TI Designs

Highly Integrated, 4½ Digit, Low-Power Handheld Digital Multimeter (DMM) Platform Reference Design

TEXAS INSTRUMENTS

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The TIDA-00879 reference design demonstrates TI's subsystem design solution for low-cost handheld digital multimeter (DMM) applications by leveraging the features, functions, performance, and state-of-the-art low-power and power management capabilities of TI's MSP430F6736 MCU.

Design Resources

|	
TIDA-00879	Design Folder
MSP430F6736	Product Folder
TPS62740	Product Folder
TS5A3359	Product Folder
TS3A24159	Product Folder
OPA333	Product Folder

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Design Features

- Basic DMM Measurement Modes:
  - Voltage: 60-mV, 600-mV, 6-V, 60-V Ranges
  - Current: 600-µA, 60-mA Ranges
- Multiple 24-Bit ΣΔ ADCs Enabling:
  - 60,000 Display Count Resolution
  - 1-µV / 10-nA Minimum Resolution
  - .05% DC Accuracy, 1% AC Accuracy at 1 kHz
  - Power Measurement Mode or Feature
- Firmware-Based True-RMS Measurement
- Integrated LCD Subsystem
- Ultra-Low Power Operation Enabling >600-Hour Battery Life on 3×AAA Batteries
- Highly Integrated System Design Solution
- Small PCB Footprint

Featured Applications

- General Purpose DMM for Engineers, Electricians, Hobbyist
- Specialized Handheld Tool for Engineers and Electricians Used for Characterization and Failure Analysis

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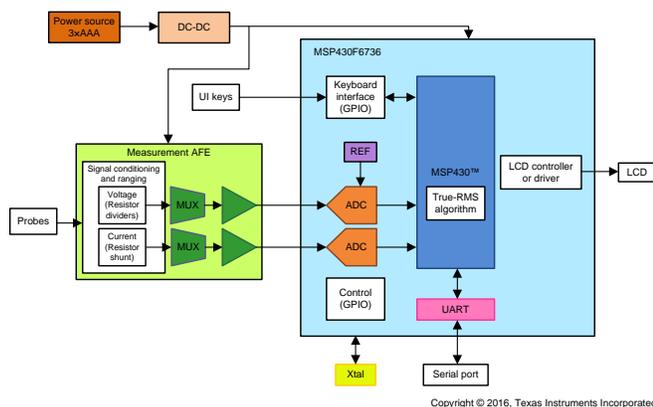
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1 Key System Specifications

Table 1. Key System Specifications

PARAMETER		SPECIFICATIONS
Voltage	Input ranges	60 mV, 600 mV, 6 V, 60 V
	Resolution	60,000 display counts
		1 µV, 10 µV, 100 µV, 1 mV
	DC accuracy	±0.03% of reading ±5 LSD
	AC accuracy (up to 1 kHz)	±1% of reading ±10 LSD
	Input impedance	10 MΩ, 100 pF
Current	Input ranges	600 µA, 60 mA
	Resolution	60,000 display counts
		10 nA, 1 µA
	DC accuracy	±0.1% of reading ±5 LSD
	AC accuracy (up to 1 kHz)	±1% of reading ±10 LSD
	Burden voltage	60 mV
Power	Input ranges	3600 µW, 3600 mW
	Resolution	60,000 display counts
		0.1 µW, 0.1 mW
	DC accuracy	±0.5% of reading ±20 LSD
	AC accuracy (up to 1 kHz)	1% of reading ±20 LSD
Current consumption	DC Measurement Mode	1.6 mA at 3.6-V input
	AC Measurement Mode	1.7 mA at 3.6-V input
	Power Mode	2.6 mA at 3.6-V input
Battery life	Continuous operating hours	> 600 hours at 70% DC, 20% AC, 10% power modes

2   System Description

Millions of handheld digital multimeters (DMMs) are developed, produced, and sold each year by numerous manufacturers and suppliers. To compete in this competitive environment, DMM product designers must develop extremely cost-effective design solutions while providing key product performance metrics and features expected by end users.

