AN5324

High-Power BLDC Motor Driver Reference Design

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SYSTEM OVERVIEW

The "**High-Power BLDC Motor Driver Reference Design**" targets high-performance, cost-effective motor control applications, such as applications for e-mobility (e-scooters, e-motorcycles, e-boats). The "High-Power BLDC Motor Driver Reference Design" can drive BLDC/PMSM motors of up to 10 kW peak power and up to 600A peak-to-peak phase currents. The input voltage range is between 18V and 85V covering the applications powered from battery strings of up to 20S (Li-Ion cells).

Block Diagram

The "High-Power 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 half-bridge MOSFET drivers family. The board is developed to meet the stringent demands of modern motor control applications: high efficiency, compact dimensions, low cost, and high performance.

The three-phase inverter is implemented using eighteen (six on each phase) 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 driven by the **MIC4104** MOSFET drivers.

A **MCP9700** temperature sensor is used to monitor the temperature of the power MOSFETs. This offers a protection feature against overheating.

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 +5V voltage rail, necessary for HALL sensor interface, is provided by the **MCP1754S-5**.

A pre-regulator circuit is used to step down the input voltage from the maximum 85V to 43V in order to support **MCP16331** capabilities.

The digital control system uses the **dsPIC33CK256MP505** high performance 100MIPS DSC. This DSC includes three internal OPAMPs used to implement the current sense amplifiers. Also this dsPIC family does support CAN transceiver which in conjunction with **ATA6561** offer complete CAN-bus communication.

Six low-side (two in parallel), on inverter legs, shunts of 250 µΩ are used to measure the phase currents.

Several auxiliary connectors are provided for the HALL sensors and additional functionality (communication interface, CAN interface, auxiliary signals, etc.).

Key Features

- +18V to +85V **VBUS** Input Voltage Range (covers up to 20S batteries setup).
- Maximum output power: 10000W.
- 150A (continuous) and up to 300A peak (for maximum 120 seconds) motor phase current.
- Low-side shunt resistors on each inverter phase for current measurement (250 µΩ).
- PWM switching frequency range 8 kHz - 20 kHz (typical 16 kHz).
- 18 N-Channel MOSFETs with low $R_{DS(ON)}$ (typical 1.7 mΩ).
- XT90 - type connector for convenient connection with the battery packs.
- Support for HALL sensor motor control algorithms.
- Support for board temperature measurement (**MPC9700**).
- Auxiliary connectors (for custom functions like CAN, I2C, UART, THROTTLE (acceleration, programming/debug, etc.).

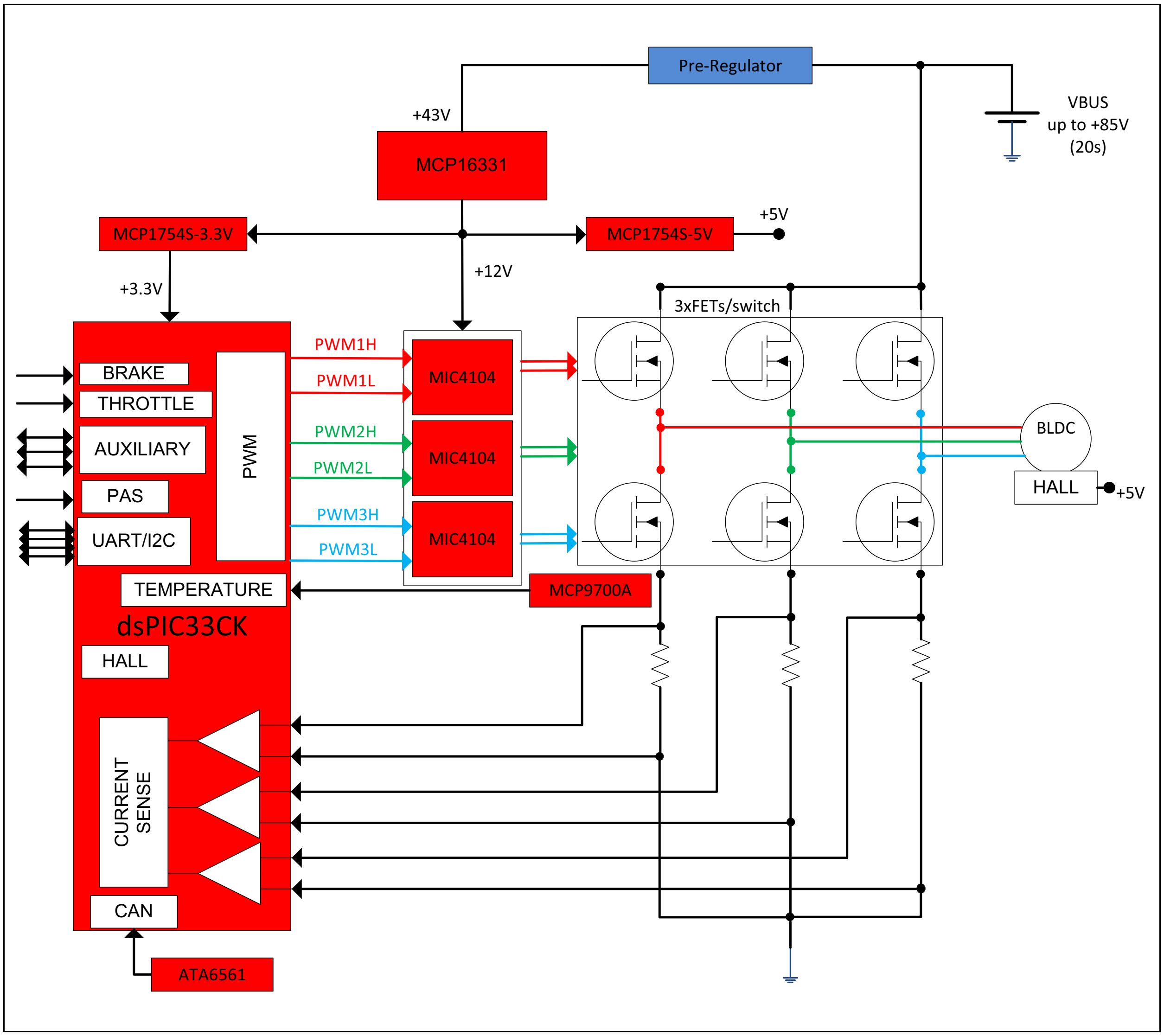

FIGURE 1: *Block Diagram.*

HARDWARE DESCRIPTION

Gate Driver – MIC4104

MIC4104 are high frequency, 100V half-bridge MOSFET drivers with 3A/2A Sinking/Sourcing current with faster turn-off characteristics. They feature fast 24 ns propagation delay times and 6 ns driver fall times.

The low-side and high-side gate drivers are independently controlled and matched to within 3 ns (typical). The **MIC4103** has CMOS input thresholds and the **MIC4104** has TTL input thresholds. The **MIC4104** includes a high-voltage internal diode that charges the high-side gate drive bootstrap capacitor.

A robust, high-speed, and low-power level shifter provides clean level transitions to the high-side output. The robust operation of the **MIC4104** ensures the outputs are not affected by supply glitches, HS ringing below ground, or HS slewing with high-speed voltage transitions.

Undervoltage protection is provided on both the low-side and high-side drivers.

The **MIC4104** also offers a wide 5.5V to 16V operating supply range to maximize system efficiency. The low 5.5V operating voltage allows longer run times in battery-powered applications. Additionally, the MIC4104's adjustable gate drive sets the gate drive voltage to VDD for optimal MOSFET $R_{DS(ON)}$, which minimizes power loss due to the MOSFET's $R_{DS(ON)}$.

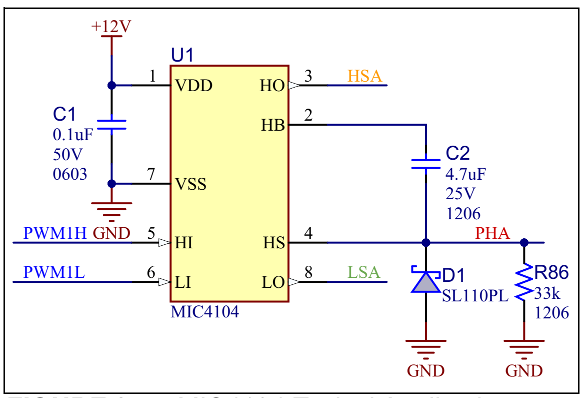

FIGURE 2: MIC4104 Typical Application.

