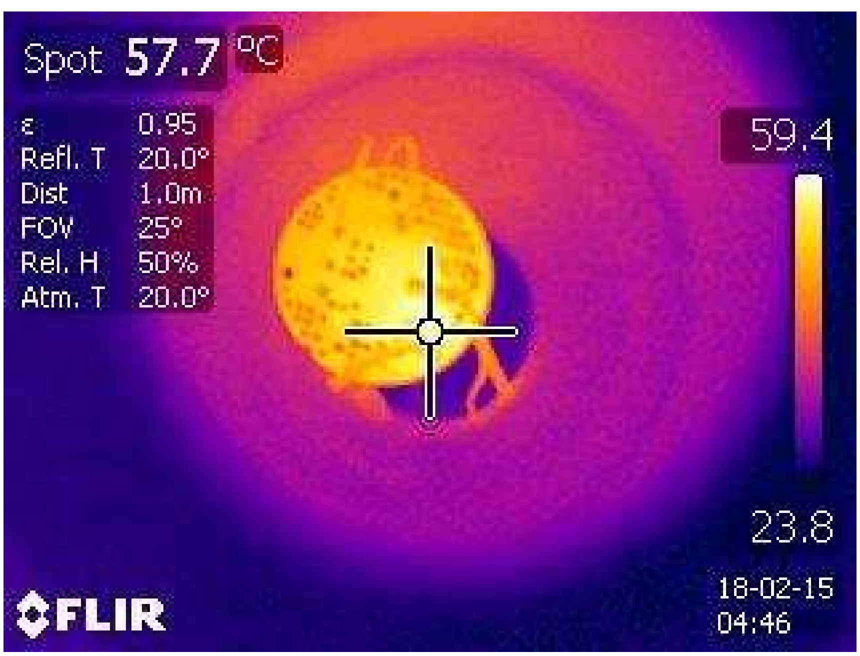


Figure 11. Reference Design Thermal Image at 25°C Ambient Temperature

3.2.2.2 Thermal Test

3.2.2.2.1 Thermal Test at 70°C Ambient Temperature

As mentioned in Section 3.2.2.1, the waveforms in Figure 12 represent the same specifications: supply current (C3), FG (C2), and Phase U current (C4) including P1, P2, P4, P5, and P6. Figure 12 shows the performance of the reference design at a 70°C ambient temperature. To simulate a 70°C ambient temperature, a thermal chamber is used and set for the test temperature. Table 6 shows the data.

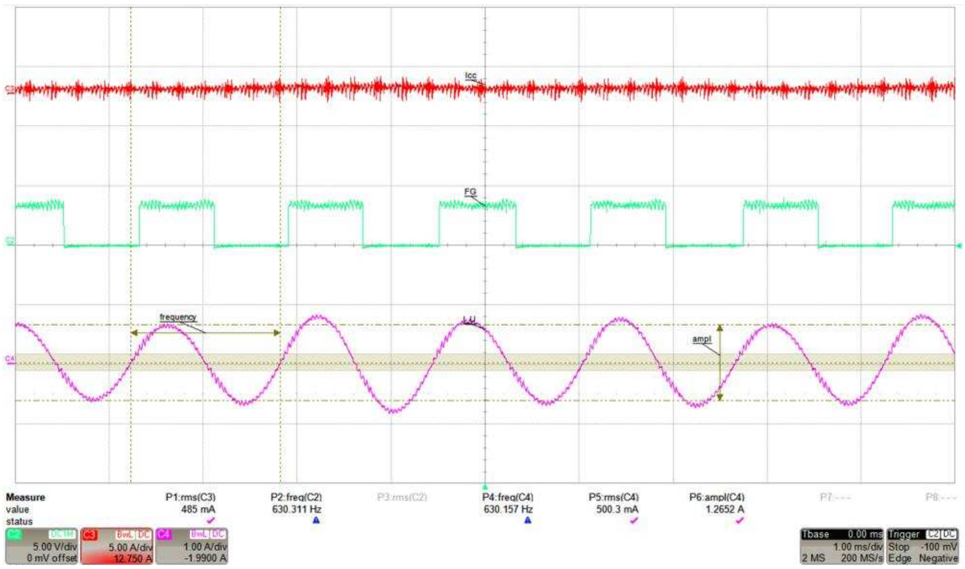


Figure 12. Phase U Current Waveform at 70°C Ambient Temperature

Figure 13 shows a top-of-case temperature of 90.7°C. The thermal chamber was set to the test temperature and waited 5 minutes after reaching the set temperature to take the images.

