Signal Processing Front End for Electronic Trip Units Used in ACBs/MCCBs

Design Overview

This design features a signal processing front-end subsystem for electronic trip units (ETU) used in molded case circuit breakers (MCCBs) and air circuit breakers (ACBs). The subsystem consists of an FRAM-based microcontroller (MCU) for processing the current inputs, signal conditioning amplifiers for three-phase current with two gains, neutral and ground current with single gain, and an option for self power with a shunt regulator. The ETU is used to achieve fast and repeatable tripping for wide current inputs over a wide temperature input. The subsystem is designed to start up, compute one full-cycle RMS current, make decisions, and provide the trip signal within 30 ms.

Design Resources

TIDA-00498	Tool Folder Containing Design Files
MSP430F5969	Product Folder
OPA4314	Product Folder
LMV614	Product Folder
LM5017	Product Folder
CSD18537NKCS	Product Folder
LM2903	Product Folder
TPS7A6533	Product Folder
LM8364	Product Folder
LMT87	Product Folder
TIDA-00128	Tool Folder

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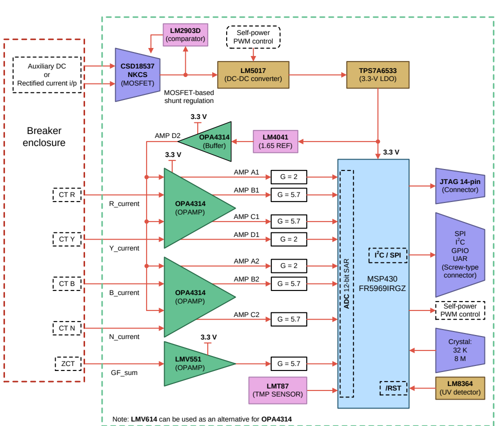
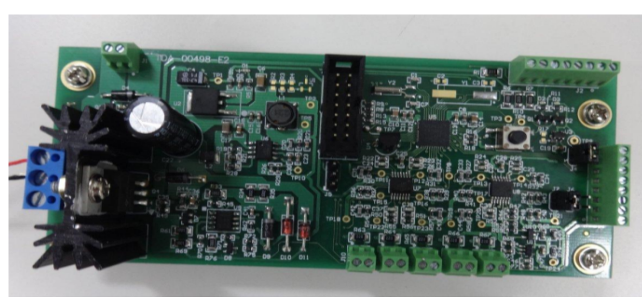
Design Features

- Uses TI's MSP430™ FRAM MCU for Fast Start Up, Start-Up Time Including One-Cycle RMS Computation is < 30 ms
- Measures Three (Phase) Currents With Input Range of 0.2 in to 12 in and Two Current Inputs (Neutral and Earth) 0.05 in to 2 in Within ±3%
- Undervoltage Sense Provides Approximate 200-µs Reset Time After Power Up
- LM5017 DC-DC Operates for Wide Input Voltage
- FRAM-Based MCU Reduces Power Consumption
- All Selected Components Have –40ºC to 125°C Rating (Except for MCU)
- OPA4314 or LMV614 Operational Amplifier (Op Amp) Based Current Sensing Front End With Two Gain Stages for Increased Measurement Range and Accuracy of Phase Currents
- Internal Temperature Sensor With Wide Range
- Self-Power Supply (Rectified Current Input Based) With MOSFET-Based Shunt Regulation

Featured Applications

- MCCB
- ACB
- Self-Powered Overcurrent and Earth Fault Relays
- Motor Protection Circuit Breaker (MPCB)





1 System Description—Description of Target Application

1.1 Electronic Trip Unit (ETU)

Electronic trip units are true RMS current-sensing devices that do not require any external supply to perform basic functions. Each ETU consists of current sensors, a processing unit, and a trip unit. The trip unit provides adjustable time and current protection functions.

True RMS sensing circuit protection is achieved by analyzing the secondary current signals received from the circuit breaker current sensors and initiating trip signals to the circuit-breaker trip actuators with a predetermined trip level and time delays.

Primary ETU features

- Higher reliability and repetitive accuracy due to the use of an MCU
- True RMS sensing with immunity to system disturbances
- Error-free and user friendly settings of current and time delay
- Self-powered by built-in current transformer inside MCCB or ACB
- Three-phase, earth fault, and sensitive earth-fault (SEF) protection in the same unit
- Light-emitting diode (LED) and liquid crystal display (LCD) indications

Why use ETU?

Electronic trip circuit breakers provide the same basic functions as standard thermal magnetic circuit breakers; however, electronic trip circuit breakers offer a variety of additional benefits:

- Provide adjustability for enhanced coordination
- Provide integral ground fault protection or alarm
- Measure and report inherent ground-fault leakage
- Provide capacity for future growth using:
  - Rating plugs
  - 100% rated full-function trip system
- Provide zone-selective interlocking to reduce fault stress on the electrical system
- Provide power monitoring communications

1.2 Self-Powered (Current Transformer-Powered) Protection Relay

Self-powered (current transformer) protection relays are numerical relays that do not require external auxiliary supply voltage. These self-powered numerical relays operate without auxiliary voltage through an integrated CT power supply. Self-powered numerical relays are an ideal choice for installation, even in remote locations where auxiliary supplies are not available. Self-powered numerical relays derive operating power from current transformers. The standard current transformers secondary outputs are 1 A or 5 A. These self-powered numerical relays have a low power consumption, typically < 1 VA to 2 VA at the nominal input current.

Self-powered protection relays increase the availability of the network and are perfectly suited to most applications. Self-powered relays are:

- Insensitive to voltage drop due to faults
- Not dependent on uninterruptible power systems (UPS), which are a weak point of electrical installations
- Less dependent on the external environment (due to overvoltage or undervoltage)

The current sensors energize self-powered protection relays and breakers. The current sensor output is used to generate the required power. MOSFET-based shunt regulators regulate output by shunting input current when the output voltage exceeds a specified threshold voltage. The startup delay of a self-powered relay varies as a function of the current through the CTs. With a load current above the minimum level required for power-up, there is no start-up time delay. Then, the relays operate within their normal time settings. In cases where the start-up delay cannot be tolerated or higher output power is required, protection relays and breakers have a provision for power from an auxiliary DC voltage supply. This provision means protection relays and breakers can be up and running before a fault occurs. The standard auxiliary input voltage varies from 18 V to 35 V for a 24-V DC system.

Dual power input ensures faster operation in the following cases:

- Auxiliary power supply is available at the time when a fault occurs
- Auxiliary power supply has failed, but the load current is above the required minimum value to power the relay

1.3 Current Transformer and Self-Power

Current transformers (CTs) are instrument transformers that are used to supply a reduced value of current from the bus bar or cables to meters, protective relays, sensors, and other instruments. CTs provide isolation from high current. CTs also permit grounding of the secondary for safety reasons. Another function of the CT is to step down the magnitude of the measured current to a value that is safe for the instruments to handle.

CT ratios are expressed as a ratio of the rated primary current to the rated secondary current. For example, a 300:5 CT produces 5 A of secondary current when 300 A flows through the primary. As the primary current changes, the secondary current varies accordingly. With 150 A through the 300-A rated primary, the secondary current is 2.5 A (150: 300 = 2.5: 5).

With a self-powered input, the system is energized by CTs and no auxiliary power is required. With a self-powered system, the CT has to feed more power compared to a device that uses power from an auxiliary voltage. With reference to the entire measuring range of the protection devices, the input impedance of the individual phases is not linear.

To ensure that the system functions over a wide range of current input (approximately 0.4 times the rated current to 10 times or more of the rated current), a shunt regulator (MOSFET and comparator) is used to clamp the voltage above a threshold > 18 V. This clamping results in a power loss, as Figure 1 shows.

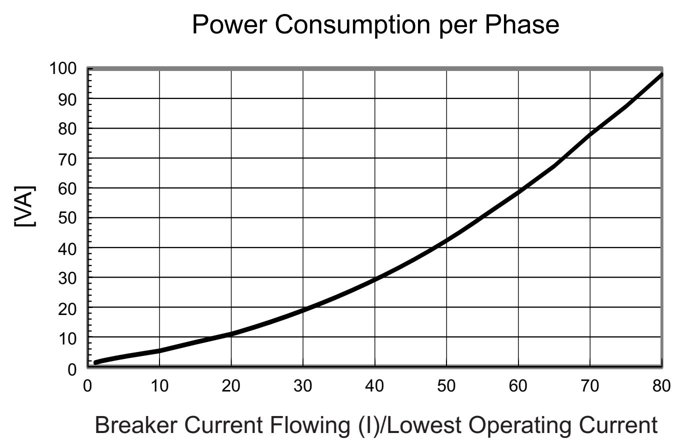


Figure 1. Typical Power Consumption for Current and Lowest Operating Current

By using an LM5017-based power supply, the clamping voltage can be adjusted as the device input is rated up to 100 V. The LM5017 device has a non-isolated output configuration in this design.

1.4 Generic Breaker Specifications

Table 1. Generic Breaker Specifications

FEATURES	MCCB	ACB
Protection accuracy	±10 %	±10 %
Metering	±1%	±1%
Self-powered operation	> 20% In	> 20% In
Communication	485,CAN	485,CAN(1)
Minimum breaking time	40 ms	40 ms
Current computation method	True RMS	True RMS
Current sensor type	CT, Rogowski	CT, Rogowski
Number of current inputs	Up to 5	Up to 5
Current measurement range	0.4 to 12 of nominal	0.4 to 12 of nominal
Operating temperature	–25° to 85°C	–25° to 85°C
Power quality	THD for V and I	Individual harmonics up to 15
Samples per cycle	≥ 64	≥ 80(2)
Display	Alphanumeric or numeric	Alphanumeric or graphic
Trip mechanism	Solenoid	Solenoid
Standards	UL489	UL489
Overtemperature protection	+85 °C	+85 °C

(1) Other communication options are add-on applications
(2) 80 samples per cycle is required to confirm to IEC61850 protection

2 Key System Specifications

Table 2. System Specifications

SERIAL NUMBER	PARAMETERS	SPECIFICATION
1	Fault current processing	FRAM-based, MSP430FR5969 16-bit, 16-MHz operating frequency
2	Oscillator options	DCO, 32 KHz, 8 MHz
3	Interface connector	13-V, 3.3-V, universal asynchronous receiver and transmitter (UART) and serial peripheral interface (SPI) signals
4	Programming interface	JTAG
5	LED indication	Two
6	Phase current inputs and range	3 and 0.5 In to 12 In (nominal current)
7	Phase current input signal conditioning	Amplifiers with X2 and X5.7 gain
8	Neutral and ground current input signal conditioning	Amplifier with X5.7 gain
9	Amplifier output accuracy	< ±1%
10	RMS measurement accuracy	< ±3%
11	Programmable reference	1.65 V (3.3 V / 2)
12	Temperature sensor	−50°C to 150°C
13	Power supply	Option 1: Current input self-powered supply with shunt regulation voltage configured for 39 V Option 2: DC auxiliary input < 18 V to 35 V
14	DC-DC converter output	13 V[(1)]
15	Power supply	Low dropout voltage (LDO), 3.3 V
16	Protection	Undervoltage sense for MCU and DC-DC converter

(1) The 13-V DC-DC converter is chosen to allow the trip unit to function with 12- or 15-V systems

3 Block Diagram and Specifications

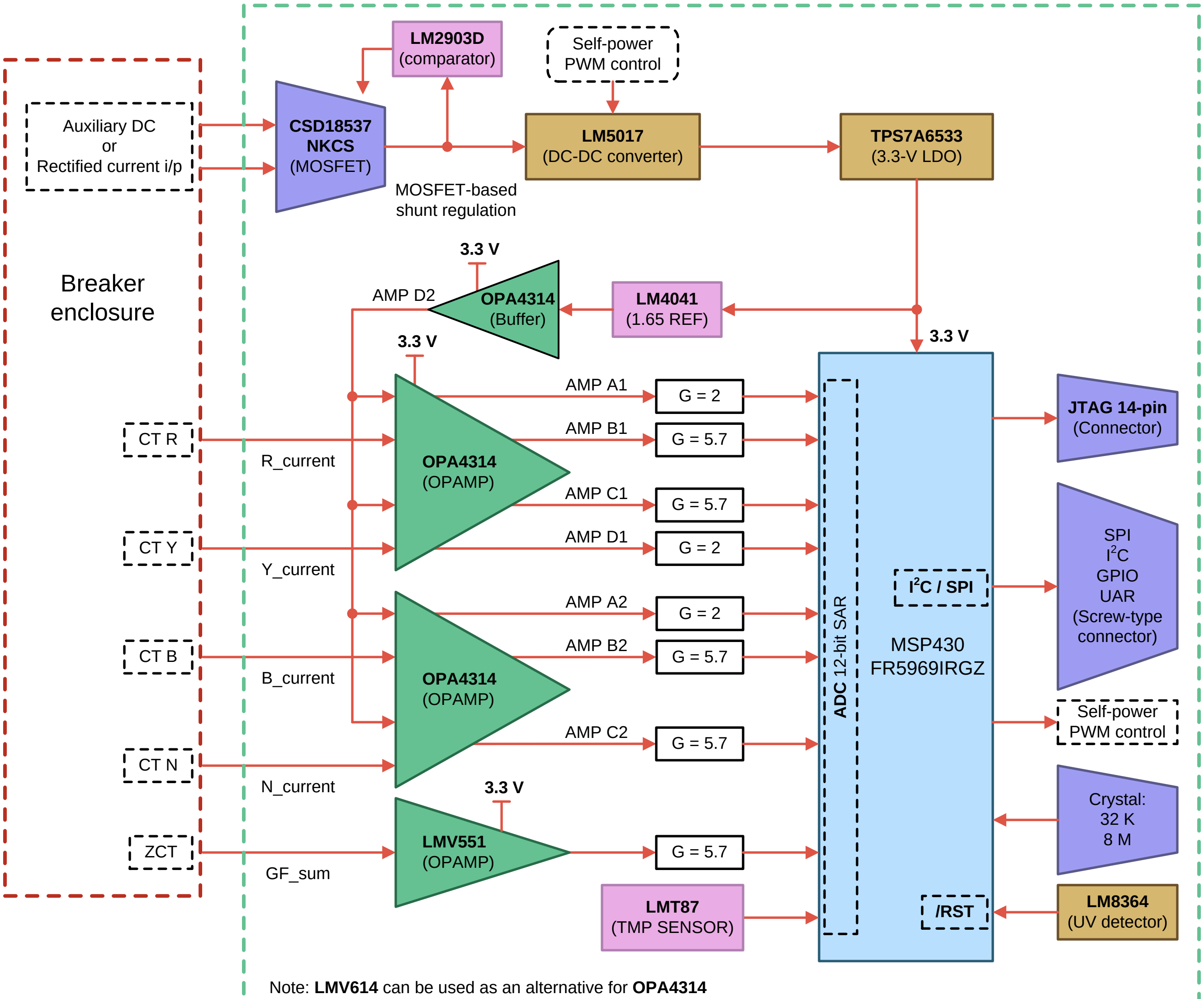


Figure 2. TIDA-00498 Block Diagram

3.1 MCU—MSP430FR5969IRGZ

The critical part of the electronic trip unit is the MCU. The MCU must start up fast (< 3 ms), measure wide input current, process the fault current, and provide a trip signal to the flux shift device (FSD) or solenoid. Another important requirement is the low power consumption. The MSP430 FRAM devices meet these requirements and are suitable for these applications. The MSP430FR5969 has the required number of analog-to-digital converters (ADCs) and other peripherals for implementing ETU functionality. The UART and SPI are accessible through connectors. The JTAG interface is provided for application development and programming. Figure 3 shows the MSP430 system block diagram.

