

# Smart Circuit Breaker Reference Design



## Description

This reference design demonstrates a single-phase smart circuit breaker combining electronic overload and short-circuit protection, electrical metering, relay control, and Zigbee® connectivity. The design enables local and remote load control, energy monitoring, and fault reporting for connected residential and building applications.

## Resources

|                                             |                |
|---------------------------------------------|----------------|
| <a href="#">TIDA-011030</a>                 | Design Folder  |
| <a href="#">SIMPLELINK-LOWPOWER-SDK</a>     | Tool Folder    |
| <a href="#">ADC-ENERGY-METROLOGY-LIB-SW</a> | Tool Folder    |
| <a href="#">CC2340R5</a>                    | Product Folder |
| <a href="#">OPA2323</a>                     | Product Folder |
| <a href="#">DRV8213</a>                     | Product Folder |

## Features

- Single-pole, 16A circuit-breaker
- Configurable Type-B trip characteristic based on EN 60898-1
- Instantaneous short-circuit and inverse-time overload protection
- Local and Zigbee remote ON/OFF control
- Real-time reporting of open, closed, tripped, and overcurrent states
- Integrated voltage, current, frequency, power, energy, and temperature measurement
- Zigbee2MQTT and Home Assistant integration

## Applications

- [Smart electrical panel](#)



## 1 System Description

Residential electrical systems are evolving as electric vehicles, photovoltaic generation, battery energy storage systems, and connected appliances become more common. These technologies increase household electrification and create more dynamic load profiles and power flows. As electrical loads and operating modes become more varied, circuit breakers become even more important for protecting electrical wiring and connected equipment against overload and short-circuit conditions. Conventional circuit breakers, however, provide little information about the operating state of the protected circuit.

Smart circuit breakers combine local electrical protection with measurement, connectivity, and remote-control capabilities. In addition to interrupting fault currents, they can monitor electrical parameters, report abnormal operating conditions, and provide information about the state of the protected load. Early warnings can indicate a developing overload and allow the user or an automation system to reduce nonessential loads before an interruption becomes necessary. This additional visibility can also help users understand energy consumption and react to faults without direct access to the breaker panel.

When integrated into a home automation or energy management system, smart circuit breakers can control selected loads based on schedules, user commands, or other automation rules. Voltage, current, power, energy consumption, and breaker state can be made available to the wider system, while the essential protection functions continue to operate locally and independently of the communication connection.

This reference design demonstrates a single-pole smart circuit breaker that combines local overcurrent protection, electrical metering, remote control, and wireless connectivity. It provides a platform for evaluating smart circuit-breaker functionality and its integration into a Zigbee-based home automation system.

### 1.1 Terminology

| Term   | Definition                                                            |
|--------|-----------------------------------------------------------------------|
| ADC    | Analog-to-digital converter                                           |
| CRC    | Cyclic redundancy check                                               |
| GUI    | Graphical user interface                                              |
| IDMT   | Inverse definite minimum time                                         |
| $I_n$  | Nominal current rating of the circuit breaker                         |
| IPROPI | DRV8213 analog output proportional to the motor or relay-coil current |
| L      | Lagging power factor, representing an inductive load                  |
| C      | Leading power factor, representing a capacitive load                  |
| MCU    | Microcontroller unit                                                  |
| PF     | Power factor                                                          |
| PWM    | Pulse-width modulation                                                |
| RMS    | Root mean square                                                      |
| RTOS   | Real-time operating system                                            |
| SWD    | Serial Wire Debug                                                     |
| THD    | Total harmonic distortion                                             |
| UART   | Universal asynchronous receiver/transmitter                           |
| ZBOSS  | Zigbee protocol stack                                                 |

### 1.2 Key System Specifications

**Table 1-1. Key System Specifications**

| Item                           | Description                              |
|--------------------------------|------------------------------------------|
| Number of poles                | Single pole                              |
| Nominal voltage                | 120VAC or 230VAC, $\pm 10\%$             |
| Nominal frequency              | 50Hz or 60Hz, configured at compile time |
| Nominal current                | 16A                                      |
| Extended current-sensing range | Up to 52A                                |

**Table 1-1. Key System Specifications (continued)**

| Item                        | Description                                                                                    |
|-----------------------------|------------------------------------------------------------------------------------------------|
| Sampling frequency          | 8kHz                                                                                           |
| Tripping characteristic     | Software characteristic based on EN 60898-1 Type B operating points                            |
| Protection                  | Instantaneous short-circuit protection, inverse-time overload protection                       |
| Breaker control             | Local push button and remote Zigbee ON/OFF control                                             |
| Metering                    | RMS voltage and current: active, reactive, and apparent power, power factor, energy, frequency |
| Temperature monitoring      | Temperature measurement for over-temperature protection                                        |
| Tested RMS-current accuracy | Less than:<br>1.5% from 5% to 10% of nominal current<br>1% from 10% to 100% of nominal current |
| Tested RMS-voltage accuracy | Less than 0.024% at approximately 207V                                                         |
| Connectivity                | Zigbee end device; UART calibration interface                                                  |

## 2 System Overview

### 2.1 Block Diagram

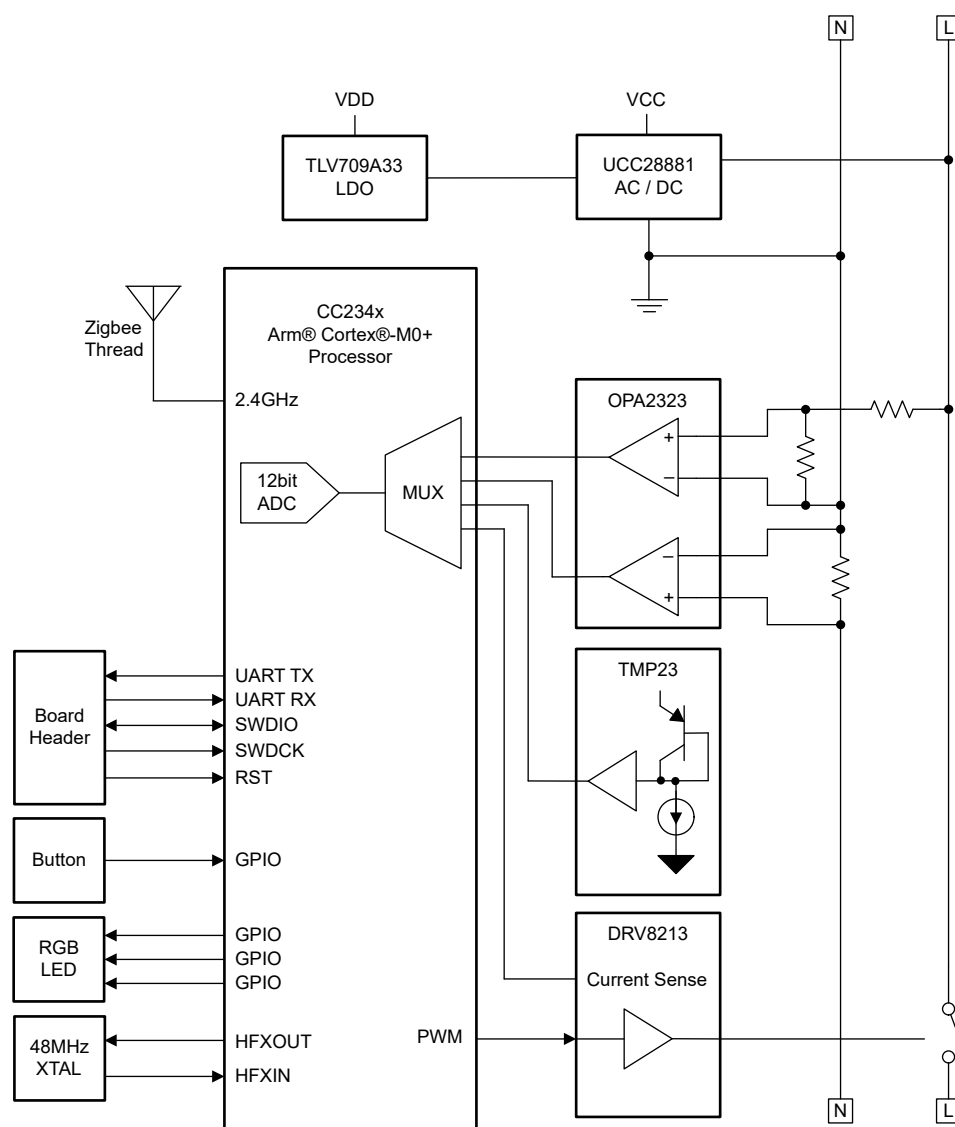


**Figure 2-1. System Block Diagram**

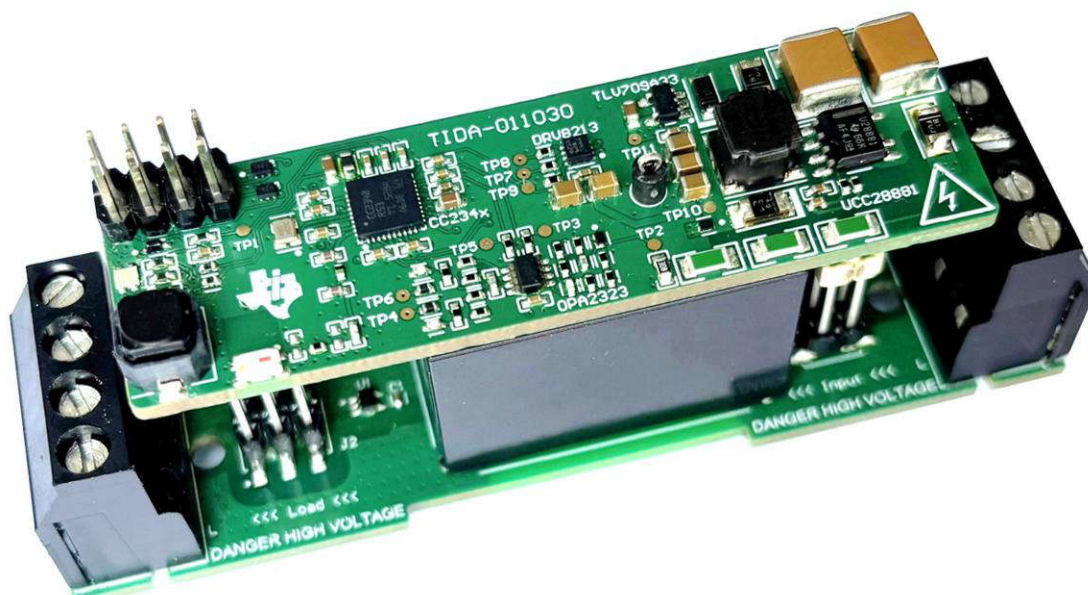


**Figure 2-2. Assembled TIDA-011030 Main Board and Power Board**

## 2.2 Design Considerations

### 2.2.1 Processing

The central processing device must combine wireless connectivity, electrical measurement, and time-critical protection functions. It must continuously acquire voltage and current signals, execute the metrology and protection algorithms, control the contactor, and maintain communication with the connected Wireless Gateway.

Most importantly, protection functions must continue to operate independently of the wireless connection. Communication activity must not delay current acquisition or the response to an overload or short-circuit condition. The processor and peripheral architecture must therefore support deterministic sample acquisition while leaving sufficient processing capacity for metrology calculations and the Zigbee protocol stack.

Because the circuit breaker is not intended to operate as a revenue-grade energy meter, a suitable ADC integrated into the MCU is preferred to avoid the additional cost and complexity of an external ADC. The ADC must still provide sufficient resolution and sampling performance for normal load currents while also covering the extended range required for overcurrent protection.

The CC2340R53 wireless MCU integrates a 2.4GHz radio, processor, internal ADC, timers, PWM generation, GPIOs, nonvolatile memory, and a watchdog. The ADC and timer peripherals are used for periodic voltage and current acquisition, while the ADC window comparator provides hardware-assisted detection when the current measurement approaches the limits of the ADC input range, as can occur during a high-current short-circuit condition. Additional peripherals provide interfaces to control the contactor, temperature sensor, local push button, status LEDs, UART, and SWD.

Integrating these functions into one wireless MCU reduces the number of external components and allows measurement, protection, relay control, and connectivity to share a common device. The protection path is prioritized over wireless communication and other noncritical processing to ensure a fast response to fault conditions. A hardware watchdog supervises firmware execution and resets the MCU if the safety-critical processing loop no longer progresses as expected.

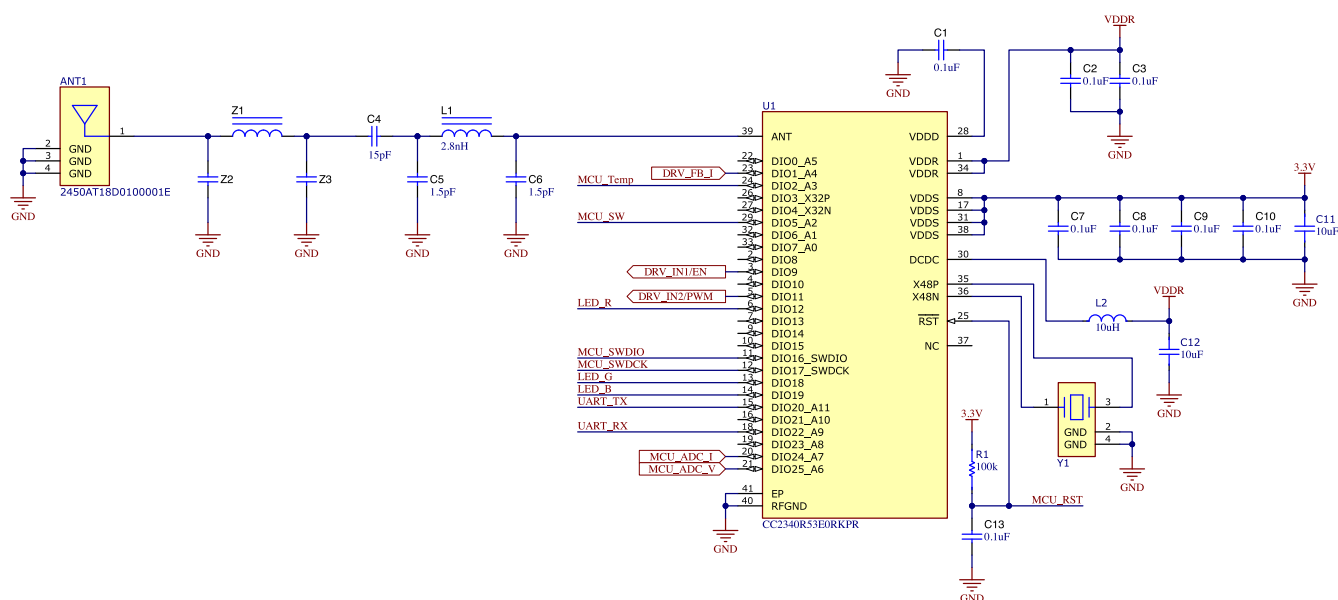


**Figure 2-3. MCU Schematics**

Figure 2-3 shows the CC2340R53 connections, including the 48MHz crystal, 2.4GHz filter and antenna matching network, power-supply decoupling, SWD and UART service interfaces, as well as the analog and digital signals used by the measurement and relay-control circuitry. The RF layout and antenna keep-out area must follow the component and CC2340R53 layout recommendations.

### 2.2.2 Voltage and Current Sensing

Current measurement is the primary input for the circuit-breaker protection functions. The protection characteristic targeted by this design is EN 60898-1 Type B, for which the instantaneous trip region lies between three and five times the rated current. For a rated current of 16A, this corresponds to a fault-current range from 48A to 80A. The current-sensing circuit must therefore provide sufficient resolution at normal load currents while also covering the extended range required for overload and short-circuit detection.

