High-Voltage Auxiliary E-Fuse User’s Guide

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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-Voltage Auxiliary E-Fuse. 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-Voltage Auxiliary E-Fuse. The manual layout is as follows:

- **Chapter 1. "Product Overview"** – Important information about the High-Voltage Auxiliary E-Fuse.
- **Chapter 2. "Installation and Operation"** – Includes instructions on installing and using the High-Voltage Auxiliary E-Fuse.
- **Appendix A. "Schematics and Layouts"** – Shows the schematic and layout diagrams for the High-Voltage Auxiliary E-Fuse.
- **Appendix B. "Bill of Materials (BOM)"** – Lists the parts used to build the High-Voltage Auxiliary E-Fuse.

CONVENTIONS USED IN THIS GUIDE

This manual uses the following documentation conventions:

DOCUMENTATION CONVENTIONS

<table>
<tr><th>Description</th><th>Represents</th><th>Examples</th></tr>
<tr><td colspan="3">Arial font:</td></tr>
<tr><td rowspan="2">Italic characters</td><td>Referenced books</td><td>MPLAB® IDE User’s Guide</td></tr>
<tr><td>Emphasized text</td><td>...is the only compiler...</td></tr>
<tr><td rowspan="3">Initial caps</td><td>A window</td><td>the Output window</td></tr>
<tr><td>A dialog</td><td>the Settings dialog</td></tr>
<tr><td>A menu selection</td><td>select Enable Programmer</td></tr>
<tr><td>Quotes</td><td>A field name in a window or dialog</td><td>“Save project before build”</td></tr>
<tr><td>Underlined, italic text with right angle bracket</td><td>A menu path</td><td><u>File>Save</u></td></tr>
<tr><td rowspan="2">Bold characters</td><td>A dialog button</td><td>Click OK</td></tr>
<tr><td>A tab</td><td>Click the Power tab</td></tr>
<tr><td>N‘Rnnnn</td><td>A number in verilog format, where N is the total number of digits, R is the radix and n is a digit.</td><td>4‘b0010, 2‘hF1</td></tr>
<tr><td>Text in angle brackets < ></td><td>A key on the keyboard</td><td>Press <Enter>, <F1></td></tr>
<tr><td colspan="3">Courier New font:</td></tr>
<tr><td rowspan="7">Plain Courier New</td><td>Sample source code</td><td><code>#define START</code></td></tr>
<tr><td>Filenames</td><td><code>autoexec.bat</code></td></tr>
<tr><td>File paths</td><td><code>c:\mcc18\h</code></td></tr>
<tr><td>Keywords</td><td><code>_asm, _endasm, static</code></td></tr>
<tr><td>Command-line options</td><td><code>-Opa+, -Opa-</code></td></tr>
<tr><td>Bit values</td><td><code>0, 1</code></td></tr>
<tr><td>Constants</td><td><code>0xFF, ‘A’</code></td></tr>
<tr><td>Italic Courier New</td><td>A variable argument</td><td><code>file.o</code>, where <code>file</code> can be any valid filename</td></tr>
<tr><td>Square brackets [ ]</td><td>Optional arguments</td><td><code>mcc18 [options] file [options]</code></td></tr>
<tr><td>Curly brackets and pipe character: { | }</td><td>Choice of mutually exclusive arguments; an OR selection</td><td><code>errorlevel {0|1}</code></td></tr>
<tr><td rowspan="2">Ellipses...</td><td>Replaces repeated text</td><td><code>var_name [, var_name...]</code></td></tr>
<tr><td>Represents code supplied by user</td><td><code>void main (void)
{ ...
}</code></td></tr>
</table>

RECOMMENDED READING

This user's guide describes how to use the High-Voltage Auxiliary E-Fuse. Other useful documents are listed below. The following Microchip documents are available and recommended as supplemental reference resources.

- **AN4616 – "Driving Microchip SiC MOSFETs" (DS00004616).**

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:

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- **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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- Technical Support

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

DOCUMENT REVISION HISTORY

Revision A (July 2022)

- Initial Release of this Document.

NOTES:

HIGH-VOLTAGE AUXILIARY E-FUSE USER'S GUIDE

Chapter 1. Product Overview

1.1 INTRODUCTION

This document provides an overview of Microchip's High-Voltage Auxiliary E-Fuse technology demonstrator. This is intended for use in Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) applications. This technology demonstrator leverages the benefits of Microchip's 700V and 1200V silicon carbide (SiC) technology as well as other Microchip technologies to provide the total system solution (TSS). Additionally, the design implements a time-current characteristic (TCC) curve, aiding migration to non-automotive applications, such as DC solid-state circuit breakers.

Safety Warning: Before continuing, please read the Note below.

This chapter covers the following:

1.2 QUICK START GUIDE

This section provides a brief overview of setting up the High-Voltage Auxiliary E-Fuse technology demonstrator. Details of the design, functionality, and performance are discussed in the subsequent sections of this document.

Note: There are high voltages present on the board when it is powered up. No part of the board must be handled when the board is being powered.

Before handling, ensure it is completely discharged across the output terminals in the high voltage zone of the circuit board and from the high voltage zone to the low voltage zone.

The board is intended for use on 400V and 800V battery systems, depending on the High-Voltage Auxiliary E-Fuse variant. However, even if the board is powered with a low voltage (< 60V), it is still capable of producing high voltages (>1000V for the 700V SiC MOSFETs and >1700V for the 1200V SiC MOSFETs). It is important to use high-voltage differential voltage probes for taking measurements. Also, many current probes are not rated for high voltage. When using current probes, ensure proper wire insulation is used. Not using the appropriate voltage or current probe could result in permanent damage due to over-voltage stress on the measurement equipment.

As shown in Figure 1-2 below, the header, J1, accepts power across terminals 1 and 2. The input operating voltage range is 9V to 16V. This powers up the High-Voltage Auxiliary E-Fuse hardware and enables the SiC MOSFETs by default. LEDs, D3 and D102, will automatically turn on. LED D3 indicates the board is powered. LED D102 indicates the SiC MOSFETs are commanded on.

The LIN input on J1:3 is an optional interface to control, configure the over-current thresholds, and read diagnostics from the High-Voltage Auxiliary E-Fuse controller. Reference designators J2 and J101 are pads for programming the microcontrollers. Additional information is found in subsequent sections.

Terminals J100 and J102 are high voltage terminals. As shown in the figure below, the default configuration is to setup the High-Voltage Auxiliary E-Fuse as a high-side switch in the system with J100 connecting to the positive rail of the DC bus and J102 connecting to the load. This configuration is shown in Figure 1-1. Alternatively, a low-side switch configuration can be used with J100 connecting to the load and J102 to the negative rail of the DC bus.

High-Voltage Auxiliary E-Fuse variants A, B, and C use 700V SiC MOSFETs and are rated for 10A, 20A, and 30A, respectively. High-Voltage Auxiliary E-Fuse variants D, E, and F use 1200V SiC MOSFETs and are rated for 10A, 20A, and 30A, respectively. Typically, variants A, B, and C are used in 400V battery systems, and variants D, E, and F for 800V battery systems.

The time-current characteristic (TCC) curves for each of these variants are found later in this document in the section titled TCC Curve. The graphs show the interruption time for a given current.

For short-circuit testing, it is important to understand the impact of the system inductance. When the High-Voltage Auxiliary E-Fuse interrupts a high current, the inductive energy will be transferred to the SiC MOSFETs unless an external snubber or clamp is included in the test setup. Although the SiC MOSFETs have high avalanche energy ratings, it is important to understand their limits in both avalanche energy and peak current during avalanche.

Additionally, it is important to use high voltage differential voltage probes when measuring the SiC MOSFETs' drain-to-source voltage, V_{DS}. When they are in avalanche, V_{DS} can reach very high voltages: >1000V for 700V SiC MOSFETs and >1700V for 1200V SiC MOSFETs. This can occur even with very low supply voltages. Not using the appropriate voltage probe could result in permanent damage due to over-voltage stress on the measurement equipment.

In addition to the LIN communication, the over-current behavior is programmable in the software. The software includes a compiler switch to compile a specific variant. These settings can be modified to build a custom TCC curve. However, keep in mind that the settings selected should be within the capabilities of the SiC MOSFETs that are used.

1.3 HIGH-VOLTAGE AUXILIARY E-FUSE DEVICE KEY FEATURES

- For use on electric vehicle applications with 400V or 800V battery systems
- Up to 30A continuous output load current
- Configurable time-current characteristics curve
- Two modes of short-current detection: edge-triggered and ride-through
- Diagnostic status of current, temperature, and bias supply measurements
- LIN communication interface for configurability and diagnostics
- Automotive hardware design using only AEC-qualified components

Six variants of this High-Voltage Auxiliary E-Fuse design are available, supporting 400V & 800V bus voltages and continuous current ratings of 10A, 20A, and 30A.

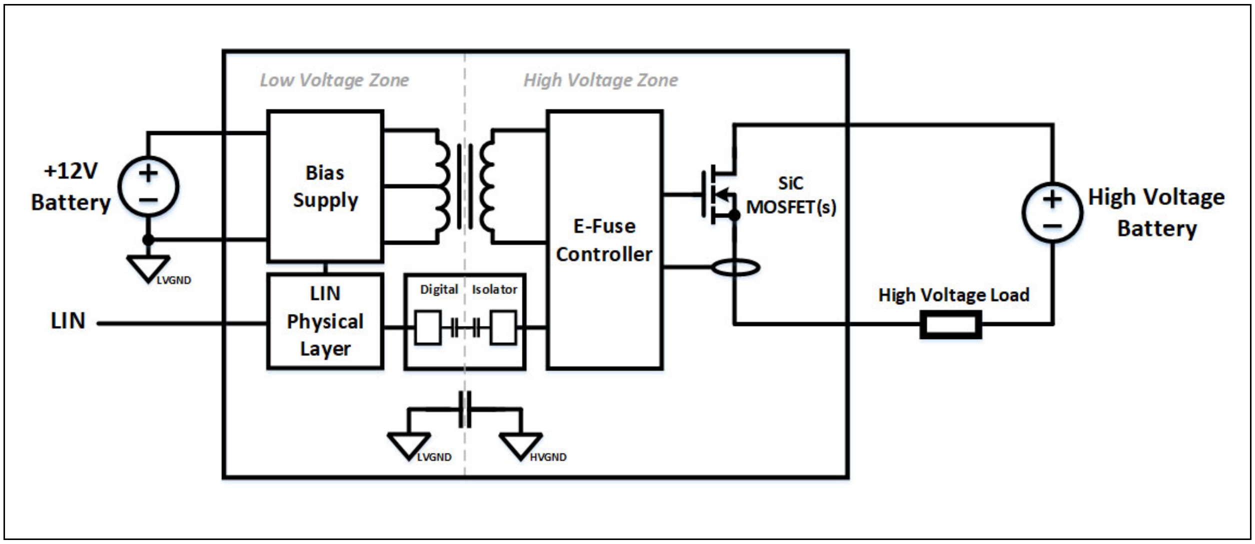


FIGURE 1-1: LV-HV Block Diagram.

1.3.1 Pinout

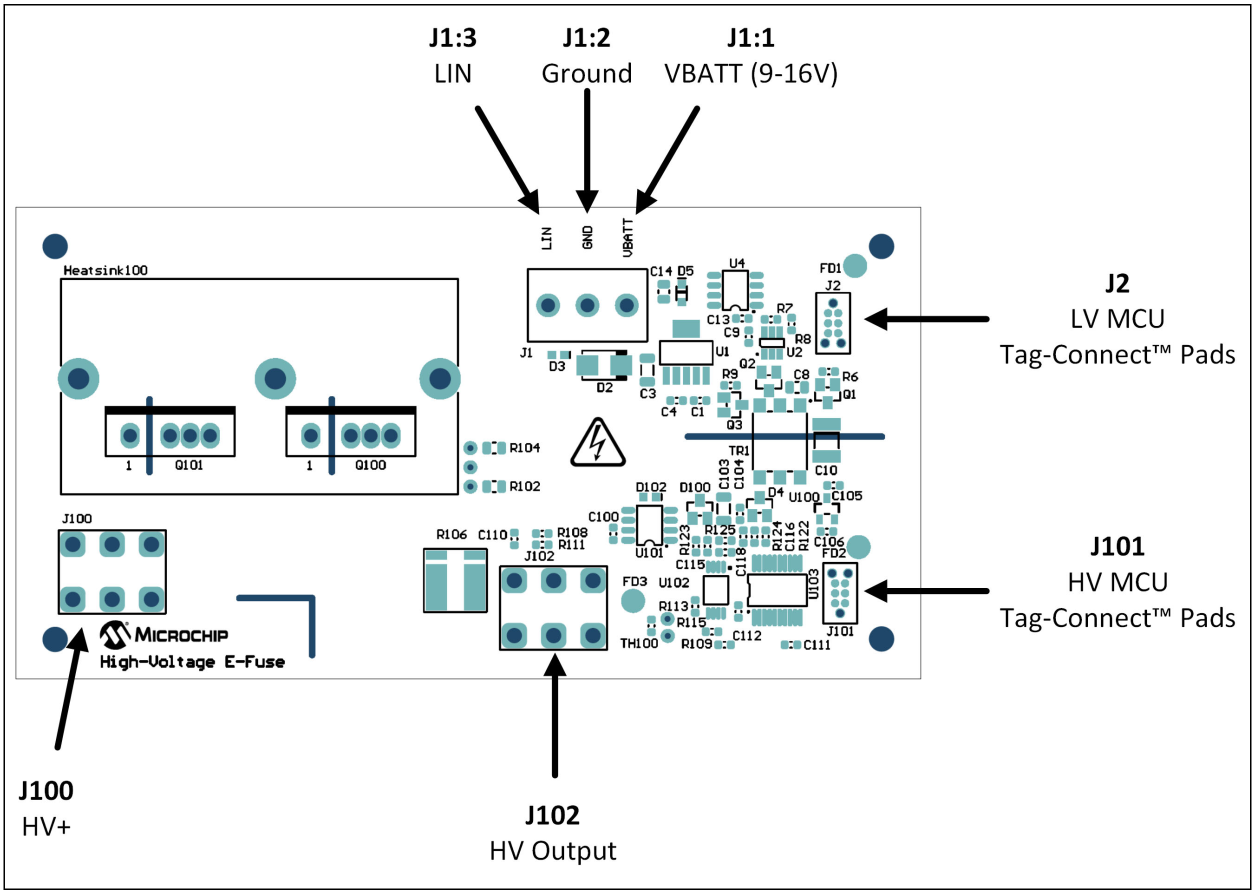


FIGURE 1-2: Pinout.

TABLE 1-1: PINOUT DESCRIPTION

Terminal	Signal Name	Description
J1-1	VBATT	+12V battery input
J1-2	Ground	Return
J1-3	LIN	Local interconnected network, Comm bus
J100	HV+	High voltage battery positive rail
J102	HV Output	High voltage load

The Tag-Connect™ interface is used to connect the programmer or debugger to the microcontroller (MCU). J2 is used to connect to the low voltage (LV) MCU and J101 for the high voltage (HV) MCU.

The Tag-Connect cable is available at https://www.tag-connect.com. Tag-Connect cable part number TC2030-PKT-NL is intended for use with the Microchip PICkit™ 3 or PICkit 4. Cable part numbers TC2030-MCP-NL and TC2030-MCP-NL-10 are intended for use with Microchip ICD 3 or ICD 4 In-Circuit Debugger.

Due to the high voltage levels in this application, a programmer or debugger should only be used when the circuit board is powered with low voltages in the LV and HV zones. Before attaching the programming cable, verify the circuit board is discharged to safe voltage levels below 60V.

1.3.2 Electrical Specifications

LV System Input Voltage ....Vehicle +12V battery, 9V to 16V continous

LV System Input Current .... < 100 mA

HV System Input Voltage .... ≤ 500V for 700V SiC MOSFETs

.... ≤ 1000V for 1200V SiC MOSFETs

HV System Output Current.................................... 10A, 20A, or 30A (400V and 800V)

Operating Temperature Range.............................-40°C to +85°C, ambient temperature

1.4 FUNCTIONALITY

The High-Voltage Auxiliary E-Fuse over-current protection behavior is represented by a time-current characteristic curve showing the response time as a function of current.

1.4.1 Time-Current Characteristic (TCC) Curve Overview

The time-current characteristic curve for this High-Voltage Auxiliary E-Fuse design is formed by three detection methods: junction-temperature estimation, over-current measurement, and short-circuit detection. In Figure 1-3, the left-most segment of the curve uses the MOSFET's junction-temperature estimation method to detect over-current. The horizontal line segment in the middle of the curve uses sampled current measurement as the basis for over-current detection. The right-most line segment is a hardware-based current measurement for fast detection of a short-circuit event.

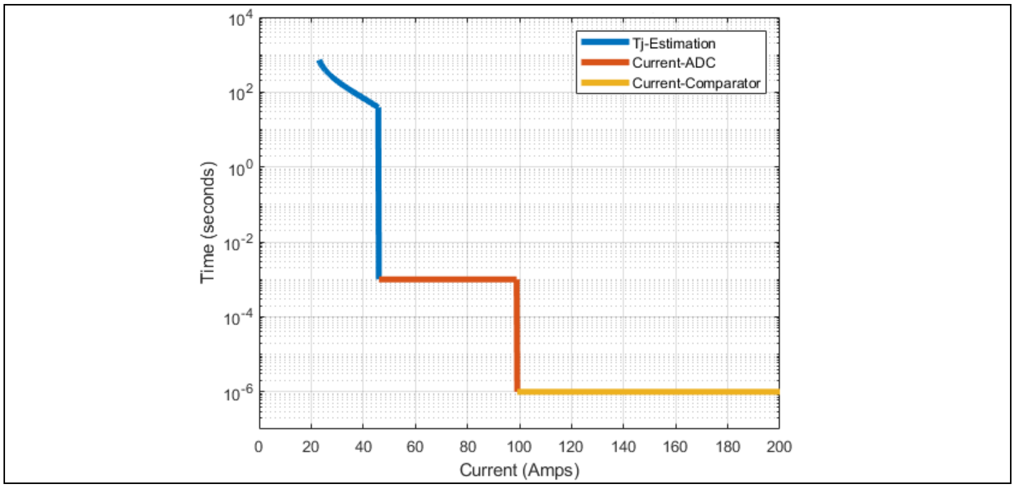


FIGURE 1-3: TCC Curve, Variant B (400V, 20A).

1.4.2 Junction-Temperature Estimation

The junction-temperature estimation is based on the High-Voltage Auxiliary E-Fuse thermal design. The MOSFET's junction temperature is estimated using the thermistor-based temperature measurement, drain current measured by the analog-to-digital converter (ADC), MOSFET's maximum drain-to-source on-resistance, $R_{DS(on)}$, and thermal resistance.

EQUATION 1-1:

$$T_J = T_A + (I_D^2 \times R_{DS(on)}) \times R_{THJA}$$

Additionally, to estimate the junction temperature more accurately during transient currents, the heat sink's thermal capacitance is also considered. Given the thermal resistance and thermal capacitance, the thermal transient response is modeled with a 1st order infinite impulse response (IIR) digital filter. The heat sink, or case temperature rise is determined by the following difference equation:

EQUATION 1-2:

$$T_{rise}[n] = a_1 \times T_{rise}[n-1] + b_0 \times T_{raw}[n] + b_1 \times T_{raw}[n-1]$$

T_{raw} is the IIR filter input based on the instantaneous, current measurement:

EQUATION 1-3:

$$T_{raw} = (I_D^2 \times R_{DS(on)}) \times R_{THCA}$$

The IIR filter coefficients are initially determined from the thermal resistance, thermal capacitance, and sampling rate and are later refined empirically to account for the increase in $R_{DS(on)}$ with temperature. Additionally, to simplify the calculations by eliminating a multiplication operation and a filter coefficient, the difference equation reduces to:

EQUATION 1-4:

$$T_{rise}[n] = a_1 \times T_{rise}[n-1] + b_1 \times (T_{raw}[n] + T_{raw}[n-1])$$

The heat sink temperature is estimated as:

EQUATION 1-5:

$$T_S = T_A + T_{rise}$$

In estimating the MOSFET's junction temperature, the MOSFET's junction-to-case thermal resistance is considered. Its thermal capacitance is not considered because it is relatively small compared to the heat sink's thermal capacitance and does not warrant the additional computations. The third term in the following MOSFET junction-temperature estimation equation represents the temperature rise from junction-to-case.

EQUATION 1-6:

$$T_S = T_A + T_{rise} + (I_D^2 \times R_{DS(on)}) \times R_{THJC}$$

The filter coefficients, $R_{DS(on)}$, thermal resistance, thermal capacitance, and maximum allowable junction temperature are configurable parameters in the High-Voltage Auxiliary E-Fuse software.

1.4.3 Over-Current Measurement

The horizontal line segment in the middle of the TCC curve represents over-current detection based on the sampled current measurement. The current is sampled by the ADC every 1 ms and requires two consecutive samples above the over-current threshold to declare an over-current event. Therefore, the response time for this detection method is between 1 ms and 2 ms. The over-current threshold is user-configurable in the software.

1.4.4 Short-Circuit Detection

Sudden, high currents that are too fast for detection by the ADC and software are deemed as short-circuit currents. These are detected through the High-Voltage Auxiliary E-Fuse hardware.

There are two possible modes of operation for responding to short-circuit events. The default mode, edge-triggered mode, interrupts the current in response to a detection of a short-circuit. Another mode that is available allows for the ability to ride through transients. A timer starts upon detection of the short-circuit and increments for the duration of the short-circuit. If the timer expires, the MOSFET(s) is switched off to interrupt the current. However, if the current drops below the short-circuit trip threshold before the timer expires, then the timer is reset by the software within the period *`tcc_sample_time`*. Additionally, to extend the short-circuit ride-through duration, the MOSFET gate voltage is reduced while the timer is active.

The short-circuit trip threshold, mode of operation, MOSFET gate drive strength and timer period are user-configurable in software or with LIN:

Parameter	Software Variable	LIN Message
Short-circuit trip threshold	`dac_i_hw_trip`	`LIN_DAC_I_HW_TRIP`
Mode of operation	`triggerType`	`LIN_TRIGGER_TYPE`
SiC MOSFET gate drive strength	`reduced_drive_time`	`LIN_REDUCED_DRIVE_TIME`
TCC timer period	`tcc_sample_time`	`LIN_TCC_SAMPLE_TIME`

See the LIN Communication section further in the document for details on configuring these parameters.

1.4.5 Current Measurement Paths

Figure 1-4 shows the hardware paths for the three current detection methods. Current is measured using a shunt resistor to achieve a wide bandwidth and fast response time.

The detection path for short-circuit currents is designed for fast, hardware-based detection utilizing the PIC® microcontroller's core independent peripherals (CIPs). The software-based detection path is used for the junction-temperature estimation and over-current detection.

The short-circuit detection path includes a differential amplifier for measuring the voltage drop across the shunt resistor. A comparator is used to detect a short-circuit by comparing the differential amplifier output with a reference voltage established by the digital-to-analog converter (DAC) output. The DAC has a 5-bit resolution, providing 31 possible reference levels, and uses the microcontroller's Fixed Voltage Reference (FVR) as its reference. The comparator output triggers the SR latch to drive the MOSFET gate voltage to a reduced voltage. In edge-triggered mode, the timer will immediately expire, setting the second SR latch, which turns off the MOSFET. In ride-through mode, the timer will increment while the short-circuit is active. If the timer expires, it will trigger the second SR latch to turn off the MOSFET. However, if the current drops below the threshold, the comparator output will no longer be active, and the timer will no longer increment. In this case, the timer is reset in the software.

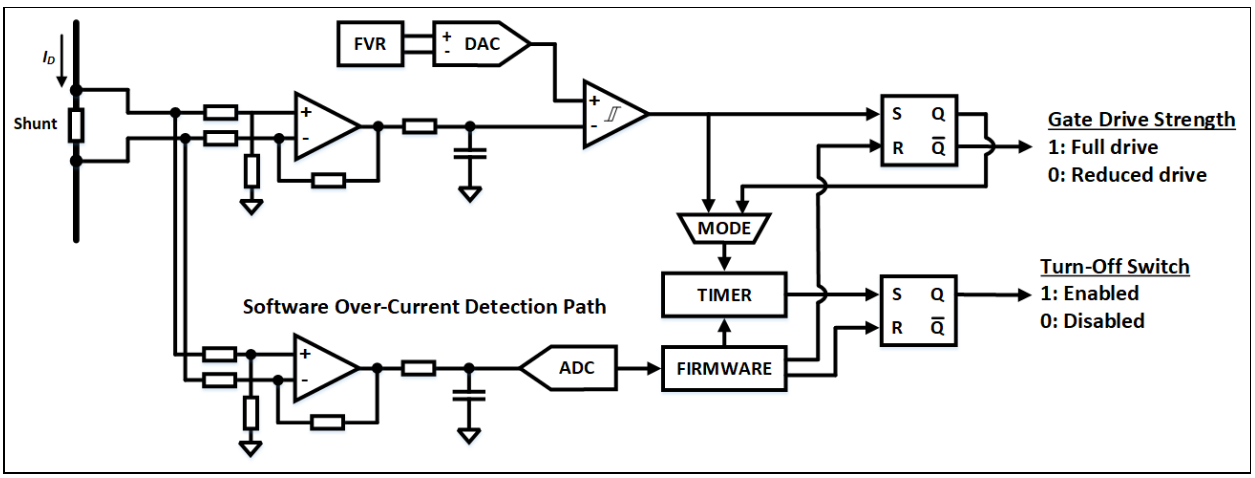


FIGURE 1-4: *Hardware Short-Circuit Detection Path.*

1.4.6 Temperature Sense

A temperature sensor is used to measure the ambient temperature. The sensor is an NTC thermistor with higher accuracy at elevated temperatures. The sensor is sampled by the ADC every 10 ms. The High-Voltage Auxiliary E-Fuse design includes out-of-range high (OORH) and out-of-range low (OORL) detection for diagnosing a faulty sensor or circuit. Two consecutive OORH or OORL readings are required to declare a fault. The sensor diagnostic status is available over the LIN communication bus.

The circuit board design includes the option of using alternate plated through-hole pads to attach wires to a thermistor mounted on a heat sink for a more accurate ambient or heat sink temperature measurement.