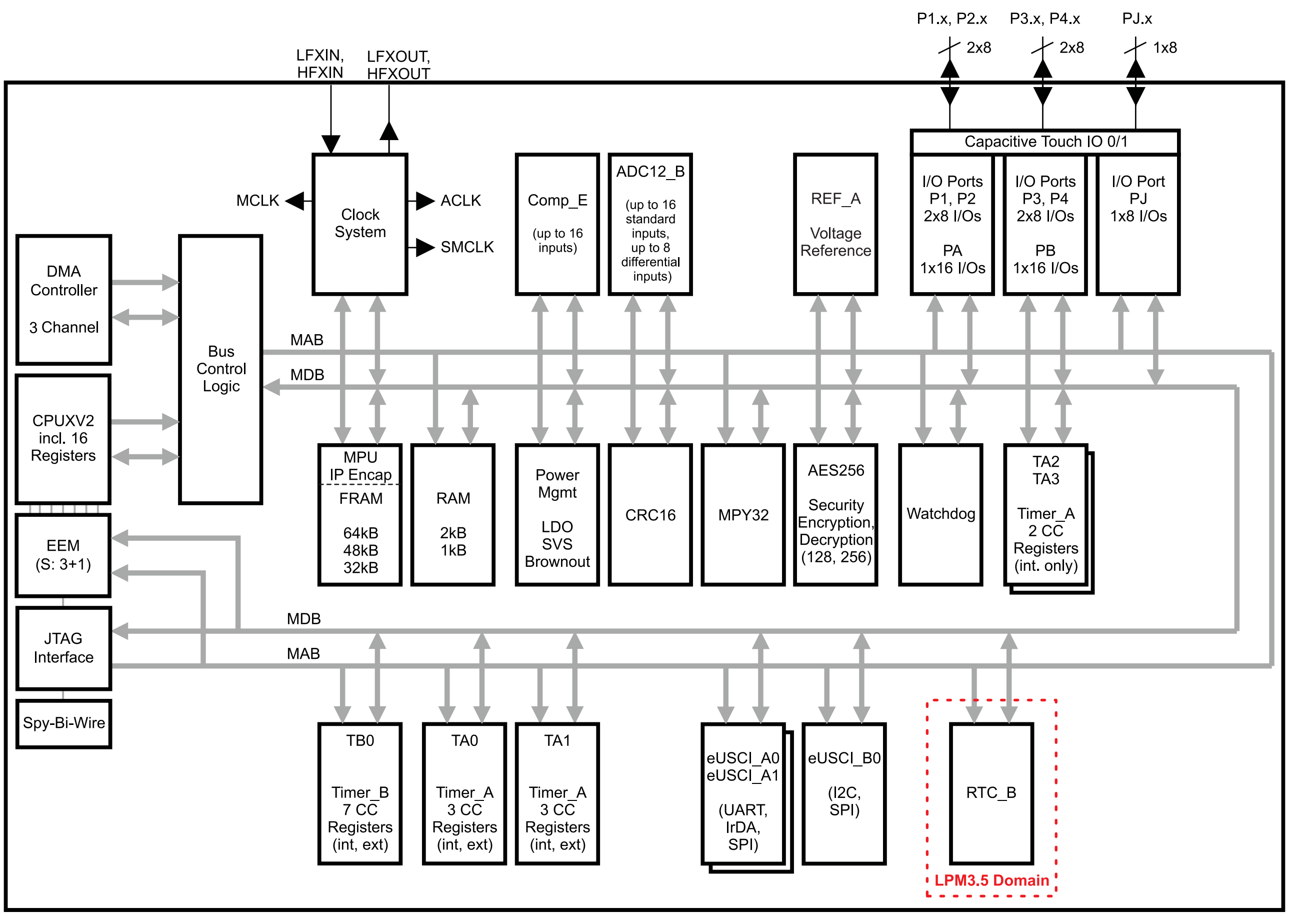


Figure 3. MSP430 System Block Diagram

The MSP430 ULP FRAM portfolio consists of a diverse set of devices featuring FRAM, the ULP 16-bit MSP430 CPU, and intelligent peripherals targeted for various applications.

Features

- Embedded microcontroller
  - 16-bit reduced instruction set computing (RISC) architecture up to 16-MHz clock
  - Wide supply voltage range: 1.8 V to 3.6 V (minimum supply voltage is restricted by supply voltage supervisor (SVS) levels)
- Optimized ultra-low-power modes
  - Active mode: approximately 100 µA/MHz
  - Standby (LPM3 with VLO): 0.4 µA (typical)
  - Real-time clock (LPM3.5): 0.25 µA (typical) (RTC is clocked by a 3.7-pF crystal)
  - Shutdown (LPM4.5): 0.02 µA (typical)

- Ultra-low-power ferroelectric RAM (FRAM)
  - Up to 64KB of non-volatile memory
  - Ultra-low-power writes
  - Fast write at 125 ns per word (64KB in 4 ms)
  - Unified memory = program + data + storage in one single space
  - 10^{15} write cycle endurance
  - Radiation resistant and nonmagnetic
- Intelligent digital peripherals
  - 32-bit hardware multiplier (MPY)
  - Three-channel internal direct memory access (DMA)
  - Real-time clock (RTC) with calendar and alarm functions
  - Five 16-bit timers with up to seven capture and compare registers each
  - 16-bit cyclic redundancy checker (CRC)
- High-performance analog
  - 16-channel analog comparator
  - 12-bit ADC with internal reference and sample-and-hold and up to 16 external input channels
- Multifunction input and output ports
  - Edge-selectable wake from LPM on all ports
  - Programmable pull-up and pull-down on all ports
- Code security and encryption
  - 128-bit or 256-bit AES security encryption and decryption coprocessor
  - Random number seed for random number generation algorithms
- Enhanced serial communication
  - eUSCI_A0 and eUSCI_A1 support
    - UART with automatic baud-rate detection
    - SPI at rates up to 10 Mbps
  - eUSCI_B0 supports
    - I^2C with multiple slave addressing
    - SPI at rates up to 8 Mbps
  - Hardware UART and I^2C bootstrap loader (BSL)
- Flexible clock system
  - Fixed-frequency digitally controlled oscillator (DCO) with ten selectable factory-trimmed frequencies
  - Low-power, low-frequency internal clock source (VLO)
  - 32-KHz crystals (LFXT)
  - High-frequency crystals (HFXT)

3.2 Signal Conditioning With OPA4314/LMV614, LMV551, and LM4041

The TIDA-00498 device must measure a wide range of current inputs. The current must be measured within the specified accuracy to ensure that the trip time is within the allowed time and is repeatable. The measurement must also be accurate over a wide range of temperature input. More than one gain stage may be required to measure the wide current range within the required accuracy. The op amp drift and offset performance are also important and low drift amplifiers have been chosen for this application. The performance testing was done using the OPA4314 and LMV614 devices.

The current inputs classify into the following two categories:

Phase inputs — R, Y, and B inputs with two gains

Neutral and ground inputs — Neutral and ground inputs with single gain

TI recommends using rail-to-rail output for the gain amplifiers, which results in increased dynamic range. The current inputs can be full-wave rectified or AC input. When the input is a AC sine wave, the AC input must be level shifted by VCC / 2 to measure using a single-ended ADC. A stable, programmable reference (LM4041) is used in this design for level shifting the AC current input.

The ground current sensing is optional in a number of applications. A single amplifier LMV551 is used for sensing the ground current input.

3.2.1 OPA4314

The OPA4314 quad-channel operational amplifier represents a new generation of low-power, general-purpose CMOS amplifiers. Rail-to-rail input and output swings, low quiescent current (150 µA typ at 5.0 VS) combined with a wide bandwidth of 3 MHz, and very-low noise (14 nV/$\sqrt{Hz}$ at 1 KHz) make this family very attractive for a variety of battery-powered applications that require a good balance between cost and performance. The low input bias current supports applications with mega-ohm source impedances.

The OPA4314 device provides ease-of-use to the circuit designer, unity-gain stability with capacitive loads of up to 300 pF, an integrated radio frequency (RF) and electromagnetic interference (EMI) rejection filter, no phase reversal in overdrive conditions, and high electrostatic discharge (ESD) protection (4-kV HBM). See Figure 4 for a pinout of the OPA4314 device.

These devices are optimized for low-voltage operation as low as +1.8 V (±0.9 V) and up to +5.5 V (±2.75 V), and are specified over the full extended temperature range of –40°C to +125°C.

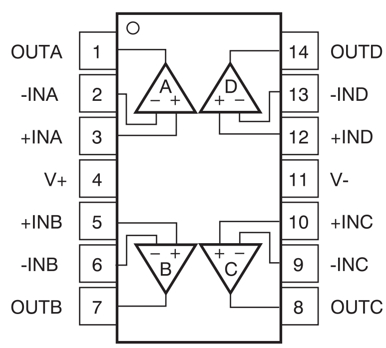


Figure 4. OPA4314 Pinout Diagram

Features

The quad-channel OPA4314 is offered in a TSSOP-14 package.

- Low I_Q: 150 µA/ch
- Wide supply range: 1.8 V to 5.5 V
- Low noise: 14 nV/√Hz at 1 KHz
- Gain bandwidth: 3 MHz
- Low input bias current: 0.2 pA
- Low offset voltage: 0.5 mV
- Unity-gain stable
- Internal RF/EMI filter
- Extended temperature range: –40°C to +125°C

3.2.2 LMV614

The LMV614 is a quad, low-voltage, low-power operational amplifier. These amplifiers are specifically designed for low-voltage, general purpose applications. Other important product characteristics are rail-to-rail input and output, a low supply voltage of 1.8 V, and a wide temperature range. The LMV614 input common mode extends 200 mV beyond the supplies and the output can swing rail-to-rail unloaded and within 30 mV with a 2-kΩ load at a 1.8-V supply. The LMV614 achieves a gain bandwidth of 1.4 MHz while drawing a 100-µA (typical) quiescent current.

The industrial-plus temperature range of −40°C to 125°C allows the LMV614 to accommodate a broad range of extended environment applications.

The LMV614 is available in a 14-pin TSSOP package (see Figure 5).

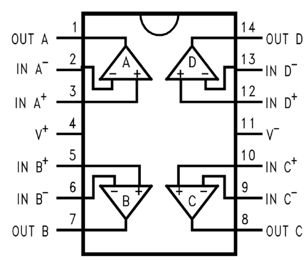


Figure 5. LMV614 Pinout Diagram

Features

- Typical 1.8-V supply values; unless otherwise noted
- Ensured 1.8-V, 2.7-V and 5-V specifications
- Output swing
  - with 600-Ω load 80 mV from rail
  - with 2-kΩ load 30 mV from rail
- V_{CM} 200 mV beyond rails
- Supply current (per channel) 100 µA
- Gain bandwidth product 1.4 MHz
- Maximum V_{OS} 4.0 mV
- Temperature range −40°C to 125°C

The user can consider using other amplifiers, such as the OPA4330, based on the requirements of the application.

3.2.3 LMV551

The LMV551 are high-performance, low-power operational amplifiers implemented with TI's advanced VIP50 process. They feature 3 MHz of bandwidth while consuming only 37 µA of current per amplifier, which is an exceptional bandwidth-to-power ratio in this op amp class. These amplifiers are unity gain stable and provide an excellent solution for low power applications requiring a wide bandwidth. The LMV551 has a rail-to-rail output stage and an input common mode range that extends below ground. The LMV551 op amps have an operating supply voltage range from 2.7 V to 5.5 V. These amplifiers can operate over a wide temperature range (−40°C to 125°C), which makes them a great choice for automotive applications, sensor applications, as well as portable instrumentation applications. The LMV551 is offered in the ultra-tiny 5-pin SC70 and 5-pin SOT-23 packages.

Features

- Typical 5-V supply, unless otherwise noted
- Guaranteed 3.0- and 5.0-V performance
- High unity gain bandwidth 3 MHz
- Supply current (per amplifier) 37 µA
- Common-mode rejection ratio (CMRR) 93 dB
- Power supply rejection ratio (PSRR) 90 dB
- Slew rate 1 V/µs
- Output swing with 100-kΩ load 70 mV from rail
- Total harmonic distortion 0.003% at 1 KHz, 2 kΩ
- Temperature range −40°C to 125°C

3.2.4 LM4041

The LM4041-N precision voltage reference is available in the sub-miniature SOT-23 surface-mount packages. The advanced design of the LM4041-N eliminates the need for an external stabilizing capacitor while ensuring stability with any capacitive load, which makes the LM4041-N easy to use. Further reducing the design effort is the availability of a fixed (1.225-V) and adjustable reverse breakdown voltage. The minimum operating current is 60 µA for the LM4041-N 1.2 and the LM4041-N ADJ.

Features

- Available in standard, AEC Q-100 grade 1 (extended temperature range) and grade 3 (industrial temperature range) qualified versions (SOT-23 only)
- Small packages: SOT-23
- No output capacitor required
- Tolerates capacitive loads
- Reverse breakdown voltage options of 1.225 V and adjustable

3.3 Temperature Sense Using LMT87

The ETU is enclosed inside the breaker and is expected to operate at higher temperatures. The internal temperature of the breaker is higher than the ambient temperature. This temperature increases during fault conditions. This overtemperature condition must be detected and the breaker must be self-protected. An on-board temperature sensor is used to provide this functionality. The LMT87 device with a wide temperature measurement range has been chosen for this application (see Figure 6).

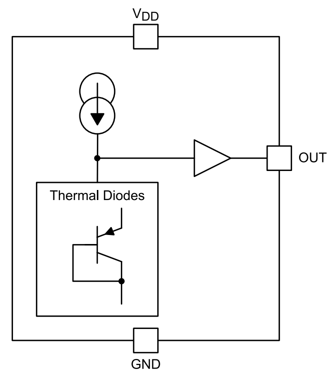


Figure 6. LMT87 Functional Block Diagram

The LMT87 and LMT87-Q1 are precision CMOS integrated-circuit temperature sensors with an analog output voltage that is linearly and inversely proportional to temperature. The features of this temperature sensor make it suitable for many general temperature sensing applications. The LMT87 can operate down to a 2.7-V supply with a 5.4-µA power consumption. TO-92 packages also allow the LMT87 to be mounted on-board and off-board. A class-AB output structure gives the LMT87/LMT87-Q1 a strong output source and sink-current capability that can directly drive up to 1.1-nF capacitive loads. This feature means that the LMT87 is well-suited to drive an ADC sample-and-hold input with its transient load requirements. The LMT87 has an accuracy specified in the operating range of −50°C to 150°C. The accuracy, three-lead package options, and other features also make the LMT87/LMT87-Q1 an alternative to thermistors.

