TI Designs: TIDA-01012

Wireless IoT, Bluetooth® Low Energy, 4½ Digit, 100-kHz True RMS Digital Multimeter Reference Design

TEXAS INSTRUMENTS

Description

The TIDA-01012 design features a low-power solution for a *Bluetooth®* low energy (BLE) enabled IoT Wireless Digital Multimeter, featuring software based, true RMS calculations, automatic Bluetooth pairing using NFC, and automatic wake-up featuring using CapTIvate™ capacitive touch technology.

Resources

TIDA-01012	Design Folder
TIDC-01012	Tool Folder
CC2640	Product Folder
ADS8885	Product Folder
REF3325	Product Folder
THS4531	Product Folder
OPA333	Product Folder
OPA313	Product Folder
TS5A3166	Product Folder
TS5A3359	Product Folder
TS3A24159	Product Folder
MSP430FR2532	Product Folder
RF430CL330H	Product Folder
bq24232	Product Folder
bq27426	Product Folder
TPS62740	Product Folder
TPS782	Product Folder
TPS3422	Product Folder
LSF0102	Product Folder
LSF02024	Product Folder
TPD1E10B06	Product Folder

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Features

- Basic DMM Measurement Modes:
  - Voltage: 50 V, 5 V, 500 mV, and 50 mV
  - Current: 50 mA and 500 µA
- 18-Bit, 400-kSPS, SAR ADC Enabling:
  - 50,000 Display Count Resolution
  - 1-µV / 10-nA Resolution
  - 0.05% DC Accuracy, 3% AC Accuracy at 100 kHz
- Wireless MCU Enabling BLE for IoT Wireless Communication
- Firmware-Based True-RMS Measurement
- Automatic Wake-Up Enabled by CapTIvate Capacitive Touch Technology
- BLE Mobile Application Pairing Enabled by NFC Dynamic Interface
- 100+ Hours on a AAA Li-Ion Battery

Applications

- Field Instrumentation
- Battery Management
- Data Acquisition (DAQ)
- Digital Multimeter (DMM)
- Internet of Things (IoT)
- Lab Instrumentation
- Sensors

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1 System Description

Many products are now becoming connected through the Internet of Things (IoT) environment, including test equipment such as digital multimeters (DMM). Enabled by Texas Instruments' SimpleLink™ ultra-low-power wireless microcontroller (MCU) platform, the TIDA-01012 reference design demonstrates a connected, 4½ digit, 100-kHz true RMS, DMM with Bluetooth low energy (BLE) connectivity, NFC Bluetooth pairing, and an automatic wake-up feature enabled by TI's CapTIvate technology.

As shown in Figure 1, the TIDA-01012 reference design is comprised of numerous subsystems including:
- A wireless MCU for system control, Bluetooth low energy communication, and data processing
- An analog front end (AFE) for signal conditioning for voltage and current measurements
- A dynamic NFC interface
- An ultra-low-power MSP430™ MCU with CapTIvate
- System power distribution
- Battery management and monitoring

The basic subsystems and capabilities defined in the TIDA-01012 design can also apply to other IoT applications such as field instrumentation, data acquisition, lab instrumentation, and remote sensing equipment.

This design guide addresses component selection, design theory, and test results of the TIDA-01012 reference design. The following subsections describe the various blocks within this reference design system and highlight the characteristics most critical in implementing the corresponding functions.

1.1 Features

Because power consumption is always a concern, incorporating a low-power MCU that is capable of efficiently processing the RMS calculations as well as transmitting the data is extremely important. Also, the wireless protocol required for the end-equipment system is an important consideration for the selection of the radio device. Finally, ultra-low-power converters are used to maintain high efficiency in standby mode.

Using TI's CC26xx SimpleLink ultra-low-power wireless MCU platform, low-power technology combined with an integrated radio and MCU enables maximum battery life of the end equipment. Furthermore, the CC26xx family covers multiple standards, including Bluetooth low energy stack support.

The primary DMM functions of the TIDA-01012 reference design are briefly described in the following subsections.

1.1.1 Basic DMM Measurement Modes

The TIDA-01012 reference design implements basic DC voltage and current measurement modes as well as true RMS AC voltage and current measurement modes inherent in most handheld DMMs in the market today. These specific measurement functions are sufficient to demonstrate the capabilities of this solution, although other basic measurement modes (such as resistance, capacitance, frequency, and so on) can be supported with minimal power consumption by using the features and capabilities of the CC2640 Wireless MCU. For demonstration purposes, four voltage ranges (50 V, 5 V, 500 mV, and 50 mV) and two current ranges (50 mA and 500 µA) are implemented in this reference design.

1.1.2 Firmware-Based True RMS Calculations

The TIDA-01012 reference design also features a firmware based true RMS measurement capability that also potentially reduces system costs associated with hardware based true RMS component solutions.

1.1.3 Battery Charging and Monitoring

Battery charging and monitoring features are supported with the TIDA-01012 reference design. Battery charging is accomplished through a micro-USB port. The battery monitoring feature reports the battery state-of-charge, as well as cell voltage of the lithium ion battery source. This feature provides greater detail to the end user as to remaining battery life compared to the simple low battery indicator used in most DMM products today. Furthermore, this capability is enabled by TI's bq27426, which provides a serial interface to communicate with the CC2640 Low-Power Wireless MCU.

1.1.4 Wake-Up Feature Using CapTIvate

For low-power applications, it is important to incorporate a power management scheme that provides multiple system power modes and operating states. For example, when the DMM is not being used to take measurements, some system components can be disabled to save energy to prolong battery life. In the case of the TIDA-01012, this ultra-low-power-down state occurs when there is no active Bluetooth low energy connection ongoing and the device has not been handled for a predetermined amount of time. When both of these conditions are met, the system enters a very low-power state whereby Bluetooth low energy communication and all other non-essential subsystems are shut down, reducing the power consumption to a few microamps.

The TIDA-01012 demonstrates an innovative solution to automatically wake-up the system from this low-power state. This feature is enabled by TI's capacitive touch CapTIvate technology implemented on the MSP430FR2532 MCU. This MSP430 allows for ultra-low-power consumption while actively monitoring for any device-handling condition. If detected while in the power-down state, the CapTIvate feature forces the TIDA-01012 back into the active mode.

1.1.5 NFC Enabled Bluetooth Low Energy Pairing

Pairing with a Bluetooth low energy device usually requires some type of interaction with the user to confirm the identity of the user or the device being paired. The TIDA-01012 features automatic Bluetooth low energy pairing enabled by the RF430CL330H Dynamic NFC Interface, which simplifies the pairing process making it easier for the user to go through a one-step pairing process.

In addition, this NFC pairing solution features battery-less operation, whereby the energy required by this subsystem is harvested from the radiated field that enables the communication with the pairing device.

> **NOTE:** The host environment that was used to support the TIDA-01012 reference design does not support the NFC Bluetooth low energy pairing feature which requires an NFC enabled host device such a smartphone or tablet.

1.1.6 Mobile App for Reporting and Calibration

The TIDA-01012 enables wireless communication of DMM measurement data and calibration constants using the CC2640 Bluetooth low energy wireless MCU. Although the TIDA-01012 hardware supports the use of any Bluetooth low energy enabled device such as smartphones and tables, the design was tested and characterized through a PC LabVIEW™ environment using a Bluetooth low energy USB dongle with a proprietary serial port communication API.

1.2 Key System Specifications

Table 1. Key System Specifications

PARAMETER		SPECIFICATIONS
Voltage	Input ranges	50 mV, 500 mV, 5 V, 50 V
	Resolution	50,000 display counts
		1 µV, 10 µV, 100 µV, 1 mV
	DC accuracy	0.05% + 5 LSD
	AC accuracy (up to 100 kHz)	3% + 10 LSD
	Input impedance	10 MΩ / 100 pF
Current	Input ranges	500 µA / 50 mA
	Resolution	50,000 display counts
		10 nA / 1 µA
	DC accuracy	0.10% + 5 LSD
	AC accuracy (up to 100 kHz)	3% + 10 LSD
	Burden voltage	50 mV
Current consumption	Active mode	5.2 mA at 3.7-V input
	Low power mode	25 µA at 3.7-V input
Battery life	Continuous operating hours	> 100 hours with 600-mAh battery

2 System Overview

2.1 Block Diagram
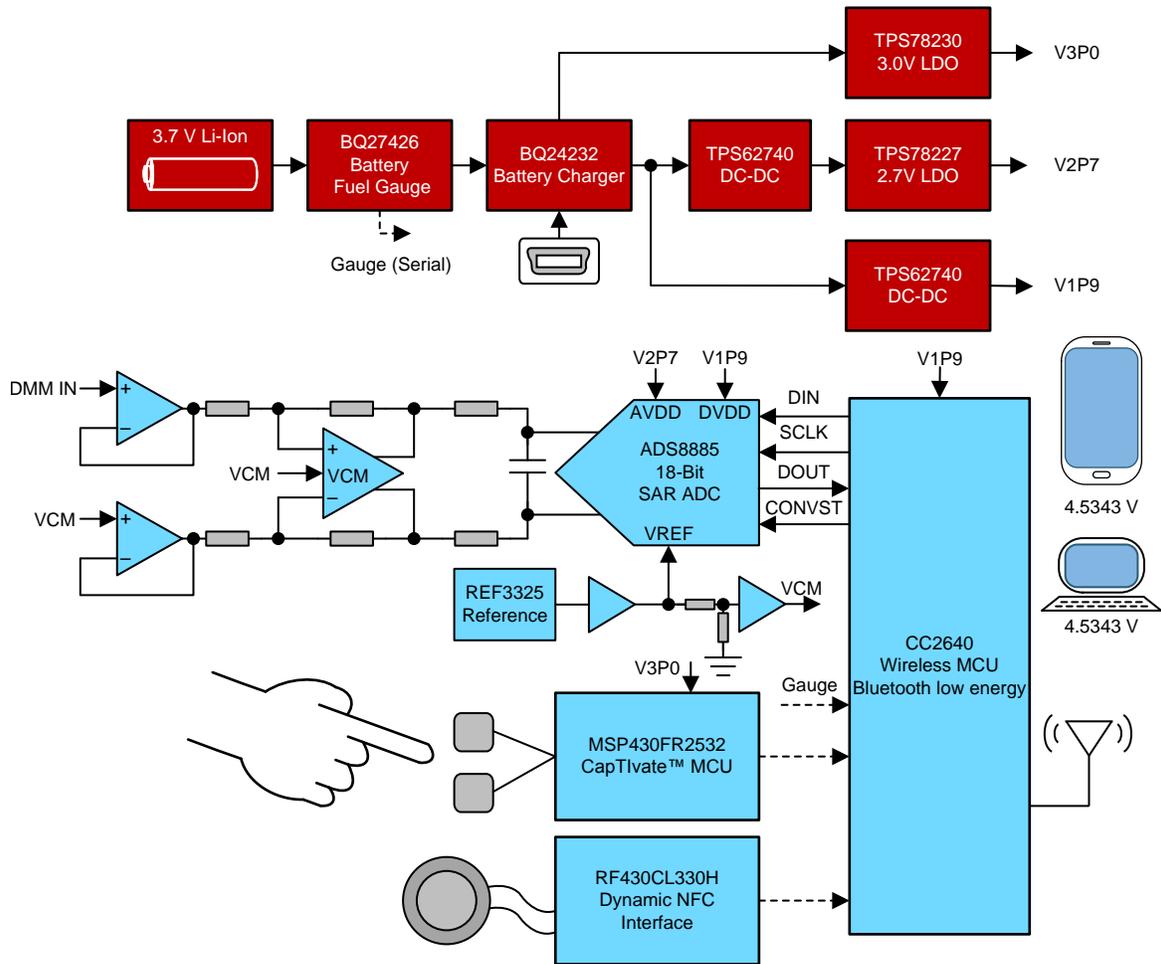
Figure 1. TIDA-01012 Block Diagram

Wireless IoT, Bluetooth® Low Energy, 4½ Digit, 100-kHz True RMS Digital Multimeter Reference Design

2.2 Highlighted Devices

The TIDA-01012 reference design features the following devices:

- CC2640 (Section 2.2.1): Low-Power Wireless MCU for Bluetooth low energy
- ADS8885 (Section 2.2.2): 18-Bit, 400-kSPS, Low-Power, Truly-Differential, Successive-Approximation Registers (SAR) Analog-to-Digital Converter (ADC)
- RF430CL330H (Section 2.2.3): Dynamic Dual Interface NFC Transponder
- MSP430FR2532 (Section 2.2.4): Low Power MCU With CapTIvate Touch Technology
- bq24232 (Section 2.2.5): 0.5-A Li+ Charger With Dynamic Power Management
- bq27426 (Section 2.2.6): Single-Cell Battery Gauge With Pre-Programmed Chemistry Profile
- TPS62740 (Section 2.2.7): Low-Power 300-mA DC-DC Buck Converter
- TPS782 (Section 2.2.8): Low-Power 150-mA LDO Linear Regulator
- TPS3422 (Section 2.2.9): Push Button Controller With Configurable Delay and Reset
- THS4531 (Section 2.2.10): Low-Power, Rail-to-Rail I/O, Fully Differential Amplifier
- OPA333 (Section 2.2.11): Low-Power, Precision, Low-Noise, Zero-Drift CMOS Op Amp
- OPA313 (Section 2.2.12): 1-MHz, Low-Power, Low-Noise, Rail-to-Rail I/O Op Amp
- REF3325 (Section 2.2.13): 30-ppm/C Drift, Low-Power, Voltage Reference
- TS5A3359 (Section 2.2.14): SP3T Analog Switch, 3:1 MUX
- TS5A3166 (Section 2.2.15): SPST Analog Switch
- TS3A24159 (Section 2.2.16): 2-Channel, SPDT Bidirectional Analog Switch
- TPD1E10B06 (Section 2.2.17): TVS Diode in 0402 Package for ESD Protection
- LSF0102 (Section 2.2.18): 2-Bit Bidirectional Multi-Voltage Level Translator
- LSF0204 (Section 2.2.19): 4-Bit Bidirectional Multi-Voltage Level Translator

For more information on each of these devices, see their respective product folders at TI.com.

2.2.1   CC2640

The CC2640 device is a wireless MCU targeting Bluetooth low energy applications. The device is a member of the CC26xx family of cost-effective, ultra-low-power, 2.4-GHz RF devices. Very low-active RF and MCU current and low-power mode current consumption provide excellent battery lifetime and allow for operation on small coin cell batteries and in energy-harvesting applications.

The CC2640 device contains a 32-bit ARM® Cortex®-M3 processor that runs at 48 MHz as the main processor and a rich peripheral feature set that includes a unique ultra-low-power sensor controller. This sensor controller is ideal for interfacing external sensors and for collecting analog and digital data autonomously while the rest of the system is in sleep mode. Thus, the CC2640 device is ideal for a wide range of applications where long battery lifetime, small form factor, and ease of use is important.

The Bluetooth low energy controller is embedded into ROM and runs partly on an ARM Cortex-M0 processor. This architecture improves overall system performance and power consumption and frees up flash memory for the application. The Bluetooth low energy software stack is available free of charge from http://www.ti.com/ble-stack.
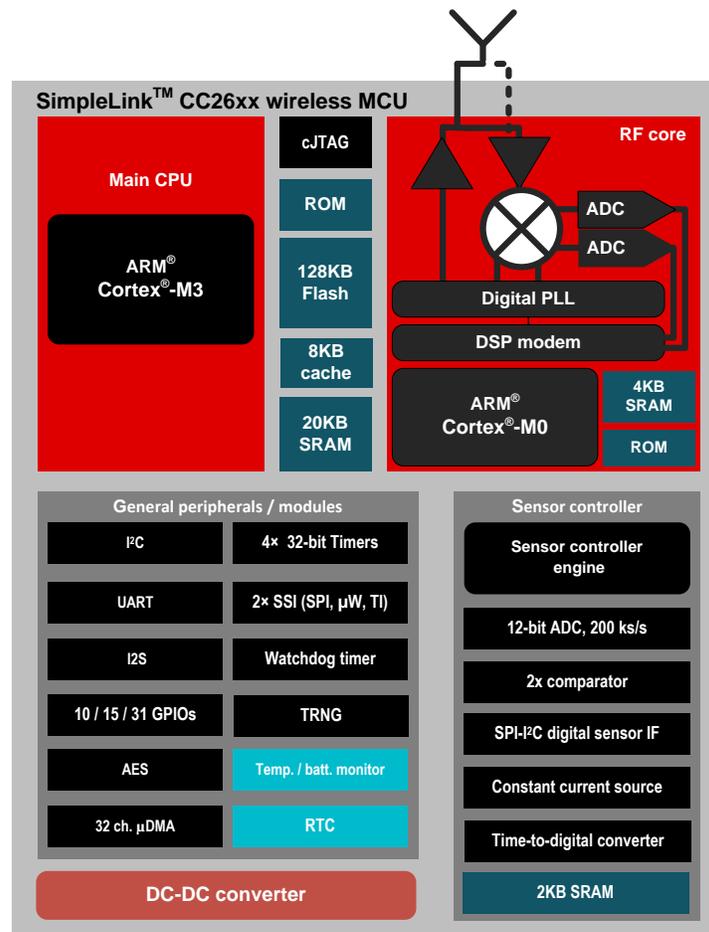
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Figure 2. CC2640 Functional Block Diagram

2.2.1.1 Relevant Features

The CC2640 makes possible some of the main features of this design; its low power operation enables long battery life time, while processing the 100 kHz firmware based true RMS calculations. The Bluetooth low energy controller embedded into ROM enables wireless communications with mobile apps in phones, laptops and other mobile devices.

2.2.1.2 Alternatives

Selecting a low-power, wireless MCU like the CC2640 helps to achieve low power consumption, while still achieving the processing power needed for 100-kHz firmware based, true RMS calculations. The comparison in Table 2 shows additional low-power and wireless MCU options from TI's portfolio, which might be considered if a different wireless protocol is needed.

Table 2. Wireless MCU Comparison

WIRELESS MCU	RF PROTOCOLS
CC2640	Bluetooth low energy
CC2650	Bluetooth low energy, ZigBee® and 6LoWPAN, and ZigBee RF4CE
CC2630	2.4-GHz IEEE 802.15.4-based RF protocols: 6LoWPAN, ZigBee
CC2620	ZigBee RF4CE
CC1310	Sub-1 GHz

Find full device features and specifications at the CC2640 Product Folder.

2.2.2   ADS8885

The ADS8885 is an 18-bit, 400-kSPS, true-differential input, ADC. The device operates with a 2.5- to 5-V external reference, offering a wide selection of signal ranges without additional input signal scaling. The reference voltage setting is independent of, and can exceed, the analog supply voltage (AVDD).

The device offers a serial peripheral interface (SPI)-compatible serial interface that also supports daisy-chain operation for cascading multiple devices. An optional busy-indicator bit makes synchronizing with the digital host easy.

The device supports unipolar, true-differential analog input signals with a differential input swing of –VREF to +VREF. This true-differential analog input structure allows for a common-mode voltage of any value in the range of 0 V to +VREF (when both inputs are within the operating input range of –0.1 V to VREF + 0.1 V).

Device operation is optimized for very low-power operation. Power consumption directly scales with speed. This feature makes the ADS8885 excellent for lower-speed applications.
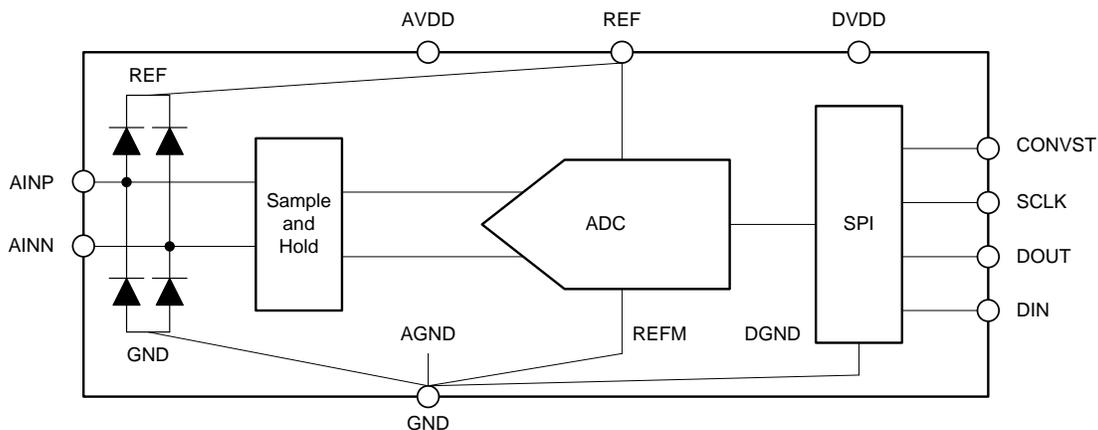
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Figure 3. ADS8885 Functional Block Diagram

2.2.2.1   Alternatives

Selecting a low-power SAR ADC like the ADS8885 helps to achieve a low-power design, while still achieving the resolution and speed needed to meet design goals. The comparison in Table 3 shows additional 18-bit low-power, high-throughput SAR ADCs.

Table 3. Comparison of SAR ADCs

DEVICE	SAMPLING RATE	AVDD RANGE	PD at 200 kSPS	PD at POWER DOWN
ADS8885	400 kSPS	2.7 to 3.6 V	1.30 mW	0.15 μW
ADS9110	2 MSPS	1.8 V	1.50 mW	1.80 μW
ADS8881	1 MSPS	2.7 to 3.6 V	1.10 mW	0.15 μW
ADS8883	680 kSPS	2.7 to 3.6 V	1.20 mW	0.15 μW
ADS8887	100 kSPS	2.7 to 3.6 V	1.40 mW	0.15 μW

For a more comprehensive list of TI's SAR ADC portfolio and companion devices, see the *SAR ADC Companion Devices Selection Guide* (SLYT653).

Find full device features and specifications at the ADS8885 Product Folder.

2.2.3 RF430CL330H

The Dynamic NFC Interface Transponder RF430CL330H is an NFC Tag Type 4 device that combines a wireless NFC interface and a wired SPI or inter-integrated circuit (I^{2}C) interface to connect the device to a host.

The NDEF message in the SRAM can be written and read from the integrated SPI or I^{2}C serial communication interface and can also be accessed and updated wirelessly through the integrated ISO14443B-compliant RF interface that supports up to 848 kbps.

This operation allows NFC connection handover for an alternative carrier like Bluetooth, Bluetooth low energy, and Wi-Fi® as an easy and intuitive pairing process or authentication process with only a tap. As a general NFC interface, the RF430CL330H enables end equipment to communicate with the fast-growing infrastructure of NFC-enabled smart phones, tablets, and notebooks.
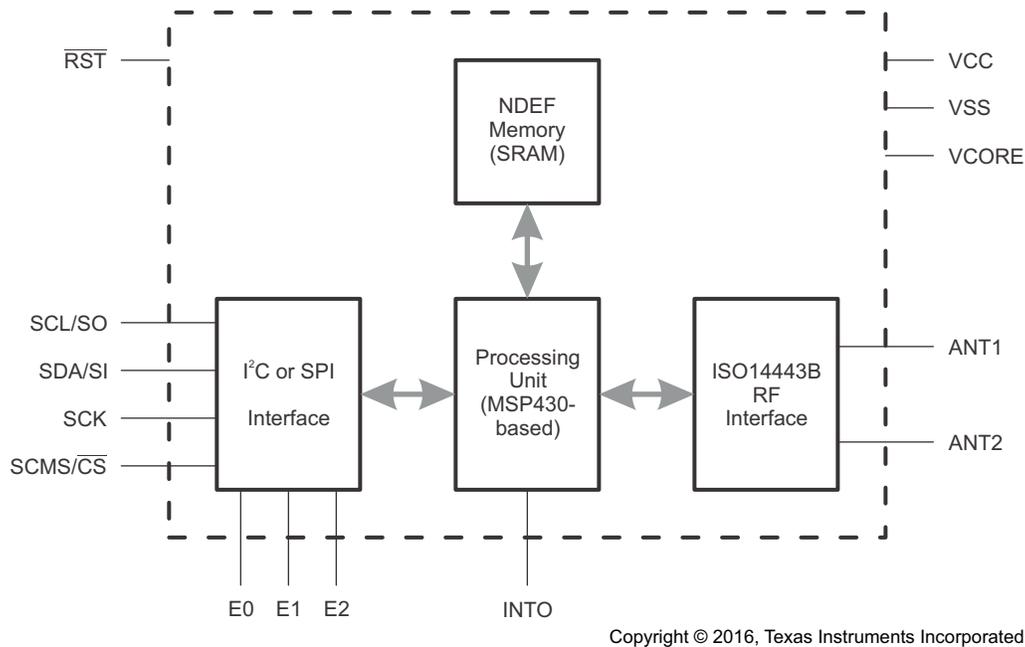
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Figure 4. RF430CL330H Functional Block Diagram

2.2.3.1 Alternatives

Having a device remain battery-less until the user powers it with an external RF field contributes to 100+ hours of battery life of the design. Allowing the NFC and Bluetooth low energy enabled device to pair to the onboard Bluetooth low energy MCU achieves an intuitive and simplified pairing solution. Table 4 shows additional NFC transponders with various features for different applications. The RF430CL330H was chosen for this TI Design for its battery-less operation, simplified over the air data transfer, and price.

Table 4. NFC Device Alternatives

DEVICE	FEATURES	STANDBY POWER (LPM3 – µA)	MAX DATA RATE (kbps)	RF STANDARD SUPPORT
RF430CL330H Dynamic NFC Transponder	Battery-less operation (RF field powered)	10	848	NFC: ISO/IEC 14443B, NFC Tag Type 4B
RF430CL331H Dynamic NFC Transponder	Battery-less operation (RF field powered), relatively unlimited file transfer	10	848	NFC: ISO/IEC 14443B, NFC Tag Type 4B

Find full device features and specifications at the RF430CL330H Product Folder.

2.2.4 MSP430FR2532

The MSP430FR263x and MSP430FR253x are FRAM-based ultra-low-power MSP MCUs that feature CapTIvate touch technology for buttons, sliders, wheels (BSW), and proximity applications. CapTIvate technology provides the highest resolution capacitive-touch solution in the market with high reliability and noise immunity at the lowest power. CapTIvate technology supports concurrent self-capacitance and mutual-capacitance electrodes on the same design for maximum flexibility. Using the CapTIvate Design Center, engineers can quickly develop BSW applications with an easy-to-use GUI.

The TI MSP family of low-power MCUs consists of several devices that feature different sets of peripherals targeted for various applications. The architecture, combined with extensive low-power modes, is optimized to achieve extended battery life in portable measurement applications. The MCU features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows the MCU to wake up from low-power modes to active mode typically in less than 10 μs.

