High-Performance E-Scooter BLDC Motor Driver Reference Design User's Guide

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HIGH-PERFORMANCE E-SCOOTER BLDC MOTOR DRIVER REFERENCE DESIGN USER'S GUIDE

Table of Contents

Preface

NOTICE TO CUSTOMERS

All documentation becomes dated, and this manual is no exception. Microchip tools and documentation are constantly evolving to meet customer needs, so some actual dialogs and/or tool descriptions may differ from those in this document. Please refer to our website (www.microchip.com) to obtain the latest documentation available.

Documents are identified with a "DS" number. This number is located on the bottom of each page, in front of the page number. The numbering convention for the DS number is "DSXXXXXXXXA", where "XXXXXXXX" is the document number and "A" is the revision level of the document.

For the most up-to-date information on development tools, see the MPLAB® IDE online help. Select the Help menu, and then Topics to open a list of available online help files.

INTRODUCTION

This chapter contains general information that will be useful to know before using the High-Performance E-Scooter BLDC Motor Driver Reference Design. Items discussed in this chapter include:

- Document Layout
- Conventions Used in this Guide
- Recommended Reading
- The Microchip Website
- Customer Support
- Document Revision History

DOCUMENT LAYOUT

This document describes how to use the High-Performance E-Scooter BLDC Motor Driver Reference Design as a development tool. The user's guide layout is as follows:

- **Chapter 1. "Product Overview"** – Important information about the High-Performance E-Scooter BLDC Motor Driver Reference Design.
- **Chapter 2. "Installation and Operation"** – This chapter includes a detailed description of each function of the evaluation board and instructions for how to begin using the High-Performance E-Scooter BLDC Motor Driver Reference Design.
- **Appendix A. "Schematics and Layouts"** – Shows the schematic and PCB layout diagrams for the High-Performance E-Scooter BLDC Motor Driver Reference Design.
- **Appendix B. "Bill of Materials (BOM)"** – Lists the parts used to build the High-Performance E-Scooter BLDC Motor Driver Reference Design User's Guide.
- **Appendix C. "Test Report (Waveforms)"** – Describes the various demo waveforms for the High-Performance E-Scooter BLDC Motor Driver Reference Design.

CONVENTIONS USED IN THIS GUIDE

This manual uses the following documentation conventions:

DOCUMENTATION CONVENTIONS

Description	Represents	Examples
Arial font:		
Italic characters	Referenced books	*MPLAB® IDE User's Guide*
	Emphasized text	...is the *only* compiler...
Initial caps	A window	the Output window
	A dialog	the Settings dialog
	A menu selection	select Enable Programmer
Quotes	A field name in a window or dialog	"Save project before build"
Underlined, italic text with right angle bracket	A menu path	*File>Save*
Bold characters	A dialog button	Click **OK**
	A tab	Click the **Power** tab
N'Rnnnn	A number in verilog format, where N is the total number of digits, R is the radix and n is a digit.	4'b0010, 2'hF1
Text in angle brackets < >	A key on the keyboard	Press <Enter>, <F1>
Courier New font:		
Plain Courier New	Sample source code	`#define START`
	Filenames	`autoexec.bat`
	File paths	`c:\mcc18\h`
	Keywords	`_asm, _endasm, static`
	Command-line options	`-Opa+, -Opa-`
	Bit values	`0, 1`
	Constants	`0xFF, 'A'`
Italic Courier New	A variable argument	*`file`*`.o`, where *`file`* can be any valid filename
Square brackets [ ]	Optional arguments	`mcc18 [options]` *`file`* `[options]`
Curly brackets and pipe character: { | }	Choice of mutually exclusive arguments; an OR selection	`errorlevel {0|1}`
Ellipses...	Replaces repeated text	`var_name [, var_name...]`
	Represents code supplied by user	`void main (void) { ... }`

RECOMMENDED READING

This user's guide describes how to use the High-Performance E-Scooter BLDC Motor Driver Reference Design. Other useful documents are listed below. The following Microchip documents are available and recommended as supplemental reference resources:

- **dsPIC33CK64MC105 Family –** ***"16-Bit Digital Signal Controllers with High-Speed ADC, Op Amps, Comparators and High-Speed PWM" (DS70005399)***
- **dsPIC33CK64MC105 Family Silicon Errata and Data Sheet Clarification (DS80000910)**
- **dsPIC33CK64MP105 Family –** ***"16-Bit Digital Signal Controllers with High-Speed ADC, Op Amps, Comparators and High-Resolution PWM"*** **(DS70005363)**
- **dsPIC33CK64MP105 Family Silicon Errata and Data Sheet Clarification (DS80000809*)***
- **AN1078 –** ***"Sensorless Field Oriented Control of a PMSM" (DS01078)***
- **AN1299 –** ***"Single-Shunt Three-Phase Current Reconstruction Algorithm for Sensorless FOC of a PMSM" (DS01299A)***
- **AN992 –** ***"Sensorless BLDC Motor Control Using dsPIC30F2010" (DS00992)***
- **AN1292 –** ***"Sensorless Field Oriented Control (FOC) for a Permanent Magnet Synchronous Motor (PMSM) Using a PLL Estimator and Field Weakening (FW)" (DS01292)***
- **AN901 –** ***"Using the dsPIC30F for Sensorless BLDC Control" (DS00901)***

THE MICROCHIP WEBSITE

Microchip provides online support via our website at www.microchip.com. This website is used as a means to make files and information easily available to customers. Accessible by using your favorite Internet browser, the website contains the following information:

- **Product Support** – Data sheets and errata, application notes and sample programs, design resources, user's guides and hardware support documents, latest software releases and archived software
- **General Technical Support** – Frequently Asked Questions (FAQs), technical support requests, online discussion groups, Microchip consultant program member listing
- **Business of Microchip** – Product selector and ordering guides, latest Microchip press releases, listing of seminars and events, listings of Microchip sales offices, distributors and factory representatives

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- Distributor or Representative
- Local Sales Office
- Field Application Engineer (FAE)
- Technical Support

Customers should contact their distributor, representative or field application engineer (FAE) for support. Local sales offices are also available to help customers. A listing of sales offices and locations is included in the back of this document.

Technical support is available through the website at:
http://www.microchip.com/support

DOCUMENT REVISION HISTORY

Revision A (July 2021)

- Initial release of this document.

Chapter 1. Product Overview

1.1 INTRODUCTION

This chapter provides an overview of the High-Performance E-Scooter BLDC Motor Driver Reference Design and covers the following topics:

- System Overview
- What is the High-Performance E-Scooter BLDC Motor Driver Reference Design?
- What the High-Performance E-Scooter BLDC Motor Driver Reference Design Kit Contains

1.2 SYSTEM OVERVIEW

The High-Performance E-Scooter BLDC Motor Driver Reference Design targets high-performance, cost-effective motor control applications: for example, applications for low-power E-mobility solutions (E-scooters, E-bikes, etc.). The High-Performance E-Scooter BLDC Motor Driver Reference Design is able to drive BLDC/PMSM motors of up to 350W power and up to 15A RMS phase currents. The input voltage range is between 18V and 42V covering the applications powered from battery strings of up to 10S (Li-Ion cells).

1.3 WHAT IS THE HIGH-PERFORMANCE E-SCOOTER BLDC MOTOR DRIVER REFERENCE DESIGN?

The High-Performance E-Scooter BLDC Motor Driver Reference Design is a high-performance BLDC/PMSM motor driver board used to demonstrate the capabilities offered by the dsPIC33CK high performance Digital Signal Controller (DSC) in conjunction with the MIC4104 (MOSFET gate driver) for motor control applications like E-scooters and E-bikes. The board is developed to meet the stringent demands of modern motor control applications: high efficiency, compact dimensions, low cost, and high performance.

1.3.1 Key Features

- 18V to 42V V_{BUS} Input Voltage Range (cover up to 10S batteries setup)
- Maximum output power: 350W
- 15A RMS (continuous) and up to 27A RMS (for short time) motor phase current
- Low-side shunt resistors on each inverter phase for current measurement (2 mΩ)
- PWM switching frequency range 8 kHz-50 kHz (typical 20 kHz)
- On board bias generator based on the MCP16331 buck regulator
- Six N-Channel MOSFETs with low $R_{DS(on)}$ (typical 1.9 mΩ)
- Faston Tab connectors for motor phases
- XT30 - type connector for convenient connection with the battery packs
- Support for sensored/sensorless motor control algorithms
- PICkit™ debugger/programmer interface
- Support for on board temperature measurement (NTC Thermistor)
- Auxiliar connectors (for custom functions like I^2C, UART, THROTTLE

(acceleration), voltage monitoring, Bluetooth, temperature, etc)

The High-Performance E-Scooter BLDC Motor Driver Reference Design block diagram is presented in Figure 1-1. There are several functional blocks:

- The three-phase inverter stage including the half-bridge gate drivers and FET's
- System bias generator (MCP16331 (12V), MCP1754S (5V), MCP1754S (3.3V))
- The digital control system based on dsPIC33CK DSC
- BEMF and motor phase currents sensing
- HALL sensors interface
- Auxiliary connectors