Features

- Very accurate: ±0.3°C typical
- Wide temperature range of −50°C to 150°C
- Low 5.4-µA quiescent current
- Sensor gain of −13.6 mV/°C
- Packages:
  - Small SC70 (SOT 5-lead) surface mount
  - Leaded TO-92
  - Leaded heatsink or chassis screw-mount TO-126
- Output is short-circuit protected
- Push-pull output with 50-µA source current capability
- Footprint compatible with the industry-standard LM20/19 and LM35 temperature sensors
- Cost-effective alternative to thermistors

3.4 Undervoltage Sense Using LM8364

Reset timing is a critical requirement for proper MCU functionality. An FRAM-based MCU requires that the reset is held low for a minimum of 2 µs after the power is applied. The undervoltage sense has a threshold time of 60 µs to 300 µs after the voltage exceeds the selected threshold.

A range of threshold voltages from 2.0 V to 4.5 V are available with an active-low open-drain output. These devices feature a very low quiescent current of 0.65 µA (typical). The LM8364 series features a highly accurate voltage reference, a comparator with precise thresholds, a built-in hysteresis to prevent erratic reset operation, and an ensured reset operation down to 1.0 V with extremely low standby current. These devices are available in the space-saving SOT-23 5-pin surface mount package. For other undervoltage thresholds and output options, please contact Texas Instruments™. Figure 7 shows a functional block diagram of the LM8364 device.

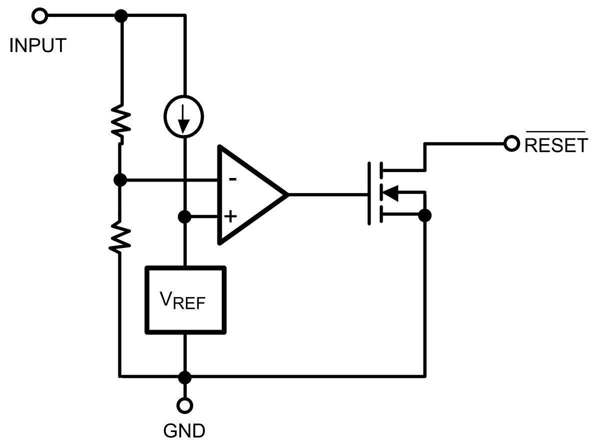


Figure 7. LM8364 Functional Block Diagram

Features

- Extremely low quiescent current: 0.65 µA, at V_{IN} = 2.87 V
- High accuracy threshold voltage (±2.5%)
- Open drain output
- Input voltage range: 1 V to 6 V
- Surface mount package (5-pin SOT-23)

3.5 LM5017MRE/NOPB

A DC-DC converter with a high input voltage rating (LM5017) is used to generate a DC output voltage for controlling an external relay/FSD and electronic circuit control voltages. An LDO (TPS7A6533) is used to generate the 3.3-V control voltage for the op amp and MCU.

The following list shows the power supplies used in this TI design:

1. 3.3-V DC for op amp, reference, and temperature sensor
2. ≥ 13-V DC for FSD and relay drive
3. Approximate 16-V DC for comparator supply
4. Self-power supply regulation: 39-V DC ±5%

The LM5017 is a 100-V, 600-mA synchronous step-down regulator with integrated high-side and low-side MOSFETs (see Figure 8). The constant on-time (COT) control scheme employed in the LM5017 requires no loop compensation, provides excellent transient response, and enables very high step-down ratios. The on-time varies inversely with the input voltage resulting in a nearly constant frequency over the input voltage range. A high voltage startup regulator provides bias power for the internal operation of the IC and for integrated gate drivers. A peak current limit circuit protects against overload conditions. The undervoltage lockout (UVLO) circuit allows the input undervoltage threshold and hysteresis to be independently programmed. Other protection features include thermal shutdown and bias supply undervoltage lockout (VCC UVLO).The LM5017 device is available in WSON-8 and HSOP PowerPAD™-8 integrated circuit plastic packages.

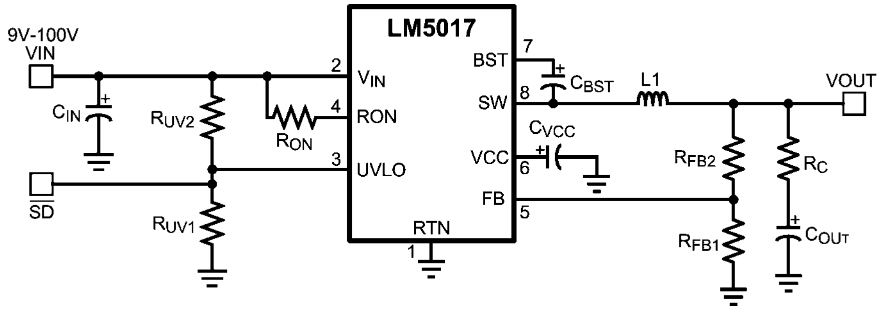


Figure 8. LM5017 Typical Application Diagram

The DC-DC converter is a buck type to generate the Relay/FSD trip voltage and the electronic circuit control voltages. The input to the DC-DC converter is the external auxiliary DC input or the output of the shunt regulator. The DC input to the DC-DC converter is provided by either a rectified current input or auxiliary DC input. The DC output is regulated to 39 V. In case both outputs are applied, the current is drawn from the supply that has a higher output voltage. The regulated output is given as the input to the DC-DC converter. The DC-DC converter used in this design is the LM5017 device. The LM5017 has the following specifications:

- Wide 7.5-V to 100-V input range
- Integrated 100-V high-side and low side switches
- No Schottky diode required
- Constant on-time control
- No loop compensation required
- Ultra-fast transient response
- Nearly constant operating frequency
- Intelligent peak current limit
- Adjustable output voltage from 1.225 V
- Precision 2% feedback
- Frequency adjustable to 1 MHz
- Adjustable UVLO
- Thermal shutdown

The wide input capability of the LM5017 device makes it the best-suited DC-DC converter for this application. The output of the DC-DC converter is programmed for approximately 13.2 V.

NOTE: The DC 39-V output can be increased to a max of 70 V based on application requirements. The component rating may require change to make this voltage increase.

3.6 LM2903D

A dual comparator is used for the following applications.

1. Shunt regulation − The DC voltage generated by the self-power supply is regulated to 39 V. The comparator is used to compare the threshold voltage. If the voltage exceeds 39 V, the comparator output drives the shunt regulation MOSFET shunting the input current.
2. Alternative method using PWM control – An alternative method that can be used to regulate the DC output of the self- power supply is to use PWM control of the shunt regulation. This technique helps reduce the MOSFET heating and can facilitate the use of a smaller heat sink for the MOSFET.

The LM2903 device consists of two independent voltage comparators that are designed to operate from a single power supply over a wide range of voltages. Operation from dual supplies is also possible as long as the difference between the two supplies is 2 V to 36 V, and VCC is at least 1.5 V more positive than the input common-mode voltage. The current drain is independent of the supply voltage. The outputs can be connected to other open-collector outputs to achieve wired-AND relationships.

The LM2903 is characterized for operation from −40°C to 125°C. Figure 9 shows a pinout diagram of the LM2903 device.

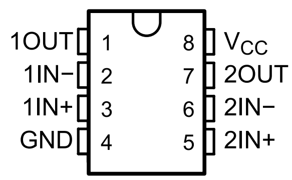


Figure 9. LM2903 Pinout Diagram

Features

- Single supply or dual supplies
- Wide range of supply voltage
  - Max rating: 2 V to 36 V
  - Tested to 30 V: non-V devices
  - Tested to 32 V: V-suffix devices
- Low supply-current drain independent of supply voltage: 0.4 mA (typical) per comparator
- Low input bias current: 25 nA (typical)
- Low input offset current: 3 nA (typical) (LM139)
- Low input offset voltage: 2 mV (typical)
- Common-mode input voltage range includes ground
- Differential input voltage range equal to maximum-rated supply voltage: ±36 V
- Low output saturation voltage
- Output compatible with TTL, MOS, and CMOS

3.7 CSD18537NKCS

The MOSFET is used as a shunt regulator to shunt the input current when the power supply voltage exceeds 39 V. The low ON resistance ensures a lower power dissipation and requirement for smaller heat sinks.

Texas Instrument's 11-mΩ, 60- TO-220 NexFET™ power MOSFET is designed to minimize losses in power conversion applications.

Features

- Ultra Low Q_g and Q_{gd}
- Low thermal resistance
- Avalanche rated
- TO-220 plastic package

3.8 *TPS7A6533QKVURQ1 Low-Dropout Regulator (LDO)*

An LDO is used to generate the 3.3-V power supply required for the microcontroller and analog signal conditioning amplifiers. The LDO used in this design is the TPS7A6533. The TPS7A6533 is a family of low-dropout, linear voltage regulators designed for low power consumption and quiescent current less than 25 µA in light-load applications. The TPS7A6533 device features integrated overcurrent protection. The TPS7A6533 LDOs are designed to achieve stable operation even with low, equivalent series resistance (ESR) ceramic output capacitors. A low-voltage tracking feature allows for a smaller input capacitor.

The TPS7A65xx-Q1 is a family of low-dropout linear voltage regulators designed for low power consumption and quiescent current less than 25 µA in light-load applications. These devices feature integrated overcurrent protection and a design to achieve stable operation even with low-ESR ceramic output capacitors. A low-voltage tracking feature allows for a smaller input capacitor and can possibly eliminate the need of using a boost converter during cold crank conditions. Because of these features, these devices are well-suited in power supplies for various automotive applications.

Features

- Low dropout voltage
  - 300 mV at I_{OUT} = 150 mA
- 4-V to 40-V wide input voltage range with up to 45-V transients
- 300-mA maximum output current
- 25-µA (typical) ultra-low quiescent current at light loads
- 3.3-V and 5-V fixed output voltage with ±2% tolerance
- Low-ESR ceramic output stability capacitor
- Integrated fault protection
  - Short-circuit and overcurrent protection
  - Thermal shutdown
- Low input-voltage tracking
- Thermally enhanced power package
  - 3-pin TO-252 (KVU/DPAK)

4 Signal Processing Front End for ETU—Design Theory

4.1 Power Supply

The breakers offer different power supply options. The following two options are common. A possible third option exists that consists of using an AC/DC converter.

Self-power (rectified-current transformer input)

The input to the self-power supply input is a full wave-rectified current input. This rectified input charges the capacitor to generate the output voltage. The regulated DC output voltage is set by a Zener diode and controlled by a MOSFET-based shunt regulator. The output voltage is compared against a set voltage by the comparator to regulate the output DC voltage.

Dual-power (auxiliary DC or rectified-current transformer input)

An auxiliary DC input voltage can also be applied to generate the required power supply, along with the self-powered current inputs. The shunt regulation is bypassed when the auxiliary voltage is applied. The supply range for the auxiliary input is 18- to 35-V DC. The self-powered output voltage threshold can be set based on the auxiliary input voltage range.

4.1.1 Self-Power Section

Figure 10 shows the schematic of the self-power supply including a DC-DC converter. Figure 11 shows the schematic of the comparator power supply generated on the input side.

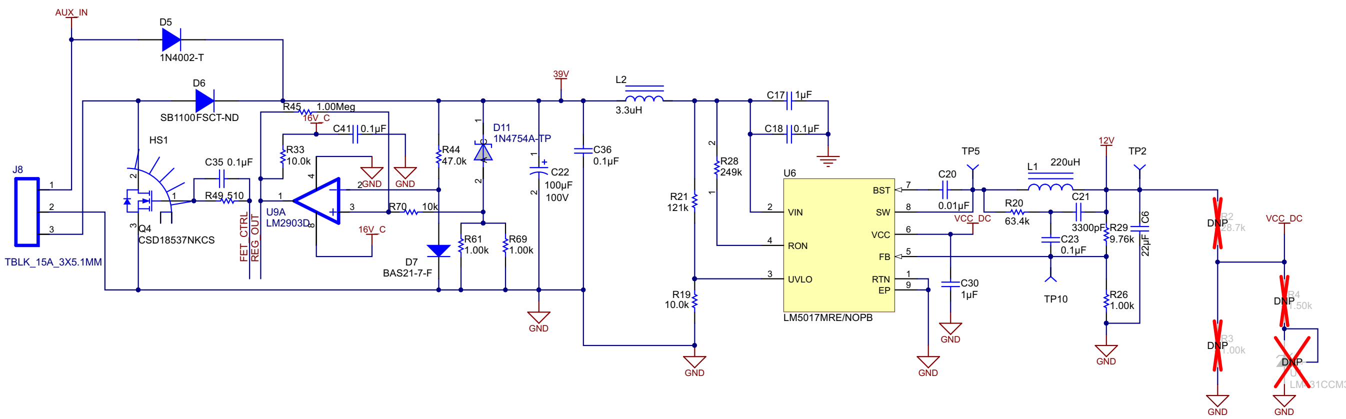


Figure 10. Self-Power Supply Including DC-DC Converter Schematic

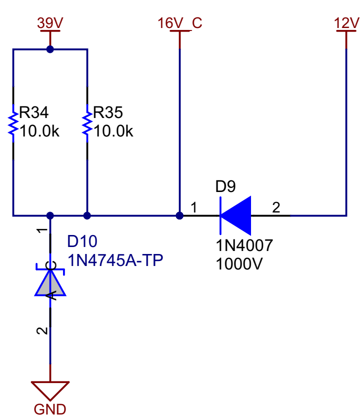


Figure 11. Comparator Power Supply Generated From 39-V Supply

Rectified current inputs-based self-power supply

The rectified current inputs based shunt regulator is configured to regulate the output voltage at 39 V. The TIDA-00498 design uses the TI MOSFET to shunt the current above the 39-V output. Increased regulation voltage reduces power dissipation and facilitates the use of a lower VA current transformer. TI has a wide range of MOSFETs that can be selected for current shunting based on the application and the configured regulation voltage.

The self-power supply generates the output voltage from the rectified currents. The input to the self-power generation circuit is a rectified output from the current transformers. The rectifier diodes must be connected externally. The Zener diode reference regulates the self-power to 39 V. If the output voltage exceeds 39 V, the comparator switches the MOSFET shunting the rectified input current, which results in the limiting of the current input to the power supply. When the output voltage reduces, the comparator switches the MOSFET off and the input current charges the output capacitor. The 39-V self-powered output is converted to 13.2 V for the FSD/relay operation and 3.3 V for the electronic circuit functioning using
DC-DC converters and an LDO. The advantage of this self-powered circuit is reduced CT loading.