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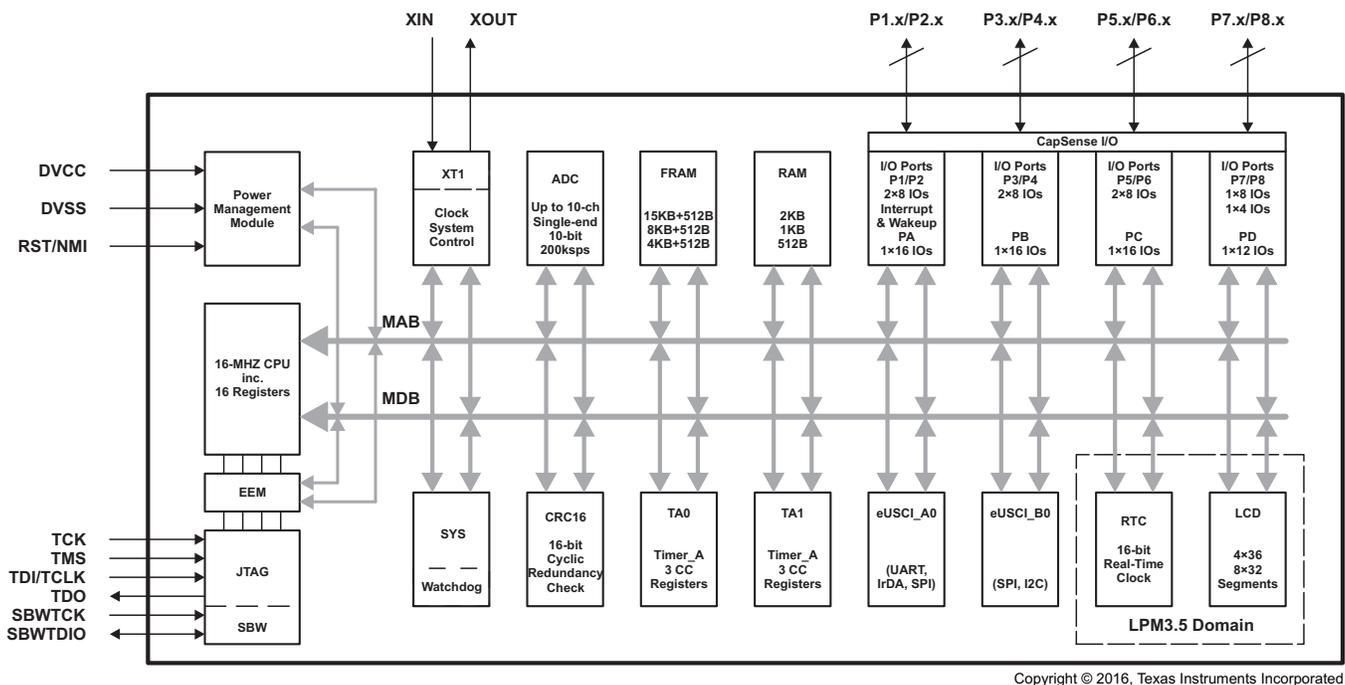
Figure 5. MSP430FR2532 Functional Block Diagram

2.2.4.1 Relevant Features

This part enables the use of CapTIvate, TI's innovative capacitive-touch technology, enabling the power-down and wake-up feature for this TI Design while maintaining the typical low-power consumption of the MSP430 family.

2.2.4.2 Alternatives

Table 5. CapTIvate Device Alternatives

DEVICE	PROGRAM FRAM + INFORMATION FRAM (bytes)	RAM (bytes)	GPIO
MSP430FR2532	8192 + 512	1024	15
MSP430FR2533	15360 + 512	2048	19
MSP430FR2632	8192 + 512	2048	15
MSP430FR2633	15360 + 512	4096	19

Find full device features and specifications at the MSP430FR2532 Product Folder.

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2.2.5   bq24232

The bq24232 devices are integrated Li-Ion linear chargers and system power-path management devices targeted at space-limited portable applications. The device powers the system while simultaneously and independently charging the battery. This feature reduces the number of charge and discharge cycles on the battery, allows for proper charge termination, and enables the system to run with a defective or absent battery pack. It also allows instant system turnon even with a totally discharged battery. The input power source for charging the battery and running the system can be an AC adapter or a USB port. The devices feature dynamic power-path management (DPPM), which shares the source current between the system and battery charging and automatically reduces the charging current if the system load increases. When charging from a USB port, the input dynamic power management (VIN-DPM) circuit reduces the input current limit if the input voltage falls below a threshold, preventing the USB port from crashing. The power-path architecture also permits the battery to supplement the system current requirements when the adapter cannot deliver the peak system currents.
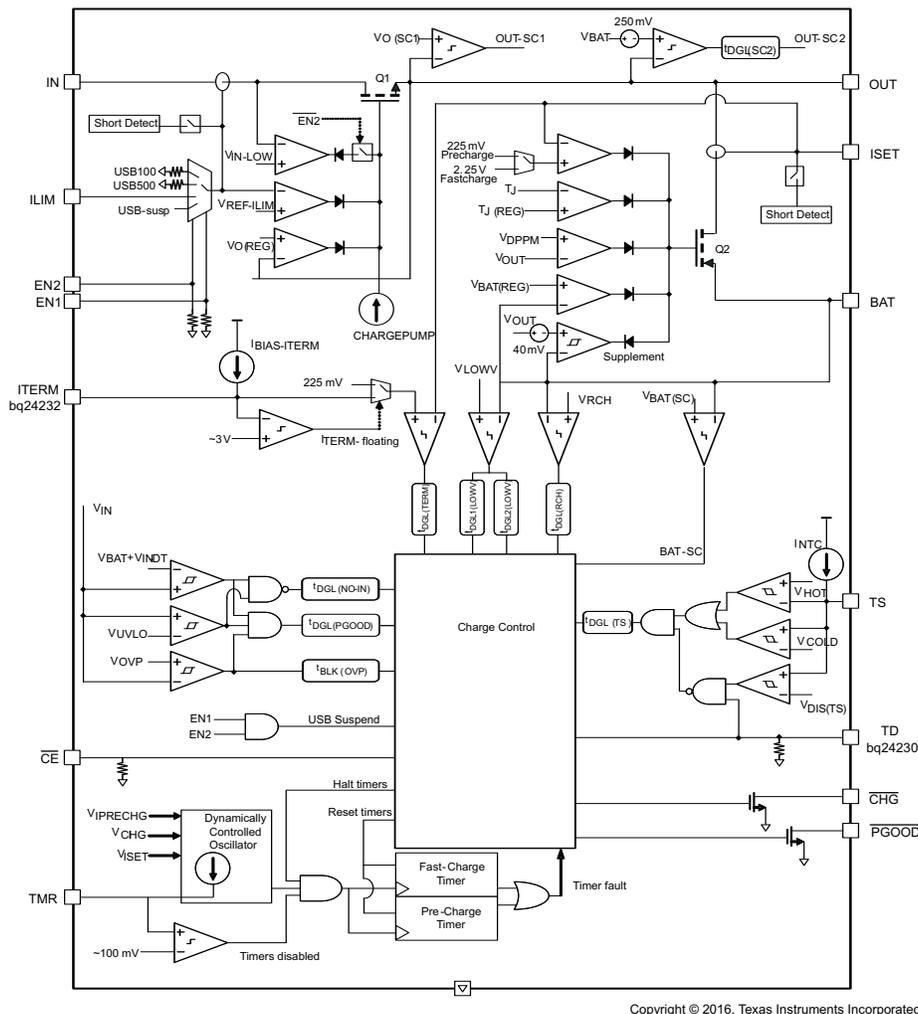
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Figure 6. bq24232 Functional Block Diagram

2.2.5.1   Relevant Features

The bq24232 battery charger enables easy configuration as it can be set using external resistors. This device also features power-path chargers used as the input source to power the system and charge the battery. If the input source is removed, the battery pack is automatically connected to the system.

2.2.5.2   Alternatives

Table 6. Battery Charger Device Alternatives

DEVICE	BATTERY CHARGE VOLTAGE (V)	CHARGE CURRENT (mA) [max]
bq24232	4.20	500
bq24232H	4.35	500

Find full device features and specifications at the bq24232 Product Folder.

2.2.6   bq27426

The bq27426 fuel gauge accurately predicts the battery capacity and other operational characteristics of a single Li-based rechargeable cell. It can be interrogated by a system processor to provide cell information such as state of charge (SoC).
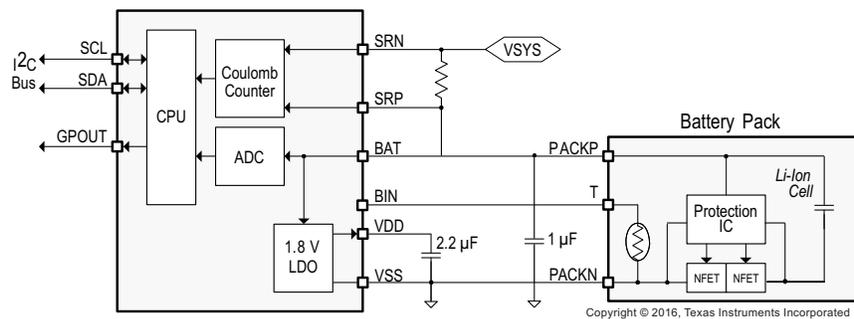
Figure 7. bq27426 Functional Block Diagram

2.2.6.1   Relevant Features

The bq27426 battery gauge device features, the option of three selectable pre-programmed profiles for 4.20-V, 4.35-V, and 4.40-V cells. It also reports the remaining capacity and state-of-charge (SOC) with smoothing filter.

Find full device features and specifications at the bq27426 Product Folder.

2.2.7 TPS62740

The TPS6274x is the first step-down converter with an ultra-low quiescent current consumption (360 nA typ.) and features TI's DCS-Control™ topology to regulate the output voltage. The device extends high efficiency operation to output currents down to a few microamps.
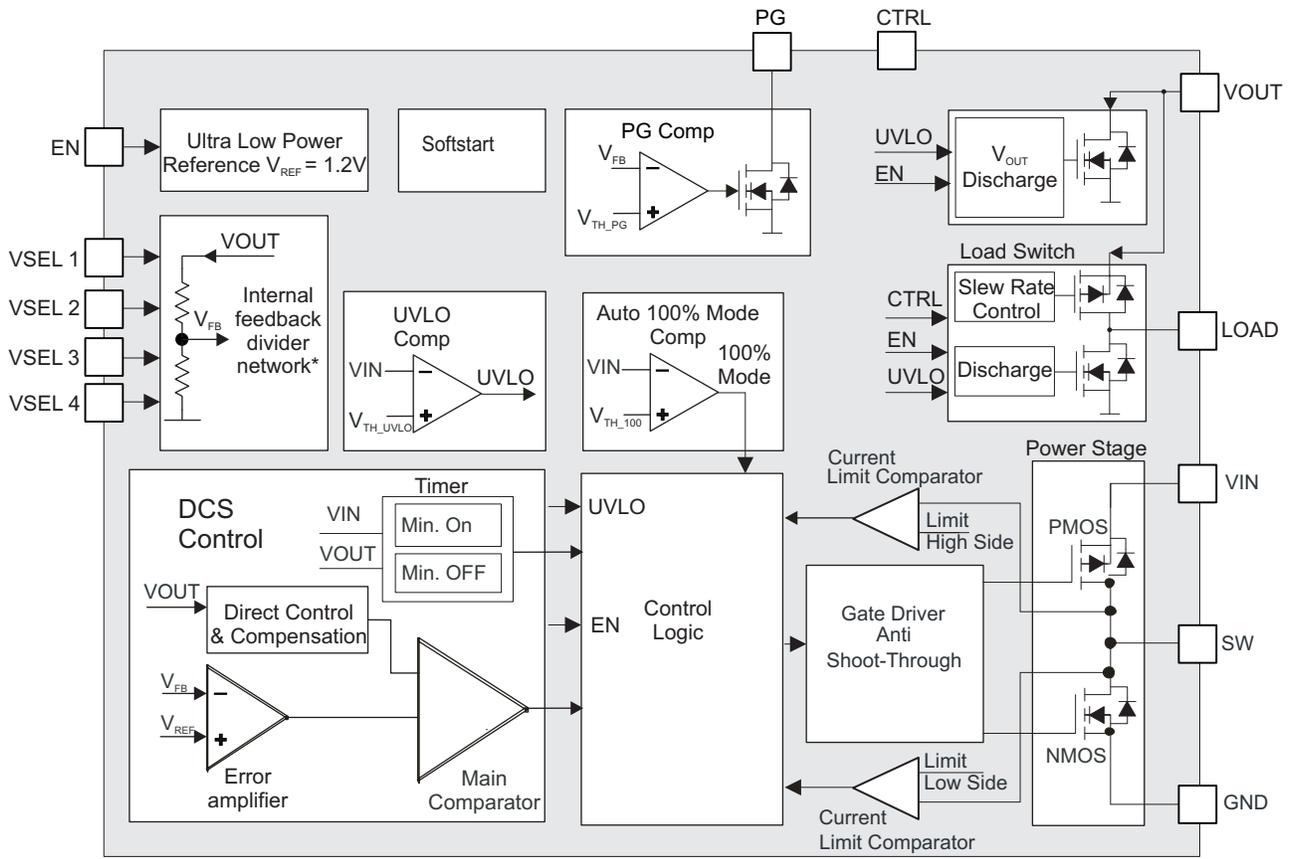
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Figure 8. TPS62740 Functional Block Diagram

2.2.7.1 Relevant Features

DC-DC converters are usually avoided in applications with low loads. However, the TPS62740 features extended light load efficiency, having an efficiency of up to 90% at loads of 10 µA. This device also features an easy way to adjust the output voltage, set by four selection pins and ranging from 1.8 to 3.3 V in increments of 100 mV.

2.2.7.2 Alternatives

Table 7. DC-DC Converter Device Alternatives

DEVICE	OUTPUT CURRENT (mA)	V_{OUT} RANGE (V)
TPS62740	300	1.8 to 3.3
TPS62742	400	1.8 to 3.3
TPS62743	300	1.2 to 3.3

Find full device features and specifications at the TPS62740 Product Folder.

2.2.8 TPS782

The TPS782 family of LDOs is designed specifically for battery-powered applications where ultra-low quiescent current is a critical parameter. The TPS782 family is compatible with the TI MSP430 and other similar products such as the CC2640. The enable pin (EN) is compatible with standard CMOS logic. This LDO family is stable with any output capacitor greater than 1.0 μF.
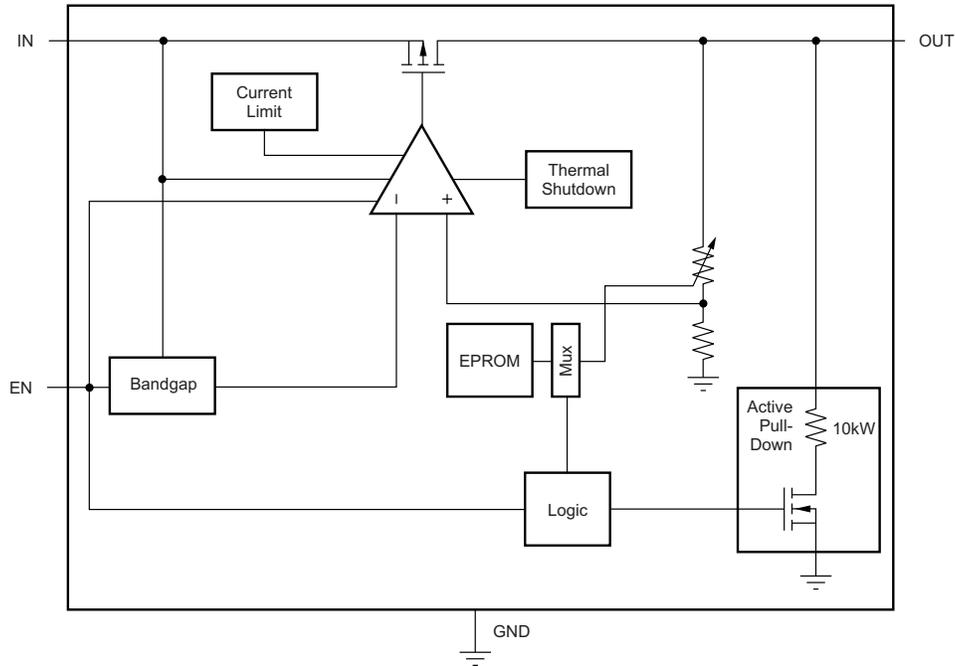
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Figure 9. TPS782xx Functional Block Diagram

Find full device features and specifications at the TPS782 Product Folder.

2.2.9 TPS3422

The TPS342x are a family of push-button reset devices with an extended setup period that prevents resets from occurring as a result of short-duration switch closures. Table 8 shows a comparison of the devices in the TPS324x family. The TPS3422 is a single-channel device with an output that asserts when the PB1 input is held low for the push-button timer duration, and deasserts after the reset time-out duration.

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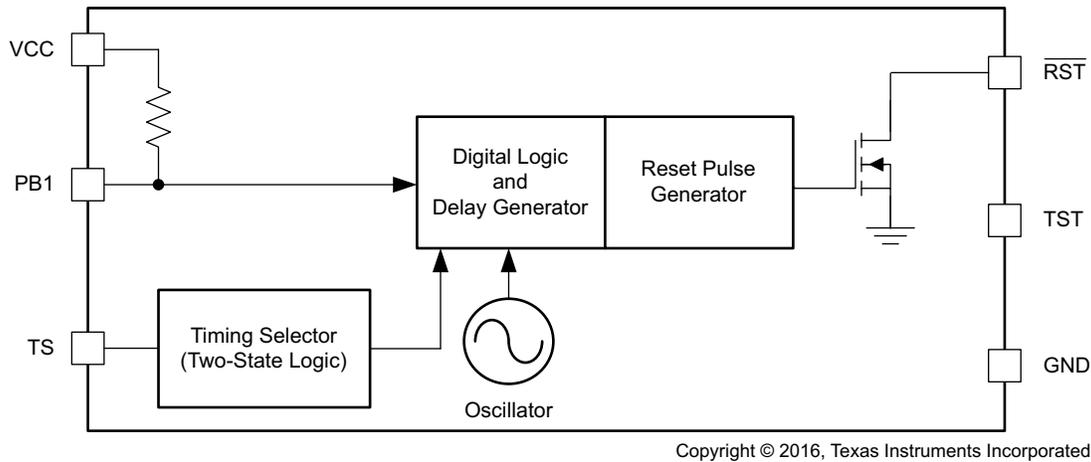
Figure 10. TPS3422 Functional Block Diagram

2.2.9.1 Alternatives

Table 8. Reset Device Alternatives

DEVICE	CHANNELS	INPUT STAGE	RESET BEHAVIOR
TPS3420	2	NMOS based threshold	Input (PBx) dependent
TPS3421	2	External pullup to VCC	Fixed pulse
TPS3422	1	Internal pullup	Fixed pulse

Find full device features and specifications at the TPS3422 Product Folder.

2.2.10 THS4531

The THS4531 is a low-power, fully-differential op amp with input common-mode range below the negative rail and rail-to-rail output. The device is designed for low-power data acquisition systems and high density applications where power consumption and dissipation are critical.

The device features accurate output common-mode control that allows for dc coupling when driving ADCs. This control, coupled with the input common-mode range below the negative rail and rail-to-rail output, allows for easy interface from single-ended ground-referenced signal sources to SARs, and delta-sigma ($\Delta\Sigma$) ADCs using only single-supply 2.5- to 5-V power. The THS4531 is also a valuable tool for general-purpose, low-power differential signal conditioning applications.
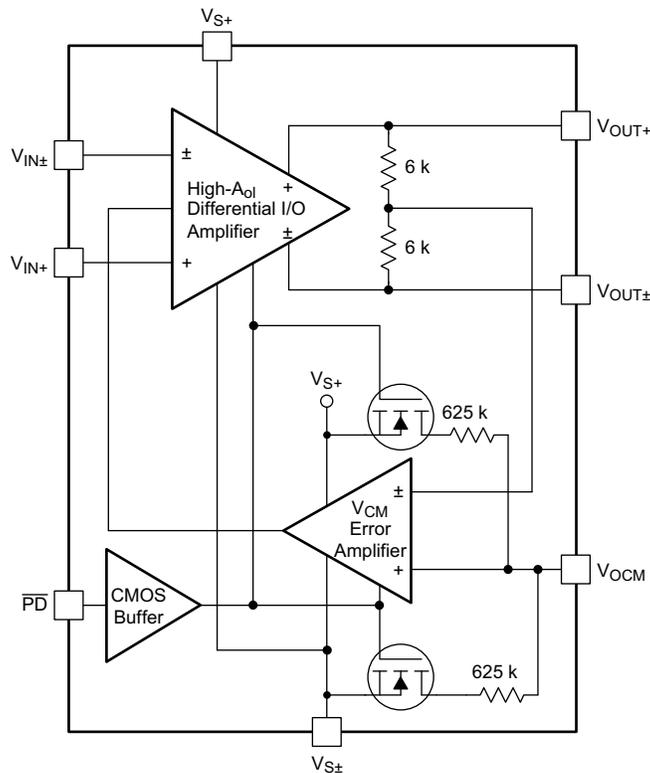
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Figure 11. THS4531 Functional Block Diagram

Find full device features and specifications at the THS4531 Product Folder.

2.2.11 OPA333

The OPAx333 is a family of zero-drift, low-power, rail-to-rail input and output operational amplifiers. These devices operate from 1.8 to 5.5 V, are unity-gain stable, and are suitable for a wide range of general-purpose applications. The zero-drift architecture provides ultra-low offset voltage and near-zero offset voltage drift.

The OPA333 and OPA2333 are unity-gain stable and free from unexpected output phase reversal. These devices use a proprietary auto-calibration technique to provide low-offset voltage and very low drift over time and temperature.
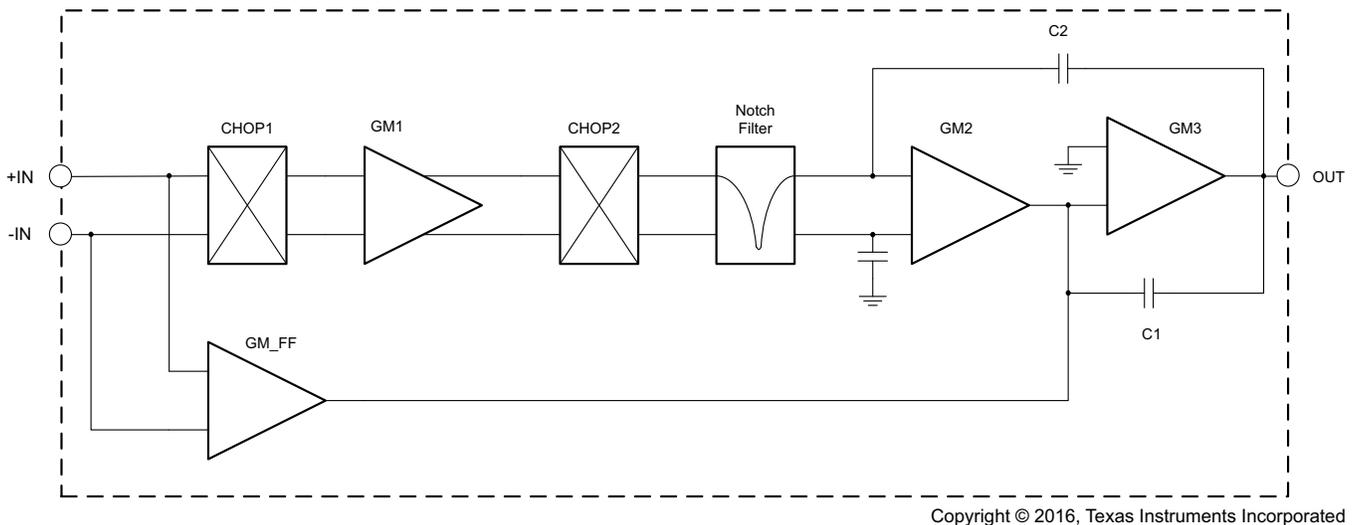
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Figure 12. OPAx333 Functional Block Diagram

Find full device features and specifications at the OPA333 Product Folder.

2.2.12 OPA313

The OPAx313 is a family of low-power, rail-to-rail input and output operational amplifiers specifically designed for portable applications. These devices operate from 1.8 to 5.5 V, are unity-gain stable, and are suitable for a wide range of general-purpose applications. The class AB output stage is capable of driving ≤ 10-kΩ loads connected to any point between V+ and ground. The input common-mode voltage range includes both rails and allows the OPAx313 family to be used in virtually any single-supply application. Rail-to-rail input and output swing significantly increases dynamic range, especially in low-supply applications, and makes them ideal for driving sampling ADCs.

The OPAx313 features 1-MHz bandwidth and 0.5-V/μs slew rate with only 50-μA supply current per channel, providing good AC performance at very low-power consumption. DC applications are also well served with a low-input noise voltage of 25 nV/√Hz at 1 kHz, low-input bias current (0.2 pA), and an input offset voltage of 0.5 mV (typical). The typical offset voltage drift is 2 μV/°C; over the full temperature range the input offset voltage changes only 200 μV (0.5 to 0.7 mV).
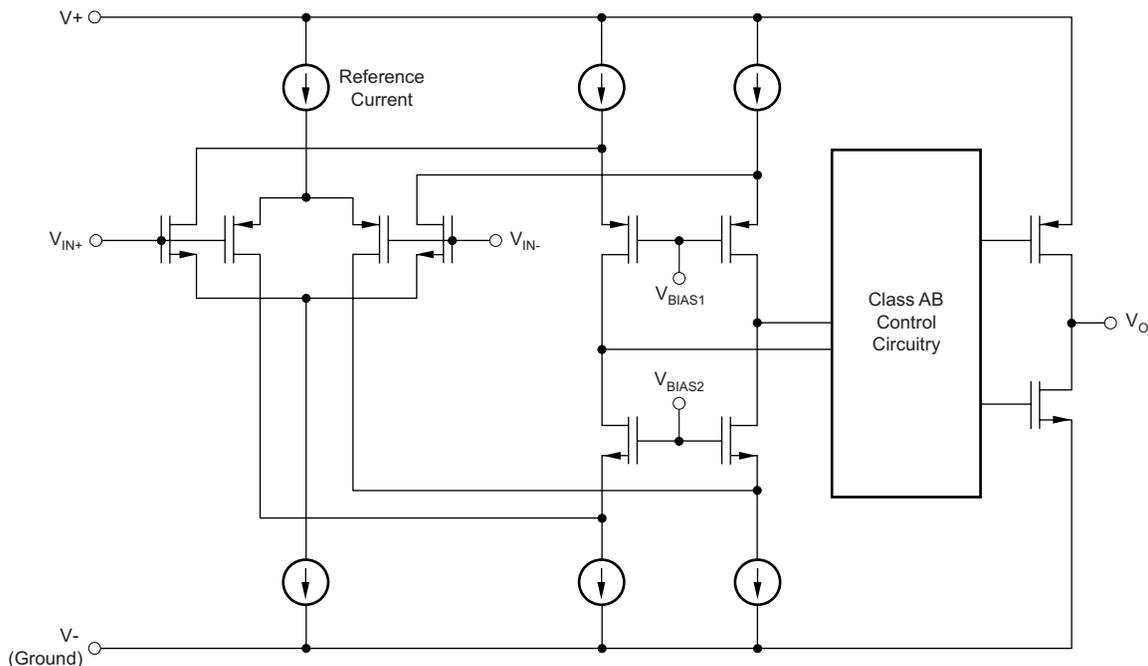
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Figure 13. OPAx313 Simplified Schematic

Find full device features and specifications at the OPA313 Product Folder.

2.2.13 REF3325

The REF33xx is a family of low-power, precision band-gap voltage references that are specifically designed for extremely low dropout, excellent initial voltage accuracy with a high output current.
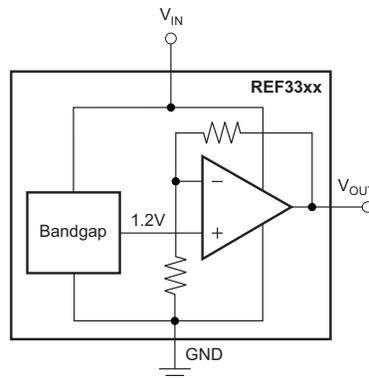

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Figure 14. REF33xx Functional Block Diagram

Find full device features and specifications at the REF3325 Product Folder.