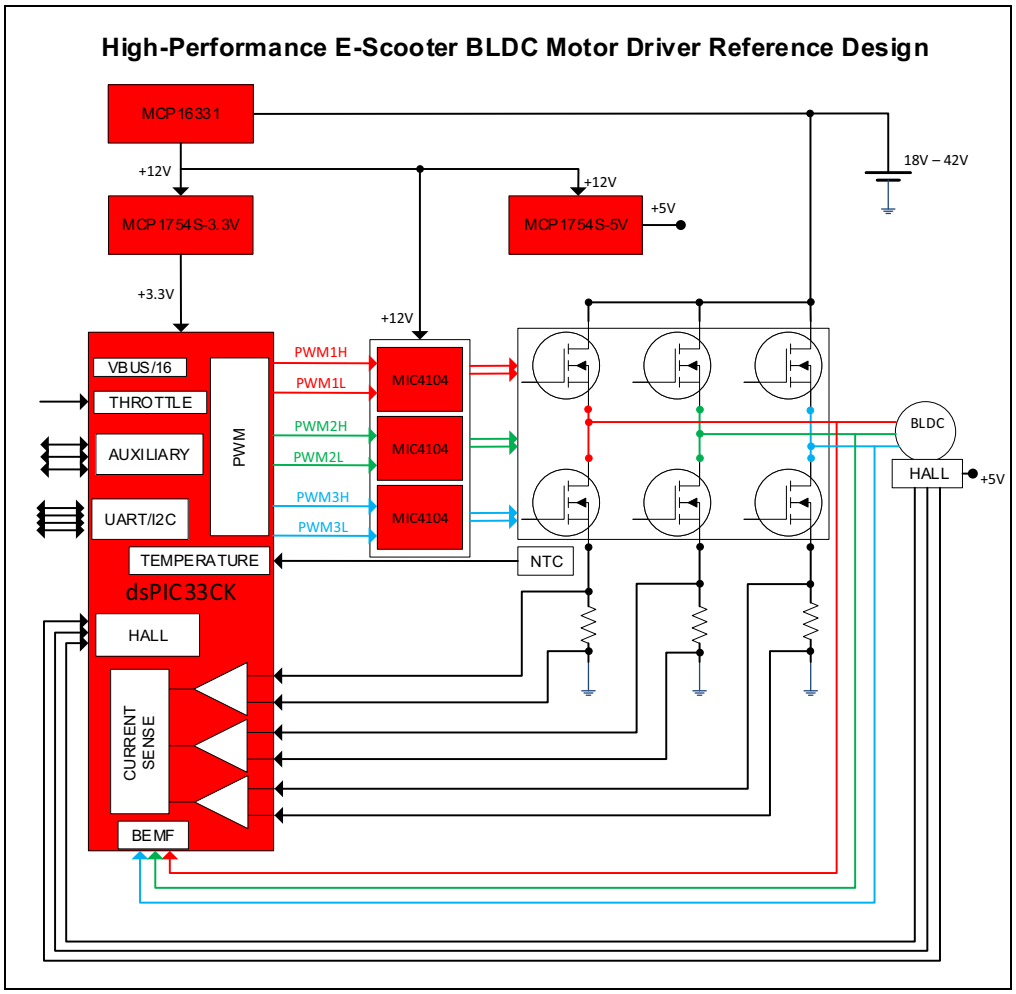


FIGURE 1-1: *High-Performance E-Scooter BLDC Motor Driver Reference Design Block Diagram.*

The three-phase inverter is implemented using six high performance MOSFET transistors with very low $R_{DS(on)}$ to be able to handle high phase currents without excessive conduction losses. These MOSFETs are drive by the MIC4104 high current MOSFET drivers. The temperature of these power MOSFETs can be monitored using an NTC thermistor.

The system bias generator provides the bias voltages for various functional blocks: +12V for the MOSFETs drivers, +3.3V for the digital control system and +5V for auxiliary functions like the Hall sensors interface. The +12V is provided by the MCP16331 switching regulator. The +3.3V for the DSC is provided by the MCP1754S-3 LDO and the +5V voltage is provided by the MCP1754S-5.

The digital control system uses the dsPIC33CK64MP105 high performance DSC. This DSC also includes three operational amplifiers used to implement the current sense amplifiers. Three low-side shunts of 2 mΩ are used to measure the phase currents.

The BEMFs of the motor are measured using three resistor dividers. Several auxiliary connectors are provided for the Hall sensors and additional functionality (communication interface, throttle key, etc.).

1.4 WHAT THE HIGH-PERFORMANCE E-SCOOTER BLDC MOTOR DRIVER REFERENCE DESIGN KIT INCLUDES

The High-Performance E-Scooter BLDC Motor Driver Reference Design includes:

- High-Performance E-Scooter BLDC Motor Driver Reference Design (INT01156)

NOTES:

Chapter 2. Installation and Operation

2.1 GETTING STARTED

The High-Performance E-Scooter BLDC Motor Driver Reference Design is a complete stand-alone motor controller for brushless DC motors (PMSM/BLDC). The board is fully assembled and tested and can drive a three-phase brushless DC motor rated at up to 15A RMS phase current and 42V.

The input voltage (+18V to +42V) is applied to the board via J5 connector (XT30U-M type). The motor is connected to the driver using three FASTON TAB 6.3x0.8mm connectors (J6, J7, J8). The motor's Hall sensors are connected to J1 using a 5-pin header connector.

Header connector J3 contains six lines that can be used to implement the additional functions like: signaling, sensing various signals, reading the potentiometer/throttle key for the speed/torque reference, etc. The +3.3V voltage and GND are also available on this connector.

A programming 5-pin, 2.54 mm header connector, (J2) is available for updating the firmware contained in the dsPIC33CK DSC using a PICkit™ programmer/debugger.

For UART and I^2C external communication, the user has the possibility to attach a 6-pin header connector (J4) to use a Serial Communication interface. Rx, Tx, SCL, SDA, +3.3V and GND signals are available.

The High-Performance E-Scooter BLDC Motor Driver Reference Design provides indicator LED's for power rails (D12, D13) and for Fault status indication (D11).

The temperature of the board can be monitored using NTC Thermistor (TH1) mainly on the inverter MOSFETs bridge.

Finally, the PCB layout design can serve as a reference for customers who want a robust and low-cost four-layer, 60x50mm, +12...+42 input V_{BUS} voltage, high-current small board.

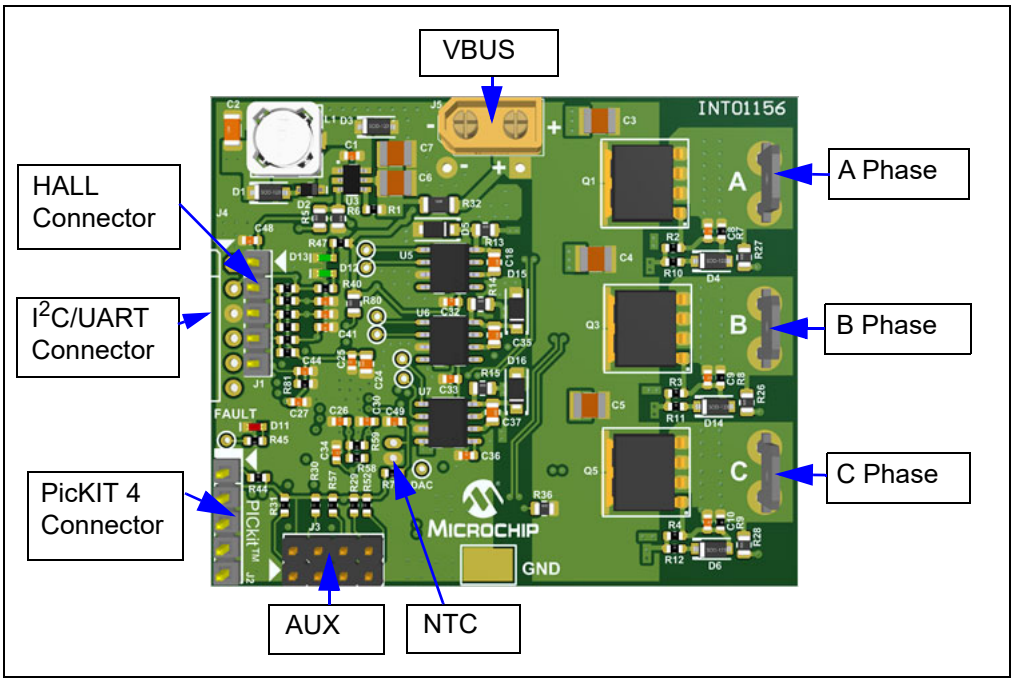


FIGURE 2-1: *Top Board View.*

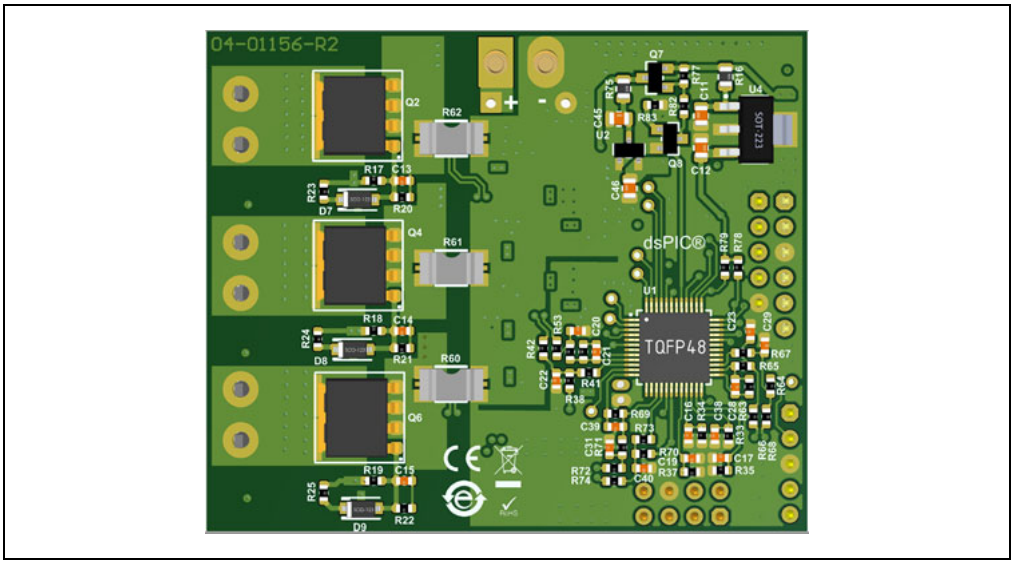


FIGURE 2-2: *Bottom Board View.*

2.1.1 Instruments and Tools

The following instruments and tools are needed:

- Adjustable DC Power Supply with 18V-42V/30A DC range output capability, or a battery with the nominal voltage between 18V and 36V
- 36V/350W 3 phase PMSM/BLDC Motor with/without HALL sensors
- A 10 kΩ potentiometer used for speed control
- Wires for connections; these wires must sustain high currents:
  - 30A for the connection between the adjustable DC Power Supply and the board
  - 30A for the connection between the board and the motor

- PicKIT 4 for programming/debugging the application
- Computer with MPLAB X IDE or MPLAB X IPE installed
- Digital oscilloscope, multimeter

Setting up the connection wires to the potentiometer can be done using the instructions below.

2.1.2 Setup Procedure

To power up the High-Performance E-Scooter BLDC Motor Driver Reference Design, the following steps must be completed:

1. Connect the motor to the board using the A, B and C connectors
2. With respect for the polarity: connect the power supply to the J5 connector board and select a voltage input range between 18V…42V.
3. With respect for the polarity: connect the MOTOR HALL sensors to the J1 connector on the board.
4. Connect the potentiometer to the AUX board connector following the setup in Figure 2-3.
5. Power up the board.
6. Start motor spinning using the potentiometer.