The critical component in the self-powered circuit is the shunt regulation MOSFET. Table 3 lists a wide range of available MOSFETs.

Table 3. TI MOSFETs With Current Shunting

PRODUCT DESCRIPTION	PRODUCT LINK
60-V, N-Channel NexFET™ Power MOSFET	CSD18537NKCS
60-V, N-Channel NexFET Power MOSFET	CSD18534KCS
80-V, N-Channel NexFET Power MOSFET	CSD19506KCS
80-V, 7.6-mΩ, N-Channel TO-220 NexFET Power MOSFET	CSD19503KCS
100-V, N-Channel NexFET Power MOSFET	CSD19535KCS
100-V, 6.4-mΩ, TO-220 NexFET Power MOSFET	CSD19531KCS

Auxiliary DC voltage inputs

Another option is to power the TIDA-00498 design with an auxiliary 24-V input. After the DC auxiliary voltage has been applied, the MOSFET-based shunt regulation is bypassed. A provision exists to detect whether or not the auxiliary voltage has been applied.

4.1.2 LM5017 DC Output Voltage

By using the LM5017 step-down regulator, the self-powered output clamping voltage can be increased because the device input is rated up to 100 V.. The LM5017 device uses a non-isolated output configuration.

$V_{OUT} = (1.225\ V \times (R_{FB2} + R_{FB1}))\ /\ R_{FB1}$

The output voltage is set to 13.2 V in this design.

NOTE: Regarding the requirements for U1, R2, R3, and R4:

These devices help to reduce the DC-DC converter startup time.

This option is not enabled in the initial design.

4.1.3 UVLO

When the V_{CC} pin exceeds the V_{CC} undervoltage threshold and the UVLO pin voltage is greater than 1.225 V, normal operation begins. An external set-point voltage divider from V_{IN} to GND can be used to set the minimum operating voltage of the regulator.

Figure 12 shows the UVLO resistor settings.

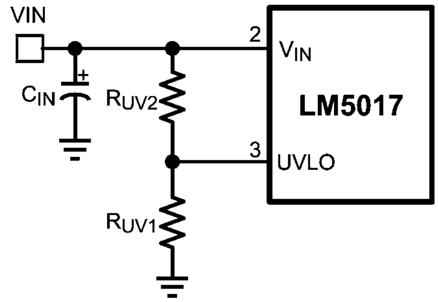


Figure 12. UVLO Resistor Setting

The UVLO is set to ≤ 16 V. Resistor R21 and R19 provide the undervoltage configuration.

4.1.4 Rectified Current Input—Shunt Regulation

The self-powered output voltage is generated from the current input. The voltage is set by the Zener diode. The comparator is used to compare the DC output voltage with the set threshold voltage. If the output voltage exceeds 39 V, the MOSFET is turned on and the rectified current input is bypassed from the power supply input.

An alternate way to regulate the power supply is by using PWM control. The PWM control output and the 39-V comparator output are the diode ORED and are applied to the MOSFET.

The comparator controlling the MOSFET shunt regulator draws power from the DC-DC output. Also, a 16-V Zener regulated supply generates from the output of the self-power supply. This regulated supply ensures the shunt regulation function for very fast rising inputs, during which the DC-DC converter may not start up.

4.1.5 Auxiliary Power Input Detection and PWM-Based Regulation Control

More features like communication and graphic LCD can be enabled when the system is powered by an auxiliary DC power input. The auxiliary input detection circuit enables the identification of an auxiliary input so that the processor can take the appropriate action based on the configured system functionality. Figure 13 shows the schematic for the comparator used for PWM control and DC supply voltage sensing.

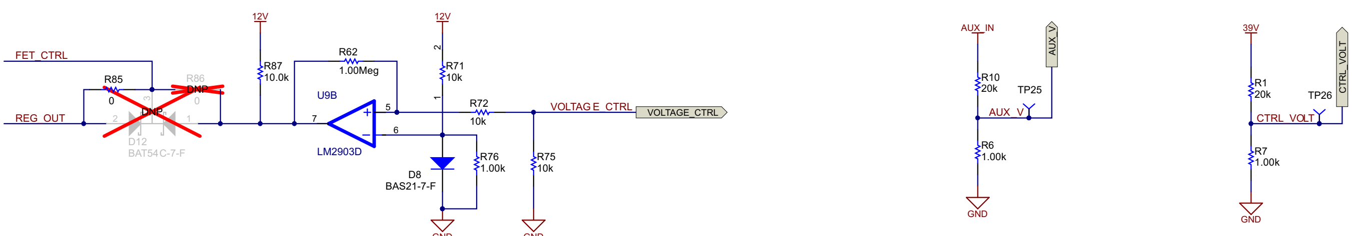


Figure 13. Comparator for PWM Control and DC Supply Voltage Sensing Schematic

4.1.6 LDO

An LDO is used to generate 3.3 V for the MCU and the signal conditioning circuit. This application uses a 300-mA maximum output current LDO. Figure 14 shows the LDO schematic.

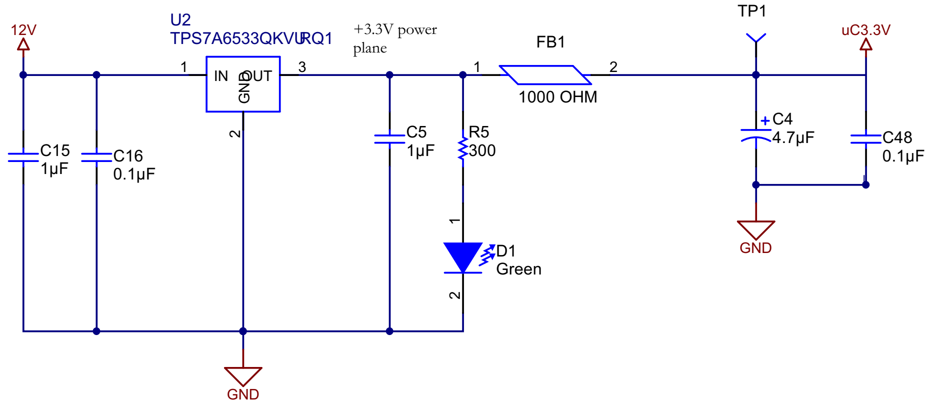


Figure 14. LDO Schematic

NOTE: Regarding the DC-DC converter and LDO:

The output of the DC-DC converter and LDO has a higher current rating than what this subsystem requires. These output voltages are terminated on an interface connector and can be used for other applications, such as LCD interface, serial communication, or other peripheral interfaces.

4.2 Signal Conditioning

The signal conditioning circuit consists of the components in the following subsections.

4.2.1 AC Current Input Connector

For the majority of the breaker application, current transformers are used and are part of the enclosure. The secondary output of the current sensors is connected to the ETU board. Connectors with burden resistors are available to connect a total of five current inputs: three phase inputs, a neutral, and ground. The current inputs can be AC input or full-wave rectified input. Depending on the type of current input, the reference must be selected.

The rectified or AC current input connects to the signal conditioning circuit using the following connectors in Figure 15. The required burden resistor and filter capacitors are provided across the connector.

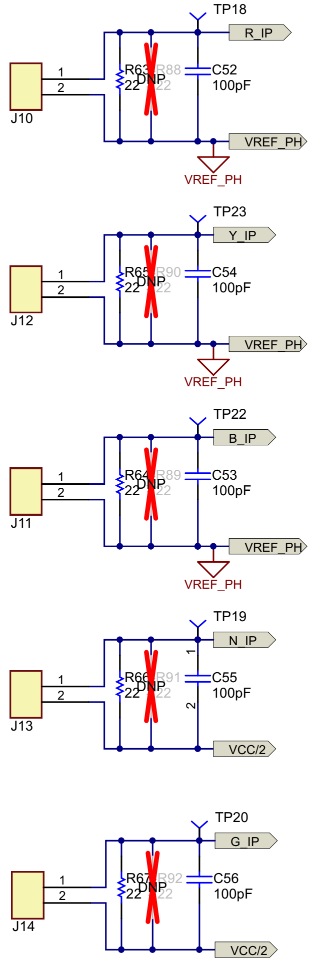


Figure 15. Current Input Connector With Burden Resistor

NOTE: Regarding current input and burden:

Do not apply current without connecting the CT secondary to the connectors.

The burden resistor is secondary current dependent and changes with the current transformer type. The total from the secondary current multiplied by the burden must not exceed 500 mV with the amplifier gain configuration in the current design.

4.2.2 Phase Current Inputs and Gain Amplifiers

The phase current inputs have a wide range, typically 0.5 In to 12 In. The current measurement must be within ± 3%. To measure a wide input current within the specified accuracy, the input must be amplified. Two gain stages (X2 and X5.7) are provided for each phase input. If additional gain is required, the burden resistor output without amplification can be connected as the X1 gain input. To connect the inputs, use the test points across the current input connectors.

Figure 16 shows the schematic for the amplifiers with two gains.

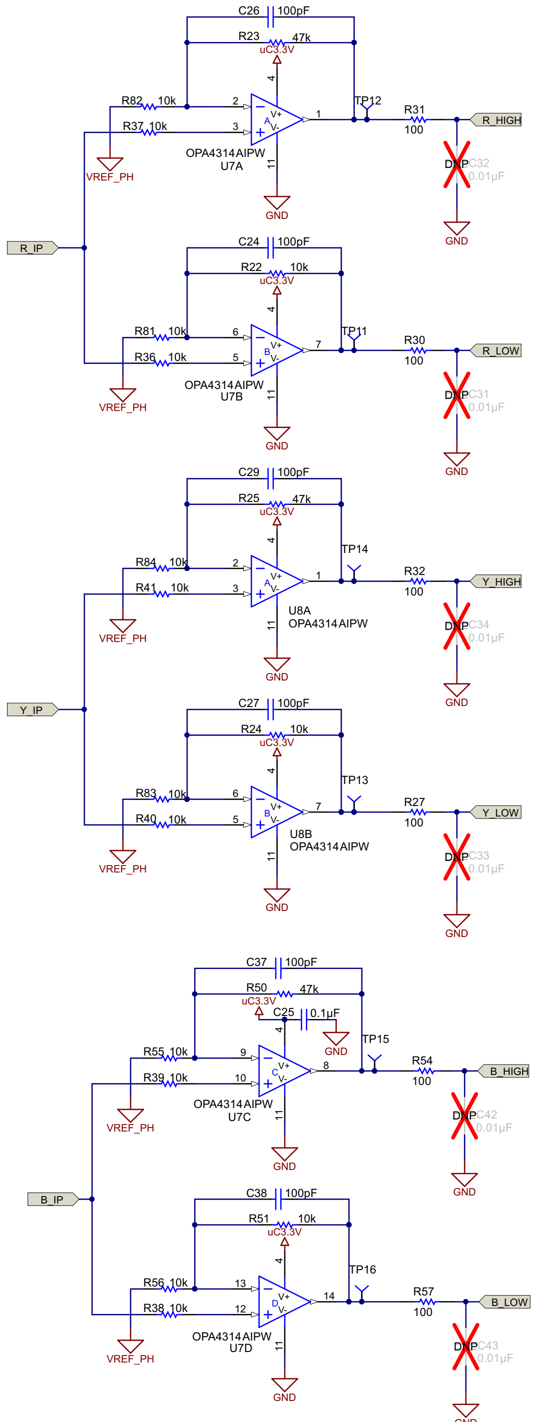


Figure 16. Amplifiers With Two Gains Schematic

4.2.3 Neutral and Ground Current Inputs and Amplifier

The neutral and ground amplifiers must measure between 0.05 In to 2.00 In. The TIDA-00498 design provides a single gain stage of X5.7. The gains are modifiable based on the requirement.

Figure 17 shows the schematic for the N and G amplifier with a single gain.

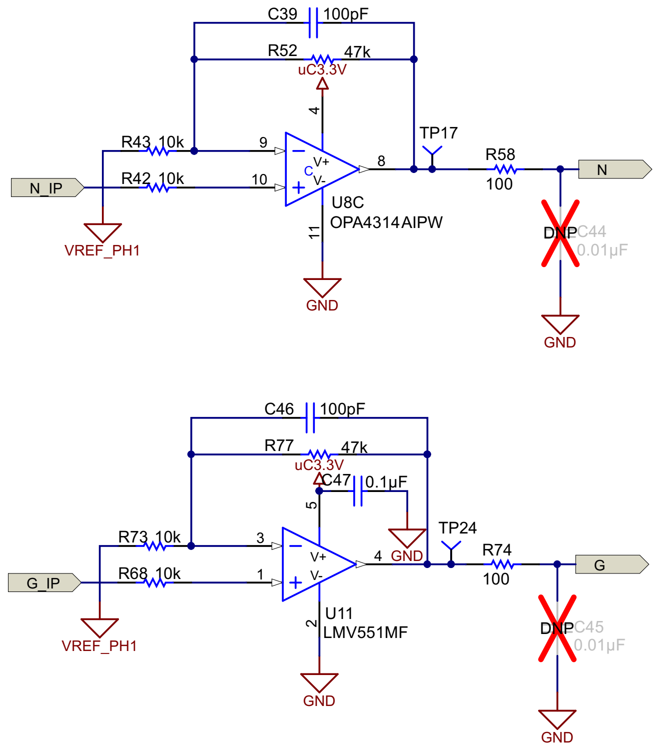


Figure 17. Amplifier With Single Gain Schematic

NOTE: Regarding the amplifier output to ADC:

- AC current input configuration – When the input is configured for AC current input, the input range is level shifted by VCC / 2 (1.65 V in this case). The maximum input across the ADC input of the MCU must not exceed 1100-mV RMS.
- Rectified input – When the current input is set as rectified input, the current directional is unidirectional and the input reference can be 0 V. The input range doubles, allowing a wider input or higher gain.

4.2.4 Reference and Buffer for Level Shifting AC Current Input

The LM4041 reference has been programmed to provide a level shift of VCC / 2. The reference output is buffered with an op amp. Figure 18 shows the schematic of the reference and buffer for a level-shifting AC current input.

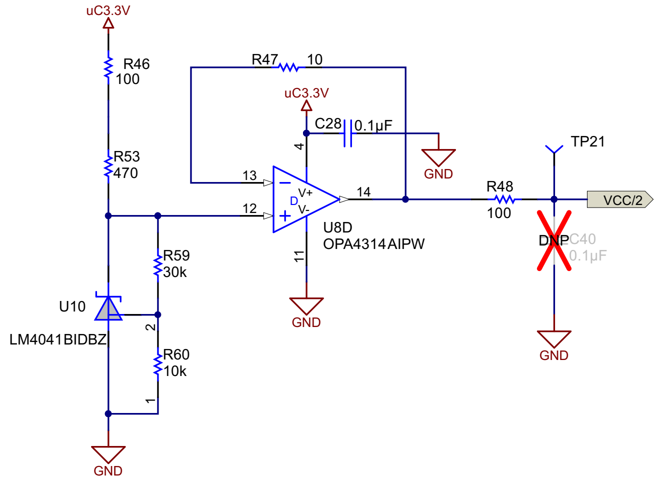


Figure 18. Reference and Buffer

4.2.5 Jumpers to Configure Input as AC Input or Full-Wave Rectified Input

Figure 19 shows a schematic for the jumper for AC current or rectified current.