Voltage measurement is required for electrical metering, power calculation, frequency measurement, and supervision of the connected supply. The voltage-sensing circuit is designed to support both nominal 120V and 230VAC systems and must accommodate the highest expected line-voltage peak without exceeding the ADC input range.

Both sensing paths convert the bipolar AC signals for the unipolar input range of the CC2340R53 ADC. The following sections describe the voltage and current sensing circuits and the scaling used to map their respective measurement ranges to the ADC.

### 2.2.2.1 Voltage Measurement

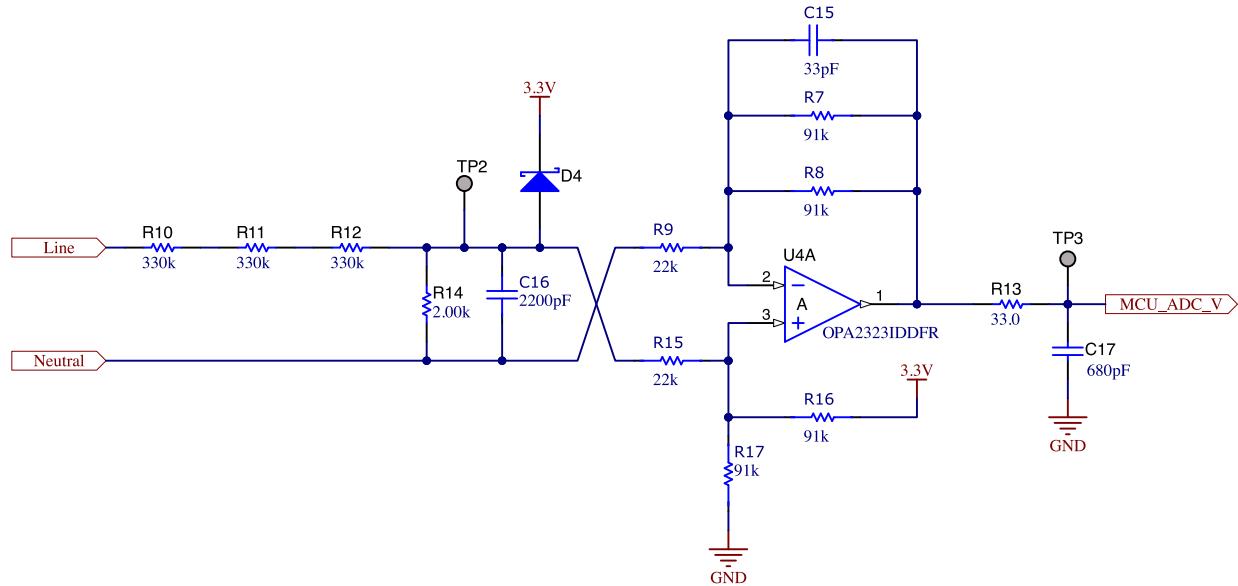


**Figure 2-4. Analog Front End for the Voltage Measurement**

The voltage measurement circuit attenuates and offsets the line voltage so that it can be measured by the internal ADC of the CC2340R53. The three series-connected 330kΩ resistors distribute the voltage drop across multiple components. Together with R14, they form the input voltage divider:

$$R_{HV} = R10 + R11 + R12 = 990k\Omega \quad (1)$$

$$K_{DIV} = \frac{R14}{R_{HV} + R14} = \frac{2k\Omega}{990k\Omega + 2k\Omega} = 0.002016 \quad (2)$$

For a nominal line voltage of 230VRMS with a tolerance of +/-10%, the maximum line-voltage peak is:

$$V_{LINE,PK,MAX} = 230V \times 1.1 \times \sqrt{2} = 357.8V \quad (3)$$

The resulting signal amplitude at the output of the voltage divider is:

$$V_{DIV,PK} = 357.8V \times 0.002016 = 0.721V \quad (4)$$

Because the ADC accepts input voltages between 0V and 3.3V, the bipolar AC signal must be amplified and centered around a midpoint of 1.65V. Without allowing for output headroom, the theoretical maximum gain would be:

$$G_{MAX} = \frac{1.65V}{0.721V} = 2.29 \quad (5)$$

A lower gain of approximately 2.07 is selected to use most of the available ADC range while retaining sufficient headroom for the op-amp output swing, offset voltage, and component tolerances. The differential gain is implemented using a 22kΩ input resistance and a 45.5kΩ feedback resistance:

$$G = \frac{45.5k\Omega}{22k\Omega} = 2.068 \quad (6)$$

The bias network at the non-inverting input is formed through the parallel combination of R16 and R17. Together with the 22kΩ input resistor R15, this network establishes an output midpoint of 1.65V when the differential input voltage is zero. As R16 and R17 are parallel, a resistor value of 91kΩ is chosen to achieve the required 45.5kΩ equivalent bias resistance.

The same effective resistance of 45.5kΩ is required in the negative-feedback path. It is implemented by connecting R7 and R8, also 91kΩ each, in parallel. Reusing the 91kΩ resistor value avoids an additional BOM entry and component reel during manufacturing while providing the required amplifier gain and matched resistor ratios. The resulting transfer function can be expressed as:

$$V_{ADC} = (V_{LINE} - V_{NEUTRAL}) \times K_{DIV} \times G + 1.65V \quad (7)$$

This leads to a maximum output voltage of:

$$V_{ADC,MAX} = 3.141V \quad (8)$$

$$V_{ADC,MIN} = 0.159V \quad (9)$$

Taking the OPA2323's maximum input offset voltage of 1.25mV and maximum output voltage swing of approximately 55mV to the rails into consideration, the available headroom therefore provides about 100mV of additional margin.

To prevent high-frequency noise from being amplified and passed to the ADC, the analog front end includes several low-pass filter stages. The first filter is located at the input of the differential amplifier and is formed by C16 together with the total resistance of the voltage divider.

$$R_{VD} = 990k\Omega \parallel 2k\Omega = 1.996k\Omega \quad (10)$$

$$f_{C16} = \frac{1}{2\pi R_{VD} C16} = \frac{1}{2\pi \times 1.996k\Omega \times 2.2nF} = 36.2kHz \quad (11)$$

C15 is connected in parallel with the 45.5kΩ feedback resistance and provides additional high-frequency attenuation. With a value of 33pF, the corresponding pole frequency is:

$$f_{C15} = \frac{1}{2\pi \times 45.5k\Omega \times 33pF} = 106kHz \quad (12)$$

The interaction of these filter poles results in a simulated bandwidth of approximately 34kHz. This limits high-frequency noise while leaving the 50Hz line-frequency signal essentially unaffected. The simulated phase shift at 50Hz is below 0.1° and therefore introduces no significant error into the fundamental voltage and power measurements.

R13 and C17 form the input stage of the ADC. C17 acts as a local charge reservoir for the ADC sample-and-hold circuit and should therefore be placed close to the input pin of the CC2340R53. R13 isolates the capacitive load presented by C17 from the output of the OPA2323, helping to maintain amplifier stability.

The conditioned signal is then digitized by the internal ADC of the CC2340R53. Under the selected operating conditions, the ADC provides an effective number of bits of approximately 11.2 according to the datasheet. For an ADC input range of 3.3V, the effective voltage step at the ADC input is:

$$V_{LSB,EFF} = \frac{3.3V}{2^{11.2}} = 1.40mV \quad (13)$$

Referred back to the line-voltage input, the effective resolution is:

$$V_{LINE,LSB} = \frac{V_{LSB,EFF}}{K_{DIV} \times G} = 0.336V \quad (14)$$

The resulting input-referred resolution is approximately 336mV per effective ADC count. This value represents the instantaneous single-sample resolution. The effective resolution of calculated RMS values can be higher because the metrology algorithm processes and averages multiple ADC samples.

### 2.2.2.2 Current Measurement

Current can be measured in multiple ways using a resistive shunt, a current transformer, or a Rogowski coil. Current transformers and Rogowski coils offer the benefit of galvanic isolation from the measured conductor but can require a more complex analog front end to condition the sensor signal. In this design, galvanic isolation within the current-sensing path is not required because the measurement and processing electronics operate in the same line-referenced domain, while communication with external systems is provided wirelessly. A resistive shunt therefore offers the simplest and most cost-effective solution.

A 1mΩ shunt resistance was selected as a compromise between measurable signal amplitude, power dissipation during normal operation, and the required overcurrent measurement range. As the circuit breaker is designed according to the Type B requirements of EN 60898-1, the specified instantaneous-tripping range must be between three and five times the nominal current. For a nominal rating of 16A, this corresponds to a current range from 48A to 80A. In this design, the nominal instantaneous-trip threshold is set to 3.25 times the rated current, corresponding to a tripping current of 52A.

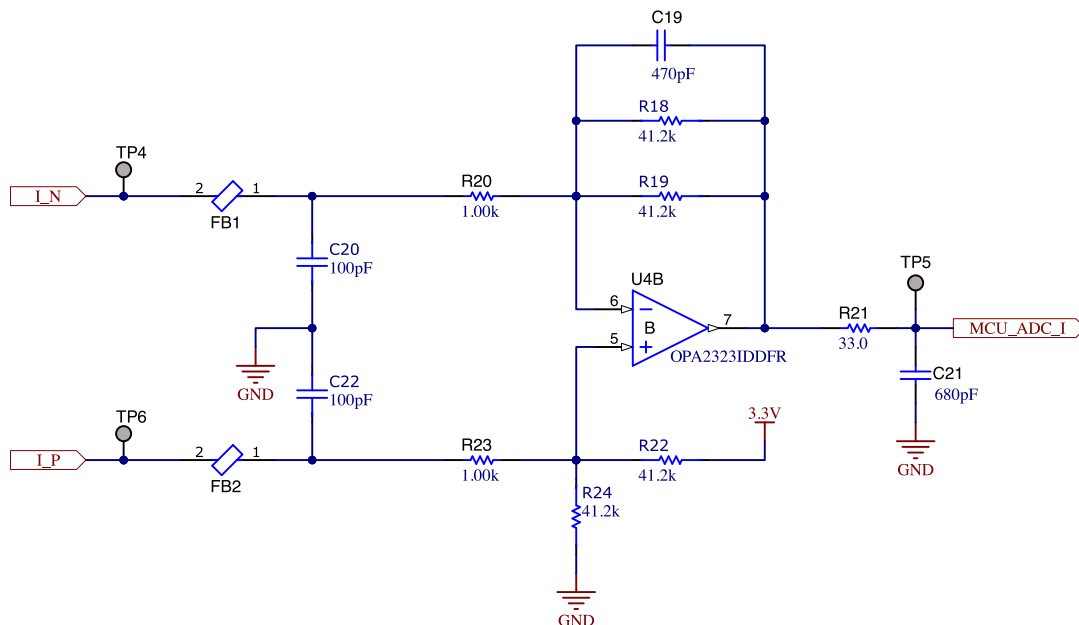


**Figure 2-5. Analog Front End for the Current Measurement**

The current-sensing analog front end uses the same differential-amplifier and midpoint-bias topology as the voltage-sensing circuit. However, the gain is adapted to the voltage generated by the 1mΩ shunt at the maximum specified measurement current. The transfer function can be expressed as:

$$V_{ADC} = I_{LOAD} \times R_{SHUNT} \times G + 1.65V \quad (15)$$

The amplifier gain is set to:

$$G = \frac{41.2k\Omega}{2k\Omega} = 20.6 \quad (16)$$

At the nominal instantaneous-trip threshold of 52ARMS, the peak voltage generated by the shunt is:

$$V_{SHUNT,PK} = 52A \times \sqrt{2} \times 1m\Omega = 73.54mV \quad (17)$$

After amplification, the corresponding ADC signal amplitude is:

$$V_{ADC,AMPL} = 73.54mV \times 20.6 = 1.515V \quad (18)$$

The corresponding maximum and minimum ADC input voltages are:

$$V_{ADC,MAX} = 3.165V \quad (19)$$

$$V_{ADC,MIN} = 0.135V \quad (20)$$

These values remain within the specified output range of the OPA2323 and the 0V to 3.3V input range of the CC2340R53 ADC. The remaining headroom accommodates the op-amp output swing, offset voltage, and component tolerances.

The bandwidths of the current- and voltage-sensing signal paths are both limited to approximately 34kHz. Matching their dominant frequency responses minimizes the relative phase shift between the measured current and voltage signals. Small residual phase errors can still result from component tolerances and the sequential ADC sampling interval and are compensated during calibration.

Limiting the analog bandwidth also reduces the integrated broadband noise because the total RMS noise increases with the square root of the equivalent noise bandwidth. The bandwidth should therefore be limited as far as practical without significantly attenuating the required current waveform or introducing excessive phase shift and settling time. The selected bandwidth represents a compromise between noise suppression and accurate reproduction of the current signal required for metrology and protection.

With an effective ADC resolution of approximately 11.2 bits, the effective single-sample current resolution is:

$$I_{LSB} = \frac{1.40mV}{1m\Omega \times 20.6} = 68mA \quad (21)$$

The resulting input-referred single-sample resolution is therefore approximately 68mA. As with the voltage measurement, the resolution of calculated RMS values can be higher because the metrology algorithm processes and averages multiple samples.

### 2.2.3 Solenoid – Relay Driver

This circuit breaker reference design uses an electromechanical relay to connect and disconnect the load. Conventional circuit breakers interrupt the current through mechanically latched power contacts and use a dedicated trip mechanism, commonly including a magnetic solenoid for rapid actuation under short-circuit conditions. For this demonstration, an electromechanical relay provides a simple and repeatable electrically controlled substitute for the final mechanical switching mechanism.

Although the relay does not represent the full interrupting capability of a certified circuit breaker, the inductive coil imposes similar requirements on the actuator driver, including sufficient pull-in current, reduced holding power, rapid de-energization, and safe handling of the stored inductive energy.

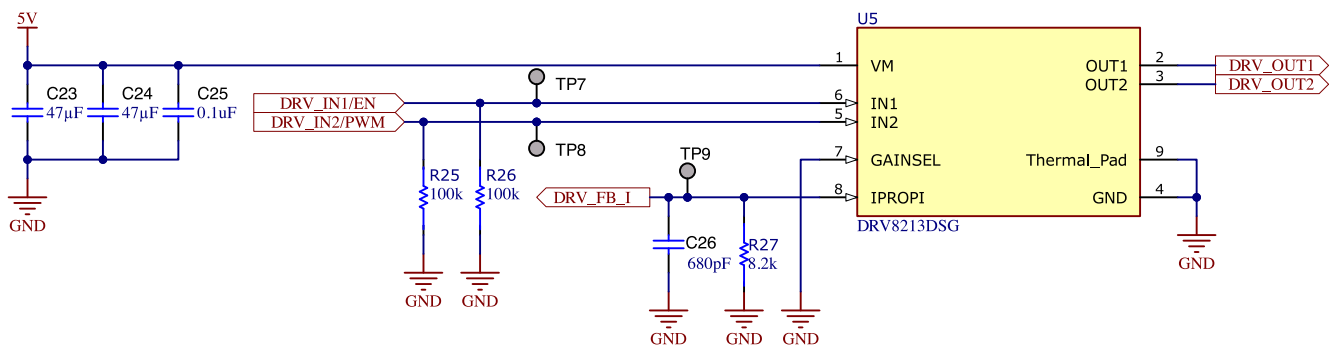


**Figure 2-6. Relay Driver Circuit**

The relay coil is driven by a DRV8213 integrated H-bridge driver. Compared with a discrete transistor driver, the H-bridge provides controlled current paths during drive and brake operation and eliminates the need for a separate flyback diode across the coil.