The TIDA-00879 reference design achieves these market and design requirements by leveraging TI's MSP430F6736 MCU and supporting components. Benefits of this platform include:

- *Ultra-high system level integration enabled by the MSP430F6736, leading to very cost-effective product design solutions*
  This system integration not only significantly reduces overall component costs, but also reduces PCB layout complexity, leading to a smaller PCB footprint and, therefore, lower PCB costs. Increasing levels of system component integration also results in manufacturing simplicities in terms of component supplier management and logistics, which lowers production costs.

- *Numerical, firmware-based true RMS calculations, which integrates additional components and lowers system cost*
  This firmware capability is enabled by the MSP430F6736 25-MHz CPU, and the 32-bit hardware multiplier and provides a more cost effective solution compared to expensive hardware-based true-RMS solutions found in most current handheld DMMs.

- *Market-leading performance in product battery life and energy efficiency*
  Leveraging the low power and power management capabilities of the MSP430F6736 and TPS62740 DC-DC buck converter, this solution improves battery life by more than 50% over most current handheld DMMs.

- *Real (active) power calculation and measurement mode*
  The simultaneous sampling capability of the MSP430F6736 multiple sigma-delta ADCs enables this unique power measurement capability not found in current handheld DMMs.

This platform solution is achieved with existing catalog components and, therefore, avoids significant development costs associated with application specific IC-based solutions.

The following subsections highlight the features, aspects, and considerations of this reference design.

2.1   DMM Features and Functions

The following subsections briefly describe the primary DMM functions of the TIDA-00879 reference design.

2.1.1   Basic DMM Measurement Modes

The TIDA-00789 reference design implements basic DC voltage and current measurement modes as well as true-RMS AC voltage and current measurement modes inherent in most current handheld DMMs. 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 cost by using the features and capabilities of the MSP430F6736 MCU. For demonstration purposes, four voltage ranges (60 mV, 600 mV, 6 V, and 60 V) and to current ranges (600 µA and 60 mA) are implemented in this reference design. See Table 1 for specific performance targets.

2.1.2   Numerical, Firmware-Based True-RMS Calculation

The TIDA-00879 reference design also features a firmware-based true-RMS measurement capability, which also significantly reduces system costs associated with hardware-based true-RMS component solutions. See Table 1 for specific performance targets.

2.1.3   Real (Active) AC Power Measurement Mode

The TIDA-00879 reference design also showcases a real or active power measurement mode not found in current handheld DMMs. The simultaneous sampling capabilities of the MSP430F6736 MCU's multiple sigma-delta ADCs enable this unique DMM feature. Two power measurement ranges (3600 µW and 3600 mW) are implemented in this design.

2.1.4 Battery Level Reporting

The TIDA-00879 reference design supports a battery level reporting feature, which estimates the charge state of a 3×AAA alkaline battery source. This feature provides the end user more information on remaining battery life compared to the simple low battery indicator used in most DMM products today. Furthermore, this capability is enabled by using a DMM-independent ADC on the MSP430F6736 MCU and requires very minimal external components and cost to implement. Although the TIDA-00879 hardware supports this feature, note that the current firmware does not support it at this time.

2.1.5 Test and Calibration Modes

An isolated serial port has been included in the TIDA-00879 reference design to support tests and calibration tasks. When in test or calibration mode, this port is enabled to allow streaming of the displayed readings to a host system where TIDA-00879 performance metrics and calibration information can be captured and measured. Although not specifically listed as a feature of the TIDA-00879 reference design, the isolated serial port could also provide DMM data logging capabilities desired in a variety of DMM applications.

2.2 Hardware Subsystems

The following subsections briefly describe the fundamental subsystems of the TIDA-00879 reference design.

2.2.1 System Control and Processing

The system control and processing subsystem is the centerpiece feature of the TIDA-00879 reference design and is based on the significant feature set and capabilities of the MSP430F6736 MCU.