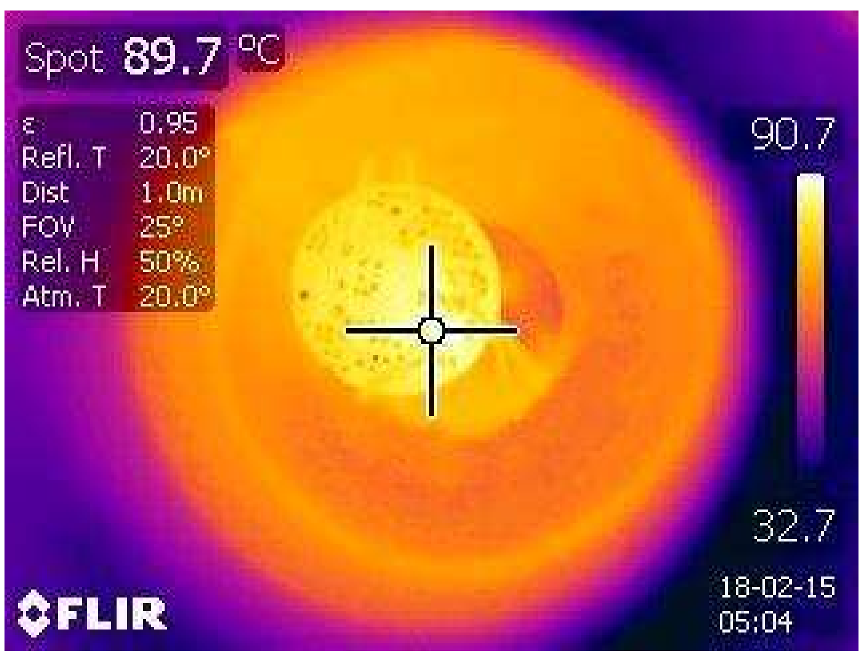


Figure 13. Reference Design Thermal Image at 70°C Ambient Temperature

3.2.2.2.2 Thermal Test at 90°C Ambient Temperature

Figure 14 shows the same specification as previous test but at a 90°C ambient temperature. Table 6 shows the data.

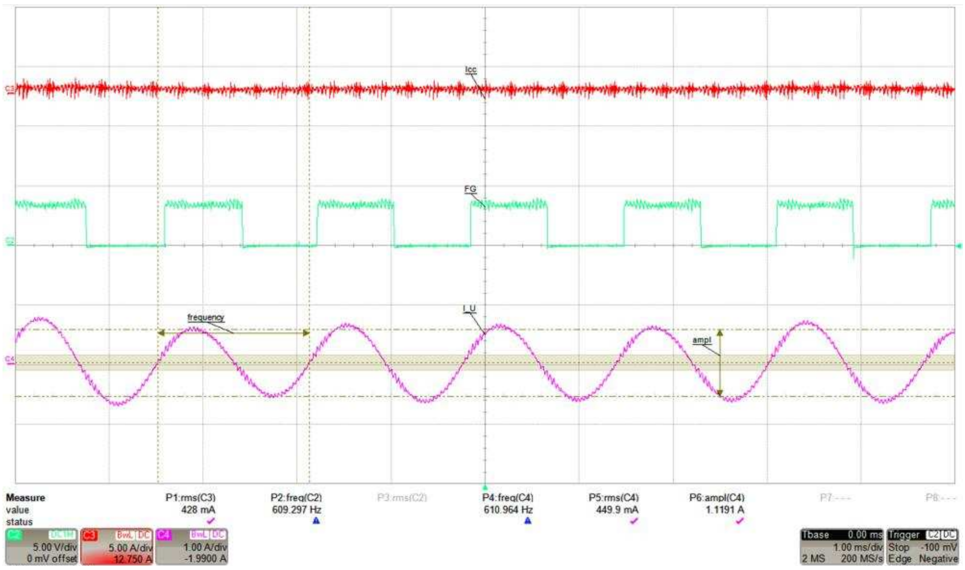


Figure 14. Phase U Current Waveform at 90°C Ambient Temperature

Figure 15 shows a top-of-case temperature of 110°C. System setup is repeated from the previous step but at a temperature set point of 90°C for the thermal chamber.