2.2.14 TS3A24159

The TS3A24159 is a two-channel single-pole double-throw (SPDT) bidirectional analog switch that is designed to operate from 1.65 to 3.60 V. It offers low ON-state resistance and excellent ON-state resistance matching with the break-before-make feature, to prevent signal distortion during the transferring of a signal from one channel to another. The device has excellent total harmonic distortion (THD) performance, low ON-state resistance, and consumes very low power. These are some of the features make this device suitable for a variety of markets and many different applications.
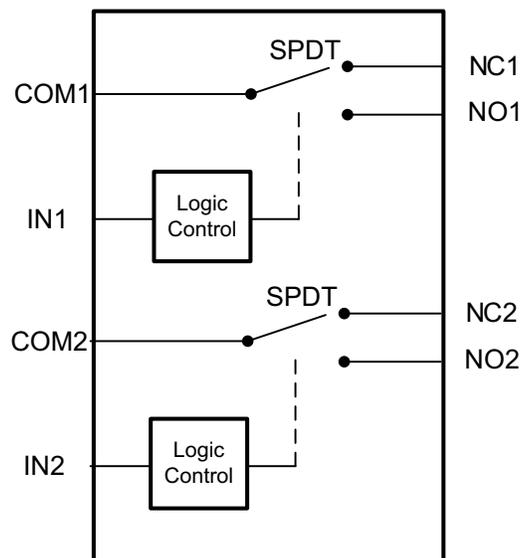
Copyright © 2016, Texas Instruments Incorporated

Figure 15. TS3A24159 Functional Block Diagram

Find full device features and specifications at the TS3A24159 Product Folder.

2.2.15 TS5A3166

The TS5A3166 is a single-pole single-throw (SPST) analog switch that is designed to operate from 1.65 to 5.5 V. The device offers a low ON-state resistance. The device has excellent THD performance and consumes very low power. These features make this device suitable for portable audio applications.
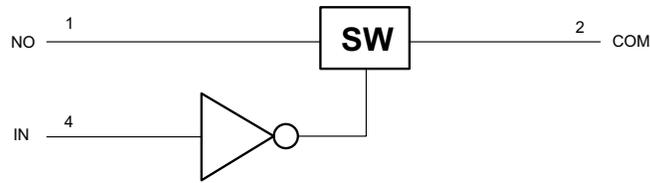

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Figure 16. TS5A3166 Functional Block Diagram

Find full device features and specifications at the TS5A3166 Product Folder.

2.2.16 TS5A3359

The TS5A3359 is a bidirectional, single-channel, single-pole triple-throw (SP3T) analog switch that is designed to operate from 1.65 to 5.5 V. This device provides a signal switching solution while maintaining excellent signal integrity, which makes the TS5A3359 suitable for a wide range of applications in various markets including personal electronics, portable instrumentation, and test and measurement equipment. The device maintains the signal integrity by its low ON-state resistance, excellent ON-state resistance matching, and THD performance. To prevent signal distortion during the transferring of a signal from one channel to another, the TS5A3359 device also has a specified break-before-make feature. The device consumes very low power and provides isolation when VCC = 0.
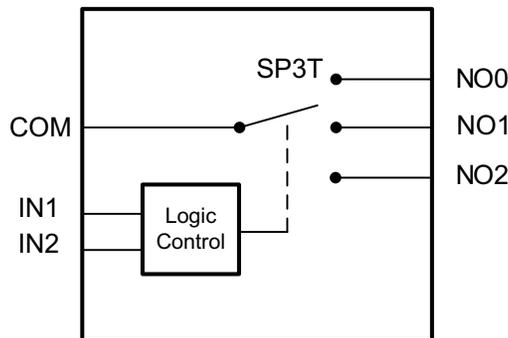
Copyright © 2016, Texas Instruments Incorporated

Figure 17. TS5A3359 Functional Block Diagram

Find full device features and specifications at the TS5A3359 Product Folder.

2.2.17 TPD1E10B06

The TPD1E10B06 is a single-channel ESD TVS diode in a small 0402 package. This TVS protection product offers ±30-kV IEC air-gap, ±30-kV contact ESD protection, and has an ESD clamp circuit with a back-to-back TVS diode for bipolar or bidirectional signal support. The 12-pF line capacitance of this ESD protection diode is suitable for a wide range of applications supporting data rates up to 400 Mbps. The 0402 package is an industry standard and is convenient for component placement in space-saving applications.

Typical application of this ESD protection product is the circuit protection for audio lines (microphone, earphone, and speakerphone), SD interfacing, keypad or other buttons, VBUS pin and ID pin of USB ports, and general-purpose I/O ports. This ESD clamp is a good fit for the protection of the end equipment like ebooks, tablets, remote controllers, wearables, set-top boxes, and electronic point of sale equipment.

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Figure 18. TPD1E10B06 Functional Block Diagram

Find full device features and specifications at the TPD1E10B06 Product Folder.

2.2.18 LSF0102

The LSF family can be used in level translation applications for interfacing devices or systems operating at different interface voltages with one another. The LSF family is ideal for use in applications where an open-drain driver is connected to the data I/Os. With appropriate pull-up resistors and layout, LSF can achieve 100 MHz. The LSF family can also be used in applications where a push-pull driver is connected to the data I/Os.
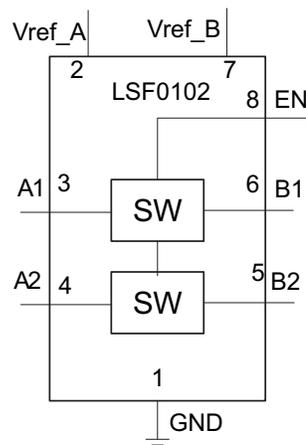
Copyright © 2016, Texas Instruments Incorporated

Figure 19. LSF0102 Functional Block Diagram

Find full device features and specifications at the LSF0102 Product Folder.

2.2.19 LSF0204

The LSF family consists of bidirectional voltage level translators that operate from 0.8 to 4.5 V (Vref_A) and 1.8 to 5.5 V (Vref_B). This range allows for bidirectional voltage translations between 0.8 and 5.0 V without the need for a direction terminal in open-drain or push-pull applications. The LSF family supports level translation applications with transmission speeds of up to 100 MHz.
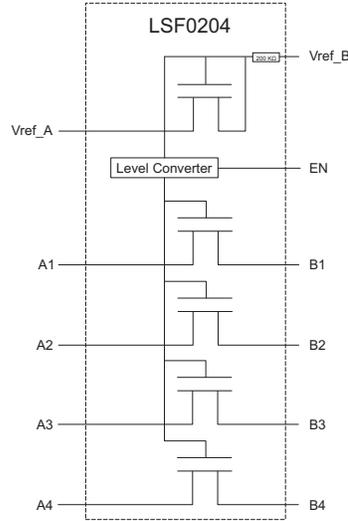

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Figure 20. LSF0204 Functional Block Diagram

Find full device features and specifications at the LSF0204 Product Folder.

2.3 Design Considerations

The following subsections briefly describe the fundamental subsystems of the TIDA-01012 reference design platform.

2.3.1 System Control, Processing, and Wireless Communication

The system control and processing subsystem is the centerpiece feature of the TIDA-01012 reference design and is based on the significant feature set and capabilities of the CC2640 Wireless MCU.

The CC2640 provides the wireless communication protocol, while also interfacing with the other TIDA-01012 subsystems including NFC, battery management, power distribution, and the AFE. In addition, it has the processing capability to efficiently calculate true RMS measurements of up to a 100-kHz input signal.

2.3.2 AFE

The TIDA-01012 AFE includes the components and circuitry associated with the voltage and current measurement input ports, range selection, voltage range scaling, current-voltage conversion, signal conditioning, and reference voltage generation. The AFE outputs the resulting voltage and current signals for input to the buffer, gain stage, and ADC, which is interfaced with the CC2640 through an SPI.

2.3.3 Power Supply

The TIDA-01012 is designed to be powered from a 3.7-V Li-Ion battery providing a very convenient rechargeable battery solution, and thus avoids the need for battery replacement.

There are a number of suppliers for AAA Li-Ion batteries in the marketplace. These batteries are available with built-in protection circuitry, as well as without protection circuitry. Although the TIDA-01012 will operate with either protection configuration, it is strongly recommended to use batteries that include this protection circuit. Also note that the addition of this protection circuit slightly extends the length of the battery, which could possibly make insertion of the battery into the TIDA-01012 battery holder a tight fit. The TrustFire 10440 AAA Li-Ion battery was used during the development of the TIDA-01012 reference design.

NOTE: The TIDA-01012 reference design uses a 3.7-V Li-Ion battery in the form factor of an AAA battery, and thus must not be operated with a regular AAA Alkaline battery.


To maximize efficiency and battery life, a DC-DC Buck converter is used in the TIDA-01012 reference design. Although most DC-DC converters are assumed to be very inefficient at light loads, the TIDA-01012 features the TPS62740, an ultra-low-power DC-DC converter that enables great light-load efficiency, providing up to 90% efficiency at 10 µA. This enables high efficiency in the low-power modes—even higher than LDOs.

2.4 System Design Theory

2.4.1 DMM Signal Chain Subsystems

Figure 21 shows a block diagram of the TIDA-01012 DMM signal and measurement flow. Details of this process along with design considerations associated with each are described in subsequent sections.
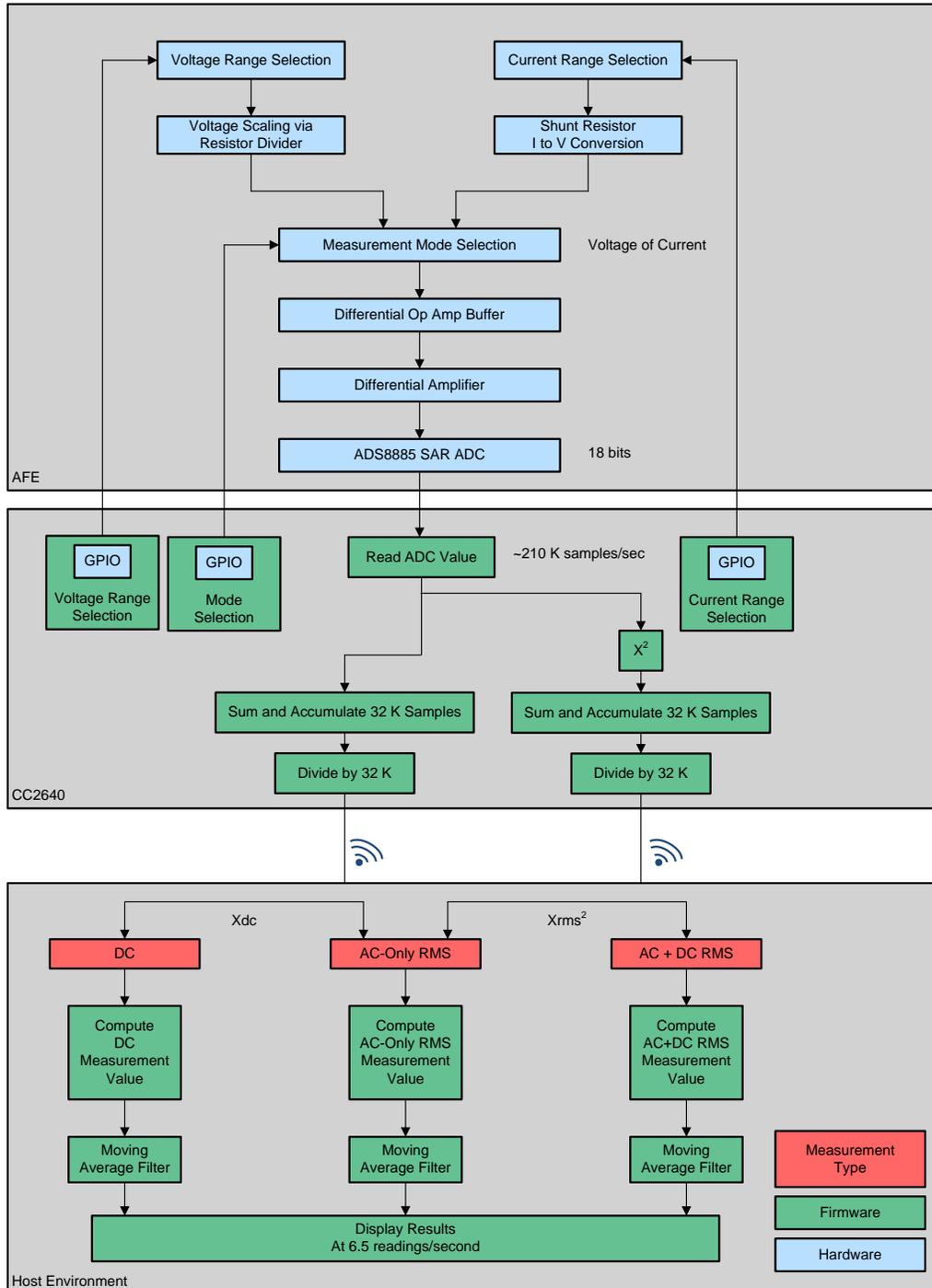

Figure 21. TIDA-01012 Signal and Measurement Flow Block Diagram

2.4.1.1 AFE
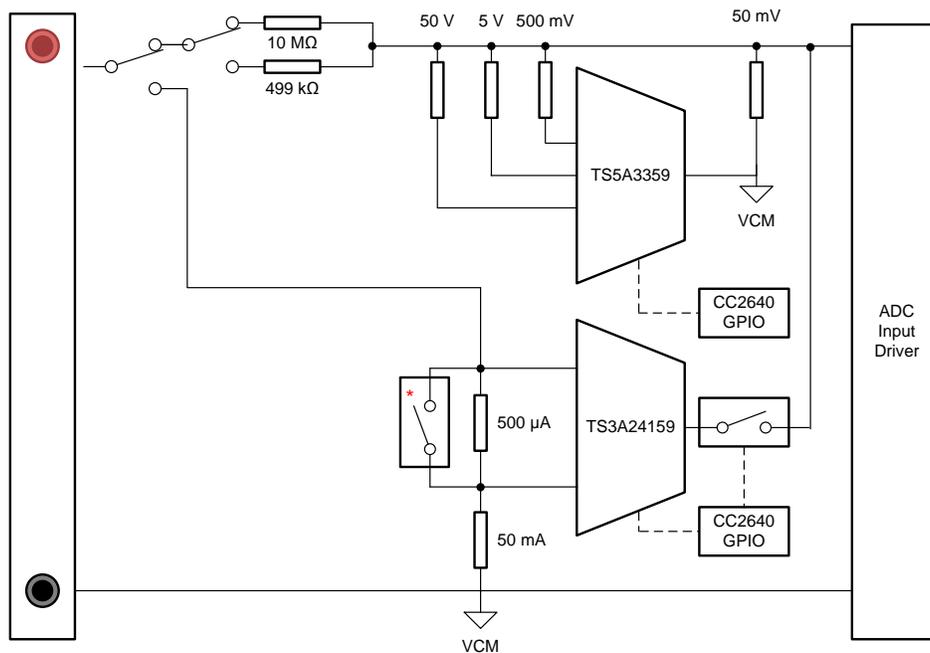
* this constitutes a part of the TS3A245159 that is configured to be used as a switch

Figure 22. Simplified DMM Front-End Block Diagram

2.4.1.1.1 Voltage Measurements

Voltage measurements are accomplished by applying the external device-under-test (DUT) voltage between the DMM input (red) and COM (black) terminals, and setting the mechanical switch to the "voltage" position. These inputs terminals support both positive and negative voltage polarities. The voltage measurement section of the AFE block provides the appropriate voltage scaling to support four available voltage ranges as selected by the MCU.

This is accomplished through a configurable resistor divider or attenuation network controlled by a 1:3 TS5A3359 analog multiplexer. The multiplexer could be either open or select a different resistor to change the resistor divider as needed for each voltage range. As shown in Figure 22, the TS5A3359 independently enables the 50-V, 5-V, or 500-mV divider resistors.

These resistors work in parallel with the 50-mV resistor to establish the required divider ratio with the voltage terminal input resistor. The 50-mV range divider ratio is established with the 50-V, 5-V, and 500-mV resistors disabled. The valid output signal level of this resistor divider network for all voltage ranges is ±50 mV.

The actual design also includes a corresponding capacitor divider network in parallel with the resistor network to compensate and calibrate for overall system AC frequency response (see the schematic for more details).

The 10-MΩ resistor shown in the voltage input terminal serves as the constant resistor for all the resistor divider network settings. A 10-MΩ value is required in order to meet the input impedance requirement listed in Table 1 across all voltage ranges, even though its relatively high value negatively impacts noise and resolution performance of the system. For this reason, a switch in Figure 22 has been included in this reference design to provide better noise and resolution performance at the low 50-mV range setting, however meeting input impedance requirements by using a 100-MΩ resistor in the voltage divide.

The DMM input (red) terminal is also used for current functions, and a SPDT switch is used to change between current and voltage, as well as signaling the MCU the change has occurred.

2.4.1.1.1.1 Resistor and Capacitor Divider Network

In order to create the resistor divider network to meet the input resistance requirements, large resistor values are needed. This poses a challenge with capacitance from a few of the surrounding components such as op amps and switches (shown as C_{eq} in Figure 23), which is in parallel to those resistors. As signal frequency increases, this capacitance tends to lower the impedance, affecting the attenuation ratios and thus affecting the measurements. In order to compensate for this effect, C_{IN} and C_{ATT} are introduced as shown in Figure 23.
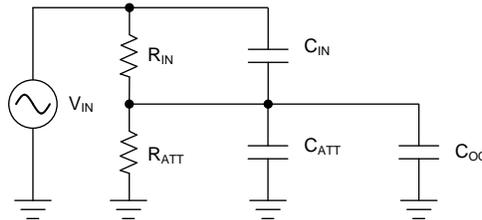
Figure 23. AFE Divider Network

Given that $R_{IN} / R_{ATT} = m$, the ratio of these should be $C_{IN} / (C_{ATT} + C_{eq}) = 1/m$. However, if $C_{ATT} >>> C_{eq}$, the effect of C_{eq} can be neglected leaving the ratio to be $CIN / CATT = 1/m$.

2.4.1.1.2 Current Measurements

The current measurement section provides 500-µA and 50-mA current range settings as selected by the MCU. Two shunt resistors connected between the DMM (red) terminal (set to the "current" position) and COM (grey) terminal are used to convert the respective currents to voltage. Like Section 2.4.1.1.1, these input terminals support both positive and negative current polarities. A dual 2:1 TS3A24159 analog mux is used to select between the two ranges. The second mux in the TS3A24159 serves as a basic analog switch function to bypass the 500-µA range shunt resistor when the 50-mA range is selected. The output voltage range of the shunt resistor network is also ≈ ±50 mV driven by the burden voltage requirement of 50 mV.

The TSA3166 SPST Analog Switch provides isolation of the current shunt resistors from being in parallel with the voltage dividers used in the voltage measurements.

> **NOTE:** Because the TIDA-01012 reference design is focused primarily on measurement performance metrics, minimal overvoltage and overcurrent protection mechanisms have been implemented in this TI Design. The AFE includes a resettable fuse in the current measurement portion of the AFE to prevent against excessive current into the board. However, input overvoltage protection is not included on the voltage input section.

2.4.1.2 *Input Buffer and Gain Network*

The AFE input buffer and gain network is shown in Figure 24.
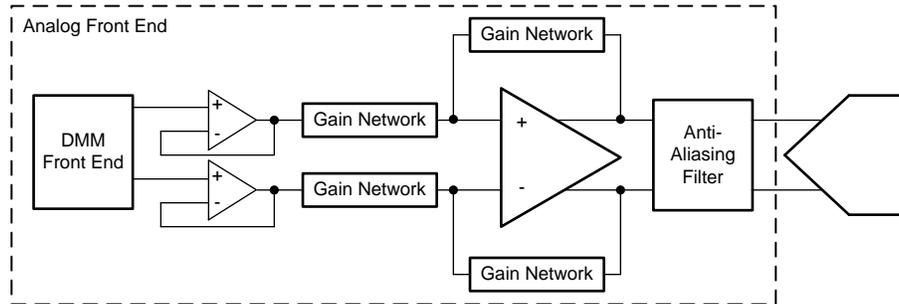
Figure 24. Input Buffer and Gain Network Block Diagram

As described in Section 2.4.1.1.1 and Section 2.4.1.1.2, the voltage and current mode output signals provide ±50 mV to the ADC input driver buffer. An OPA313 configured as a voltage follower has been chosen to buffer this signal to provide a low-impedance output to the THS4531 fully differential amplifier (FDA). Also, the OPA313 has sufficient bandwidth to support the TIDA-01012 accuracy design target of 3% at 100 kHz by delivering <1% signal roll-off at 100 kHz.

This THD4531 FDA is used to gain up the 50-mV signal to match the 2.5-V reference voltage of the ADC. A nominal gain of 44.2 was chosen for this reference design to provide up to ≈ ±2.2 V to the ADC, allowing for design tolerances and rail-to-rail voltage margins of the THS4531 output buffer. The THS4531 also has excellent bandwidth characteristics required to support the TIDA-01012 accuracy design targets.

2.4.1.3 *ADC*

The two primary design considerations to maximize the performance of a high-resolution SAR ADC are the input driver and the reference driver design. The overall system block diagram is shown in Figure 25. This figure shows a block diagram comprised of the critical analog circuit blocks, which should be carefully designed to achieve the design specifications of an 18-bit, 200 kSPS acquisition front-end block.

The diagram includes the most important specifications for each individual analog block in the order of design priority. This is important because the design criterion for each block is dependent on the desired ADC performance as well as the input signal type.
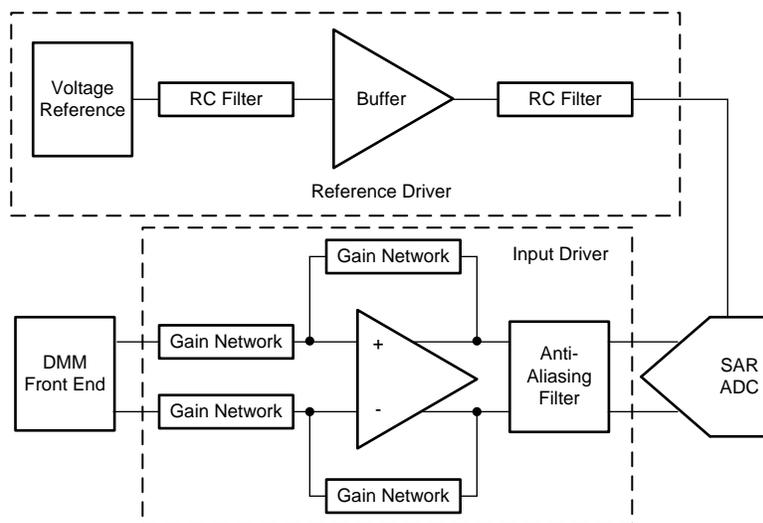
Figure 25. SAR ADC Subsystem Block Diagram

2.4.1.3.1 Anti-Aliasing Filter Design

Follow these steps to design the anti-aliasing filter:

1. Determine the acquisition time, t_{ACQ}, and conversion time, t_{CONV}.
   The minimum acquisition time "t_{ACQ}" and conversion time "t_{CONV}" can be determined by referring to the ADS8885 datasheet. As stated in the datasheet, a minimum conversion time ($t_{CONV(max)}$) of 1300 ns is required. Given the ≈ 200-kSPS sampling rate (or 5 μs per sample) chosen for this TI Design in order to meet the 100-kHz measurement bandwidth requirement this has:

$$t_{ACQ(min)} = 5000 \text{ ns} - 1300 \text{ ns} = 3700 \text{ ns} \tag{1}$$

2. Compute the charge (Q_{SH}) for the sampling capacitor (C_{SH} based on the full-scale ADC input voltage. C_{SH} can be found on the input stage equivalent circuit, usually provided in the ADC datasheet, as seen in Figure 26.
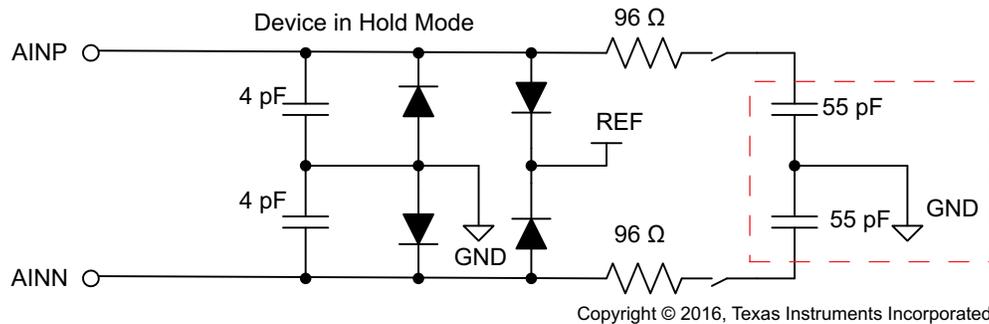
Figure 26. ADS8885 Input Sampling Stage Equivalent Circuit

$$Q_{SH} = C_{SH} \times V_{IN(full\text{-}scale)} = 275 \text{ pC} \tag{2}$$

where:

- C_{SH} = 55 pF
- $V_{IN(full\text{-}scale)} = 2 \times V_{REF} = 5.0 \text{ V}$

3. Compute Q_{FLT}, assuming that a ½ charge will come from C_{FLT} and a ½ charge from the op amp.

$$Q_{FLT} = 0.5 \times Q_{SH} = 137.5 \text{ pC} \tag{3}$$
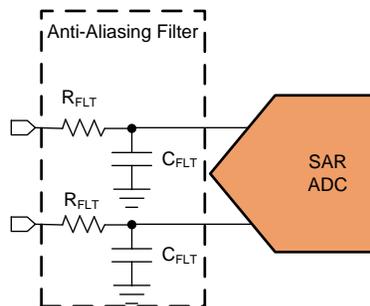
Figure 27. Anti-Aliasing Filter

4. Assume the initial drop (ΔV_{FLT} on C_{FLT} will be 100 mV) could vary in a different application at beginning of t_{ACQ}.

$$\Delta V_{FLT} = 100 \text{ mV} \tag{4}$$

5. Choose C_{FLT} based on Q_{FLT}.

$$Q_{FLT} = 0.5 \times Q_{SH} = 137.5 \text{ pC}$$

$$Q_{FLT} = C_{FLT} \times \Delta V_{FLT} = C_{FLT} \times 100 \text{ mV} \tag{5}$$

Using these equations, C_{FLT} = 1.375 nF, which is the minimum capacitance required so that at least half the charge is delivered by this capacitor. A 2.2-nF capacitance was chosen for this TI Design.

NOTE: To ensure C_{FLT} is the dominant load for the op amp, the following check is performed; $C_{FLT} > 10 \times C_{SH}$. In this case, 2.2 nF > 0.055 nF, which meets this criteria.