The MSP430F6736 integrates the majority of components and subsystems necessary in a handheld DMM product design, including ultra-low power 25-MHz MSP430™ core processor, multiple 24-bit sigma-delta ADCs, integrated LCD controller and driver, power management unit, 32-bit hardware multiplier, 12-bit SAR ADC, temperature sensor, voltage reference, and communication protocol support. The CPU and hardware multiplier combine to efficiently calculate true-RMS and real power measurements.

2.2.2 Analog Front End (AFE)

The TIDA-00879 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 MCU PGAs and ADCs.

2.2.3 Power Supply

The TIDA-00879 is designed to be powered from three AAA alkaline batteries, which are ubiquitous and provide a very cost effective solution for ongoing battery replacement.

The low operating voltage of the AFE and MCU subsystems enables the use of a DC-DC buck converter to efficiently convert the higher battery voltage to the lower system operating voltage, thereby significantly increasing product battery life. The DC-DC buck converter chosen for this design also includes programmable output voltage control and a separately switched power rail used to power the AFE section for further power management efficiencies.

2.2.4 Test and Evaluation Support

A UART serial port has been included in this design for test and evaluation support purposes. The port has been implemented using optical isolation components to avoid operational and measurement issues associated with potential grounding interaction of test equipment, bench supply power sources, software development devices, and so on. See Section 4.4 for functional details.