1.4.7 VCC Supply Monitor

The secondary-side bias supply, VCC, is used to power the gate drive circuit and supply the linear voltage regulator that produces VDDHV. Because the gate driver does not include an undervoltage lockout feature, the protection is designed into the controller software. Upon detection of an undervoltage, the controller disables the gate driver and turns off the MOSFET.

The supply is sampled by the ADC in the 1 ms interrupt. The interrupt samples either the VCC supply or the temperature sensor. In the first 1 ms interrupt, the temperature sensor is sampled. In the next nine interrupts, the VCC supply is sampled.

Two consecutive undervoltage readings are required to declare a fault. The sensor diagnostic status is available over the LIN communication bus.

1.5 HIGH-VOLTAGE AUXILIARY E-FUSE DESIGN FILES

The following design files regarding the High-Voltage Auxiliary E-Fuse are available:

- Altium Design Files
- Software
- PLECS Model
- User's Guide
- Bill of Materials

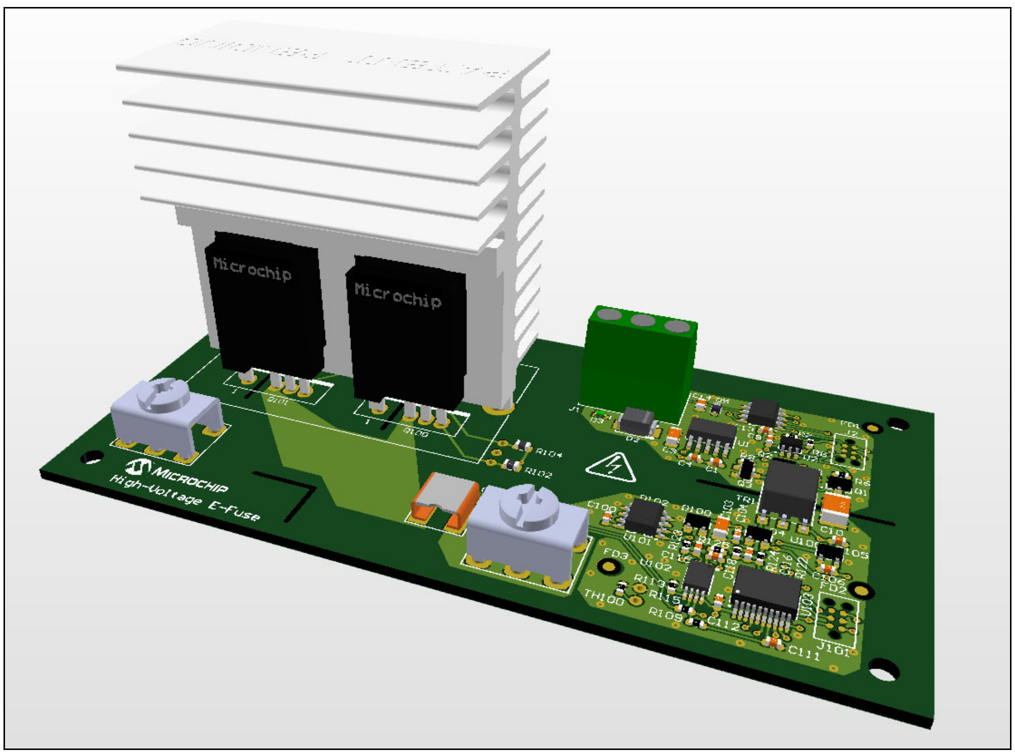


FIGURE 1-5: *High-Voltage Auxiliary E-Fuse PCB Assembly (Top 3D View).*

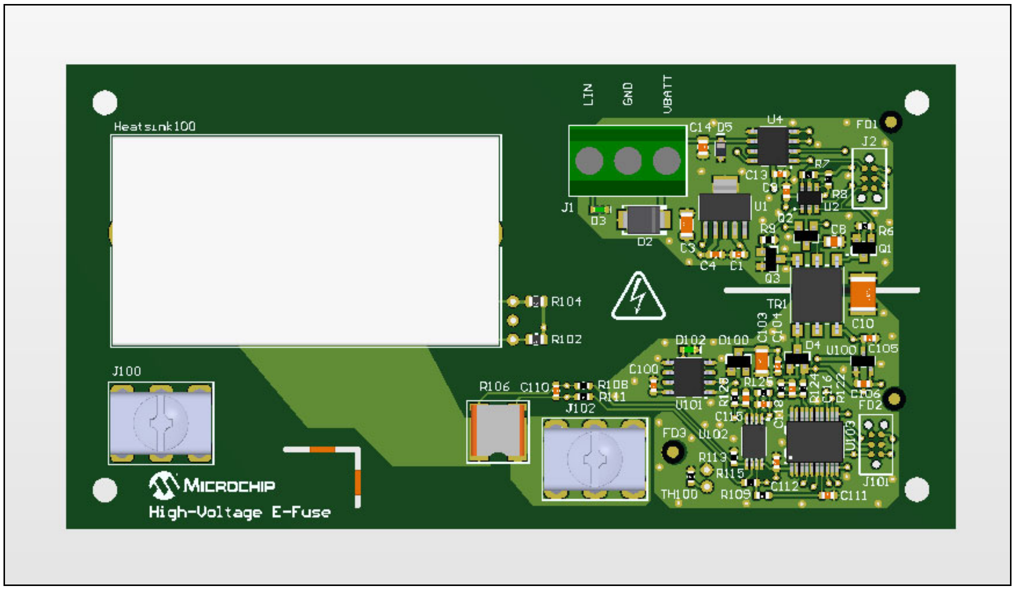


FIGURE 1-6: *High-Voltage Auxiliary E-Fuse PCB Assembly (Top View).*

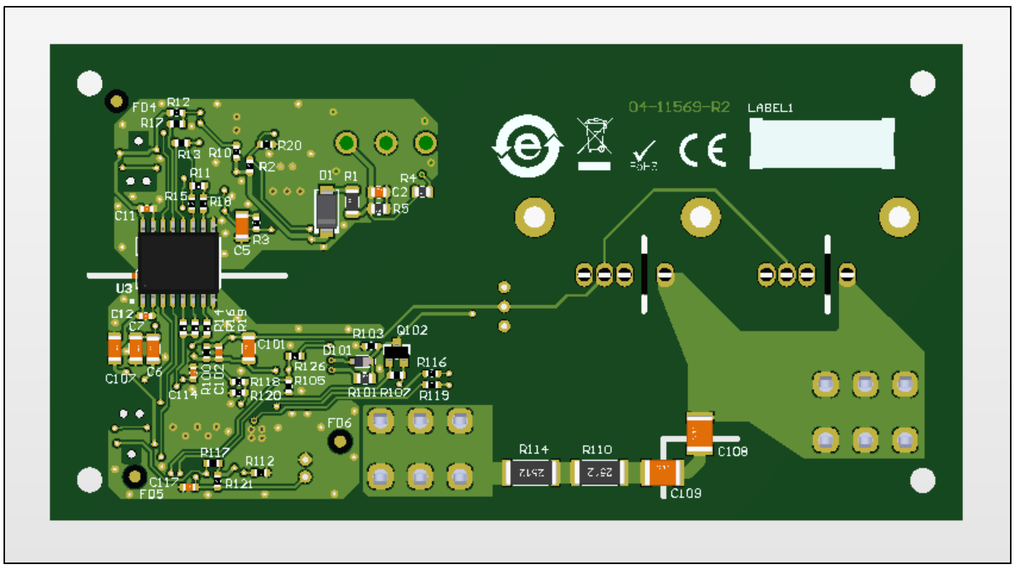


FIGURE 1-7: *High-Voltage Auxiliary E-Fuse PCB Assembly (Bottom View).*

NOTES:

Chapter 2. Installation and Operation

2.1 CIRCUIT OPERATION

2.1.1 Hardware Overview

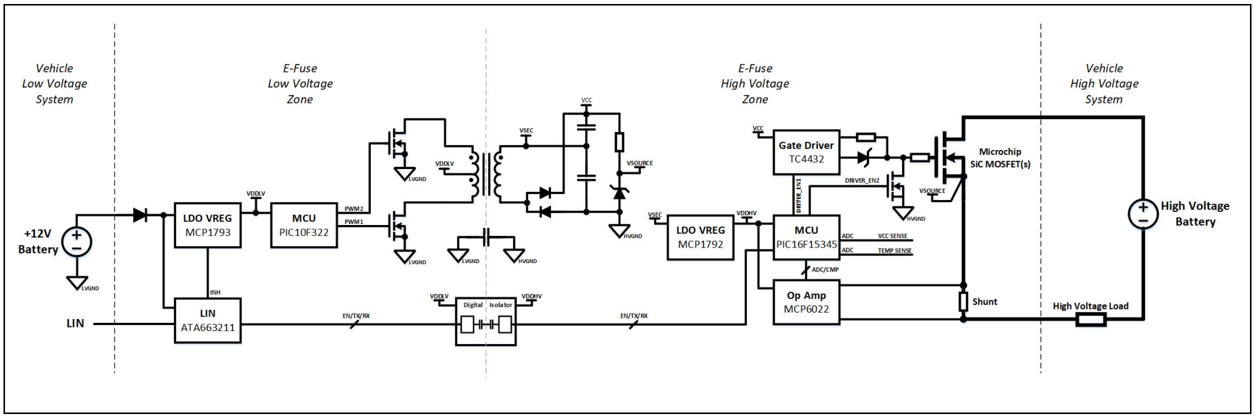


FIGURE 2-1: High-Voltage Auxiliary E-Fuse Block Diagram.

The block diagram in Figure 2-1 has the main High-Voltage Auxiliary E-Fuse circuit blocks. It is divided into two isolated zones: the low voltage (LV) zone and high voltage (HV) zone. The LV zone connects to the vehicle 12V system to power the High-Voltage Auxiliary E-Fuse and the LIN network to communicate with the vehicle controller. The HV zone has the High-Voltage Auxiliary E-Fuse microcontroller, gate drive, high voltage MOSFET(s), and protection. Because the HV zone is isolated, the High-Voltage Auxiliary E-Fuse can be connected to the system in a high-side or low-side driver configuration. Power is delivered from the LV zone to the HV zone through an isolated bias supply (push-pull converter). A digital isolator is used for transmitting the LIN transceiver signals over the isolation barrier to the High-Voltage Auxiliary E-Fuse microcontroller.

2.1.2 Input Circuit

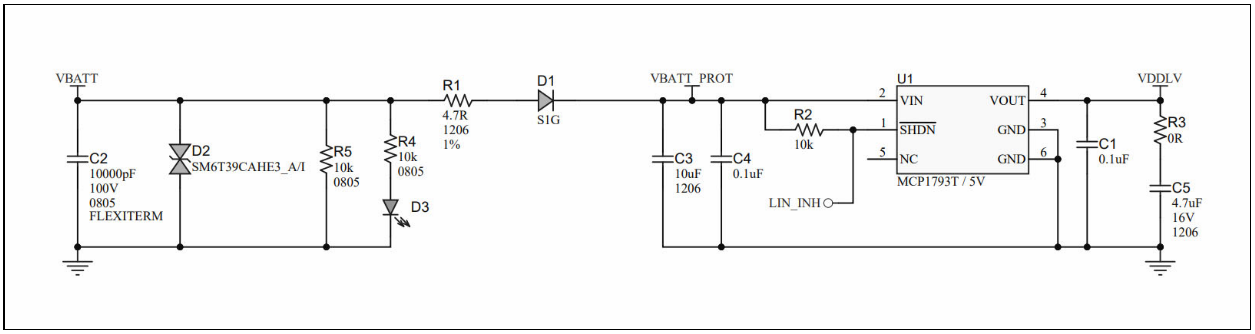


FIGURE 2-2: Battery Input Circuit.

Figure 2-2 shows the battery input circuit. As it is intended for an automotive 12V system, it is designed to provide VDDLV, a +5V output, over a continuous battery operating voltage range of 9V to 16V as well as temporary overvoltage conditions due to jump-start or load dump. The linear dropout voltage regulator IC is rated for a maximum continuous voltage of 55V and absolute maximum rating of 70V, allowing it to withstand transient pulses described in ISO 7637.

The input capacitor C2 was selected for conducted RF immunity and ESD withstand capability. Because it connects across the battery, it is an automotive-grade, ceramic capacitor with flexible terminations to improve protection against mechanical flexure and temperature stress.

Diode D2 is a bi-directional transient voltage suppressor (TVS) with a nominal breakdown voltage of 39V. It is intended to protect the LIN transceiver against the ISO pulses. Additionally, if the High-Voltage Auxiliary E-Fuse is required to operate at a lower operating voltage, such as 6V, then diode D1 would change to a Schottky diode, which generally has a lower reverse voltage capability than silicon rectifiers. In this case, the TVS protects the Schottky diode against negative ISO pulses.

Resistor R4 and LED D3 are only for evaluation purposes, and are not intended in the final design.

Resistor R1 limits the peak inrush current. Also, because the downstream circuit contains a switch-mode power supply, this resistor may help in reducing potential high-frequency, differential-mode currents.

Diode D1 is a silicon rectifier for reverse battery protection. As mentioned above, it can be replaced by a Schottky diode to allow for a lower operating voltage range.

Capacitors C1, C3, C4 and C5, are for high frequency decoupling or local energy storage for downstream circuits. Depending on the customer requirements, C3, may need to be resized to support battery voltage dip and dropout requirements.

The R2 resistor is a pull-up resistor that ensures the voltage regulator remains enabled. However, if the High-Voltage Auxiliary E-Fuse is powered by a direct connection to the battery instead of a high-side driver, then this resistor is to be depopulated. In this case, the LIN transceiver LIN_INH signal will control the state of the voltage regulator. This allows the voltage regulator to enter shutdown when the vehicle ignition is off.

Resistor R3 is intended as a placeholder to protect for PWM operation. During PWM operation, this resistor can act as artificial ESR in capacitor, C5, to help stabilize the output voltage, reducing dips and overshoots during switching.

The voltage regulator IC U1 is a Microchip MCP1793 +5V, 100 mA output regulator in a 5-lead SOT-223 package. As with all the devices in the High-Voltage Auxiliary E-Fuse design, it is automotive-grade. The operating junction temperature range is –40°C to +150°C, with a maximum junction temperature rating of 175°C. It enters thermal shutdown at +175°C (typical). The estimated maximum junction temperature in this application is:

EQUATION 2-1:

$$T_J = T_A + R_{THJA} \times P_D$$

EXAMPLE 2-1:

$T_J = 85°C + \left(75\frac{°C}{W}\right) \times (60\ mA \times (16V - 5V)) \approx 135°C$	Continuous operation
$T_J = 65°C + \left(75\frac{°C}{W}\right) \times (60\ mA \times (18V - 5V)) \approx 124°C$	Over-voltage
$T_J = 25°C + \left(75\frac{°C}{W}\right) \times (60\ mA \times (26V - 5V)) \approx 120°C$	Jump-start

2.1.3 Push-Pull Converter

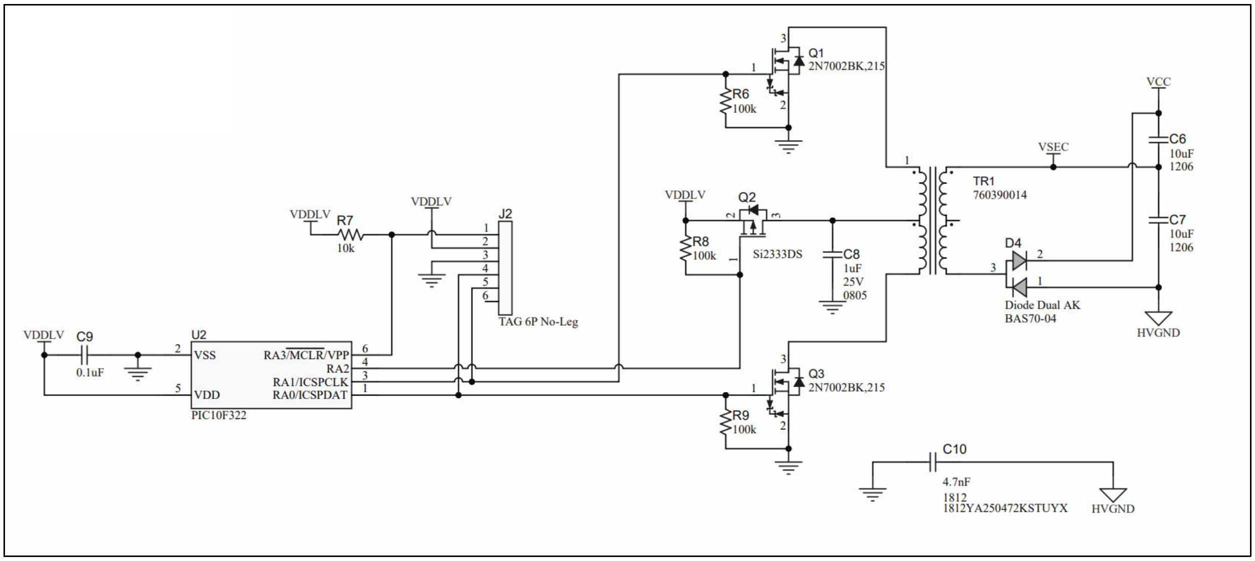


FIGURE 2-3: *Push-Pull Converter Schematic.*

Powered by VDDLV, the push-pull converter in Figure 2-3, produces isolated output voltages VCC and VSEC used in the HV zone.

The PWM signals generated by U2 drive the push-pull transistors, Q1 and Q2, which are 60V, 300 mA, N-channel MOSFETs. The transformer, which has a turn's ratio of 1:1.3, has a primary winding with each end driven by a MOSFET and center-tapped connection to VDDLV. However, because the two secondary windings are connected in series, the effective turns ratio is 1:2.6. The secondary winding of the transformer connects to a voltage doubler arrangement.

U2 is a Microchip PIC10F322 8-bit microcontroller in a 6-lead SOT-23 package with the following pinout:

Pin #	Port	Assigned Function	Name	Active State
1	`RA0/ICSPDAT`	CWG1A/ICSP	PWM 1 / ICSP	Output high
2	`VSS`	Return	Return	—
3	`RA1/ICSPCLK`	CWG1B/ICSP	PWM 2 / ICSP	Output high
4	`RA2`	GPIO	Push-pull enable	Output low
5	`VDD`	+5V supply	VDDLV	—
6	`RA3/MCLR/VPP`	MCLR	Master Clear, MCU reset	Input low

The code is auto-generated with only the basic PWM settings configured in Microchip Code Configurator (MCC) using the peripherals in the table below and pin RA2 configured as an output low.

Peripheral	Name	Setting
CWG1	Complementary Waveform Generator 1	62 ns to 125 ns dead time
PWM2	Pulse Width Modulator 2	444 kHz, 50% duty cycle
TMR2	Timer 2	2.25 µs period

The push-pull converter's unloaded output voltages are:

EXAMPLE 2-2:

$$VSEC = VDDLV \times \left(\frac{2N_2}{N_1}\right) - V_f = 5V \times \left(\frac{2 \times 1.3}{1}\right) - 0.6V = 12.4V$$

$$VCC = 2 \times VSEC = 24.8V$$

If desired, the switching frequency can be adjusted using MCC. To support in-circuit programming, Tag-Connect™ pads on the circuit board are at locations designated by header J2. Also, to in-circuit support programming is a transistor, Q2, which is a P-channel MOSFET. This allows a programmer, such as the PICkit4, clock and data lines to connect with the microcontroller without saturating the transformer primary windings or drawing excessive currents. This programming header J2 and transistor Q2 are for development purposes only and can be eliminated in a production design.

Capacitor C8 provides a low-impedance energy source to the transformer primary windings. Capacitor C9 is a high-frequency decoupling capacitor for the microcontroller. Capacitor C10, an automotive-grade safety capacitor with 4 kV with withstand capability, provides a return path for the high-frequency, common-mode, switching currents to reduce the RF conducted emissions.

Resistor R7 ensures that the microcontroller master clear $\overline{\text{MCLR}}$ is pulled high. Resistors R6, R8, and R9 are terminating resistors to ensure the MOSFETs remain off when the circuit is unpowered.

Transformer TR1 has two secondary windings wired in series. Each have a turns ratio of 1.3 resulting in a total turns ratio of 2.6. During the first switching sub-interval, when the voltage induced in the secondary windings is positive (with respect to transformer pin 6), the secondary current will charge capacitor C7 and conduct through Schottky diode D4 from pin 1 to pin 3. During the second switching sub-interval, the induced voltage will be negative. The current will flow through diode D4 from pin 3 to 2 to charge capacitor C6. This results in the induced voltage, less a diode forward voltage drop, across each capacitor. Therefore, VSEC, the voltage across capacitor C7 is approximately 12V and VCC is approximately 24V with respect to HVGND. However, due to difference in loads, the voltage across the two capacitors is not equal. The voltage across capacitor C7, VSEC, will be lower than the voltage across C8, VCC-VSEC, because of an additional downstream load. In this application, the typical voltage for VSEC is 11.5V and for VCC is 23.8V.

2.1.4 Secondary Supply Voltages

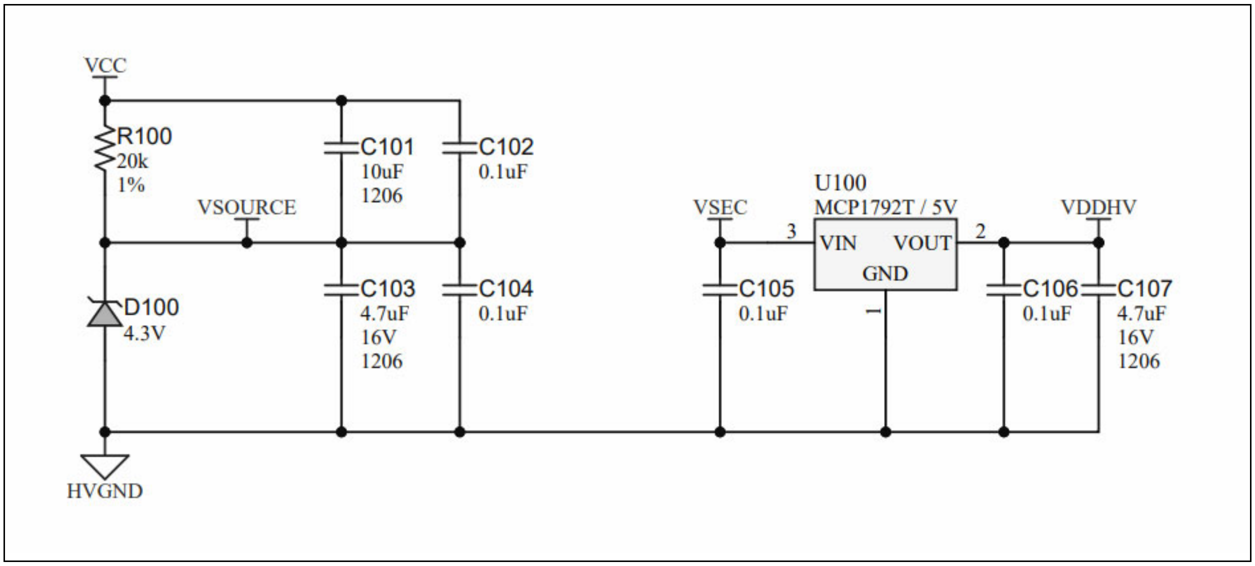


FIGURE 2-4: *Secondary Power Schematic.*

Figure 2-4 shows the voltage regulators for producing VSOURCE and VDDHV from VCC and VSEC, respectively. VSOURCE connects to the source terminal of the SiC MOSFET(s). VDDHV supplies the control circuitry, such as the microcontroller, digital isolator, operational amplifiers and sense circuits.

A Zener diode voltage regulator is used to regulate VSOURCE to 3.7V with respect to HVGND. Resistor R100 limits the Zener regulator current is approximately 1 mA. The Zener D100 is rated for 4.3V at 5mA, and approximately 3.7V at 1 mA. With the SiC MOSFET source terminal connecting to VSOURCE, the gate drive on-voltage will be VCC – VSOURCE = 20V.

The gate drive off-voltage will be HVGND – VSOURCE= –3.7V. Capacitors C101, C102, C103 and C104 stabilize the regulated voltage.

The voltage regulator IC, U100, is a Microchip MCP1792 +5V, 100 mA output regulator in a 3-lead SOT-23 package. The operating junction temperature range is -40°C to 150°C with a maximum junction temperature rating of 175°C and enters thermal shutdown at 175°C (typical).The estimated maximum junction temperature in this application is:

EQUATION 2-2:

$$T_J = T_A + R_{THJA} \times P_D$$

EXAMPLE 2-3: CONTINUOUS OPERATION

$$T_J = 85°C + \left(147\frac{°C}{W}\right) \times (10\ mA \times (12V - 5V)) \approx 95°C$$

Capacitors C105, C106 and C107 are used for RF immunity and power supply stability.

2.1.5 Isolated LIN Circuit

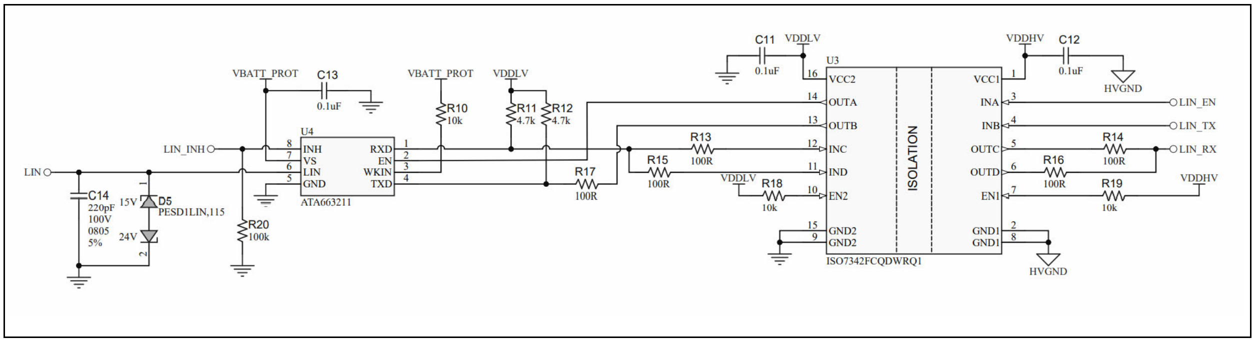


FIGURE 2-5: *Isolated LIN Circuit.*

Figure 2-5 is the isolated LIN circuit. The LIN transceiver, Microchip ATA66321, is an automotive-approved device in compliance with LIN 2.0, 2.1, 2.2, 2.2A, and SAE J2602-2 with improved slope control, ensuring data communication up to 20 Kbaud. The digital isolator IC facilitates the communication of digital signals over the isolation barrier (between the low voltage and high voltage zones).