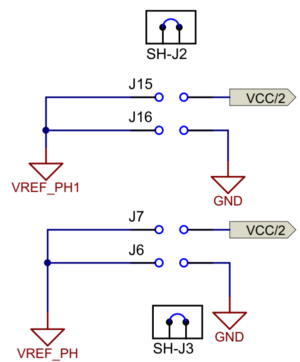


Figure 19. Jumper for AC Current or Rectified Current Schematic

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NOTE: Separate jumpers are available for phase inputs and neutral or ground inputs. This provision allows the user to independently configure the inputs based on the application.

Table 4 shows the jumper settings required to configure the reference.

Table 4. Jumper Setting for Reference Configuration

CURRENT TYPE	REFERENCE	JUMPER TO BE MOUNTED
Phase currents	VCC / 2	J7
	GND	J6
Neutral and ground	VCC / 2	J15
	GND	J16

4.3 MCU

The MCU has the following interfaces:

- ADC input: 12-bit ADC with an option to scan the current input channels
- ADC reference: The reference option selected is the external reference and 3.3 V
- Oscillator: The MCU can operate with a DCO, 32-KHz oscillator, or 8-MHz oscillator; this design uses a DCO
- GPIO for LEDs: Two LEDs are available onboard; the user can use these LEDs for the required system functionality
- GPIO for MOSFET control to drive FSD/relay drive: A MOSFET driver for FSD is available
- JTAG: A 14-pin JTAG interface is available for programming
- PWM control of self-power: The self-powered DC inputs are sensed and controlled using PWM from the microcontroller (in addition to the hardware shunt regulation)
- Interface connector: An interface connector with UART, SPI, and I^{2}C interface signals are available for future expansion
- Power-on-reset: A 60- to 300-µs power-on-reset is available

Figure 20 shows a schematic for the MCU configuration.

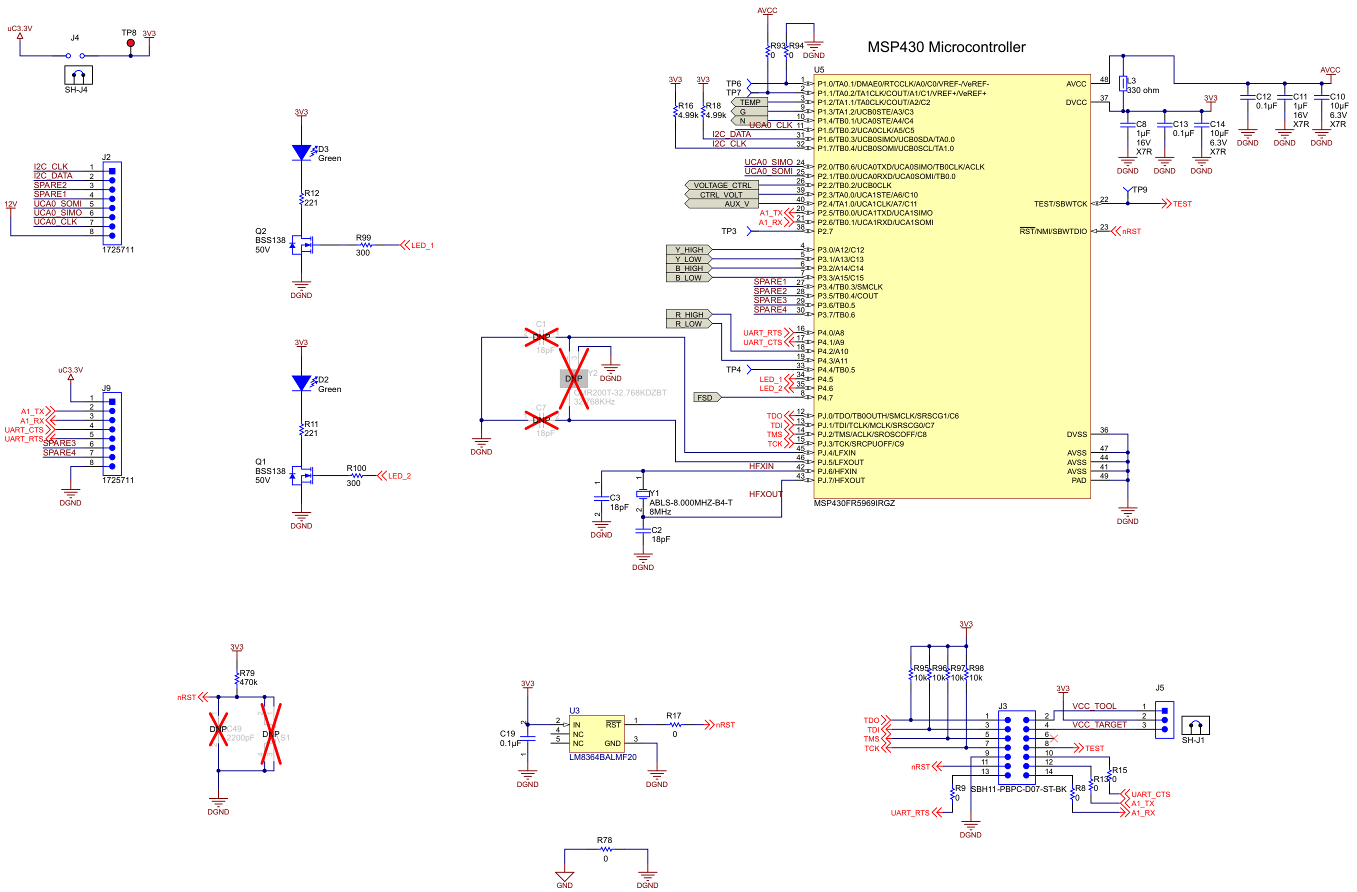

Figure 20. MCU Configuration Schematic

4.4 Temperature Sensor

Figure 21 shows a schematic of the temperature sensor.

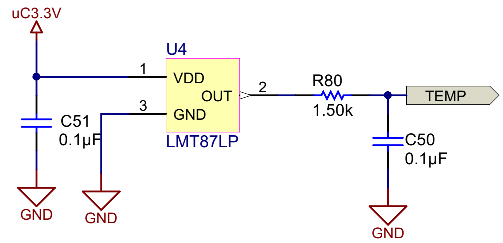

Figure 21. Temperature Sensor Schematic

The temperature sensor can measure a range between −50°C to 150°C, which meets the required operation range of −20°C to 105°C. The following Table 5 lists the load capacitor and series resistor requirements.

Table 5. Capacitive Loading for LMT87

C_{LOAD}	MINIMUM R_S
1.1 nF to 99 nF	3 kΩ
100 nF to 999 nF	1.5 kΩ
1 µF	800 Ω

4.5 Undervoltage Sensor

The MCU reset timing requirement at V_{CC} = 2 V or 3 V is 2 µs (minimum). The propagation delay of the undervoltage sensor is 60 µs to 300 µs. This configuration is one the few options that can be used as a power-on reset. The device has a threshold of 2 V.

Figure 22 shows a schematic for the undervoltage sense input connected to the /reset of the MCU.

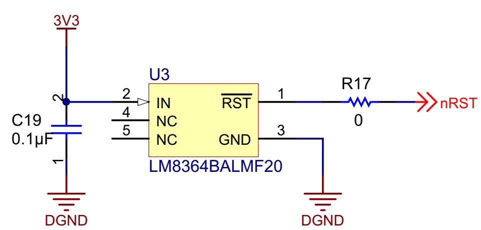

Figure 22. Undervoltage Sense Input to MCU Schematic

4.6 Enhancements

4.6.1 Adding AC Voltage Measurement

In the TIDA-00498 design, a provision for connecting voltage inputs does not exist. In situations when measuring the three phase voltages inputs is required, the design can be modified to implement the required potential divider.

4.6.2 Filters Across Op Amp Output

All of the op amp outputs have a provision for an RC filter, which is not enabled in the initial design. Depending on the requirements of the application, the RC filters can be used.

4.6.3 Using Dual Amplifiers Instead of Quad Amplifiers

The TIDA-00498 design uses quad amplifiers for signal conditioning. The use of a dual op amp is preferable in some applications because of the simple PCB design and increased flexibility. Any of the following dual op amps can be used:

1. OPA2314
2. OPA2330
3. LMV612

4.6.4 Increasing Gain Stages

In situations where more than two stages are required, the following options are possible: Adding a gain stage or connecting the current sensor output directly to the ADC channels.

4.6.5 Adding Communication Interface

The ETU has one of the following communication interfaces:

- LPR
- RS485
- Bluetooth

The following subsections show some of the options for easily evaluating the communication interface along with the subsystem.

4.6.5.1 Wireless—LPR

The designer can use the following kits to test RF connectivity. Consult TI for more options.

1. CC2545EMK Quick Start Guide (SWRU320)
2. CC2543-CC2544 Development Kit (SWRU315)

4.6.5.2 RS485

The TIDA-00308 device can be used along with the TIDA-00498 device to implement the RS485 interface. Consult TI for more options.

The RS485 (isolated, non-isolated) is a popular interface for the grid infrastructure space and is one of the most important options on newly-designed pieces of equipment. The TIDA-00308 enables customers to quickly evaluate and design with TI RS485 devices for three different application scenarios, with an isolated power supply provided in this design. Additionally, test results in the user's guide demonstrate the IEC61000-4-2 ESD and IEC61000-4-5 surge tests performed on this design.

4.6.5.3 Bluetooth

The designer can use the following kits to test the Bluetooth connectivity. Consult TI for more options.

1. CC256x Bluetooth Reference Design (SWRU417)
2. Small Form Factor Bluetooth Low Energy (BLE) Reference Design – TIDA-00358 (TIDU691)

4.6.6 Interfacing to Rogowski Coil

The current transformer inputs can be replaced with a 333-mV output Rogowski sensor for measuring purposes. These Rogowski sensors provide a voltage output that is proportional to current input.

If using custom Rogowski coils, the analog integrator must be externally provided. The output of the integrator can be measured by the signal processing front end.

4.7 Design Guidelines

LM5017 layout guidelines

A proper layout is essential for optimum performance of the circuit. In particular, the following guidelines must be observed:

1. C_{IN}: The loop consisting of the input capacitor (C_{IN}), V_{IN} pin, and RTN pin carries switching currents. Therefore, the input capacitor must be placed close to the IC, directly across the V_{IN} and RTN pins. The connections to these two pins must be direct to minimize the loop area. In general it is not possible to accommodate all of input capacitance near the IC. A good practice is to use a 0.1-µF or 0.47-µF capacitor directly across the V_{IN} and RTN pins close to the IC, and the remaining bulk capacitor as close as possible.
2. C_{VCC} and C_{BST}: The V_{CC} and bootstrap (BST) bypass capacitors supply switching currents to the high and low side gate drivers. These two capacitors should also be placed as close to the IC as possible, and the connecting trace length and loop area should be minimized.
3. The feedback trace: The feedback trace carries the output voltage information and a small ripple component that is necessary for proper operation of LM5017. Therefore, care should be taken while routing the feedback trace to avoid coupling any noise to this pin. In particular, the feedback trace must not run close to any magnetic components, or parallel to any other switching trace.
4. SW trace: The SW node switches rapidly between VIN and GND every cycle and is therefore a possible source of noise. The SW node area should be minimized. In particular, the SW node should not be inadvertently connected to a copper plane or pour.

LMT87 power supply recommendations

The LMT87's low supply current and supply range of 2.7 V to 5.5 V allow the device to easily be powered from many sources.

Power supply bypassing is optional and is mainly dependent on the noise on the power supply used. In noisy systems it may be necessary to add bypass capacitors to lower the noise that is coupled to the LMT87's output.

OPA4314—EMI susceptibility and input filtering

Operational amplifiers vary with regard to the susceptibility of the device to electromagnetic interference (EMI). If conducted EMI enters the op amp, the dc offset observed at the amplifier output may shift from its nominal value while EMI is present. This shift is a result of signal rectification associated with the internal semiconductor junctions. While all op amp pin functions can be affected by EMI, the signal input pins are likely to be the most susceptible. The OPA314 operational amplifier family incorporates an internal input low-pass filter that reduces the amplifiers response to EMI. Both common-mode and differential mode filtering are provided by this filter. The filter is designed for a cutoff frequency of approximately 80 MHz (–3 dB), with a roll-off of 20 dB per decade.

4.8 MCU Features

4.8.1 MSP430 Advanced Power Optimizations

MSP430 microcontrollers are designed for ultra-low-power applications. Features such as multiple low-power modes, instant wake-up, intelligent autonomous peripherals, and much more to enable such ultra-low-power (ULP) capabilities. Texas Instruments™ provides valuable tools to help the programmer fully use these benefits and optimize power consumption of the target application.

ULP Advisor: tool overview

The ULP Advisor™ software can be used at compile time to draw attention to inefficient code and help the developer to fully utilize the ULP capabilities of MSP430 microcontrollers. This tool works at build time to check the code against a list of ULP rules and identify possible areas where energy and power use is inefficient. Visit the ULP Advisor Wiki page at: http://www.ti.com/ulpadvisor.

EnergyTrace technology: energy measurement method

Power is traditionally measured by amplifying the signal of interest and measuring the current consumption and voltage drop over a shunt resistor at discrete times. EnergyTrace technology implements a new method for measuring power. In debuggers that support EnergyTrace technology, a software controlled DC-DC converter generates the target power supply (1.2 V to 3.6 V). The time density of the DC-DC converter charge pulses equals the energy consumption of the target microcontroller. A built-in calibration circuit in the debug tool defines the energy equivalent for a single charge pulse. The width of each charge pulse remains constant. The debug tool counts every charge pulse and the sum of the charge pulses are used in combination with the time elapsed to calculate an average current. Because this measurement technique continually samples the energy supplied to the microcontroller, even the shortest device activity that consumes energy contributes to the overall recorded energy. This is a clear benefit over shunt-based measurement systems, which cannot detect extremely short durations of energy consumption.

4.8.2 IP Encapsulation

Protecting code or data on-chip

(a) Protecting from external readout attacks using the standard debug or firmware upgrade channels:
Two commonly used methods to program microcontrollers are through the programming interface, such as JTAG, and through a boot strap loader (used mainly for firmware upgrade functions). MSP430 FRAM MCUs provide the means to either secure JTAG using a password or to disable it completely by programming a fuse signature in FRAM. In cases where the JTAG is disabled, access to the device is only possible using bootstrap loader (BSL). The BSL requires a password to read out or receive data. This password is the content of the interrupt vector table—which is a list of addresses or locations for interrupt service routines used in the application. On the FRAM-based MSP430 devices, providing an incorrect password results in the entire FRAM code area being mass erased. This approach is inherently secure because it prevents the attacker from reading out any sensitive information from the microcontroller. An additional way to increase the strength of the password is by filling any unused address spaces in the interrupt vector table with valid address values or by creating a double jump table, which makes performing a brute force attack more difficult. In a system where many such nodes are deployed to the field, ideally, each node would contain random (or pseudo-random) values populating the interrupt vector table that are unique to that node (perhaps using the device identifier, manufacturer time stamp, and so on). In such a case applying a brute force attack to one node is not useful because it is inefficient and expensive to replicate such an attack on every node.