3 Block Diagram
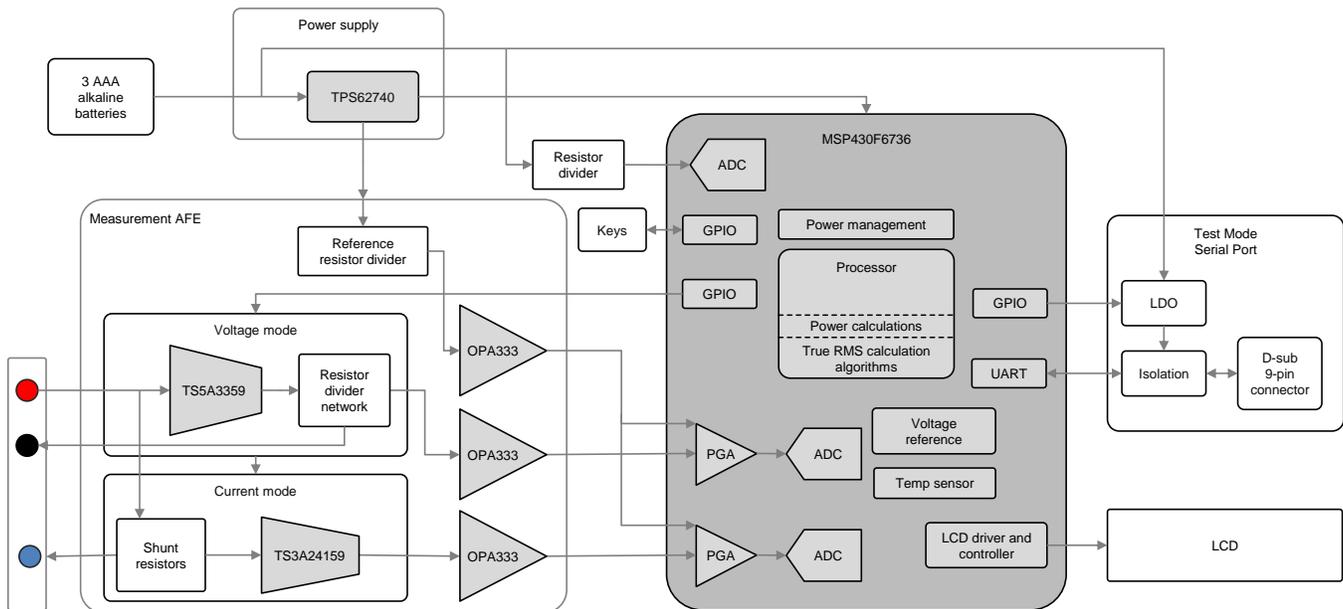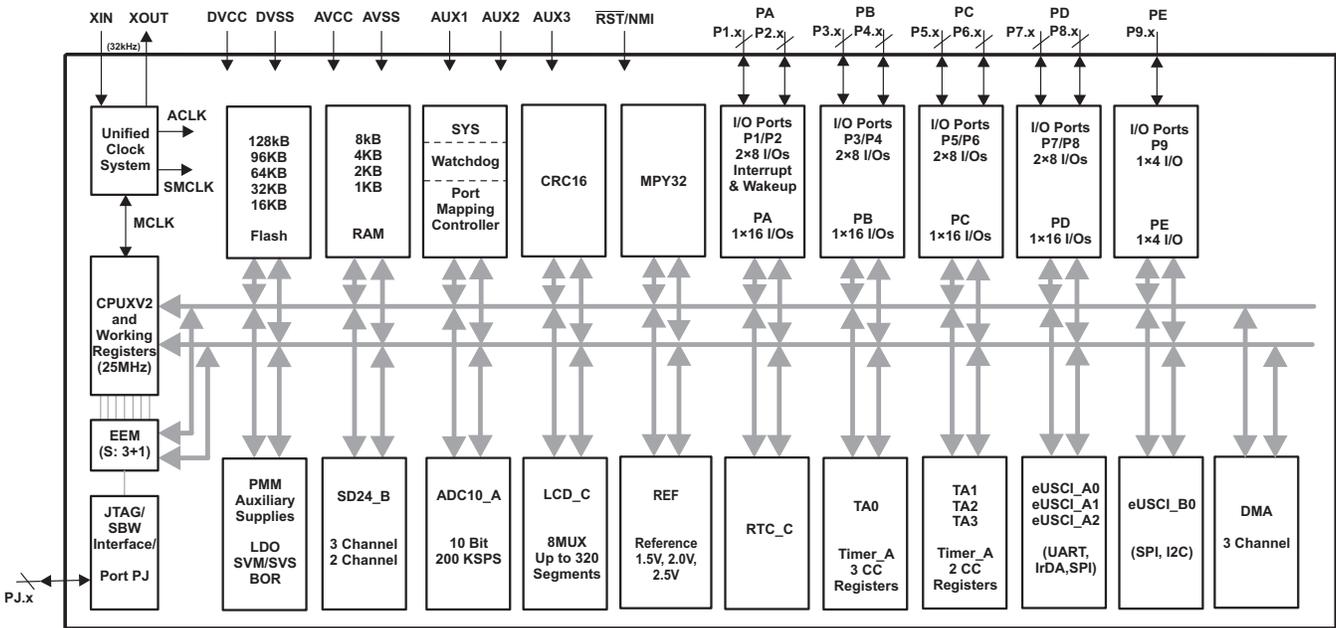

Figure 1. Block Diagram

3.1 Highlighted Products

The TIDA-00879 reference design features the following devices:

- MSP430F6736: Mixed signal microcontroller (see Section 3.1.1)
- TPS62740: 360-nA I_Q step-down converter with 300 mA and integrated load switch (see Section 3.1.2)
- TS5A3359: 1-Ω SP3T analog switch 5-V/3.3-V single-channel 3:1 multiplexer and demultiplexer (see Section 3.1.3)
- TS3A24159: 0.3-Ω 2-channel SPDT bidirectional switch (see Section 3.1.4)
- OPA333: 1.8-V, 17-μA, microPower, precision, zero drift CMOS op amp (see Section 3.1.5)

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

3.1.1 MSP430F6736—Mixed Signal Microcontroller

The architecture of the MSP430F6736 ultra-low-power microcontroller, combined with extensive low power modes, is optimized to extend battery life in portable measurement applications. The device 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 wake-up from low-power modes to active mode in 3 µs (typical). The MSP430F6736 has three high-performance 24-bit sigma-delta ADCs, a 10-bit ADC, four enhanced universal serial communication interfaces (three eUSCI_A and one eUSCI_B), four 16-bit timers, hardware multiplier, DMA, real-time clock module with alarm capabilities, LCD driver with integrated contrast control, auxiliary supply system, and up to 72 I/O pins in 100-pin devices and 52 I/O pins in 80-pin devices.