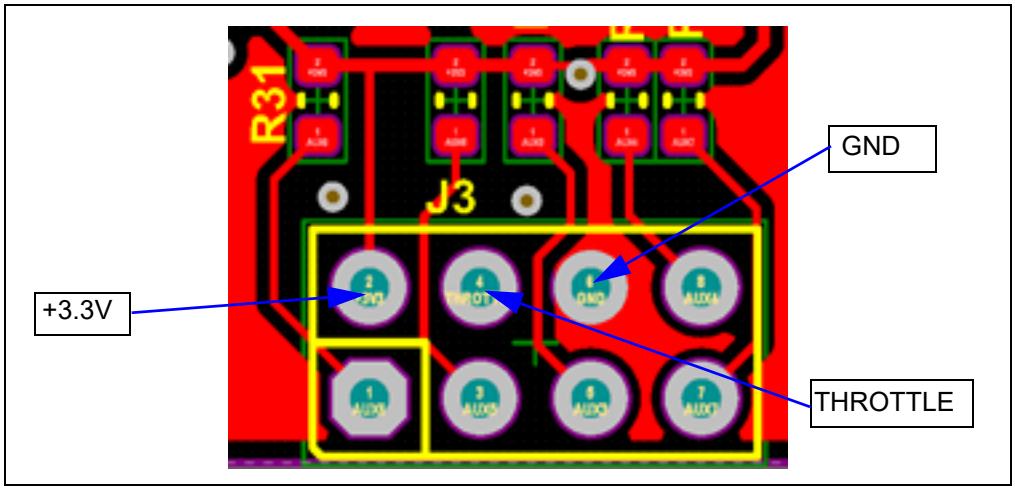


FIGURE 2-3: *J3 Wire Connections to the Potentiometer.*

2.1.3 Programming/Debugging

The board is fully equipped from both a hardware and software perspective, but customers have the flexibility to improve or tune the firmware provided, using a PicKIT4 and MPLAB X IDE In-Circuit Debugger/Programmer which allows fast and easy debugging and programming of the dsPIC®.

The PicKIT4 Programmer/Debugger should be connected to J2 connector on the board, with respect for the polarity (pin 1 of the J2 is marked on the board).

2.1.4 Connectors Pinout

Table 2-1: HALL Connector

	Pin	Signal
J1	1	+5V
	2	HALL1
	3	HALL2
	4	HALL3
	5	GND

Table 2-2: UART/I^{2}C Connector

	Pin	Signal
J4	1	UART_RX
	2	+3.3V
	3	GND
	4	SCL
	5	SDA
	6	UART_tX

TABLE 2-3: Auxiliary Connector

	Pin	Signal	PIN Function
J3	1	AUX6	Digital IO
	2	+3.3V	POWER
	3	AUX5	Digital IO
	4	THROTTLE	Analog/Digital IO
	5	AUX3	Digital IO
	6	GND	POWER
	7	AUX7	Digital IO
	8	AUX4	Digital IO

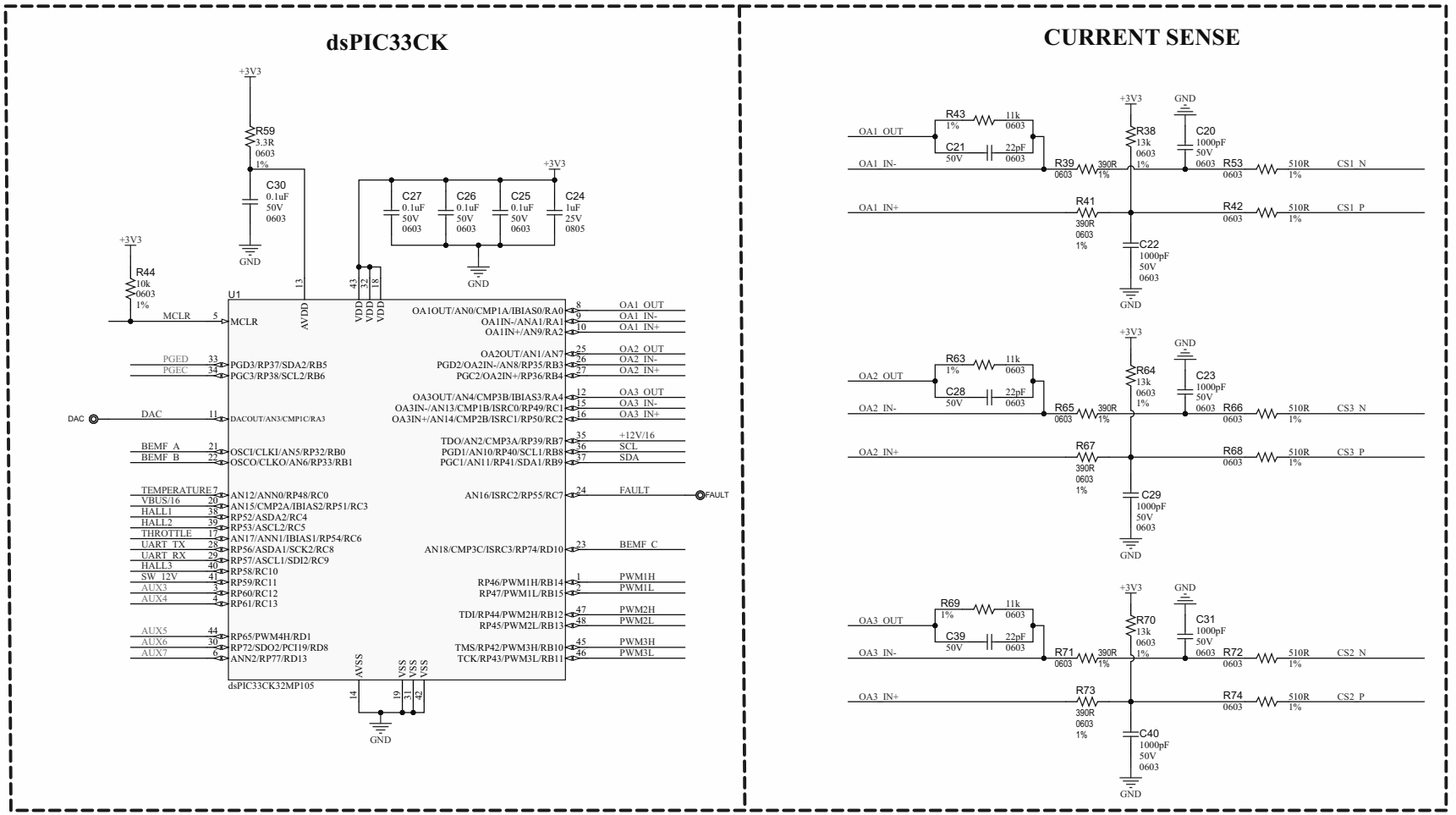
Appendix A. Schematics and Layouts

A.1 INTRODUCTION

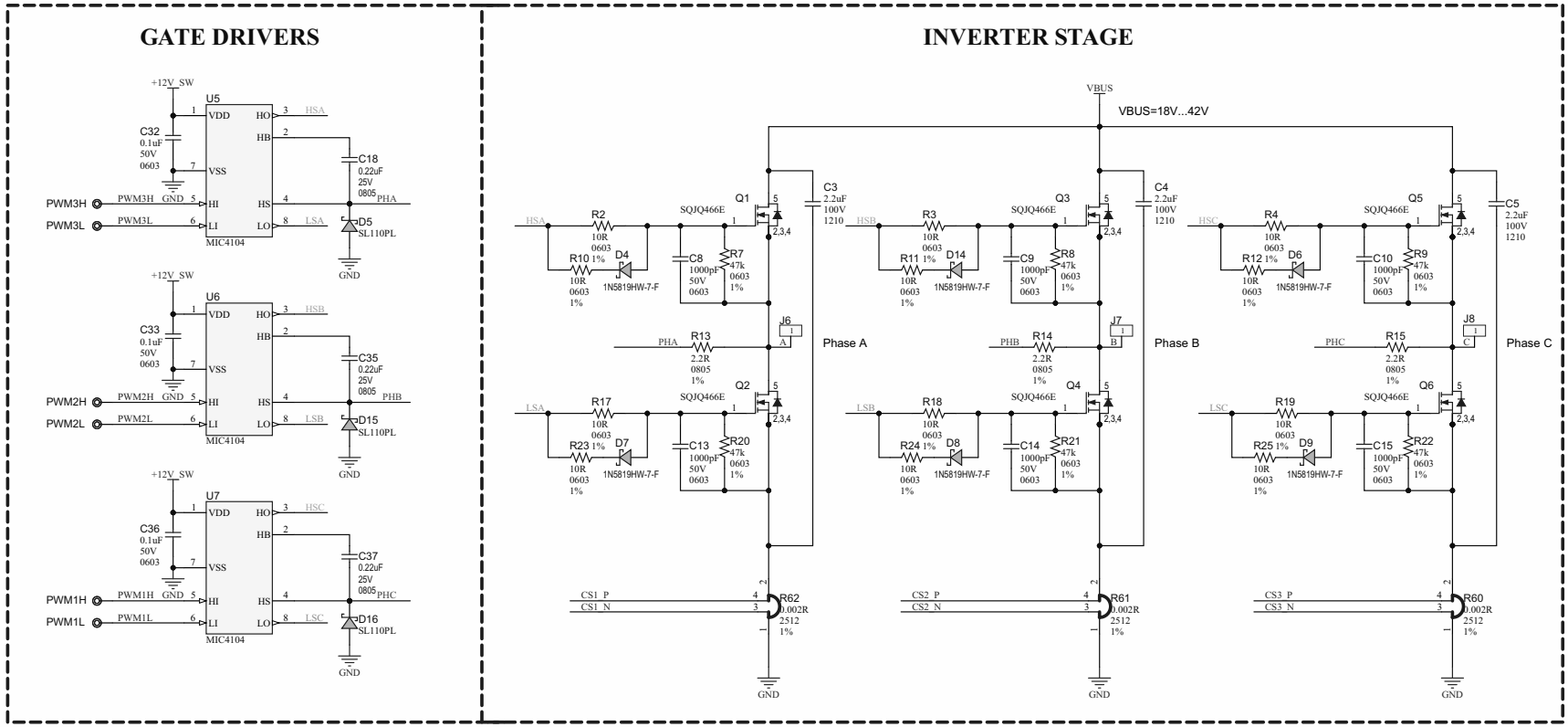
This appendix contains the following schematics and layouts for the High-Performance E-Scooter BLDC Motor Driver Reference Design:

- **Schematic 1**
- **Schematic 2**
- **Schematic 3**
- **Board – Top Silk**
- **Board – Top Copper and Silk**
- **Board – Top Copper**
- **Board – Internal Copper 1**
- **Board – Internal Copper 2**
- **Board – Bottom Copper**
- **Board – Bottom Copper and Silk**
- **Board – Bottom Silk**