In this application, the transceiver circuit is designed as a secondary node. The design, including selection of capacitor C14, diode D5 and transceiver IC U4, proximity of the transceiver IC to the connector and reverse-battery protected supply voltage, is based on OEM LIN physical layer requirements.

The node labeled LIN connects to the vehicle LIN network. The signals *LIN_EN*, *LIN_TX*, and *LIN_RX* are internal signals connecting to the microcontroller in the high voltage zone.

During sleep mode, the LIN transceiver's internal switch connecting VS to INH is off. Resistor R20 is a weak-pull down. If resistor R2, previously discussed in the input circuit section, is populated, then R20 is not needed and may be depopulated from the design. This is in the case when the High-Voltage Auxiliary E-Fuse is powered by an external high-side driver that is switched off during sleep mode. However, if the High-Voltage Auxiliary E-Fuse connects directly to the vehicle 12V battery, then to achieve low sleep current, resistor R2 is to be depopulated and the state of voltage regulator U1 is controlled by the signal *LIN_INH*. During sleep mode, *LIN_INH* will be low. Upon receiving the LIN message, `LIN_ENTER_SLEEP_MODE`, the transceiver will wake up and enable the internal switch connecting *VBATT_PROT* to *LIN_INH*. This, in turn, enables the voltage regulator U1.

Resistors R10, R11, R12, R18 and R19 are pull up resistors to keep their respective nodes terminated high. Resistors R17 is a series resistor need to prevent shoot-through because the transceiver *TXD* pin can be an output during fail-safe mode. Resistors R13, R14, R15 and R16 are not required in the production design as they are used only to support alternate digital isolator ICs, including 3-channel versions.

Capacitors C11, C12 and C13 are for high frequency decoupling.

2.1.6 High-Voltage Auxiliary E-Fuse Controller

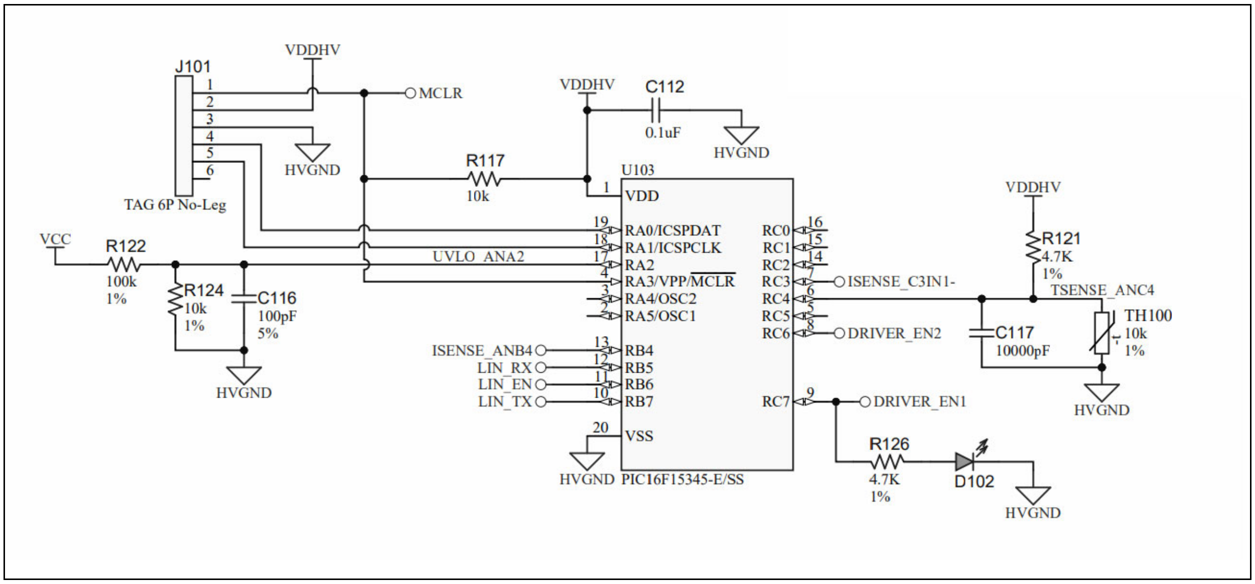


FIGURE 2-6: *High-Voltage Auxiliary E-Fuse Controller Schematic.*

Figure 2-6 is of the High-Voltage Auxiliary E-Fuse controller circuit, VCC voltage monitor circuit and temperature monitor circuit. The latter two circuits are described in detail in subsequent sections. The High-Voltage Auxiliary E-Fuse controller U103 is a Microchip PIC16F15345 8-bit microcontroller.

- The controller has the following functionality:
- Time-Current Characteristics (TCC) curve algorithm
  - Junction-temperature estimation
  - Over-current measurement
  - Short-circuit detection
- LIN communication bus
  - Enable/disable
  - TCC configuration
  - Diagnostics
- Gate drive voltage reduction
- Analog-to-digital conversion
  - Output current sensing
  - VCC voltage sensing
  - Ambient temperature sensing
- Comparator-based over-current detection and protection
- Undervoltage lockout using VCC monitor
- Over-temperature protection and diagnostics
- Over-current diagnostics

TABLE 2-1: MICROCONTROLLER U103 PINOUT.

Pin #	Port	Assigned Function	Name	Active State
1	`VDD`	+5V	VDDHV	—
2	`RA5/OSC1`	GPIO	n/c	Output low
3	`RA4/OSC2`	GPIO	n/c	Output low
4	`RA3/VPP/MCLR`	MCLR	Master Clear, MCU reset	Input low

TABLE 2-1: MICROCONTROLLER U103 PINOUT. (CONTINUED)

Pin #	Port	Assigned Function	Name	Active State
5	RC5	GPIO	n/c	Output low
6	RC4	ADC ANC4	TSENSE_ANC4	—
7	RC3	CMP2 C2IN3-	ISENSE_C3IN-	—
8	RC6	CLC2OUT	DRIVER_EN2	Output high
9	RC7	CLC1OUT	DRIVER_EN1	Output high
10	RB7	EUSART1 TX1	LIN_TX	Output high
11	RB6	GPIO	LIN_EN	Output high
12	RB5	EUSART1 RX1	LIN_RX	Output high
13	RB4	ADC ANB4	ISENSE_ANB4	Output high
14	RC2	GPIO	n/c	Output low
15	RC1	GPIO	n/c	Output low
16	RC0	GPIO	n/c	Output low
17	RA2	ADC ANA2	UVLO_ANA2	—
18	RA1/ICSPCLK	ICSP	ICSP	Input high
19	RA0/ICSPDAT	ICSP	ICSP	Input high
20	VSS	Return	HVGND	—

TABLE 2-2: MICROCONTROLLER U103 INTERNAL PERIPHERALS, CONFIGURED IN MCC.

Peripheral	Name	Setting
ADC	Analog-to-digital converter	Clock source: Frc
CLC1	Configurable logic cell 1	SR latch
CLC2	Configurable logic cell 2	SR latch
CLC3	Configurable logic cell 3	AND-OR
CLC4	Configurable logic cell 4	AND-OR
CMP2	Comparator 2	Positive reference: DACOUT
DAC1	Digital-to-analog converter 1	Positive reference: FVR_buf2
EUSART1	Enhanced universal synchronous synchronous receiver transmitter 1	Baud rate: 19200 Tx/Rx bits: 8-bit Data polarity: Non-Inverted
FVR	Fixed voltage reference	FVR_buffer2 gain: 1x (1.024V)
TMR0	Timer 0	Clock source: FOSC/4 Timer period: 1 ms Interrupt enabled
TMR1	Timer 1	Clock source: HFINTOSC Gate source: CLC1OUT Gate polarity: low
TMR2	Timer 2	Clock source: LC3_out Clock frequency: 32 MHzTimer period: 250 ns

To support in-circuit programming, Tag-Connect pads on the circuit board are at locations designated by header J101. **Because this microcontroller is in the circuit's high voltage zone, take safety precautions to ensure the circuit board is disconnected from the high voltage power supply or battery and that it is complete discharged before attaching a programmer or debugger. When the programming is complete, disconnect the programmer from the High-Voltage Auxiliary E-Fuse before re-applying high voltage power.**

Capacitor C13 is for high frequency decoupling.

Resistor R117 ensures that the microcontroller master clear MCLR is pulled high.

Resistor R126, and LED D102, are only for evaluation purposes not intended in the final design.

Timer 0 is setup with a 1 ms interrupt rate, which establishes the software's timebase. Timer 1 and Timer 2 are configured to support the ride-through triggering mode. This mode reduces the gate drive for a duration up to 63.75 µs in 250 ns steps.

The analog-to-digital converter (ADC) has a 10-bit resolution and is configured to use VDDHV as its reference.

EQUATION 2-3: ADC OUTPUT (COUNTS)

$$K_{ADCOUT} = V_{ADC,\,input} \times \left(\frac{(2^{ADCRES} - 1)counts}{VDDHV}\right)$$

EXAMPLE 2-4: ADC VOLTAGE RESOLUTION

$$V_{ADCOUT,\,res} = 5V + \left(\frac{1count}{2^{10} - 1}\right) \approx 4.88\ mV$$

The MCU's internal comparator reference is based on the internal digital-to-analog converter (DAC). The DAC uses the internal fixed voltage reference (FVR) peripheral as its reference. It has a 5-bit resolution providing configurability in a 32 voltage-level range. Using the FVR configured as 1.024V as the DAC's reference voltage, the DAC output voltage equation and output voltage resolution are given below. The `DAC1R` register determines the DAC's output voltage.

EQUATION 2-4: DAC OUTPUT VOLTAGE

$$V_{DACOUT} = V_{FVR} \times \left(\frac{DAC1R\langle 4{:}0\rangle}{2^{DACRES} - 1}\right)$$

EXAMPLE 2-5: DAC OUTPUT VOLTAGE RESOLUTION

$$V_{DACOUT,\,res} = 1.024V \times \left(\frac{1}{2^{5} - 1}\right) \approx 33\,mV$$

Therefore, the comparator can be configured with a voltage reference level resolution of 33 mV. In this High-Voltage Auxiliary E-Fuse design, given the shunt resistance and operation amplifier gain, the 33 mV comparator input voltage corresponds to an output current of 33A. This allows the High-Voltage Auxiliary E-Fuse fast, hardware-based short-circuit detection to be configured in multiples of 33A up to 1024A.

The comparator output, *CMP2OUT*, connects to configurable logic cell 1 (CLC1). The state of CMP2OUT is active-high during a short-circuit. CLC1 is configured as an SR latch as shown in Figure 2-7 below. As shown in the microcontroller pinout table, the output of CLC1, *CLC1OUT*, connects to RC7/U103 pin 9, which controls the state of the gate driver IC. During a short-circuit event, the comparator triggers CLC1 to output a low to the gate driver IC input. As will be discussed in subsequent sections, this reduces the gate drive voltage to allow increased short-circuit withstand time for ride-through mode.

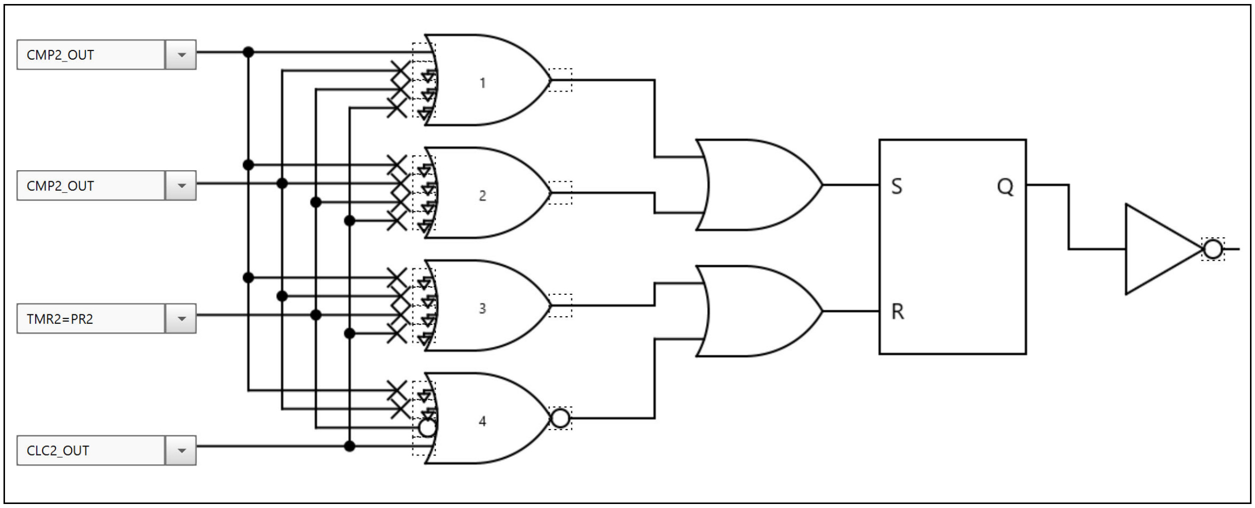


FIGURE 2-7: *Configurable Logic Cell 1.*

In addition to connecting to U103 pin 9, *DRIVER_EN1*, the output of CLC1 connects to Timer 1 and CLC3. Timer 1 is gated with the low state of *CLC1OUT*. If Timer 1 overflows, the High-Voltage Auxiliary E-Fuse will turn off the SiC MOSFET(s). This is implemented using CLC2 configured as an SR latch as shown in Figure 2-8 below. The output of CLC2, *CLC2OUT*, connects to U103 pin 8, *DRIVER_EN2*. This drives an N-channel MOSFET to discharge the SiC MOSFET(s) gate, turning it off. For edge-triggered mode, the same logic is used but with Timer 1 configured to overflow after one clock tick, with a resolution of 250 ns.

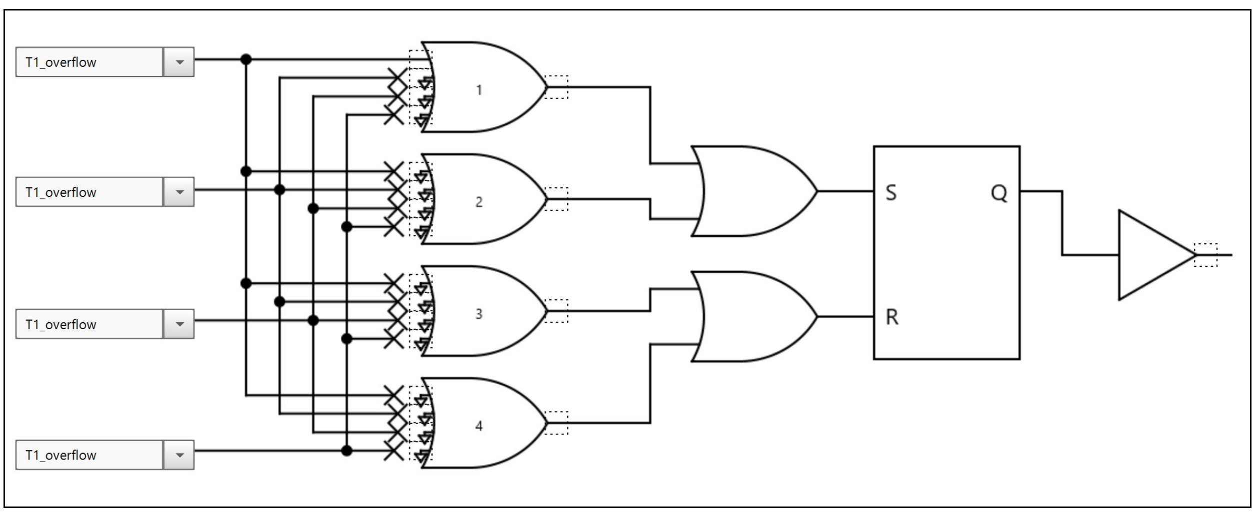


FIGURE 2-8: *Configurable Logic Cell 2.*

To support ride-through mode, additional logic is implemented. CLC3 is configured as an AND-OR gate as shown below in figure Figure 2-9. The output of CLC3, *CLC3OUT*, is the *HFINTOSC* clock gated with the active low state of *CLC1OUT*. This becomes the clock source for Timer 2. The timer increments during short-circuit events but does not automatically clear in the case of transient events. This enables the detection of multiple transient, short-circuit events within a brief period of time.

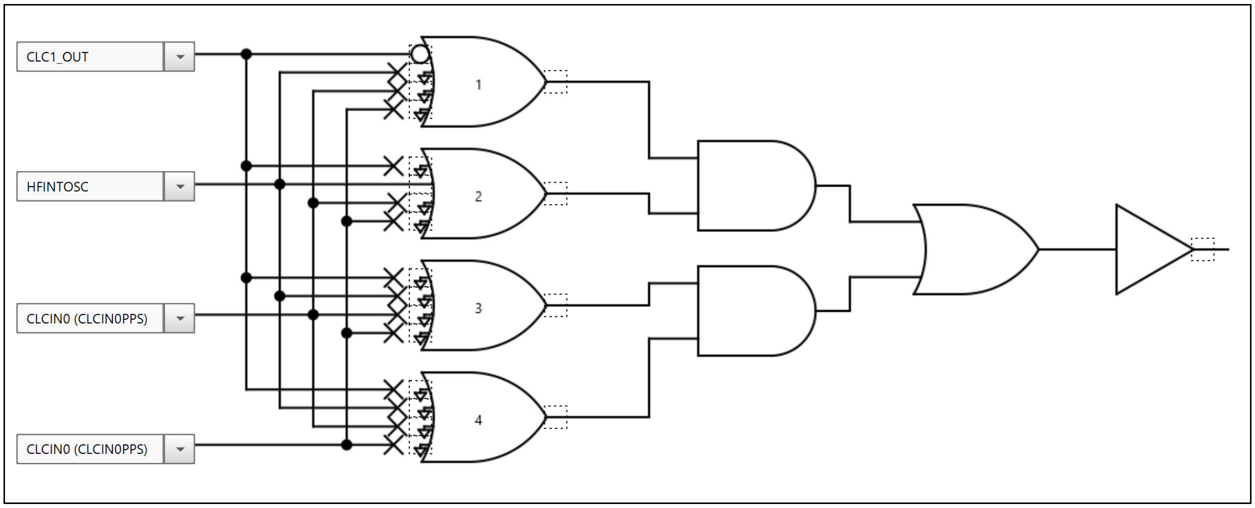


FIGURE 2-9: *Configurable Logic Cell 3.*

If Timer 2 overflows, the *TMR2-PR2* flag is set. The flag connects to CLC1 in order to drive its output low, keeping the gate driver IC input low. Because this flag is not readable by software, it is processed into a readable signal using CLC4. CLC4, as shown in the figure Figure 2-10 below, is configured as a non-inverter buffer. The CLC4 output, *CLC4OUT*, is polled by the software to reset the Timer 2 holding register `T2TMR`. This is to ensure that the timer does not slowly increment over a long period of time due to occasional brief events.

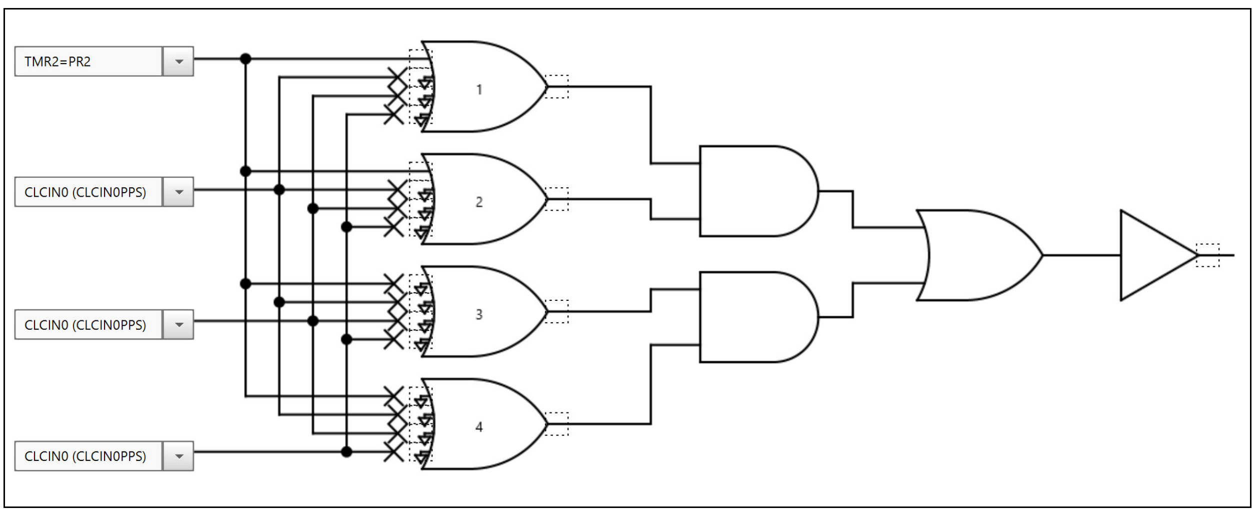


FIGURE 2-10: *Configurable Logic Cell 4.*

2.1.7 Current Sense

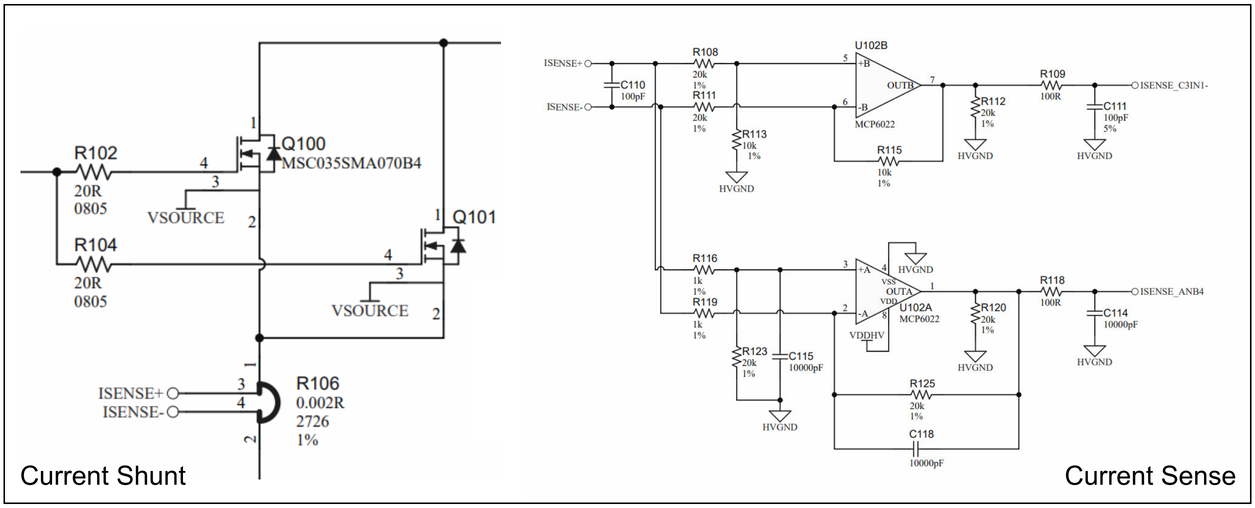


FIGURE 2-11: *Current Shunt (Left) and Current Sense (Right) Schematics.*

To achieve a fast response time to short-circuits, a wide-bandwidth current sense circuit as shown in Figure 2-11 is implemented. The current sensing circuit uses a low-inductance shunt resistor R106. The shunt is monitored by two independent differential amplifier circuits. The operational amplifiers are packaged in the same device, a Microchip MCP6022 dual rail-to-rail input/output operational amplifier with 10 MHz gain-bandwidth product. However, the two circuits are configured differently in terms of gain and bandwidth.

The sensing path using U102B has a gain determined by the resistors R108, R111, R113, and R115. This allows full use of the operation amplifier's bandwidth. Because the circuit is configured as a differential amplifier, resistors R113 and R115 should be equal as should resistors R108 and R111.

EXAMPLE 2-6: U102B VOLTAGE GAIN

$$A_{U102B} = \frac{R_{115}}{R_{111}} = \frac{10\ k\Omega}{20\ k\Omega} = 0.5$$

As the shunt's resistance is 2 mΩ, the total gain of this current sensing path is:

EQUATION 2-5:

$$V_{U102B} = I_{R106} \times R_{R106} \times A_{U102B}$$

U102B output voltage

$$V_{U102B} = I_{R106} \times 2\,m\Omega \times 0.5 = I_{R106} \times 1\,m\Omega$$

Shunt current to U102B voltage conversion

Therefore, a simple conversion of 1A per 1 mV is achieved. As discussed above, the microcontroller's on-board comparator is setup with a configurable reference in steps of 33 mV, which equates to 33A in this design.

Resistor R109 and capacitor C111 form a placeholder for a first-order low pass filter with a high-cutoff frequency. This can be configured with the design cutoff frequency based on the system requirements. The time constant should be kept in mind as it delays the signal to the comparator and over system response time to short-circuits.

EQUATION 2-6: FILTER TIME CONSTANT EQUATION

$$\tau = R109 \times C111$$

EXAMPLE 2-7: FILTER TIME CONSTANT RESULT

$$\tau = 100\Omega \times 100\ pF = 10\ ns$$ Filter time constant result

$$fc = \frac{1}{2\pi\tau} = 15.9\ MHz$$ Low pass filter cutoff frequency

Capacitor C110 has a low capacitance, intended as a placeholder to stabilize the shunt voltage when subjected to RF disturbances.

The second current sensing path using U102A is configured with increased gain for higher-resolution at lower currents as well as a low pass filter with a lower cutoff frequency. The output of this circuit connects to the microcontroller's analog input.