The DRV8213 also integrates current sensing and current regulation. The IPROPI output provides an analog signal proportional to the relay-coil current and is connected to the CC2340R53 through the DRV\_FB\_I signal.

This feedback signal allows the controller to verify that the coil draws the expected current and can later be used to detect an open coil, mechanical blockage, or other faults.

Independent current regulation protects the driver and coil against excessive current. GAINSEL is connected to ground, selecting an IPROPI current-mirror gain of:

$$A_{IPROPI} = 205\mu A / A \quad (22)$$

At the maximum relay current of 0.28A, the IPROPI output current is:

$$I_{IPROPI} = 0.28A \times 205\mu A / A = 57.4\mu A \quad (23)$$

With the selected IPROPI resistance of 8.2kΩ, this produces:

$$V_{IPROPI} = 57.4\mu A \times 8.2k\Omega = 0.471V \quad (24)$$

The DSG package uses an internal nominal reference voltage of 510mV. The nominal current-regulation threshold is therefore:

$$I_{LIMIT} = \frac{0.510V}{205\mu A / A \times 8.2k\Omega} = 0.303A \quad (25)$$

When the IPROPI voltage reaches the reference voltage, the DRV8213 limits the coil current using its internal fixed-off-time current-regulation mechanism. Capacitor C26 filters short switching transients to prevent premature current regulation.

The DRV8213 is controlled by two PWM inputs IN1 and IN2 as listed in [Table 2-1](#).

**Table 2-1. DRV8213 H-Bridge Control**

| Operating mode     | IN1 | IN2 | H-bridge state          |
|--------------------|-----|-----|-------------------------|
| Coast / relay open | 0   | 0   | High-Z                  |
| Forward drive      | 1   | 0   | Coil actively energized |
| Brake / slow decay | 1   | 1   | Both outputs driven low |

To close the relay, IN1 is set high and IN2 is held low for approximately 100ms, applying the full supply voltage to the coil. After pull-in, IN2 alternates between forward drive and brake at 20kHz to reduce the average holding current. A 35% effective drive duty cycle requires IN2 to remain low for 35% and high for 65% of each PWM period. During the high interval, the H-bridge enters the brake/slow-decay state and allows the coil current to recirculate. To open the relay, both inputs are set low, placing the H-bridge in coast mode and allowing the coil current to decay.

External 100kΩ pull-down resistors are connected to IN1 and IN2. They keep both control inputs low while the CC2340R53 is held in reset, unpowered, or the GPIOs are still configured as high-impedance inputs. The resulting default state is coast mode, in which the H-bridge outputs are disabled and the relay is de-energized. The external resistors complement the pull-down resistors integrated into the DRV8213 and provide a defined hardware-safe state independent of MCU initialization.

## 2.2.4 Temperature Measurement

Temperature monitoring is used to detect excessive heating around the relay, shunt resistor, and other current-carrying components. A TMP236 analog temperature sensor is placed close to the relay, which represents one of the thermally critical areas of the design. The sensor measures the local board temperature rather than the internal temperature of the relay or shunt directly. Therefore, the final protection thresholds must be correlated with component temperatures during thermal validation.

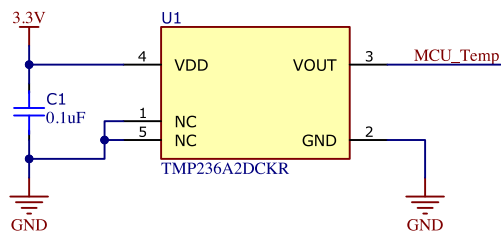


**Figure 2-7. Temperature Sensor Circuit**

The TMP236 provides an analog output voltage proportional to temperature. The output is connected to an ADC input of the CC2340R53 through the MCU\_Temp signal. The temperature can be calculated using:

$$T_A = \frac{V_{OUT} - V_{OFFS}}{T_C} + T_{INFL} \quad (26)$$

where:

$$T_A \text{ is the measured ambient temperature in } ^\circ\text{C} \quad (27)$$

$$V_{OUT} \text{ is the TMP236 output voltage} \quad (28)$$

$$V_{OFFS} \text{ is the TMP236 voltage offset} \quad (29)$$

$$T_C \text{ is the TMP236 temperature coefficient or gain} \quad (30)$$

$$T_{INFL} \text{ is the temperature inflection point for a piecewise segment in } ^\circ\text{C} \quad (31)$$

For temperatures up to 100°C, the TMP236 uses the following coefficients:

$$T_{INFL} = 0^\circ\text{C} \quad (32)$$

$$T_C = 19.5\text{mV}/^\circ\text{C} \quad (33)$$

$$V_{OFFS} = 400\text{mV} \quad (34)$$

For example, an output voltage of 985mV corresponds to:

$$T_A = \frac{0.985\text{V} - 0.4\text{V}}{0.0195\text{V}/^\circ\text{C}} = 30^\circ\text{C} \quad (35)$$

## 2.3 Highlighted Products

### 2.3.1 CC2340R53

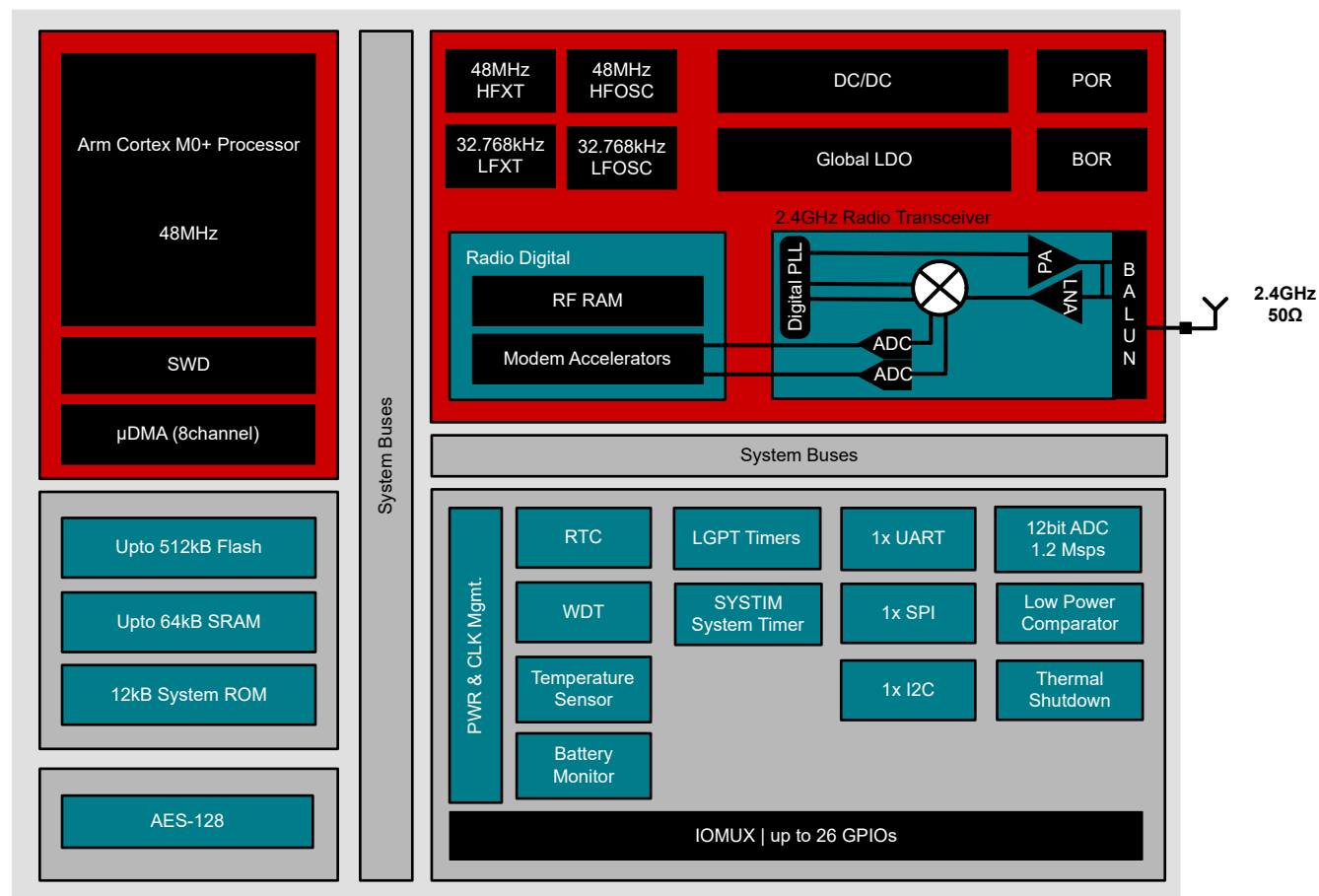


**Figure 2-8. CC2340R5 Functional Block Diagram**

The CC2340R SimpleLink™ family of devices are 2.4GHz wireless microcontrollers (MCUs), targeting Bluetooth Low Energy, Zigbee, Thread, and Proprietary 2.4GHz applications. These devices are optimized for low-power wireless communication with over the air download (OAD) support in building automation (wireless sensors, lighting control, beacons), asset tracking, medical, retail EPOS (electronic point of sale), ESL (electronic shelf), and personal electronics (toys, HID, stylus pens) markets. Highlighted features of this device include:

- Support for Bluetooth 5 features: high-speed mode (2Mbps PHY), long-range (LE Coded 125kbps and 500kbps PHYs), privacy 1.2.1 and channel selection algorithm #2, as well as backward compatibility and support for key features from the earlier Bluetooth LE specifications.
- Fully qualified Bluetooth software protocol stack included with the [SimpleLink™ Low Power F3 software development kit \(SDK\)](#)
- Zigbee protocol stack support in the [SimpleLink™ Low Power F3 software development kit \(SDK\)](#)
- Thread protocol stack support in [SIMPLELINK TI OPENTHREAD SDK](#)
- Ultra-low standby current less than 0.71μA with RTC operational and full RAM retention that enables significant battery life extension, especially for applications with longer sleep intervals.
- Integrated balun for reduced bill-of-material (BOM) board layout
- Excellent radio sensitivity and robustness (selectivity and blocking) performance for Bluetooth Low Energy (−102dBm for 125kbps LE Coded PHY, with integrated balun)

The CC2340R53 family is part of the SimpleLink MCU platform, which consists of Wi-Fi, Bluetooth Low Energy, Thread, Zigbee, Sub1GHz MCUs, and host MCUs that all share a common, easy-to-use development environment with a single-core software development kit (SDK) and rich tool set. A one-time integration of the SimpleLink platform enables you to add any combination of the portfolio's devices into your design, allowing

100-percent code reuse when your design requirements change. For more information, visit the [SimpleLink™ MCU platform](#).

### 2.3.2 OPA2323

The OPAx323 family of op amps includes single (OPA323), dual (OPA2323), and quad-channel (OPA4323), low-voltage (1.7V to 5.5V), high-bandwidth (20MHz) amplifiers (op amps) with a zero-crossover input stage and a rail-to-rail output stage. The zero-crossover input stage enables OPAx323 to achieve high linearity and low distortion for input signals with rail-to-rail swing that are typical in ADC driver applications. Gain-bandwidth of 20MHz provides a fast settling response for ADC sampling speeds between 0.5MSPS to 5MSPS depending on the settling performance required.

The OPAx323 easily supports precision performance in high gain voltage sensing applications, with a maximum offset drift of  $2\mu\text{V}/^\circ\text{C}$  and thermal noise floor of  $5.5\text{nV}/\text{rt-Hz}$  with a minimum of 100dB CMRR. This unique combination of higher precision (low offset, drift, noise, distortion, and CMRR) and higher gain-bandwidth (fast settling and slewing) enables use in multiple applications such as the motor rotary encoders, microphone audio pre-amplifiers and ultrasonic transducers.

The OPAx323 achieves a high slew-rate of  $33\text{V}/\mu\text{s}$  allowing for fast detection of faults in motor current sensing applications. Unlike traditional amplifiers, the zero-cross over input stage allows for identical precision performance for both low and high-side sensing applications, thus making OPAx323 the best choice for current sensing in a variety of end equipments such as the solar string inverters, power delivery, grid and EV infrastructure.

### 2.3.3 DRV8213

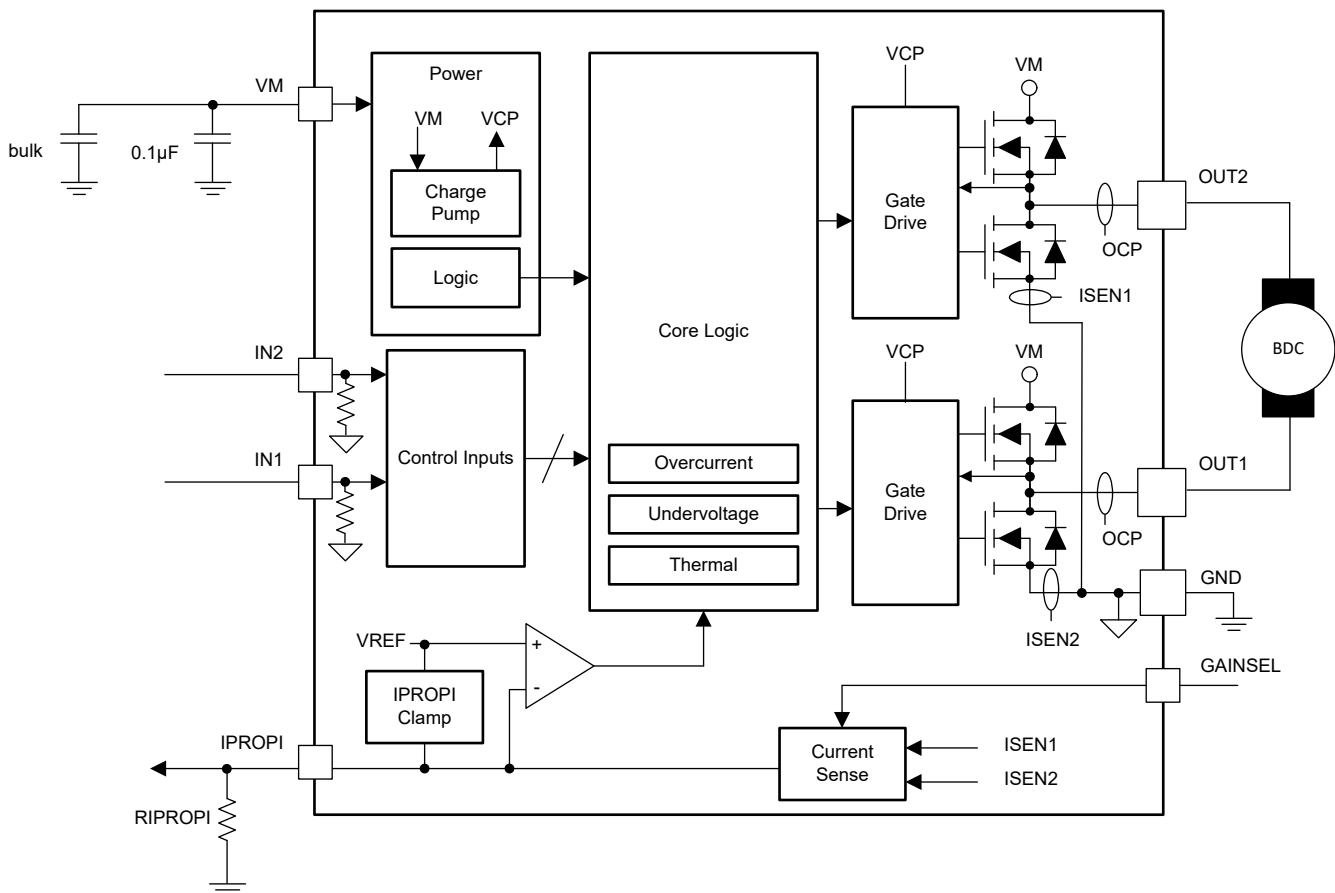


**Figure 2-9. DRV8213 Functional Block Diagram**

The DRV8213 is an integrated motor driver with N-channel H-bridge, charge pump, current sense output, current regulation, and protection circuitry. The tripler charge pump allows the device to operate down to 1.65V to

accommodate 1.8V supply rails and low-battery conditions. The charge pump integrates all capacitors and allows for 100% duty cycle operation.