(b) Protecting from unauthorized access of sensitive intellectual property (IP):
In many cases the MCU code area is divided into secure and non-secure zones. An example of this could be a smart metering application that has both a display algorithm stored in an unsecure zone and a billing algorithm, an IP that requires protection. While field upgrades can modify the display algorithm, the billing IP is considered confidential and must be secured. An attacker may attempt to modify the critical IP by introducing code that can read out or change the algorithm. To protect against such threats, MSP430 FRAM MCUs provide IP encapsulation (IPE), a feature that allows code or data to be stored in a secure zone. In a secure environment, such as the factory, the address area that requires IP encapsulation is stored in FRAM. After the first power cycle, this address is mapped into the boot code area. Any further modification of this address is no longer possible and the area stays secure for the lifetime of the device. An IP encapsulated area cannot be accessed through JTAG, BSL, or even in-system reads using DMA or direct register reads. To access code functions in the IPE area, the functions are called from outside the secure zone. Data reads in the IPE area are only possible when code inside the secure area is executed, which is useful for authentication algorithms where the nodes must verify a signature (for example, when pairing). In this case the signature key and the algorithm that is used for the authentication are both located in the IPE area. The external application performs a function call and acts according to the results of the algorithm (signature identified or denied).

(c) Protecting from physical attacks to the memory:
One of the key advantages MSP430 MCUs bring is TI's innovative non-volatile FRAM technology. In addition to features in the system architecture that prevent unauthorized reading and writing of application code and data, MCUs must also protect against malevolent manipulation of parameters to gain access to sensitive information as well as against invasive attacks against the physical MCU itself. MCUs can be vulnerable to a variety of attacks to extract data, extract application code, or secure keys stored in memory. In many cases, the goal of an attack on an MCU is to alter data stored on the device. For example, the usage data on an automatic utility meter can be modified to show lower than actual usage to result in a reduced monthly bill. In general, rather than attempt to modify the data that is collected, hackers attempt to alter the application code itself. To achieve this, the hackers must first be able to obtain an image of the application code to reverse engineer and then overlay a modified version successfully within the system. Numerous methods exist that have been developed to force systems to expose confidential information or even their application code. For example, fault attacks can induce faulty operation by placing systems in an unpredictable state where they may output security keys or blocks of application code. Alternatively, hackers may attack a system physically, either by taking an MCU apart or inducing faults using optical means.

Securing the communication channel

In the preceding example, the sensor nodes must communicate data (such as ambient temperature and other environmental data) quickly and securely. Similarly, a smart meter must be able to log usage measurements with the utility company. In addition, many such systems use the Internet as their primary communication channel to keep infrastructure costs down. There are a multitude of ways to compromise the exchange of information over public networks. For example, by eavesdropping on an exchange, sensitive data from a legitimate transaction can be captured. Similarly, there are a wide range of effective countermeasures that have been developed to prevent such compromises. The following list briefly describes some areas and methods where MSP430FRxx MCUs bring advantages when securing communication:

(a) Encryption:
Currently, the primary technology used to protect exchanges is cryptography. MCUs use encryption to ensure the confidentially of data, as well as authentication, to establish the identity of both parties in a transaction. MCUs can also verify the integrity of data (that is, detect whether data has been corrupted in any way), as well as repudiate the credentials of any participant that is discovered to no longer be trustworthy. Commonly known cryptographic standards include 3DES, AES, RSA, and ECC. These standards are well-established and have been proven in real-world applications to provide sufficient security for the exchange of sensitive data. Many manufacturers are already familiar with these standards through their use in protocols such as ZigBee®, Wi-Fi, and Bluetooth. Today, such technology is straightforward to implement, but it does have an impact on the overall code size and power consumption, which are especially important in portable, battery-powered applications.
To enable an efficient and low-power means to implement cryptography, the MSP430FR5xx and MSP430FR6xx family of microcontrollers provide a 256-bit AES accelerator. This accelerator can perform 256-bit encryption in a fraction of the time and power required by software algorithms. In addition, the AES accelerator can be used to encrypt and decrypt data on-the-fly, that is, without having to store confidential information in RAM/EEPROM or other unsecured areas while waiting for an encryption or decryption operation to complete.

(b) Key storage:
A common requirement with encryption algorithms is the secure storage of the key. This secure storage can easily and efficiently be achieved with FRAM microcontrollers, because generating a new key for every session and storing it in FRAM is easy. In traditional battery-powered systems, the option to perform a high-energy flash write is not always available. Also, for an attacker snooping the power rails of the system, it is an easy give-away if there is a huge spike in power exactly before storing the key due to the flash charge pump being turned on. FRAM makes this easier and more secure because FRAM writes do not require pre-erase or charge pumps and complete very quickly. FRAM also provides near infinite endurance (10^{15} cycles), ensuring that these key locations can be overwritten multiple times over the lifetime of the product.

(c) Key generation:
AES keys are used to encrypt and decrypt the plaintext (sensitive data that must be transmitted or received). The longer the length of the key, the more secure the encrypted information. An important parameter for key generation is the availability of a true random number seed. The MSP430FR5xx and MSP430FR6xx devices provide a random number seed that is unique to the device. The device descriptor information (TLV) section contains a 128-bit true random seed that can be used to implement a deterministic random number generator for key creation.

(d) Integrating external memory:
In many applications, a bulk of the data is stored off-chip either in external flash, EEPROM, or FRAM chips. This type of storage presents another challenge in terms of securely transmitting the data to and from the external memory. TI's MSP430 FRAM MCUs are available from 4-kB FRAM to 128-kB FRAM sizes, allowing external memory requirements to be integrated into the MCU—providing a more secure and power efficient form of information storage.

5 Getting Started Hardware

Ensure that the following jumpers in Table 6 are configured for the TIDA-00498 design:

Table 6. Jumper Table for Testing Board

CONFIGURATIONS	JUMPERS
3.3-V input to MCU	J4
JTAG power source	J5
Phase current inputs	J6 or J7
Neutral and ground inputs	J15 or J16

5.1 Power Supply

Table 7. Jumper Configuration for Power Input

INPUT TYPE	J8 CONNECTOR WIRING
Rectified current input	J8 → 3-2
Auxiliary input	J8 → 1-2

Table 8. Signal Conditioning Input

INPUT	CONNECTOR
R phase	J10
Y phase	J12
B phase	J11
Neutral	J13
Ground	J14

CAUTION

Do not leave the current terminal open and apply current during testing. Before applying current for testing, ensure that the current inputs are connected and the terminal screws are tightened.

5.2 JTAG Programming

J3 is the JTAG connector that can be used for programming and debugging of the TIDA-00498 design.

6 Getting Started Firmware

6.1 MCU Initialization

6.1.1 Watchdog Timer

The watchdog timer is not initially used and is currently disabled.

6.1.2 Initializing LED Port Pins

The ports P4.5 and P4.6 direction must be set as outputs.

6.1.3 Initializing Oscillator Port Pins

Set the port bits PJ.4, PJ.5, PJ.6, and PJ.7 if the low frequency (LF) clock or high frequency (HF) clock is required. Clear the bit LOCKLPM5 in register PM5CTL0.

6.1.4 Initializing FRAM

Configure the FRAM control register FRCTL0 (using a password) for one wait state because the clock is configured for 16 MHz.

6.1.5 Initializing Oscillator

- Unlock CS registers using CSCTL0_H register using CSKEY password
- Using register CSCTL1, select DCORSEL (= 1) and DCOFSEL (= 4) to select 16 MHz
- Using register CSCTL2, select SELS and SELM as DCO clock (SELA defaults to VLO clock and can be changed to the desired setting)
- Using register CSCTL3, select divider A, divider S, and divider M value as 1
- Lock CS registers using CSCTL0_H register

6.1.6 Initializing Port Pins

To configure ADC inputs A10 and A11:

- Select P4SEL1: bit2 and bit3
- Select P4SEL0: bit2 and bit3

To configure ADC inputs A12, A13 and A14, A15:

- Select P3SEL1: bit0, bit1, bit2, and bit3
- Select P3SEL0: bit0, bit1, bit2, and bit3

To configure ADC inputs A2, A3, and A4:

- Select P1SEL1: bit2, bit3, and bit4
- Select P1SEL0: bit2, bit3, and bit4

6.1.7 Initializing ADC

Set the ADC control register ADC12CTL0 as follows:

- Enable sample and hold0, bit4 (64 clock cycles)
- Enable sample and hold1, bit4
- Enable ADC12MSC bit to enable multiple sample conversion (to enable a sequence of conversions)
- Enable ADC12ON bit

Set the ADC control register ADC12CTL1 as follows:

- Enable ADC12SHP to source SAMPCON signal from sampling timer (timer B)
- Set ADC12CONSEQx (bits 2−1) to 01b to choose a sequence of channels
- Set ADC12SHSx = {3}, to select Timer B0 as the sampling timer source
- Set ADC12SSELx = 11b to select SMCLK as the ADC clock source select
- Set the ADC control register ADC12CTL2; ADC12RES bits to 10b to select the 12-bit mode

ADC channel selection

- Select ADC channel2 in ADC12MCTL0 register
- Select ADC channel3 in ADC12MCTL1 register
- Select ADC channel4 in ADC12MCTL2 register
- Select ADC channel10 in ADC12MCTL3 register
- Select ADC channel11 in ADC12MCTL4 register
- Select ADC channel12 in ADC12MCTL5 register
- Select ADC channel13 in ADC12MCTL6 register
- Select ADC channel14 in ADC12MCTL7 register
- Select ADC channel15 in ADC12MCTL8 register.
- Also set the EOS bit to indicate the end of the conversion sequence
- Enable ADC12IER0; bit 8 to enable the ADC interrupt when ADC12MEM8 is filled with data
- In the ADC12CTL0 register, set the ADC12ENC bit

6.1.8 Initializing Timer

Use the following settings to initialize the timer:

- Set the TB0R register value to 0
- Set the TB0CCR0 register to 2500 (sampling interval)
- Set the TB0CCTL1 to mode 3 (set/reset)
- Set the TB0CTL register as follows:
  - TBSSEL bits to 11b (SMCLK)
  - CNTL bits to 00b (16 bits)
  - MC bits to 11b (up/down mode)
  - Enable TBCLR bit

6.1.9 Processing ADC Interrupt

When the ADC12IFG8 is set, the interrupt occurs and the conversion results are copied from the registers, ADC12MEM0: ADC12MEM8 to the results [] array.

Set a flag using a (volatile) variable to indicate that the data is available: Toggle the ADC12CTL0, ADC12ENC bit.

6.2 RMS Computation

As soon as the device initialization is complete, the program waits for a flag (that indicates data available). When the flag is set, the data is copied from the results array into In_data[sample_count], where n = 1 through 8 and the sample_count = 0 through 63.

Then the sample value is corrected for an offset of 2048 and is made absolute (sign is ignored). The sample counter is incremented. This process repeats until the sample counter obtains 64 samples.

As soon as the 64 samples are obtained, the root mean square is computed in the following manner:

- Each sample (64 samples) is squared and added in a float variable sum.
- The sum is divided by 64 in a float variable temperature.
- Then the square root of the temperature is calculated (the resulting value is the RMS for a particular channel).

This process of RMS computation is used for channels A3, A4, A10, A11, A12, A13, A14, and A15.

6.3 Miscellaneous

6.3.1 Initialization for Auxiliary-In/Self-Powered Control Voltage Measurement

To configure ADC inputs A6 and A7:

- Select P2SEL1: bit3 and bit4
- Select P2SEL0: bit3 and bit4
- Select ADC channel6 in the ADC12MCTL0 register
- Select ADC channel7 in the ADC12MCTL1 register
- Enable ADC12IER0; bit 1 to enable the ADC interrupt when ADC12MEM1 is filled with data
- In the ADC12CTL0 register, set the ADC12ENC bit

Use of these ADC inputs depends on the application.

NOTE: The ADC12MCTL0 and ADC12MCTL1 registers are re-used for other ADC channels.

6.3.2 Port Pin Configuration for FSD

Set the P4.7 port direction as the output.