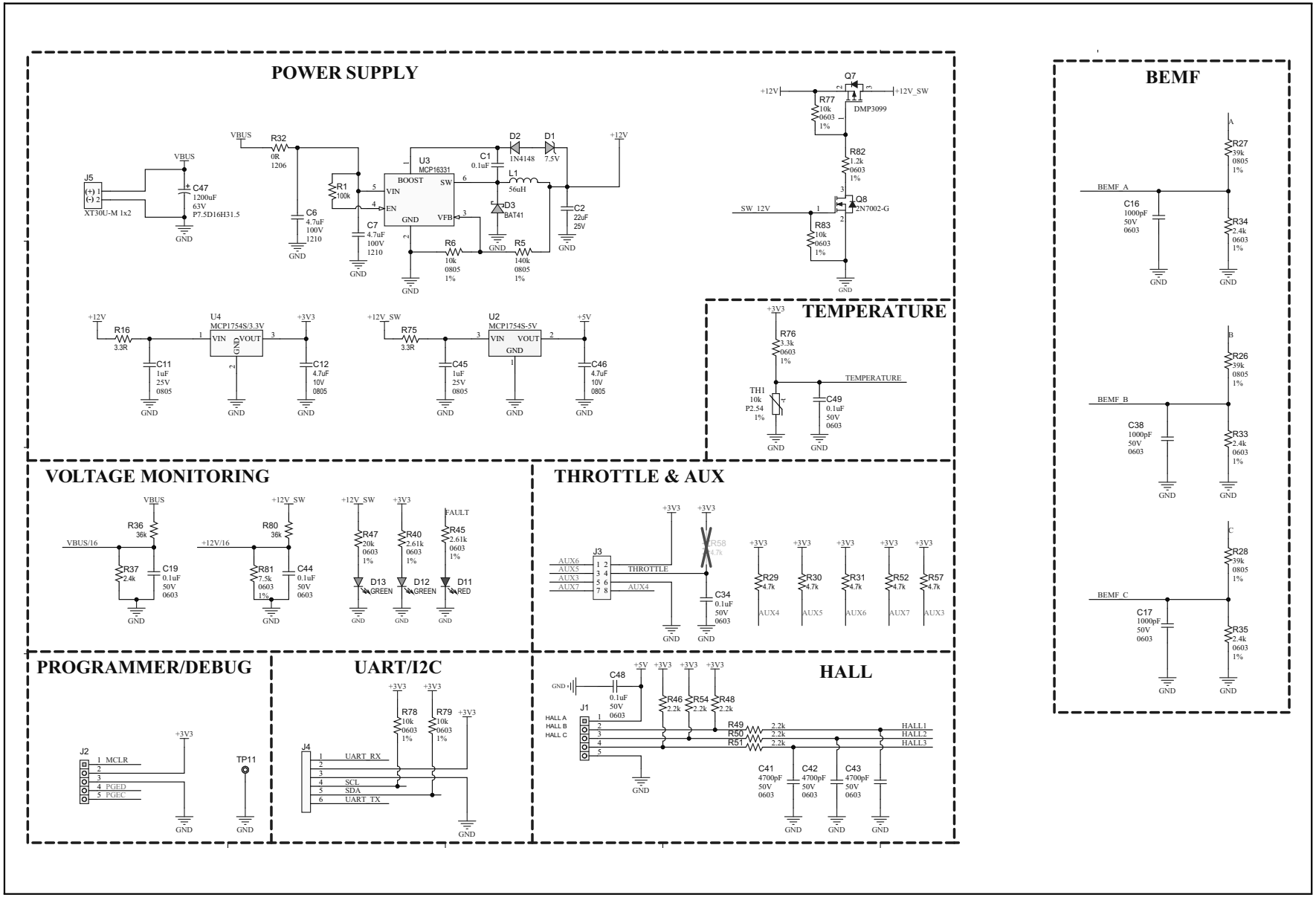
A.2 SCHEMATIC 1



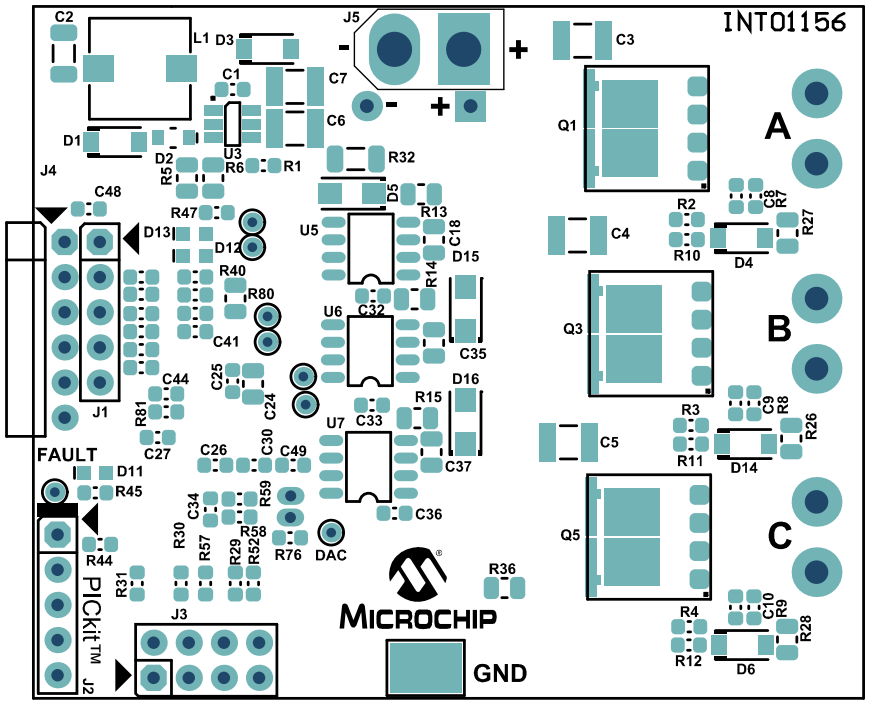
A.3 SCHEMATIC 2



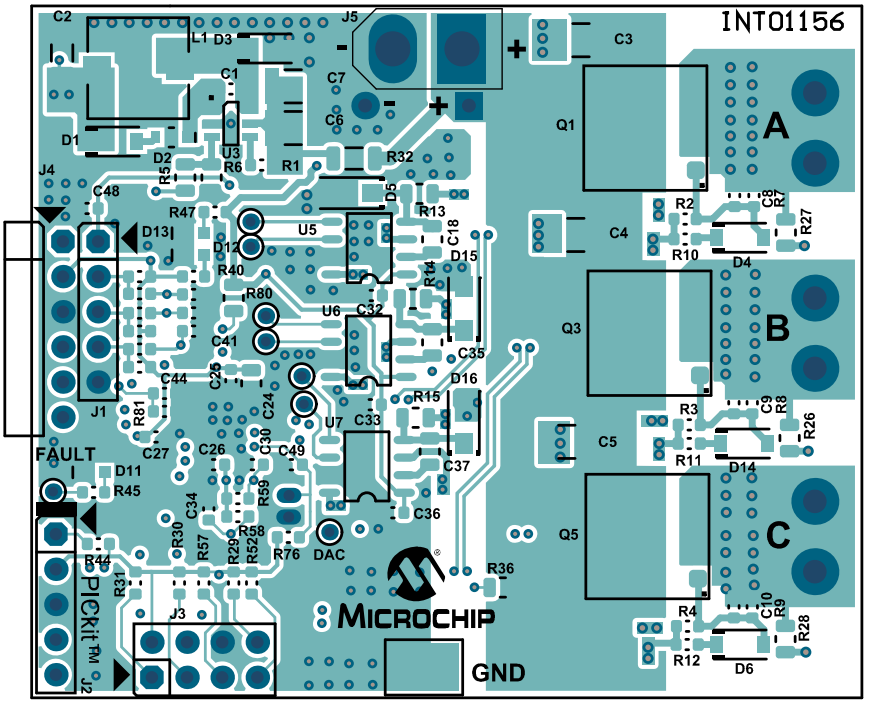
A.4 SCHEMATIC 3



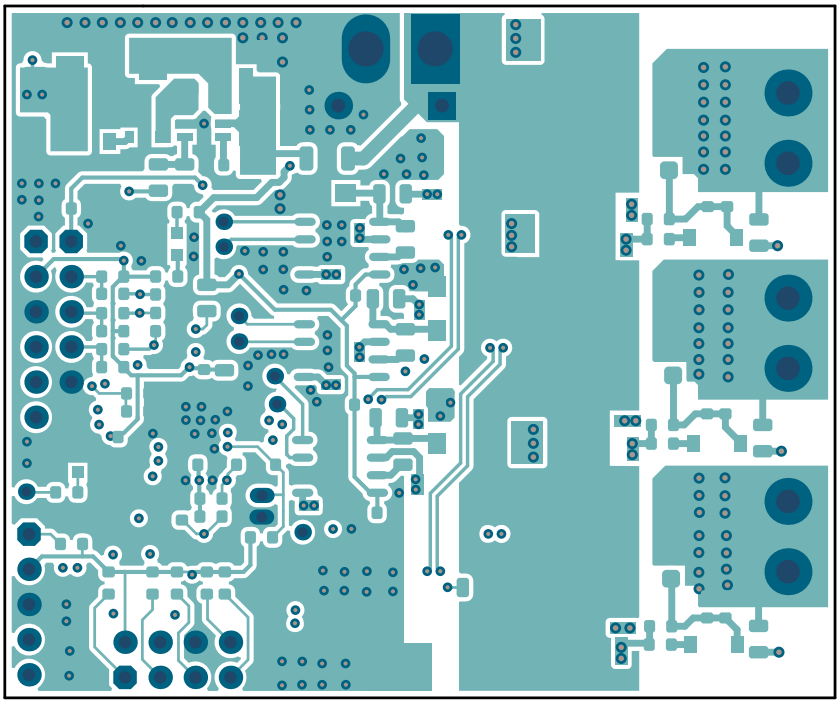
A.5 BOARD – TOP SILK



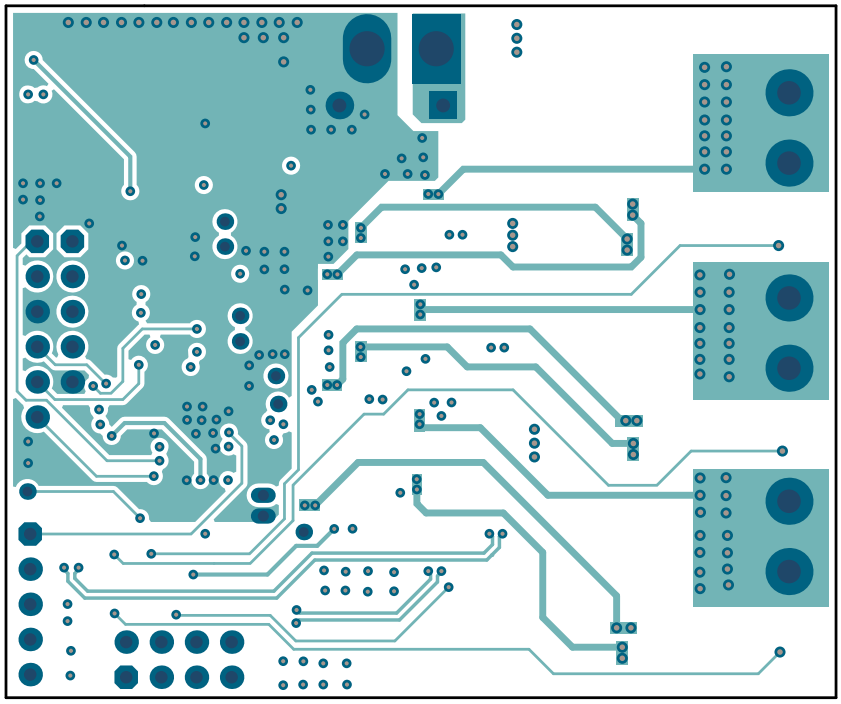
A.6 BOARD – TOP COPPER AND SILK



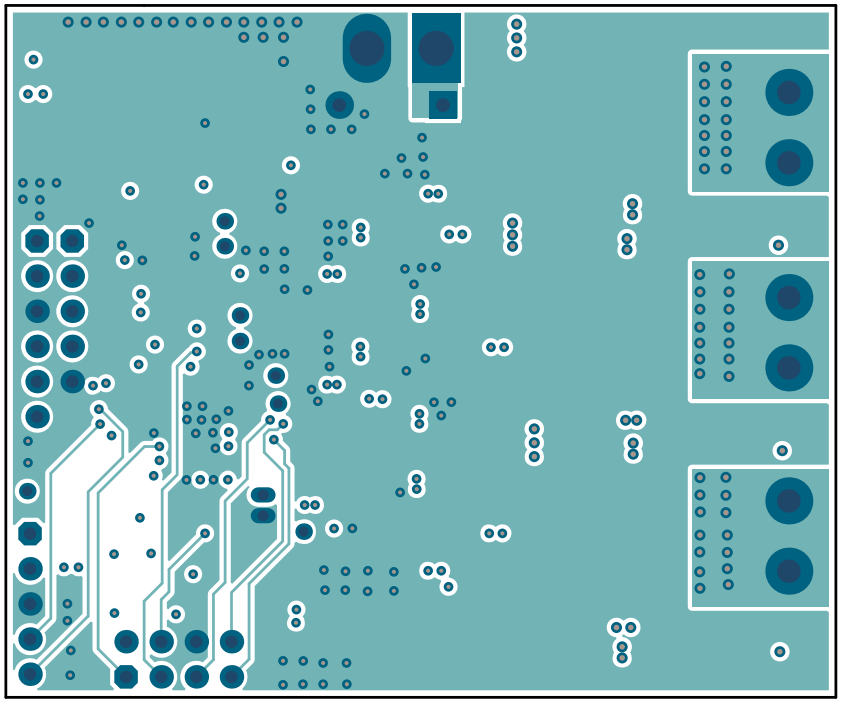
A.7 BOARD – TOP COPPER