An internal current mirror implements current sensing and regulation. This eliminates the need for a large power shunt resistor, saving board area and reducing system cost. The IPROPI current sense output allows a microcontroller to detect motor stall or changes in load conditions. The gain select (GAINSEL) feature allows high accuracy current sensing down to 10mA average current. The integrated current-regulation function limits the relay-coil current if it reaches the configured threshold during pull-in or a fault condition, without intervention by the microcontroller.

A low-power sleep mode achieves ultra-low quiescent current by shutting down most of the internal circuitry. Internal protection features include undervoltage lockout, overcurrent, and overtemperature.

### 2.3.4 TMP236A2

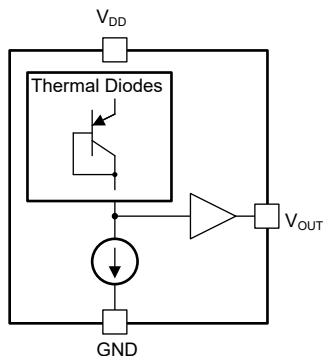


**Figure 2-10. TMP236A2 Functional Block Diagram**

The TMP23x devices are a family of precision CMOS integrated-circuit linear analog temperature sensors with an output voltage proportional to temperature engineers can use in multiple analog temperature-sensing applications. These temperature sensors are more accurate than similar pin-compatible devices on the market, featuring typical accuracy from 0°C to +70°C of  $\pm 0.5^\circ\text{C}$ . The increased accuracy of the series is designed for many analog temperature-sensing applications. The TMP235 device provides a positive slope output of 10 mV/°C cover the full  $-40^\circ\text{C}$  to  $+150^\circ\text{C}$  temperature range and a supply range from 2.3V to 5.5V. The higher gain TMP236 sensor provides a positive slope output of 19.5mV/°C from  $-10^\circ\text{C}$  to  $+125^\circ\text{C}$  and a supply range from 3.1V to 5.5V.

The 9 $\mu\text{A}$  typical quiescent current and 800 $\mu\text{s}$  typical power-on time enable effective power-cycling architectures to minimize power consumption for battery-powered devices. A class-AB output driver provides a strong 500 $\mu\text{A}$  maximum output to drive capacitive loads up to 1000pF and is designed to directly interface to analog-to-digital converter sample and hold inputs. With excellent accuracy and a strong linear output driver, the TMP23x analog output temperature sensors are cost-effective alternatives to passive thermistors.

## 3 System Design Theory

### 3.1 Software Architecture

The software architecture is divided into three main stages: system initialization, sample acquisition, and task-based sample processing. FreeRTOS separates the time-critical protection path from Zigbee communication. The following sections describe the purpose and execution of each stage.

#### 3.1.1 System Initialization

After reset, the generated board initialization configures the device clocks, power management, and TI driver infrastructure according to the SysConfig settings. A low-priority Zigbee application task is then created, and the FreeRTOS scheduler is started.

The Zigbee application first initializes the ZBOSS platform, configures the CC2340R53 as a Zigbee end device, and registers the application endpoint and supported clusters. Previously stored network information is retained in nonvolatile memory and evaluated by ZBOSS when the stack starts. Network steering, rejoining, and commissioning are handled through ZBOSS application signals.

The metering application then initializes the hardware abstraction layer, calibration storage, status LEDs, relay driver, and local push button. The breaker is placed in its hardware-safe open state before normal operation begins. The Metrology library is initialized using the stored calibration data. The optional UART interface intended for the calibration GUI is also initialized at this stage.

Next, the four-channel ADC sequence, ADC window comparator, and ADC interrupt are configured. The hardware sampling timer is connected to the ADC through the event fabric and started at 8kHz. From this point onward, voltage, load current, relay current, and temperature are acquired periodically without software-triggering individual conversions.

After sample acquisition and local protection are operational, the watchdog is initialized. The application then creates the high-priority Protection task and, if enabled, the lower-priority calibration GUI task. The Protection task executes periodically every 1ms, while the GUI task is serviced every 5ms.

Finally, the ZBOSS stack is started, and the original application task enters the Zigbee service loop. The resulting FreeRTOS priorities are:

- Protection task: priority 6
- Calibration GUI task: priority 2
- Zigbee task: priority 1

This initialization order ensures that ADC acquisition, metrology processing, breaker control, and watchdog supervision remain operational even if Zigbee startup or network communication fails.

#### 3.1.2 Sample Acquisition

A general-purpose timer generates a periodic target event at a sampling frequency of 8kHz, corresponding to one acquisition cycle every 125 $\mu$ s. The timer event is routed directly to the ADC through the CC2340R53 hardware event fabric. No timer interrupt or software-issued ADC trigger is required.

Each timer event starts a four-channel ADC sequence in the following order:

1. Load current
2. Line voltage
3. Relay-coil current
4. Temperature

The channels are sampled sequentially using the same ADC reference, resolution, clock divider, and sampling duration. After the temperature conversion has been written to the memory, the ADC generates one sequence-complete interrupt.

During initialization, the factory-programmed ADC gain trim is read once and retained for subsequent conversions. Inside the ADC interrupt handler, the four conversion results are read and corrected using this cached gain value. This compensates for the device-specific internal ADC gain error characterized during

production and maintains that the corrected conversion results meet the ADC accuracy specifications stated in the device datasheet.

The corrected load-current and line-voltage values form one metrology sample pair and are written to a 256-entry ring buffer. At 8kHz, this buffer can retain up to 32ms of unprocessed measurement data. Relay-current and temperature samples are not required by the per-sample Metrology processing and are therefore retained only as the latest corrected values.

The ADC window comparator monitors the uncorrected load-current conversion against thresholds calculated during initialization. If the load-current signal crosses either threshold, the comparator generates an ADC interrupt without waiting for the sample pair to be processed by the Protection task. The interrupt handler forwards the current result directly to the breaker protection logic. After the configured number of consecutive comparator events, the trip is latched and the relay is de-energized from the interrupt context.

This hardware-assisted saturation path complements the regular instantaneous-current protection, which evaluates every corrected current sample during task-based sample processing. It provides a low-latency response when a fault drives the analog current signal close to the usable limits of the measurement front end.

### 3.1.3 Sample Processing and Task Prioritization

FreeRTOS separates protection-critical sample processing from calibration and wireless communication. The application uses the execution contexts listed in [Table 3-1](#).

**Table 3-1. FreeRTOS Task Prioritization**

| Execution context             | Priority           | Period           | Main responsibility                                                                                                  |
|-------------------------------|--------------------|------------------|----------------------------------------------------------------------------------------------------------------------|
| ADC interrupt                 | Hardware interrupt | 125µs            | Read ADC sequence, evaluate window-comparator event, and buffer the sample pair                                      |
| Protection task               | 6                  | 1ms              | Process buffered samples, execute protection and Metrology calculations, control the relay, and service the watchdog |
| Optional calibration GUI task | 2                  | 5ms              | Service UART calibration commands during production or laboratory use                                                |
| Zigbee task                   | 1                  | Stack controlled | Synchronize Zigbee attributes, process commissioning requests, and execute ZBOSS                                     |

The Protection task has the highest software priority and is activated periodically every 1ms using `vTaskDelayUntil()`. At an acquisition rate of 8kHz, approximately eight new current-and-voltage sample pairs are normally available during each task period. Temporary execution delays are absorbed by the 256-entry ring buffer, and all pending samples are processed in their original acquisition order.

At the beginning of every Protection-task execution, the current sample backlog and task start time are recorded for diagnostic purposes. The task then locks the shared Metrology data structure and drains the ring buffer. For each sample pair, the corrected ADC codes are converted into the fixed-point format expected by the Metrology library. The following operations are then executed:

1. Metrology per-sample background processing
2. Instantaneous-current evaluation
3. Overload-current accumulation

After all pending samples have been processed, `Breaker_service()` handles pending local or Zigbee control commands and updates the relay-driver state machine. Metrology foreground calculations are executed only when the background processing indicates that a new measurement frame or mains cycle is available. These calculations produce RMS values, power, energy, frequency, phase, and the other reported quantities.

The resulting measurement and breaker state are copied into a coherent application snapshot. The short snapshot update is protected against interrupts so that the Zigbee task cannot observe a partially updated breaker or measurement state. Zigbee reads only this published snapshot and therefore does not need to lock the internal Metrology working data.

An optional lower-priority task services the UART calibration interface every 5ms. This interface is intended only for controlled production calibration and laboratory debugging and is not required during normal breaker operation. UART processing is bounded to 64 received bytes per service call and is skipped when the sample backlog exceeds 32 pairs. Access to the shared Metrology data is protected by a FreeRTOS mutex with priority inheritance, ensuring that calibration activity cannot indefinitely block the Protection task.

Because the Protection task has a higher priority, it can preempt Zigbee processing whenever its periodic execution becomes ready. Consequently, protection processing does not have to wait for a complete ZBOSS operation before it can continue.

After completing the protection-critical processing, the task services the watchdog. The watchdog is fed only if at least one sample pair was processed, no sample loss was detected, and the remaining backlog does not exceed 96 sample pairs. A sustained violation of these conditions prevents the watchdog from being fed and causes a system reset after the configured 50ms watchdog period.

The execution time and start interval of the Protection task are continuously monitored. A diagnostic deadline counter is incremented if either value exceeds 5ms. This threshold does not control task scheduling directly but provides a measurable indication that the protection timing budget has been violated. Task stack usage, maximum backlog, processed-sample count, and individual processing times are also retained as debugger-visible diagnostic values.

The hardware window-comparator path remains independent of this task scheduling. It can latch an over current-related trip directly from the ADC interrupt. Regular instantaneous-current and overload protection are executed by the Protection task using the buffered, gain-corrected current samples.

## 3.2 Circuit Breaker Functionality

The circuit-breaker subsystem controls the relay and provides local protection against short-circuit and overload conditions. All protection decisions are made directly on the CC2340R53 and do not depend on the Zigbee connection or an external home automation system.

The breaker starts in the hardware-safe open state and can be opened or closed using the local push button or a Zigbee command. Protection events always take priority over user commands. The stored trip reason identifies which protection path caused the disconnection.

The following functions are implemented:

- Sample-based instantaneous overcurrent trip
- Hardware-assisted ADC window-comparator trip
- Inverse-time overload protection with heating and cooling behavior
- Zigbee reporting of breaker state, service-disconnect status, and trip reason
- Zigbee overcurrent warning with hysteresis

The Zigbee overcurrent warning is asserted when the measured RMS current reaches the nominal breaker rating and is released when the current falls below 95% of that value. This warning does not itself open the breaker. This indicates that the nominal current has been exceeded while the inverse-time overload protection continues to evaluate the duration and magnitude of the overload.

The current firmware does not implement overtemperature or overvoltage and undervoltage protection. Temperature and line voltage are already measured and reported, allowing these protection functions to be added later without changing the analog measurement hardware. Relay-coil current is also sampled, but automatic relay fault diagnostics are not yet implemented.

The implemented protection behavior is designed around the Type B requirements of EN 60898-1. Final trip thresholds, timing, relay opening time, and thermal behavior must nevertheless be validated on the completed hardware using calibrated test equipment.

### 3.2.1 Breaker State and Relay Control

The breaker control is implemented as a state machine with the three states listed in [Table 3-2](#).

**Table 3-2. Circuit Breaker States**

| State   | Relay command | Status indication  |
|---------|---------------|--------------------|
| OPEN    | De-energized  | Open - Blue LED    |
| CLOSED  | Energized     | Closed - Green LED |
| TRIPPED | De-energized  | Trip - Red LED     |

After reset, the breaker always enters the OPEN state. The relay driver is disabled, the open LED is activated, and no current can intentionally flow through the load path. This provides a defined hardware-safe startup condition independent of the previously commanded Zigbee state.

A short press of the local button toggles the requested breaker state. Zigbee On/Off commands explicitly request either an open or closed state. Both interfaces write to a common control mailbox, and the most recently received normal control command is processed by the Protection task.

Protection events have priority over all user commands. When an instantaneous-current, ADC window-comparator, or overload trip occurs, the breaker:

1. Changes to the TRIPPED state
2. Stores the corresponding trip reason
3. Discards any pending close request
4. De-energizes the relay driver
5. Activates the red trip LED

The trip state remains latched until a new explicit open or close command is processed. An open command clears the trip indication and places the breaker in the OPEN state. A close command resets the trip state and attempts to energize the relay again.

The relay is controlled through the DRV8213. To close the breaker, the PWM output is prepared before IN1 is enabled. The coil then receives full drive for 100ms. This interval is monitored using a timestamp without blocking the Protection task. Afterwards, the driver changes to a 20kHz holding waveform with 35% effective coil drive, corresponding to IN2 being low for 35% and high for 65% of each PWM period.

Opening or tripping clears IN1 immediately and subsequently stops the PWM output. A protection trip can initiate this sequence directly from the ADC interrupt path. If the relay driver cannot be prepared successfully, the close operation is aborted and the breaker remains OPEN.

### 3.2.2 Instantaneous Short-Circuit Trip

The instantaneous short-circuit protection uses two complementary detection paths: a sample-based current threshold and the ADC hardware window comparator.

The sample-based protection is configured in `breaker_config.h` using the following parameters:

- Rated current: 16A
- Instantaneous-trip multiplier: 3.25
- Consecutive-sample requirement: 3 samples

The resulting RMS and peak trip thresholds are:

$$I_{trip,RMS} = 16A \times 3.25 = 52A \quad (36)$$

$$I_{trip,PK} = 52A \times \sqrt{2} = 73.54A \quad (37)$$

Each DC-filtered current sample produced by the Metrology background processing is converted into an absolute peak-current value. If three consecutive samples exceed the configured peak threshold, the breaker latches an `INSTANT_CURRENT` trip and de-energizes the relay. A sample below the threshold resets the evidence counter.

The comparator evaluates the load-current ADC result directly in hardware. Samples inside the configured window require no additional limit comparison in the ADC interrupt handler. Its thresholds are derived from the usable range of the current-sensing analog front end and reserve approximately 70mV of headroom to each

ADC rail. When either limit is crossed, the ADC generates an interrupt and forwards the current result directly to the breaker logic. Three consecutive window violations latch an ADC\_SATURATION trip.

Three consecutive threshold violations are defined to reject isolated transients. Currents only marginally above the instantaneous threshold remain covered by the inverse-time overload protection. Higher short-circuit currents produce multiple consecutive threshold violations and are disconnected through the instantaneous path.

The window-comparator path therefore provides the fastest response when the current signal approaches the analog input limits. The sample-based path independently applies the configured physical-current threshold using the scaled and DC-filtered Metrology samples.