Inverter Stage

The inverter stage is equipped with 18 AOTL66912, 100V MOSFETs with a typical $R_{DS(ON)}$ of 1.7 mΩ. Each power switch comprise of three MOSFETs in parallel to minimize the total $R_{DS(ON)}$. The gate drive circuitry controls the slew-rate of the phase node voltage ensuring a clean, ringing-free commutation for bus voltages up to 85V and phase currents up to 300A peak. A proper heat-sink is attached to the board using M3 screws and a thermal interface material. The temperature of this heat-sink must be continuously monitored using the on-board temperature sensor (**MCP9700A).**

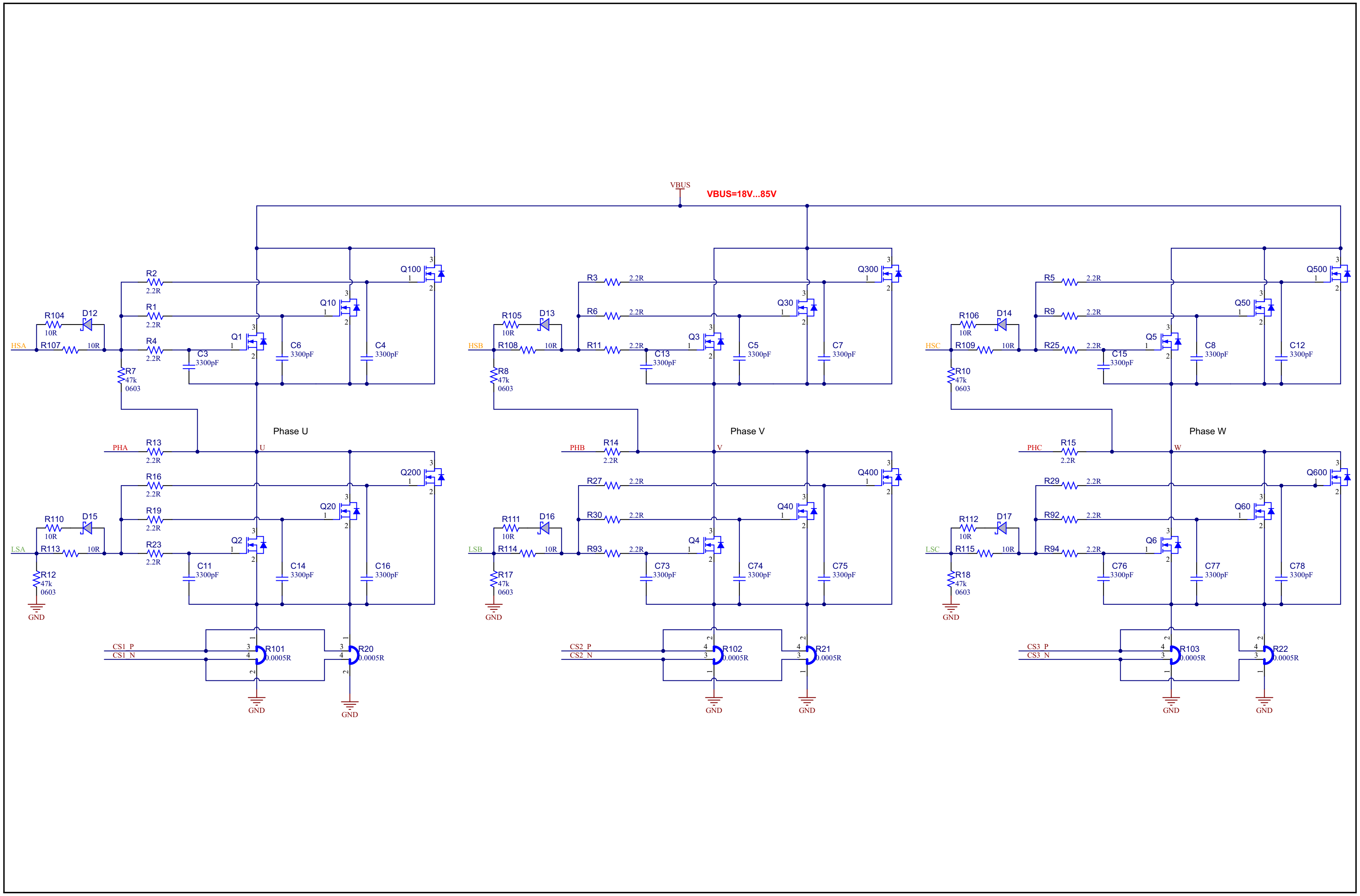

FIGURE 3: *Three Phase Inverter Stage (Three FETs on Each Switch).*

Input Voltage (VBUS)

The input voltage is supplied to the board via a XT90-M connector. The bulk capacitor comprises of four 820 µF/100V electrolytic capacitors in parallel. Additionally, six ceramic capacitors of 10 µF/100V, X7R type are place close to the inverter's legs to minimize the inductance of the current loops. A linear voltage pre-regulator is used to decrease to bus voltage from 85V down to 43V, a value necessary for the **MCP16331** buck regulator. The schematic of the voltage pre-regulator is presented in Figure 4.

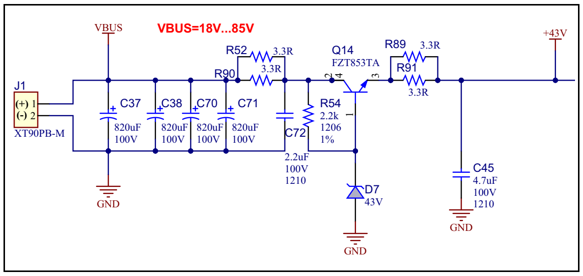

FIGURE 4: XT90 Input Voltage Connector and Pre-Regulator Section.

WARNING:

There is no reverse polarity protection implemented on this board. Catastrophic hardware failure occurs if the correct polarity is not observed!

Voltage Rails

The board can withstand a supply voltage in the range between 18V and 85V. However, to supply the DSC, gate drivers and HALL sensors of the BLDC motor, we need to provide next voltage rails:

- +12V for gate drivers
- +3.3V for DSC
- +5V for HALL sensors

MCP16331

The MCP16331 device is a highly integrated, high-efficiency, fixed-frequency, step-down DC-DC converter in a popular 6-pin SOT-23 or 8-pin 2 mm x 3 mm TDFN package, that operates from input voltage sources up to 50V. Integrated features include a high-side switch, fixed frequency Peak Current-Mode control, internal compensation, peak current limit and overtemperature protection. Only a few external components are necessary to develop a complete step-down DC-DC converter power supply.

High converter efficiency is achieved by integrating the current-limited, low-resistance, high-speed N-Channel MOSFET and its associated driving circuitry. High switching frequency minimizes the size of external filtering components, resulting in a small solution size.

The MCP16331 can supply 500 mA of continuous current while regulating the output voltage from 2.0V to 24V. An integrated, high-performance Peak Current-Mode architecture keeps the output voltage tightly regulated, even during input voltage steps and output current transient conditions that are common in power systems.

The EN input is used to turn the device on and off. While off, only a few µA of current are consumed from the input for power shedding and load distribution applications. This pin is internally pulled up, so the device will start, even if the EN pin is left floating.

Output voltage is set with an external resistor divider.

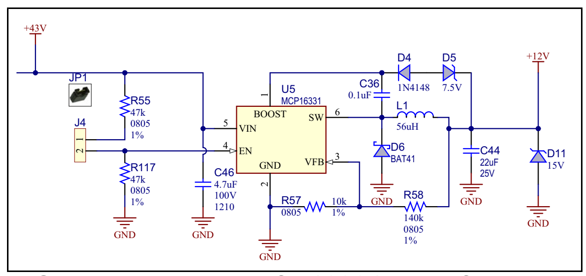

FIGURE 5: MCP16331 Buck Converter Circuit for a 43V to 12V Application.

Rails +3V3 & +5V

The MCP1754/MCP1754S is a family of CMOS low dropout (LDO) voltage regulators that can deliver up to 150 mA of current while consuming only 56 µA of quiescent current (typical). The input operating range is specified from 3.6V to 16.0V, making it an ideal choice for four to six primary cell battery-powered applications, 12V mobile applications and one to three-cell Li-Ion - powered applications.

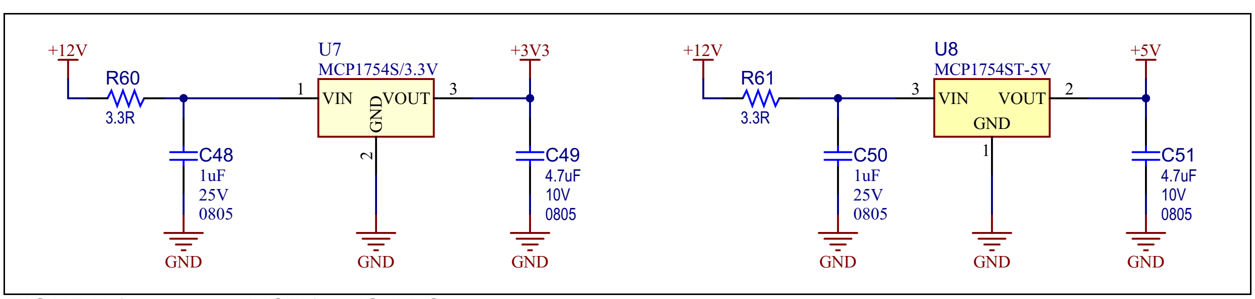

FIGURE 6: MCP1754S LDOs.

Current Sense Circuitry

The motor phase current is measured using low-side shunt resistors placed on each leg of the inverter. The signal conditioning circuitry is implemented using the DSC internal operational amplifiers and some external components. The schematic is presented in Figure 7. To minimize the effects of the noise that is produced by the power inverter, the current sense amplifiers are of differential type. Also the traces that goes to each shunt resistor are of differential type and routed accordingly on PCB. An output DC offset of 1.65V is provided by each amplifier to accommodate with the ADC range of the DSC (0V to 3.3V or -32768 to 32767).