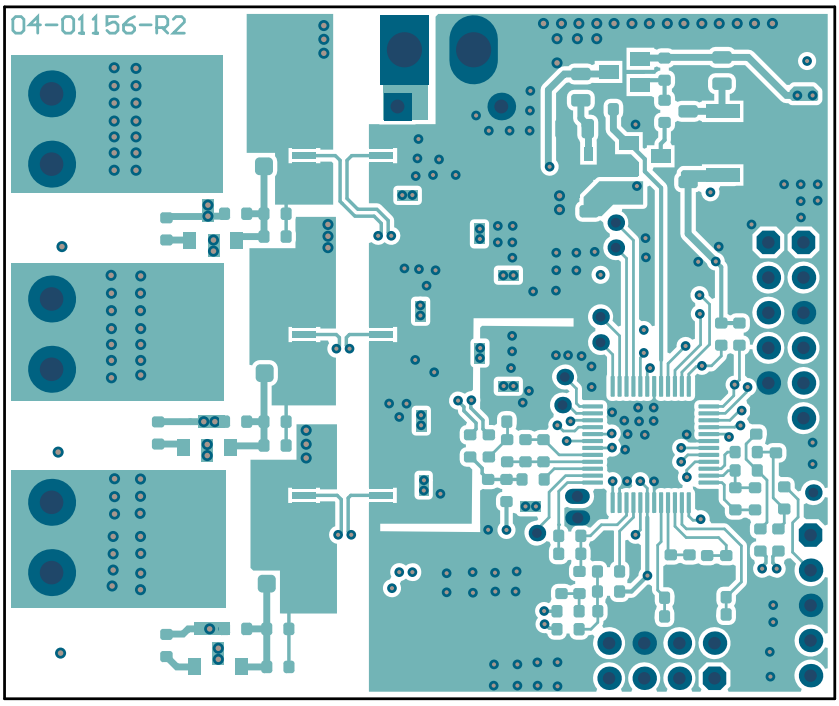
A.8 BOARD – INTERNAL COPPER 1



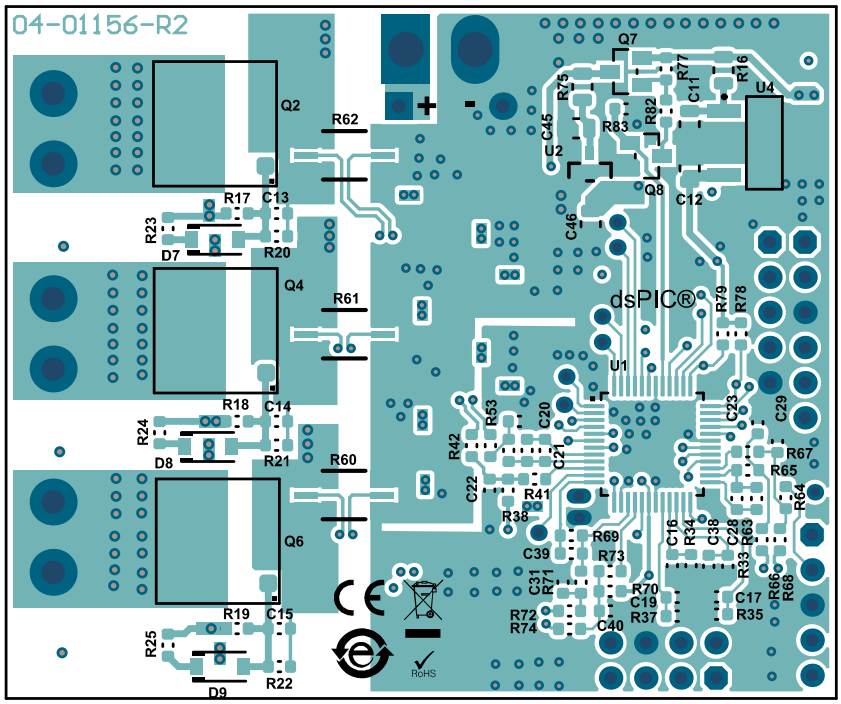
A.9 BOARD – INTERNAL COPPER 2



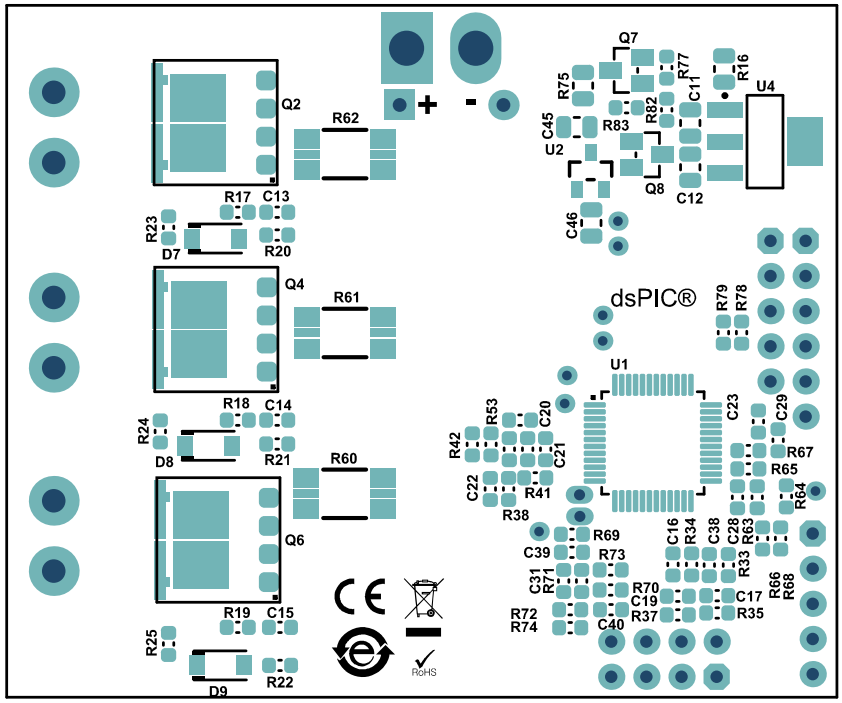
A.10 BOARD – BOTTOM COPPER



A.11 BOARD – BOTTOM COPPER AND SILK



A.12 BOARD – BOTTOM SILK



NOTES:

Appendix B. Bill of Materials (BOM)

TABLE B-1: BILL OF MATERIALS (BOM)