### 3.2.3 Inverse-Time Overload Trip

The inverse-time overload protection is configured in breaker\_config.h. The principal configuration parameters are:

- Pickup current:  $1.13 \times I_n$
- Curve point 1:  $1.45 \times I_n$  with a target trip time of 1800s
- Curve point 2:  $2.55 \times I_n$  with a target trip time of 30s
- Cooling time: 1800s
- Overload update interval: 20ms at 50Hz or 50ms at 60Hz

The overload model uses an inverse-time characteristic together with thermal-memory-like damage accumulation. The selected equation is based on the general inverse definite minimum time (IDMT) form used for overcurrent protection in IEC 60255-151. However, the curve parameters are fitted specifically to the selected EN 60898-1 operating points.

$$t_{(x)} = \frac{k}{\left(\frac{x}{x_0}\right)^p - 1} \quad (38)$$

Where:

$t_{(x)}$  is the calculated trip time

$x = I_{rms} / I_{rated}$  is the measured current ratio

$x_0$  is the pickup ratio

$k$  is the curve time constant

$p$  determines the steepness of the curve

At or below the pickup ratio, the equation does not produce a finite trip time. In this region, the overload-damage accumulator cools instead of increasing.

The constants  $k$  and  $p$  are calculated from the two configured operating points. With:

$$M_{1.45} = \frac{1.45}{1.13} \quad (39)$$

$$M_{2.55} = \frac{2.55}{1.13} \quad (40)$$

the two desired trip times are:

$$1800s = \frac{k}{M_{1.45}^p - 1} \quad (41)$$

$$30s = \frac{k}{M_{2.55}^p - 1} \quad (42)$$

Dividing the two equations eliminates  $k$ :

$$\frac{1800s}{30s} = 60 = \frac{M_{2.55}^p - 1}{M_{1.45}^p - 1} \quad (43)$$

Numerically solving this equation results in:

$$p \approx 6.9108 \quad (44)$$

The time constant can then be calculated using either operating point:

$$k = 1800s \times \left[ \left( \frac{1.45}{1.13} \right)^{6.9108} - 1 \right] \quad (45)$$

$$k \approx 8284.1s \quad (46)$$

Substituting these constants into the second operating point verifies the result:

$$t_{(2.55)} = \frac{8284.1}{\left( \frac{2.55}{1.13} \right)^{6.9108} - 1} \approx 30s \quad (47)$$

The firmware calculates these constants during initialization. This provides flexibility for testing different curve points during development and validation. After the final characteristic has been verified, the resulting constants can be stored as fixed values.

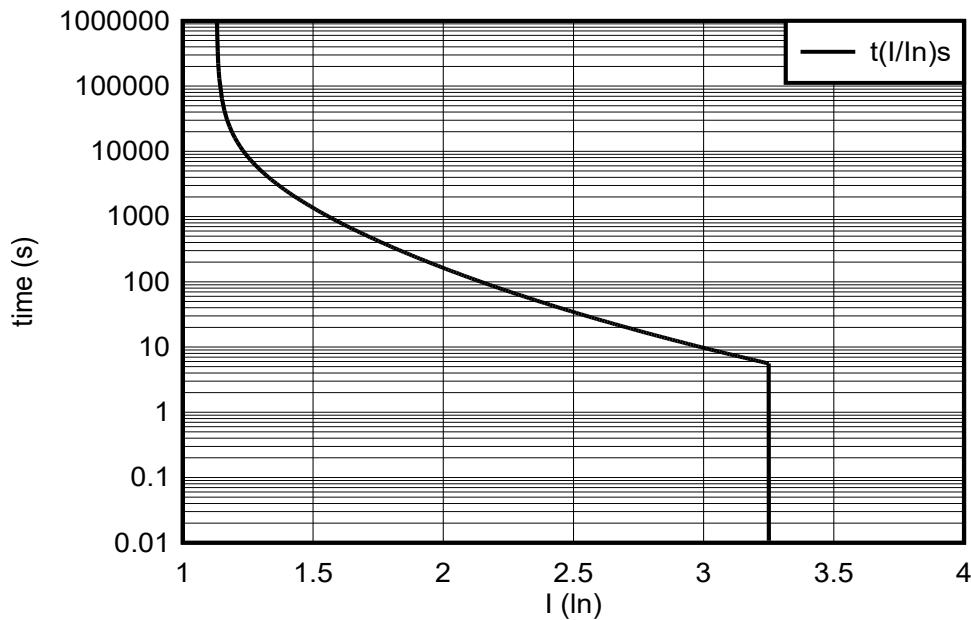


**Figure 3-1. Inverse-Time Overload Characteristic**

Figure 3-1 shows the resulting trip time for various overload conditions. The inverse-time curve applies below the instantaneous-trip threshold of  $3.25 \times I_n$ . At and above this threshold, the instantaneous protection path is triggered.

For each processed current sample, the firmware accumulates the squared instantaneous current. Once a complete RMS window has been collected, the window current is calculated as:

$$I_{RMS} = \sqrt{\frac{1}{N} \sum_{n=1}^N i_n^2} \quad (48)$$

At 50Hz,  $N = 160$  samples are accumulated over one complete 20 ms mains cycle. At 60Hz,  $N = 400$  samples are accumulated over three complete cycles, corresponding to 50ms. Using complete nominal mains cycles prevents the phase-dependent RMS error that would occur with a partial-cycle window. The overload-window

length is derived from the nominal mains frequency defined by MAINS\_NOMINAL\_FREQUENCY in template.h. It is not adjusted dynamically from the measured frequency.

The resulting RMS current determines the trip time from the inverse characteristic. Instead of starting a countdown timer, the firmware maintains a normalized damage accumulator  $D$ , where zero represents a cold breaker and one represents the trip threshold. For every completed RMS window with duration  $\Delta t$ , the accumulator is updated by:

$$D_{new} = \min\left(1, D_{old} + \frac{\Delta t}{t(x)}\right) \quad (49)$$

For a constant overload current, the accumulator therefore reaches one after the calculated trip time. If the current changes, the existing damage is retained while the accumulation rate is adjusted to the new current. A higher current increases the accumulator more rapidly, whereas a lower current above pickup continues increasing it at a slower rate. When the accumulator reaches one, an overload trip is latched and the relay is de-energized.

If the RMS current is at or below the pickup threshold, the accumulator cools linearly according to the configured cooling time:

$$D_{new} = \max\left(0, D_{old} - \frac{\Delta t}{t_{cool}}\right) \quad (50)$$

With a cooling time of 1800s, a damage state close to the trip threshold requires almost 30 minutes below pickup to return to zero. A partially accumulated damage state cools proportionally faster.

The sample-based instantaneous protection is evaluated before the overload accumulator is updated. Consequently, currents that reach the configured instantaneous threshold are disconnected through the faster short-circuit path, while the inverse-time model covers sustained overload currents below that threshold.

### 3.3 Electrical Metrology

The design uses the [TI Energy Measurement Library](#) originally provided for MSPM0-based metrology applications. The device-independent calculation modules are retained without functional modifications. Detailed descriptions of the RMS, power, energy, phase, and harmonic calculations are available in the corresponding [TI Energy Measurement Library documentation](#). This section therefore focuses on the integration of the library into the CC2340R53 application.

The original platform-specific sample acquisition is replaced by the internal ADC of the CC2340R53. After applying the factory-programmed ADC gain correction, the current and voltage codes are centered around the ADC midpoint and converted into the signed IQ23 fixed-point format expected by the library. Only the load-current and line-voltage channels are passed to the Metrology processing. Relay-current and temperature measurements are handled separately by the application.

For every processed sample pair, the Protection task calls the Metrology background process. This process performs DC-offset filtering, zero-crossing detection, and accumulation of the intermediate quantities required for the electrical calculations. When the background process indicates that a complete measurement frame is available, the foreground process calculates the reported electrical parameters. These include:

- RMS voltage and current
- Active, reactive, and apparent power
- Power factor
- Mains frequency and voltage-to-current phase angle
- Imported active energy

The library is configured for single-phase operation through template.h. The principal configuration parameters include the 8kHz sampling rate, nominal mains frequency, nominal voltage, and default current and voltage scaling factors. These default values provide initial operation before the device has been calibrated.

The hardware abstraction layer maps the library's platform-dependent functions to the CC2340R53 application. This includes nonvolatile calibration storage and the optional UART calibration interface. Calibration parameters

are stored in a dedicated NVS region together with a versioned header and CRC. At start-up, valid stored parameters are loaded by the Metrology library. Otherwise, the compiled default calibration values are used. Energy-pulse GPIO outputs are disabled because they are not required by this circuit-breaker design.

After each Protection-task execution, the latest measurements and breaker state are copied into a coherent application snapshot. The Zigbee task reads only this published snapshot. The optional calibration GUI accesses the internal Metrology working data.

### 3.4 Zigbee Connectivity

The Zigbee implementation is based on the `on_off_switch` example provided with the SimpleLink Low Power F3 SDK. This example supplies the fundamental ZBOSS stack integration, Zigbee Base Device Behavior commissioning, network-data persistence, endpoint registration, and On/Off command handling. Building on this existing example reduces the amount of application-specific protocol code and provides a tested foundation for network joining and rejoining.

The application configures the CC2340R53 as a Zigbee end device. On first start, the device automatically initiates network steering and searches for a network that permits joining. After a successful connection, the network information is retained in nonvolatile memory and reused after subsequent resets.

The local breaker button is also used for commissioning. A long press starts network steering if the device is factory new. If network information is already stored, a long press performs a local Zigbee reset, clears the stored network data, and restarts network steering.

The circuit breaker is represented as a Home Automation Smart Plug on endpoint 10. The original On/Off device definition is extended with metering, electrical-measurement, and temperature functionality.

**Table 3-3. Zigbee Cluster Configurations**

| Server Cluster          | Main Function                                                                                   |
|-------------------------|-------------------------------------------------------------------------------------------------|
| Basic                   | Device manufacturer, model, and application information                                         |
| Identify                | Standard Zigbee device-identification functionality                                             |
| On/Off                  | Remote breaker open and close commands and breaker-state reporting                              |
| Metering                | Active energy, instantaneous demand, alarm status, and disconnect reason                        |
| Electrical Measurement  | RMS voltage and current, active, reactive and apparent power, power factor, and mains frequency |
| Temperature Measurement | Temperature measured close to the relay                                                         |

Remote On/Off commands do not manipulate the relay GPIOs directly. The Zigbee callback forwards the requested state to the breaker-control module, where it is processed by the higher-priority Protection task. A protection trip takes precedence over remote commands and invalidates any older pending close request. Local button operations and protection trips are copied back to the On/Off attribute so that the Zigbee state remains synchronized with the actual breaker state.

The latest coherent measurement snapshot is periodically converted into the units and data types required by the Zigbee Cluster Library attributes. Breaker trips and overload conditions are additionally mapped to Metering-cluster status fields and service-disconnect reasons.

A project-specific Zigbee2MQTT external converter, `tida_011030.mjs`, identifies the device and applies the configured attribute multipliers and divisors. The converter periodically reads the electrical measurements and exposes the breaker state, metrology values, temperature, overcurrent alarm, protection-disconnect alarm, and disconnect reason to Zigbee2MQTT and Home Assistant. State and alarm changes are reported separately when the corresponding Zigbee attributes change. The Zigbee2MQTT external converter is included in the TIDA-011030 firmware folder.

Zigbee communication is intentionally separated from the protection-critical processing. The Zigbee task runs at a lower FreeRTOS priority than the Protection task and can be preempted whenever new protection processing becomes due. Network joining, attribute reads, reporting, or device configuration therefore cannot prevent the ADC interrupt and Protection task from continuing to process current samples and control the circuit breaker.

## 4 Hardware, Software, Testing Requirements, and Test Results

### 4.1 Hardware Requirements

#### 4.1.1 Hardware Connections and Test Points

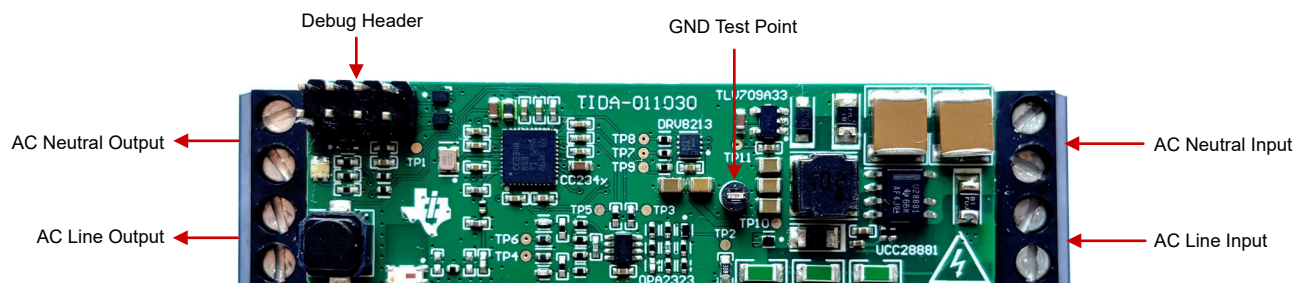


**Figure 4-1. TIDA-011030 Service and Power Connections**

Figure 4-1 identifies the service connections and line connections available on the mainboard and power board. Their pin assignments and functions are summarized in Table 4-1 through Table 4-3.

**Table 4-1. Debug Header Pinout**

| PIN | SIGNAL  | DESCRIPTION                                      |
|-----|---------|--------------------------------------------------|
| 1   | SWDCK   | Serial Wire Debug clock signal                   |
| 2   | 5V      | External 5V supply input for low-voltage testing |
| 3   | GND     | Local circuit-ground reference                   |
| 4   | UART TX | UART transmit output from the CC2340R53          |
| 5   | SWDIO   | Serial Wire Debug bidirectional data signal      |
| 6   | GND     | Local circuit-ground reference                   |
| 7   | MCU RST | Active-low reset input of the CC2340R53          |
| 8   | UART RX | UART receive input to the CC2340R53              |

**Table 4-2. Test Points**

| DESIGNATOR | SIGNAL      | DESCRIPTION                                                  |
|------------|-------------|--------------------------------------------------------------|
| TP1        | MCU_Temp    | Filtered TMP236 output at the MCU ADC input                  |
| TP2        | V Divider   | Attenuated line-voltage signal at the voltage-divider output |
| TP3        | MCU_ADC_V   | Voltage-channel amplifier output and MCU ADC input           |
| TP4        | I_N         | Shunt-resistor low-side sense node                           |
| TP5        | MCU_ADC_I   | Current-channel amplifier output and MCU ADC input           |
| TP6        | I_P         | Shunt-resistor high-side sense node                          |
| TP7        | DRV_IN1_EN  | DRV8213 enable and direction-control input                   |
| TP8        | DRV_IN2_PWM | DRV8213 PWM control input                                    |
| TP9        | DRV_FB_I    | DRV8213 IPROPI current-sense output                          |
| TP10       | 5V          | Regulated 5V rail                                            |
| TP11       | 3.3V        | Regulated 3.3V rail                                          |
| GND1       | GND         | Local circuit-ground reference                               |

**Table 4-3. Power-Board Screw Terminals**

| DESIGNATOR | PIN  | DESCRIPTION                                                      |
|------------|------|------------------------------------------------------------------|
| J1         | 1, 2 | AC line input, both terminals are connected in parallel          |
| J1         | 3, 4 | AC neutral input, both terminals are connected in parallel       |
| J4         | 1, 2 | Neutral output to the load through the current-measurement shunt |
| J4         | 3, 4 | Switched line output to the load through the relay contact       |



#### CAUTION

*Do not leave the design powered when unattended.*



#### WARNING

**High voltage!** Accessible high voltages are present on the board. Electric shock is possible. The board operates at voltages and currents that can cause shock, fire, or injury if not properly handled. Use the equipment with necessary caution and appropriate safeguards to avoid injuring yourself or damaging property. For safety, use of isolated test equipment with overvoltage and overcurrent protection is highly recommended.