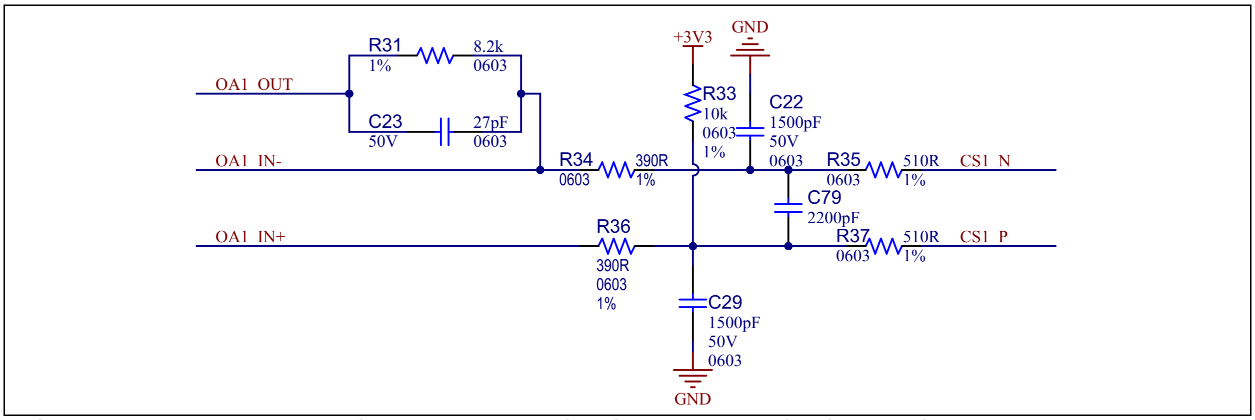

FIGURE 7: *External Operational Amplifier Circuitry Used for Current Sense.*

The gain of the differential amplifier is computed using Equation 1:

EQUATION 1:

$$Gain = \left(1 + \frac{R_{31}}{R_{34} + R_{35}}\right) \times \left(\frac{R_{33}}{R_{37} + R_{33}}\right)$$

$$Gain \simeq 11$$

The voltage drop on the shunt resistor will be:

EQUATION 2:

$$U_{sh} = \frac{V_{out}}{Gain} = \frac{1.65V}{11} \simeq 150\ mV$$

Since the value of the shunt resistor is 0.25 mΩ, the full range phase current is computed using the Equation 3:

EQUATION 3:

$$I_{peak} = \frac{U_{sh}}{R_{sh}} = \frac{150\ mV}{0.25\ m\Omega} = 600A$$

The maximum current that can be sensed by this amplifier is 600A. Due to the maximum dissipated power of the inverter, the maximum phase current of the motor is limited to 300A peak.

Temperature

As a safety feature, temperature monitoring is a must. In this sense, **MCP9700A** has been successfully implemented in the design.

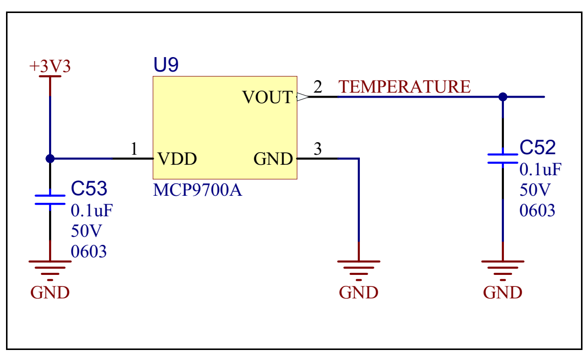

FIGURE 8: *Temperature Monitoring Example Using **MCP9700A**.*

Interfaces

J5 header is assembled on the board with the main purpose of external interface. We can control the motor speed (THROTTLE) using an external classic potentiometer or a dedicated throttle key.

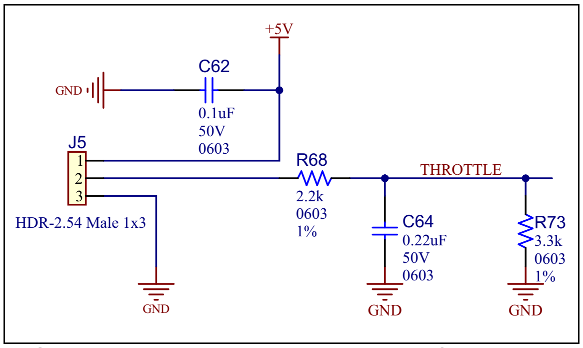

FIGURE 9: *Throttle Key J5 Connector.*

With J9, the rest of AUX signals can be used for different functions in any custom utilization.

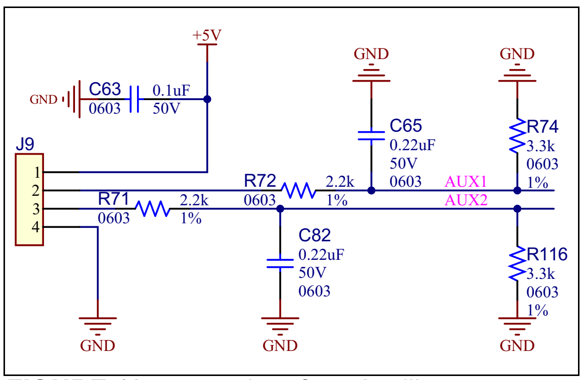

FIGURE 10: *Interface Auxiliary Connector.*

HALL SENSORS INTERFACE

J6 header is used as interface to BLDC motor HALL sensors, powered at 5V rail (Figure 11).

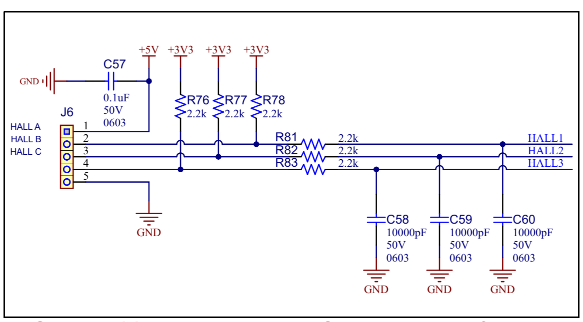

FIGURE 11: *HALL Sensors Interface.*

CAN INTERFACE

The interface between a Controller Area Network (CAN) protocol controller and the physical Two-Wire CAN bus is realized through high speed CAN transceiver **ATA6561**. The transceiver is designed for high-speed (up to 5 Mbps) CAN applications in the automotive industry, providing differential transmit and receive capability to **dsPIC33CK256MP505**, a CAN protocol controller.

It offers improved electromagnetic compatibility (EMC) and ESD performance as well as features such as:

- Ideal passive behavior to the CAN bus when the supply voltage is off.
- Direct interfacing to microcontrollers with supply voltages from 3V to 5V.

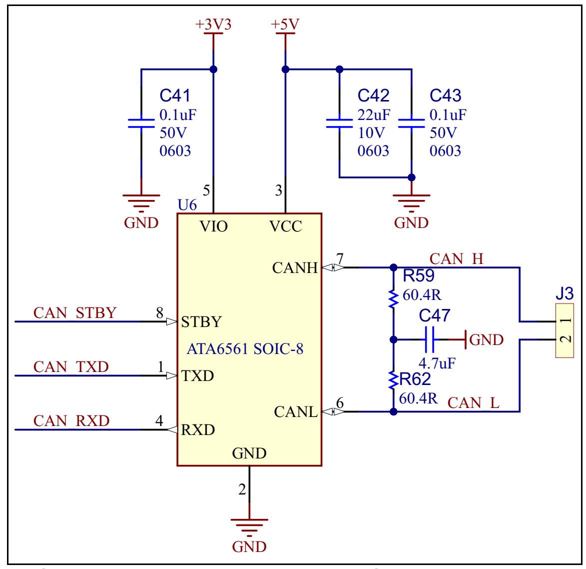

FIGURE 12: ***ATA6561*** *CAN Transceiver.*

INSTALLATION AND OPERATION

The "High-Power 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 continuous 500A peak phase current in a voltage range between 18V and 85V.

The input voltage (+18V to +85V) is applied to the board via J1 connector (XT90U-M type). The motor is connected to the driver using three cables mounted on the board (A, B, C). The motor's HALL sensors are connected to J6 using a 5-pin header connector.

A programming 5-pin, 2.54 mm header connector, (J8) is available for updating the firmware contained in the **dsPIC33CK** DSC using a PICkit™ programmer/debugger.

For UART and I2C external communication, the user has the possibility to attach a 6-pin header connector (J7) to use a Serial Communication interface. Rx,Tx, SCL, SDA, +3.3V and GND signals are available.

Throttle key, or a simple 3-wire potentiometer, for speed regulation can be connected to J5.

Similar headers connectors are used as interfaces for AUXILIARY (J9), EBRAKE (J10) and MOTOR TEMPERATURE (J11) functions.

The "High-Power BLDC Motor Driver Reference Design" provides indicator LED for Fault status indication (D10).

The temperature of the board can be monitored using **MCP9700A** (U9) 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, 200 x 100 mm, +18V to +85V input VBUS voltage, high-current small board.