Qty.	Reference	Description	Manufacturer	Part Number
13	C1, C19, C25, C26, C27, C30, C32, C33, C34, C36, C44, C48, C49	Capacitor, Ceramic, 0.1 µF, 50V, 10%, X7R, AEC-Q200, SMD, 0603	Kyocera AVX	06035C104K4Z4A
1	C2	Capacitor, Ceramic, 22 µF, 25V, 10%, X5R, SMD, 1206	Murata Electronics®	GRM31CR61E226KE15L
3	C3, C4, C5	Capacitor, Ceramic, 2.2 µF, 100V, 10%, X7R, SMD, 1210	Kyocera AVX	12101C225KAT2A
2	C6, C7	Capacitor, Ceramic, 4.7 µF, 100V, 10%, X7S, SMD, 1210 AEC-Q200	Taiyo Yuden Co. Ltd.	HMK325C7475KMHPE
6	C8, C9, C10, C13, C14, C15	Capacitor, Ceramic, 1000 pF, 10%, 50V, X7R, SMD, 0603, AEC-Q200	TDK Corporation	CGA3E2X7R1H102K080AA
3	C11, C24, C45	Capacitor, Ceramic, 1 µF, 25V, 10%, X7R, SMD, 0805	Kyocera AVX	08053C105K4Z2A
2	C12, C46	Capacitor, Ceramic, 4.7 µF, 10V, 20%, X7R, SMD, 0805	TDK Corporation	C2012X7R1A475M125AC
9	C16, C17, C20, C22, C23, C29, C31, C38, C40	Capacitor, Ceramic, 1000 pF, 50V, 10%, X7R, SMD, 0603	Wurth Elektronik	885012206083
3	C18, C35, C37	Capacitor, Ceramic, 0.22 µF, 25V, 10%, X7R, SMD, 0805	Panasonic	ECJ-2YB1E224K
3	C21, C28, C39	Capacitor, Ceramic, 22 pF, 50V, 5%, NP0, SMD, 0603	Cal-Chip Electronics Inc.	GMC10CG220J50NTLF
3	C41, C42, C43	Capacitor, Ceramic, 4700 pF, 50V, 10%, X7R, SMD, 0603	KEMET	C0603C472K5RACTU
1	C47	Capacitor, Aluminum, 1200 µF, 63V, 20%, RAD, P7.5D16H31.5	Wurth Elektronik	860040780019
1	D1	Diode, Zener, MMSZ7V5T1G, 7.5V, 500 mW, SMD, SOD-123	Rochester Electronics, LLC	MMSZ7V5T1G
1	D2	Diode, RECT, 1N4148, 1V, 150 mA, 100V, SOD-323	ON Semiconductor® / Fairchild Semiconductor®	1N4148WS
1	D3	Diode, Schottky, BAT41, 1V, 200 mA, 100V, SOD-123	STMicroelectronics	BAT41ZFILM
6	D4, D6, D7, D8, D9, D14	Diode, Schottky, 1N5819HW-7-F, 450 mV, 1A, 40V, SMD, SOD-123	Diodes Incorporated®	1N5819HW-7-F
3	D5, D15, D16	Diode, Schottky, SL110PL-TP, 600 mV, 1A, 100V, SOD-123FL	Micro Commercial Components Corp. (MCC)	SL110PL-TP
1	D11	Diode, LED, Red, 2V, 30 mA, 2mcd, Clear, SMD 0603	Vishay Lite-On	LTST-C190EKT

Note 1: The components listed in this Bill of Materials are representative of the PCB assembly. The released BOM used in manufacturing uses all RoHS-compliant components.

TABLE B-1: BILL OF MATERIALS (BOM) (CONTINUED)

Qty.	Reference	Description	Manufacturer	Part Number
2	D12, D13	Diode, LED, Green, 2V, 30 mA, 35mcd, Clear, SMD, 0603	Vishay Lite-On	LTST-C191KGKT
2	J1, J2	Connector, HDR-2.54, Male, 1x5, Gold, 5.84MH, TH, Vertical	Amphenol Corporation	68000-105HLF
1	J3	Connector, HDR-2.54, Male, 2x4, Gold, 5.84MH, TH, Vertical	Wurth Elektronik	61300821121
1	J4	Connector, HDR-2.54, Male, 1x6, Gold, 5.84MH, TH, R/A	Amphenol Corporation	68016-106HLF
1	J5	Connector, Power, XT30U-M 5mm 1x2, Male, 15A, TH, Vertical	AMASS	XT30U-M
3	J6, J7, J8	Connector, Contact, QC, TAB, 0.250, Male, 1x1, TH, Vertical	TE Connectivity	1-726386-2
1	L1	Inductor, 56 µH, 0.93A, 20%, SMD, L7.3W7.3H4.5	Wurth Elektronik	7447779156
6	Q1, Q2, Q3, Q4, Q5, Q6	Transistor, FET N-CH, SQJQ466E 60V, 200A, PowerPAK, SO-8L, AEC-Q101	Vishay Precision Group (VPG)	SQJQ466E-T1_GE3
1	Q7	Transistor, FET P-CH, DMP3099L-7, -30V, -3.8A, 1.08W, SOT-23-3	Diodes Incorporated®	DMP3099L-7
1	Q8	Microchip Analog MOSFET N-CH 2N7002-G, 60V, 115 mA, SOT-23-3	Microchip Technology Inc.	**2N7002-G**
1	R1	Resistor, TF, 100k, 1%, 1/8W, SMD, 0603	Vishay Beyschlag	MCT06030C1003FP500
12	R2, R3, R4, R10, R11, R12, R17, R18, R19, R23, R24, R25	Resistor, TKF, 10R, 1%, 1/10W, SMD, 0603	Panasonic	ERJ3EKF10R0V
1	R5	Resistor, TKF, 140k, 1%, 1/8W, SMD, 0805	Vishay Precision Group (VPG)	CRCW0805140KFKEA
1	R6	Resistor, TKF, 10k, 1%, 1/8W, SMD, 0805	Panasonic	ERJ-6ENF1002V
6	R7, R8, R9, R20, R21, R22	Resistor, TKF, 47k, 1%, 1/10W, SMD, 0603	Panasonic	ERJ3EKF4702V
3	R13, R14, R15	Resistor, TKF, 2.2R, 1%, 1/8W, SMD, 0805 AEC-Q200	Vishay Precision Group (VPG)	CRCW08052R20FKEA
2	R16, R75	Resistor, TKF, 3.3R, 1%, 1/8W, SMD, 0805, AEC-Q200	Stackpole Electronics, Inc.	RMCF0805FT3R30
3	R26, R27, R28	Resistor, TKF, 39k, 1%, 1/8W, SMD, 0805	Stackpole Electronics, Inc.	RMCF0805FT39K0
6	R29, R30, R31, R52, R57	Resistor, TKF, 4.7k, 1%, 1/10W, SMD, 0603	Yageo Corporation	RC0603FR-074K7L
1	R32	Resistor, TKF, 0R, SMD, 1206	Yageo Corporation	RC1206JR-070RL
4	R33, R34, R35, R37	Resistor, TKF, 2.4k, 1%, 1/10W, SMD, 0603	Yageo Corporation	RC0603FR-072K4L
2	R36, R80	Resistor, TKF, 36k, 1%, 1/8W, SMD, 0805	Panasonic	ERJ-6ENF3602V
3	R38, R64, R70	Resistor, TKF, 13k, 1%, 1/10W, SMD, 0603	Panasonic	ERJ-3EKF1302V

Note 1: The components listed in this Bill of Materials are representative of the PCB assembly. The released BOM used in manufacturing uses all RoHS-compliant components.

TABLE B-1: BILL OF MATERIALS (BOM) (CONTINUED)

Qty.	Reference	Description	Manufacturer	Part Number
6	R39, R41, R65, R67, R71, R73	Resistor, TKF, 390R, 1%, 1/10W, SMD, 0603	Panasonic	ERJ-3EKF3900V
2	R40, R45	Resistor, TKF, 2.61k, 1%, 1/16W, SMD, 0603	Multicomp Inc.	MC0063W060312K61
6	R42, R53, R66, R68, R72, R74	Resistor, TKF, 510R, 1%, 1/10W, SMD, 0603	Vishay Precision Group (VPG)	CRCW0603510RFKEA
3	R43, R63, R69	Resistor, TKF, 11k, 1%, 1/10W, SMD, 0603	Panasonic	ERJ-3EKF1102V
6	R44, R77, R78, R79, R83	Resistor, TKF, 10k, 1%, 1/10W, SMD, 0603	Panasonic	ERJ-3EKF1002V
6	R46, R48, R49, R50, R51, R54	Resistor, TKF, 2.2k, 1%, 1/10W, SMD, 0603	Panasonic	ERJ-3EKF2201V
1	R47	Resistor, TKF, 20k, 1%, 1/10W, SMD, 0603	Panasonic	ERJ3EKF2002V
0	R58	Resistor, TKF, 4.7k, 1%, 1/10W, SMD, 0603 – DO NOT POPULATE	Vishay Precision Group (VPG)	CRCW04025R10JNEDC
1	R59	Resistor, TKF, 3.3R, 1%, 1/10W, SMD, 0603	Panasonic	ERJ-3RQF3R3V
3	R60, R61, R62	Resistor, Shunt, ME, 0.002R, 1%, 5W, AEC-Q200, SMD, 2512	Vishay/Dale	WSLF25122L000FEA
1	R76	Resistor, TKF, 3.3k, 1%, 1/10W, SMD, 0603	Vishay/Dale	CRCW06033K30FKEA
1	R81	Resistor, TKF, 7.5k, 1%, 1/10W, SMD, 0603	Panasonic	ERJ-3EKF7501V
1	R82	Resistor, TKF, 1.2k, 1%, 1/10W, SMD, 0603	Stackpole Electronics, Inc.	RMCF0603FT1K20
1	TH1	Resistor, Thermistor, NTC, Radial, 10k, TH, P2.54mm, 3988K BEAD	TDK Electronics (previously EPCOS)	B57861S0103F040
1	U1	Microchip, MCU, 16-bit, 100 MHz, 256 kB, 64 kB dsPIC33CK32MP105-I/PT TQFP-48	Microchip Technology Inc.	**dsPIC33CK32MP105-I/PT**
1	U2	Microchip, Analog, LDO 5V MCP1754ST-5002E/CB SOT-23A-3	Microchip Technology Inc.	**MCP1754ST-5002E/CB**
1	U3	Microchip, Analog, Switcher, Buck 2 to 24V, MCP16331T-E/CH SOT-23-6	Microchip Technology Inc.	**MCP16331T-E/CH**
1	U4	Microchip, Analog, LDO, 3.3V, MCP1754ST-3302E/DB SOT-223-3	Microchip Technology Inc.	**MCP1754ST-3302E/DB**
3	U5, U6, U7	Microchip, Analog, FET, Driver, Dual-Non-Inverting MIC4104 SOIC-8	Microchip Technology Inc.	**MIC4104YM**

Note 1: The components listed in this Bill of Materials are representative of the PCB assembly. The released BOM used in manufacturing uses all RoHS-compliant components.

NOTES:

Appendix C. Test Report (Waveforms)

C.1 TEST CONDITIONS

The tests on the High-Performance E-Scooter BLDC Motor Driver Reference Design were conducted in the following conditions:

- Three different motors were used. The type of the motor is specified for each waveform/parameter.
- The V_{BUS} electrolytic capacitor is 1200 µF/63V (860040780019 from Wurth Electronics).
- No active cooling solutions were used to cool the board. The board was placed in still air.
- Both operating modes, sensorless and sensored were used for tests. The operating mode is specified for each waveform/parameter.

Test equipment:

- QPX1200SP 60V/50A adjustable power supply
- Tektronix DPO3034 digital oscilloscope with TCP0030A 30A current probe
- 10S 7500 mA/h Li-Ion battery
- Magtrol TM 306/011 Torque sensor and AHB-1-4884 programmable brake

C.2 EFFICIENCY

The efficiency of the driver is measured using the Magtrol test bench with programmable brake load. The motor used during this test is EBM-PAPS M3G074-CFA4-VL and the operating mode is sensorless. This is the electrical-to-mechanical efficiency and includes all losses associated with the motor driver as well as the losses associated with the motor. Table C-1 summarizes the results.