6. Determine the targeted settling time (t_{SETTLE}).

As a rule-of-thumb, it is recommended to have the op amp settled at 75% of t_{ACQ} to account for process variation tolerances of ICs. Therefore:

$$t_{SETTLE} = 0.75 \times t_{ACQ} \tag{6}$$

$$t_{SETTLE} = 0.75 \times 3700 \text{ ns} = 2775 \text{ ns}$$

7. Compute the required time constant, τ_C, based on the 100-mV drop on C_{FLT}.

$$V_{FLT} = (V_{INITIAL} - V_{FINAL}) \times e^{-(t/\tau)} + V_{FINAL} \tag{7}$$

$$\tau_C = \frac{-\tau_{SETTLE}}{\ln\left(\dfrac{V_{FLT} - V_{FINAL}}{V_{INITIAL} - V_{FINAL}}\right)} = \frac{-2775 \text{ ns}}{\ln\left(\dfrac{4.99999049 - 5.0}{4.99 - 5.0}\right)} = 398.8 \text{ ns} \tag{8}$$

8. Solve for t_{RC} and t_{OA}.

$$\tau_{RC} = 2 \times \tau_{OA} \tag{9}$$

$$\tau_C = \sqrt{\tau_{RC}^2 + \tau_{OA}^2} \tag{10}$$

$$\tau_C = \sqrt{(2 \times \tau_{OA})^2 + \tau_{OA}^2} = \tau_C = \sqrt{5 \times \tau_{OA}^2}$$

$$\tau_{OA} = \sqrt{\frac{\tau_C^2}{5}} = \frac{1}{\sqrt{5}} \tau_C \tag{11}$$

$$\tau_{OA} = \frac{1}{\sqrt{5}} \times 398.8 \text{ ns} = 178.4 \text{ ns}$$

$$\tau_{RC} \leq 2 \times 178.4 \text{ ns} = 356.7 \text{ ns} \tag{12}$$

9. Calculate R_{FLT} based on C_{FLT}, τ_{RC}, and system bandwidth requirements.

$$356.7 \text{ ns} = R_{FLT} \times 2.2 \text{ nF} \tag{13}$$

$$R_{FLT} \leq 162.1 \text{ } \Omega$$

Also, the anti-aliasing filter must have sufficient bandwidth to support the 3% at 100-kHz AC accuracy design target. For this TI Design, a 692-kHz cutoff frequency was chosen, which provides <1% signal roll-off at 100 kHz while also limiting system noise bandwidth as much as possible. Given these constraints, R_{FLT} is calculated as follows and meets all constraints:

$$R_{FLT} = \frac{1}{2\pi \times fz_{RC} \times C_{FLT}} = \frac{1}{2\pi \times 692 \text{ kHz} \times 4.4 \text{ nF}} = 52.3 \text{ } \Omega \tag{14}$$

The previous values are for a single-ended filter. To make it differential, follow Figure 28.
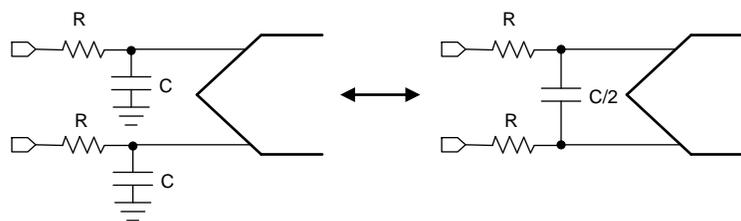
Figure 28. Single-Ended to Differential

10. Find the minimum fp_{3dB} for the driving op amp using τ_{OA}.

Since the filter has a reduced R_{FLT}, now adjust the calculated time constant for the op amp (τ_{OA} = 178.4 ns). Since this new $\tau_{RC(new)}$ = 71.91 ns, the new time constant for the op amp is $\tau_{OA(new)}$ = 35.95 ns. Using this time constant, find the minimum fp_{3dB}.

$$fp_{OA} = \frac{1}{2\pi \times \tau_{OA}} = \frac{1}{2\pi \times 35.95 \text{ ns}} = 4.4 \text{ MH} \tag{15}$$

11. Two last checks are done to verify the previous steps to design the input driver. Using the ADC SPICE Model, verify the following:
   - Settling time < ¾ t$_{ACQ}$
   - Check that error < ½ LSB, a 0.2 LSB is achieved by the end of t$_{ACQ}$

2.4.1.3.2 Reference Driver

SAR ADCs compare an input to a known reference and its binary scaled weights to estimate an equivalent digital code. For a capacitor-based ADC reference input, the load at the reference pin spikes out every time a bit value is estimated. Not only does reference current transient multiple times within a conversion cycle, but the magnitude of the transient current also varies between conversions.

An ideal ADC is one that gives the same digital code for a given input. However, a noisy reference shows up as variation of code out at the output of the ADC for a fixed input. It also degrades the linearity, THD, and SNR. A good system design should ensure good noise performance at low reference voltages, which translates to a good performance at higher reference voltages. This TI Design optimizes reference drive circuit at the lowest supported reference voltage where it is most demanding. The lowest reference voltage ADS8885 can operate is 2.5 V.

There are two types of noise that a reference can introduce. Flicker noise is the noise dominant at low frequencies and broadband noise dominates at high frequencies. The broadband noise, in particular, can be of the order of 100's of microvolts and can easily exceed the 10's of microvolts of RMS noise of the converter. Typically, flicker noise is specified on the datasheet as peak-to-peak noise up to 10 Hz. This has to be scaled down by a factor of 6.6 to convert it into RMS noise. Broadband spectral noise density on the other hand may not be specified on the datasheet and for a band-gap reference this will be of the order of 0.1 µV$_{RMS}$/Hz to 10 µV$_{RMS}$/Hz in magnitude. It is inversely proportional to the square root of the quiescent current of the reference. If it is not specified, a good approximation is given by Equation 16.

$$REF_{Broadband\_Noise\_Destiny} = \frac{10,000\,nV}{\sqrt{Hz}} = \frac{\sqrt{\mu A}}{\sqrt{2 \times I_{Q\_REF}\,(in\,\mu A)}} \times 4.4\,MH$$

(16)
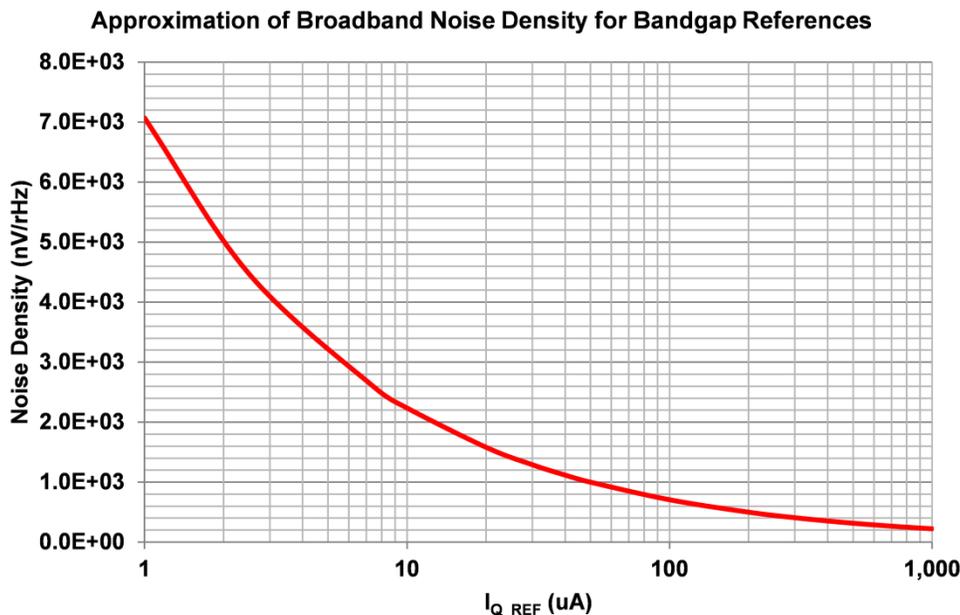
Figure 29. Broadband Noise Density versus Reference I$_Q$

Designing the reference drive circuitry is a four-step optimization process that involves:
- Identifying a reference that is suitable for low power applications
- Designing a filter that limits the broadband noise from the reference

A good rule of thumb for scaling the noise of the reference buffer is given in Equation 17. Note that a first-order low-pass filter must be inserted between the voltage reference and the buffer amplifier to limit EN to ≤ 3x (around 9.5 dB less) the RMS noise of the ADC (E_{N_ADC}).

$$E_N \leq \frac{1}{3} \times E_{N\_ADC}$$
(17)

The RMS noise of the reference is composed of broadband noise and 1/f noise:

$$E_N \leq \sqrt{E_{N_{BB}}{}^2 + E_{N_{1/f}}{}^2} = \sqrt{\left(e_{BB} \times \sqrt{BW_N}\right)^2 + \left(e_{BF} \times \sqrt{\ln\left(\frac{f_H}{f_L}\right)}\right)^2}$$
(18)

where:
- E_{N_BB} is the total RMS noise from the broadband
- $E_{N\_1/f}$ is the total RMS noise from the 1/f region
- e_{BB} is the broadband noise spectral density
- e_{BF} is the noise spectral density of the 1/f region
- BW_N the noise bandwidth, that is, the bandwidth with a brick-wall correction factor
- f_H is the upper cutoff frequency of the 1/f region
- f_L, is the lower cutoff frequency of the 1/f region, usually 0.1 Hz
- $E_{N\_1/f}$ can also be approximated by using the peak-to-peak 1/f RMS noise provided in the datasheet:

$$E_{N_{1/f}} = \frac{E_{N_{1/f}(p-p)}}{6.6} = \frac{70\,\mu Vpp}{6.6} = 10.61\,\mu Vrm$$
(19)

Equation 20 was derived on the basis of the measured characteristic between the output noise density and quiescent current of several TI reference circuits. The equation can be used to approximate the broadband noise spectral density based on the reference's quiescent current of REF3325:

$$e_{BB} = \frac{10\,\mu V}{\sqrt{Hz}} \times \frac{\sqrt{\mu A}}{\sqrt{2 \times I_{Q,REF}}} = \frac{10\,\mu V}{\sqrt{Hz}} \times \frac{\sqrt{\mu A}}{\sqrt{2 \times 5\,\mu A}} = 3.16\,\frac{\mu V}{\sqrt{Hz}}$$
(20)

The RMS noise of the ADC, E_{N_ADC}, is derived from the SNR, which is specified in the datasheet. Using Equation 21, it is possible to relate the RMS noise to the SNR and the full-scale input range of the ADC based on the value of the voltage reference (V_{REF}):

$$SNR\,(dB) = 20 \times \log_{10}\left(\frac{V_{REF}}{\sqrt{2}} \times \frac{1}{E_{N\_ADC}}\right)$$
(21)

Solving for EN_ADC gives the following:

$$E_{N\_ADC} = \frac{V_{REF}}{\sqrt{2} \times 10^{(SNR/20)}} = \frac{2.5\,V}{\sqrt{2} \times 10^{(93.3\,dB/20)}} = 38.23\,\mu Vrm$$
(22)

Back to the equation:

$$\sqrt{\left(3.16\,\mu V / \sqrt{Hz} \times \sqrt{BW_N}\right)^2 + \left(10.61\,\mu Vrms\right)^2} \leq \frac{1}{3} \times 38.23\,\mu Vrm$$
(23)

Using Equation 23, find BW_N = 4.99 ≈ 5 Hz, then the bandwidth or cutoff frequency of the filter is determined by using a brick-wall correction factor, K_N, which in this case is 1.57 for a one-pole filter.

$$fc = \frac{BW_N}{K_N} = \frac{5\,Hz}{1.57} = 3.2\,H$$
(24)

By choosing CA1 = 4.6 μF and RA1 = 10 kΩ, a cutoff frequency of f_C = 3.1 Hz is achieved, which is less frequency than needed and meets the requirement.

- Determine the capacitor value needed for providing the reference drive current.

  The ADS8885 datasheet recommends using up to 22 µF

- Identify an op amp that is suitable for low power that can recharge the capacitor.

  To reduce the number of op-amp choices for buffer, start by selecting op amps that can operate on a 2.7-V power supply. Then, select op amps that consume less than 145 µA.

  Although the OPA333 has one of the lowest quiescent currents (that is, 17 µA), it exhibits an inductive behavior from 10 Hz to 10 kHz as can be seen by looking at the output Impedance on TINA-TI™. This along with the reactance of 22 µF acts like a resonant circuit that can make the buffer prone to oscillations. At around 100 Hz, there will be an effective L-C resonance formed by the open loop output impedance of the OPA333 and the capacitive load and make stability an issue. The op amp with the next lowest current and high enough GBW (≈ 1 MHz) is OPA313. However, without any compensation and given the capacitive load, the OPA313 would be unstable. Therefore, a R_{ISO} dual feedback configuration is implemented in this design to ensure that the buffer stability.
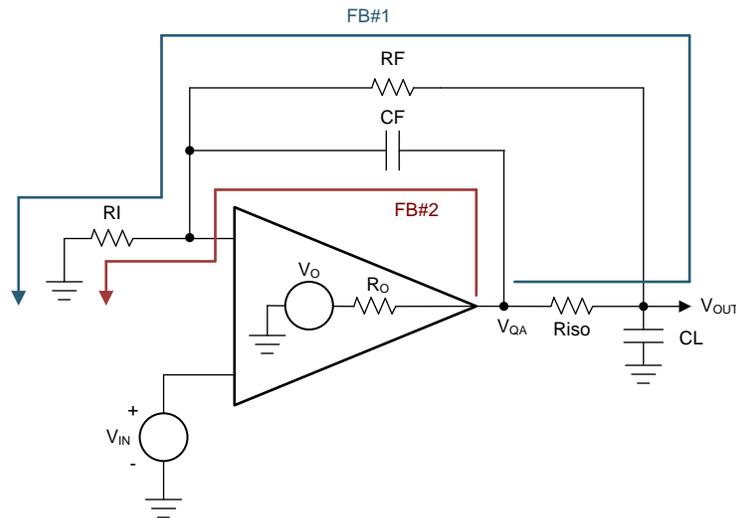
Figure 30. RISO Dual Feedback Configuration for Stability

Performing stability analysis with TINA-TI on the circuit shown in Figure 31 is used to confirm the stability concerns. The phase margin (PM) is nearly 0 degrees as shown in Figure 32. This figure also contains information that will be used to implement the stability topology known as R_{ISO} Dual Feedback shown in Figure 30.
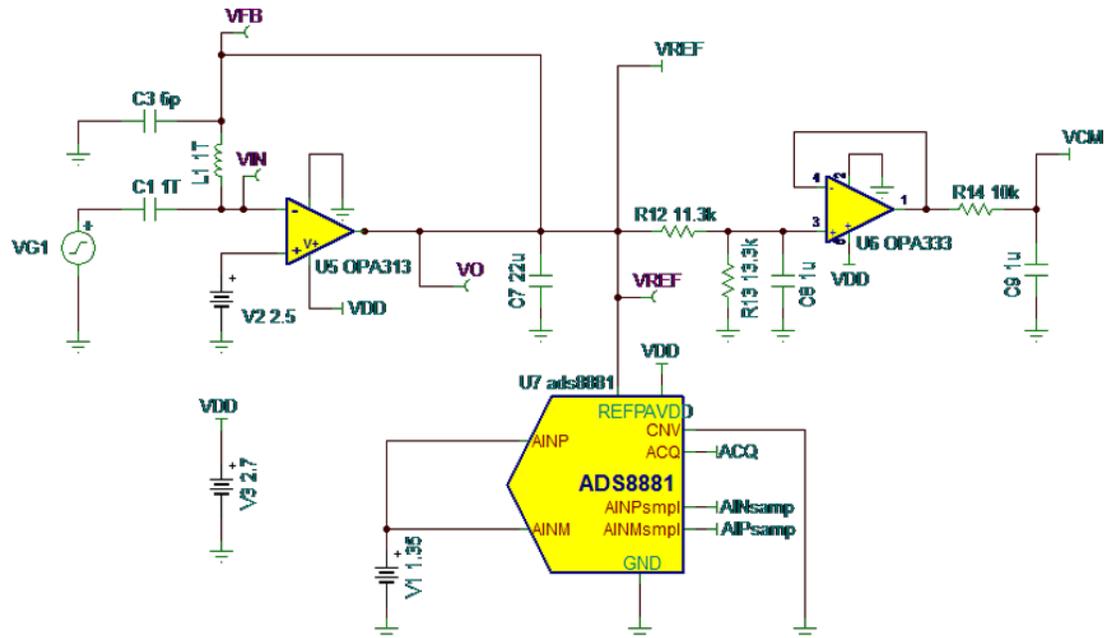
Figure 31. TINA-TI Simulation Schematic
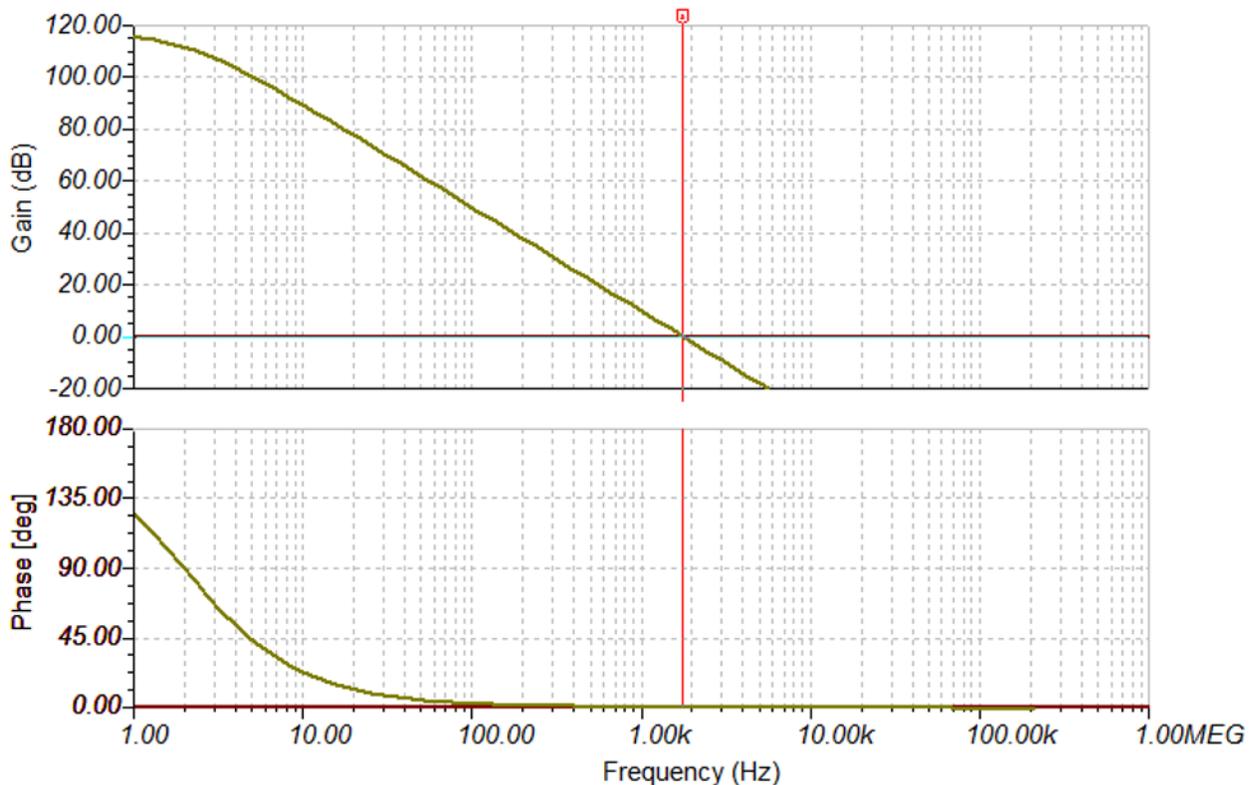
Figure 32. TINA-TI PM Simulation Output

In order to increase the PM, introduce a zero, which is introduced in between the frequencies at which the open loop gain is 20 dB and 0 dB, yielding a PM approximately between 90 and 45 degrees. From Figure 32:

$$f(AOL = 0 \text{ dB}) = 1.76 \text{ kHz} \tag{25}$$

$$f(AOL = 20 \text{ dB}) = 558.11 \text{ Hz} \tag{26}$$

In order to find the right isolation resistor, R_{ISO}, use Equation 27:

$$R_{ISO} = \frac{1}{2\pi \times f(\text{zero}) \times C_{LOAD}} \tag{27}$$

Using Equation 27, R_{ISO} is determined to be between 12.96 and 4.11 Ω. A standard value of 8.2 Ω is selected. Once R_{ISO} is chosen, RF can be selected to any value greater than 100 × R_{ISO} in order to prevent interactions with R_{ISO}.

The last step is to select a value of CF in the range shown. Using this range ensures that the two feedback paths, RF and CF, will never create a resonance that would cause instability. Smaller values for CF will result in faster settling time at the expense of overshoot for certain load ranges. Choosing RF = 13.3 kΩ allows the user to find a range for CF that will ensure that the two feedback paths will not create a resonance that would cause instability.

$$\frac{6 \times R_{ISO} \times C_{LOAD}}{R_F} \leq C_F \leq \frac{10 \times R_{ISO} \times C_{LOAD}}{R_F} \tag{28}$$

Given the previously chosen values gets 0.0814 µF ≤ CF ≤ 0.1356 µF, and thus 0.1 µF (100 nF) is chosen.
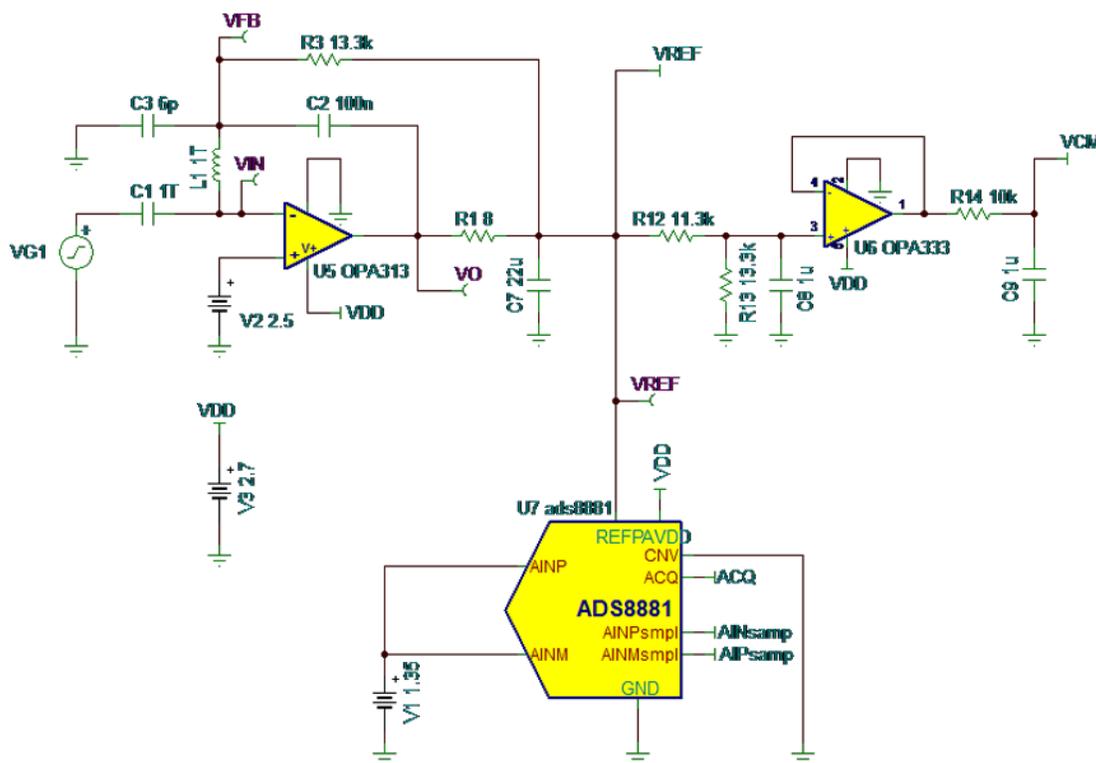
Figure 33. TINA-TI Dual R$_{ISO}$ Simulation Schematic

NOTE: L1/C1 are used only for stability analysis purposes.

Performing stability analysis using TINA-TI yields to a PM = 76.29 degrees.

The following check ensures that the voltage drop that occurs during conversion (7.07 μV according to the simulation) is still under a half LSB (9.51 μV) of change as seen in Figure 34.

> **NOTE:** To perform this voltage drop test, C1, L1, and VG1 were removed (which were used for AC stability analysis), and the CONVST signal was added to the ADC model.
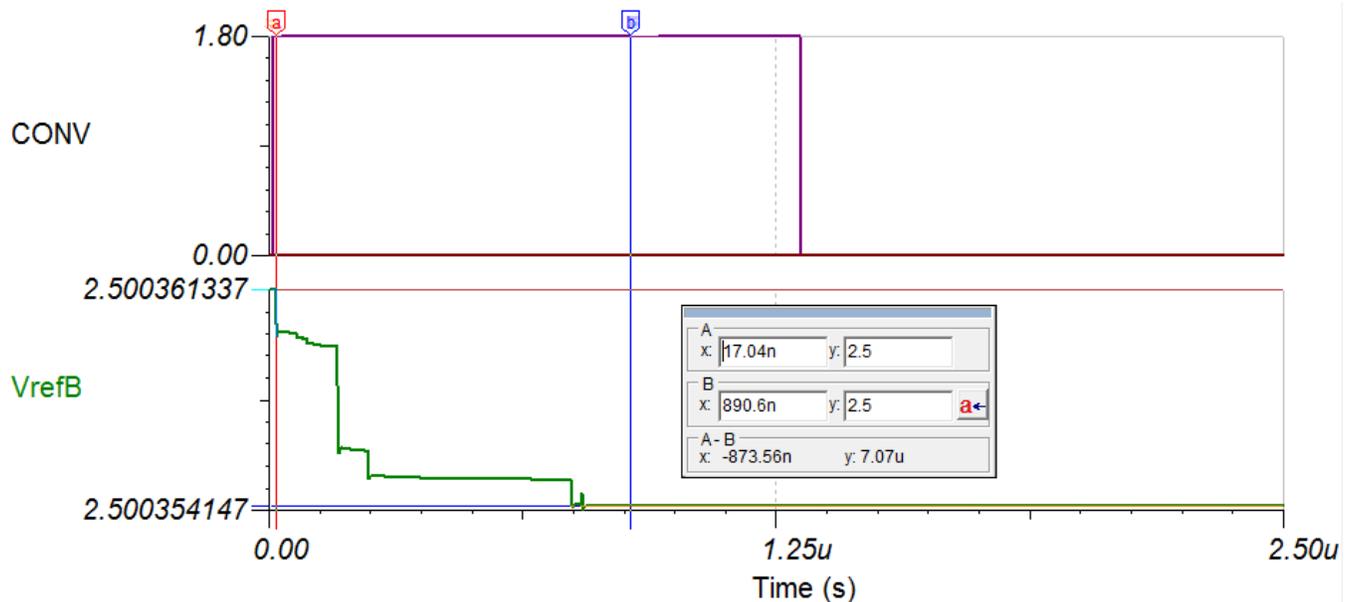
Figure 34. TINA-TI Simulation Voltage Drop Output
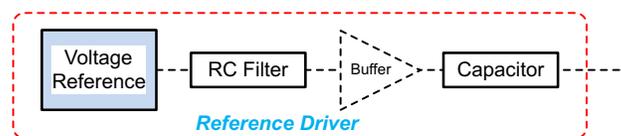
Figure 35. External Voltage Reference for SAR ADC

2.4.1.3.3 *Common-Mode Voltage*

A common-mode voltage is used to offset the signal to set an offset in the input signal equal to half the voltage rail of the AFE of 2.7 V. This voltage is derived from the REF3325 2.5-V voltage reference using a voltage divider. The common-mode voltage is set to 1.35 V to maximize the dynamic range of the ADS8885 ADC.
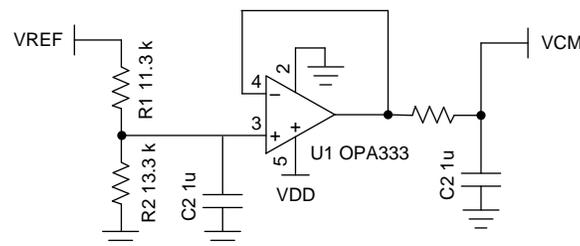
Figure 36. Common-Mode Buffer

2.4.1.4   CC2640 Wireless MCU

The CC26xx family of cost-effective, ultra-low-power, 2.4-GHz RF devices with very low-active RF and MCU current and low-power mode current consumption provide excellent battery lifetime and allow for operation on small coin cell batteries and in energy-harvesting applications. The CC2640 allows for a Bluetooth low energy application.