This circuit is also configured as a different amplifier, therefore, resistors R116 and R119, resistors R123 and R125 and capacitors C115 and C118 should be equal. The DC gain for this circuit is:

EXAMPLE 2-8:

$$A_{U102A} = \frac{R_{125}}{R_{119}} = \frac{20\ k\Omega}{1\ k\Omega} = 20$$ U102A DC voltage gain

Accounting for the shunt's resistance of 2 mΩ, the total gain of this current sensing path is:

EQUATION 2-7:

$$V_{U102A} = I_{R106} \times R_{R106} \times A_{U102A}$$ U102B output voltage

$$V_{U102A} = I_{R106} \times 2\ m\Omega \times 20 = I_{R106} \times 40\ m\Omega$$ Shunt current to U102B voltage conversion

Therefore, the conversion from current to voltage is 1A results in 40 mV at the output of this circuit. Since the ADC uses VDDHV as its reference, the maximum current that can be read with this circuit is:

EXAMPLE 2-9:

$$A_{U102A,\,max} = \frac{5V}{40\ m\Omega} = 125A$$

The current measurement resolution is:

EXAMPLE 2-10:

$$V_{I\_ADCres} = \frac{V_{I\_ADCres}}{V_{U102A}} = \frac{V_{I\_ADCres}}{I_{R106} \times 40\ m\Omega} \approx \frac{4.88\ mV}{1A \times 40\ m\Omega} \approx 122\ mA$$

Resistor R109 and capacitor C111 form a placeholder for a first-order low pass filter with a high-cutoff frequency. This can be configured with the design cutoff frequency based on the system requirements. The time constant should be kept in mind as it delays the signal to the comparator and over system response time to short-circuits.

EXAMPLE 2-11:

$\tau = R125 \times C118$	Filter time constant equation
$\tau = 20\ k\Omega \times 10000\ pF = 200\ \mu s$	Filter time constant result
$fc = \frac{1}{2\pi\tau} = 800\ Hz$	Low pass filter cutoff frequency

Resistor R118 and capacitor C114 form a placeholder for an additional first-order low pass filter. This can be configured with the design cutoff frequency based on the system requirements. The time constant should be kept in mind as it delays the signal.

EXAMPLE 2-12:

$\tau = R118 \times C114$	Filter time constant equation
$\tau = 100\Omega \times 10000\ pF = 1000\ ns$	Filter time constant result
$fc = \frac{1}{2\pi\tau} = 159\ kHz$	Low pass filter cutoff frequency

Capacitor C114, in addition to being used in the low pass filter, also serves as a low-impedance charge well for the ADC’s analog input.

Resistors R112 and R120 are placeholders providing a constant DC bias in addition to the feedback path.

The shunt resistor, R106, is a Vishay Power Metal Strip® 2 mΩ resistor, part number WSLP27262L000FEA. This has a nominal power rating of 5W at 70°C, maximum operating temperature of 170°C and an inductance of less than 5 nH. A 7W version is available for resistances of ≤1 mΩ. Example 2-13 shows the calculation for the shunt resistor's current capability. Depending on the substrate or circuit board temperature limitations, it may need to be de-rated to a lower current.

The thermal resistance is provided by the manufacturer, allowing analysis similar that done on power semiconductors.

EXAMPLE 2-13:

$$T_J = T_A + R_{THJA} \times (I_{R106}^2 \times R_{R106})$$

$$I_{R106} = \sqrt{\frac{T_J - T_A}{R_{THJA} \times R_{R106}}}$$

$$I_{R106,\,max} = \sqrt{\frac{170°C - 85°C}{16\frac{°C}{W} \times 2\ m\Omega}} = 51.5A$$

This current is the shunt resistor's maximum continuous current capability. This continuous current capability applies to transient currents with durations greater than 1 second. Transient currents are limited by its energy capability of 10 J nominal. However, derating for temperature it is recommended to limit the transient energy to 5J, satisfying the following inequality:

EQUATION 2-8:

$$\int_0^{t_p} (i_{R106}(t))^2 \times 2\ m\Omega\ dt \le 5J$$

The maximum shunt current capability limits the over-current detection and programmed in the software in constant `ISHUNT_CURRENT_MAX` with a value of 422 counts.

EXAMPLE 2-14:

$$K_{shunt} = \frac{I_{R106,\,max}}{V_{I\_ADCres}} = 422\ counts$$

2.1.8 Gate Drive Circuit

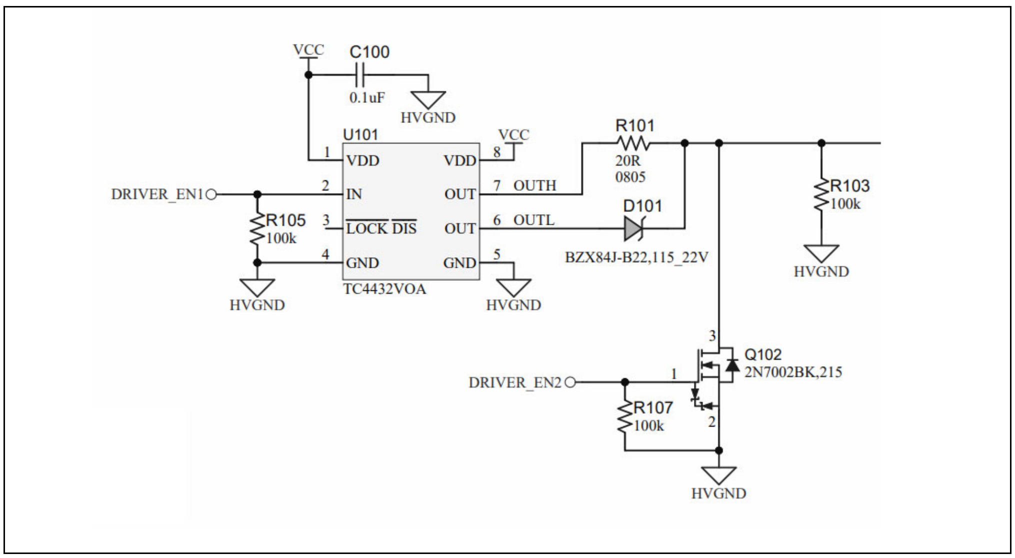


FIGURE 2-12: *Gate Drive Schematic.*

Figure 2-12 is the SiC MOSFET gate drive circuit. It is powered by VCC, which is about 24V with respect to HVGND. Both inputs, DRIVER_EN1 and DRIVER_EN2 are signals from the microcontroller. A logic high on DRIVER_EN1 enables the high side output of U101, Microchip TC4432VOA 1.5A, 30V MOSFET gate driver with split outputs. Pin 7 is the high side output and pin 6 is the low side output. This applies VCC to the SiC MOSFET gate resulting in a turn-on gate to source voltage of:

EXAMPLE 2-15:

$$V_{GS,\,on} = VCC - VSOURCE$$ SiC MOSFET $V_{GS,on}$ equation

$$V_{GS,\,on} = 23.8V - 3.7V = 20.1V$$ SiC MOSFET $V_{GS,on}$ calculation

U101 high side output resistance, resistor R101 and a downstream resistor in series combine to form the turn-on gate resistance.

A logic low on *DRIVER_EN1* enables the low side output of U101 to support ride-through mode, which reduces the SiC MOSFET's gate voltage to increase the short-circuit withstand time. The Zener diode D101 voltage rating can be selected to achieve the desired reduced gate voltage. The duration in this mode also depends on the SiC MOSFET's input capacitance, as it holds the charge to maintain a constant voltage at the gate. However, resistor R103 does provide a discharge path that must be considered in determining the target duration.

DRIVER_EN2 enables Q102, a 60V, 300 mA, N-channel MOSFET. This can only be set to a logic high when *DRIVER_EN1* is a logic low. When enabled, Q102 provides the discharge path to *HVGND*, which turns off the SiC MOSFET.

EXAMPLE 2-16:

$V_{GS,\,off} = HVGND - VSOURCE$	SiC MOSFET $V_{GS,off}$ equation
$V_{GS,\,off} = 0V - 3.7V = -3.7V$	SiC MOSFET $V_{GS,off}$ calculation

Resistors R103, R105 and R107 ensure the driver and SiC MOSFET are off when unpowered.

Capacitor C100 is a high frequency decoupling capacitor.

2.1.9 SiC Power MOSFETs

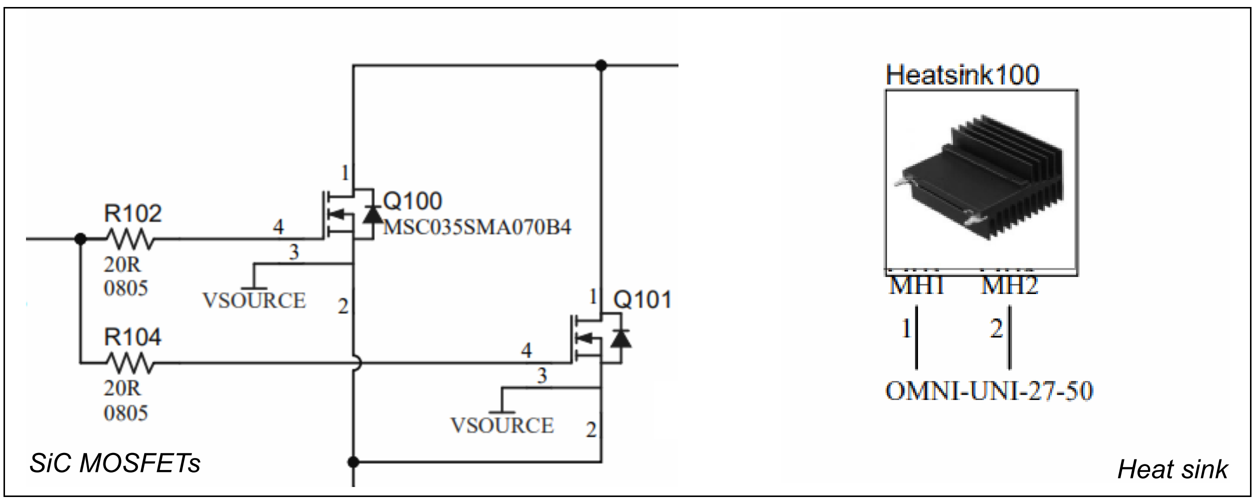


FIGURE 2-13: *SiC MOSFETs (Left) and Heat Sink (Right) Schematic.*

Figure 2-13 has the circuit for the gate resistors, SiC MOSFETs, and heat sink. As mentioned above, there is a gate resistor in series with the gate driver high side output. The resistance of the gate driver high side output, resistor R101 and resistors R102/R104 form the total turn on gate resistance. The turn off resistance is determined by the $R_{DS(on)}$ of Q102 (see Figure 2-12) and resistance of R102 and R104.

The SiC MOSFETs Q100 and Q101 are in a TO-247 4-lead package. This package provides access to the Kelvin source, which is wire bonded directly to the die, bypassing the effect of *di/dt* in the source inductance. This provides greater control over the SiC MOSFET, especially during fast, high current transient conditions. The circuit layout includes slots and sufficient creepage distance to accommodate both 700V and

1200V SiC MOSFETs. The heat sink, Wakefield-Vette OMNI-UNI-27-50, has a length of 50 mm and uses two clips, Wakefield-Vette OMNI-UC, to mount two TO-247 MOSFETs. The circuit board also accommodates a single MOSFET/heat sink configuration. In this case, the heat sink part number is Wakefield-Vette OMNI-UNI-27-25, which has a length of 25 mm and uses one clip. The electrically-insulating thermal interface material (TIM) part number is Parker Chomerics 66-10-0505-T609. This includes an acrylic pressure sensitive adhesive (PSA).

Depending on the target voltage and current rating, the High-Voltage Auxiliary E-Fuse design may be populated with the devices as shown in the table below:

High-Voltage Auxiliary E-Fuse Variant	Rating	Q100	Q101	Heatsink100
A	10A, 400V	MSC035SMA070B4	—	OMNI-UNI-27-25
B	20A, 400V	MSC035SMA070B4	MSC035SMA070B4	OMNI-UNI-27-50
C	30A, 400V	MSC015SMA070B4	MSC015SMA070B4	OMNI-UNI-27-50
D	10A, 800V	MSC040SMA120B4	—	OMNI-UNI-27-25
E	20A, 800V	MSC040SMA120B4	MSC040SMA120B4	OMNI-UNI-27-50
F	30A, 800V	MSC025SMA120B4	MSC025SMA120B4	OMNI-UNI-27-50

The heat sink is intended for evaluating the High-Voltage Auxiliary E-Fuse design. A production design may rely on alternative methods of cooling within the vehicle. This may allow for high current capability than that listed in the table above.

The SiC MOSFET power dissipation is calculated:

EQUATION 2-9:

$$P_D = I_D^2 \times R_{DS(on)}$$

See the section on the test results for more details on thermal calculations.

2.1.10 Snubber

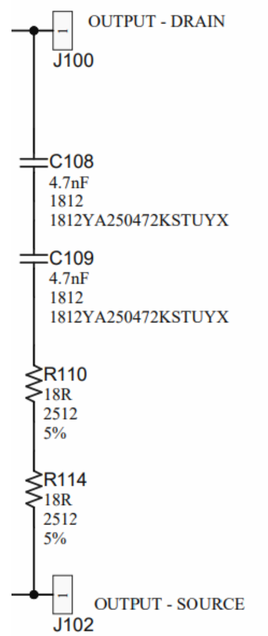


FIGURE 2-14: *Snubber Schematic.*

The design provides for a snubber circuit as shown in Figure 2-14. These are not populated but the pads are available if a snubber is required. Capacitors C108 and C109 are high voltage, automotive-grade, safety capacitors in an 1812 surface-mount package. The two capacitors are connected in series and placed on the board perpendicular to each other to minimize the effect of fault conditions, such as cracked capacitors. Resistors R110 and R114 are in series to split both voltage and the power dissipation. The resistors are in 2512 surface-mount packages. Depending on the system requirements, an external snubber with higher power capability may be required.

If operating the High-Voltage Auxiliary E-Fuse in ride-through mode, the reduced gate voltage extends the short-circuit withstand time. However, the increased duration of the SiC MOSFET during an over-current event can result in significantly higher currents. This, in turn, increases the system’s inductive energy:

EQUATION 2-10:

$$E_L = \frac{1}{2}L \times \Delta I^2$$

Therefore, when running the High-Voltage Auxiliary E-Fuse in ride-through mode, consider the impact of system inductance and the duration of the reduced gate drive. The reduced drive increases the withstand time but also increases losses in the SiC MOSFET. Switching off the SiC MOSFET after some duration, the additional inductive energy may exceed its avalanche capability, potentially requiring a snubber or clamp circuit.

2.1.11 Temperature Sensing

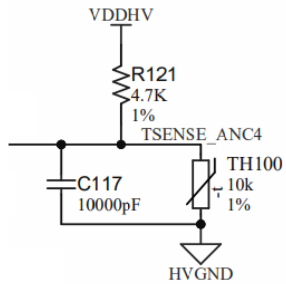


FIGURE 2-15: Temperature Sense Schematic.

Figure 2-15 is of the temperature sense circuit. This is based on a negative temperature coefficient (NTC) thermistor. The thermistor TH100, Murata NCU18XH103F6SRB, is in an 0603 surface-mount package with a nominal resistance at 25°C of 10 kΩ and B-constant of 3380K. The thermistor and resistor R121 form voltage divider. The value of R121 was selected using Murata’s web-based SimSurfing NTC thermistor simulation tool. Capacitor C117 stabilize the voltage, forming a low pass filter, as well as a low impedance charge well for the ADC’s analog input. A lookup table is implemented in the software to correlate the voltage measurement with a temperature. Additionally, the circuit board layout includes two plated-through holes (PTHs) providing the option of wiring a thermistor to the heat sink for a higher accuracy in place of TH100.

2.1.12 VCC Supply Monitor

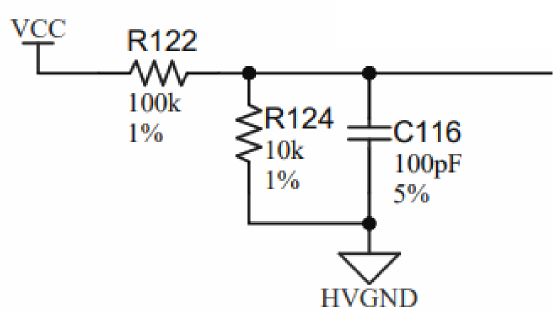


FIGURE 2-16: VCC Monitor Schematic.

Figure 2-16 is the VCC supply monitor. Resistors R122 and R124 and capacitor C116 is a voltage divider and low pass filter, providing a scaled, filtered version of VCC to the microcontroller analog input

EXAMPLE 2-17:

$$A_{VCC} = \frac{R124}{R122 + R124}$$ VCC monitor DC gain equation

$$A_{VCC} = \frac{10\,k\Omega}{100\,k\Omega + 10\,k\Omega} = 0.\overline{09}$$ VCC monitor DC gain calculation

The monitor circuit has a measurement range and resolution of:

EXAMPLE 2-18:

$$VCC_{ADC,\,max} = \frac{VDDHV}{A_{VCC}} = \frac{5V}{0.\overline{09}} = 55V$$ VCC maximum measurement capability

$$VCC_{ADCres} = \frac{V_{ADC,\,res}}{A_{VCC}} \approx \frac{4.88\,mV}{0.\overline{09}} \approx 53.8\,mV$$ VCC measurement resolution

The circuit cutoff frequency is:

EXAMPLE 2-19:

$$R_{TH,\,VCC} = \frac{R122 \times R124}{R122 + R124} = \frac{100\,k\Omega \times 10\,k\Omega}{100\,k\Omega + 10\,k\Omega} = 9.\overline{90}\,k\Omega$$ Thevenin equivalent

$$\tau = R_{TH,\,VCC} \times C116 = 0.\overline{90}\,\mu s$$ VCC monitor DC gain calculation

$$f_c = \frac{1}{2\pi\tau} = \frac{1}{2\pi(0.\overline{90}\,\mu s)} = 175\,kHz$$ VCC monitor cutoff frequency

Capacitor C116 also provides a low impedance charge well for the ADC’s analog input.

2.2 HIGH VOLTAGE ISOLATION

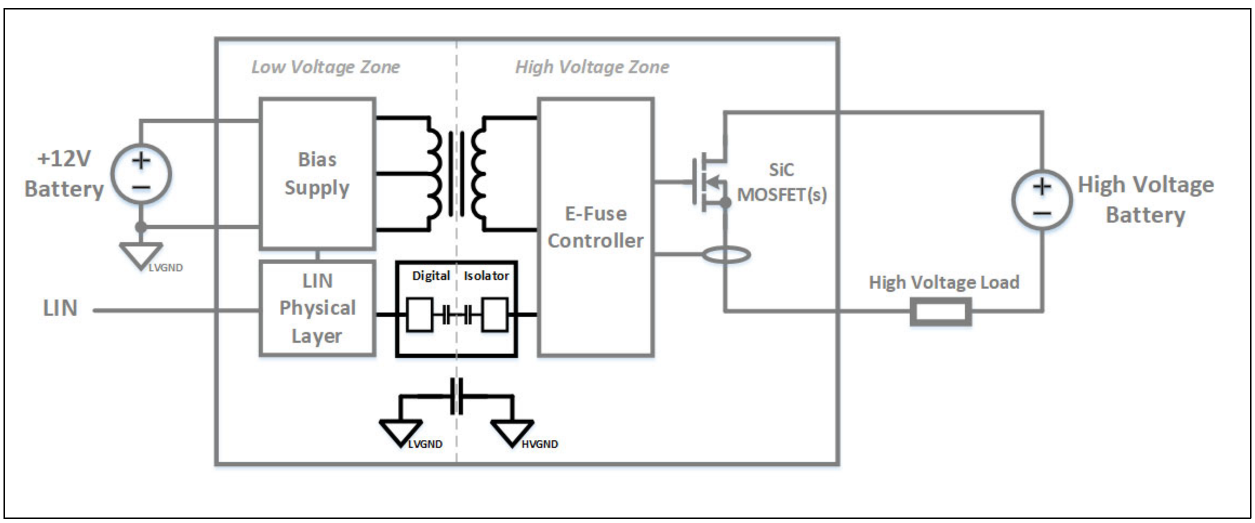


FIGURE 2-17: Isolation of Components.

As shown in Figure 2-17, the transformer, digital isolator IC, and a safety capacitor cross the isolation barrier (separating the low voltage and high voltage zones). Additionally, the printed circuit board (PCB) also should be considered.

2.2.1 Transformer

The transformer part number is Wuerth 760390014. It is qualified to AEC-Q200 with an operating temperature range of –40°C to 125°C. The primary to secondary dielectric rating is 3125 V_{RMS} for 1 second and 2500 V_{RMS} for 1 minute.

2.2.2 Digital Isolator IC

The digital isolator IC part number is Texas Instruments ISO7342FCQDWRQ1. It is qualified to AEC-Q100 with an operating temperature range of –40°C to 125°C. The device is in a wide-body SOIC-16 package. The comparative tracking index (CTI) rating is > 400V, per DIN EN 60112. The creepage and clearance distance is specified as > 8 mm. The isolation rating is 3 kV_{RMS} for 1 minute.

2.2.3 Safety Capacitor

The safety capacitor part number is Knowles 1812YA250472KSTUYX. It is qualified to AEC-Q200 with an operating temperature range of –55°C to +125°C. The capacitor is in an 1812 package. The safety capacitor has a Y2/X1 class rating. The voltage with-stand capability is rated to 4000V for 1 minute. The CTI rating is ≥ 600V.

2.2.4 Printed Circuit Board

The High-Voltage Auxiliary E-Fuse PCB layout separates the LV and HV zones so that they do not overlap between layers. The PCB creepage distance between these zones is 9 mm. This is implemented using non-plated through hole (NPTH) slots. The figure below shows the separation of the zones on the top side using a slot in the PCB.

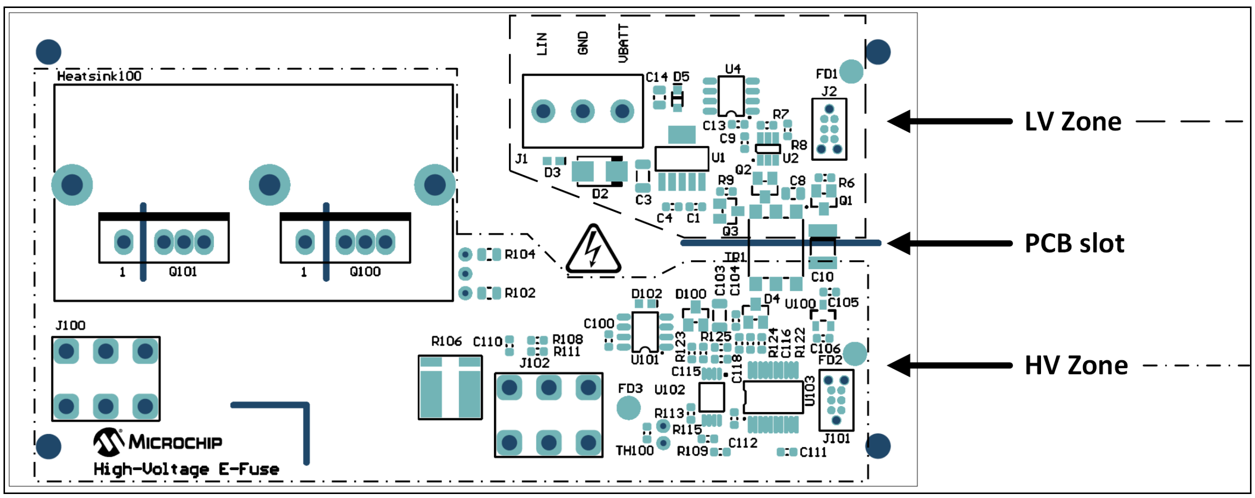


FIGURE 2-18: PCB Creepage.

2.3 SOFTWARE FUNCTIONALITY

The flowchart in Figure 2-19 shows the `main` () functionality from power-on reset. The High-Voltage Auxiliary E-Fuse output is enabled following initialization and enabling of the interrupts. A `while` loop is then continually executed, calling the LIN handler and the High-Voltage Auxiliary E-Fuse function.