7 Test Setup

7.1 Test Setup Block Diagram

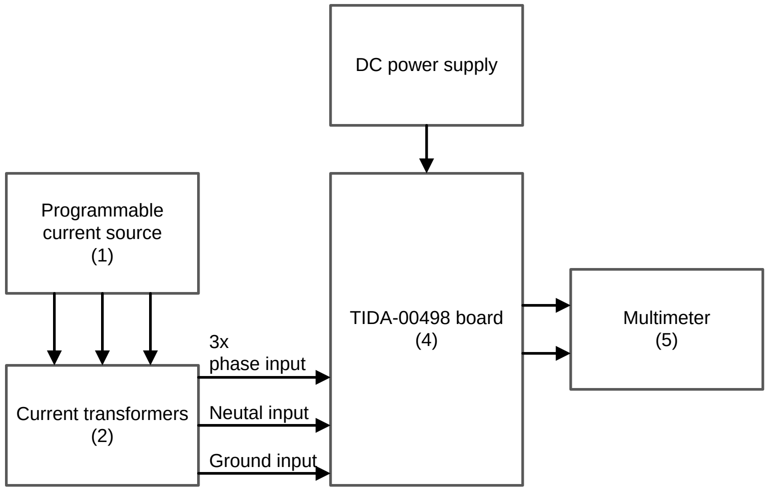

Figure 23. Test Setup Block Diagram

7.1.1 Test Setup Photos

Figure 24. Programmable Current Source

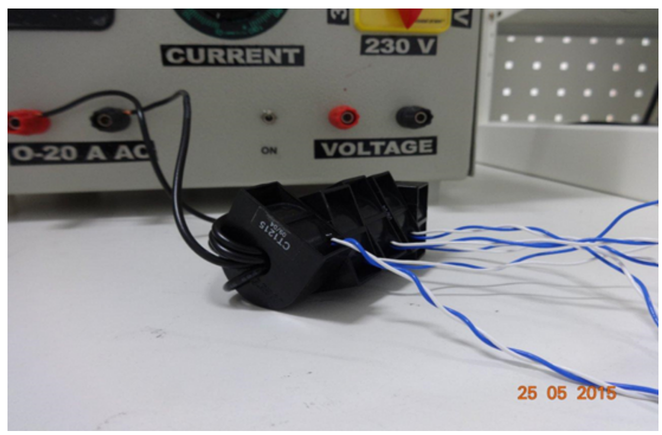

Figure 25. Current Transformer

Figure 26. DC Power Supply

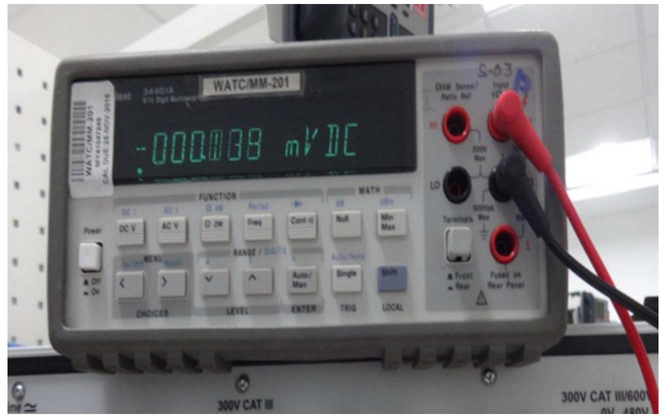

Figure 27. Multimeter

Figure 28. Temperature Chamber Setup

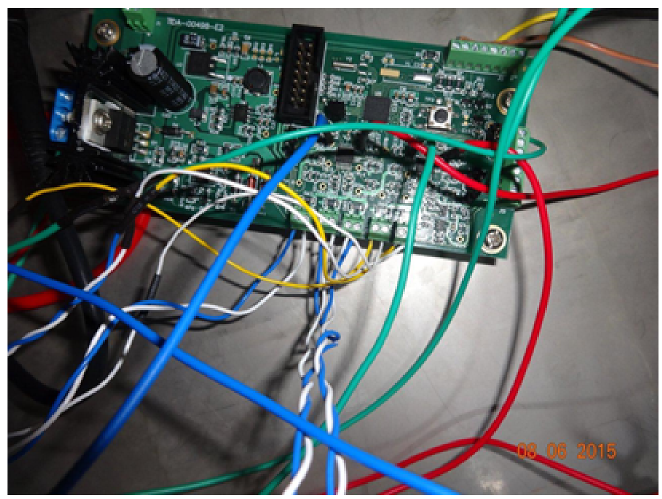

Figure 29. TIDA-00498 Inside Chamber

8 Test Data

The errors observed include errors due to current transformer non-linearity.

8.1 Functional Testing

Table 9. Functional Testing—Boards 1 and 2

PARAMETERS		EXPECTED	MEASURED
Power supply	Self-power	13.11-V DC	13.17
		3.3 V	3.306
		Shunt regulation > 39 V	OK
	Auxiliary power supply	13.11-V DC	13.17
		3.3 V	3.306
Protection	Undervoltage sense	DC-DC converter	OK
		MCU	OK
Startup with MCU and power supply	Startup time after 18 V applied to the input	With DCO	< 5 ms
		With 8-M crystal	< 5 ms
Temperature sensing	Temperature sensor	Sensor output at room temperature: 2.298	2.231
DC power supply voltage sensing	Auxiliary DC voltage	1 V at 21-V input	OK
	Self-power supply voltage	1 V at 21-V input	OK
LED indication	LED operation	LED1	OK
		LED2	OK

Table 10. Amplifier Output

PARAMETERS		EXPECTED	MEASURED
DC reference	Reference output	Across buffer	1.646
	R phase	X2 Gain	1.641
		X5.7 Gain	1.637
	Y phase	X2 Gain	1.641
		X5.7 Gain	1.624
	B phase	X2 Gain	1.641
		X5.7 Gain	1.644
	Neutral	X5.7 Gain	1.632
	Ground	X5.7 Gain	1.648
Measurement with multimeter	R phase	X2 Gain	OK
		X5.7 Gain	OK
	Y phase	X2 Gain	OK
		X5.7 Gain	OK
	B phase	X2 Gain	OK
		X5.7 Gain	OK
	Neutral	X5.7 Gain	OK
	Ground	X5.7 Gain	OK

Table 10. Amplifier Output (continued)

PARAMETERS		EXPECTED	MEASURED
Measurement with MCU	Programming	JTAG	OK
	ADC - R phase	X2 Gain	OK
		X5.7 Gain	OK
	ADC - Y phase	X2 Gain	OK
		X5.7 Gain	OK
	ADC - B phase	X2 Gain	OK
		X5.7 Gain	OK
	ADC - Neutral	X5.7 Gain	OK
	ADC - Ground	X5.7 Gain	OK

Table 11. MOSFET Shunt Regulation

BOARD NUMBER	CONDITION	OBSERVATIONS	COMMENTS
1	> 39 V applied as auxiliary input	Detects at 39.6 V and the comparator output goes high	MOSFET should not operate
	> 39 V applied as auxiliary input	MOSFET shunts the input after 39.4 V	MOSFET must operate
2	> 39 V applied as auxiliary input	Detects at 40.3 V and the comparator output goes high	MOSFET should not operate
	> 39 V applied as auxiliary input	MOSFET shunts the input after 40.10 V	MOSFET must operate

Table 12. Undervoltage Test With LM8364

BOARD NUMBER	CONDITION	OBSERVATIONS	COMMENTS
1	Propagation delay 60 µs to 300 µs after applying 3.3 V	140 µs	MCU requires approximately 10-µs reset time
2	Propagation delay 60 µs to 300 µs after applying 3.3 V	160 µs	

8.2 Performance Testing

All of the measured output voltages are in millivolts (mV). The input current is in amperes (A).

8.2.1 Amplifier Output Measurement With LMV614

The following tables in this subsection show the measurements taken with a multimeter for the LMV614 device.

Table 13. R-Phase Amplifier Outputs

CURRENT INPUT	R_L OUTPUT MEASURED	EXPECTED OUTPUT	R_L OUTPUT_% ERROR	R_H OUTPUT MEASURED	EXPECTED OUTPUT	R_H OUTPUT_% ERROR
0.050	4.475	4.400	1.196	12.600	12.540	0.278
0.075	6.715	6.600	1.234	18.870	18.810	0.118
0.100	8.950	8.800	0.484	25.130	25.080	–0.001
0.250	22.340	22.000	0.327	62.800	62.700	–0.041
0.500	44.600	44.000	0.147	125.700	125.400	0.039
1.000	89.220	88.000	0.170	251.300	250.800	–0.001
2.500	223.200	220.000	0.237	628.500	627.000	0.039
3.000	267.500	264.000	0.110	754.000	752.400	0.012
4.000	357.000	352.000	0.203	1006.000	1003.200	0.079
5.000	446.100	440.000	0.170	1229.000	1254.000	–2.190
7.500	668.100	660.000	0.013	1404.000	1881.000	–25.508
10.000	891.100	880.000	0.046			
12.000	1065.000	1056.000	–0.358			
Gain		0.985			1.000	

Table 14. Y-Phase Amplifier Outputs

CURRENT INPUT	Y_L OUTPUT MEASURED	EXPECTED OUTPUT	Y_L OUTPUT_% ERROR	Y_H OUTPUT	EXPECTED OUTPUT	Y_H OUTPUT_% ERROR
0.050	4.413	4.400	0.697	12.550	12.540	0.080
0.075	6.590	6.600	0.248	18.780	18.810	–0.159
0.100	8.750	8.800	0.128	25.015	25.080	–0.259
0.250	21.850	22.000	0.013	62.500	62.700	–0.319
0.500	43.660	44.000	–0.078	125.100	125.400	–0.239
1.000	87.350	88.000	–0.044	250.100	250.800	–0.279
2.500	218.100	220.000	–0.170	626.000	627.000	–0.159
3.000	262.100	264.000	–0.025	750.500	752.400	–0.253
4.000	349.100	352.000	–0.130	1001.100	1003.200	–0.209
5.000	436.000	440.000	–0.215	1226.000	1254.000	–2.233
7.500	656.100	660.000	0.105	1404.000	1881.000	–25.359
10.000	875.200	880.000	0.151			
12.000	1046.000	1056.000	–0.254			
Gain		1.004			1.000	

Table 15. B-Phase Amplifier Outputs

CURRENT INPUT	B_L OUTPUT MEASURED	EXPECTED OUTPUT	B_L OUTPUT_% ERROR	B_H OUTPUT	EXPECTED OUTPUT	B_H OUTPUT_% ERROR
0.050	4.460	4.400	0.451	12.550	12.540	0.080
0.075	6.680	6.600	0.301	18.840	18.810	0.159
0.100	8.890	8.800	0.114	25.082	25.080	0.008
0.250	22.260	22.000	0.271	62.670	62.700	–0.048
0.500	44.400	44.000	0.001	125.420	125.400	0.016
1.000	88.800	88.000	0.001	250.810	250.800	0.004
2.500	222.210	220.000	0.096	627.200	627.000	0.032
3.000	266.200	264.000	–0.074	752.500	752.400	0.013
4.000	355.200	352.000	0.001	1002.100	1003.200	–0.110
5.000	444.100	440.000	0.023	1227.000	1254.000	–2.153
7.500	665.500	660.000	–0.074	1404.000	1881.000	–25.359
10.000	886.800	880.000	–0.134			
12.000	1064.000	1056.000	–0.149			
Gain		0.991			1.000	

Table 16. N and G Amplifier Outputs

CURRENT INPUT	N_H OUTPUT MEASURED	EXPECTED OUTPUT	N_H OUTPUT_% ERROR	G_H OUTPUT MEASURED	EXPECTED OUTPUT	G_H OUTPUT_% ERROR
0.050	12.600	12.540	0.177	12.520	12.540	0.140
0.075	18.900	18.810	0.177	18.730	18.810	–0.127
0.100	25.170	25.080	0.058	24.960	25.080	–0.180
0.250	62.800	62.700	–0.141	62.400	62.700	–0.180
0.500	125.720	125.400	–0.046	124.900	125.400	–0.100
1.000	251.400	250.800	–0.061	249.700	250.800	–0.140
2.500	629.000	627.000	0.018	624.000	627.000	–0.180
3.000	754.500	752.400	–0.022	749.100	752.400	–0.140
4.000	1006.000	1003.200	–0.022	999.200	1003.200	–0.100
5.000	1229.000	1254.000	–2.288	1195.000	1254.000	–4.419
7.500	1404.000	1881.000	–25.583	1363.000	1881.000	–27.321
Gain			0.997		1.003	

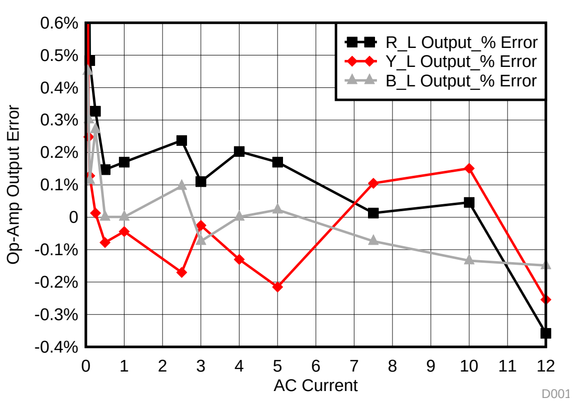

Figure 30. Current Versus Output Error for Low Gain Amplifier Using LMV614

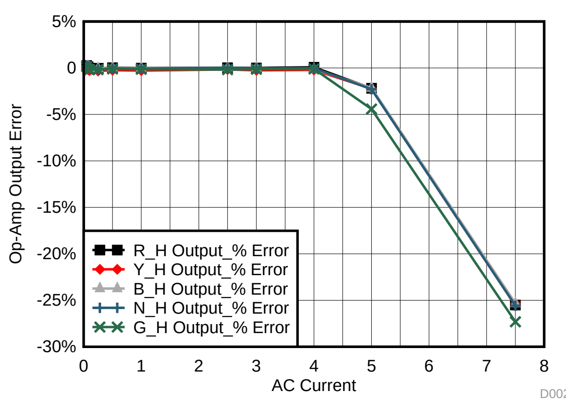

Figure 31. Current Versus Output Error for High Gain Amplifier Using LMV614

8.2.2 Amplifier Output Measurement With OPA4314

The following tables in this subsection show the measurements taken with a multimeter for the OPA4314 device.

Table 17. R-Phase Amplifier Outputs

CURRENT INPUT	R_L OUTPUT MEASURED	EXPECTED OUTPUT	R_L OUTPUT_% ERROR	R_H OUTPUT MEASURED	EXPECTED OUTPUT	R_H OUTPUT_% ERROR
0.05	4.615	4.400	0.709	12.704	12.540	0.396
0.075	6.903	6.600	0.426	19.000	18.810	0.101
0.1	9.180	8.800	0.164	25.320	25.080	0.048
0.25	22.881	22.000	–0.137	63.300	62.700	0.048
0.5	45.800	44.000	–0.055	126.500	125.400	–0.031
1	91.550	88.000	–0.109	253.000	250.800	–0.031
2.5	229.000	220.000	–0.055	633.000	627.000	0.048
3	274.500	264.000	–0.164	758.200	752.400	–0.136
4	366.000	352.000	–0.164	1012.000	1003.200	–0.031
5	457.500	440.000	–0.164	1232.000	1254.000	–2.639
7.5	683.000	660.000	–0.636	1404.000	1881.000	–26.031
10	908.000	880.000	–0.927			
12	1091.000	1056.000	–0.800			
Gain		0.965			1.000	

Table 18. Y-Phase Amplifier Outputs

CURRENT INPUT	Y_L OUTPUT MEASURED	EXPECTED OUTPUT	Y_L OUTPUT_% ERROR	Y_H OUTPUT MEASURED	EXPECTED OUTPUT	Y_H OUTPUT_% ERROR
0.05	4.605	4.400	1.101	12.631	12.540	0.474
0.075	6.875	6.600	0.625	18.889	18.810	0.169
0.1	9.150	8.800	0.442	25.200	25.080	0.227
0.25	22.860	22.000	0.376	62.860	62.700	0.005
0.5	45.700	44.000	0.332	125.800	125.400	0.068
1	91.500	88.000	0.442	251.500	250.800	0.028
2.5	228.700	220.000	0.420	628.500	627.000	–0.011
3	274.500	264.000	0.442	754.000	752.400	–0.038
4	365.500	352.000	0.305	1006.000	1003.200	0.028
5	457.000	440.000	0.332	1227.000	1254.000	–2.398
7.5	681.500	660.000	–0.253	1403.000	1881.000	–25.598
10	905.500	880.000	–0.601			
12	1086.000	1056.000	–0.656			
Gain		0.966			0.9975	