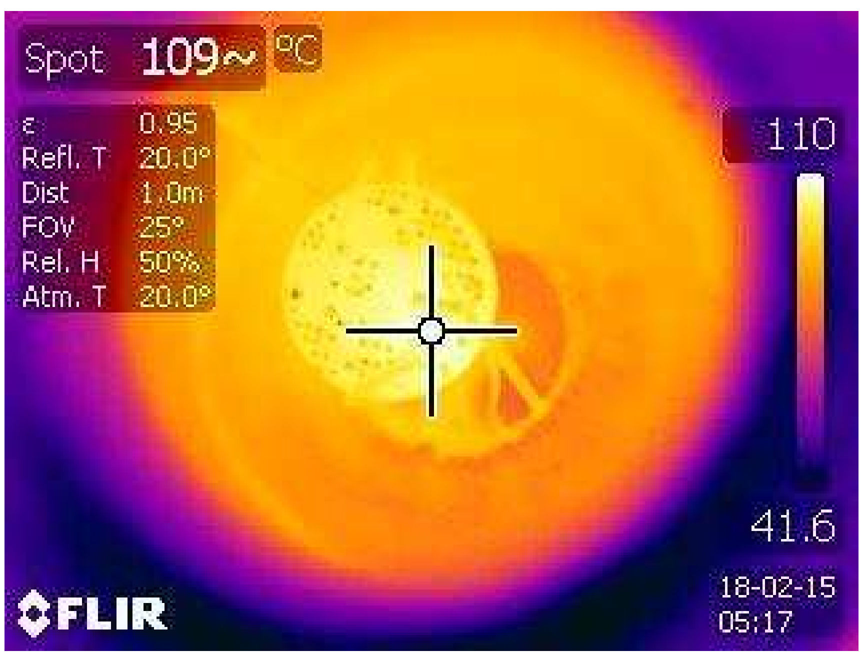


Figure 15. Reference Design Thermal Image at 90°C Ambient Temperature

3.2.2.2.3 Thermal Test at 110°C Ambient Temperature

Figure 16 shows the same specification as the previous test but at a 110°C ambient temperature. Table 6 shows the data.

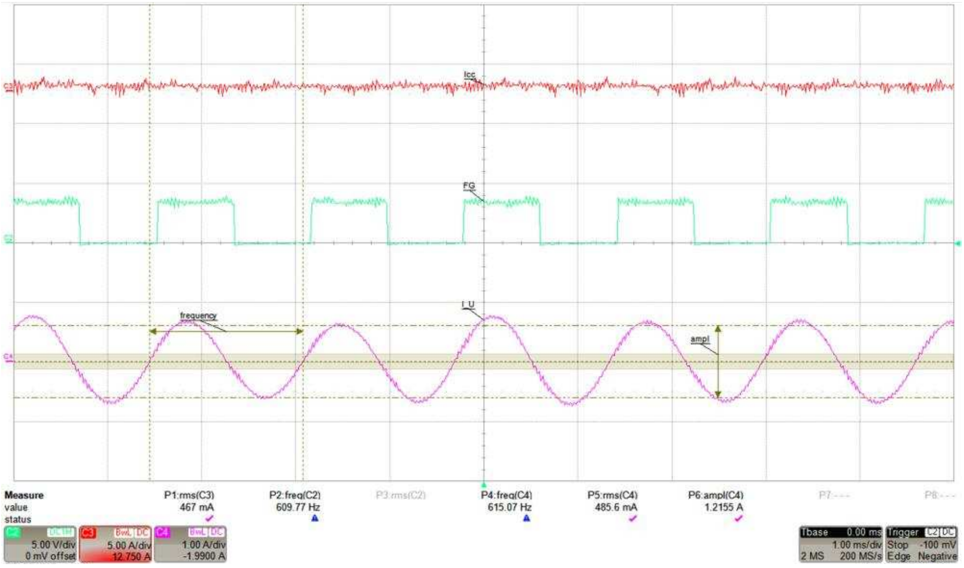


Figure 16. Phase U Current Waveform at 110°C Ambient Temperature

Figure 17 shows a top-of-case temperature of 131°C. System setup is repeated from the previous test but at a temperature set point of 110°C for the thermal chamber.