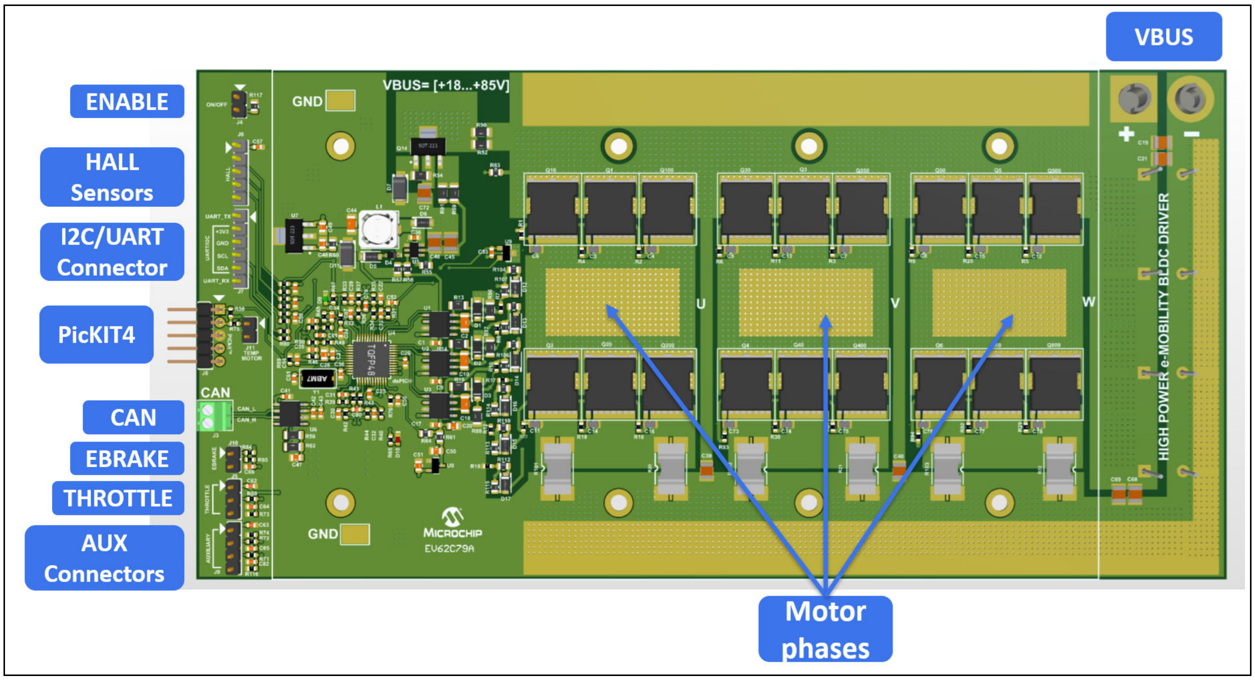

FIGURE 13: *Top View of the Board.*

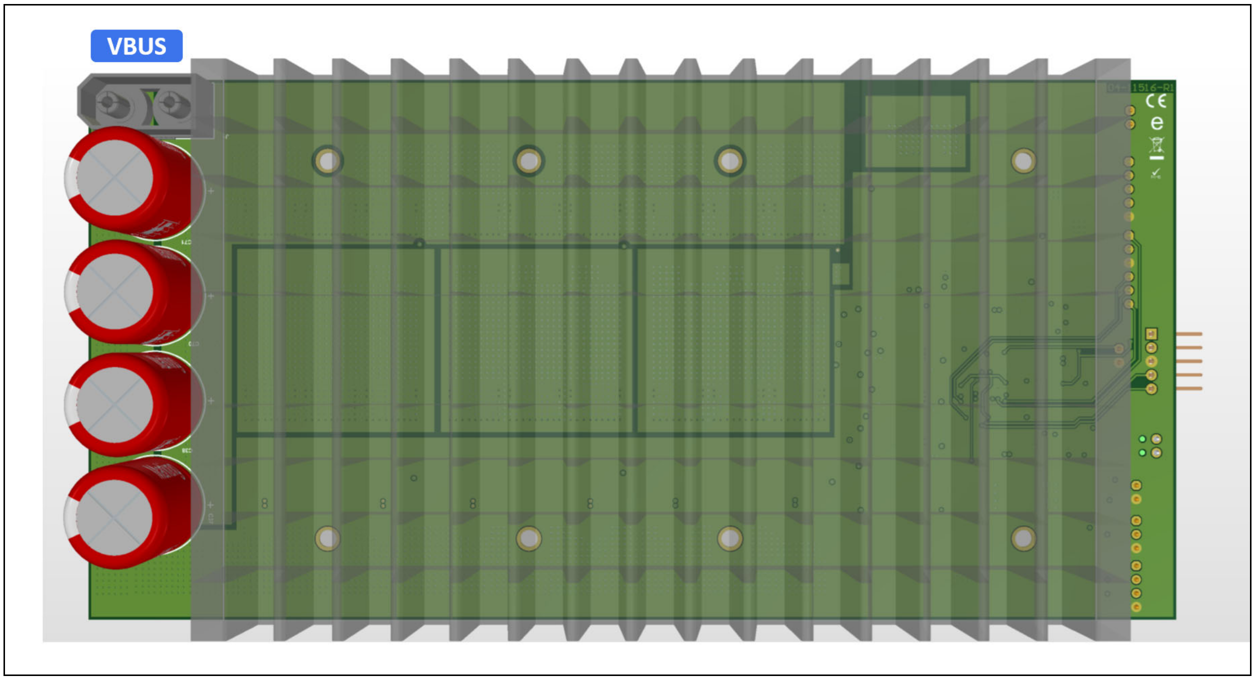

FIGURE 14: Bottom View of the Board.

Setup Procedure

To power up the “High-Power 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. Taking into account polarity: connect the power supply to the XT90, J1 connector board, and select a voltage input range between 18V - 84V.
3. Taking into account polarity: connect the MOTOR HALL sensors to the J6 connector on the board (see Figure 13).
4. Taking into account polarity: connect the throttle key to the J5 (see Figure 13).
5. Power up the board.
6. Perform the specific calibration/tuning for the motor.
7. Start motor spinning using the potentiometer.

Programming/Debugging

For a fast evaluation of the motor driver, the board is equipped by default with the firmware for the **EeZeeFOC BLDC Motor Control Graphical User Interface (DS00005331).**

The user has the option to develop a specific motor control application using the latest tools provided by Microchip. These tools are available here: https://www.microchip.com/en-us/solutions/motor-control-and-drive.

The **PICkit 4** Programmer/Debugger should be connected to the J4 connector on the board, taking into account polarity (pin 1 of the J6 is marked on the board).

TEST REPORT

Instruments and Tools

The following instruments and tools are needed:

- 20S Li-Io or Li-PO Battery, or compatible power supply 85V/250A DC range output capability.
- 72V/10000W 3 phase BLDC Motor with HALL sensors.
- A dynamometer stand to load the motor during test (optional). If this device is not available, the driver can be tested using the open-loop operation mode.
- A 10 kΩ potentiometer or compatible throttle key used for motor speed or current regulation.
- Wires for connections; these wires must support high current:
  - 250A peak for the connection between the adjustable DC Power Supply and the board.
  - 600A peak for the connection cables between the board and the motor phases.
- **PICkit 4** for programming/debugging the application.
- ADM00559 - MCP2221A BREAKOUT MODULE (UART interface to GUI).
- Computer with **MPLAB X IDE** or **MPLAB X IPE** installed.
- Digital oscilloscope, multimeter.

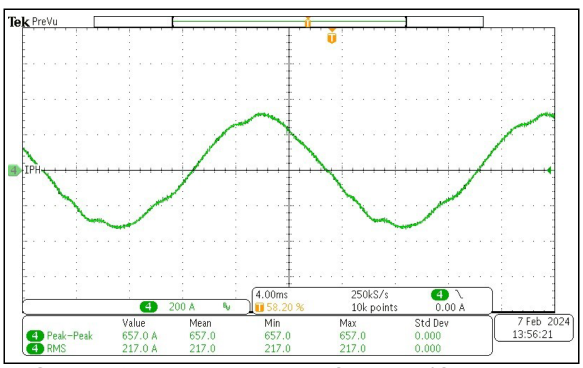

FIGURE 15: *Phase Current (Open Loop Test).*

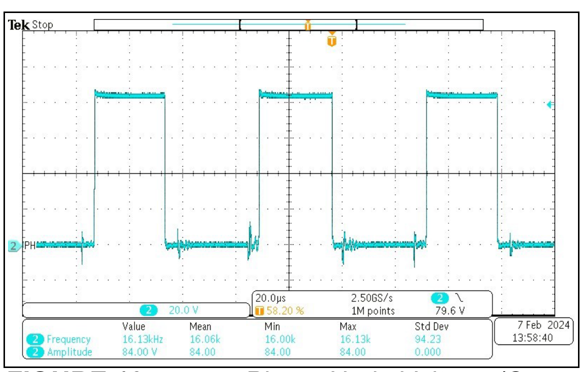

FIGURE 16: *Phase Node Voltage (Open Loop, 300A Peak Phase Current).*

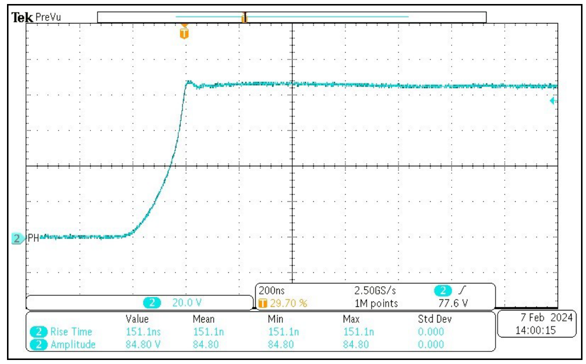

FIGURE 17: *Rising Edge of the Phase Node Voltage (Open Loop, 300A Peak Phase Current).*