2.4.1.4.1   Power

The CC2640 datasheet details a few different options for power. The TIDA-01012 reference design uses the external regulator configuration, which enables the use of a clean supply from an external LDO, which is also shared with the digital supply of the ADC for the AFE. Figure 37 shows the mentioned configuration, although note that not all power supply decoupling capacitors or digital I/Os are shown. Exact pin positions will vary between the different package options. For a detailed overview of power supply decoupling and wiring, see the schematic provided with this TI Design.
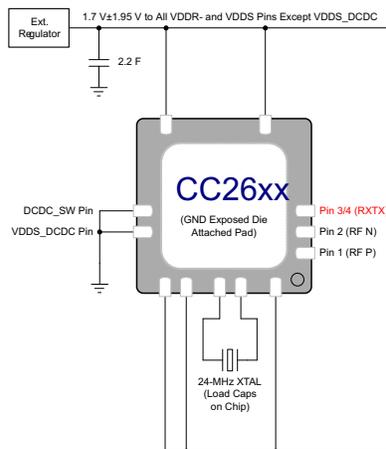
Copyright © 2016, Texas Instruments Incorporated

Figure 37. CC2640 External Regulator

2.4.1.4.1.1   Filtering (Capacitors and Ferrite Bead)

For filtering purposes, a ferrite bead was added in series to the CC2640 power line. In addition to the bead, a shunt capacitor was added, although not populated during the testing of the device. The following decoupling capacitors were also added near the respective pins as listed on Table 9.

Table 9. CC2640 Decoupling Capacitors

PIN NUMBER	CAPACITOR VALUE
13	0.1 µF
22	0.1 µF
44	0.1 µF
44	1.0 µF
45	0.1 µF
48	0.1 µF

2.4.1.4.2   Antenna and Matching Network

The CC2640 datasheet shows the various RF front-end configuration options. The RF front-end can be used in differential- or single-ended configurations with the options of having internal or external biasing. These options allow for various trade-offs between cost, board space, and RF performance. Differential operation with external bias gives the best performance while single-ended operation with internal bias gives the least amount of external components and the lowest power consumption.

2.4.1.4.2.1 Matching Network

The differential operation was chosen for this application. However, a discrete network, as seen on the datasheet, was not used. Instead, an integrated balun replaces the discrete component balun network. Murata's LFB182G45BG5D920 Balun is specifically designed to match TI's CC26xx family of products and replaces the discrete network while providing the small footprint needed for this application.
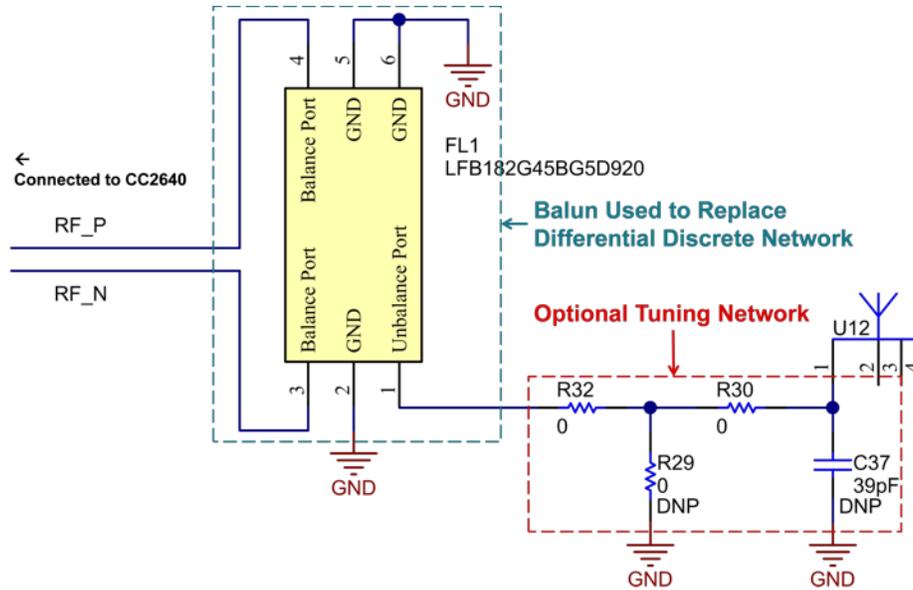

Figure 38. CC2640 Antenna Tuning Network

2.4.1.4.2.2 Antenna

Molex's 2.4-GHz SMT On-Ground MID Chip Antenna was used on this TI Design. An image of the antenna as well as the matching network can be seen in Figure 39.
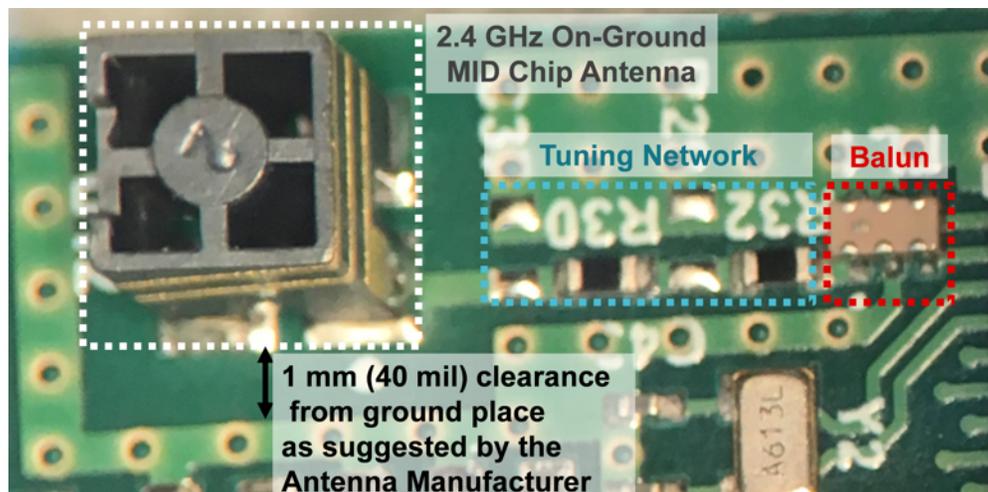
Figure 39. Tuning Network PCB Image

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2.4.1.5   DMM Measurement and Computation Process

The DMM voltage and current measurements demonstrated in the TIDA-01012 reference design include the following:

- DC
- AC-ONLY (RMS)
- DC + AC (RMS)

Signal processing is shared by both the CC2640 MCU and host platform as described in the following sections. The system was designed to minimize the amount of computation performed by the CC2640 MCU in order to leverage the computational performance of the host system, while minimizing TIDA-01012 hardware power and maximizing battery life.

2.4.1.5.1   DC Measurement

The equations for DC measurement are as follows:

$$Xdc = \left(\frac{\sum_{k=0}^{N} Xsample(k)}{N} \right) = \left(Xdc\_signal + Xdc\_offset \right)$$

(29)

where:

- Xdc = DC value of the ADC input signal
- Xsample(k) = ADC value of sampled instance
- N = number of samples accumulated for each measurement
- Xdc_signal = DC value of the DMM input (actual signal component of the sampled ADC value)
- Xdc_offset = AFE DC offset component of the sampled ADC value (determined from the calibration procedure described in section 5.2)

As illustrated in Figure 21, Xdc represents the DC value of the ADC input signal. Xdc is calculated by the CC2640 firmware by summing and accumulating 32K samples, and dividing the accumulated result by 32K. This value is then sent to the host system for final processing according to Equation 30.

DC_Value = Gain × (Xdc − Xdc_offset)

(30)

where:

- DC_Value = reported DC value of the DMM input signal
- Gain = gain factor (determined from the calibration procedure described in Section 3.1.2)

2.4.1.5.2   AC-Only (RMS) Measurement

The equations for AC-Only (RMS) measurement are described as follows:

$$Xrms = \sqrt{\frac{\sum_{k=0}^{N} Xsample^2(k)}{N}} = \sqrt{Xdc^2 + Xac\_rms^2 + Xnoise^2}$$

(31)

where:

- Xrms = total AC+DC RMS value of the ADC input signal (measured value from the system)
- Xsample(k) = ADC value of sampled instance
- N = number of samples accumulated for each measurement
- Xac_rms = AC-Only RMS value of the DMM input (actual signal component of the sampled ADC value)
- Xnoise = system intrinsic RMS noise component (determined from the calibration procedure described in Section 3.1.2)
- Xdc = DC value of the ADC input signal as described in Section 2.4.1.5.1

As illustrated in Figure 21, Xrms represents the total AC+DC RMS value of the ADC input signal. Xrms2 is calculated by the CC2640 firmware by squaring, summing, and accumulating 32K samples, and dividing the accumulated result by 32K. This value is sent to the host system for completion of the AC-Only RMS measurement calculation according to Equation 32.

$$AC_{Only}RMS = Gain \times Xac_{rms} = Gain \times \sqrt{\left| Xrms^2 - Xdc^2 - Xnoise^2 \right|} \qquad (32)$$

where:

- ACOnlyRMS = reported ACOnly RMS value of the DMM input signal
- Gain = gain factor (determined from the calibration procedure described in Section 3.1.2)

2.4.1.5.3 AC+DC (RMS) Measurement

Finally, the AC+DC RMS value of the input signal can then be calculated using the value computed DC and AC-Only values in Section 2.4.1.5.1 and Section 2.4.1.5.2 using Equation 33:

$$ACplusDC\,RMS = \sqrt{DC\_Value^2 + AC_{Only}RMS^2} \qquad (33)$$

2.4.1.5.4 Exponential Moving Average Filter

An exponential moving averaging filter has been implemented in the host environment for DC, AC-Only RMS, and AC+DC RMS measurements for output value smoothing purposes. The equation for this filter is shown in Equation 34:

$$OUTPUT_t = a \times X_t + (1 - a) \times OUTPUT_{(t-1)} \qquad (34)$$

where:

- $OUTPUT_t$ = filter output value at the present time t
- X_t = value of the measurement reading at time t
- a = filter weighting factor coefficient (value of 0 to 1)
- $OUTPUT_{(t-1)}$ = filter output value at the previous sampling time t-1

Lower values of the filter weighting coefficient a decreases the weighting of the current measurement while increasing the weighting on the previous output filter value, thus increases the smoothing effect of the filter. However, a smaller value also increases the initial measurement settling response time. A default value of 0.25 was used as the weighting factor coefficient for the TIDA-01012 reference design characterization, which provides a good balance of measurement stability and initial measurement settling time.

2.4.2 DMM Supporting Subsystems

2.4.2.1 Proximity Wake-Up Feature Enabled by CapTIvate

The wake-up on proximity feature is enabled by Texas Instrument's CapTIvate Technology. CapTIvate is a capacitive user interface design ecosystem that takes the next big step in design process evolution. It brings together a capacitive measurement technology, a design GUI, a capacitive touch software library, and a hardware development platform.

Proximity sensors are electrodes designed to detect a hand or other conductive object at some distance using greater sensitivity compared to buttons, sliders or wheels. For this reason, proximity sensors are self-capacitive and can have one or more electrodes.

For more details, see the CapTIvate Technology Guide.

2.4.2.1.1 Wake on Proximity Functionality

The CapTIvate technology in the MSP430 MCU enables the wake-on proximity feature for TIDA-01012. The electrodes used for this design are in self-capacitive mode; once proximity is detected, the MSP430 will toggle a GPIO high. Figure 40 shows a flow chart that describes the simple functionality implemented with the MSP430.
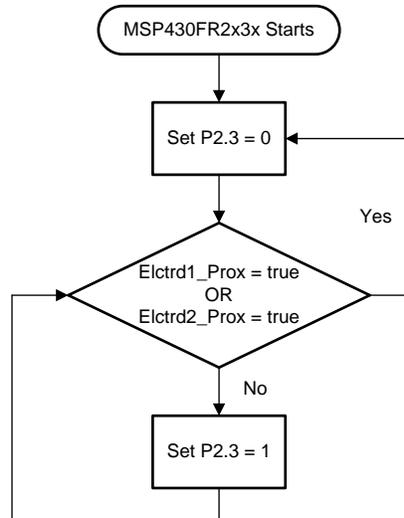

Figure 40. CapTIvate Wake-up Feature Flow Chart

2.4.2.1.2 CapTIvate Sensors

PCB sensors, also known as electrodes, are used to detect the proximity and touch to enable the use of capacitive touch. Also, as an extension to the electrodes on the PCB, the half-rings that are used to keep the of the red connector used for DMM measurements, J1, seen in Figure 41, were used to expand the electrodes on a third dimension in order to maximize the sensitivity of the CapTIvate peripheral.
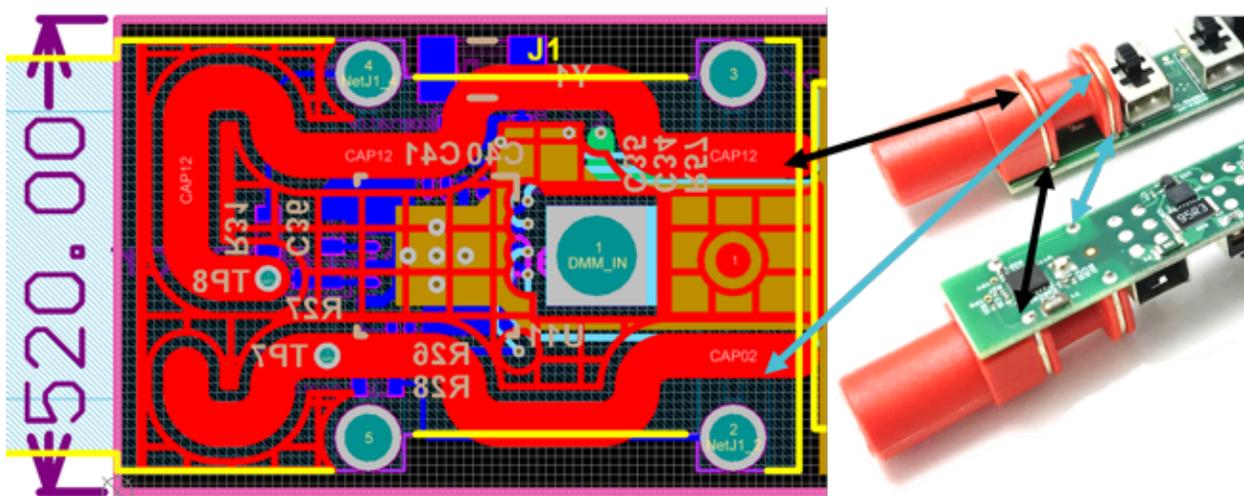
Figure 41. CapTIvate Electrodes

For more details on recommendations for the electrodes, see the CapTIvate Technology Guide.

2.4.2.1.3 Programming Interface

To enable the form factor for TIDA-01012, custom strapping was used along with a small 6-pin header to perform the programming for the MSP430 device. A custom connector was made to be used with the CapTIvate Development Kit with the connection details shown in Figure 42.
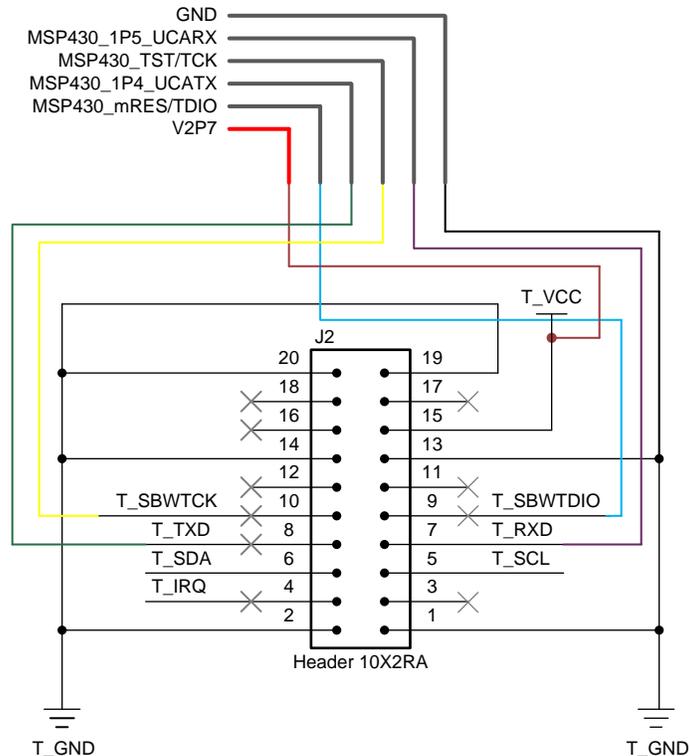
Figure 42. CapTIvate Custom Strapping

The MSP430 was programmed using the programmer included in the CapTIvate MCU Development Kit. For more details, see the CapTIvate Technology Guide.

2.4.2.1.4 Logic Level Translator

The logic level for the MSP430 device is 3.0 V. Because of the logic level difference between the host wireless MCU and the CC2640 device, a voltage level translator is used. The bidirectional LSF0102 level translator is used to translate between 3.0 V and 1.8 V. The signals translated are the MSP430's reset signal and the GPIO that the MSP430 device will use to signal CC2640 to change the power mode.

2.4.2.2 NFC Bluetooth Low Energy Pairing

The RF430CL330H device is used for Bluetooth low energy pairing. This device also enables low-power consumption by means of battery-less, RF powered operation, and details associated with each are described in subsequent sections.

2.4.2.2.1 Battery-Less Operation

The RF430CL330H can be RF Field Powered. The AC voltage provided on the antenna is rectified using a half bridge rectifier. Figure 43 shows the external rectifier diodes and storage capacitor as used in this TI Design. Schottky diodes are used to minimize the voltage drop. The RF430CL330H internally limits the voltage to 3.00 V, so the voltage used to power the RF430CL330H as well as the level translator used is ≈ 2.65 V to the connected MCU after the ≈ 0.35-V drop from the CDBU0130L Schottky diodes.
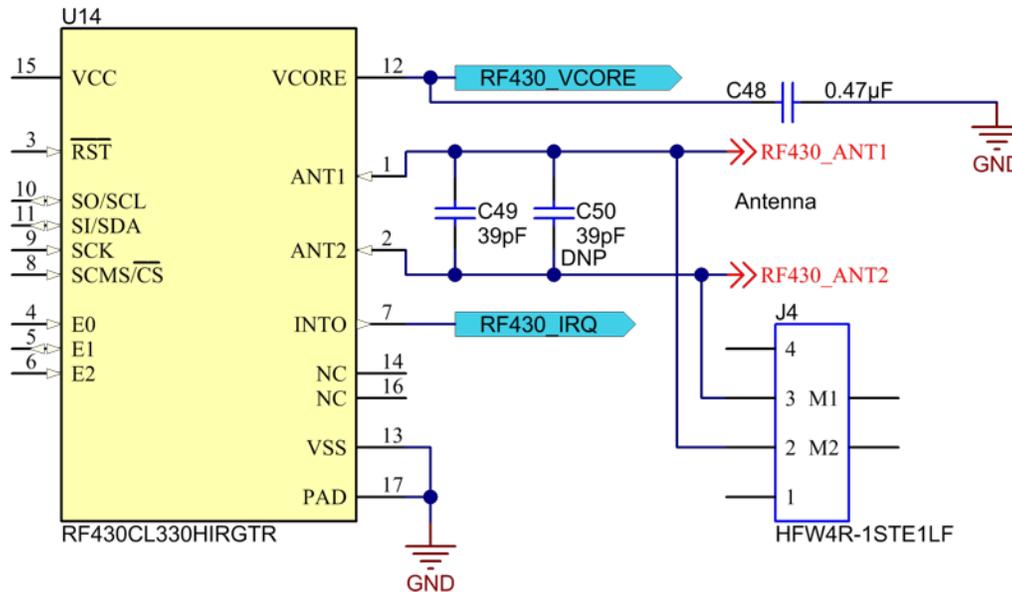
Figure 43. NFC Power Rail

2.4.2.2.2 Antenna

Due to the form factor of the TIDA-01012, an off-board flex PCB, antenna is used for the NFC Bluetooth low energy pairing and RF field power functionalities. The following sections describe the design and tuning process for the NFC antenna.

2.4.2.2.2.1 *Antenna Design*

A flex PCB antenna was designed for TIDA-01012. The NFC functionality was tested with an antenna similar to the one seen in Figure 44. For antenna design details, see the RF430CL330H Practical Antenna Design Guide.

Figure 44. NFC Flex PCB Antenna

2.4.2.2.2.2 *Antenna Tuning*

The Texas Instruments Dynamic NFC Interface Transponder RF430CL330H is an NFC Tag Type 4 device. It is the intermediary between wireless NFC communication and wired serial I^2C interface. The antenna connection is the interface from the RF430CL330H RF module to the outside world, and it is necessary to tune the antenna for best communication distance.

The external antenna is connected to Pin 2 and 3 of the RF430CL330H, and a resonance circuit is generated with the antenna, acting as an inductor, in parallel with the on-chip resonance capacitor as shown in Figure 45.
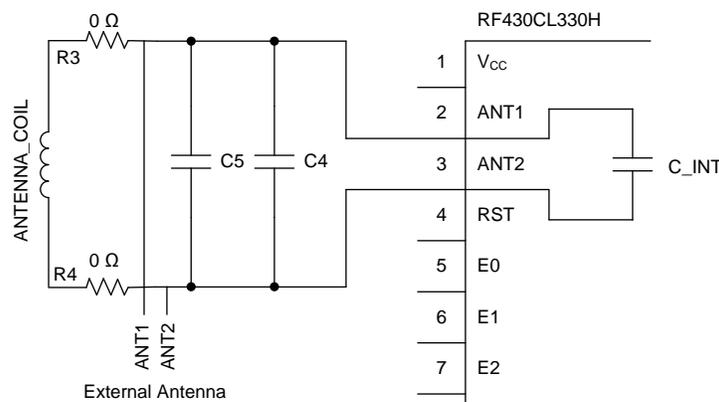
Figure 45. NFC Antenna Tuning

The goal when tuning an antenna for a tag is to generate a Q factor within the 30 to 50 range. The Q factor is calculated using the bandwidth and resonant frequency as shown in Equation 35. For optimum performance, the recommended operating resonance frequency (fres) is ≈ 13.7 MHz.

$$\frac{\text{Resonant Frequency} \left(13.56\,\text{MHz}\right)}{\text{Bandwidth}} = \text{Q Facto}$$

(35)

Note that the actual resonant frequency of the tag antenna is 13.70 MHz, but the operating frequency of the reader is 13.56 MHz. The tag is tuned to a slightly higher frequency (13.70 MHz) because there will be some detuning effect when it is brought near the reader antenna.

Resonant frequency and bandwidth should be captured using a spectrum analyzer. The test fixture should consist of a pickup coil connected to the input of a spectrum analyzer and a larger coil connected to the output of the spectrum analyzer tracking generator shown in Figure 46.
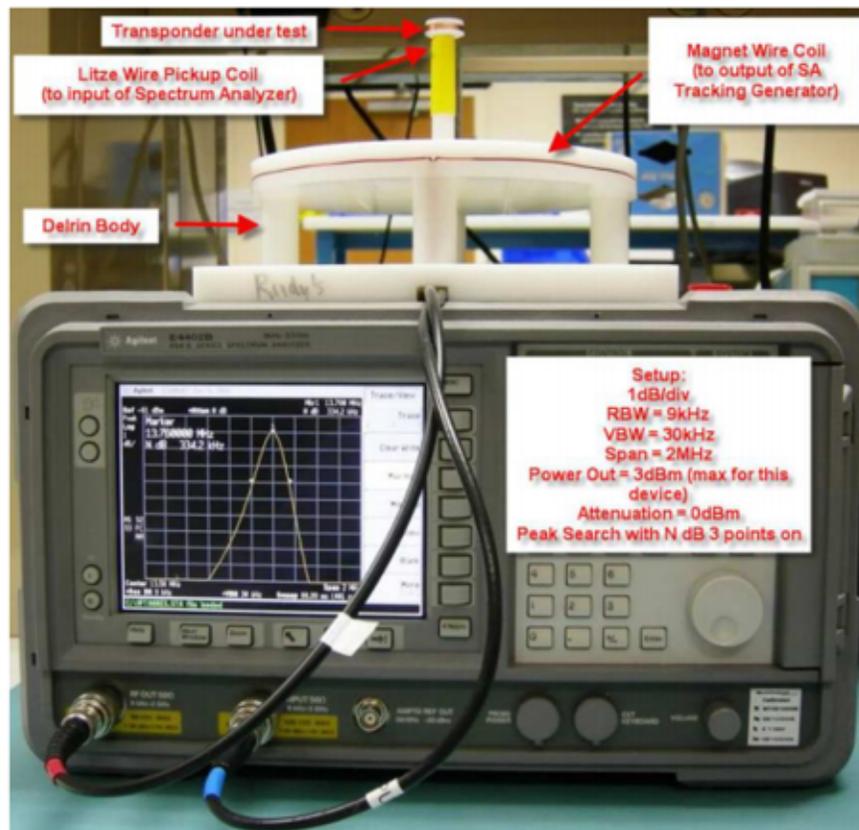
Figure 46. Spectrum Analyzer Tracking Generator

Once the fixture is connected to the analyzer, place the tag on top and enable the tracking generator output. The screen should center on the resonant frequency with a 2-MHz span. It should have at least –60-dBm reference level with a vertical scale of 1 dB/div in order to see a resonance curve. An example of a resonance curve can be seen in Figure 47.
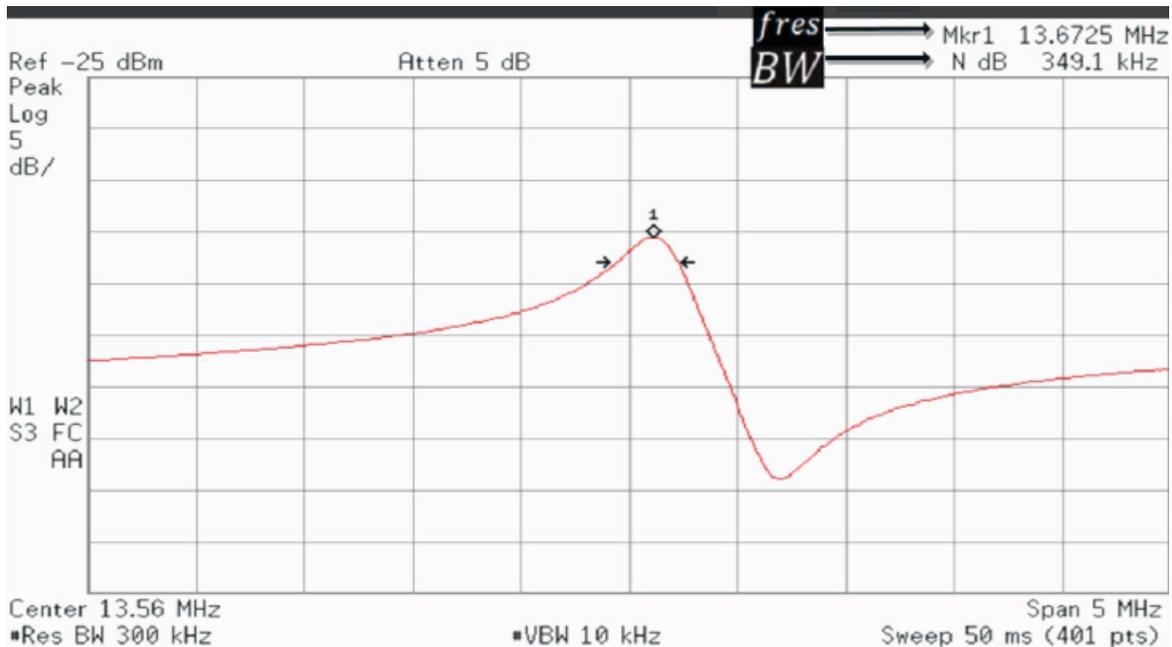
Figure 47. Example of Resonance Curve

View the bandwidth by enabling the N dB 3 points through the peak search menu, and use the bandwidth to calculate the Q factor. In order to manipulate the antenna Q factor, an external resonance capacitor can be added. It is recommended to use an external adjustable capacitor for fine-tuning. For production, it is recommended that the value of the variable capacitor is measured and replaced by an external fixed capacitor with the same value.