TI considers the user's responsibility to confirm that the voltages and isolation requirements are identified and understood before energizing the board or simulation. *When energized, do not touch the design or components connected to the design.*



#### WARNING

**Hot surface! Contact can cause burns. Do not touch!**

Some components can reach high temperatures > 55°C when the board is powered on. Do not touch the board at any point during operation or immediately after operating, as high temperatures can be present.



#### WARNING

TI intends this reference design to be operated in a **lab environment only and does not consider the design as a finished product** for general consumer use. The design is intended to be run at ambient room temperature and is not tested for operation under other ambient temperatures.

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

There are **accessible high voltages present on the board**. The board operates at voltages and currents that can cause shock, fire, or injury if not properly handled or applied. Use the equipment with necessary caution and appropriate safeguards to avoid injuring yourself or damaging property.

## 4.2 Test Setup

### 4.2.1 Connecting the TIDA-011030 to the Metering Test Equipment

The TIDA-011030 is connected like a conventional single-phase circuit breaker and is installed between the AC supply and the protected load. The AC line and neutral conductors are connected to the input terminals, while the corresponding output terminals are connected to the load. Internally, the line conductor is switched by the relay and the neutral conductor is routed through the current-measurement shunt.

- J1 pins 1 and 2 are the AC line input.
- J1 pins 3 and 4 are the AC neutral input.
- J4 pins 3 and 4 provide the switched line output to the load.
- J4 pins 1 and 2 provide the neutral connection to the load through the current-measurement shunt.

The two terminals assigned to each signal are internally connected in parallel. Either terminal can be used, or both can be used where required by the test setup.

Connect the programmable AC voltage source between the line and neutral terminals of J1. Connect the test load or current-generation circuit to J4. During normal operation, the current path is:

*J1 Line -> relay contact -> J4 Line -> test load -> J4 Neutral -> current-measurement shunt -> J1 Neutral*

The voltage-measurement circuit measures the potential between line and neutral at J1. Consequently, the input voltage can be measured while the breaker is open, whereas load current can flow only after the relay has been closed.

The breaker starts in the open state after reset. After verifying all connections and enabling the test source, close the breaker using the local push button, Zigbee control, or the selected test interface. A protection trip opens the relay and latches the tripped state until the breaker is manually reset.

If the metering test equipment provides separate voltage and current sources, its outputs must be configured so that the generated current follows the complete series path through both the relay contact and the current-measurement shunt.

For metrology testing, the nominal continuous-current range is up to 16A. Higher currents are intended only for controlled protection testing and should not be applied for a longer period than the intended protection time. Before energizing the setup, verify that all screw-terminal connections are secure and that the conductors and test equipment are rated for the applied voltage and current.

#### 4.2.2 Power-Supply Options

During normal operation, the TIDA-011030 is powered directly from the AC line and neutral input. The onboard non-isolated power supply converts the AC input voltage to 5V, from which the 3.3V supply for the CC2340R53 and the remaining low-voltage circuitry is generated. No external supply is required during normal operation.

For low-voltage functional testing or current-channel calibration, the board can alternatively be powered from an external regulated 5V supply through pin 2 of the debug header. The supply return is connected to either GND pin of the header. When this option is used, the AC input should remain disconnected unless the complete test setup is appropriately isolated.

External supply operation is particularly useful when calibrating the current channel. If the board is powered from the same AC source as the measurement setup, the current consumed by the onboard power supply can be included in the reference instrument's current reading, even though it does not represent load current flowing through the measurement shunt. Powering the electronics separately from 5V allows the reference current to be applied only through the intended current-measurement path.

#### 4.2.3 Metrology Calibration

The voltage, current, power, and phase measurements must be calibrated to compensate for ADC, sensor, analog-front-end, and component tolerances. The general calibration procedure follows the [TI Energy Metrology Library](#) and [Energy Library GUI User Guide](#). This section describes the adaptations and additional considerations specific to the TIDA-011030.

The calibration GUI communicates with the CC2340R53 through the UART signals on the debug header at 115200 baud. Because this interface belongs to the line-referenced circuit domain, an isolated UART connection is required, when connected to high-voltage AC.

Calibration requires an accurate AC source and reference measurement instrument. After the applied voltage, current, frequency, and phase have stabilized, the corresponding voltage, current, power, and phase-correction parameters can be adjusted using the GUI.

The signed relative measurement error used by the calibration procedure is calculated as:

$$Error_{cal} = \left( \frac{Value_{TIDA}}{Value_{reference}} - 1 \right) \times 100\% \quad (51)$$

A positive value indicates that the TIDA-011030 reports a value above the reference value, while a negative value indicates that it reports a value below the reference value. This signed error value is entered in the calibration GUI, which updates the corresponding calibration parameter.

Voltage, current, and power scaling factors are independent. Voltage and current gain should therefore be calibrated first, followed by active-power gain and phase compensation.

For current-only calibration, the board can be powered from the external 5V input as described in Section 4.2.2. This prevents the current consumed by the onboard AC power supply from affecting the reference instrument reading. The exact applied calibration points must be recorded and excluded from the independent accuracy evaluation.

Updated calibration parameters are stored in a dedicated nonvolatile-memory region. Each record contains a format identifier, version, payload length, sequence number, and CRC-32 checksum. During start-up, the firmware validates the stored record before applying it. If no valid record is available, the default values defined by the firmware are loaded.

In addition to the TI calibration parameters, the TIDA-011030 applies a project-specific quadratic correction to the RMS current reported through UART and Zigbee:

$$I_{corrected} = \sqrt{\max(I_{measured}^2 - I_{noise}^2, 0)} \quad (52)$$

Where  $I_{noise}$  is the RMS current reported with zero applied current and the current input shorted.

The noise value is determined with zero current and the current input shorted after gain calibration. It is configured separately in METERING\_CURRENT\_RMS\_NOISE\_FLOOR\_UA and is not modified by the TI calibration GUI. This correction affects only the reported RMS current and does not modify active-power calculation or the current samples used by the protection functions. The Metrology linear current-offset parameter should not be used to compensate for the same noise contribution simultaneously.

#### 4.2.4 Test-Data Acquisition and Error Calculation

For each operating point, the test source was allowed to stabilize before data acquisition began. At least 30 TIDA-011030 measurement samples were recorded at intervals of one second. Multiple reference-instrument readings were collected over the same stabilized interval. The TIDA-011030 and reference readings were averaged:

$$\bar{x}_{reference} = \frac{1}{M} \sum_{j=1}^M x_{reference,j} \quad (53)$$

$$\bar{x}_{TIDA} = \frac{1}{N} \sum_{i=1}^N x_{TIDA,i} \quad (54)$$

where  $M$  and  $N$  are the numbers of reference-instrument and TIDA-011030 readings, respectively.

The averaged reference reading, rather than the programmed source setpoint, was used for the error calculation. Consequently, reference values can contain additional decimal places, such as 16.00142A instead of the nominal source setting of 16A.

The relative measurement error was calculated separately for each operating point:

$$Error_{relative} = \frac{\bar{x}_{TIDA} - \bar{x}_{reference}}{\bar{x}_{reference}} \times 100\% \quad (55)$$

A positive result indicates that the TIDA-011030 reports a value above the reference value, while a negative result indicates that it reports a value below the reference value.

Short-term repeatability of the RMS-voltage and RMS-current measurements was characterized using the sample standard deviation:

$$s = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_{TIDA,i} - \bar{x}_{TIDA})^2} \quad (56)$$

RMS-current measurements were performed under unity-power-factor, inductive, and capacitive load conditions. For each current level, the relative error and sample standard deviation were calculated separately for each load condition. The highest absolute relative error and the largest standard deviation among the three load conditions are reported in the result tables.

## 4.3 Test Results

### 4.3.1 Relay Control and Protection

#### 4.3.1.1 Relay Pull-In and Holding PWM

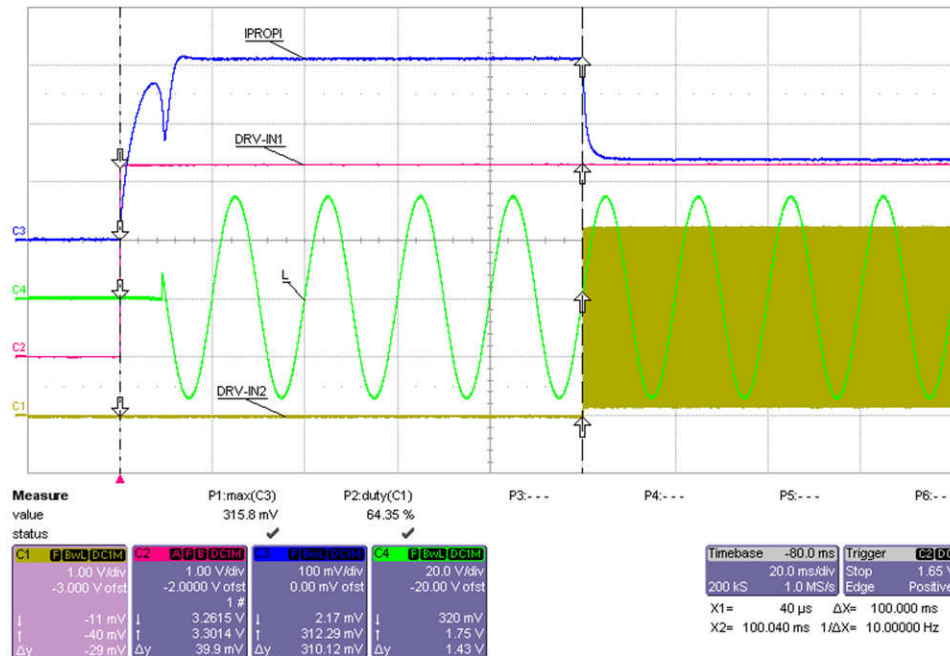


**Figure 4-2. Relay Pull-In and Transition to the PWM Holding Phase**

The relay coil is fully driven for 100ms before changing to a 35% effective drive duty cycle.

Figure 4-2 shows the relay-control signals during a transition from the open to the closed state. DRV\_IN1\_EN is driven high while DRV\_IN2\_PWM initially remains low. This applies the full supply voltage to the relay coil during the pull-in interval.

The oscilloscope cursors indicate a pull-in duration of 100ms. During this interval, the IPROPI signal reaches a maximum of 315.8mV. Using the configured IPROPI gain and resistance, the corresponding peak coil current is:

$$I_{COIL} = \frac{315.8 \text{ mV}}{205 \mu\text{A/A} \times 8.2 \text{ k}\Omega} = 187.9 \text{ mA} \quad (57)$$

The measured IPROPI voltage remains below the nominal 510mV current-regulation threshold of the DRV8213. Consequently, the driver does not enter current regulation during normal relay pull-in.

After 100ms, DRV\_IN2\_PWM starts switching while DRV\_IN1\_EN remains high. During this holding phase, DRV\_IN2\_PWM remains high for approximately 65% of each PWM period. The oscilloscope reports 64.35% for the complete acquisition, with the small deviation from the nominal value influenced by the preceding low state during relay pull-in. Because a low level on DRV\_IN2\_PWM selects forward drive, whereas a high level selects the brake state, the effective coil-drive duty cycle is:

$$D_{DRIVE} = 100\% - 65\% = 35\% \quad (58)$$

This matches the configured effective drive duty cycle of 35%. The lower IPROPI level after the transition confirms the expected reduction in relay-coil current during the holding phase.

#### 4.3.1.2 Instantaneous Trip and Relay-Opening Latency

The instantaneous-trip function was tested using a 50Hz current waveform with a peak current exceeding the configured trip threshold. The following oscilloscope signals were recorded:

- ADC-I: amplified current-sensing signal at the MCU ADC input

- Shunt-P: voltage measured single-ended at the positive terminal of the shunt, referenced to the local circuit ground
- DRV-IN1: relay-driver enable signal

The current source was operated close to the maximum output capability and produced a visibly distorted waveform. In particular, the current waveform became clipped at high amplitudes. The voltage measured directly at the shunt exhibits the same waveform shape as the amplified ADC signal. This confirms that the observed distortion originated from the test source rather than from the current-sensing analog front end.

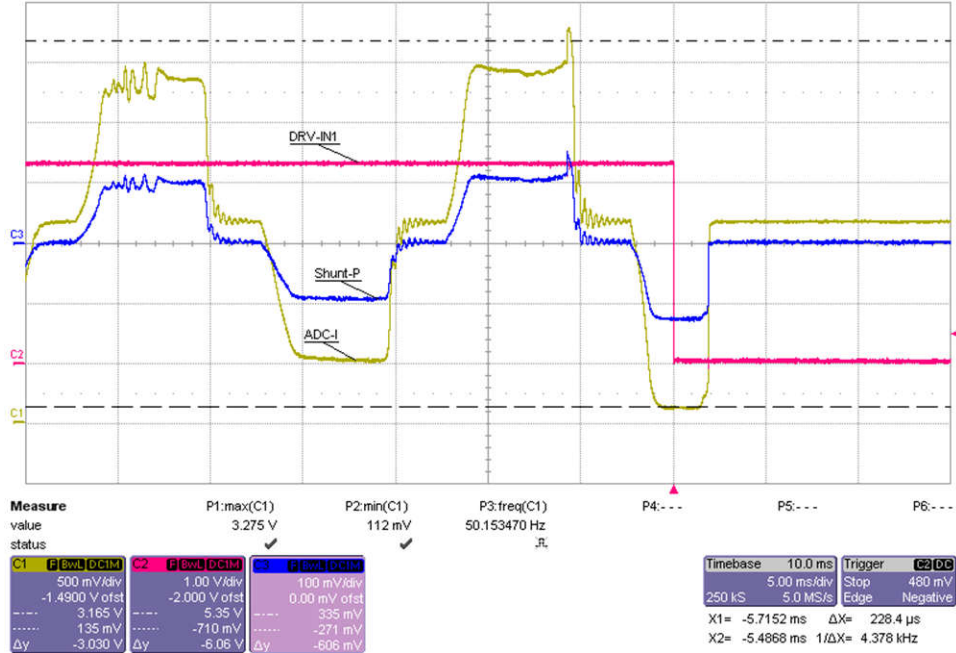


**Figure 4-3. Current Waveform and Upper and Lower Software Instantaneous-Current Thresholds**

The configured software instantaneous-current thresholds are 3.165V and 0.135V. With an ADC midpoint of 1.65V, a 1mΩ shunt, and an amplifier gain of 20.6, these values correspond to a peak-current threshold of:

$$I_{TH, PK} = \frac{3.165 \text{ V} - 1.65 \text{ V}}{1 \text{ m}\Omega \times 20.6} = 73.54 \text{ A} \quad (59)$$

For a sinusoidal current, the corresponding RMS threshold is:

$$I_{TH, RMS} = \frac{73.54 \text{ A}}{\sqrt{2}} = 52.0 \text{ A} = 3.25 \times I_n \quad (60)$$

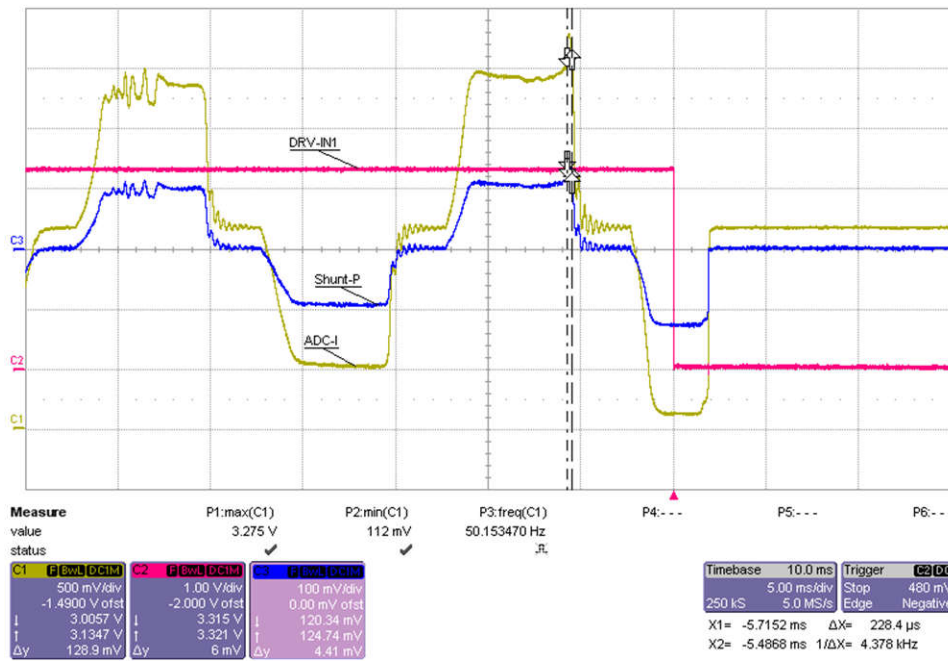


**Figure 4-4. Short Positive Threshold Violation Rejected by the Three-Sample Debounce Qualification**

During the positive half-cycle of the second mains period, a short current peak exceeded the upper threshold for approximately 228.4μs. Since the ADC samples the current every 125μs and the instantaneous protection requires three consecutive threshold violations, this transient did not satisfy the trip criterion and was rejected.