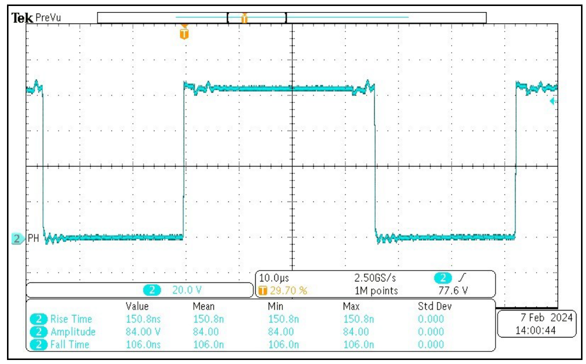

FIGURE 18: *Phase Node Voltage (Open Loop, 300A Peak Phase Current).*

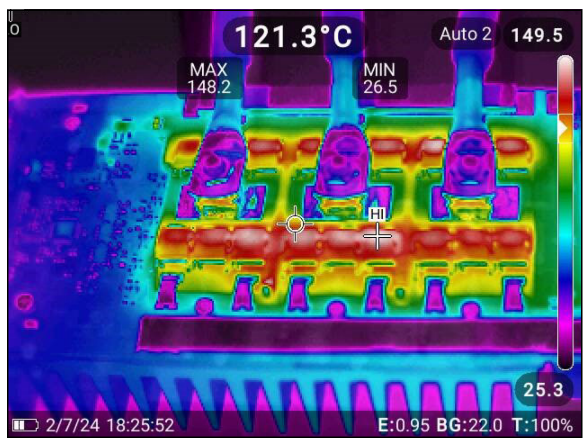

FIGURE 19: *Board Temperature after 2 Minutes Operating at 300A motor Phase Current.*

CONCLUSIONS

With its low form factor, low cost and high performance, the **High-Power BLDC Motor Driver Reference Design** is very well suited for modern e-mobility motor control applications, like E-scooters and E-bikes. Additionally, it can be used to drive the BLDC motors of high power drones and UAVs.

REFERENCES

1. MIC4104 Data Sheet – *"100V Half-Bridge MOSFET Drivers with 3A/2A Sinking/Sourcing Current"*
2. MCP16331 Data Sheet – *"High-Voltage Input Integrated Switch Step-Down Regulator"* (DS20005308)
3. MCP1754 Data Sheet – *"150 mA, 16V, High-Performance LDO"* (DS20002276)
4. MCP9700A Data Sheet – *"Low-Power Linear Active Thermistor ICs"* (DS20001942)
5. ATA6561 Data Sheet – "*High-Speed CAN Transceiver with Standby Mode CAN FD Ready"* (DS20005991)
6. dsPIC33CK256MP505 Data Sheet – *"28/36/48/64/80-Pin Digital Signal Controllers with High-Resolution PWM and CAN Flexible Data (CAN FD)* (DS70005349)