2.4.2.2.3   Pairing Sequence

The Bluetooth low energy pairing sequence implemented in the TIDA-01012 reference design is shown in Figure 48.
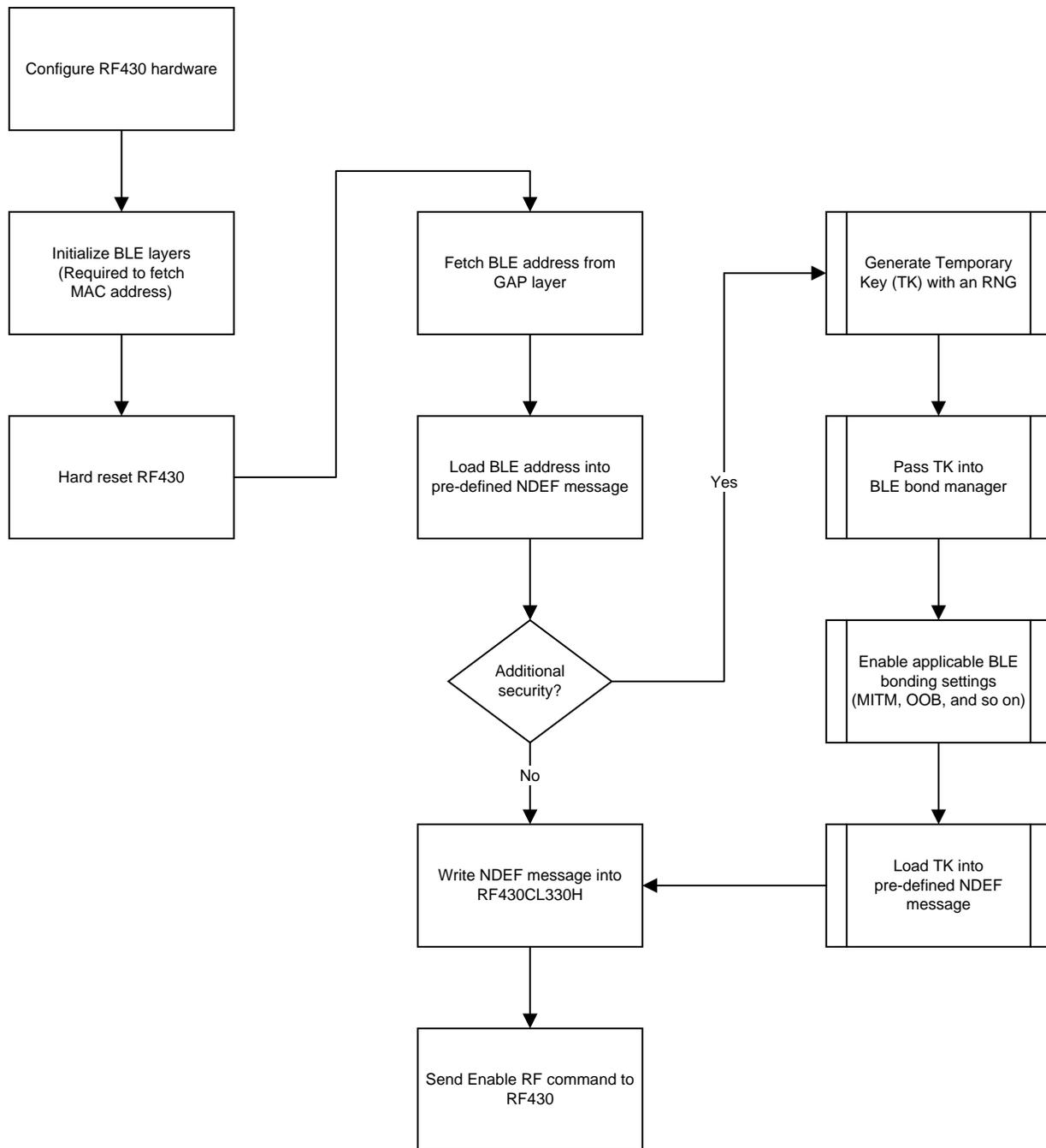
Figure 48. Bluetooth Low Energy Pairing Sequence Flow Chart

The Bluetooth low energy pairing is initiated when an NFC-enabled device reads the static message from the RF430CL330H that contains pairing information including the MAC address of the CC2640. This information can then be used by a Bluetooth low energy central device to connect to the CC2640. The Bluetooth low energy pairing application which has been implemented uses Just Works pairing and does not leverage the secure pairing capabilities that Bluetooth low energy offers. It is possible to add further security by using an out-of-band pairing configuration. However, at the time this TI Design was made, NFC-enabled smartphones in the market were not supporting the use of out-of-band pairing through NFC.

2.4.2.2.4 Logic Level Translator

The logic level for the RF430CL330H device is VRF. The voltage provided by the RF field, which will be approximately 2.6 V. Because of the logic level difference between the host wireless MCU and the CC2640 device, a voltage level translator is used. The bidirectional LSF0204 level translator is used to translate between VRF and 1.8 V. The signals translated are those used for I2C communication, the interrupt output (INTO/IRQ) and the nReset for the RF430.

2.4.2.3 Battery Management

This section details the details of this process along with design considerations associated with each blocks regarding battery management, details associated with each are described in subsequent sections.

2.4.2.3.1 Battery

The TIDA-01012 is designed to be powered by a rechargeable, 3.7-V, Lithium-Ion battery, allowing for a solution which can be easily charge, avoiding the need for alkaline batteries.

The battery used has the following characteristics:

- Capacity = C = 600 mAh
- Voltage range from 4.20 to 2.75 V

2.4.2.3.2 Charging

The bq24232 battery charger and power-path management IC was used for this TI Design. The battery is charged in three phases: conditioning pre-charge, constant-current fast charge (current regulation), and a constant-voltage tapering (voltage regulation). In all charge phases, an internal control loop monitors the IC junction temperature and reduces the charge current if an internal temperature threshold is exceeded.

Figure 49 illustrates a normal Li-ion charge cycle using the bq2423x:
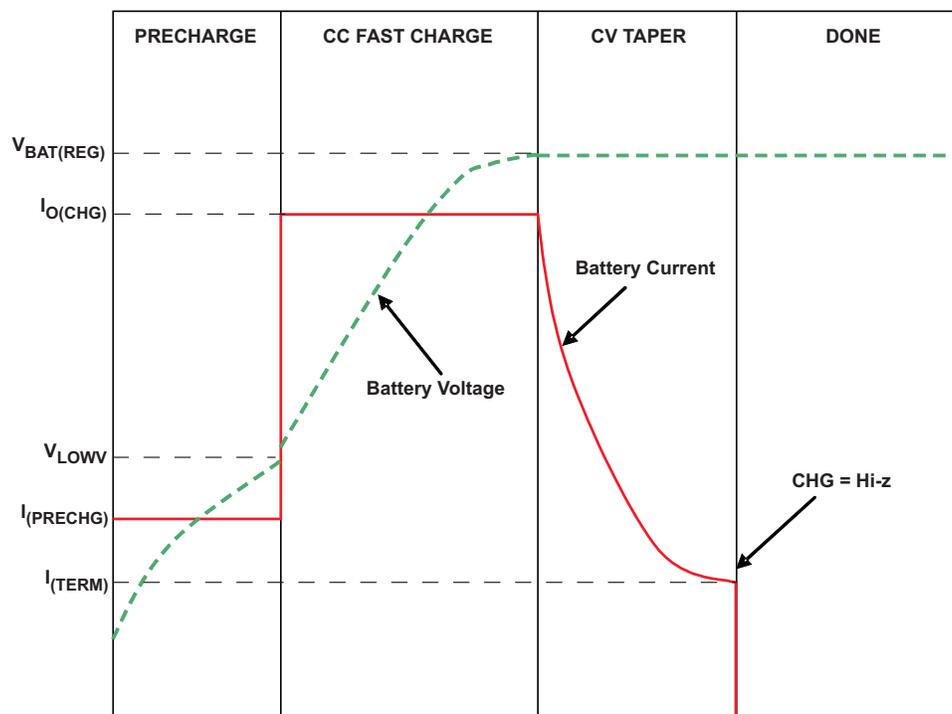
Figure 49. Li-Ion Battery Charge Cycle

$V_{BAT(REG)}$ is determined by the battery, so the device used matches the maximum battery voltage of 4.2 V. The $I_{O(CHG)}$ or I_{CHG} is determined by the battery manufacturer, usually being located between 0.20°C to 0.70°C. For this TI Design, I_{CHG} was selected to be 0.25°C and I_{TERM}, was selected be 0.01°C. For this TI Design, the enable pins EN1 and EN2 are set as follows: EN1 = 0 and EN2 = 1, which means that the maximum input current to the system will be set by a resistor on the I_{LIM} pin.

2.4.2.3.2.1 TS Function, TS Pin

This TI Design does not use the TS function. Thus, a fixed 10.00-kΩ resistor was connected from TS to VSS to maintain a valid voltage level on TS.

2.4.2.3.2.2 Fast Charge Current, I_{SET} Pin

The charge current, I_{CHG}, is set by a resistor, R_{ISET}, on the I_{SET} pin. R_{ISET} can be determined using K_{ISET}, which is found in the datasheet to be typically 870 AΩ and the targeted I_{CHG}. In this case, 0.25°C or 150 mA.

$$R_{ISET} = \frac{K_{ISET}}{I_{CHG}} = \frac{870 \text{ A}\Omega}{150 \text{ mA}} = 5.80 \text{ k}\Omega$$

(36)

The closest standard resistor value was selected so, R_{ISET} = 5.76 kΩ.

2.4.2.3.2.3 System Input Current Limit, I_{LIM} Pin

For this system, the maximum current input is set to 165 mA, allowing for the fast charge current as well as the current required by the system. I_{LIM} is set by a resistor, R_{ILIM}, on the I_{LIM} pin. R_{ILIM} can be determined using K_{ILIM}, which is found in the datasheet to be typically 1530 AΩ and the targeted I_{CHG} (165 mA in this case).

$$R_{ILIM} = \frac{K_{ILIM}}{I_{LIM}} = \frac{1530 \text{ A}\Omega}{165 \text{ mA}} = 9.27 \text{ k}\Omega$$

(37)

The closest standard resistor value was selected so, R_{ISET} = 9.31 kΩ.

2.4.2.3.2.4 Termination Current Threshold, I_{TERM} Pin

For this design, I_{TERM} is set to 0.01°C or 6 mA and it is set by a resistor, R_{ITERM}, on the I_{TERM} pin. R_{ITERM} is calculated using R_{ISET}, I_{TERM}, and K_{ITERM}, where K_{ITERM} can be found in the datasheet and it is typically 0.030 A.

$$R_{ITERM} = \frac{R_{ISET} \times I_{ITERM}}{K_{ITERM}} = \frac{5.76 \text{ k}\Omega \times 6 \text{ mA}}{0.030 \text{ A}} = 1.152 \text{ k}\Omega$$

(38)

The closest standard resistor value was selected so, R_{ITERM} = 1.15 kΩ.

2.4.2.3.2.5 Four-Hour Fast-Charge Safety Timer, TMR Pin

The bq24232 device contains internal safety timers for the pre-charge and fast-charge phases to prevent potential damage to the battery and the system. The timers begin at the start of the respective charge cycles. The timer values are programmed by connecting a resistor from TMR to VSS. Given that the maximum charging time, t_{MAXCHG}, has been set to 4 hours, the resistor value is calculated using Equation 39:

$$R_{TMR} = \frac{t_{MAXCHG}}{10 \times K_{TMR}} = \frac{4 \text{ hr} \times 3600 \text{ s/hr}}{10 \times 48 \text{ s/k}\Omega} = 30.0 \text{ k}\Omega$$

(39)

The closest standard resistor value was selected, so R_{TMR} = 30.1 kΩ.

2.4.2.3.3 Battery Gauge

The TIDA-01012 reference design uses the bq27426 to monitor and report state of charge of the LI-Ion battery. Although the bq27426 has the capability to monitor a number of battery parameters, the TIDA-01012 reads and reports state-of-charge and battery voltage for demonstration purposes. Features, programming, and device interrogation information and procedures can be found in the bq27426 Technical Reference Manual.

2.4.2.4 Power and Reset

As shown in Figure 50, a very simple, efficient, and cost-effective power supply has been implemented in the TIDA-01012 reference design. 3.0 V, 2.7 V, and 1.9 V were selected as the system operating voltage driven by the minimum voltages required by the ADC and the MSP430 CapTIvate development kit. With an overall voltage range of 2.75 to 4.20 V for the Li-Ion battery, the TPS62740 DC-DC buck converters serve to maximize battery life on the 2.7-V and 1.9-V rails, which consume most of the power.
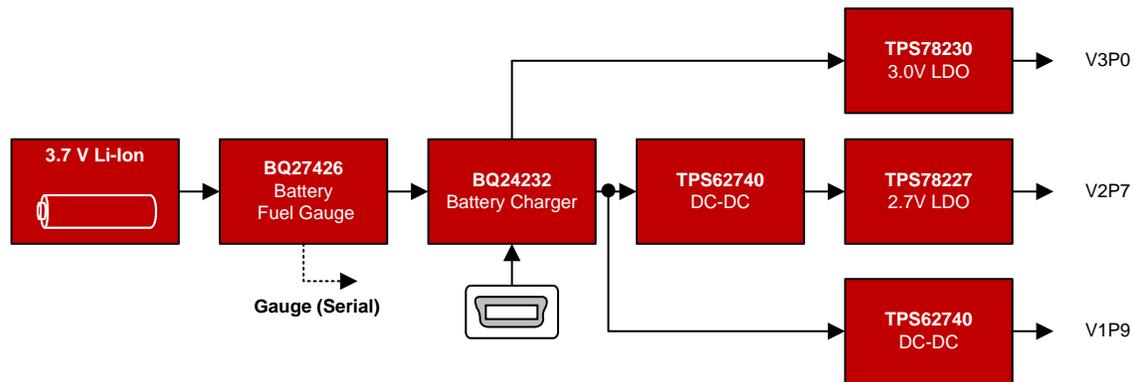
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Figure 50. Power Supply Subsystem

2.4.2.4.1 Battery Charger Regulation

Table 10 shows the voltage ranges for the input and output of the bq24232 battery charger device. The output of this device goes to the input of one LDO and two DC-DC converters.

Table 10. Battery Charger Input/Output Voltage Ranges

INPUT	VOLTAGE INPUT RANGE	VOLTAGE OUTPUT RANGE (TYP)
Battery	2.75 to 4.20 V	2.69 to 4.14 V
USB	5.00 V	4.85 V

2.4.2.4.2 3-V Rail

This rail is provided by TPS78230 fixed LDO. It powers the MSP430, which enables the CapTIvate capacitive touch used for wake-up feature. For this reason, this rail is always active, with an expected current draw of less than 10 µA.

2.4.2.4.3 2.7-V Rail

This rail is used to power the AFE. It is composed of two parts: the TPS62740 is set to 2.8 V, and the TPS78227 is a fixed gain 2.7-V LDO to maximize efficiency while providing a clean supply for the AFE.

2.4.2.4.4 1.9-V Rail

This rail is used to power the digital components of this reference design. It consists of a TPS62740 DC-DC converter set to 1.9 V to maximize system efficiency and battery life.

2.4.2.4.5 Reset Button

It is usually the case that for reset buttons, an RC debouncer circuit is used. However, in this TI Design, the TPS3422 replaces the RC debouncer as a push-button controller. This device allows for configurability of push duration time required for a reset, avoiding issues with the signal "bouncing" due to the mechanical properties of the button. The push time can be easily configured by driving the TS pin either high or low. In this TI Design, TS is driven high, setting the push-button time to "0 seconds" option (typically 150 μs).

For more details on this device, see the TPS3422 Product Folder.

3   Hardware, Software, Testing Requirements, and Test Results

3.1   Getting Started Hardware

Figure 51 highlights the various features of the TIDA-01012 hardware.
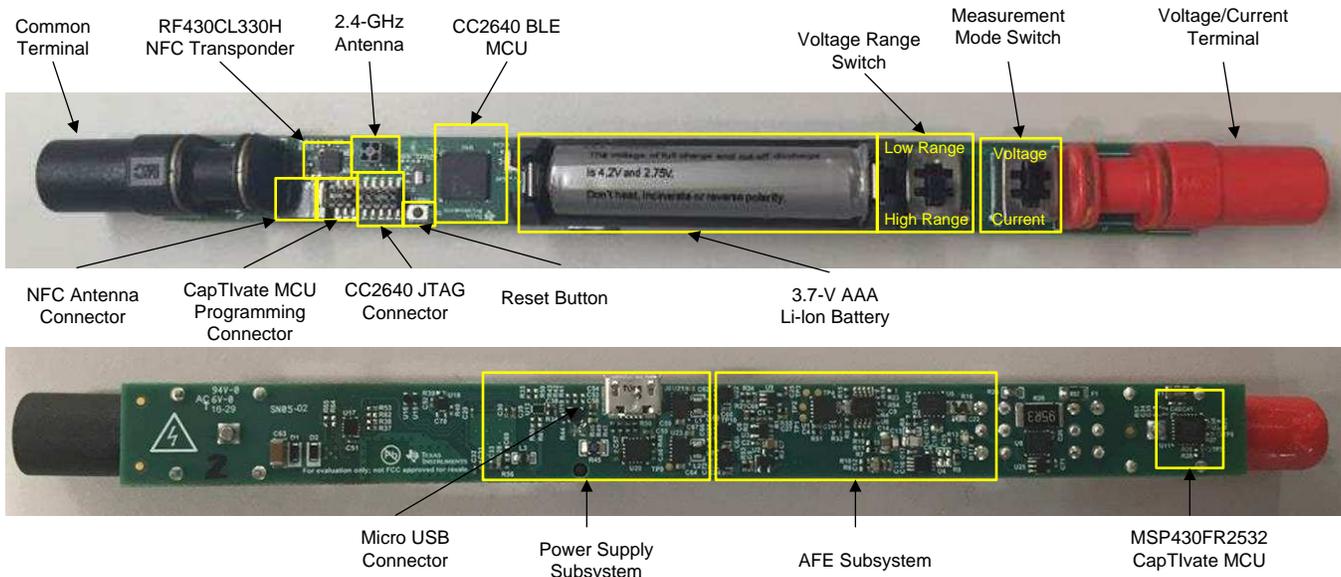
Figure 51. TIDA-01012 Hardware Features

3.1.1   Hardware Operation Overview

After the CC2640 firmware has loaded through the procedure outlined in Section 3.2.2, the board hardware and firmware can be initialized by momentarily pressing the reset button. The system will enter its active state and begin sending Bluetooth low energy advertisement beacons waiting for a host environment to recognize the system and begin the Bluetooth low energy connection process. The Bluetooth low energy host-device connection procedure is described in Section 3.2.4.2.

The TIDA-01012 will continue Bluetooth low energy advertisements for approximately 15 minutes. If a host has not initiated a connection within that time, the TIDA-01012 will automatically power down to conserve battery life. When in this power-down mode, the TIDA-01012 will no longer send Bluetooth low energy advertisement packets and, therefore, cannot connect to a host until the system returns to active mode through a CapTIvate event or the reset button is pressed. If a Bluetooth low energy connection is established, the auto-power-down counter is reset and will remain in a reset state until a Bluetooth low energy disconnect event occurs.

When a Bluetooth low energy connection with a host is established, the TIDA-01012 will begin streaming both DC and AC measurement data described in Section 2.4.1.5 to the host at approximately 6.5 samples per second. The TIDA-01012 will also send battery state-of-charge as well as battery voltage information to the host at approximately 1 sample per minute. The TIDA-01012 firmware also monitors the voltage range and measurement mode switches and sends the new state of these switches to the host when a change has been detected. The host will respond back to the TIDA-01012 with appropriate voltage or current range settings.

Initiating battery charges is accomplished by simply plugging in a powered micro-USB cable to the TIDA-01012 USB port. The system battery is charged at a rate of approximately 150 mA, so a completely discharged 600-mA hour battery can be charged in approximately 4 hours. The TIDA-01012 is or becomes completely operational when powered by the USB port, regardless of the state of the battery. Battery charge state is constantly monitored by the bq27426 battery gauge device.

Voltage and current measurements can be made by setting the switches as required for the measurement desired and connecting the device under test to the red and black terminals of the TIDA-01012. Switch mode settings are shown in Figure 51.

> NOTE: Because the TIDA-01012 reference design is focused primarily on measurement performance metrics, limited overvoltage and overcurrent protection mechanisms have been implemented in this design. The AFE includes a resettable fuse in the current measurement portion of the AFE to prevent against excessive current into the board. However, input overvoltage protection is not included on the voltage input section

Also, because the TIDA-01012 reference design uses the same terminals for both current and voltage measurements, take care when setting or changing the measurement mode switch when a device under test is connected to ensure overvoltage and overcurrent limits are not exceeded.

3.1.2 Calibration

To start calibration, open and connect to the LabVIEW environment and select the default offset and gain factor values as seen on Table 11.

Table 11. Calibration Setting Defaults

RANGE	GAIN	DC OFFSET	SYSTEM INTRINSIC RMS NOISE
Voltage, 50 mV	0.001	0	0
Voltage, 500 mV	0.001	0	0
Voltage, 5 V	1	0	0
Voltage, 50 V	1	0	0
Current, 50 mA	0.001	0	0
Current, 500 µA	0.000001	0	0

The gain factors were chosen to scale the full-range ADC values to a value that can be displayed on the LabVIEW environment. The following three-point calibration procedure was used to calibrate the TIDA-01012 board.
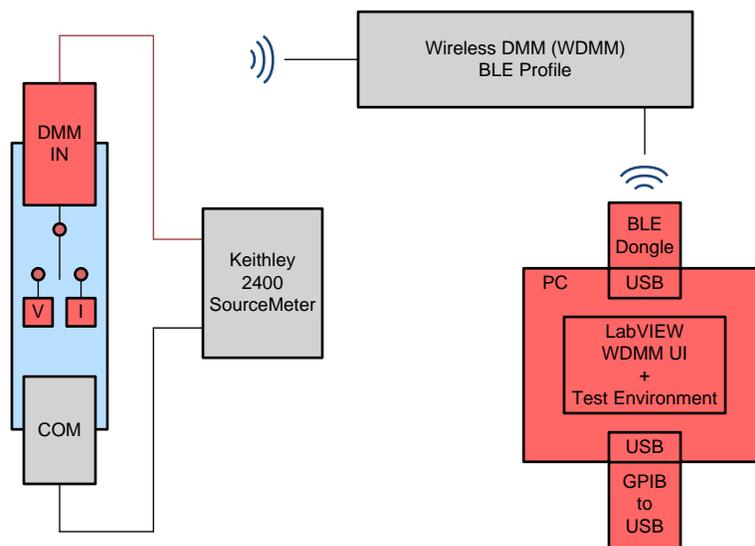
Figure 52. Calibration Setup

Calibration procedure is as follows:

1. Configure the system as shown on Figure 52.

2. Set the measurement mode switch to voltage or current.

3. Capture the TIDA-01012 voltage and current readings versus the Keithley 2400 voltage and current input at full range negative, zero (0), and full range positive settings.

4. Perform linear regression using these three data points to determine the gain (1/slope) and the DC and AC-Only (system intrinsic noise) offsets (y-intercept) values.

5. Repeat Steps 2 through 4 for all voltage and current ranges.

6. Enter the measured calibration constants on the "Calibration Constants" tab in the TIDA-01012 WDMM LabVIEW application environment (see Section 3.2.4.2).

7. Send and update the device calibration constants by clicking the "Update Device Calibration Constants" button.

3.2 Getting Started Firmware

3.2.1 Compiling Firmware

TI's Code Composer Studio™ (CCS) software (version 6.1.2), TI-RTOS 2.13.0.06, ARM Compiler Tools 5.2.5, and BLE-STACK V2.1.1 were used to develop the TIDA-01012 reference design.

The instructions to build the firmware assume that CCS and software packages have been setup and configured correctly. For more information on how to setup the development environment, consult the CC2640 Bluetooth low energy Software Developer's Guide that is provided in the Bluetooth low energy SDK's docs folder.

To import the CCS project:

1. Open CCS.

2. Click on the "Project" tool bar.

3. Select "Import CCS Projects…".

4. Select the radio option "Select archive file".

5. Navigate to the location where the TIDA-01012 Firmware.zip file is installed, then select and open the .zip file.

6. Check the selection box for both the "TIDA01012_ BLE _STACK" and "TIDA-01012 Application" projects.

7. Click the "Finish" button.

At this point, the CCS workspace should have both "TIDA-01012 Application" and "TIDA-01012_BLE _STACK" projects.

To build the firmware:

1. Set the TIDA-01012 _BLE _STACK project as the active project and build the project using Project → Build Project.

2. Set the TIDA-01012 Application project as the active project and build the project using Project → Build Project.

3.2.2   Loading Firmware

The SmartRF06 Evaluation Board Kit was used to program the CC2640. A 2-wire cJTAG interface was chosen to minimize TIDA-01012 PCB routing and footprint. The setup procedure is as follows:

1. Connect the 10-pin mini ribbon cable from J5 of the TIDA-01012 board to the P410 connector of the SmartRF06 EVM (10-pin ARM Cortex Debug Connector).
2. On the SmartRF06 EVM, set the source switch to "USB".
3. Remove the "VDD to EM" jumper.
4. Move the SmartRF06 EVM POWER switch to the ON position.