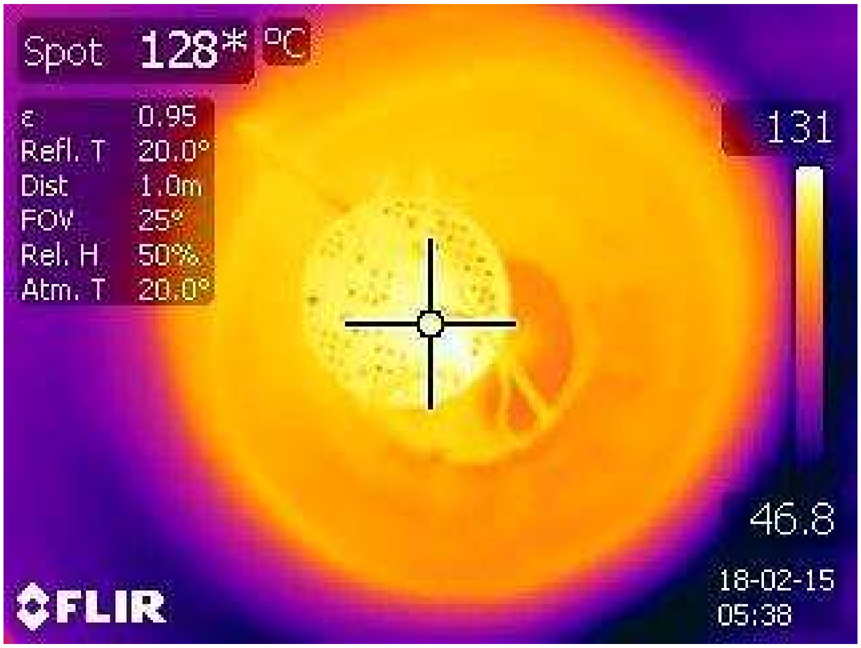


Figure 17. Reference Design Thermal Image at 110°C Ambient Temperature

3.2.2.2.4 Thermal Test at 120°C Ambient Temperature

Figure 18 shows the same specification as previous test but at a 120°C ambient temperature. Table 6 shows the data.

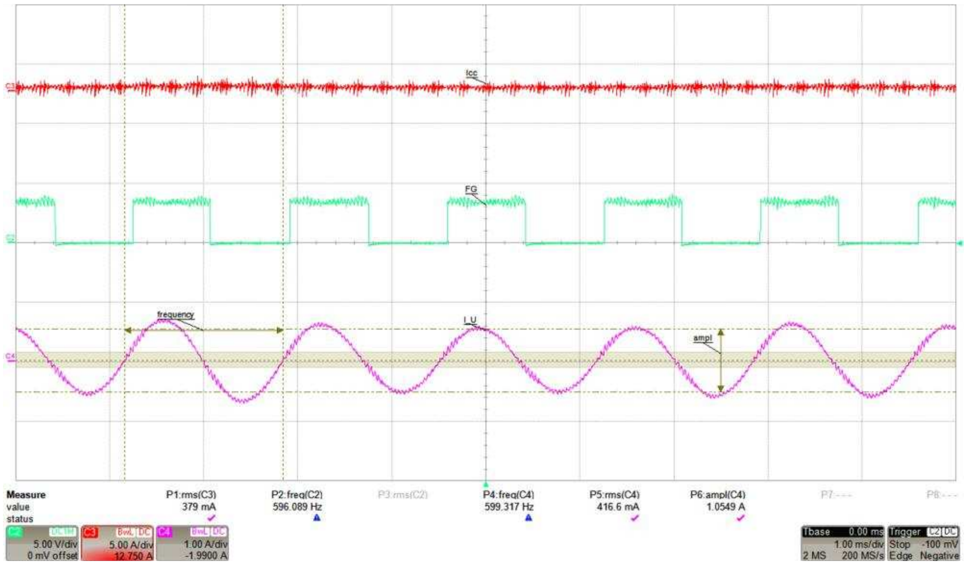


Figure 18. Phase U Current Waveform at 120°C Ambient Temperature

Figure 19 shows a top-of-case temperature of 137°C. System setup is repeated from previous test but at a temperature set point of 120°C for the thermal chamber.