SCHEMATICS

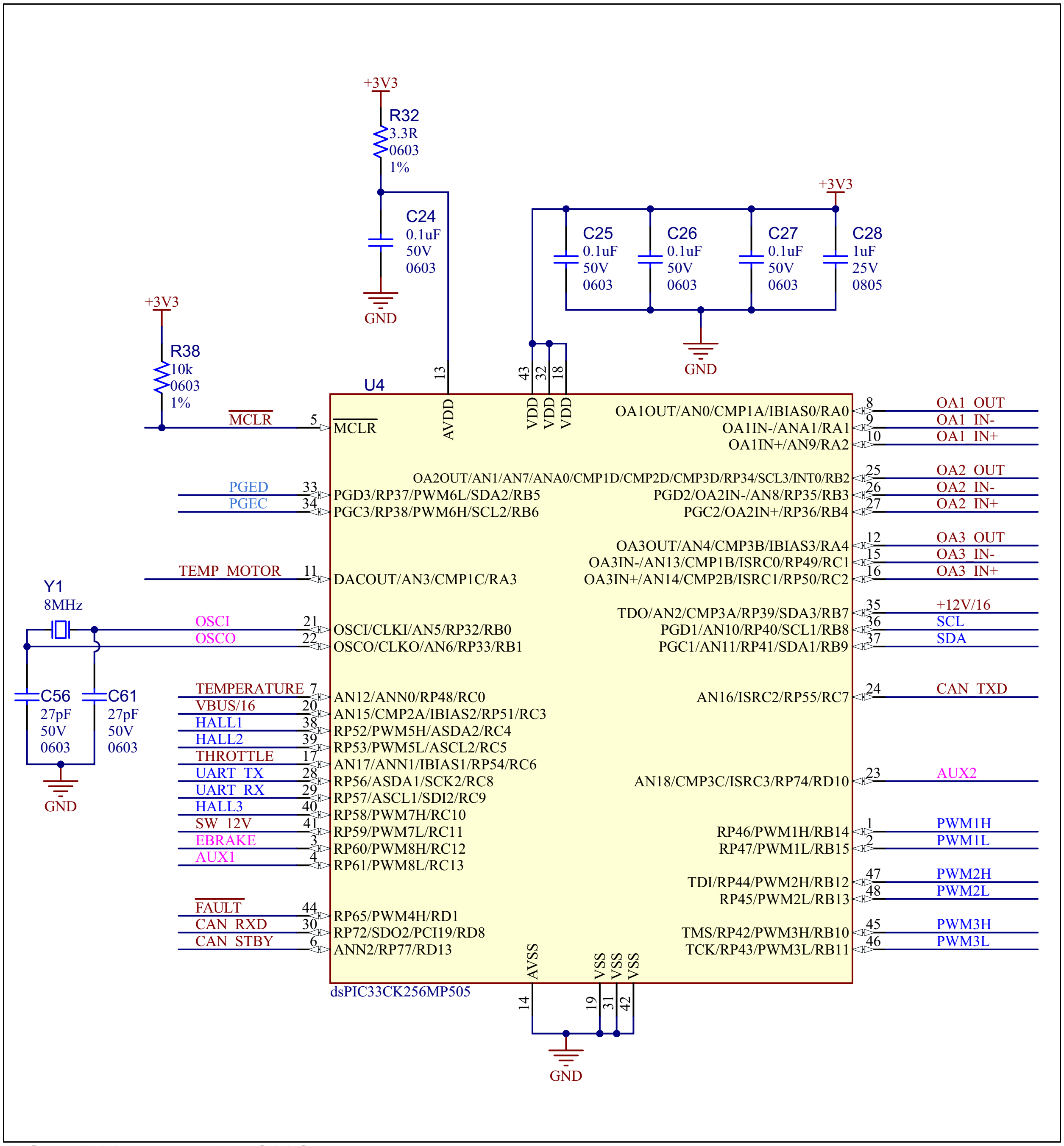

FIGURE 20: *dsPIC33CK.*

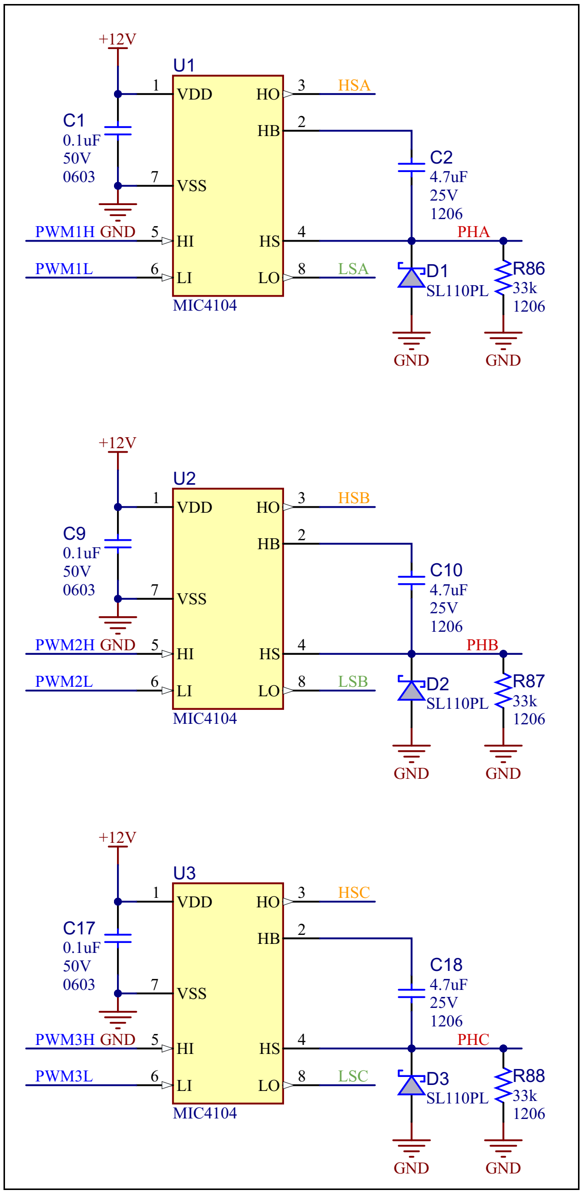

FIGURE 21: *Gate Drivers.*

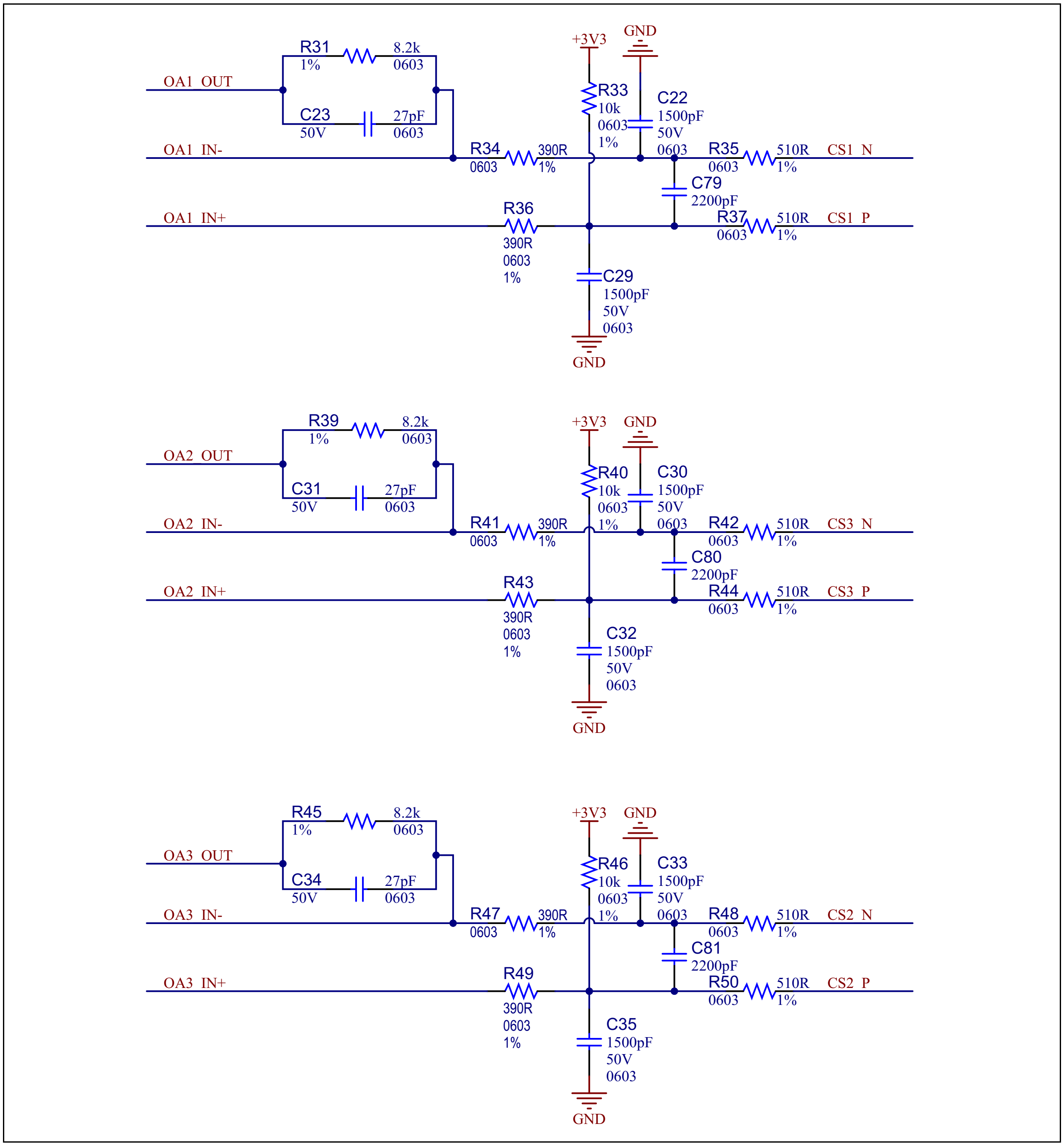

FIGURE 22: *Current Sense.*

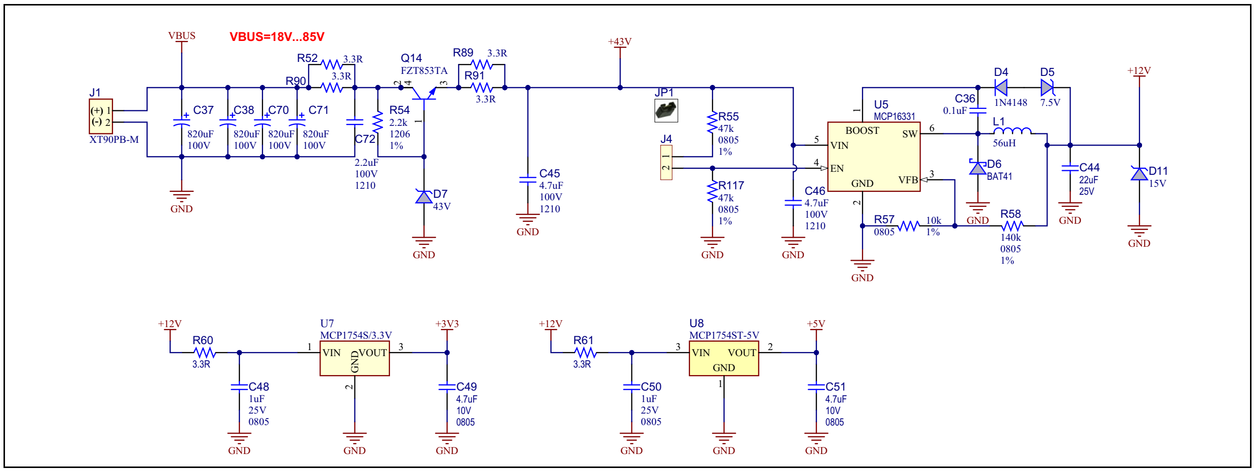

FIGURE 23: Power Supply.

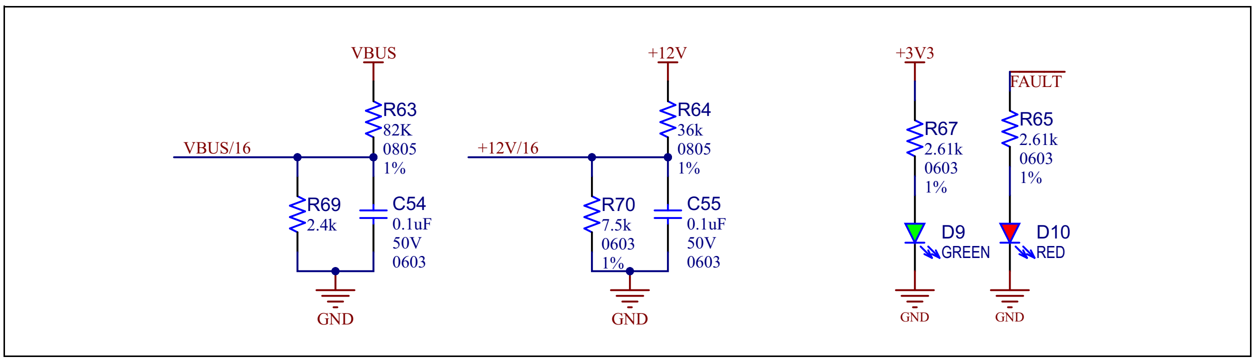

FIGURE 24: Voltage Monitoring.

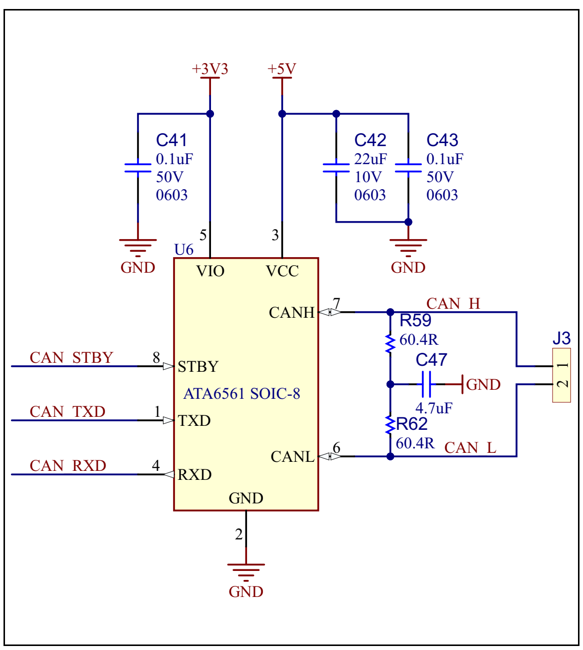

FIGURE 25: CAN.

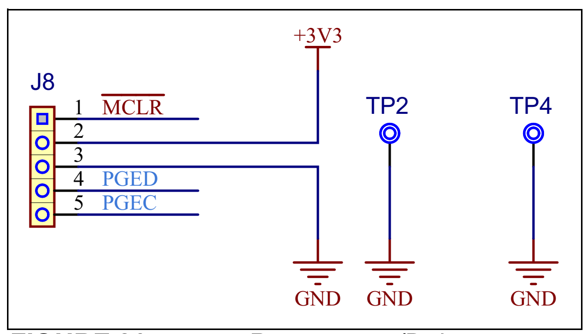

FIGURE 26: Programmer/Debug.

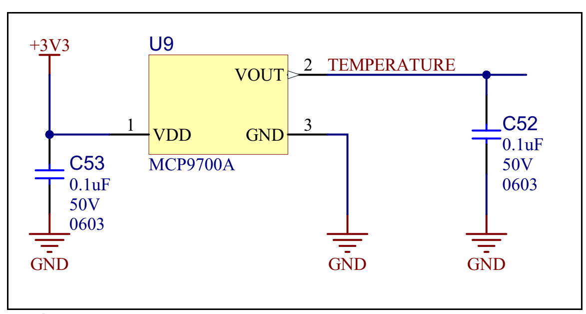

FIGURE 27: Temperature.