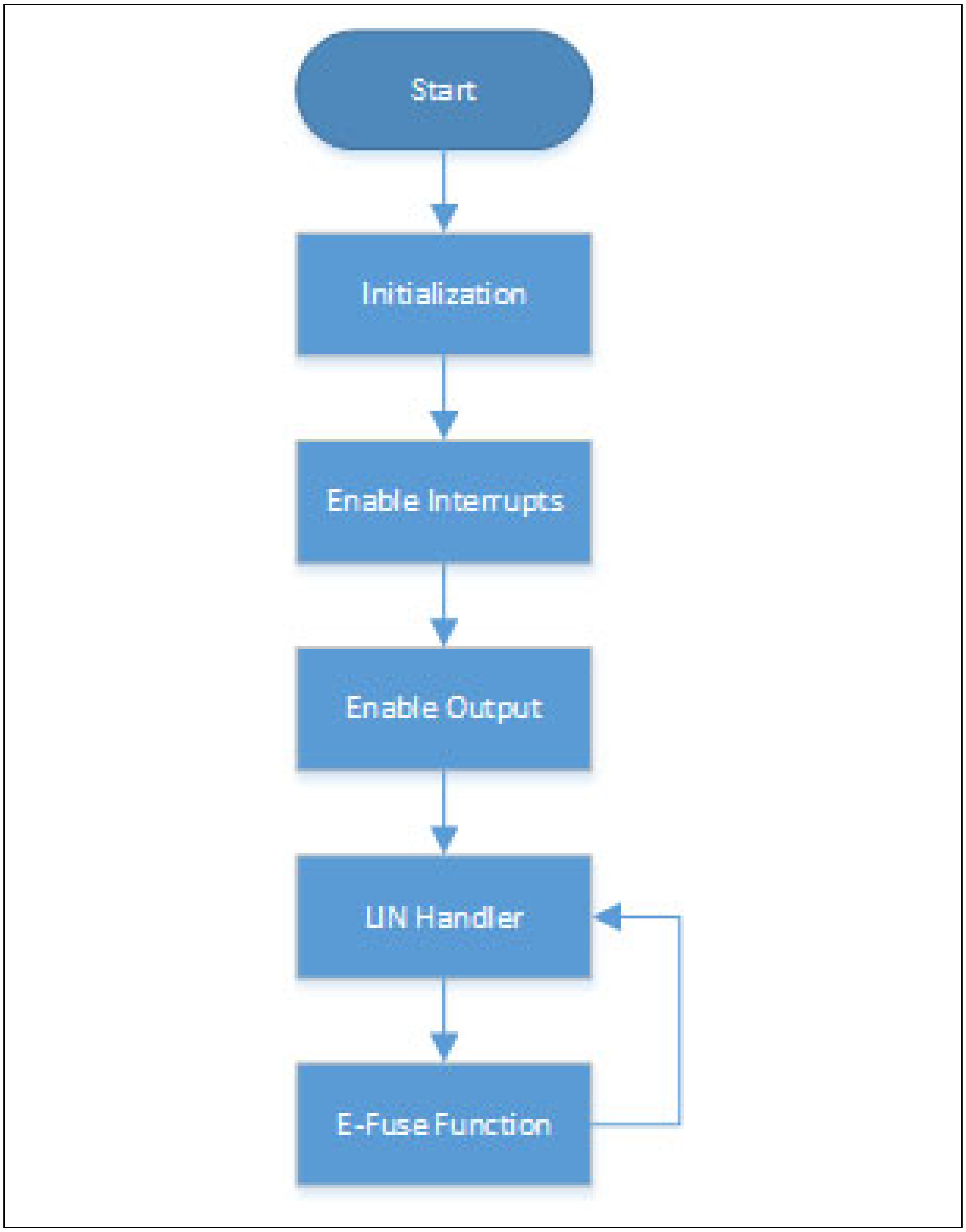


FIGURE 2-19: *`Main` () Flowchart.*

Figure 2-20 is the flowchart for the High-Voltage Auxiliary E-Fuse function. Each time it is called, it checks if a hardware-trip had occurred, and sets the fault accordingly. This is for the short-circuit, detection method 3. Periodically, based on the software settings, it will execute the TCC algorithm, for detection method 1, and set 'slow over-current' and over-temperature faults accordingly. The ADC-based current, VCC, and the ambient temperature analog inputs are measured periodically and called from the 1 ms Timer0 interrupt service routine.

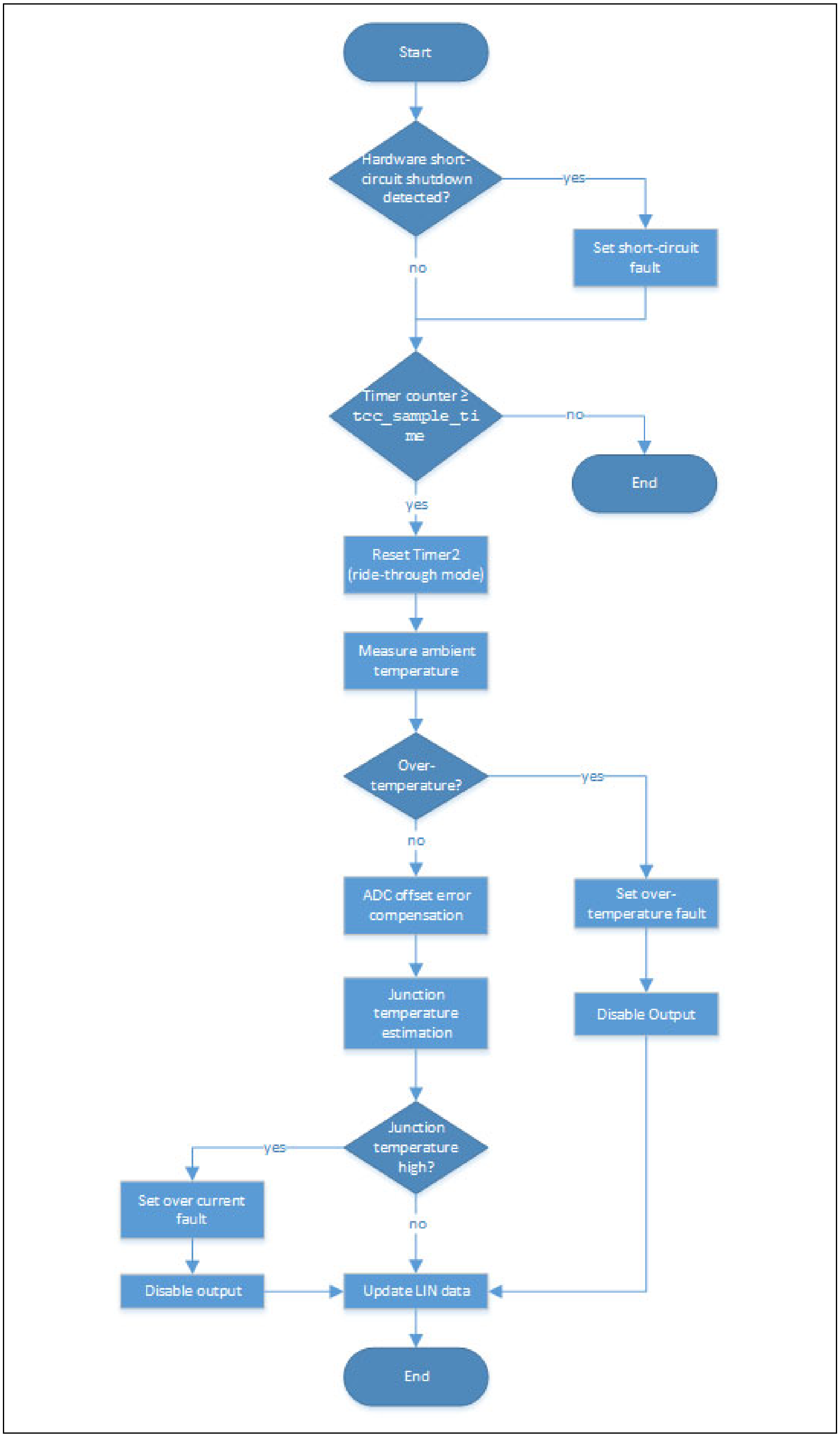


FIGURE 2-20: `EFuse` *() Flowchart.*

2.4 LIN COMMUNICATION

The tables below have the LIN messages to command, configure and check status of the High-Voltage Auxiliary E-Fuse over the LIN bus. The High-Voltage Auxiliary E-Fuse is setup as a secondary node and the baud rate is 19,200 Kbps. The format of the data is unsigned 8-bit or 16-bit integers, except for temperature related messages, which are signed 16-bit integers. Both signed and unsigned 16-bit integers are least significant byte (LSB) first.

2.4.1 Host to High-Voltage Auxiliary E-Fuse

Message Name	Message ID	Length	Description
LIN_COMMAND	0x00	1	0 = off, 1 = on
LIN_TRIGGER_TYPE	0x01	1	0 = edge triggered mode, 1 = ride-through mode
LIN_ENTER_SLEEP_MODE	0x02	1	Enters sleep mode
LIN_TJ_LIMIT	0x10	1	1°C resolution, max 255°C
LIN_FACTOR_RDSON_RTHJS	0x11	2	By characterization
LIN_FACTOR_RDSON_RTHSA	0x12	2	By characterization
LIN_CURRENT2COUNTS_SQUARED	0x13	2	By characterization
LIN_ISENSE_MAX	0x14	2	0.1222A res., 125A max
LIN_DAC_I_HW_TRIP	0x15	1	33A res., 1023A max
LIN_B1_COEF	0x16	1	By characterization
LIN_REDUCED_DRIVE_TIME	0x17	1	250 ns res., max 63.75 us
LIN_TCC_SAMPLE_TIME	0x18	2	1 ms res., max 65535 ms

The LIN_COMMAND message is used to turn on or off the SiC MOSFETs.

2.4.2 High-Voltage Auxiliary E-Fuse to Host

Message Name	Message ID	Length	Description
LIN_OUTPUT_STATE	0x20	1	0 = off, 1 = on
LIN_GET_TRIGGER_TYPE	0x21	1	0 = edge-triggered mode, 1 = ride-through mode
LIN_OVER_CURRENT_FAULT	0x22	1	0 = no fault 1 = slow over-current (T_j estimation-based) 2 = fast over-current (ADC-based current) 3 = short-circuit (HW comparator-based)
LIN_UVLO_FAULT	0x23	1	0 = no fault, 1 = fault
LIN_OVER_TEMP_FAULT	0x24	1	1 = over temp. 2 = sensor OORL 3 = sensor OORH
LIN_ADC_VCC_SENSE	0x25	2	0.0538V res., 55V max
LIN_ADC_CURRENT_SENSE_UNCORRECTED	0x26	2	0.1222A res., 125A max
LIN_ADC_TEMP_SENSE	0x27	2	See look-up table, LSB first
LIN_ADC_TEMP_SENSE_CORRECTED	0x28	2	0.1222A res., 125A max
LIN_CURRENT_SENSE_OFFSET	0x29	2	0.1222A res., 1.22A max
LIN_AMBIENT_TEMPERATURE	0x2A	2	1°C res., –40°C to 125°C range, signed integer
LIN_HEATSINK_TEMPERATURE	0x2B	2	1 °C res. , signed integer
LIN_JUNCTION_TEMPERATURE	0x2C	2	1 °C res. , signed integer
LIN_TEMPERATURE_RISE_JS	0x2D	2	1 °C res. , signed integer
LIN_TEMPERATURE_RISE_SA	0x2E	2	1 °C res. , signed integer

As described by the messages’ names, `LIN_OUTPUT_STATE` returns the state of the SiC MOSFETs and `LIN_GET_TRIGGER_TYPE` returns the trigger mode the software is configured to; edge-triggered mode or ride-through mode.

2.4.3 LIN Serial Analyzer

The High-Voltage Auxiliary E-Fuse uses a standard LIN interface. Microchip offers a LIN serial communication tool, LIN Serial Analyzer. The Microchip part number is APG-DT001.

A free LIN graphical user interface (GUI), LIN Serial Analyzer Debug Tool, is available for download. The GUI, shown in the figure below, enables serial communications with the High-Voltage Auxiliary E-Fuse. The LIN message frames can be entered manually below or saved in an initialization (*.ini) file, as in the example shown below. The file contains the messages and the baud rate.

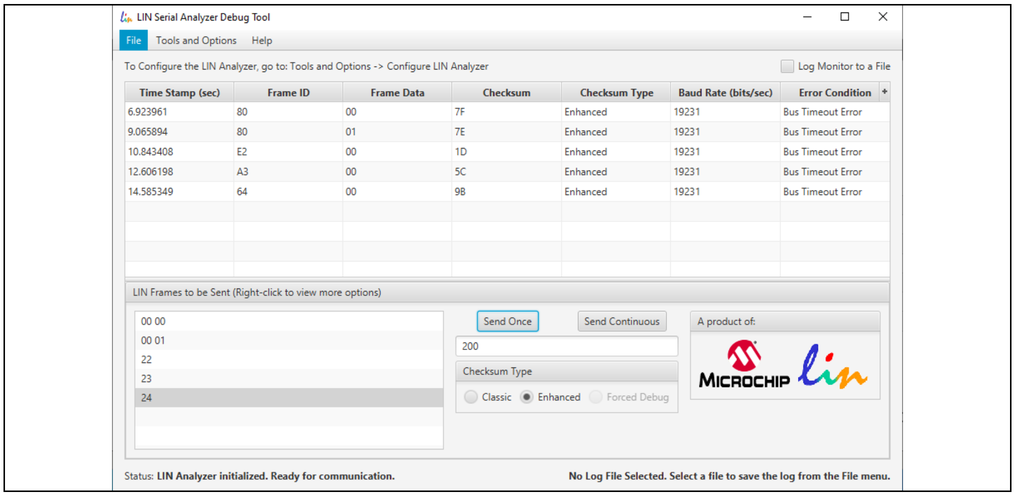


FIGURE 2-21: LIN GUI.

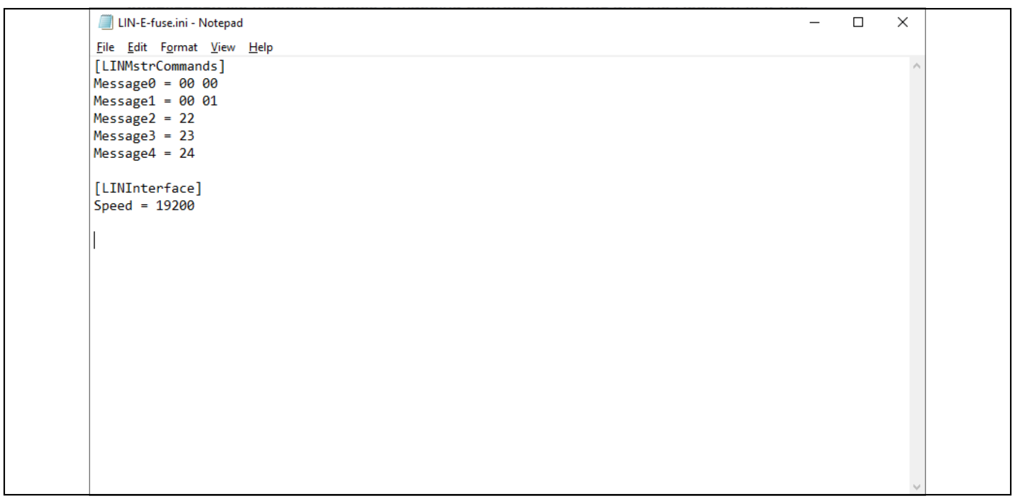


FIGURE 2-22: LIN INI.

2.5 DIAGNOSTICS

2.5.1 Output Current Measurement Diagnostic

The time-current characteristic curve for this High-Voltage Auxiliary E-Fuse design is formed by three detection methods: junction-temperature estimation, over-current measurement, and short-circuit detection. Fault status associated with high output current is available using the LIN message `LIN_OVER_CURRENT_FAULT`.

The junction-temperature estimation triggers a fault when the estimated junction temperature calculation exceeds the software variable `tj_limit`. On power-on reset (POR), this variable is loaded with a default value defined by constant `TJ_LIMIT`. It is also configurable over LIN using message `LIN_TJ_LIMIT`. This updates the variable only and it is not stored in non-volatile memory. The variable and constant both are in units of degrees Celsius.

The over-current measurement triggers a fault when the ADC-based current measurement exceeds the value set in software variable `isense_max`. On power-on reset (POR), this variable is loaded with a default value defined by constant `ISENSE_MAX`. It is also configurable over LIN using message `LIN_ISENSE_MAX`. This updates the variable only and it is not stored in non-volatile memory. The variable and constant both are in units of ADC counts, with each count approximately 122 mA. For example, a value of 368 counts corresponds to a 45A threshold.

The short-circuit detection triggers a fault when the Timer1 overflows, which is due to an over-current detection by the comparator. The comparator reference is configured by software variable `dac_i_hw_trip`. On power-on reset (POR), this variable is loaded with a default value defined by a constant defined in the enumeration `HW_TRIP_CURRENT_THRESHOLD`. It is also configurable over LIN using message `LIN_DAC_I_HW_TRIP`. This updates the variable only and it is not stored in non-volatile memory. The variable and constant both are in units of DAC counts, with each count approximately 33A.

2.5.2 VCC Supply Measurement Diagnostic

The VCC supply monitor is used to ensure sufficient voltage is available to the gate driver IC and SiC MOSFET, functioning as an undervoltage lockout (UVLO) feature. The UVLO status is available over LIN using message `LIN_UVLO_FAULT`.

The threshold, in ADC counts, is configured as a software constant, `VCCSENSE_MIN`. For example, a threshold of 372 counts establishes a UVLO threshold of:

EXAMPLE 2-20:

$$V_{ULVO} = VCC_{ADCres} \times 372\,counts = 20V$$

Note that this threshold is with respect to HVGND, not the SiC MOSFET source voltage, VSOURCE. A V_{UVLO} of 20V corresponds to a V_{GS} of approximately 16.3V.

2.5.3 Ambient Temperature Measurement Diagnostic

The status of the ambient temperature sensor is available using LIN message `LIN_OVER_TEMP_FAULT`. The three faults related to the ambient temperature measurement are: exceeded maximum ambient temperature, temperature sensor out-of-range low (OORL) and temperature sensor out-of-range high (OORH).

The threshold for the maximum ambient temperature is configured as software constants, `TEMP_MAX_AMBIENT`. The unit for this constant is in degrees Celsius.

The software constants setting the OORL and OORH thresholds are `TEMP_SENSE_OORL` and `TEMP_SENSE_OORH`, respectively. These constants are in units of ADC counts. For example, an OORL setting of 10 counts corresponds to approximately 50 mV at the ADC analog input and an OORH setting of 1013 corresponds to 4.95V. In this case, the software will set an OORL fault if the analog voltage falls below 50 mV or an OORH fault if the voltage exceeds 4.95V.

2.6 THERMAL CHARACTERIZATION

Figure 2-23 shows the heat sink temperature measurement at rated current and room temperature for each of the six High-Voltage Auxiliary E-Fuse variants. Variants A through E range from 55°C to 71°C, which is good performance. However, variant F is an outlier with max temperature of 83°C. At elevated temperatures variant F will have less margin than the others. Note that the thermal design is not production-intent but instead allows evaluation of the High-Voltage Auxiliary E-Fuse design without requiring external cooling as would be in the target application.

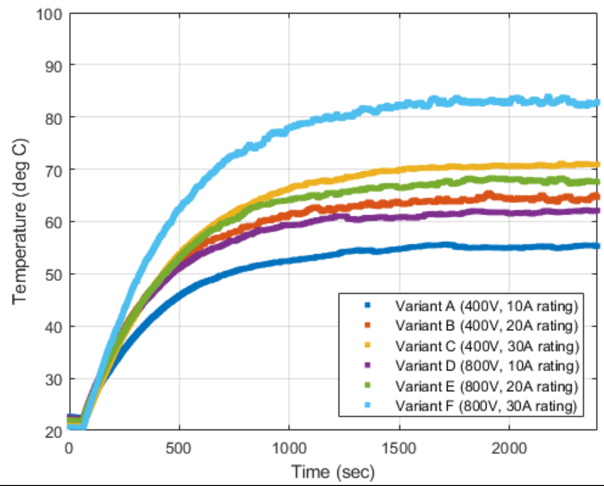


FIGURE 2-23: Heat Sink Temperature at Rated Current.

The heat sinks' thermal resistance is extracted from this data to model the thermal performance at elevated temperatures as well as use in the TCC curve algorithm. Variants A and D use the 25mm heat sink while the others use the 50 mm heat sink.

EXAMPLE 2-21:

$$R_{THSA,\,25mm} = \frac{T_s - T_a}{I_D - V_{DS}} \approx \frac{55.7°C - 22.7°C}{10A \times 312.4\,mV} \approx 10.6\frac{°C}{W}$$

Heat sink to ambient thermal resistance 25 mm length

$$R_{THSA,\,50mm} = \frac{T_s - T_a}{I_D - V_{DS}} \approx \frac{65.5°C - 22.1°C}{20A \times 340.2\,mV} \approx 6.4\frac{°C}{W}$$

Heat sink to ambient thermal resistance 50 mm length

The thermal interface material, Parker Chomerics T609 CHO-TERM®, has a thermal impedance of 0.33°C-in^2/W at 300 psi. However, there is an additional 0.05°C-in^2/W for the PSA material as well as a derating factor provided by the manufacturer for the lower compression due to heat sink clip force of 18 lbf. Note the MOSFET area is approximately 0.487 in^2.

The applied pressure is:

EXAMPLE 2-22:

$$P = \frac{F}{A} = \frac{18\ lbf}{0.487^2} \approx 37\ psi$$

The TIM thermal resistance at 37 psi is:

EXAMPLE 2-23:

$$R_{THCS} = \left(\frac{0.64°C\frac{in^2}{W}}{0.33°C\frac{in^2}{W}} \right) \times 0.38°C\frac{in^2}{W} = 1.51\frac{°C}{W}$$

Using the heat sink, TIM and MOSFET thermal resistances and accounting for the MOSFET's $R_{ds(on)}$ increase over temperature, the MOSFETs' junction temperature at elevated temperatures can be estimated. The MOSFET's thermal resistance and its $R_{ds(on)}$ performance over temperature are published in the datasheet. The TIM's approximate thermal resistance is 1.51°C/W.

Alternatively, for a lower TIM thermal resistance, the TIM on the High-Voltage Auxiliary E-Fuse can be replaced with a phase-change TIM with superior thermal conductivity, such as Wakefield-Vette's ulTIMiFlux™ dielectric phase change material. The Wakefield-Vette part number is CD-02-05-247-N. Its thermal resistance is approximately 0.283°C/W.

With this information, the estimated junction temperature is:

EQUATION 2-11:

$$T_J = T_A + (R_{THJC} + R_{THCS} + R_{THSA}) \times I_D \times V_{DS} \times K_{Rds}$$ Junction temperature

Variant	Rating	MOSFET	Qty.	$T_j@T_A$ = 23°C	$T_j@T_A$ = 85°C
A	400V, 10A	MSC035SMA070B4	1	62°C	126°C
B	400V, 20A	MSC035SMA070B4	2	72°C	137°C
C	400V, 30A	MSC015SMA070B4	2	77°C	146°C
D	800V, 10A	MSC040SMA120B4	1	69°C	140°C
E	800V, 20A	MSC040SMA120B4	2	75°C	147°C
F	800V, 30A	MSC025SMA120B4	2	93°C	173°C

Additionally, the heat sinks' thermal capacitance can be estimated. The heat sinks use AL 6063-T5 material, which has a specific heat capacity of:

EXAMPLE 2-24:

$$C_S = 900\frac{J}{kg°C}$$

The mass of the 25 mm and 50 mm heat sinks is 28g and 54g. The thermal capacitance can be calculated as:

EXAMPLE 2-25:

Heat sink to ambient thermal resistance 25 mm length:

$$C_{THSA,\,25mm} = m_{25mm} \times c_s = 0.028\ kg \times 900\frac{J}{kg°C} = 25.2\frac{J}{°C}$$

Heat sink to ambient thermal resistance 50 mm length:

$$C_{THSA,\,50mm} = m_{50mm} \times c_s = 0.054\ kg \times 900\frac{J}{kg°C} = 48.6\frac{J}{°C}$$

Thermal capacitance from the circuit board and MOSFET is negligible and therefore not considered in this estimation.

Using "thermal Ohm's law," the thermal response can be modeled like an electrical RC circuit by using the heat sink's estimated thermal resistance and capacitance in place of the resistor and capacitor, as shown in the figure below. This enables use of the transient response equation to find the High-Voltage Auxiliary E-Fuse's heat sink temperature. This is used in the junction-temperature estimation algorithm.

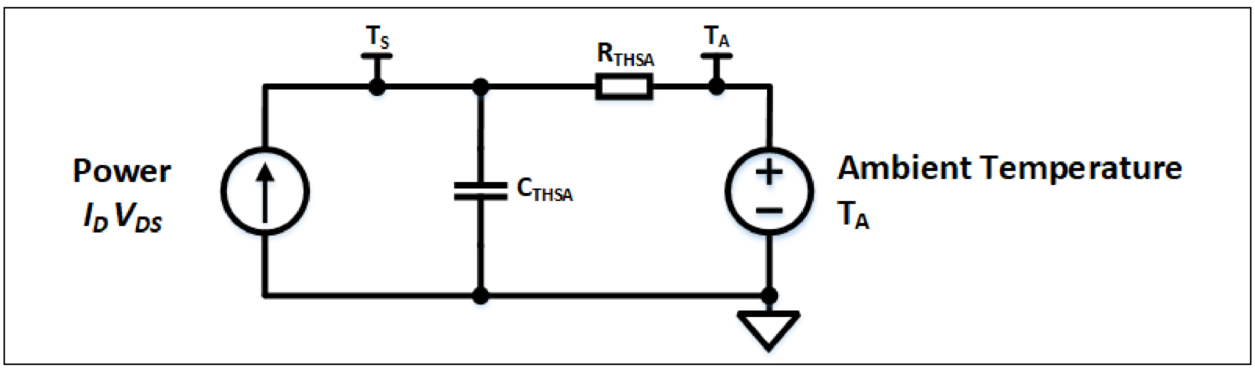


FIGURE 2-24: *HS Thermal Model.*

EQUATION 2-12:

$$v_o(t) = V_i \times \left(1 - e^{-\frac{t}{RC}}\right)$$

Transient response of electrical RC circuit

$$v_o(t) = I_D \times V_{DS} \times R_{THSA} \times \left(1 - e^{-\frac{t}{R_{THSA}C_{THSA}}}\right) + T_A$$

Thermal transient response

The following thermal model includes the thermal resistance of the MOSFET and TIM.

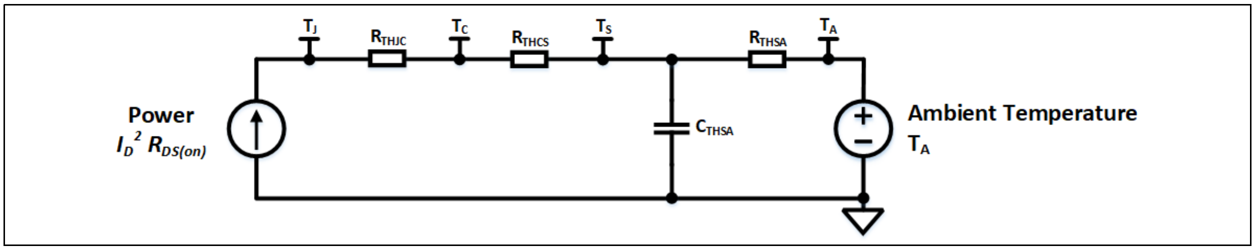


FIGURE 2-25: *Thermal Model.*

The thermal resistance and thermal capacitance for the 25 mm and 50 mm heat sinks were verified with the data from Variant A and B. This is shown in the two figures below. The thermal models' steady state value closely matches the measured data, indicating a good estimate for the thermal resistance. However, during the transient period, the estimation is a few degrees higher than the measured data. This is because the model assumes a constant forcing function, that is, a constant power. The actual power starts lower and gradually increases as $R_{DS(on)}$ increases with temperature. Using a constant power in the thermal model adds a few degrees of safety margin in the temperature estimation.