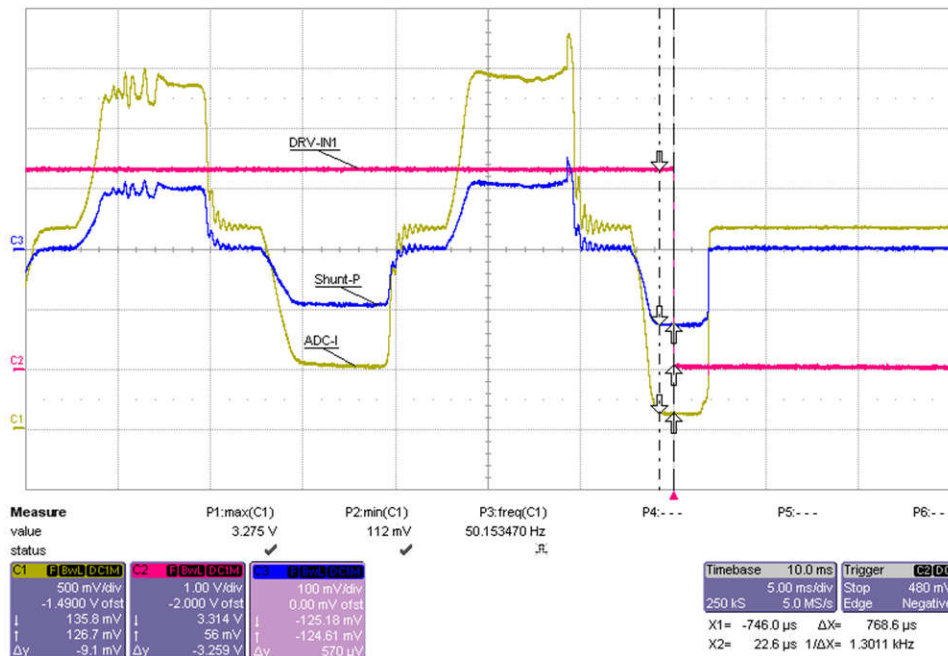


**Figure 4-5. Time From the Sustained Lower-Threshold Crossing to Disabling DRV\_IN1\_EN**

During the subsequent negative half-cycle, the current remained outside the configured window for sufficiently long to satisfy the three-sample qualification. The measured interval from the selected lower-threshold crossing to disabling of DRV\_IN1\_EN was 768.6μs. This represents the observed electronic response and includes ADC sample alignment, threshold qualification, firmware processing, and GPIO actuation.

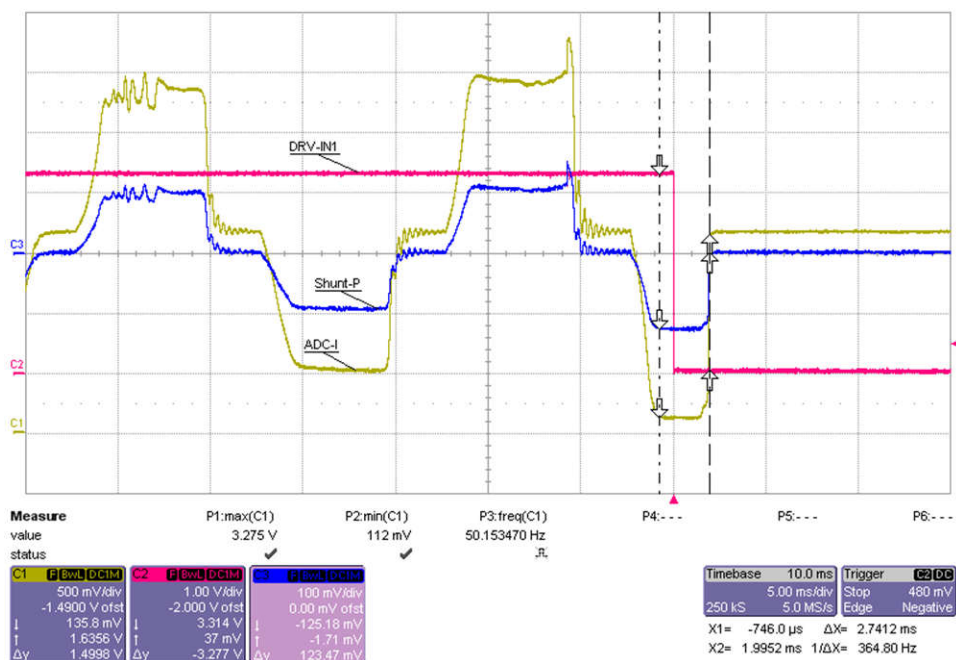


**Figure 4-6. Total Time from Threshold Crossing to Complete Interruption of the Load Current**

After DRV\_IN1\_EN was disabled, the current continued briefly while the relay contacts moved. The measured interval from the threshold crossing to complete current interruption was 2.7412ms. The resulting approximate mechanical relay-opening interval after the driver command was therefore:

$$t_{\text{RELAY}} = 2.7412 \text{ ms} - 0.7686 \text{ ms} = 1.9726 \text{ ms} \quad (61)$$

The complete measured response from the selected threshold crossing to current interruption was approximately 2.74ms. During this test, the sustained negative current exceeded the software instantaneous-current threshold but remained within the hardware comparator window. The trip was therefore initiated by the sample-based software protection rather than the ADC-saturation path. The measured response is well below the 100ms maximum operating-time target used for instantaneous protection.

#### 4.3.1.3 Inverse-Time Overload Trip

The inverse-time overload function was tested at the configured curve point of 2.55 times the nominal current. For a rated current of 16A, the target overload current is:

$$I_{\text{TEST}} = 2.55 \times 16 \text{ A} = 40.8 \text{ A} \quad (62)$$

According to the configured inverse-time characteristic, the target trip time at this current is 30s. The applied current remains below the instantaneous-trip threshold of 52A RMS, maintain that the test exercises the inverse-time overload path rather than the instantaneous protection.

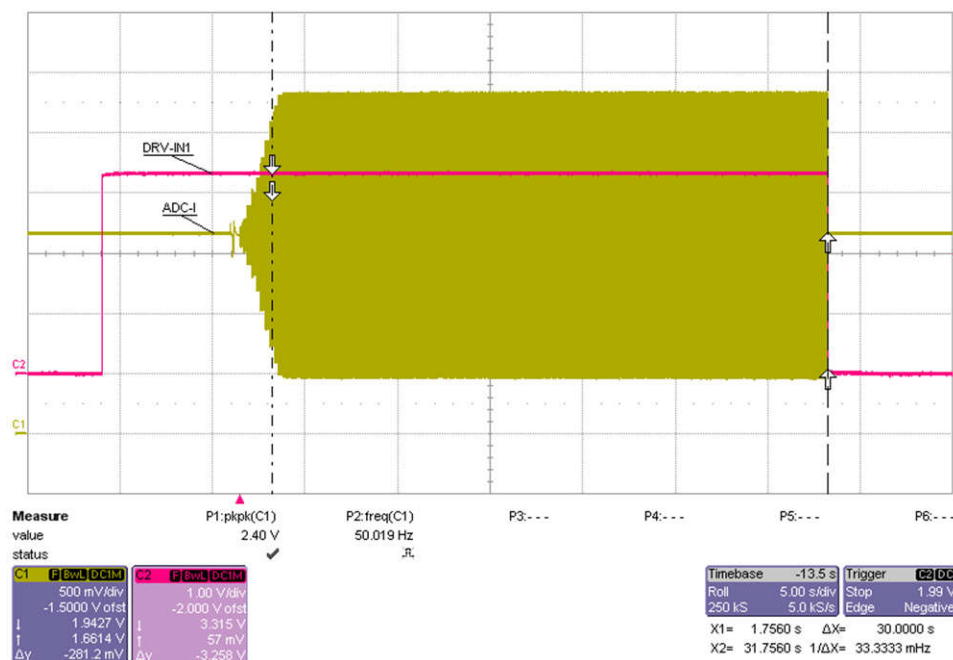


**Figure 4-7. Inverse-Time Overload Test at  $2.55 \times I_n$**

Figure 4-7 shows the current-channel ADC signal and the DRV8213 enable signal during the overload test. The current-channel signal had a maximum measured amplitude of approximately 2.40V peak-to-peak at 50Hz, which is consistent with the applied test current of 40.8A RMS. The relay remained energized until DRV\_IN1\_EN was disabled 30s later. The measured operating time therefore agrees with the configured 30s target at  $2.55 \times I_n$ .

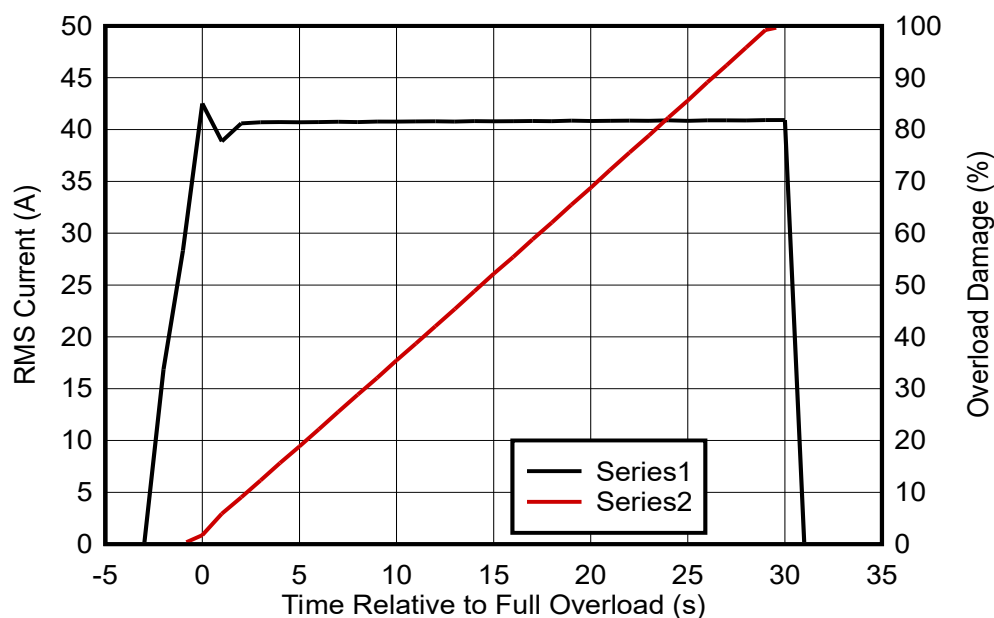


**Figure 4-8. RMS Current and Overload-Damage Accumulation During the  $2.55 \times I_n$  Test**

The internal operation of the inverse-time model was additionally recorded through the debugger. Figure 4-8 shows the measured RMS current (Series1) together with the normalized overload-damage accumulator (Series2). The time axis is referenced to the first complete overload RMS window. The transitional current values around  $t = 0$ s result from the current step and the filling of the RMS calculation window.

After this transition, the measured current stabilizes at approximately 40.9A. Because the current remains nearly constant, the calculated trip time also remains nearly constant and the overload-damage value increases approximately linearly. When the accumulator reaches 100%, the overload trip is latched and the relay is de-energized.

### 4.3.2 Metering

**Table 4-4. RMS Current Measurement Error**

| Mean Reference Current | Load (% of In) | PF = 1  | PF = 0.5L | PF = 0.8C | Maximum Standard Deviation | Maximum Absolute Relative Error |
|------------------------|----------------|---------|-----------|-----------|----------------------------|---------------------------------|
| 0.800110A              | 5.0%           | +1.229% | +1.261%   | +1.237%   | 0.663mA                    | 1.261%                          |
| 1.000100A              | 6.25%          | +1.131% | +1.159%   | +1.156%   | 0.732mA                    | 1.159%                          |
| 1.601712A              | 10.0%          | +0.651% | +0.683%   | +0.654%   | 0.733mA                    | 0.683%                          |
| 2.001274A              | 12.5%          | +0.196% | +0.231%   | +0.211%   | 0.749mA                    | 0.231%                          |
| 4.001386A              | 25.0%          | -0.244% | -0.223%   | -0.231%   | 0.893mA                    | 0.244%                          |
| 6.000832A              | 37.5%          | -0.365% | -0.345%   | -0.356%   | 1.566mA                    | 0.365%                          |
| 8.000929A              | 50.0%          | -0.386% | -0.374%   | -0.372%   | 2.371mA                    | 0.386%                          |
| 10.001415A             | 62.5%          | -0.501% | -0.483%   | -0.481%   | 2.190mA                    | 0.501%                          |
| 12.010968A             | 75.0%          | -0.575% | -0.560%   | -0.558%   | 10.405mA                   | 0.575%                          |
| 14.013064A             | 87.5%          | -0.576% | -0.574%   | -0.563%   | 11.510mA                   | 0.576%                          |
| 16.009736A             | 100.0%         | -0.503% | -0.496%   | -0.504%   | 12.690mA                   | 0.504%                          |

Between 5% and less than 10% of the nominal current, the highest observed absolute RMS-current error was 1.261% at 0.8A with an inductive power factor of 0.5. Between 10% and 100% of the nominal current, the highest observed absolute error was 0.683% at 1.6A under the same load condition. Above 2A, the absolute current error remained below 0.6% throughout the nominal metering range.

**Table 4-5. Extended Current-Range Characterization**

| Mean Reference Current | PF = 1  | PF = 0.5 L | PF = 0.8C | Maximum Standard Deviation | Maximum Absolute Relative Error |
|------------------------|---------|------------|-----------|----------------------------|---------------------------------|
| 32.047744A             | -0.209% | -0.194%    | -0.211%   | 26.771mA                   | 0.211%                          |
| 42.011713A             | +0.316% | +0.344%    | +0.419%   | 29.467mA                   | 0.419%                          |
| 52.093418A             | +0.709% | +0.702%    | +0.724%   | 28.478mA                   | 0.724%                          |

The extended current range up to approximately 52A was characterized to verify the measurement path used by the protection functions. This range is outside the nominal 16A metering range. The maximum observed absolute RMS-current error was 0.724% at 52A.