In this configuration, the TIDA-01012 board requires its own power source by installing the AAA Li-Ion battery or connecting a powered USB cable. See Figure 53 for a photo of the correct setup for connecting the TI Designs hardware to the SmartRF06 EVM. For more details on the SmartRF06 Evaluation Board Kit, see its user's guide.
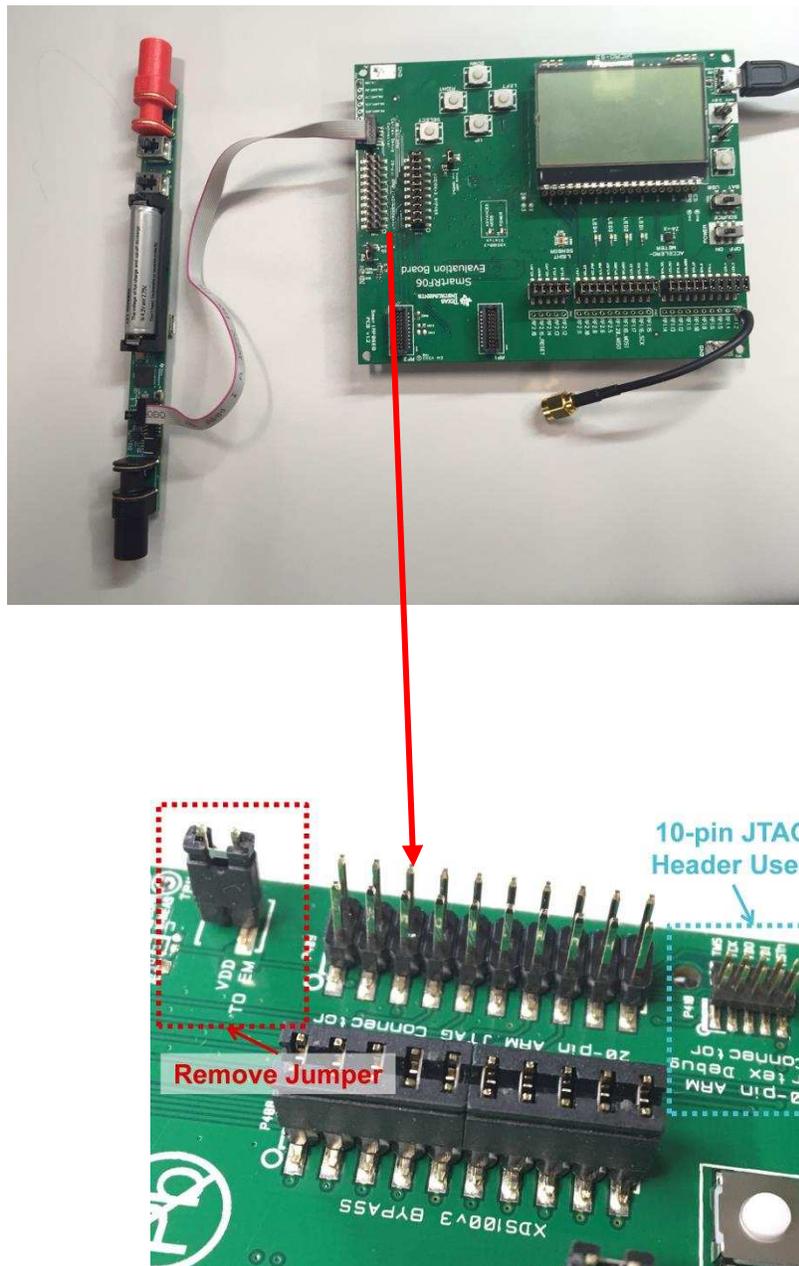
Figure 53. SmartRF06 Evaluation Board for Programming and Debugging

The following steps can be used for programming the CC2640 with CCS:

1. Download the TIDA01012 Peripheral Stack to the TIDA-01012 board by selecting the TIDA01012_Peripheral_Stack project as the active project and choosing Run → Debug.
2. Choose Run → Terminate to stop the debug.
3. Download the TIDA-01012 application by selecting the TIDA01012_Application project as the active project and choosing Run → Debug.

Note that the previous procedure is only needed for the initial download and whenever the Stack project is modified. As long as the Stack project is not modified, the only steps required are:

1. Build the application.
2. Download the application.

3.2.3   Firmware Task Description

The TI-RTOS based TIDA-01012 firmware includes three basic RTOS level tasks:

• Wireless DMM and Bluetooth low energy communication task (BLE_WDMM_taskFxn)
• ADC Reading and Measurement Calculations (WDMM_adcreadTaskFxn)
• System Power Management and Control (WDMM_pwr_mgmtTaskFxn)

3.2.3.1   *Wireless DMM and Bluetooth Low Energy Communication Task (BLE_WDMM_taskFxn)*

This task is responsible for managing the basic Bluetooth low energy GATT and GAP protocol communications, as well as handling general system and Bluetooth low energy communication related events originating from the other application tasks.

Events originating from other tasks include:

• Updating voltage and current ADC readings
• Updating battery status information
• CapTIvate sensing detection
• NFC sensing and handling
• System active or idle status

3.2.3.2   *ADC Reading and Measurement Calculations (WDMM_adcreadTaskFxn)*

This task is responsible for sampling and reading the ADS8885 ADC values, performing squaring, summing, and accumulating according to Equation 40, and forwarding the results to the BLE_WDMM_taskFxn for wireless communication to the host.

$$Xdc = \left(\frac{\sum_{k=0}^{N} Sample(k)}{N} \right)$$

(40)

$$Xrms^2 = \left(\frac{\sum_{k=0}^{N} Vsample^2(k)}{N} \right)$$

(41)

> **NOTE:** All required subsequent DMM calculations are performed in the host environment as described in Section 2.4.1.5.

3.2.3.3   *System Power Management and Control (WDMM_pwr_mgmtTaskFxn)*

This task is responsible for power management activities including battery state monitoring, auto-power-down control, and CapTIvate sensing, and NFC control based on Bluetooth low energy connectivity status.

3.2.4 Host Environment

A PC-based LabVIEW application in conjunction with a BlueBridge® BR-LE4.0-D2A Smart Ready BLE USB module from BlueRadios was chosen as the host environment for the TIDA-01012. The LabVIEW application provides not only the digital multimeter user interface, display, and control features for the digital multimeter application, but also the test instrumentation and automation mechanisms for system characterization and performance metrics. Note that NFC functionality is not supported with this platform. However, other popular mobile products such as NFC-ready smartphones, tablets, and so on also make ideal host platforms to support the TIDA-01012 reference design as demonstrated by the TIDC-01012 Android™ application. See the TIDC-01012 design guide for installation and feature details. The various features of the LabVIEW UI are shown in Figure 54.
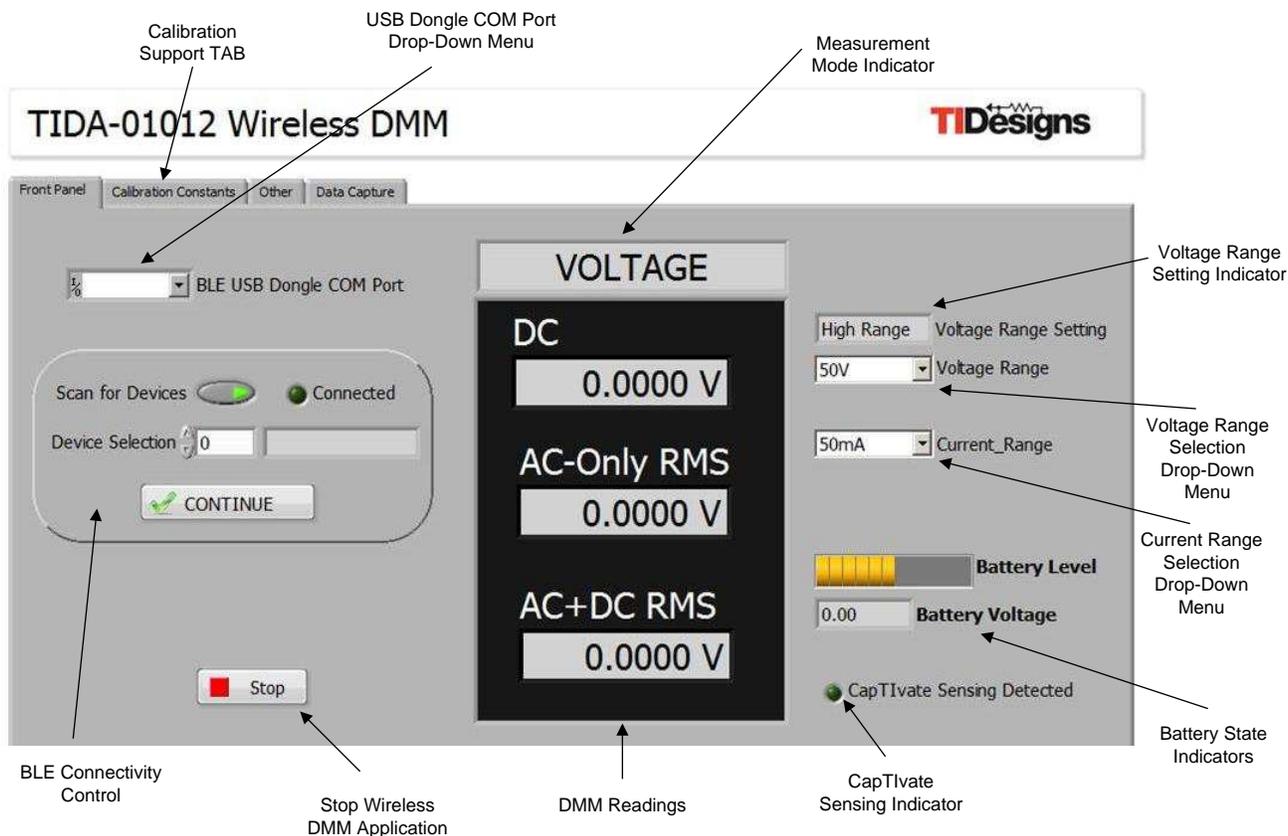
Figure 54. LabVIEW Host Environment Features

3.2.4.1 LabVIEW Host Environment Setup

The following describes the procedure for initial system setup, configuration, and launch:

- Download and install the National Instruments "LabVIEW Run-Time Engine 2014 - (32-bit)"
- Download and install the National Instruments "NI-VISA Run-Time Engine 14.0.1"
- Insert BR-LE4.0-D2A Smart Ready Bluetooth low energy dongle into computer or laptop. Windows should automatically locate and install the appropriate device driver.
- Insert a AAA Li-Ion battery in the TIDA-01012 hardware platform and press the reset button shown in Figure 51.
- Start the TIDA-01012 Wireless DMM application by launching the "TIDA-01012 Wireless DMM.exe" file found in the TIDA-01012 software downloads. Note that the TIDA-01012 Wireless DMM LabVIEW source files are also included in the software download for use and customization in the LabVIEW development environment.

> **NOTE:** A simple National Instruments registration process is required before downloading these installation files. This registration process prompt will appear automatically when the download is initiated.

The system is now ready for operation.

3.2.4.2 LabVIEW Host Environment Operation

The following procedure is used to search, identify, and connect the LabVIEW application to the TIDA-01012 hardware device:

1. Select the Bluetooth low energy dongle COM port from the "USB BLE Dongle COM Port" drop-down menu. If multiple COM options are shown and it is unclear which one to choose, unplug the Bluetooth low energy USB dongle, choose "Refresh" from the drop-down menu, and note which COM port is no longer listed. Re-insert the dongle and choose refresh again. The associated dongle COM port should reappear for selection.
2. Ensure the "Scan for Devices" indicator button in the BLE Connectivity Control section is enabled (that is, green). If not, click this button to enable scan for devices.
3. Start the application using the LabVIEW "Run" button found in the upper left corner of the screen. The system will spend several seconds searching for available Wireless DMM devices. The "Scan for Devices" indicator will remain green until the search is completed.
4. A list of available devices will now appear in the Device Selection drop-down list. Select the chosen device and press "Continue" to complete the Bluetooth low energy connection process. If no devices or the incorrect device is shown in the drop-down list, press reset on the TIDA-01012 hardware and press the "Scan for Devices" button again to retry.

Once connected, the "Connected" indicator will turn green and DMM readings will automatically begin to appear in the readings window. The various operations and features shown in Figure 54 can be used to control the hardware system are as follows:

- DMM Readings: This section automatically updates the DC, AC-only, and AC+DC readings approximately 6.5 updates per section.
- Measurement Mode Indicator: Indicates the DMM measurement mode (that is, voltage or current) as determined by the measurement mode switch shown in Figure 51.
- Voltage Range Setting Indicator: Indicates the DMM voltage range setting (that is, high voltage or low voltage) as determined by the voltage range switch shown in Figure 51. In high-voltage mode, voltage ranges 50 V, 5 V, or 500 mV can be selected. In low-voltage mode, only the 50-mV voltage range is available.
- Voltage Range Selection: This drop-down menu is used to select the desired voltage range (that is, 50 V, 5 V, 500 mV, 50 mV) as permitted by the voltage range switch previously described. If the chosen setting is not allowed by the voltage range switch setting, the default range is automatically selected instead.
- Current Range Selection: This drop-down menu is used to select the desired current range (that is, 50 mA, 500 µA).
- Battery State Indicators: These indicators are automatically updated once per minute to show approximate charge level of the battery as well as battery voltage.
- CapTIvate Sensing Indicator: This indicator momentarily turns green when the TIDA-01012 CapTIvate sensor has been activated.
- Stop Wireless DMM Application: This button can be used to stop the LabVIEW application.
- Calibration Support: This TAB provides support for setting and updating device calibration constants as determined by the calibration procedure described in Section 3.1.2.

3.2.4.3 Bluetooth Low Energy Attribute Table

A custom Bluetooth low energy profile was defined for a wireless DMM application. This profile was paired with the official SIG Device Information Service profile to create the complete table shown in Table 12.

NOTE: Attributes highlighted in blue represent those directly used by the TIDA-01012 Bluetooth low energy communications.

Table 12. TIDA-01012 Bluetooth Low Energy Profile Attribute Table

ATTRIBUTE HANDLE (DEC)	UUID	DESCRIPTION	READ/ WRITE	LENGTH (BYTES)	VALUE	DATA TYPE
1	0x2800	GATT primary service declaration				
2	0x2803	GATT characteristic declaration				
3	0x2A00	Device name			—	
4	0x2803	GATT characteristic declaration				
5	0x2A01	Appearance			—	
6	0x2803	GATT characteristic declaration				
7	0x2A04	Preferred connection parameters			—	
8	0x2800	GATT primary service declaration				
9	0x2800	GATT primary service declaration				
10	0x2803	GATT characteristic declaration				
11	0x2A23	System ID			—	
12	0x2803	GATT characteristic declaration				
13	0x2A24	Model number string			TIDA-01012 TI Design	
14	0x2803	GATT characteristic declaration				
15	0x2A25	Serial number string			Serial Number	
16	0x2803	GATT characteristic declaration				
17	0x2A26	Firmware revision string			Firmware Rev: 1.0	
18	0x2803	GATT characteristic declaration				
19	0x2A27	Hardware revision string			Hardware Rev: 1.0	
20	0x2803	GATT characteristic declaration				
21	0x2A28	Software revision string			Software Rev: 1.0	
22	0x2803	GATT characteristic declaration				
23	0x2A29	Manufacturer name string			Texas Instruments	
24	0x2803	GATT characteristic declaration				
25	0x2A2A	IEEE 11073-20601 regulatory certification data list			Experimental	
26	0x2803	GATT characteristic declaration				

Table 12. TIDA-01012 Bluetooth Low Energy Profile Attribute Table (continued)

ATTRIBUTE HANDLE (DEC)	UUID	DESCRIPTION	READ/ WRITE	LENGTH (BYTES)	VALUE	DATA TYPE
27	0x2A50	PnP ID			—	
28	0x2800	GATT primary service declaration				
29	0x2803	GATT characteristic declaration				
30	0x1F2B[1]	DC reading	R	4	—	INT32
31	0x2902	DC_Reading notification control	W	2	—	UINT16
32	0x2803	GATT characteristic declaration				
33	0xDE2F[1]	AC reading	R	8	—	INT64
34	0x2902	AC reading notification control	W	2	—	UINT16
35	0x2803	GATT characteristic declaration				
36	0x5D3D[1]	Voltage range 1 cal constants	R/W	12	—	FLOAT, INT32, INT32[2]
37	0x2803	GATT characteristic declaration				
38	0x44B6[1]	Voltage range 2 cal constants	R/W	12	—	FLOAT, INT32, INT32[2]
39	0x2803	GATT characteristic declaration				
40	0xDB69[1]	Voltage range 3 cal constants	R/W	12	—	FLOAT, INT32, INT32[2]
41	0x2803	GATT characteristic declaration				
42	0x0602[3]	Voltage range 4 cal constants	R/W	12	—	FLOAT, INT32, INT32[4]
43	0x2803	GATT characteristic declaration				
44	0x4084[3]	Current range 1 cal constants	R/W	12	—	FLOAT, INT32, INT32[4]
45	0x2803	GATT characteristic declaration				
46	0xD358[3]	Current range 2 cal constants	R/W	12	—	FLOAT, INT32, INT32[4]
47	0x2803	GATT characteristic declaration				
48	0xACE3[3]	Initiate power down	W	1	—	UINT8
49	0x2803	GATT characteristic declaration				
50	0xE636[3]	Voltage range select	W	1	—	UINT8
51	0x2803	GATT characteristic declaration				
52	0x76FF[3]	Voltage range mode	R	1	—	UINT8
53	0x2902	Voltage range mode notification	W	2	—	UINT16
54	0x2803	GATT characteristic declaration				

[1]   "XXXX" subset of the 128-bit F000-XXXX-0451-4000-B000-0000-0000-0000 UUID
[2]   Gain, DC_Offset, AC_Offset
[3]   "XXXX" subset of the 128-bit F000-XXXX-0451-4000-B000-0000-0000-0000 UUID
[4]   Gain, DC_Offset, AC_Offset

Table 12. TIDA-01012 Bluetooth Low Energy Profile Attribute Table (continued)

ATTRIBUTE HANDLE (DEC)	UUID	DESCRIPTION	READ/ WRITE	LENGTH (BYTES)	VALUE	DATA TYPE
55	0xDB7F[3]	Measurement mode	R	1	—	UINT8
56	0x2902	Measurement mode notification	W	2	—	UINT16
57	0x2803	GATT characteristic declaration				
58	0x4323[3]	Current range select	W	1	—	UINT8
59	0x2803	GATT characteristic declaration				
60	0xA367[3]	Battery capacity level	R	2	—	UINT16
61	0x2902	Battery capacity level notification	W	2	—	UINT16
62	0x2803	GATT characteristic declaration				
63	0x9117[3]	Battery voltage level	R	2	—	UINT16
64	0x2902	Battery voltage level notification	W	2	—	UINT16
65	0x2803	GATT characteristic declaration				
66	0xFC10[3]	CapTIvate signal	R	1	—	UINT8
67	0x2902	CapTIvate notification	W	2	—	UINT16

3.3 Testing and Results

The following test equipment was used in the various characterization tasks for capturing, reporting, and evaluating the performance of the TIDA-01012 reference design.

- Keithley 2400 Source and Measurement Unit
- HP 33120A Function and Waveform Generator
- Agilent 34401A Multimeter
- GPIB-to-USB Interface

The following specific test configurations for each characterization activity are described in detail in Section 3.3.1.

- Voltage Measurement Mode Resolution (see Section 3.3.1.1)
- Current Measurement Mode Resolution (see Section 3.3.1.2)
- Voltage Measurement Mode Accuracy and Linearity (see Section 3.3.1.3)
- Current Measurement Mode Accuracy and Linearity (see Section 3.3.1.4)
- AC Voltage Measurement Mode Frequency Response (see Section 3.3.1.5)
- AC Current Measurement Mode Frequency Response (see Section 3.3.1.6)

3.3.1 Test Setups, Procedures, and Results

The following sections describe the test setups, procedures, and performance results for the various tests that were performed on the TIDA-00879 reference design board. Offset and gain calibration at room temperature was performed on the target board prior to executing and capturing data.

3.3.1.1 Voltage Measurement Mode Resolution

Figure 55 shows the test setup for characterizing voltage measurement resolution performance. The DC voltage mode was used for these measurements.
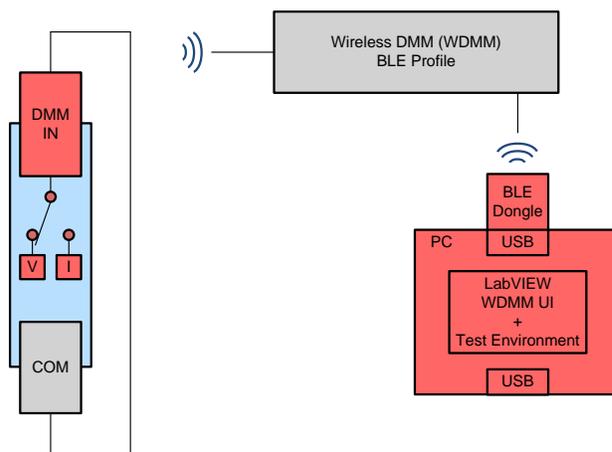
Test procedure:

1. Short the DMM IN and COM terminals.
2. Connect the TIDA-01012 board to the LabVIEW test environment.
3. Select the TIDA-01012 voltage mode.
4. Select the desired TIDA-01012 voltage range.
5. Capture and plot 1000 readings using the serial port and host environment (for example, LabVIEW).
6. Repeat for all four TIDA-01012 voltage ranges.

Figure 55. Voltage Resolution Test Configuration

The following graphs show the results from all four voltage ranges. The red plot lines represent the targeted resolution accuracy limits shown in Table 1.
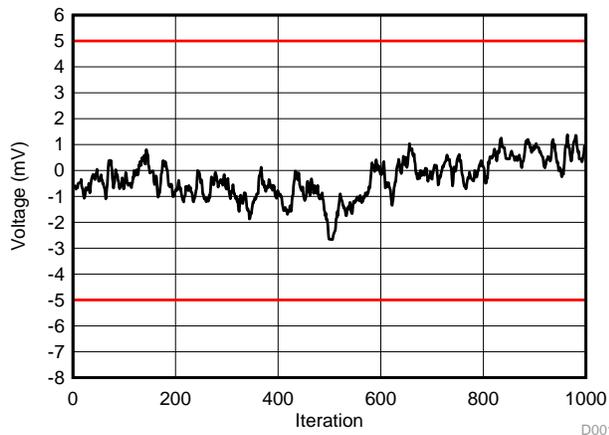

Figure 56. Noise Floor, DC Voltage Mode (50-V Range, 0-V Input)
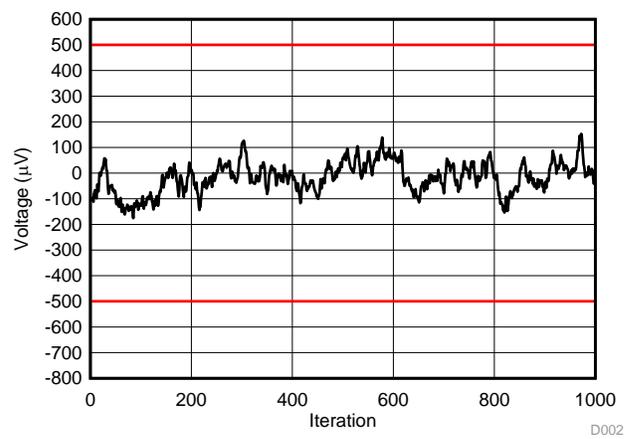
Figure 57. Noise Floor, DC Voltage Mode (5-V Range, 0-V Input)
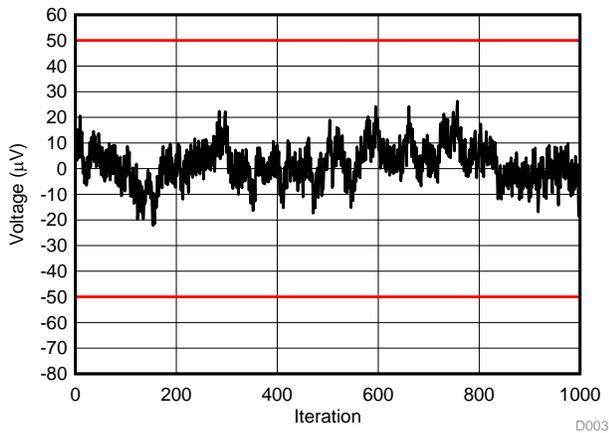
Figure 58. Noise Floor, DC Voltage Mode (500-mV Range, 0-V Input)
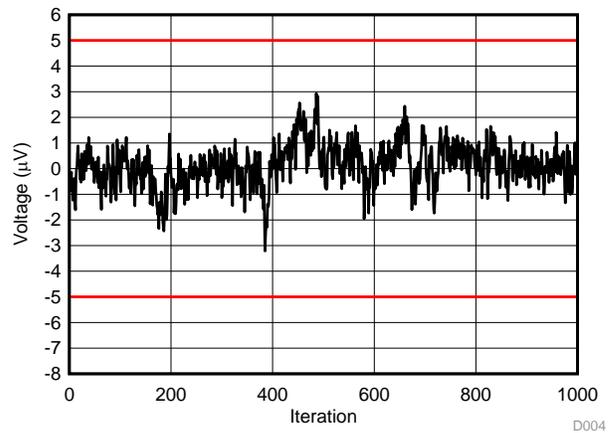
Figure 59. Noise Floor, DC Voltage Mode (50-mV Range, 0-V Input)

3.3.1.2 *Current Measurement Mode Resolution*

Figure 60 shows the test setup for characterizing current measurement resolution performance. The DC current mode was used for these measurements.
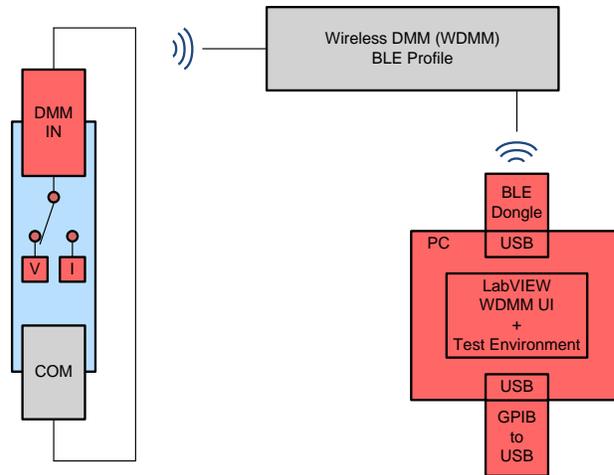
Test procedure:

1. Short the DMM IN and COM terminals.
2. Open LabVIEW's TIDA-01012 test environment.
3. Select the TIDA-01012 DC current mode.
4. Select the desired TIDA-01012 current range.
5. Capture and plot 1000 readings using the serial port and LabVIEW host environment.
6. Repeat for both TIDA-01012 current ranges.