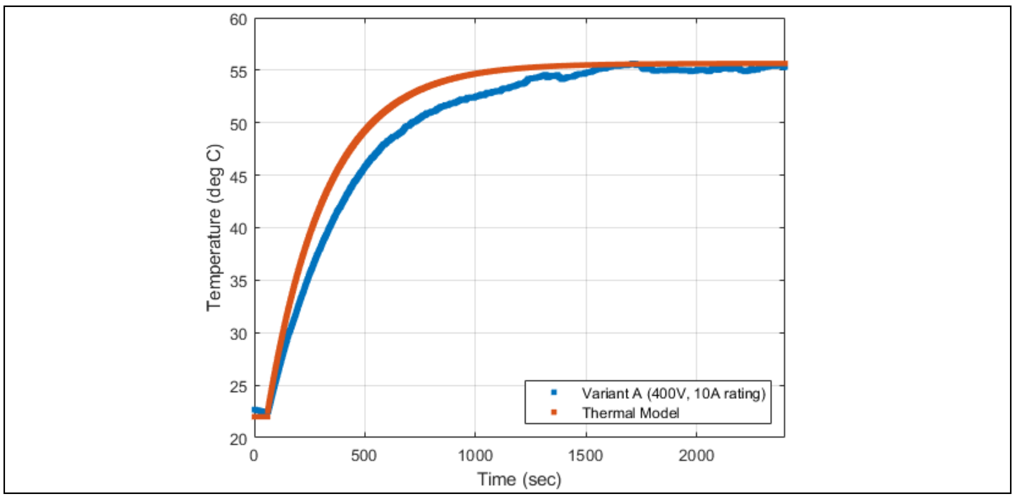


FIGURE 2-26: *25 mm Heat Sink RC Thermal Model Transient Response.*

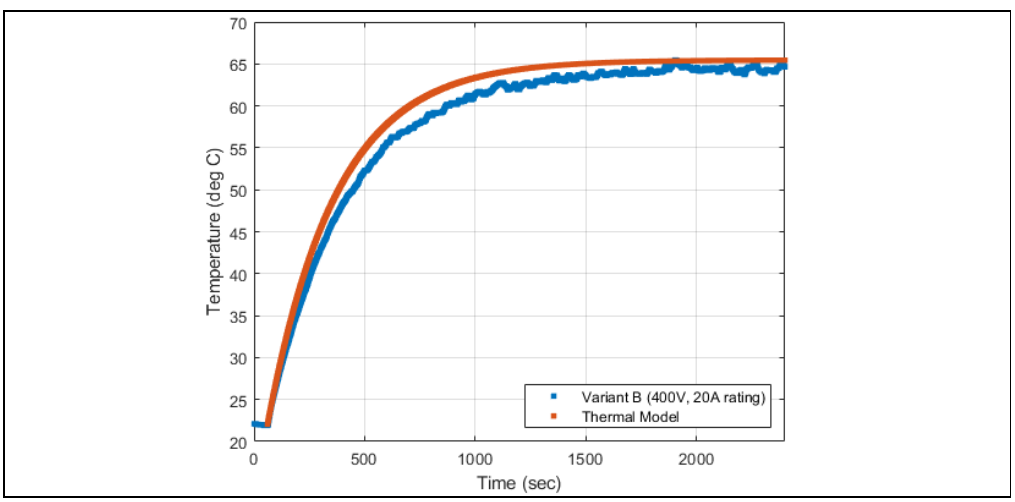


FIGURE 2-27: *50 mm Heat Sink RC Thermal Model Transient Response.*

2.7 TCC CURVE

The TCC curves were designed for each of the six variants based on the thermal characterization discussed in the previous section.

The equation describing the thermal model below, which assumes uniform current-sharing between *N* number of MOSFETs, as shown in figure is:

EQUATION 2-13:

$$T_J = T_A + \left(I_D^2 \times \frac{R_{DS(on)}}{N}\right) \times \left[R_{THJC} + R_{THCS} + R_{THSA} \times \left(1 - e^{-\frac{t}{R_{THSA}C_{THSA}}}\right)\right]$$

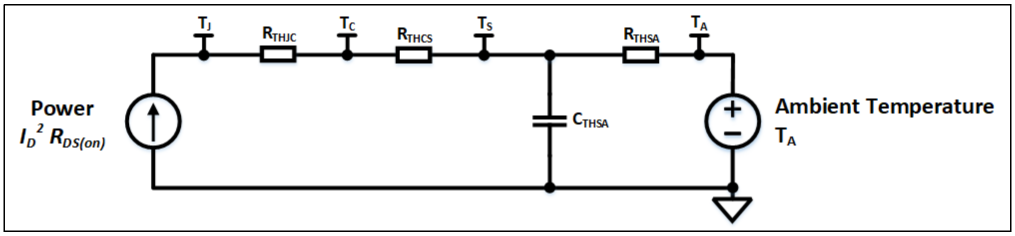


FIGURE 2-28: *TCC Thermal Model.*

To determine the maximum duration at a given current to reach the target junction temperature, the above equation is solved for time, t. This equation is used in the junction-temperature estimation algorithm.

EQUATION 2-14:

$$t = -R_{THSA} \times C_{THSA} \times ln\left(1 - \frac{N \times (T_J - T_A)}{I_D^2 \times R_{DS(on)} \times R_{THSA}} + \frac{R_{THJC} + R_{THCS}}{N \times R_{THJA}}\right)$$

As the current increases, the curve produces a vertical asymptote, representing the thermal limit of the design. Figure 2-29shows an example of a vertical asymptote at 93.6A

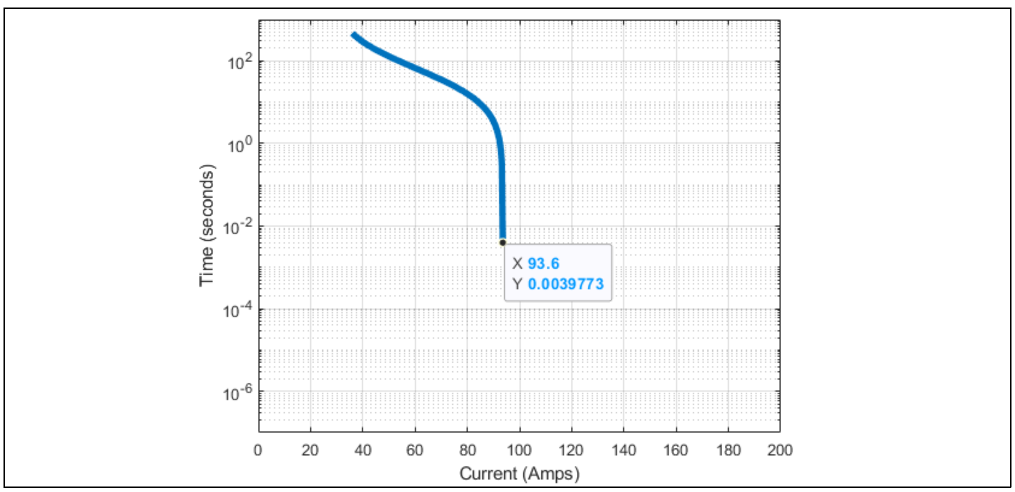


FIGURE 2-29: *TCC Curve Asymptote.*

One option can be to set the hardware short-circuit comparator threshold to trip below this current. However, in this High-Voltage Auxiliary E-Fuse implementation, there is an over-current detection based on 1 ms ADC samples. This is set to 25% below the current corresponding to the vertical asymptote to provide sufficient margin. In the example above, with a vertical asymptote at 93.6A, the over-current threshold is set as shown in Example 2-26.

EXAMPLE 2-26:

$$I_{thresh,\,ADC} = \frac{75}{100} \times 93.6A = 70.2A$$

This is shown in Figure 2-30.

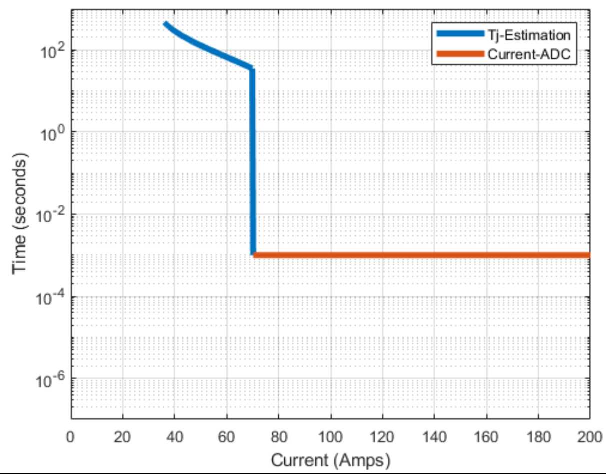


FIGURE 2-30: *TCC Curve with Over-Current Detection.*

Additionally, in the hardware design, the shunt resistor, R106, has a limit of 51.5A. Therefore, $I_{thresh,ADC}$ is limited to a maximum of 51.5A.

The third, and last segment, of the TCC curve is for short-circuit detection and protection.

It is critical to understand the electrical system parameters including the maximum supply voltage and inductance, both source and load inductance. The High-Voltage Auxiliary E-Fuse response to a short-circuit may be as short at 1 µs depending on the settings. Knowing the relationship between these parameters, the trip point can be determined:

EQUATION 2-15:

$$V_{HV} = L \times \frac{di}{dt}$$

$$\Delta i = \frac{V_{HV}}{L} \times t_{response}$$

The current, Δi, is the additional increase in current after detection of a short-circuit. Therefore, the peak current before interruption is:

EQUATION 2-16:

$$I_{PK} = I_{thresh} + \Delta i$$

The current threshold, I_{thresh}, is configurable in steps of 33A, up to 1023A. It is configurable in the software with variable, `dac_i_hw_trip`, or over the LIN bus with message `DAC_I_HW_TRIP`. The comparator reference is established by the DAC. For example, setting the DAC to 3 counts, the current threshold is:

EXAMPLE 2-27:

$$I_{thresh} = K_{DACcounts} \times I_{DACOUT, res} = 3 \times 33A = 99A$$

As an example, a system voltage of 500V, bus inductance of 5 µH, 1 µs response time and trip current of 99A, the peak current will reach 199A:

EXAMPLE 2-28:

$$I_{PK} = I_{thresh} + \frac{V_{HV}}{L} \times t_{response} = 99A + \left(\frac{500V}{5\ \mu H}\right) \times 1\ \mu s = 199A$$

Note that this is using the High-Voltage Auxiliary E-Fuse in edge-triggered mode. In ride-through mode, the gate drive strength is reduced to extend the SiC MOSFET’s short-circuit withstand time. However, extending the time, increases the Δi, potentially significantly depending on the system parameters. The inductive energy may be so high that the SiC MOSFET may not be able to handle that energy in avalanche mode. Therefore, an external snubber or clamp circuit may be necessary. Although, SiC MOSFETs have superior avalanche capability to silicon MOSFETs, there are practical limitations in terms of inductive energy and peak current capability. Additionally, variation in breakdown characteristics from part to part limits the ability of the SiC MOSFETs in parallel to share the inductive energy during avalanche. Unless detailed device characterization is completed, assume only one SiC MOSFET will take all the inductive energy.

To configure the High-Voltage Auxiliary E-Fuse software for the three detection methods, variables and constants in the software must be calculated.

For the first detection method, junction-temperature estimation, the following constant are configured: `A1_COEF`, `B1_COEF`, `FACTOR_RDSON_RTHJS`, `FACTOR_RDSON_RTHSA`, `NUM_DEVICES` and `TJ_LIMIT`. The latter two are self-explanatory while the first four constants are set based on the thermal design and setup to support the software fixed-point operation. The constants, `A1_COEF` and `B1_COEF`, are the thermal RC model coefficients and can be computed in Matlab or Octave with the following code:

```
% Thermal RC model
fc=1/(2*pi*Rthsa*Cthsa); % cutoff frequency
Ts=1; % sampling time
fs = 1/Ts; % sampling frequency
[b,a] = butter(1,fc/(fs/2)); % returns LPF coefficients
B1_COEF=round(abs(b(2))*2^16);
A1_COEF=2^16-(2*B1_COEF);
```


EQUATION 2-17:

$$FACTOR\_RDSON\_RTHJS = round(10240R_{DS(on),\,max} \times (R_{THJC} + R_{THCS}))$$

$$FACTOR\_RDSON\_RTHSA = round\left(10240\frac{R_{DS(on),\,max}}{N} \times R_{THSA}\right)$$

For the second detection method, over-current measurement, there is only one constant to configure, `ISENSE_MAX`. This is in units of counts as previously discussed in this document.

For the third detection method, short-circuit detection, it has a variable and a constant to set it up. The variable, `dac_i_hw_trip`, is units of counts as previously discussed in this document. The constant, `REDUCED_DRIVE_TIME`, is in units of counts with a resolution of 250 ns.

The table below shows the default configuration for the six High-Voltage Auxiliary E-Fuse variants. The corresponding TCC curves at an ambient temperature of 85°C follow the table:

Software Constants/Variables	Variant A	Variant B	Variant C	Variant D	Variant E	Variant F
—	400V, 10A	400V, 20A	400V, 30A	800V, 10A	800V, 20A	800V, 30A
—	—	—	—	—	—	—
Detection Method 1: Junction-Temperature Estimation						
`A1_CEOF`	65292	65326	65326	65292	65326	65326
`B1_CEOF`	122	105	105	122	105	105
`FACTOR_RDSON_RTHJS`	979	979	421	1444	1444	787
`FACTOR_RDSON_RTHSA`	5492	1658	778	8412	2540	1473
`NUM_DEVICES`	1	2	2	1	2	2
`TJ_LIMIT`	175	175	175	175	175	175
—	—	—	—	—	—	—
Detection Method 2: Over-Current Measurement (ADC-based)						
`ISENSE_MAX`	188	376	422	155	311	417
—	—	—	—	—	—	—
Detection Method 3: Short-Circuit Detection (Comparator-based)						
`dac_i_hw_trip`	3	3	3	3	3	3
`REDUCED_DRIVE_TIME`	0	0	0	0	0	0

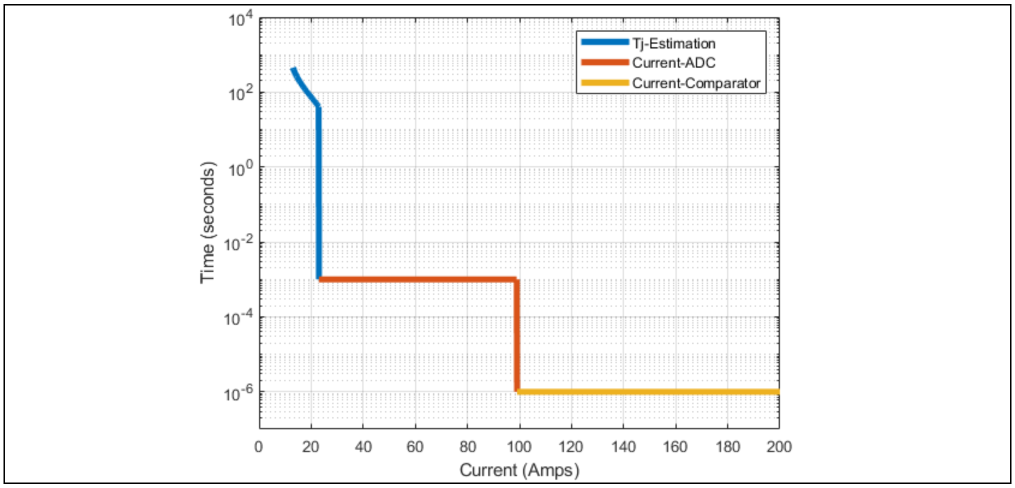


FIGURE 2-31: *TCC Curve, Variant A (400V, 10A).*

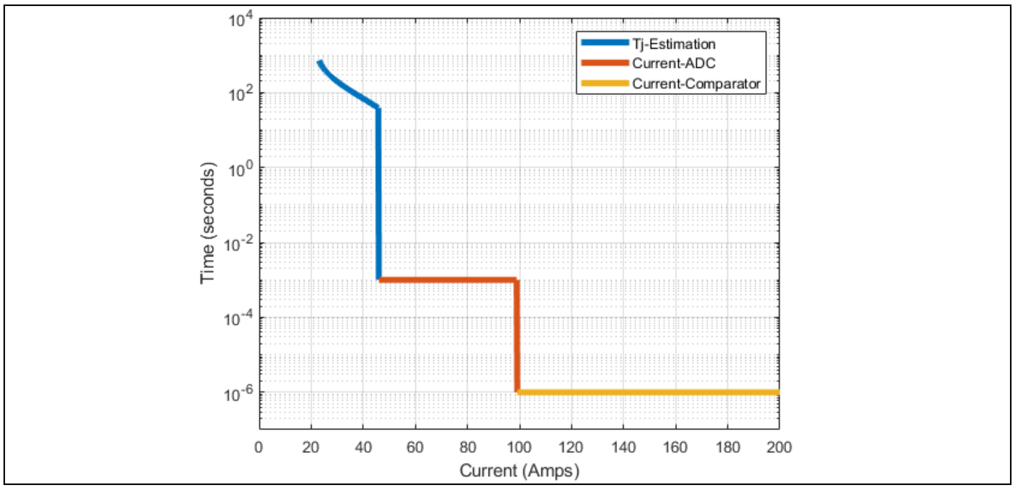


FIGURE 2-32: *TCC Curve, Variant B (400V, 20A).*

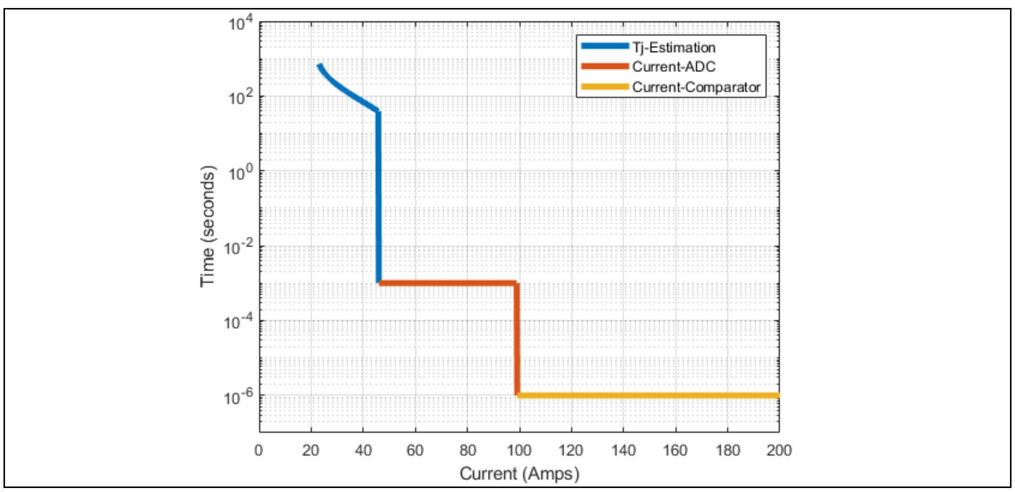


FIGURE 2-33: *TCC Curve, Variant C (400V, 30A).*

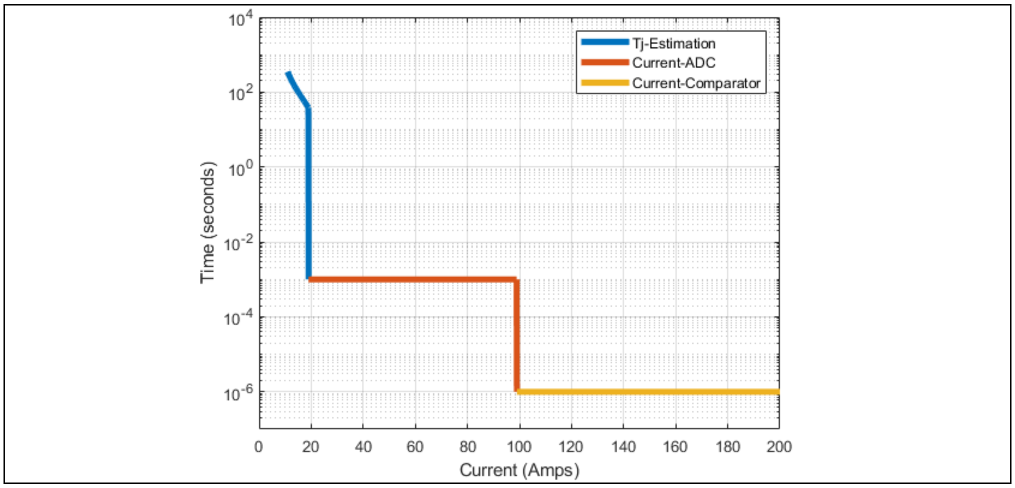


FIGURE 2-34: *TCC Curve, Variant D (800V, 10A).*

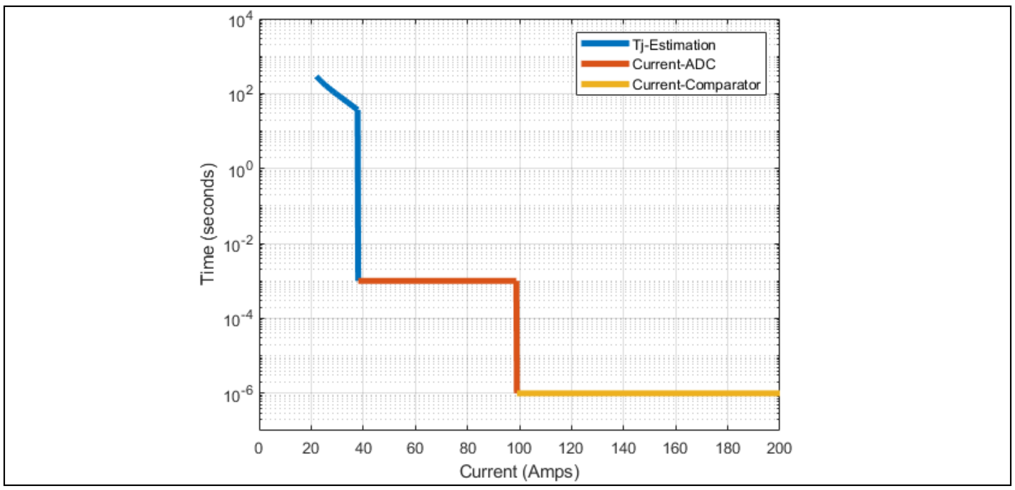


FIGURE 2-35: *TCC Curve, Variant E (800V, 20A).*

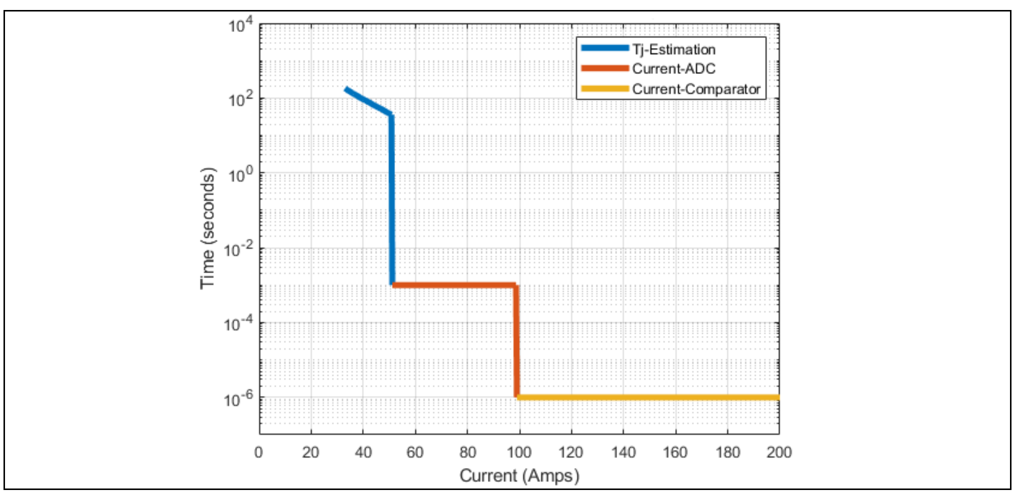


FIGURE 2-36: *TCC Curve, Variant F (800V, 30A).*

2.8 TEST RESULTS

2.8.1 Junction-Temperature Estimation

The table below has the measured time to trip based on the test currents. To eliminate the measurement variability due to increasing ambient temperature, test software was used to keep the ambient temperature variable in the algorithm fixed at 85°C. The two test currents selected were near the two ends of the curve.

—	Variant A	Variant B	Variant C	Variant D	Variant E	Variant F
—	400V, 10A	400V, 20A	400V, 30A	800V, 10A	800V, 20A	800V, 30A
—	—	—	—	—	—	—
Test Current 1 (A)	13	23	33	11	22	33
Measured trip time (s)	466	687	871	359	306	183
—	—	—	—	—	—	—
Test Current 2 (A)	21	41	46	17	34	46
Measured trip time (s)	61	60	168	64	60	55

The PCB reached high temperatures with continuous over-currents above 40A. The recommendation is to limit the ambient temperature to 50°C when testing with high over-currents for long durations. The PCB copper weight, which is 2 oz (70 µm), needs to increase to support over-current at elevated ambient temperatures.

2.8.2 Over-Current Measurement

The figure below shows an over-current detection on Variant A hardware. The threshold set in the software was 188 counts, or 23.0A. The High-Voltage Auxiliary E-Fuse correctly tripped in approximately 2.3 ms when subjected to a 25A current pulse as evident by the gate voltage, in the blue trace, switching to –3.3V and the current, in the red trace, dropping to 0A.

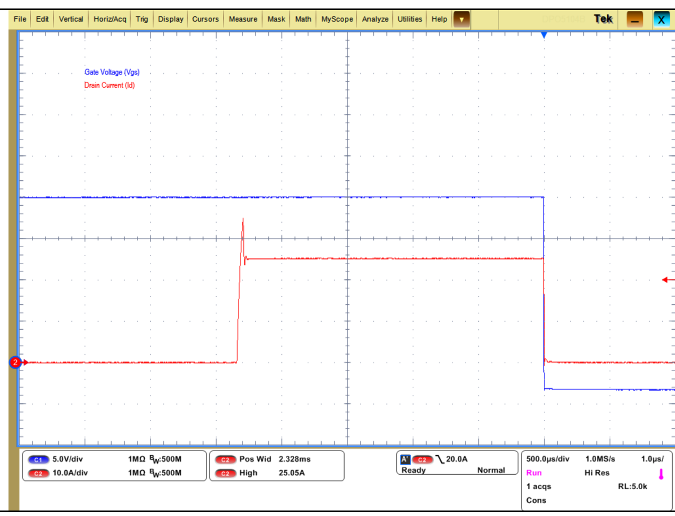


FIGURE 2-37: *Variant A, Detection 2.*

As shown in the figure below, hardware variant B, with a 45.9A threshold, tripped in approximately 2.5 ms.