During the current and power-factor sweep, the mean reference voltage was approximately 230.005V. Within the nominal current range from 0.8A to 16A, the maximum observed absolute RMS-voltage error was 0.041%. This indicates that the current magnitude and load phase had no significant effect on the voltage measurement.

**Table 4-6. Voltage Measurement Error, 120V at 60Hz**

| Nominal Voltage | Mean Reference Voltage | Mean TIDA Voltage | Standard Deviation | Relative Error |
|-----------------|------------------------|-------------------|--------------------|----------------|
| 108V            | 108.0022V              | 108.0054V         | 0.0076V            | +0.0029%       |
| 120V            | 120.0022V              | 119.9993V         | 0.0041V            | -0.0024% (1)   |
| 132V            | 132.0025V              | 132.0026V         | 0.0082V            | +0.0001%       |

**Table 4-7. Voltage Measurement Error, 230V at 50Hz**

| Nominal Voltage | Mean Reference Voltage | Mean TIDA Voltage | Standard Deviation | Relative Error |
|-----------------|------------------------|-------------------|--------------------|----------------|
| 207V            | 207.0070V              | 207.0560V         | 0.0218V            | +0.0237%       |
| 230V            | 230.0047V              | 230.0304V         | 0.0178V            | +0.0112% (1)   |

**Table 4-7. Voltage Measurement Error, 230V at 50Hz (continued)**

| Nominal Voltage | Mean Reference Voltage | Mean TIDA Voltage | Standard Deviation | Relative Error |
|-----------------|------------------------|-------------------|--------------------|----------------|
| 253V            | 253.0079V              | 252.9926V         | 0.0084V            | -0.0060%       |

#### (1) Calibration point

Voltage-measurement accuracy was evaluated at  $\pm 10\%$  around the nominal 120V and 230V operating points. The 120V measurements were performed at 60Hz, while the 230V measurements were performed at 50Hz. Each operating point contains 31 TIDA-011030 readings recorded at intervals of one second.

Across all six operating points, the maximum absolute mean relative error was 0.0237%, measured at 207V. The maximum standard deviation was 21.8mV at the same operating point.

#### 4.3.3 Real-Time Software Performance

The real-time behavior was evaluated while metrology, UART communication, and Zigbee communication were active simultaneously. The device was connected to the calibration GUI and joined to a Zigbee network. Periodic metering communication, repeated device interviews, and Zigbee reconfiguration were used to generate additional communication load.

The protection tests described in Section 4.3.1 were performed under these conditions. Consequently, the measured instantaneous-trip and relay-opening latency includes the effect of concurrent metrology, UART, and Zigbee processing.

The firmware instrumentation recorded the maximum Protection-task execution time, task-start interval, sample backlog, stack usage, missed ADC samples, and watchdog behavior. [Table 4-8](#) summarizes the maximum values observed during the stress test.

**Table 4-8. Protection-task Execution Time**

| Diagnostic Value                                            | Observed Result   | Interpretation                                                         |
|-------------------------------------------------------------|-------------------|------------------------------------------------------------------------|
| Missed ADC sample ticks                                     | 0                 | No acquisition events were lost                                        |
| Configured Protection-task period                           | 1ms               | Nominal execution interval of the protection processing                |
| Maximum interval between consecutive Protection-task starts | 2.008ms           | Maximum observed delay relative to the nominal period was 1.008ms      |
| Maximum Protection-task execution time                      | 1.976ms           | The longest execution extended beyond one nominal task period          |
| Maximum backlog before processing                           | 10 sample pairs   | Equivalent to 1.250ms at 8kHz                                          |
| Maximum samples processed in one execution                  | 22 sample pairs   | Pending and newly arriving samples were processed in acquisition order |
| Minimum free Protection-task stack                          | 921 of 1024 words | Maximum stack usage was 103 words                                      |
| Watchdog feed operations                                    | 2,518,964         | The watchdog was serviced continuously throughout the test             |
| Watchdog service skips                                      | 0                 | All watchdog service conditions remained valid                         |
| Watchdog missed-sample detections                           | 0                 | No sample loss was observed between task executions                    |

The Protection task is configured with a nominal execution period of 1ms. During the stress test, the maximum measured interval between consecutive task starts was 2.008ms. This corresponds to a maximum observed scheduling delay of 1.008ms relative to the nominal period. The maximum Protection-task execution time was 1.976ms.

Despite these temporary delays, no ADC samples were lost. The sample backlog did not exceed 10 pairs before processing or eight pairs after processing, corresponding to 1.25ms and 1ms of acquisition data, respectively.

The ADC window-comparator protection remains independent of the Protection-task scheduling and can initiate an immediate trip directly from the ADC interrupt. The watchdog was successfully serviced more than 2.5 million times without a skipped service operation or detected sample loss.

These results show that the protection-critical acquisition and processing remained bounded and stable under the tested communication and metrology workload. The oscilloscope measurements additionally confirm that protection and relay opening remained responsive while UART and Zigbee communication were active.

#### 4.3.4 Zigbee Functional Test

The Zigbee functionality was tested using a Zigbee coordinator running [Zigbee2MQTT](#). The TIDA-011030 joined the network as a Zigbee end device and completed the device interview successfully. It was identified using its model name and manufacturer information. The device interview detected the On/Off, Metering, Electrical Measurement, and Temperature Measurement clusters on endpoint 10. A project-specific Zigbee2MQTT external converter was used to expose the supported measurement, breaker-state, alarm, and service-disconnect attributes. This converter is included in the TIDA-011030 CC2340R53 firmware folder.

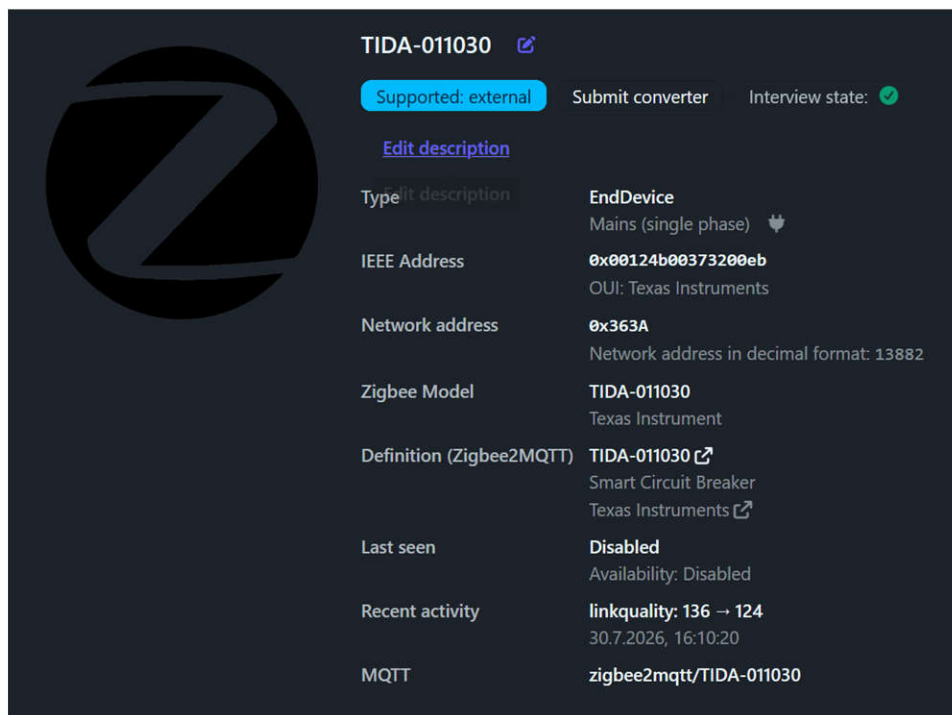


**Figure 4-9. TIDA-011030 Device Information After Successful Zigbee Commissioning and Interview**

During normal operation, Zigbee2MQTT requested the electrical measurement attributes at five-second intervals. The received data included voltage, current, active power, reactive power, apparent power, power factor, frequency, accumulated energy, and temperature. The breaker could also be opened and closed using the On/Off control exposed by Zigbee2MQTT.

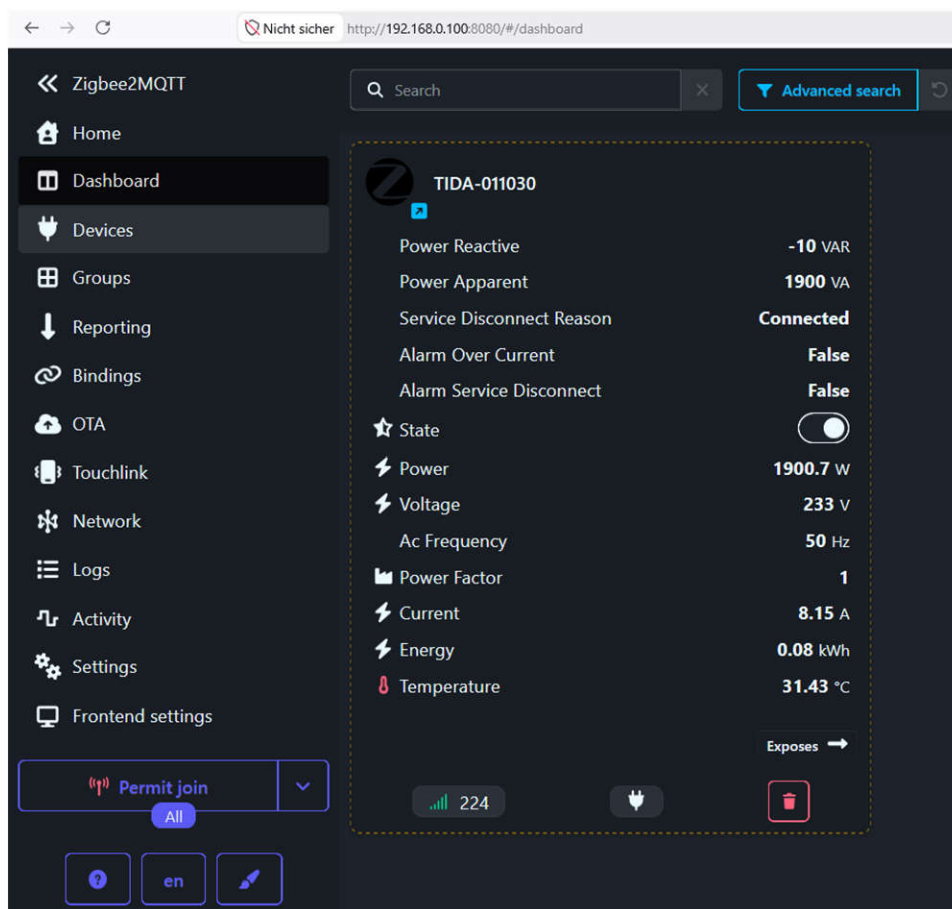


**Figure 4-10. Metering Values and Breaker Control Displayed in Zigbee2MQTT**

Breaker-state changes, protection alarms, and service-disconnect reasons were transmitted using Zigbee attribute reporting when their state changed. This event-driven path does not depend on the five-second measurement polling interval.

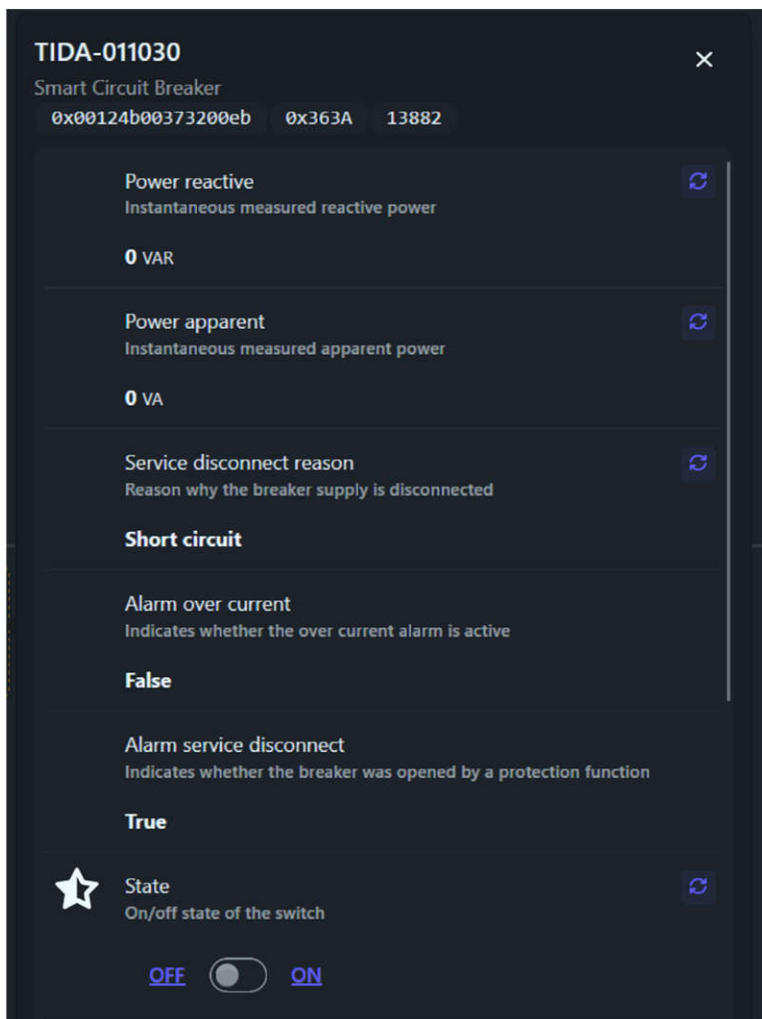


**Figure 4-11. Zigbee2MQTT Status Following a Short-Circuit Protection Trip**

The reporting behavior was verified by initiating a short-circuit trip. After the protection function opened the breaker, Zigbee2MQTT displayed the breaker state as OFF, asserted the service-disconnect alarm, and reported Short circuit as the disconnect reason. The overcurrent alarm returned to False after the current was interrupted, while the latched service-disconnect alarm and trip reason remained available to identify the protection event.

## 5 Design and Documentation Support

### 5.1 Tools and Software

#### 5.1.1 Tools

[CCSTUDIO](#) CCStudio™ integrated development environment (IDE).

#### 5.1.2 Software

[SIMPLELINK-LOWPOWER-SDK](#) SimpleLink™ low power software development kits (SDKs)

[Zigbee2MQTT](#) Zigbee to MQTT bridge

[CCStudio™ Resource Explorer](#) TI Resource Explorer Software package

### 5.2 Documentation Support

1. Texas Instruments, [CC2340R SimpleLink™ Family of 2.4GHz Wireless MCUs Data Sheet](#)
2. Texas Instruments, [DRV8213 4-A Brushed DC Motor Driver with Integrated Current Sense, Current Regulation and Stall Detection Data Sheet](#)
3. Texas Instruments, [OPAx323 20MHz High Bandwidth, 114dB CMRR, Low Voltage \(1.7V to 5.5V\), RRIO Zero-Cross Operational Amplifier Data Sheet](#)
4. Texas Instruments, [TMP23x Low-Power, High-Accuracy Analog Output Temperature Sensors](#)
5. Zigbee2MQTT, [Configure external converters](#)

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## 6 About the Author

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Last updated 10/2025