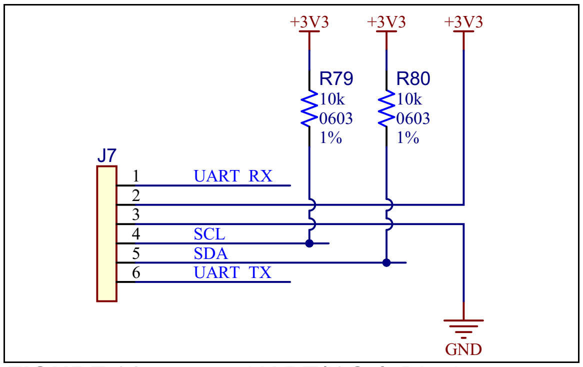

FIGURE 28: *UART/I2C & Display.*

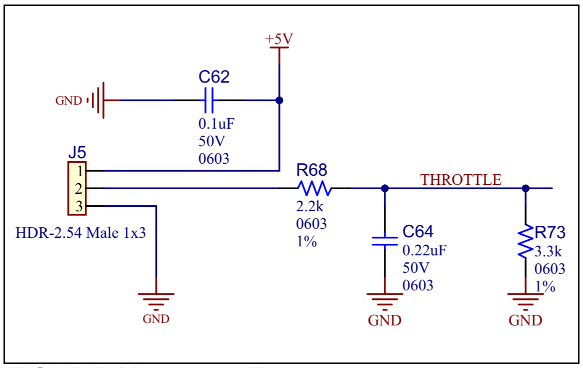

FIGURE 29: *Throttle.*

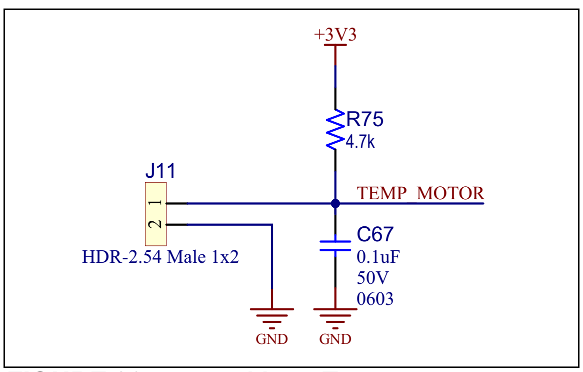

FIGURE 30: *Motor Temperature.*

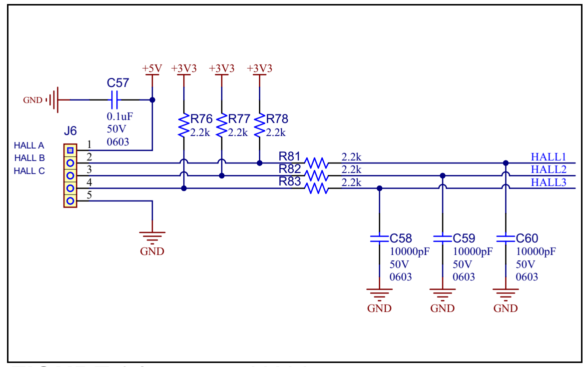

FIGURE 31: *HALL.*

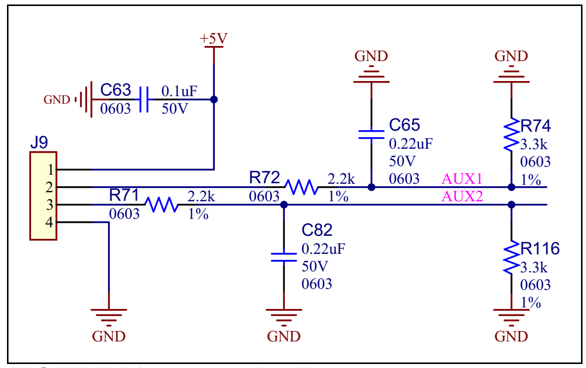

FIGURE 32: *Auxiliar.*

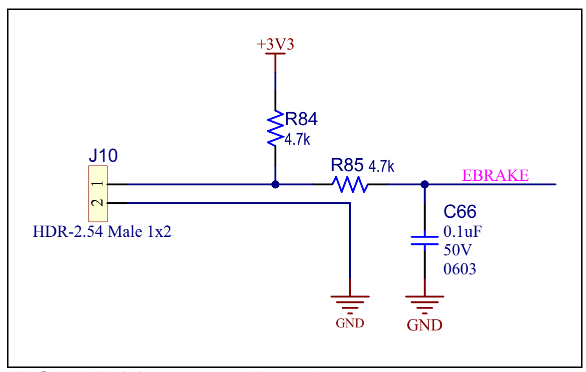

FIGURE 33: *E-brake.*

BILL OF MATERIALS

TABLE 1-1: BILL OF MATERIALS (BOM)

Qty.	Reference	Description	Manufacturer	Manufacturer Part Number
18	C1, C9, C17, C24, C25, C26, C27, C36, C41, C43, C53, C54, C55, C57, C62, C63, C66, C67	Capacitor, Ceramic, 0.1 µF, 50V, 10%, X7R, AEC-Q200, SMD, 0603	Kyocera AVX	06035C104K4Z4A
3	C2, C10, C18	Capacitor, Ceramic, 4.7 µF, 50V, 10%, X7R, SMD, 1206	Murata Electronics North America, Inc.	GRM31CR71H475KA12L
18	C3, C4, C5, C6, C7, C8, C11, C12, C13, C14, C15, C16, C73, C74, C75, C76, C77, C78	Capacitor, Ceramic, 3300 pF, 50V, 5%, NP0, SMD, 0805	Würth Elektronik	885012007066
7	C19, C21, C39, C40, C68, C69, C72	Capacitor, Ceramic, 2.2 µF, 100V, 10%, X7R, SMD, 1210	Kyocera AVX, KEMET	12101C225KAT2A, C1210C225K1RAC
1	C20	Capacitor, Ceramic, 1 µF, 25V, 10%, X5R, SMD, 0805	Murata Electronics North America, Inc.	GRM216R61E105KA12D
6	C22, C29, C30, C32, C33, C35	Capacitor, Ceramic, 1500 pF, 50V, 5%, C0G, SMD, 0603	Murata Electronics North America, Inc.	GRM1885C1H152JA01D
5	C23, C31, C34, C56, C61	Capacitor, Ceramic, 27 pF, 50V, 5%, NP0, SMD, 0603	KEMET	C0603C270J5GACTU
3	C28, C48, C50	Capacitor, Ceramic, 1 µF, 25V, 10%, X7R, SMD, 0805	Kyocera AVX	KAF21KR71E105KU
4	C37, C38, C70, C71	Capacitor, Aluminum, 820 µF, 100V, 20%, 0.13R, RAD, P7.5D18H41	Würth Elektronik	860040881014
1	C42	Capacitor, Ceramic, 22 µF, 10V, 20%, X5R, SMD, 0603	TDK Corporation	C1608X5R1A226M080AC
1	C44	Capacitor, Ceramic, 22 µF, 25V, 10%, X5R, SMD, 1206	Murata Electronics North America, Inc.	GRM31CR61E226KE15L
2	C45, C46	Capacitor, Ceramic, 4.7 µF, 100V, 10%, X7S, SMD, 1210, AEC-Q200	Taiyo Yuden Co., Ltd.	HMK325C7475KMHPE
1	C47	Capacitor, Ceramic, 4.7 µF, 50V, 10%, X5R, SMD, 0805	TDK Corporation	C2012X5R1H475K125AB
2	C49, C51	Capacitor, Ceramic, 4.7 µF, 10V, 20%, X7R, SMD 0805	TDK Corporation	C2012X7R1A475M125AC
1	C52	Capacitor, Ceramic, 0.1 µF, 50V, 10%, X7R, SMD, 0603, AEC-Q200	Vishay Intertechnology, Inc.	GA0603Y104KBAAT31G
3	C58, C59, C60	Capacitor, Ceramic, 10000 pF, 50V, 5%, X7R, SMD, 0603	KEMET	C0603C103J5REC7411
3	C64, C65, C82	Capacitor, Ceramic, 0.22 µF, 50V, 10%, X7R, SMD, 0603, AEC-Q200	TDK Corporation	CGA3E3X7R1H224K080AB