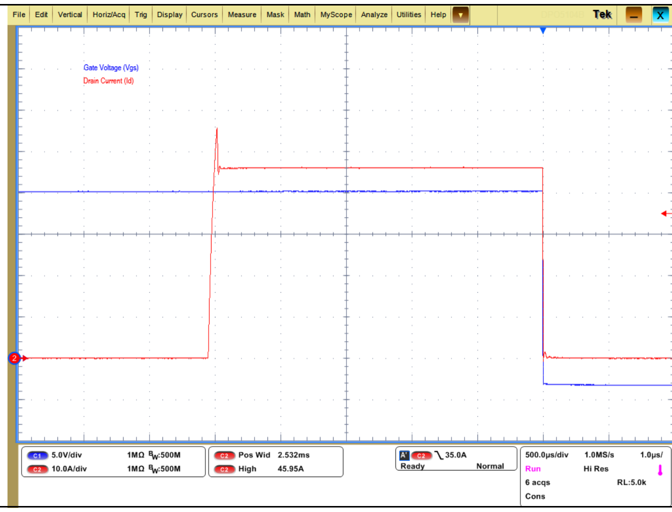


FIGURE 2-38: *Variant B, Detection 2.*

As shown in the figure below, hardware variant C, with a 51.5A threshold, tripped in approximately 2.2 ms.

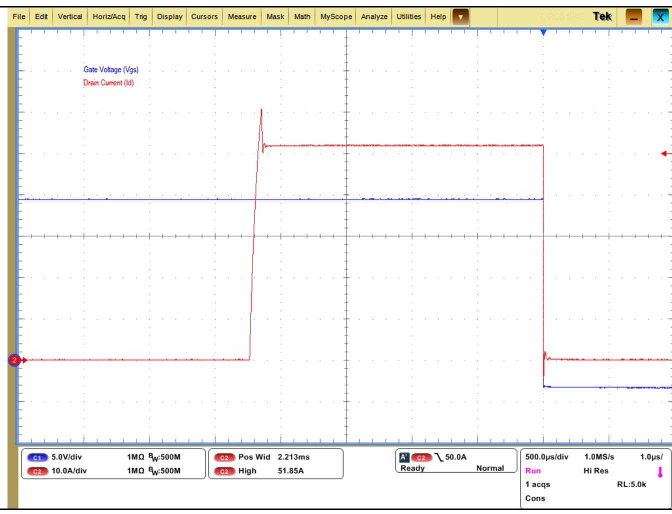


FIGURE 2-39: *Variant C, Detection 2.*

As shown in the figure below, hardware variant D, with an 18.9A threshold, tripped in approximately 2.4 ms.

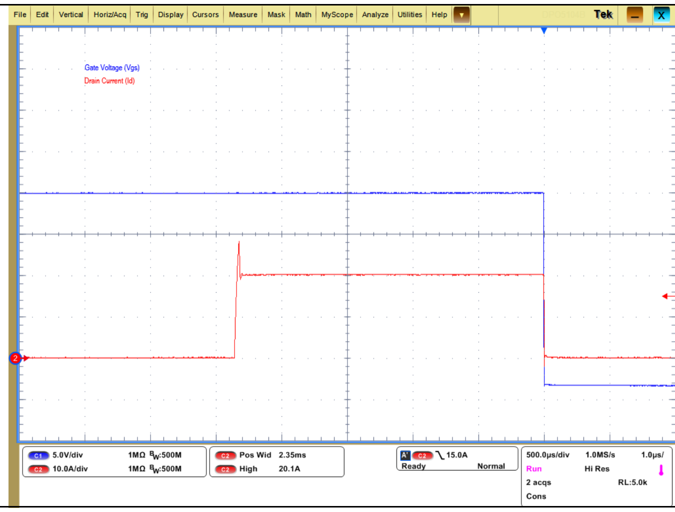


FIGURE 2-40: *Variant D, Detection 2.*

As shown in the figure below, hardware variant E, with a 38A threshold, tripped in approximately 1.8 ms.

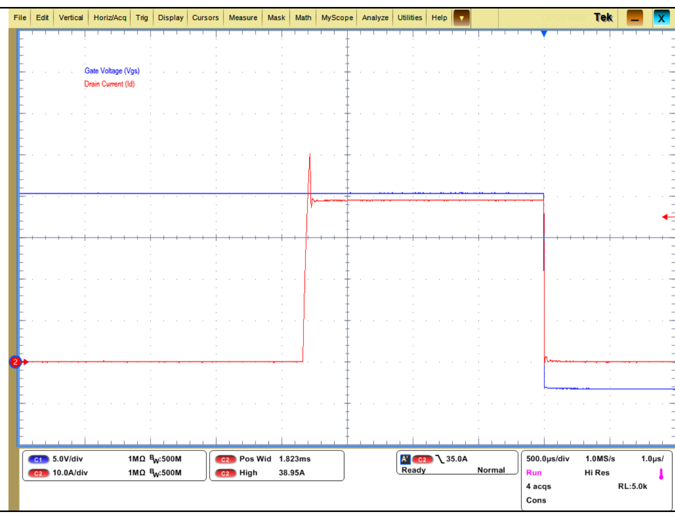


FIGURE 2-41: *Variant E, Detection 2.*

Similarly, Variant F hardware, which has a threshold of 51A, was tested. The figure below shows it interrupted the current in approximately 2.4 ms.

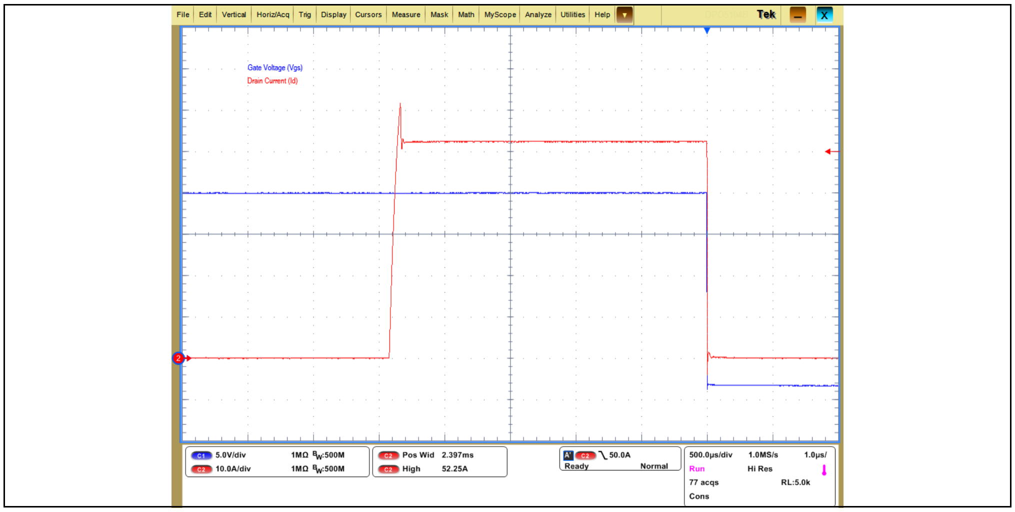


FIGURE 2-42: *Variant F, Detection 2.*

2.8.3 Short-Circuit Detection

To verify the High-Voltage Auxiliary E-Fuse hardware-based short-circuit detection, the test setup includes an inductor that emulates the parasitic source inductance of the system. The source inductance limits the current rise during a short-circuit at the High-Voltage Auxiliary E-Fuse HV terminals. The measurements in this section are with an inductance of approximately 6 µH. The inductance value in the end application may vary based on the specific system parasitics. The 400V and 800V High-Voltage Auxiliary E-Fuse variants are measured with a supply voltage of 500V and 1000V, respectively.

In the oscilloscope captures in the figures below, the blue waveform is the SiC MOSFET's gate-to-source voltage, VGS. This is measured with a high-voltage differential probe. Due to the nature of the measurement setup, common-mode noise is present in the measurement. However, this is strictly a measurement error, not the actual noise on the gate of the SiC MOSFET. The gate voltage is initially at 20V, and then drops to –3.3V to turn off the SiC MOSFET.

The green waveform is the drain-to-source voltage, VDS. In the measurements below, it is near 0V as the SiC MOSFET is on and no current conduction in the circuit. It rises slightly as the drain current, in red, increases. Eventually, when the current is interrupted by switching the gate voltage low, the drain-to-source voltage increases to the SiC MOSFET's breakdown voltage. In this condition, the SiC MOSFET is operating in avalanche mode, and will continue in this mode until the current drops to 0A. Following avalanche mode, the drain-to-source voltage will ring based on the test setup's parasitic inductance and capacitance and settle at the supply voltage (e.g., 500V, 1000V). It is important to note that the drain-to-source voltage reaches very high voltages, well beyond the supply voltage or SiC MOSFET's published breakdown voltage rating in the datasheet, which is specified at a low current. In this short-circuit test, with the currents greater than 100A, the breakdown voltage will be higher. For example, 700V SiC MOSFETs can have a breakdown voltage greater than 1000V, and 1200V SiC MOSFETs can have a breakdown voltage greater than 1700V. **It is important to always use a high-voltage differential probe with a voltage rating significantly higher than the breakdown voltage of the device at the test current.** This is necessary even when powering the system up with a low supply voltage.

The High-Voltage Auxiliary E-Fuse current, in the red waveform, increases when a short-circuit is introduced at its terminals. Due to the presence of the source inductance, the current increases linearly. A short-circuit test board using a 1700V, 35 mΩ SiC MOSFET connected in series with the High-Voltage Auxiliary E-Fuse provides the short-circuit conduction path. In all six variants, the detection threshold is configured to 99A by default. There is a few hundred nanosecond response time to propagate the signal through the circuit, microcontroller peripherals, and gate driver to turn off the SiC MOSFET(s). This results in a peak current greater than the configured threshold, as discussed in previously in this document.

The High-Voltage Auxiliary E-Fuse allows detection thresholds greater than 99A. However, depending on the threshold and the parasitic inductance, the current may increase to a value beyond the capability of the SiC MOSFET. The peak current in avalanche mode and the avalanche energy capability are important ratings in determining whether external snubber circuits are needed to meet specific system requirements. Contact your local Microchip sales office for support related to avalanche capabilities of specific SiC MOSFETs.

FIGURE 2-43: *High-Voltage Auxiliary E-Fuse Variant A Short-Circuit. Measurement.*

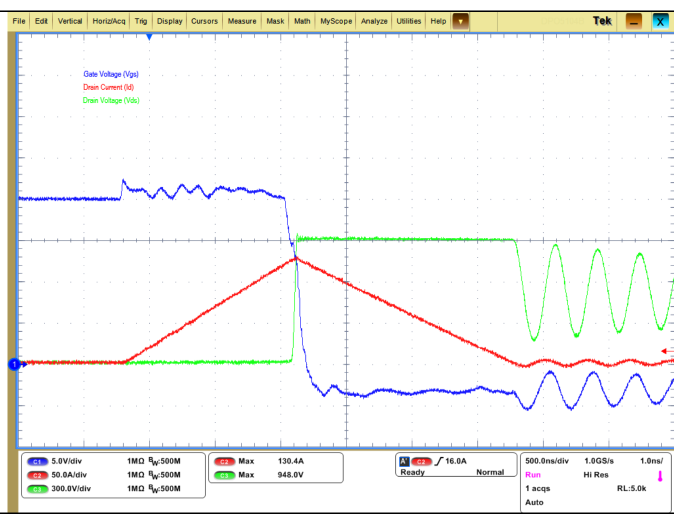


FIGURE 2-44: *High-Voltage Auxiliary E-Fuse Variant B Short-Circuit. Measurement.*

FIGURE 2-45: *High-Voltage Auxiliary E-Fuse Variant C Short-Circuit Measurement.*

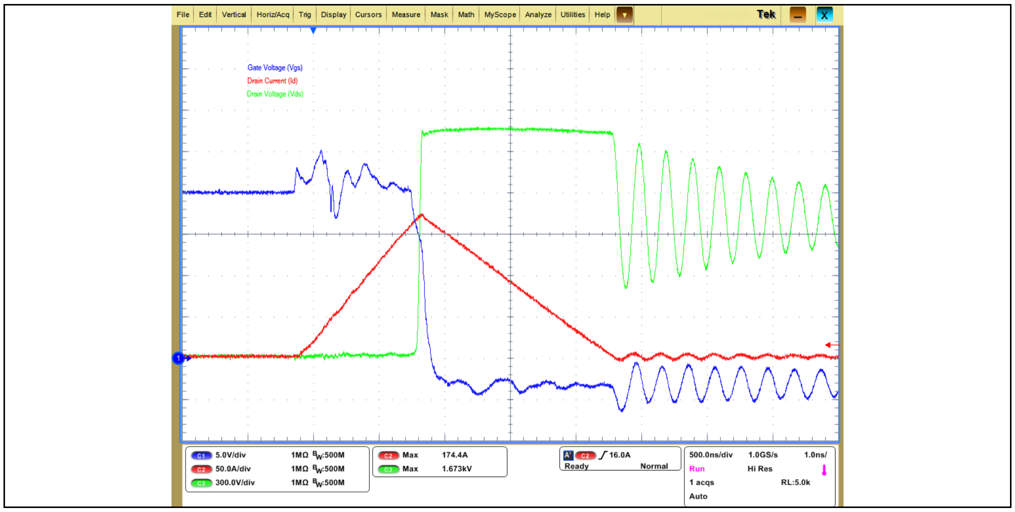


FIGURE 2-46: *High-Voltage Auxiliary E-Fuse Variant D Short-Circuit Measurement.*

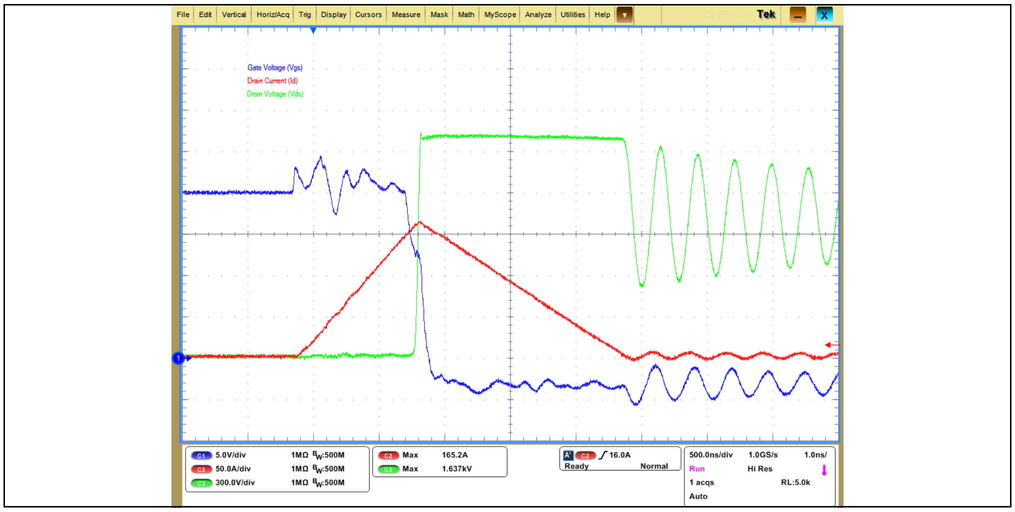


FIGURE 2-47: *High-Voltage Auxiliary E-Fuse Variant E Short-Circuit Measurement.*

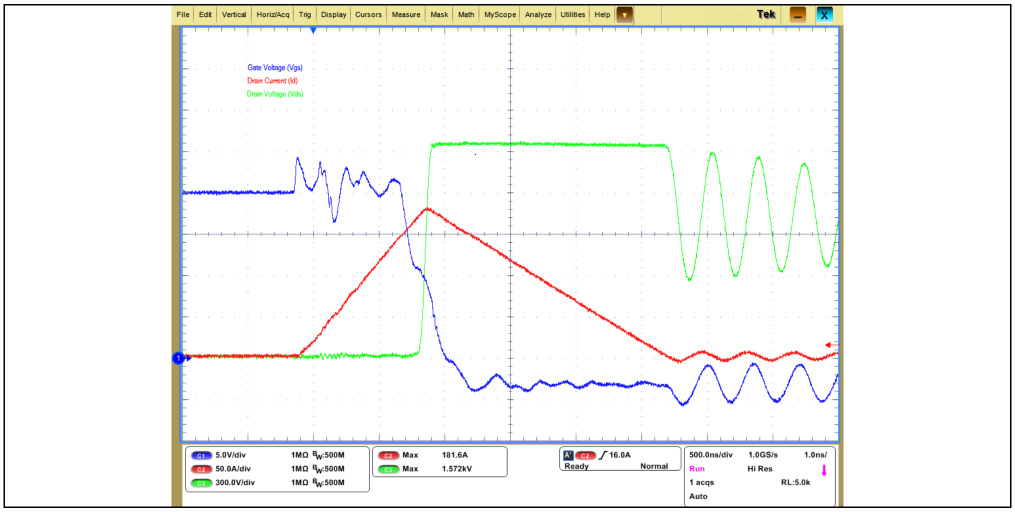


FIGURE 2-48: *High-Voltage Auxiliary E-Fuse Variant F Short-Circuit Measurement.*

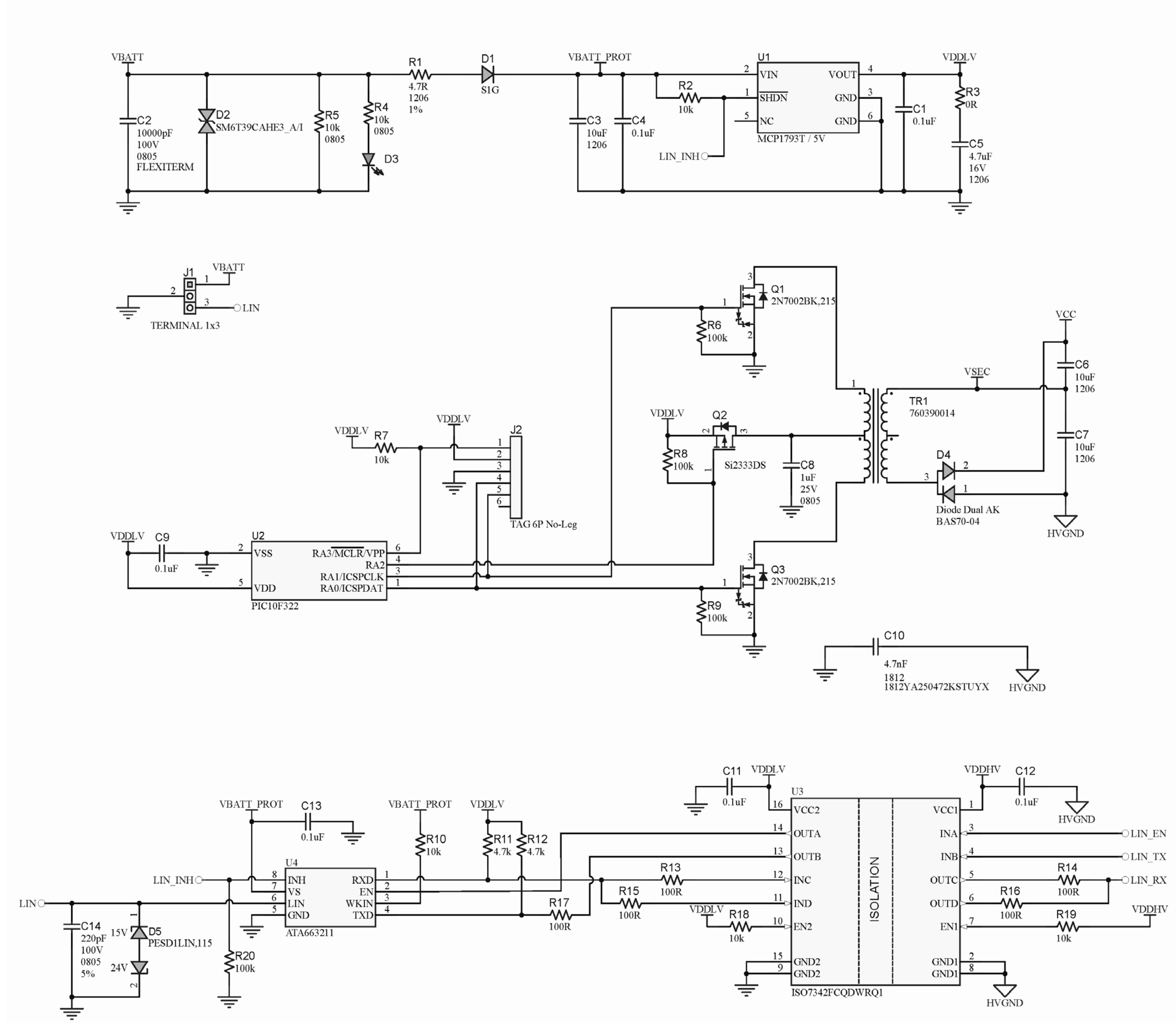
Appendix A. Schematics and Layouts

A.1 INTRODUCTION

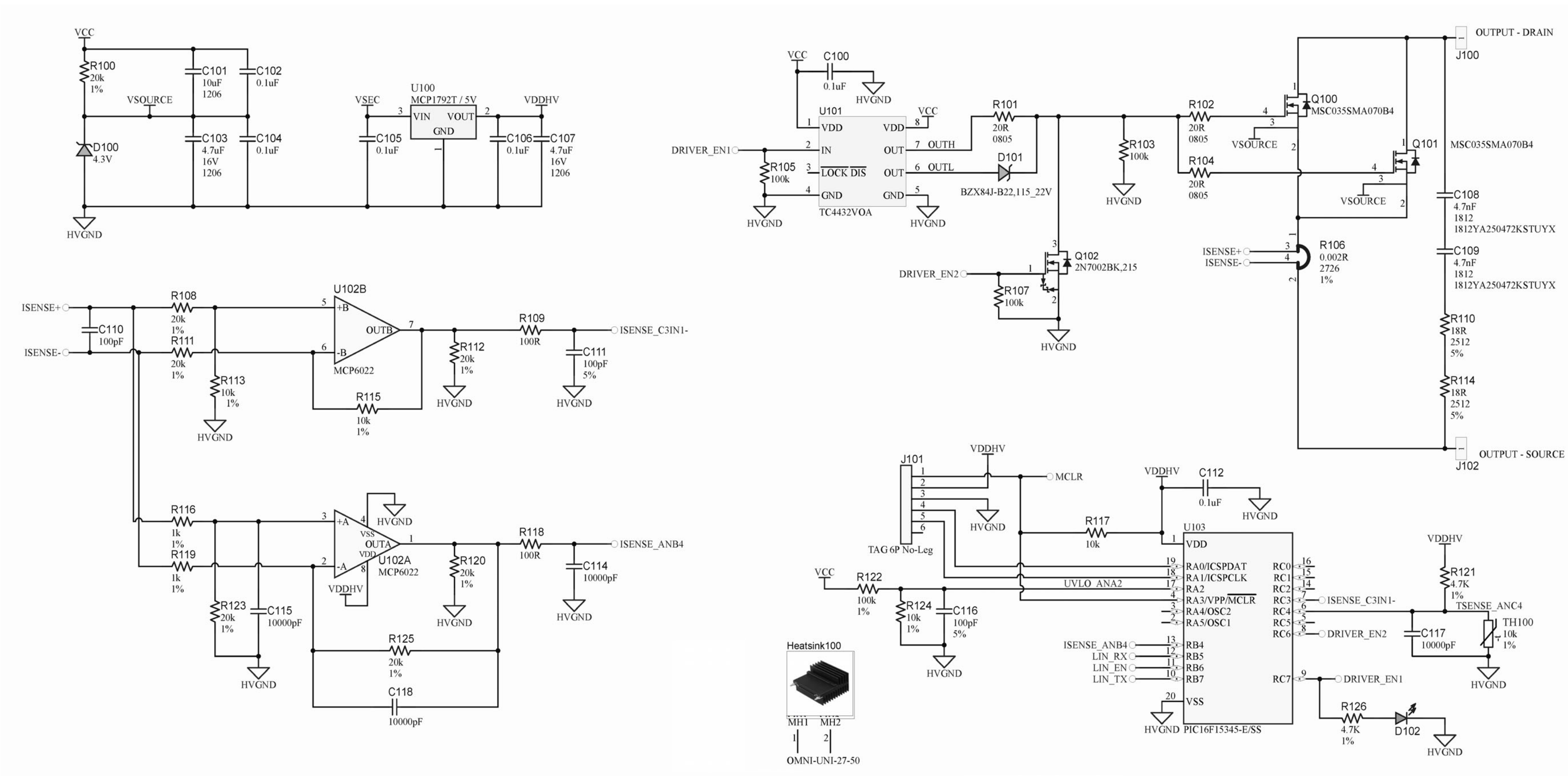
This appendix contains the schematics and layouts of the High-Voltage Auxiliary E-Fuse:

- High-Voltage Auxiliary E-Fuse Board – Schematics
- High-Voltage Auxiliary E-Fuse Board – Top Silk
- High-Voltage Auxiliary E-Fuse Board – Top Assembly
- High-Voltage Auxiliary E-Fuse Board – Top Copper
- High-Voltage Auxiliary E-Fuse Board – Bottom Silk
- High-Voltage Auxiliary E-Fuse Board – Bottom Assembly
- High-Voltage Auxiliary E-Fuse Board – Bottom Copper