TABLE C-1:

Parameter	Value	Units
Input voltage	39	V
Load torque	1	Nm
Output mechanical power	388	W
Efficiency	84.5	%

C.3 TYPICAL WAVEFORMS

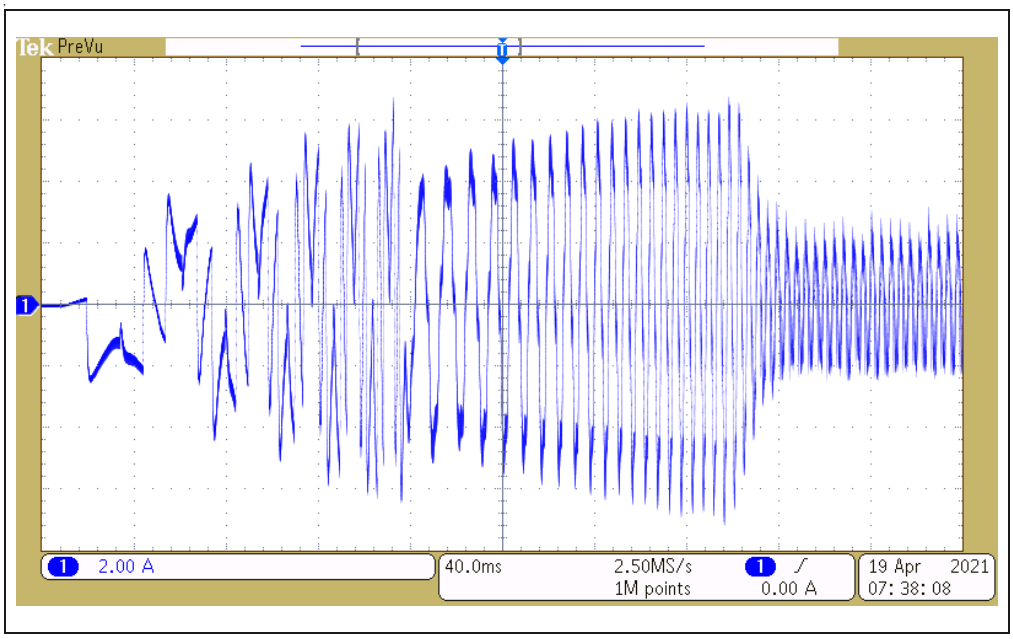


FIGURE C-1: *Start-up in Sensored Mode;*
Motor: Anahaim Automation BLY342D-24V-3000. Input Voltage is 24V..

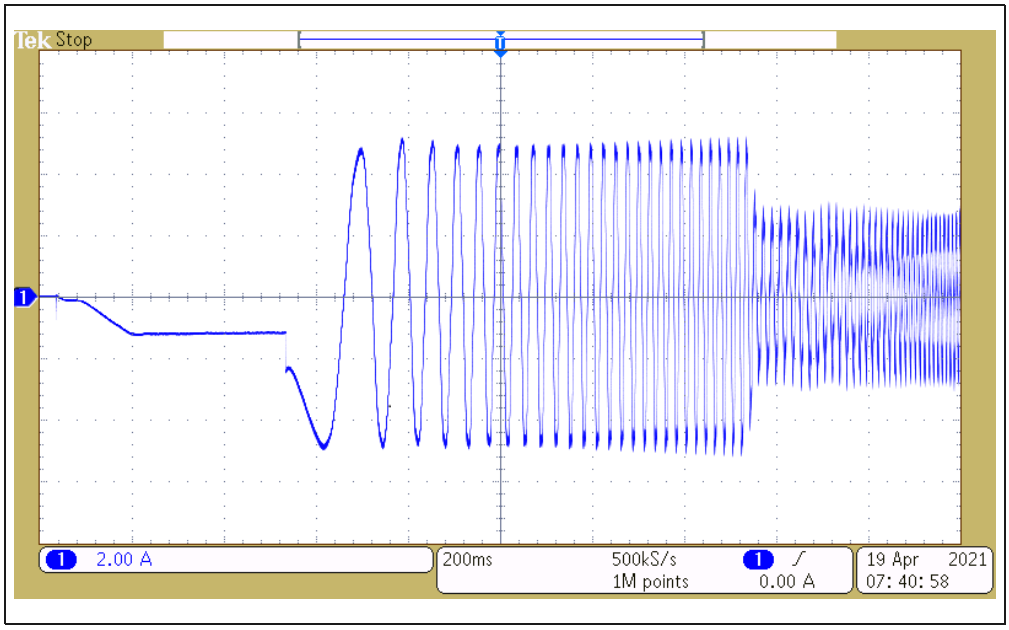


FIGURE C-2: *Start-up in Sensorless Mode.*
Motor: Anahaim Automation BLY342D-24V-3000. Input Voltage is 24V.

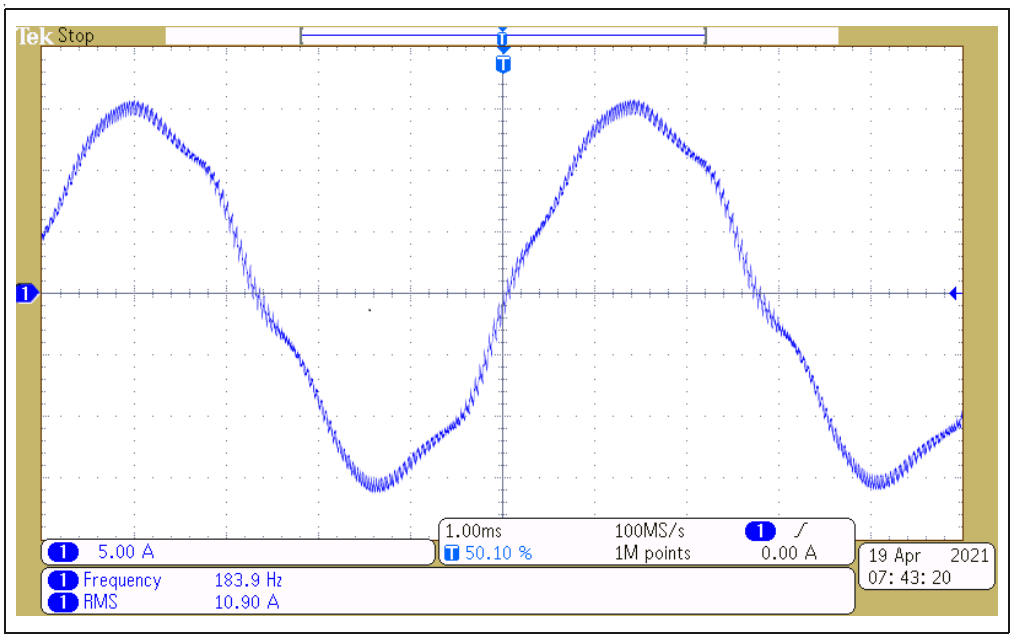


FIGURE C-3: *Phase Current in Sensored Mode;*
Motor: Anahaim Automation BLY342D-24V-3000. Input Voltage is 24V.

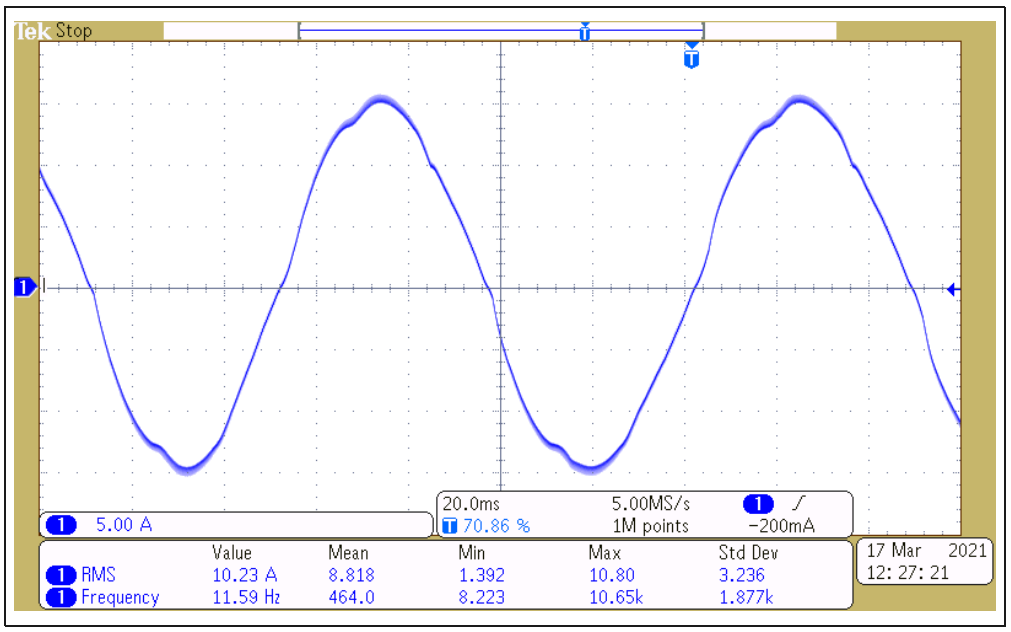


FIGURE C-4: *Phase Current in Sensored Mode;*
Motor: Anahaim Automation BLY342D-24V-3000. Input Voltage is 24V.

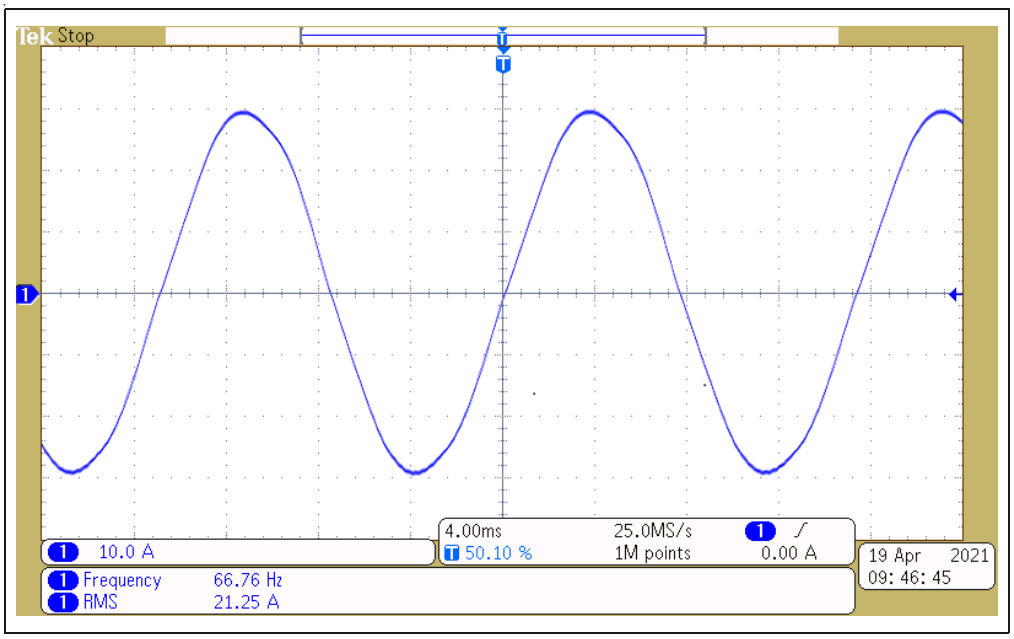


FIGURE C-5: *Phase Current in Sensored Mode;*
Motor: Hub Motor, 250W, 15 Pole Pairs. Input Voltage is 39V.