Figure 60. Current Resolution Test Configuration

The following graphs show the results for both current ranges. The red plot lines represent the targeted resolution accuracy limits shown in Table 1.
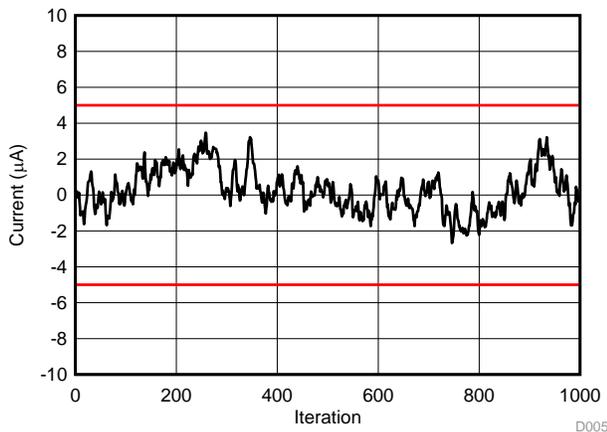
Figure 61. Noise Floor (50-mA Range, 0-V Input)
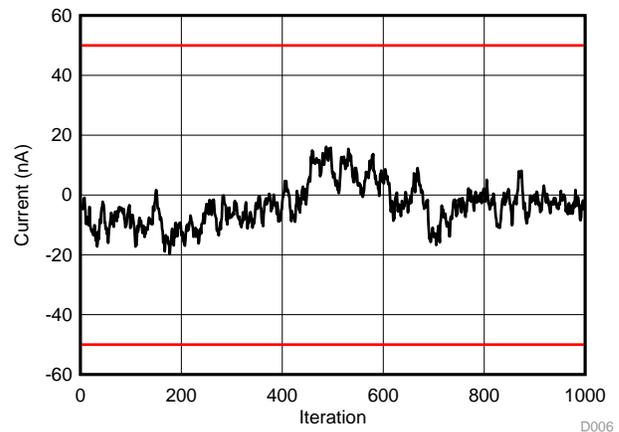
Figure 62. Noise Floor (500-µA Range, 0-V Input)

3.3.1.3   *Voltage Measurement Mode Accuracy and Linearity*

Figure 63 shows the test setup for characterizing voltage measurement accuracy and linearity. The DC voltage mode was used for these measurements.
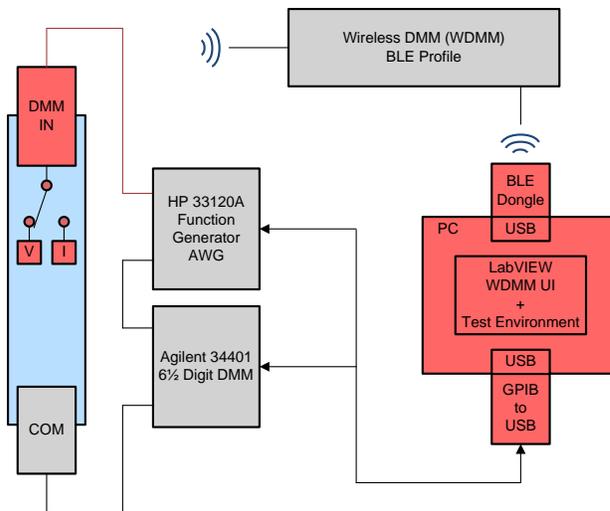
Figure 63. Voltage Accuracy and Linearity Test Configuration

Test procedure:

1. Connect the test equipment to the TIDA-01012 board as shown in Figure 63.

2. Open the LabVIEW test environment.

3. Select the TIDA-01012 DC voltage mode.

4. Select the TIDA-01012 desired voltage range.

5. Set the Keithley 2400 to Vsource mode.

6. Set the AG 34401 to DC voltage mode.

7. Sweep the Keithley 2400 SourceMeter DC voltage from the minimum range voltage to maximum range voltage for 500 steps.

8. Capture the TIDA-01012 readings and AG 33401 Multimeter (V_{DC}) readings using the host system.

9. Plot the error voltage (TIDA-01012 value minus the V_{DC} value) versus the V_{DC} values.

10. Repeat steps 4 through 9 for all voltage ranges

The following graphs show the data taken from all four voltage ranges. The red plot lines represent the targeted resolution accuracy limits shown in Table 1.
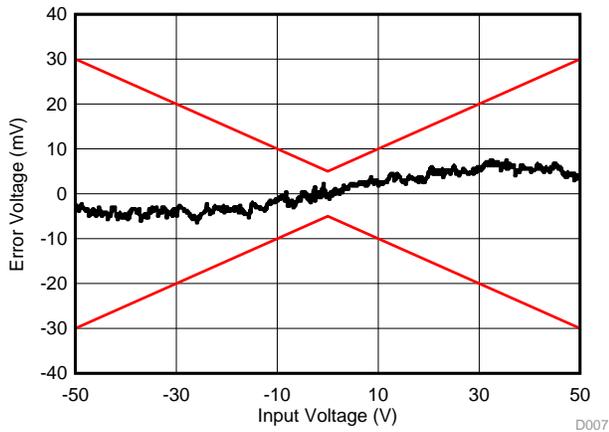
Figure 64. Linearity Plot (50-V Range)
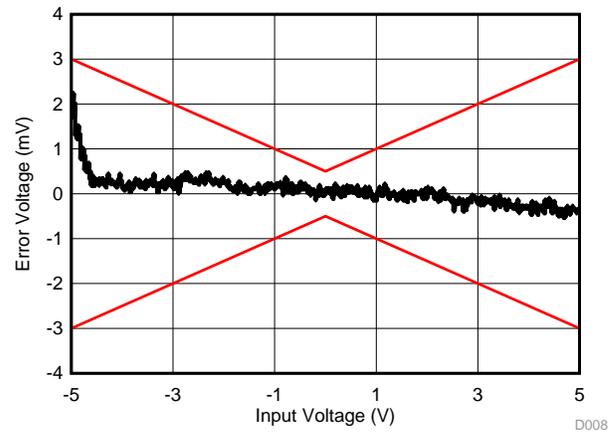
Figure 65. Linearity Plot (5-V Range)
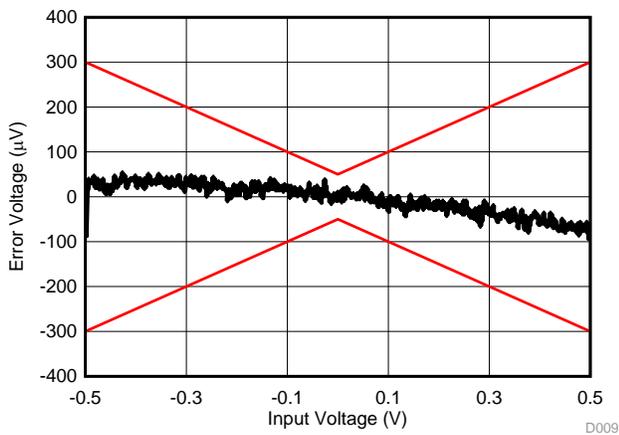
Figure 66. Linearity Plot (500-mV Range)
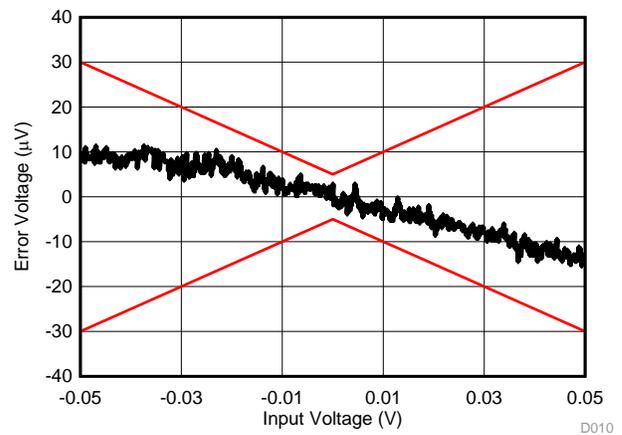
Figure 67. Linearity Plot (50-mV Range)

3.3.1.4 Current Measurement Mode Accuracy and Linearity

Figure 68 shows the test setup for characterizing current measurement accuracy and linearity. The DC current mode was used for these measurements.
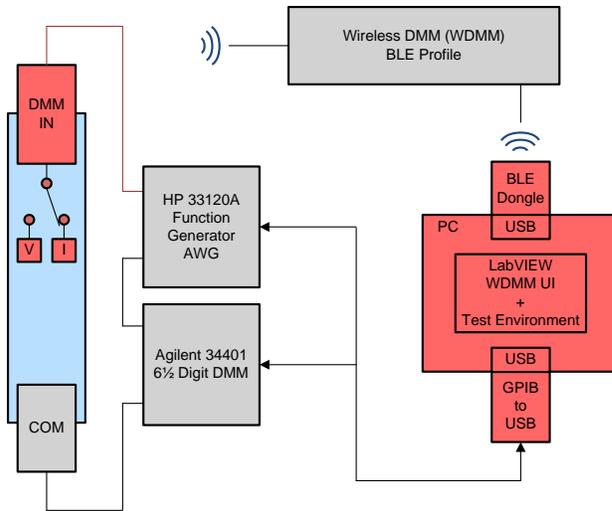
Figure 68. Current Accuracy and Linearity Test Configuration

Test procedure:

1. Connect the test equipment to the TIDA-01012 board as shown in Figure 68.
2. Power up the TIDA-01012 board in test mode.
3. Select the TIDA-01012 DC current mode.
4. Select the desired TIDA-01012 current range.
5. Set the Keithley 2400 to Isource mode.
6. Set the AG 34401 to DC current mode.
7. Sweep the Keithley 2400 SourceMeter DC current from the minimum range current to maximum range current for 600 steps.
8. Capture the TIDA-01012 readings and AG 34401 MultiMeter (I_{DC}) readings using the host system.
9. Plot the error voltage (TIDA-01012 value minus the I_{DC} value) versus the I_{DC}.
10. Repeat steps 4 through 9 for both current ranges.

The following graphs show the data taken from both current ranges. The red plot lines represent the targeted resolution accuracy limits shown in Table 1.
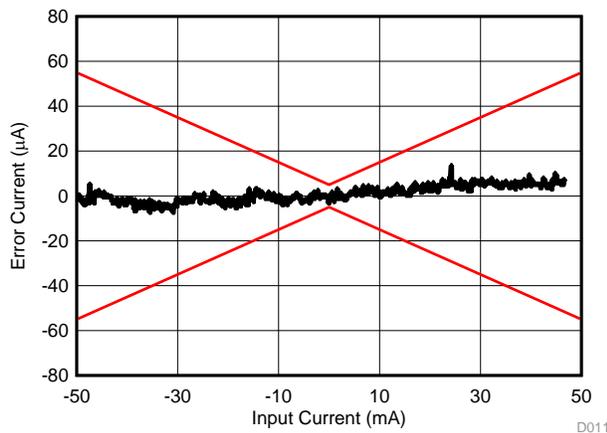

Figure 69. Linearity Plot (50-mA Range)
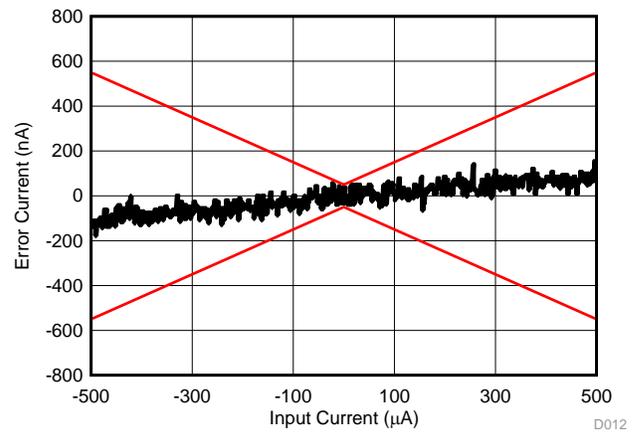
Figure 70. Linearity Plot (500-µA Range)

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3.3.1.5   AC Voltage Measurement Mode Frequency Response

Figure 71 shows the test setup for characterizing AC voltage measurement accuracy as a function of frequency. The AC voltage mode was used for these measurements.
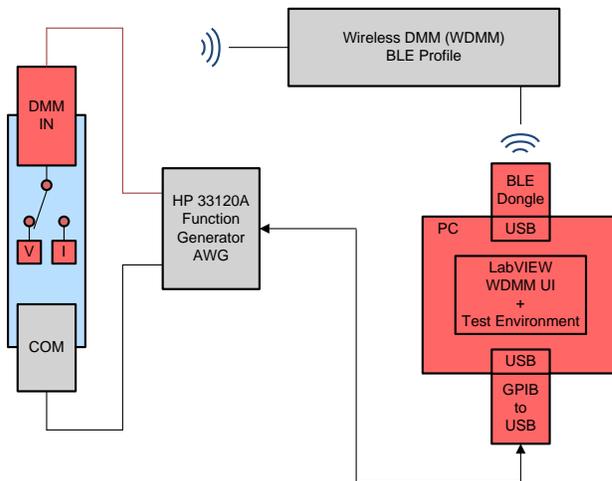
Figure 71. AC Voltage Frequency Response Test Configuration

Test procedure:

1. Connect the test equipment to the TIDA-01012 board as shown in Figure 71.
2. Use the LabVIEW TIDA-01012 test environment.
3. Select the TIDA-01012 AC voltage mode.
4. Select the TIDA-01012 5-V range setting.
5. Set the HP 33120A to sine wave mode with a 2.5-V amplitude and 0-V DC offset voltage.
6. Sweep the HP 33120A from 10 Hz to 100 kHz.
7. Capture and plot the TIDA-01012 readings versus frequency.
8. Repeat steps 5 through 7 for the following settings:

   (a) Sine wave, 2.5-V amplitude, 2.5-V DC offset
   (b) Square wave, 2.5-V amplitude, 50% duty cycle, 0.0-V DC offset
   (c) Square wave, 2.5-V amplitude, 50% duty cycle, 2.5-V DC offset
   (d) Square wave, 2.5-V amplitude, 20% duty cycle, 2.5-V DC offset

The following graphs show the results from these measurements.
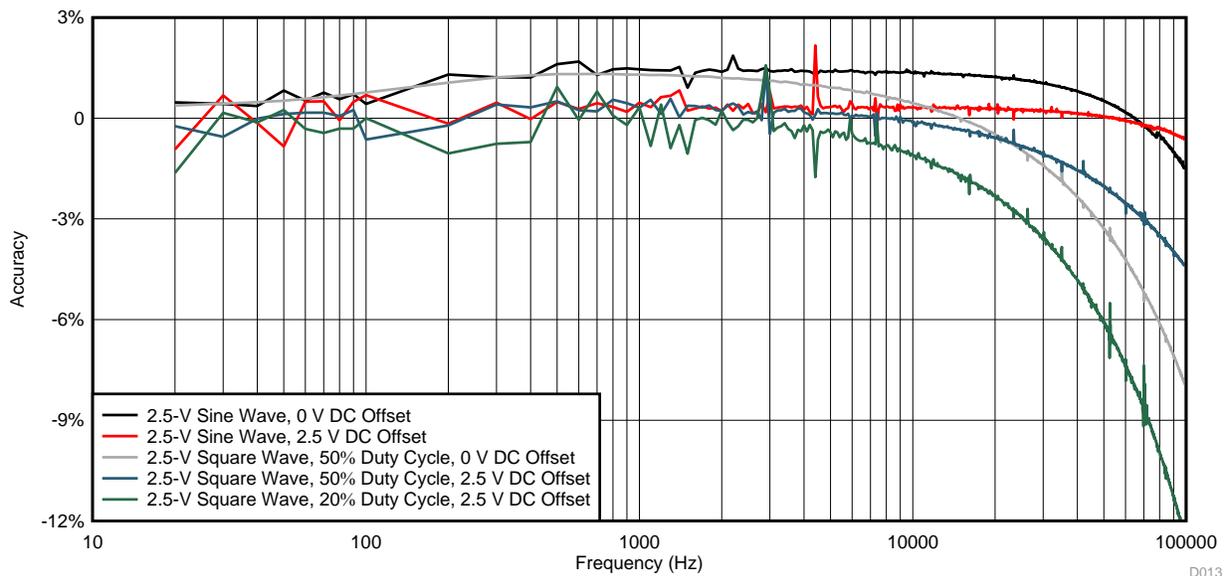
Figure 72. AC Voltage Frequency Response (5-V Range)

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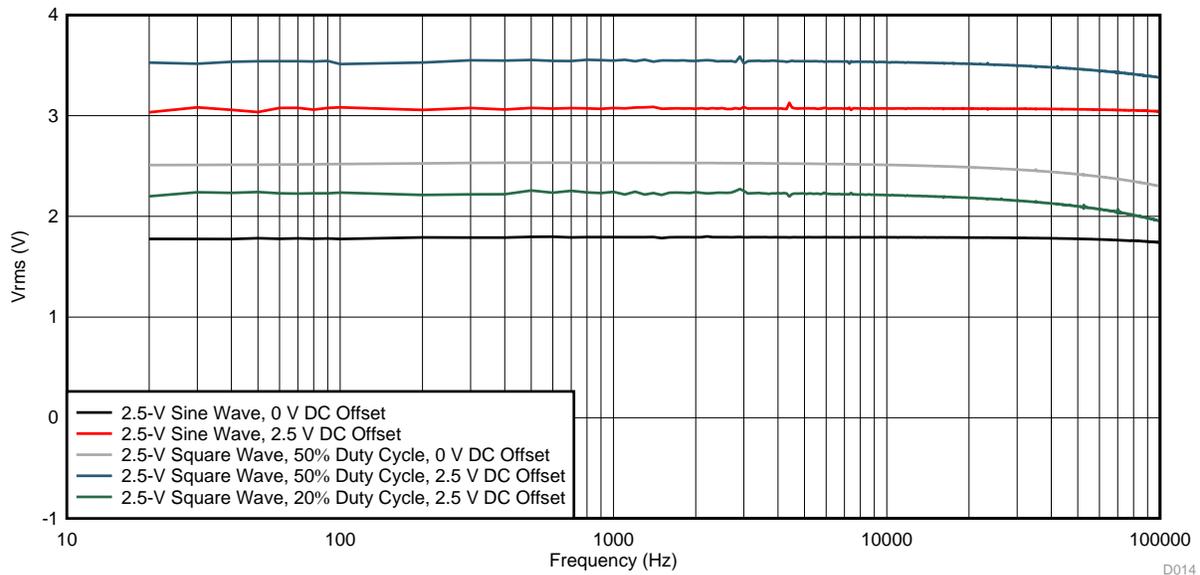
Figure 73. AC Voltage Frequency Response (5-V Range)
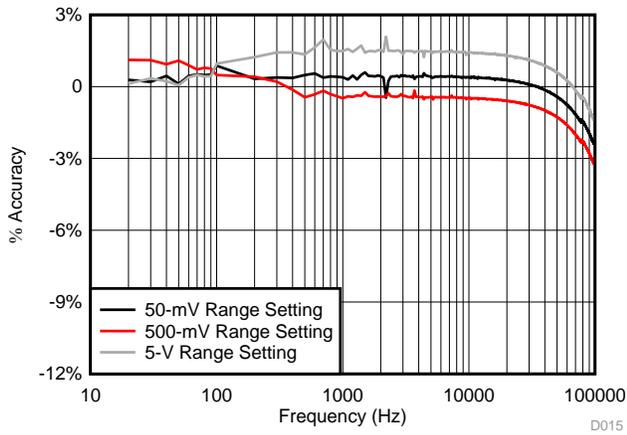
**Figure 74. AC Voltage Frequency Response
(5-V, 500-mV, 50-mV Sine Wave With 0-V DC Offset)**
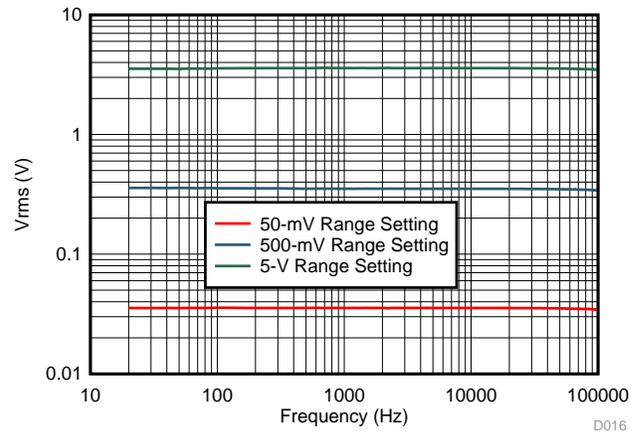
**Figure 75. AC Voltage Frequency Response
(5-V, 500-mV, 50-mV Sine Wave With 0-V DC Offset)**

3.3.1.6   AC Current Measurement Mode Frequency Response

Figure 76 shows the test setup for characterizing AC current measurement as a function of frequency. The AC current mode was used for these measurements.
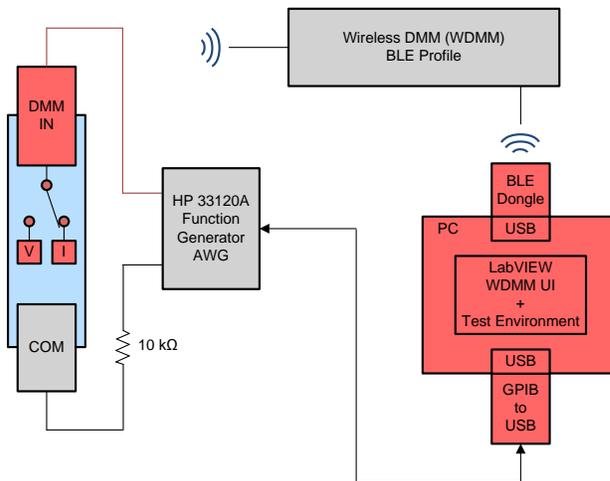
Figure 76. AC Current Frequency Response Test Configuration

Test procedure:

1. Connect the test equipment to the TIDA-01012 board as shown in Figure 76.
2. Use the LabVIEW test environment.
3. Select the TIDA-01012 AC current mode.
4. Select the TIDA-01012 500-µA range setting.
5. Set the HP 33120A to sine wave mode with a 2.5-V amplitude and 0-V DC offset voltage.
6. Sweep the HP 33120A from 10 Hz to 100 kHz.
7. Capture and plot the TIDA-00879 readings versus frequency.
8. Repeat steps 5 through 7 for the following settings:

    (a) Sine wave, 2.5-V amplitude, 2.5-V DC offset

    (b) Square wave, 2.5-V amplitude, 50% duty cycle, 0.0-V DC offset

    (c) Square wave, 2.5-V amplitude, 50% duty cycle, 2.5-V DC offset

    (d) Square wave, 2.5-V amplitude, 20% duty cycle, 2.5-V DC offset

The following graphs show the data taken from both current ranges. The red plot lines represent the targeted resolution accuracy limits shown in Table 1.
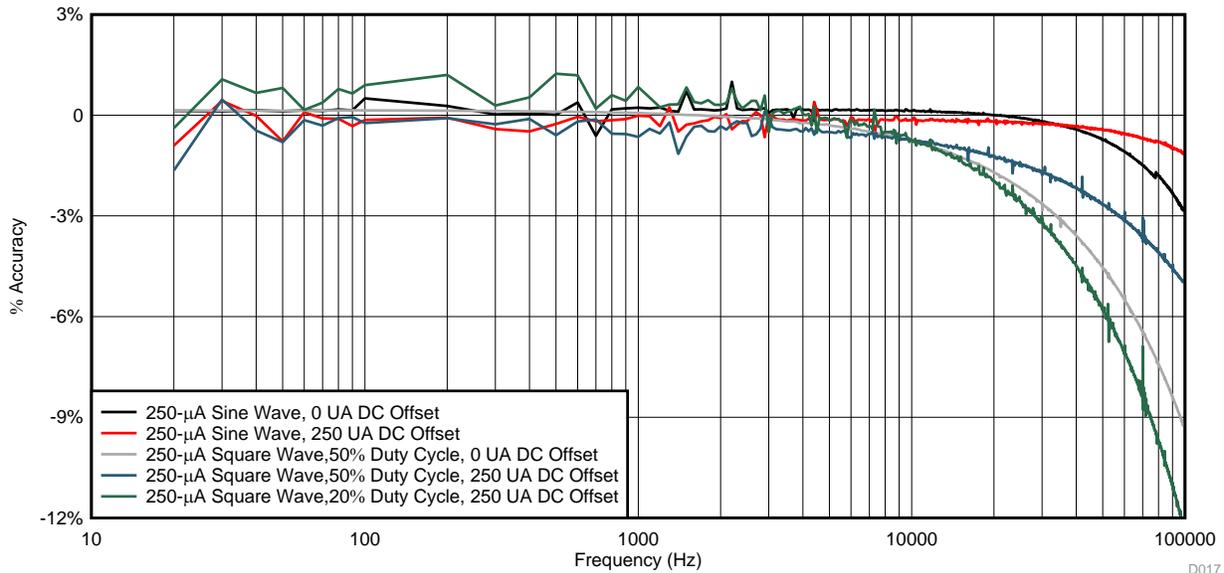
Figure 77. AC Current Frequency Response (500-µA Range)

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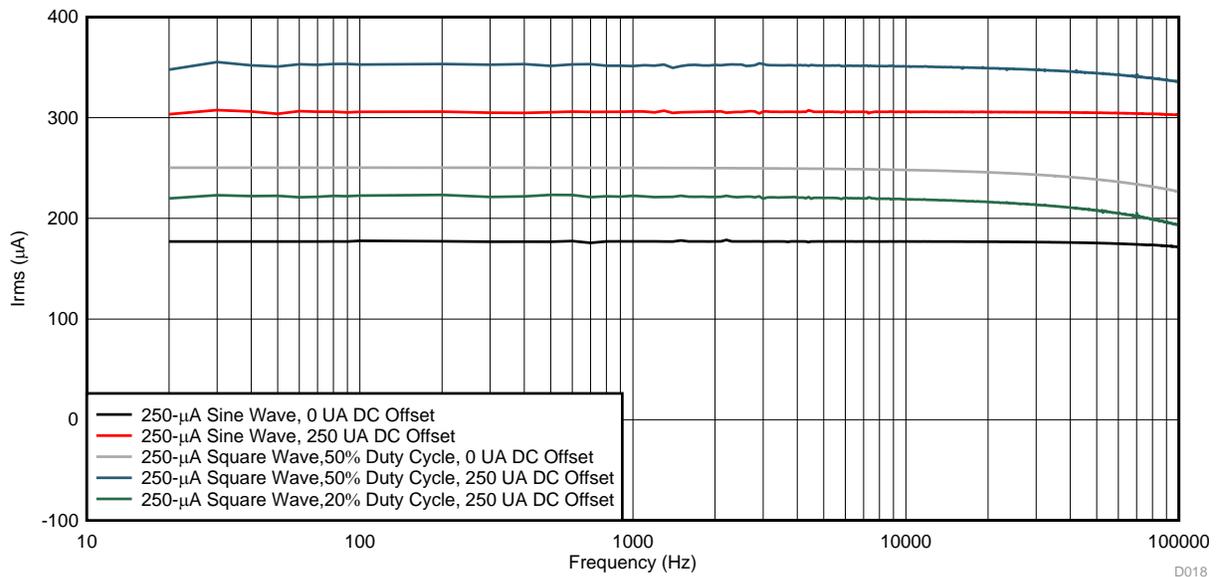
Figure 78. AC Current Frequency Response (500-µA Range)

3.3.1.7   *System Power Measurements and Battery Life Calculations*

Table 13 shows the current consumed by the TIDA-01012 device. These measurements were taken at a 3.7-V input, which represents a nominal voltage of the AAA Li-Ion battery source over its entire operating voltage range.

Table 13. TIDA-01012 System Currents

MODE	CURRENT	UNIT
Active	5.2	mA
Power-down	25	µA

Using the stated AAA Li-Ion battery capacity of 600 mAh, the estimated battery life of the TIDA-01012 system is ≈ 115 hours of actual operating time.

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01012.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01012.

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layout prints for each board, see the design files at TIDA-01012.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01012.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01012.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01012.

5 Software Files

To download the software files, see the design files at TIDA-01012.

6 Related Documentation and Acknowledgments

6.1 Related Documentation

1. Texas Instruments, *18-Bit, 1-MSPS Data Acquisition (DAQ) Block Optimized for Lowest Distortion and Noise*, TIPD115 Design Guide (SLAU515)
2. Texas Instruments, *RF430CL330H Practical Antenna Design Guide*, RF430CL330H Application Report (SLOA197)
3. Texas Instruments, *18 bit, 10kSPS Data Acquisition (DAQ) Block Optimized for Ultra Low Power < 1 mW*, TIPD114 Design Guide (SLAU514)
4. Texas Instruments, *Using RF430CL330H VCORE Pin to Wake Up Host MCU via a Presented NFC/RFID High Frequency Magnetic Field*, RF430CL330H Application Report (SLOA200)
5. Texas Instruments, *CapTIvate™ Technology Guide*
6. Texas Instruments, *Murata Balun for CC253x and CC254x*, Application Note AN107 (SWRA380)
7. Texas Instruments, *Highly Integrated, 4½ Digit, Low-Power Handheld Digital Multimeter (DMM) Platform Reference Design*, TIDA-00879 Design Guide (TIDUBM4)

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- NFC Bluetooth Low Energy Pairing Subsystem: Eddie LaCost, Ralph Jacobi, and Caitlin Ramsey

7 Terminology

DMM— Digital Multimeter

WDMM— Wireless Digital Multimeter

IoT— Internet of Things

BLE— Bluetooth Low Energy

RISO— Isolation Resistor (usually used with op amps for stability purposes)

8 About the Authors

VICTOR SALOMON is a systems designer at Texas Instruments, where he is responsible for developing reference design solutions for the Industrial Test and Measurements sector. Victor earned his bachelor of science in electrical engineering (BSEE) from University of Central Florida in Orlando, FL. Victor is a member of the Institute of Electrical and Electronics Engineers (IEEE) and IEEE-Eta Kappa Nu (IEEE-HKN).

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Revision B History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Revision A History