A.2 HIGH-VOLTAGE AUXILIARY E-FUSE BOARD – SCHEMATICS

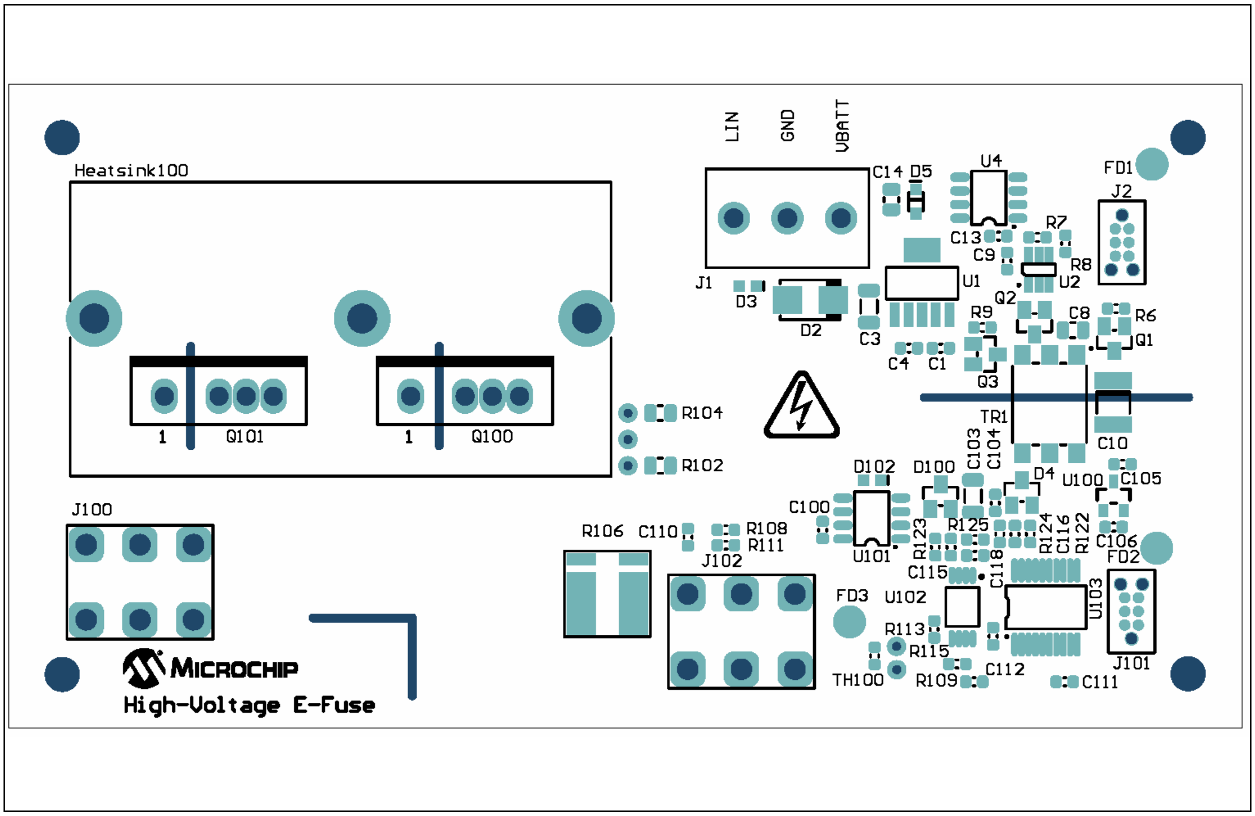


A.3 HIGH-VOLTAGE AUXILIARY E-FUSE BOARD – SCHEMATICS 2

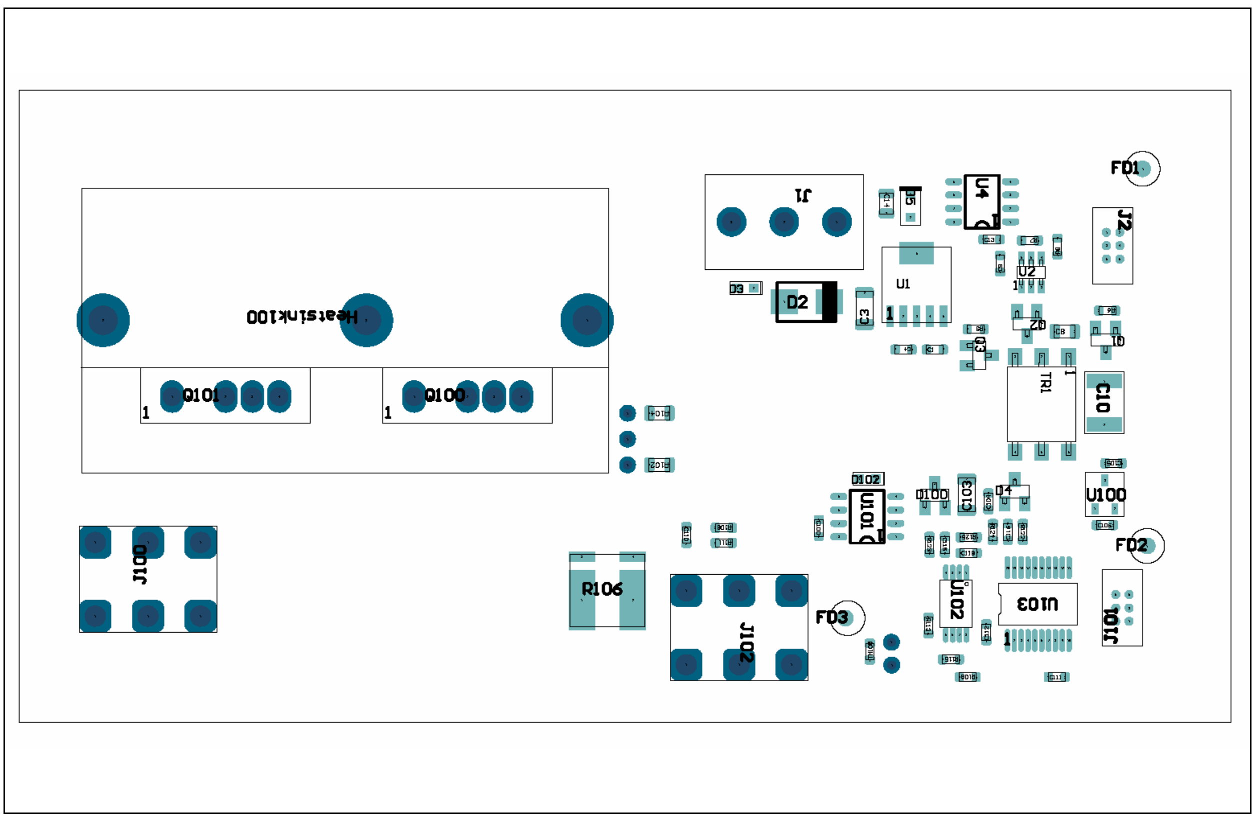


Unless otherwise specified, capacitors are 10%, 50V, 0603 and resistors are 5%, 0603.

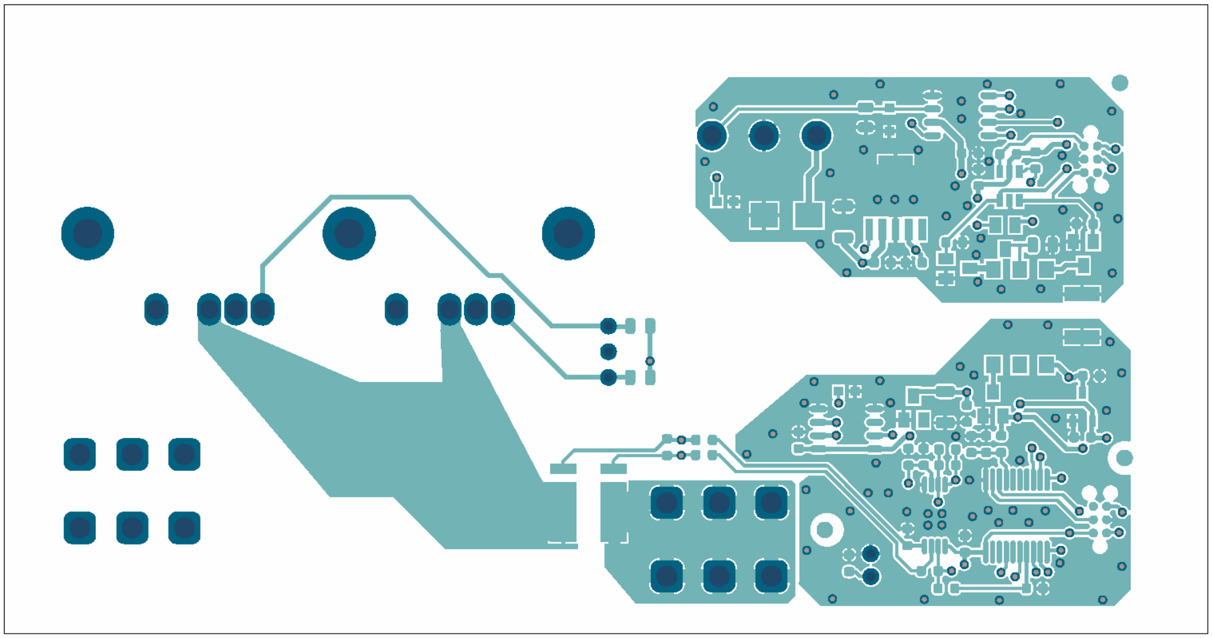
A.4 HIGH-VOLTAGE AUXILIARY E-FUSE BOARD – TOP SILK



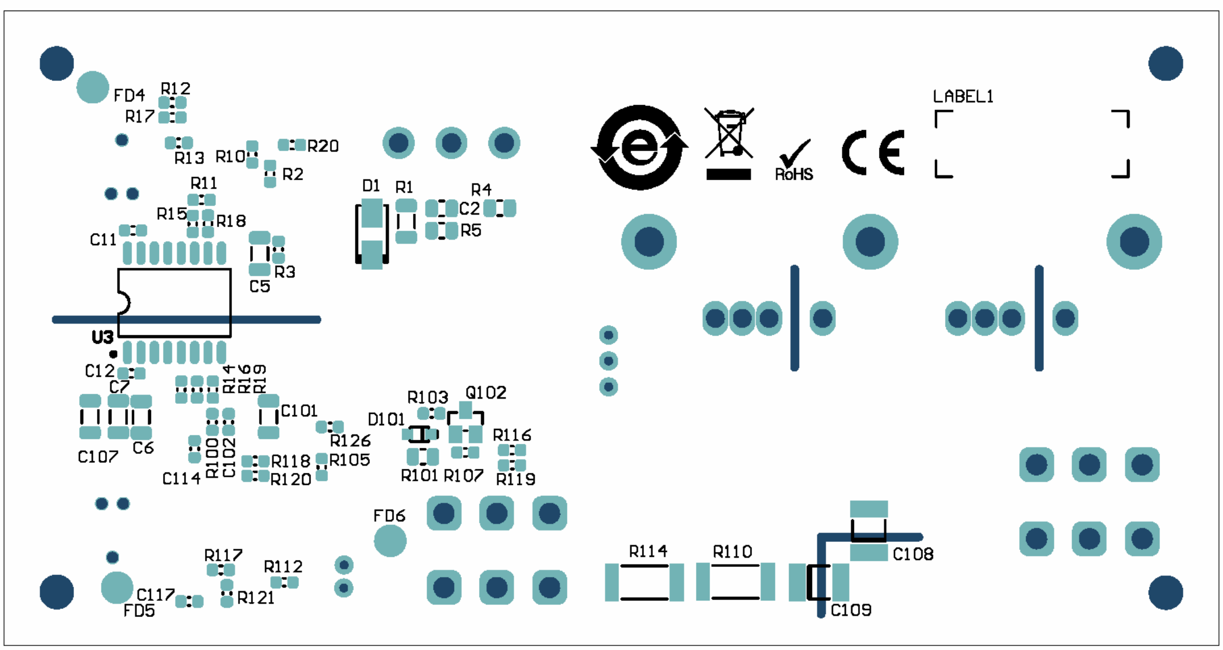
A.5 HIGH-VOLTAGE AUXILIARY E-FUSE BOARD – TOP ASSEMBLY



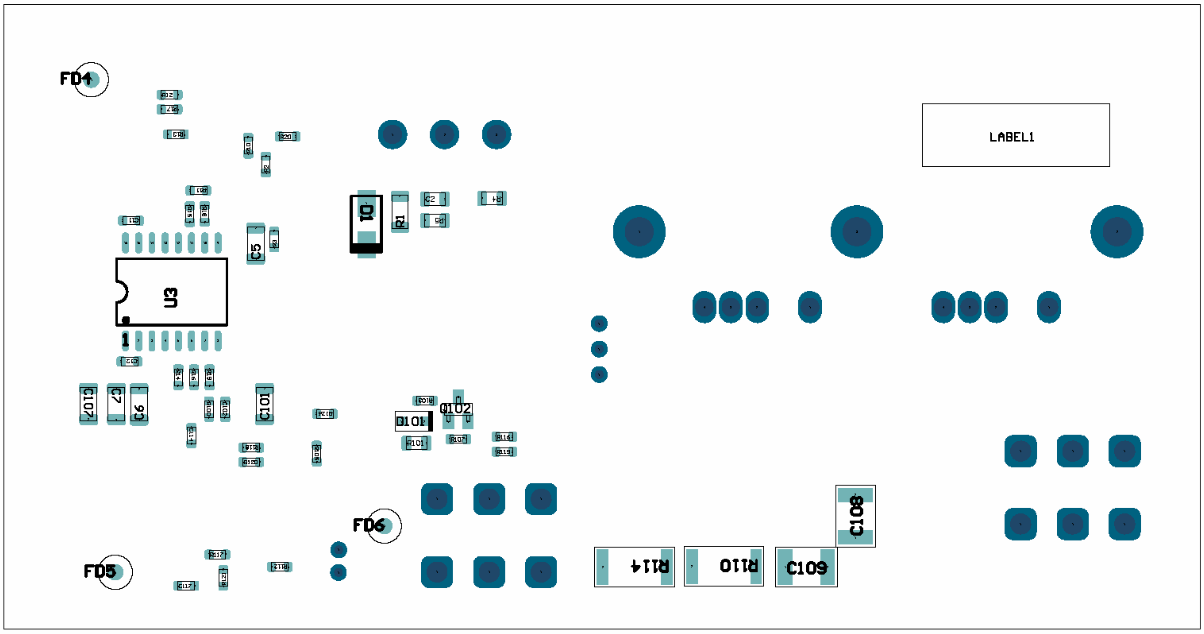
A.6 HIGH-VOLTAGE AUXILIARY E-FUSE BOARD – TOP COPPER



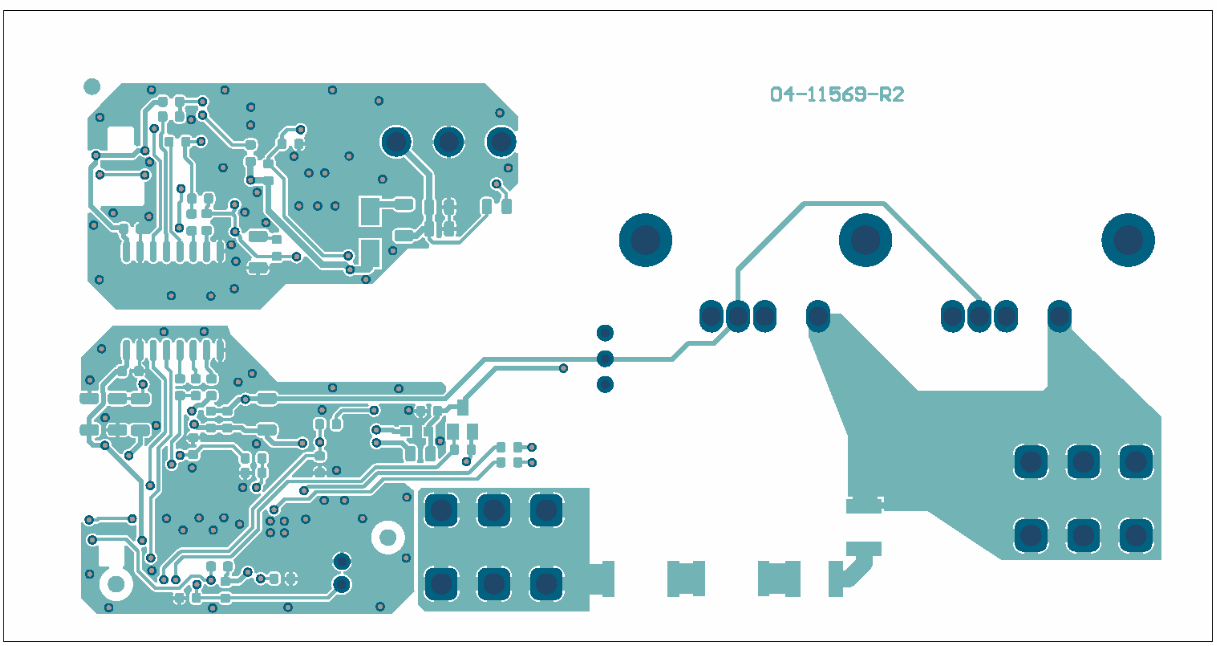
A.7 HIGH-VOLTAGE AUXILIARY E-FUSE BOARD – BOTTOM SILK



A.8 HIGH-VOLTAGE AUXILIARY E-FUSE BOARD – BOTTOM ASSEMBLY



A.9 HIGH-VOLTAGE AUXILIARY E-FUSE BOARD – BOTTOM COPPER



Appendix B. Bill of Materials (BOM)

TABLE B-1: BILL OF MATERIALS (BOM)

Qty.	Reference	Description	Manufacturer	Manufacturer Part Number
2	C1, C17	Capacitor, ceramic, 10000pF, 50V, 10%, X7R, SMD 0603	Wurth Elektronik	885012206089
12	C1, C4, C9, C11, C12, C13, C100, C102, C104, C105, C106, C112	Capacitor, ceramic, 100nF, 50V, 10%, X7R, SMD 0603, AEC-Q200	AVX Corporation	06035C104K4T2A
1	C2	Capacitor, ceramic, 10000pF, 100V, 10%, X7R, SMD 0805	AVX Corporation	08051C103K4Z2A
4	C3, C6, C7, C101	Capacitor, Ceramic, 10uF, 50V, 10%, X7R, AEC-Q200, SMD 1206	TDK Electronics	CGA5L1X7R1H106K160A C
3	C5, C103, C107	Capacitor, Ceramic, 4.7uF, 16V, 10%, X7R, SMD 1206	KEMET	C1206C475K4RACTU
1	C8	Capacitor, Ceramic, 1uF, 25V, 10%, X7R, SMD 0805	AVX Corporation	08053C105K4Z2A
1	C10	Capacitor, Ceramic, 4.7uF, 2.5kV, 10%, X7R, 1812 AEC-Q200	Knowles Corporation	1812YA250472KSTUYX
1	C14	Capacitor, Ceramic, 220pF 100V 5% C0G SMD 0805 AEC-Q200	AVX Corporation	08051A221J4T2A
3	C110, C111, C116	Capacitor, Ceramic, 100pF 50V 5% C0G AEC-Q200 SMD 0603	AVX Corporation	06035A101J4T2A
4	C114, C115, C117, C118	Capacitor, Ceramic, 10nF 50V 10% X7R SMD 0603 AEC-Q200	AVX Corporation	06035C103K4T2A
1	D1	Diode, Rectifier, S1G 1.1V 1A 400V DO-214AC_SMA	Diodes Incorporated®	S1GB-13-F
1	D2	Diode, Transient Voltage Suppressor, Bi-directional, SM6T39CAHE3_A/I 39V 11.1A DO214AA	Vishay Semiconductor Diodes Division	SM6T39CAHE3_A/I
2	D3, D102	Diode, LED Green, 2.2V 25mA 15mcd Clear SMD 0603	Kingbright Electronic Co., Ltd.	APT1608SGC
1	D4	Diode, Schottky Array, BAS70-04-7-F 1V 15mA SOT-23-3	Diodes Incorporated	BAS70-04-7-F
1	D5	Diode, Transient Voltage Suppressor, PESD1LIN,115 15V/24V 44V/70V 160W SMD SOD-323F	Nexperia	PESD1LIN,115

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	Manufacturer Part Number
1	D100	Diode, Zener BZX84C4V3 4.3V 350mW SOT-23-3	Nexperia	BZX84-C4V3
1	D101	Diode, Zener BZX84J-B22,115 22V 550mW SMD SOD-323F	Nexperia	BZX84J-B22,115
1	J1	Connector, Terminal, 5mm 1x3 Female 12-28AWG 16A TH R/A	On-Shore Technology, Inc.	OSTVI030152
2	J100, J102	Connector, Terminal, 30A Female 1x1 TH VERT	Keystone® Electronics Corp.	8197
3	Q1, Q3, Q102	Transistor, MOSFET N-Ch, 2N7002BK,215 60V 350mA 370mW SOT-23-3	Nexperia	2N7002BK,215
1	Q2	Transistor, MOSFET P-Ch, Si2333DS -12V -4.1A 750mW SOT-23-3	Vishay Intertechnology, Inc.	SI2333DS-T1-E3
1	R1	Resistor, Thick Film, 4.7R 1% 1/4W SMD 1206	Panasonic® - ECG	ERJ-8RQF4R7V
6	R2, R7, R10, R18, R19, R117	Resistor, Thick Film, 10k 5% 1/10W SMD 0603	Panasonic - ECG	ERJ-3GEYJ103V
1	R3	Resistor, Thick Film, 0R 1/10W AEC-Q200 SMD 0603	Panasonic - ECG	ERJ-3GEY0R00V
2	R4, R5	Resistor, Thick Film, 10k 5% 1/8W SMD 0805	Panasonic - ECG	ERJ-6GEYJ103V
7	R6, R8, R9, R20, R103, R105, R107	Resistor, Thick Film, 100k 5% 1/10W SMD 0603	Panasonic - ECG	ERJ-3GEYJ104V
2	R11, R12	Resistor, Thick Film, 4.7k 5% 1/10W SMD 0603	Panasonic - ECG	ERJ-3GEYJ472V
6	R13, R14, R15, R17, R109, R118	Resistor, Thick Film, 100R 5% 1/10W SMD 0603	Panasonic - ECG	ERJ-3GEYJ101V
7	R100, R108, R111, R112, R120, R123, R125	Resistor, Thick Film, 20k 1% 1/10W SMD 0603	Panasonic - ECG	ERJ-3EKF2002V
3	R101, R102, R104	Resistor, Thick Film, 20R 5% 1/16W SMD 0805	Panasonic - ECG	ERJ-6GEYJ200V
1	R106	Resistor, Shunt Metal Strip, 0.002R 1% 5W SMD 2726 AEC-Q200	Vishay Intertechnology, Inc.	WSLP27262L000FEA
2	R113, R115	Resistor, Thick Film, 10k 1% 1/10W SMD 0603 AEC-Q200	Panasonic - ECG	ERJ-3EKF1002V
2	R116, R119	Resistor, Thick Film, 1k 1% 1/10W SMD 0603	Panasonic - ECG	ERJ-3EKF1001V
2	R121, R126	Resistor, Thick Film, 4.7K 1% 1/10W SMD 0603	Panasonic - ECG	ERJ-3EKF4701V
1	R122	Resistor, Thick Film, 100k 1% 1/10W AEC-Q200 SMD 0603	Panasonic - ECG	ERJ-3EKF1003V
1	R124	Resistor, Thick Film, 10k ,1% 1/10W AEC-Q200 SMD 0603	Panasonic - ECG	ERJ-3EKF1002V

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	Manufacturer Part Number
1	TH100	Resistor, Thermistor, Negative Temperature Coefficient, 10K 3380K 1% SMD 0603	Murata Manufacturing Co., Ltd.	NCU18XH103F6SRB
1	TR1	Transformer, Switched-mode Power Supply, 1:1.3 5V 350mA 475UH SMD AEC-Q200	Wurth Elektronik	760390014
1	U3	IC Isolator, Digital, ISO7342FC-QDWRQ1 2.5kV SOIC-16	Texas Instruments	ISO7342FCQDWRQ1

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

Qty.	Reference	Description	Manufacturer	Manufacturer Part Number
2	Q100, Q101	Transistor, MOSFET N-Ch SiC, MSC035SMA070B4 700V 77A 283W, TO-247-4	Microchip Technology, Inc.	**MSC035SMA070B4**
1	U1	Microchip Analog Regulator, 5V, MCP1793T-5002H/DC, SOT-223-5	Microchip Technology, Inc.	**MCP1793T-5002H/DC**
1	U2	Microchip MCU 8-BIT, 16MHz, 918B, 64B, PIC10F322-I/OT, SOT-23-6	Microchip Technology, Inc.	**PIC10F322-I/OT**
1	U4	Microchip Interface LIN, ATA663211-GAQW SO-8	Microchip Technology, Inc.	**ATA663211-GAQW**
1	U100	Microchip Analog Voltage Regulator, 5.0V, 3LD MCP1792T-5002H/CB, SOT-23A-3	Microchip Technology, Inc.	**MCP1792T-5002H/CB**
1	U101	Microchip Analog, TC4432VOA, 30V, SOIC-8	Microchip Technology, Inc.	**TC4432VOA713**
1	U102	Microchip Analog Operational Amplifier, 2-Ch 10MHz, MCP6022-E/ST, TSSOP-8	Microchip Technology, Inc.	**MCP6022-E/ST**
1	U103	Microchip MCU 8-BIT, 32MHz, 14kB, 1kB, PIC16F15345-E/SS, 20-SSOP	Microchip Technology, Inc.	**PIC16F15345-E/SS**

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

Qty.	Reference	Description	Manufacturer	Manufacturer Part Number
1	—	Heat Sink Clip	Wakefield-Vette	OMNI-UC
—	—	Thermal Pad	Parker Chomerics, Inc.	66-10-0505-T609

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

Qty.	Reference	Description	Manufacturer	Manufacturer Part Number
1	Heatsink100	Mechanical HW Heatsink, TO-247, TO-264, TO-220 OMNI-UNI-27-50	Wakefield-Vette	OMNI-UNI-27-50
1	PCB1	Printed Circuit Board, 2 Layers, 2OZ, 0.062", HASL	—	04-11569-R2

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-4: BILL OF MATERIALS (BOM) – DO NOT POPULATE PARTS

Qty.	Reference	Description	Manufacturer	Part Number
0	C108, C109, R16, R110, R114	Do not populate	—	—

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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