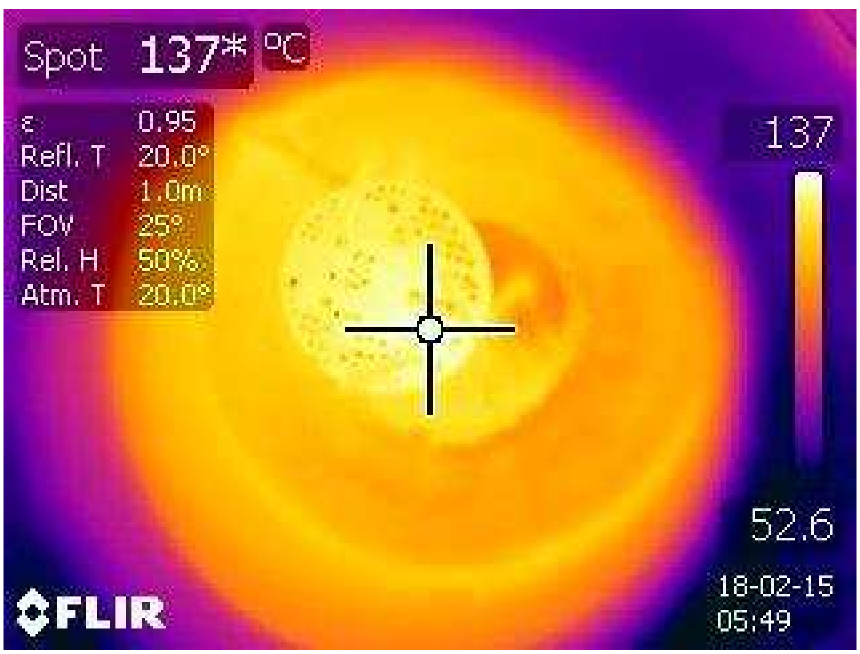


Figure 19. Reference Design Thermal Image at 120°C Ambient Temperature

3.2.2.2.5 Thermal Test at 130°C Ambient Temperature

For a 130°C ambient temperature, there is no data to show because the DRV10974 detected overtemperature and protection procedure shut off the device. The top-of-case temperature drops, so there is no thermal image to capture either.

3.2.2.3 Results

Table 6 compares the results of the functional test at 25°C and the thermal test from 70°C to 120°C. The speed command is set to 100% for all tests. Comparing ambient and top-of-case temperatures, the thermal tests show signs of proportionality. Equation 2 shows that top-of-case temperature (T_C) is directly related to ambient temperature (T_A).

$$T_C = P_D \times \theta_{CA} + T_A \quad (2)$$

For this test $P_D \times \theta_{CA}$ is constant at 20°C, where:

- P_D= power dissipated
- θ_{CA}= thermal resistance between top of case and ambient

Values for P_D and θ_{CA} can be neglected for thermal comparison, including phase current and supply current. This reference design allows proportional change from ambient temperature to top-of-case temperature.

This design allows the system to perform at a high ambient temperature without triggering overtemperature protection. This design allows the system to operate at 120°C ambient temperature.

Table 6. Result Comparison

AMBIENT TEMPERATURE (°C)	SPEED (Hz)	PHASE CURRENT (A_{RMS})	PHASE CURRENT (A_{pk-pk})	SUPPLY CURRENT DRAW (A)	TOP OF CASE TEMPERATURE (°C)
25	634	0.550	1.38	0.56	59.4
70	630	0.500	1.26	0.485	90.7
90	610	0.449	1.11	0.428	110
110	615	0.485	1.21	0.467	131
120	600	0.416	1.05	0.379	137

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01619.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01619.

4.3 PCB Layout Recommendations

To design an efficient PCB layout follow these guidelines:

- To save space, minimize clearance rules in Altium.
- Verify with PCB manufacturer minimum clearance rules.
- Add multiple layers.
- Make 2-oz copper thickness.
- Add multiple vias for better heat dissipation.
- Add silkscreen to all vias intended to use on both sides of PCB.

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01619.

4.4 Altium Project

To download the Altium Designer® project files, see the design files at TIDA-01619.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01619.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01619.

5 Related Documentation

1. Texas Instruments, *How to Design a Thermally-Efficient Integrated BLDC Motor Drive PCB Application Report*
2. Texas Instruments, *DRV10974 12-V, Three-Phase, Sensorless BLDC Motor Driver Data Sheet*

5.1 Trademarks

E2E is a trademark of Texas Instruments.
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6 Terminology

BLDC— Brushless DC

OCP— Overcurrent protection

UVLO— Undervoltage lockout

OTP— Overtemperature protection

GND— Ground

FETs, MOSFETs— Metal-oxide-semiconductor field-effect transistor

PWM— Pulse width modulation

°C— Temperature in Celsius

oz— Ounce

MCU— Microcontroller

LDO— Low drop regulator

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