Table 19. B-Phase Amplifier Outputs

CURRENT INPUT	B_L OUTPUT MEASURED	EXPECTED OUTPUT	B_L OUTPUT_% ERROR	B_H OUTPUT	EXPECTED OUTPUT	B_H OUTPUT_% ERROR
0.05	4.614	4.400	0.459	12.812	12.540	0.330
0.075	6.932	6.600	0.619	19.180	18.810	0.132
0.1	9.250	8.800	0.699	25.550	25.080	0.040
0.25	22.950	22.000	–0.063	63.830	62.700	–0.030
0.5	45.900	44.000	–0.063	127.600	125.400	–0.077
1	91.800	88.000	–0.063	255.100	250.800	–0.116
2.5	229.200	220.000	–0.194	638.200	627.000	–0.046
3	275.000	264.000	–0.208	766.000	752.400	–0.025
4	367.200	352.000	–0.063	1021.000	1003.200	–0.058
5	458.500	440.000	–0.172	1237.000	1254.000	–3.131
7.5	683.400	660.000	–0.803	1404.000	1881.000	–26.702
10	909.200	880.000	–1.021			
12	1092.000	1056.000	–0.934			
Gain		0.958			0.982	

Table 20. N and G Amplifier Outputs

CURRENT INPUT	N_H OUTPUT MEASURED	EXPECTED OUTPUT	N_H OUTPUT_% ERROR	G_H OUTPUT MEASURED	EXPECTED OUTPUT	G_H OUTPUT_% ERROR
0.05	12.690	12.540	0.285	12.760	12.540	0.533
0.075	19.020	18.810	0.206	19.070	18.810	0.166
0.1	25.360	25.080	0.206	25.410	25.080	0.100
0.25	63.350	62.700	0.127	63.560	62.700	0.155
0.5	126.700	125.400	0.127	127.000	125.400	0.061
1	253.200	250.800	0.048	254.100	250.800	0.100
2.5	633.000	627.000	0.048	635.000	627.000	0.061
3	760.000	752.400	0.101	762.500	752.400	0.126
4	1013.000	1003.200	0.068	1017.000	1003.200	0.159
5	1232.000	1254.000	–2.639	1204.000	1254.000	–5.139
7.5	1404.000	1881.000	–26.031	1375.000	1881.000	–27.778
Gain		0.991			0.988	

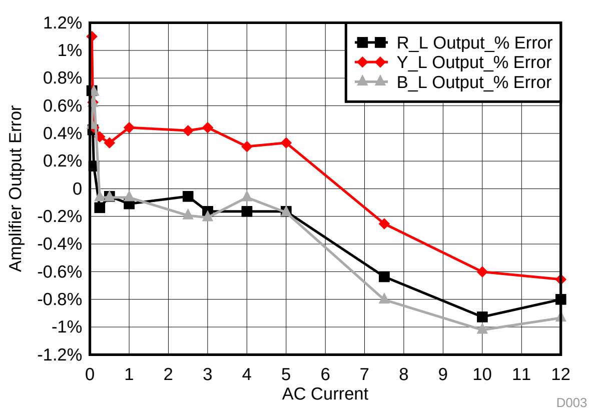

Figure 32. Current Versus Output Error for Low Gain Amplifier Using OPA4314

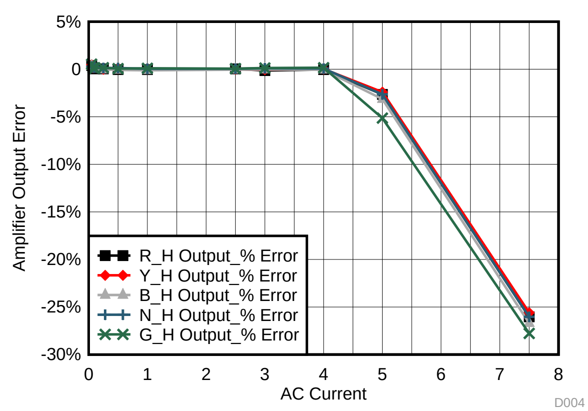

Figure 33. Current Versus Output Error for High Gain Amplifier Using OPA4314

8.2.3 LMV614 Interfaced to MCU

The following tables in this subsection show the measurements taken with the MCU's internal ADC (12 bit).

NOTE: **For choosing the gain in the firmware**: The "ERROR" cells with blue backgrounds indicate the values that must be considered for use with the protection function. The color indicates the gain to be chosen for the protection function, which is based on the input current.

Table 21. R-Phase Amplifier Outputs

CURRENT INPUT	R_L OUTPUT MEASURED	EXPECTED OUTPUT	R_L OUTPUT_% ERROR	R_H OUTPUT MEASURED	EXPECTED OUTPUT	R_H OUTPUT_% ERROR
0.100	9.045	8.800	–0.812	25.623	25.080	1.040
0.200	18.245	17.600	0.037	50.907	50.160	0.373
0.500	46.046	44.000	0.988	126.919	125.400	0.098
1.000	91.699	88.000	0.556	254.040	250.800	0.178
4.000	367.043	352.000	0.624	1014.098	1003.200	–0.026
5.000	458.268	440.000	0.507	1234.589	1254.000	–2.631
7.500	683.514	660.000	–0.062	1408.470	1881.000	–25.945
10.000	908.362	880.000	–0.390	1475.216	2508.000	–41.827
Gain		0.965			0.989	

Table 22. Y-Phase Amplifier Outputs

CURRENT INPUT	Y_L OUTPUT MEASURED	EXPECTED OUTPUT	Y_L OUTPUT_% ERROR	Y_H OUTPUT MEASURED	EXPECTED OUTPUT	Y_H OUTPUT_% ERROR
0.100	9.617	8.800	5.130	25.267	25.080	–0.062
0.200	18.529	17.600	1.277	51.017	50.160	0.895
0.500	46.012	44.000	0.599	126.696	125.400	0.225
1.000	91.765	88.000	0.316	253.710	250.800	0.351
4.000	366.798	352.000	0.244	1009.000	1003.200	–0.226
5.000	458.341	440.000	0.210	1231.269	1254.000	–2.598
7.500	683.347	660.000	–0.397	1406.551	1881.000	–25.821
10.000	907.829	880.000	–0.758	1474.080	2508.000	–41.695
Gain		0.962			0.992	

Table 23. B-Phase Amplifier Outputs

CURRENT INPUT	B_L OUTPUT MEASURED	EXPECTED OUTPUT	B_L OUTPUT_% ERROR	B_H OUTPUT	EXPECTED OUTPUT	B_H OUTPUT_% ERROR
0.100	9.258	8.800	0.996	25.739	25.080	0.371
0.200	18.344	17.600	0.058	51.228	50.160	–0.118
0.500	45.990	44.000	0.342	128.238	125.400	0.013
1.000	91.843	88.000	0.192	256.229	250.800	–0.083
4.000	368.212	352.000	0.421	1023.540	1003.200	–0.217
5.000	459.909	440.000	0.344	1240.610	1254.000	–3.244
7.500	685.834	660.000	–0.242	1411.200	1881.000	–26.627
10.000	911.198	880.000	–0.597	1477.260	2508.000	–42.394
Gain		0.96			0.978	

Table 24. N and G Amplifier Outputs

CURRENT INPUT	N_H OUTPUT MEASURED	EXPECTED OUTPUT	N_H OUTPUT_% ERROR	G_H OUTPUT MEASURED	EXPECTED OUTPUT	G_H OUTPUT_% ERROR
0.1	25.529	25.080	0.771	25.795	25.080	1.205
0.2	50.631	50.160	–0.070	51.078	50.160	0.201
0.2	50.631	50.160	–0.070	51.078	50.160	0.201
0.5	127.044	125.400	0.298	127.384	125.400	–0.043
1	254.012	250.800	0.268	255.013	250.800	0.053
4	1015.435	1003.200	0.207	1018.618	1003.200	–0.088
Gain		0.99			0.984	

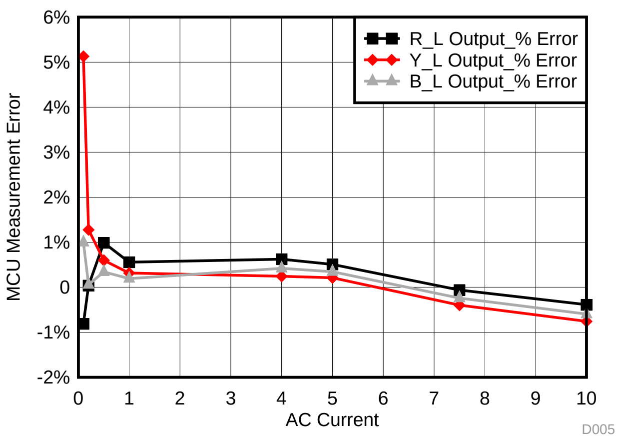

Figure 34. Low Gain Measurement Error With Internal 12-Bit ADC

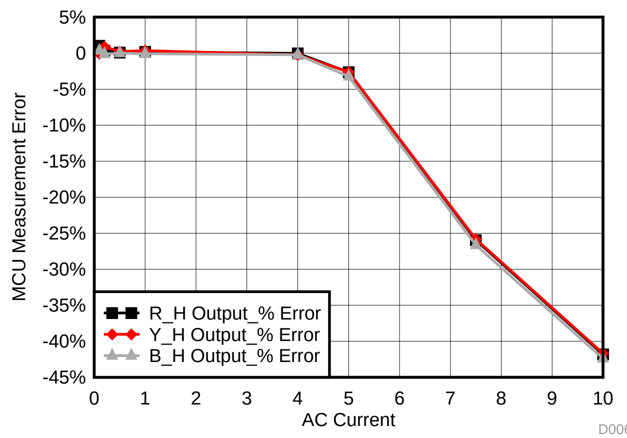

Figure 35. High Gain Measurement Error With Internal 12-Bit ADC

8.2.4 Amplifier Output Variation With Temperature

The following tables in this subsection show the voltage gain measurements taken with a multimeter at 50 Hz.

Table 25. R-Phase Measurement

CURRENT INPUT	R_L OUTPUT _EXPECTED OUTPUT	REF 25°C	70°C	%ERROR	85°C	%ERROR	–10°C	%ERROR
5	440.00	450.33	450.50	0.0378	450.6000	0.0600	450.2200	–0.0244
10	880.00	895.50	896.00	0.0558	896.2000	0.0782	895.8000	0.0335
CURRENT INPUT	**R_H OUTPUT _EXPECTED OUTPUT**	**REF 25°C**	**70°C**	**%ERROR**	**85°C**	**%ERROR**	**–10°C**	**%ERROR**
1	250.80	252.22	252.40	0.0714	252.3000	0.0317	252.3000	0.0317
4	1003.20	1008.80	1009.20	0.0397	1009.3000	0.0496	1008.5000	–0.0297

Table 26. Y-Phase Measurement

CURRENT INPUT	Y_L OUTPUT _EXPECTED OUTPUT	REF 25°C	70°C	%ERROR	85°C	%ERROR	–10°C	%ERROR
5	440.00	432.55	432.50	–0.0116	432.5510	0.0002	432.3000	–0.0578
10	880.00	870.70	870.88	0.0207	870.7100	0.0011	871.2000	0.0574
CURRENT INPUT	**Y_H OUTPUT _EXPECTED OUTPUT**	**REF 25°C**	**70°C**	**%ERROR**	**85°C**	**%ERROR**	**–10°C**	**%ERROR**
1	250.80	248.50	249.15	0.2616	249.0600	0.2254	249.2200	0.2897
4	1003.20	997.75	998.10	0.0351	998.2000	0.0451	998.1000	0.0351

Table 27. Temperature Sensor With 2° Uncertainty

TEMPERATURE °C	EXPECTED OUTPUT (V)	MEASURED (V)	ERROR °C
85	1.4830	1.5066	1.5914
70	1.6790	1.6923	0.7921
25	2.2980	2.2690	–1.2620
–10	2.7670	2.7251	–1.5143

The temperature measurement uncertainty is ±1°C.

The following Table 28, Table 29, and Table 30 show the DC offset measurements using a multimeter. The reference output voltage is in volts (V).

Table 28. R-Phase Measurement

LOW GAIN	DC REFERENCE	REF 25°C	70°C	%ERROR	85°C	%ERROR	–10°C	%ERROR
	1.65	1.6390	1.6400	–0.0610	1.6400	–0.0610	1.6394	–0.0244
HIGH GAIN	**DC REFERENCE**	**REF 25°C**	**70°C**	**%ERROR**	**85°C**	**%ERROR**	**–10°C**	**%ERROR**
	1.65	1.6366	1.6367	–0.0061	1.6370	–0.0244	1.6360	0.0367

Table 29. Y-Phase Measurement

LOW GAIN	DC REFERENCE	REF 25°C	70°C	%ERROR	85°C	%ERROR	–10°C	%ERROR
	1.65	1.6400	1.6410	-0.0610	1.6400	0.0000	1.6406	-0.0366
HIGH GAIN	**DC REFERENCE**	**REF 25°C**	**70°C**	**%ERROR**	**85°C**	**%ERROR**	**–10°C**	**%ERROR**
	1.65	1.6223	1.6200	0.1418	1.6300	-0.4746	1.6216	0.0431

Table 30. Buffer Output

NA	DC REFERENCE	REF 25°C	70°C	%ERROR	85°C	%ERROR	–10°C	%ERROR
	1.65	1.6450	1.6451	-0.0061	1.6452	-0.0122	1.6445	0.0304

8.3 Test Results Summary

Table 31. Tests Results

SERIAL NUMBER	PARAMETERS	RESULT
1	DC output with self-powered supply input	OK
2	DC output with auxiliary DC input	OK
3	MCU programming and functionality with DCO and 8 MHz	OK
4	Measurement of five current Inputs	OK
5	Op amp output accuracy with current transformer	< ±1%
6	Measurement accuracy including source errors and sensor errors	< ±3%
7	Temperature measurement	< ±2°C
8	Variation in amplifier output with respect to reference temperature −10°C to +85°C	< ±0.2%

9 Design Files

9.1 Schematics

To download the schematics for each board, see the design files at TIDA-00498.

9.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00498.

9.3 Layout Prints

To download the layer plots for each board, see the design files at TIDA-00498.

9.4 Altium Project

To download the Altium project files for each board, see the design files at TIDA-00498.

9.5 Gerber Files

To download the Gerber files for each board, see the design files at TIDA-00498.

9.6 Assembly Drawings

To download the assembly drawings for each board, see the design files at TIDA-00498.

10 Software Files

To download the software files for this reference design, see the software files at TIDA-00498.

11 References

1. Texas Instruments, *Self/Dual-Powered (Current or Auxiliary DC) Supply for MCCB/ACB/Protection Relay*, TIDA-00229 User's Guide (TIDU304)
2. Texas Instruments, *High Precision Analog Front End Amplifier and Peripherals for MCCB - Electronic Trip Unit*, TIDA-00128 User's Guide (TIDU224)
3. Texas Instruments, *MSP-EXP430FR5969 LaunchPad™ Development Kit*, MSP-EXP430FR5969 LaunchPad™ Development Kit User's Guide (SLAU535)

12 Terminology

ETU— Electronic trip unit

MCCB— Molded case circuit breaker

ACB— Air circuit breaker

MPCB — Motor protection circuit breaker

FSD— Flux shift device

CT— Current transformer

In— Nominal current

13 About the Author

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