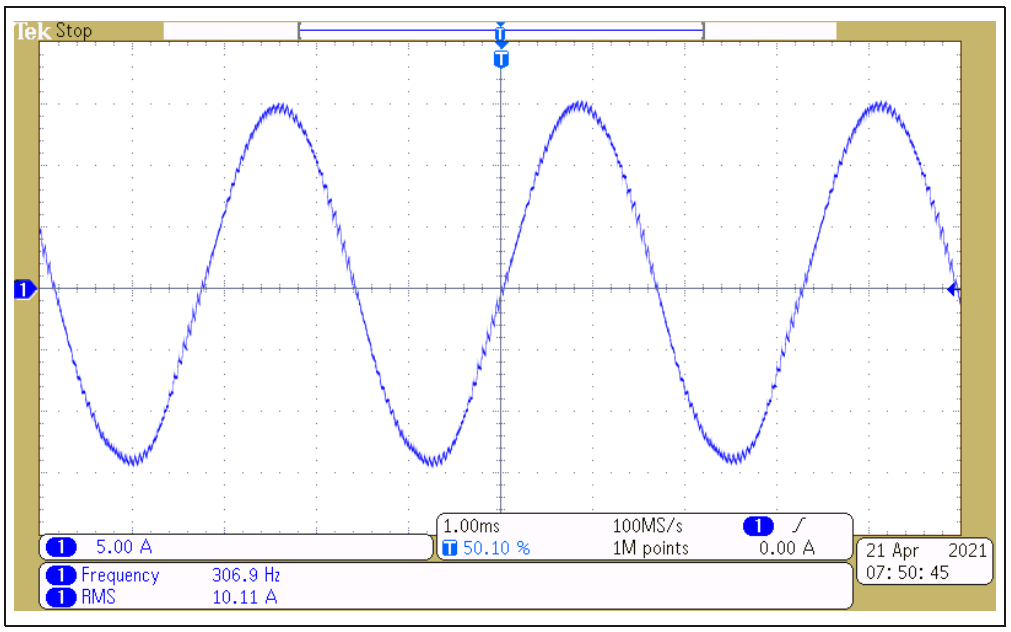


FIGURE C-6: *Phase Current in Sensorless Mode;*
Motor: EBM-PAPS M3G074-CFA4-VL. Input Voltage is 39V.

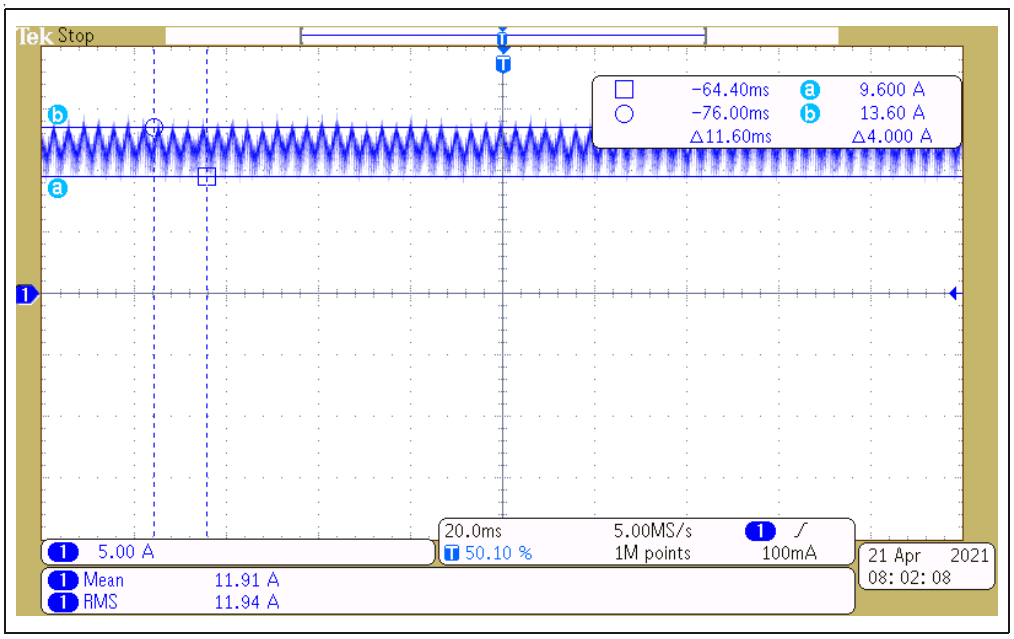


FIGURE C-7: *Input Current (DC Coupled) in Sensorless Mode. Motor: EBM-PAPS M3G074-CFA4-VL. Input Voltage is 39V. Mechanical Load is 1 Nm and Delivered Mechanical Power is 388W.*

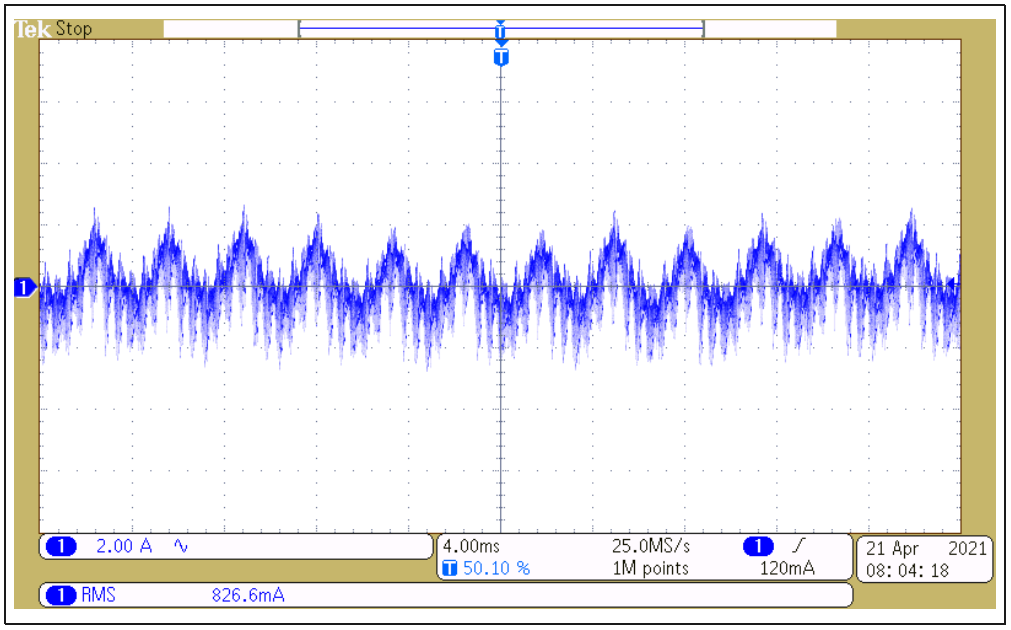


FIGURE C-8: *Input Current (AC Coupled) in Sensorless Mode. Motor: EBM-PAPS M3G074-CFA4-VL. Input Voltage is 39V. Mechanical Load is 1 Nm and Delivered Mechanical Power is 388W.*

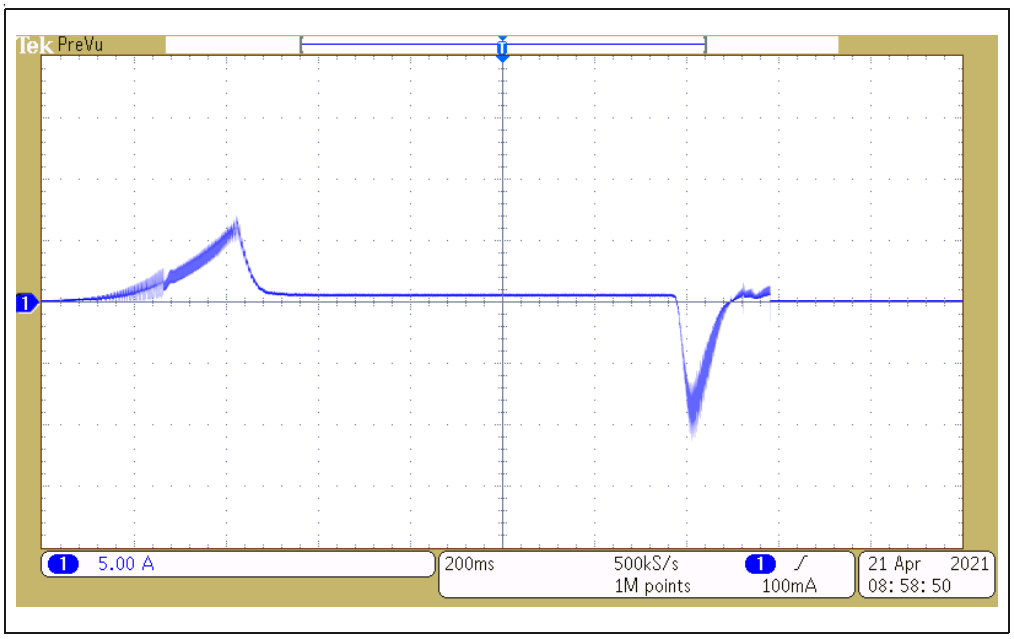


FIGURE C-9: *Input Current during Acceleration and Regenerative Braking Phases. Sensored, Constant Torque Mode.*
Motor: Hub Motor, 250W, 15 Pole Pairs. Input Voltage is 41V delivered by a 10S, 7500 mA/h Li-Ion Battery. Top Speed is 762 RPM.

C.4 THERMAL MEASUREMENTS

The thermal measurements were done using the open-loop operating mode of the motor. The thickness of the prototype board cooper layers is 1 oz. The phase current was set to 15A RMS. The input voltage was set to 39V. The thermal image of the board was taken after 15 minutes of continuous operation and is presented in Figure C-10.

FIGURE C-10: *Thermal Image of the Board.*

NOTES:

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