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

Qty.	Reference	Description	Manufacturer	Manufacturer Part Number
3	C79, C80, C81	Capacitor, Ceramic, 2200 pF, 25V, 5%, X7R, SMD, 0603	Kyocera AVX	KAM15AR71E222JT
3	D1, D2, D3	Diode, Schottky, 600 mV, 1A, 100V, SOD-123FL	Micro Commercial Components (MCC)	SL110PL-TP
1	D4	Diode, Rectifier, 1V, 150 mA, 100V, SOD-323	ON Semiconductor®	1N4148WS
1	D5	Diode, Zener, 7.5V, 500 mW, SMD, SOD-123	ON Semiconductor®	MMSZ7V5T1G
1	D6	Diode, Schottky, 1V, 200 mA, 100V, SOD-123	STMicroelectronics	BAT41ZFILM
1	D7	Diode, Zener, 43V, 3W, DO-214AC	Vishay Intertechnology, Inc.	BZG03C43-HM3-08
1	D9	Diode, LED, Green, 2V, 30 mA, 35 mcd, Clear, SMD, 0603	Lite-On®, Inc.	LTST-C191KGKT
1	D10	Diode, LED, Red, 2V, 30 mA, 2 mcd, Clear, SMD, 0603	Lite-On®, Inc.	LTST-C190EKT
1	D11	Diode, Zener, 15V, 1.5W, SMD, DO-214AC, SMA	ON Semiconductor®	BZG03C15G
6	D12, D13, D14, D15, D16, D17	Diode, Schottky, 530 mV, 1A, 60V, SMD, SOD-123	NXP Semiconductors	PMEG6010ER,115
1	J1	Connector, Terminal, 11 mm, 1x2, Male, DC, 500V, 40A, TH	Changzhou Amass Electronics Co. Ltd	XT90PB-M
1	J3	Connector, Terminal, 2.54 mm, 1x2, Female, 20-30AWG, 6A, TH, R/A	Degson Electronics Co., Ltd.	DG308-2.54-02P-14-00A(H)
1	J4	Connector, HDR-2.54, Male, 1x2, Gold, 5.84 MH, TH, VERT	FCI	68001-202HLF
1	J5	Connector, HDR-2.54, Male, 1x3, Gold, 6.0 MH, TH, VERT	Jameco® Electronics	7000-1X3SG-R
1	J6	Connector, HDR-2.54, Male, 1x5, Gold, 5.84 MH, TH, VERT	FCI	68000-105HLF
1	J7	Connector, HDR-2.54, Male, 1x6, Tin, 5.84 MH, TH, VERT	Würth Elektronik	61300611121
1	J8	Connector, HDR-2.54, Male, 1x5, Gold, 6 MH, TH, R/A	Würth Elektronik	61300511021
1	J9	Connector, HDR-2.54, Male, 1x4, Gold, 5.84 MH, TH, VERT	Samtec, Inc.	TSW-104-07-G-S
2	J10, J11	Connector, HDR-2.54, Male, 1x2, Gold, 5.84 MH, TH, VERT	Würth Elektronik	61300211121
1	L1	Inductor, 56 µH, 0.93A, 20%, SMD, L7.3W7.3H4.5	Würth Elektronik	7447779156

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

Qty.	Reference	Description	Manufacturer	Manufacturer Part Number
18	Q1, Q2, Q3, Q4, Q5, Q6, Q10, Q20, Q30, Q40, Q50, Q60, Q100, Q200, Q300, Q400, Q500, Q600	Transistor, MOSFET, N-Channel, 100V, 380A, TOLLA-8	Alpha & Omega Semiconductor	AOTL66912
1	Q14	Transistor, BJT, NPN, 100V, 6A, 3W, SOT223	Diodes Incorporated®	FZT853TA
18	R1, R2, R3, R4, R5, R6, R9, R11, R16, R19, R23, R25, R27, R29, R30, R92, R93, R94	Resistor, Thick Film, 2.2R, 1%, 1/10W, SMD, 0603, AEC-Q200	Yageo Corporation	AF0603FR-072R2L
6	R7, R8, R10, R12, R17, R18	Resistor, Thick Film, 47k, 1%, 1/10W, SMD, 0603	Panasonic® - ECG	ERJ-3EKF4702V
3	R13, R14, R15	Resistor, Thin Film, 2.2R, 1%, 1/2W, SMD, 1206	Susumu Co., Ltd.	RL1632R-2R20-F
6	R20, R21, R22, R101, R102, R103	Resistor, Shunt, ME, 0.0005R, 1%, 9W, SMD, 3920, AEC-Q200	Bourns®, Inc.	CSS2H-3920R-L500F
3	R31, R39, R45	Resistor, Thick Film, 8.2k, 1%, 1/10W, SMD, 0603	Panasonic® - ECG	ERJ-3EKF8201V
1	R32	Resistor, Thick Film, 3.3R, 1%, 1/10W, SMD, 0603	Panasonic® - ECG	ERJ-3RQF3R3V
4	R33, R38, R40, R46	Resistor, Thin Film, 10k, 1%, 1/16W, SMD, 0603	TE Connectivity, Ltd.	CPF0603F10KC1
6	R34, R36, R41, R43, R47, R49	Resistor, Thick Film, 390R, 1%, 1/10W, SMD, 0603	Panasonic® - ECG	ERJ-3EKF3900V
6	R35, R37, R42, R44, R48, R50	Resistor, Thick Film, 510R, 1%, 1/10W, SMD, 0603	Vishay Intertechnology, Inc.	CRCW0603510RFKEA
4	R52, R89, R90, R91	Resistor, Thin Film, 3.3R, 1%, 1/2W, SMD, 1206	Susumu Co., Ltd.	RL1632R-3R30-F
1	R54	Resistor, Thick Film, 2.2k, 1%, 1/4W, SMD, 1206	ROHM Semiconductor	MCR18EZHF2201
2	R55, R117	Resistor, Thick Film, 47k, 1%, 1/8W, SMD, 0805, AEC-Q200	Yageo Corporation	AC0805FR-0747KL
1	R57	Resistor, Thick Film, 10k, 1%, 1/8W, SMD, 0805	Panasonic® - ECG	ERJ-6ENF1002V
1	R58	Resistor, Thick Film, 140k, 1%, 1/8W, SMD, 0805	Vishay Intertechnology, Inc.	CRCW0805140KFKEA
2	R59, R62	Resistor, Thick Film, 60.4R, 1%, 1/4W, SMD, 1206	Yageo Corporation	RC1206FR-0760R4L
2	R60, R61	Resistor, Thick Film, 3.3R, 1%, 1/8W, SMD, 0805, AEC-Q200	Stackpole Electronics Inc	RMCF0805FT3R30
1	R63	Resistor, Thick Film, 82k, 1%, 1/2W, SMD, 0805	Panasonic® - ECG	ERJ-P6WF8202V

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

Qty.	Reference	Description	Manufacturer	Manufacturer Part Number
1	R64	Resistor, Thick Film, 36k, 1%, 1/8W, SMD, 0805	Panasonic® - ECG	ERJ6ENF3602V
2	R65, R67	Resistor, Thick Film, 2.61k, 1%, 1/16W, SMD, 0603	Multicomp Pro	MC 0.063W 0603 1% 2K61
3	R68, R71, R72	Resistor, Thick Film, 2.2k, 1%, 1/10W, SMD, 0603	ROHM Semiconductor	MCR03EZPFX2201
1	R69	Resistor, Thick Film, 2.4k, 1%, 1/10W, SMD, 0603	Stackpole Electronics, Inc.	RMCF0603FT2K40
1	R70	Resistor, Thick Film, 7.5k, 1%, 1/10W, SMD, 0603	Panasonic® - ECG	ERJ3EKF7501V
3	R73, R74, R116	Resistor, Thick Film, 3.3k, 1%, 1/10W, SMD, 0603	Panasonic® - ECG	ERJ3EKF3301V
3	R75, R84, R85	Resistor, Thick Film, 4.7k, 1%, 1/10W, SMD, 0603	Digi-Key® Electronics	311-4.70KHRTR-ND
6	R76, R77, R78, R81, R82, R83	Resistor, Thick Film, 2.2k, 1%, 1/10W, SMD, 0603	Panasonic® - ECG	ERJ3EKF2201V
2	R79, R80	Resistor, Thick Film, 10k, 1%, 1/10W, SMD, 0603	Panasonic® - ECG	ERJ3EKF1002V
3	R86, R87, R88	Resistor, Thick Film, 33k, 5%, 1/4W, SMD, 1206	Panasonic® - ECG	ERJ8GEYJ333V
12	R104, R105, R106, R107, R108, R109, R110, R111, R112, R113, R114, R115	Resistor, Thick Film, 10R, 1%, 1/8W, SMD, 0805, AEC-Q200	Stackpole Electronics, Inc.	RMCF0805FT10R0
1	Y1	Crystal, 8 MHz, 18 pF, SMD	Abracon® Corporation (LLC)	ABM7-8.000MHZ-D2Y-T
1	PCB	Printed Circuit Board	—	04-11516-R1

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 1-2: BILL OF MATERIALS (BOM) – MICROCHIP PARTS

Qty.	Reference	Description	Manufacturer	Part Number
3	U1, U2, U3	Analog, MOSFET, Driver, Dual-Non-Inverting, SOIC-8	Microchip Technology Inc.	MIC4104YM
1	U4	Microcontroller, 16-Bit, 256 KB, 100 MHz, AEC-Q100, 48TQFP	Microchip Technology Inc.	dsPIC33CK256MP505-I/PT
1	U5	Analog, Switcher, Buck, 2 to 24V, SOT-23-6	Microchip Technology Inc.	MCP16331T-E/CH
1	U6	Interface, CAN, SOIC-8	Microchip Technology Inc.	ATA6561-GAQW
1	U7	Analog, LDO, 3.3V, SOT-223-3	Microchip Technology Inc.	MCP1754ST-3302E/DB
1	U8	Analog, LDO, 5V, SOT-23A-3	Microchip Technology Inc.	MCP1754ST-5002E/CB
1	U9	Analog, Temperature Sensor, -40°C to +150°C, SOT-23-3	Microchip Technology Inc.	MCP9700AT-E/TT

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 1-3: BILL OF MATERIALS (BOM) – MECHANICAL PARTS

Qty.	Reference	Description	Manufacturer	Part Number
1	HS1	Mechanical, Headers & Wires, Heatsink, L160W100H40	Fischer Elektronik	SK 85/100 SA
1	JP1	Mechanical, Headers & Wires, Jumper, 2.54 mm, 1x2	FCI	63429-202LF

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.

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