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Figure 2. MSP430F6736 Functional Block Diagram

Key TIDA-00879 reference design related features:

- 16-bit RISC architecture, extended memory, up to 25-MHz system clock
- Three 24-bit sigma-delta ADCs with differential PGA inputs
- Integrated LCD driver with contrast control for up to 320 segments in 8-mux mode
- Low supply voltage range: 1.8 to 3.6 V
- Ultra-low power consumption:
  - Active mode
    - All system clocks active
    - 265 µA/MHz at 8 MHz, 3.0 V, flash program execution (typical)
    - 140 µA/MHz at 8 MHz, 3.0 V, RAM program execution (typical)
  - Off mode
    - Full RAM retention, supply supervisor operational, fast wake-up: 1.6 µA at 3.0 V (typical)
- Flexible power management system
- Enhanced universal serial communication interfaces
- Hardware multiplier supports 32-bit operations
- 10-bit 200-ksps ADC
- Temperature sensor

Find full device features and specifications at the MSP430F6736 product folder.

3.1.2   TPS62740—360-nA I_Q Step-Down Converter With 300 mA and Integrated Load Switch

The TPS62740 is the industry's first step-down converter featuring a 360-nA quiescent current (typical) and operating with a tiny 2.2-µH inductor and 10-µF output capacitor. This new DCS-Control™ based device extends the light load efficiency range below 10-µA load currents. The TPS62740 supports output currents up to 300 mA. The device operates from rechargeable Li-Ion batteries, with chemistries such as Li-SOCl2 and Li-MnO2, and two or three cell alkaline batteries. The input voltage range up to 5.5 V allows the device to operate from a USB port and between 1.8-V to 3.3-V thin-film solar modules. The output voltage is user selectable by four VSEL pins within a range from 1.8 V to 3.3 V in 100-mV steps. The TPS62740 features low output ripple voltage and low noise with a small output capacitor. Once the battery voltage comes close to the output voltage (close to 100% duty cycle), the device operates in a no ripple, 100% mode to prevent an increase of output ripple voltage. The device then stops switching and the output is connected to the input voltage. The integrated slew rate controlled load switch provides 0.6-Ω on-resistance (typical) and can distribute the selected output voltage to a temporarily used subsystem. The TPS62740 is available in a small 12-pin 2×3-mm^2 package and supports a total solutions size of 31 mm^2.
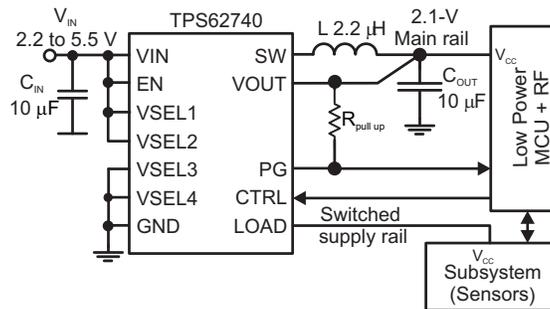
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Figure 3. TPS62740 Functional Block Diagram

Key TIDA-00879 reference design related features:

- Input voltage range V_{IN} from 2.2 to 5.5 V
- Typical 360-nA quiescent current
- Up to 90% efficiency at 10-µA output current
- 16 selectable output voltages from 1.8 to 3.3 V in 100-mV steps
- Slew rate controlled load switch

Find full device features and specifications at the TPS62740 product folder.

3.1.3 TS5A3359—1-Ω SP3T Analog Switch 5-V/3.3-V Single-Channel 3:1 Multiplexer and Demultiplexer

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, test and measurement equipment, and portable instrumentation. The device maintains the signal integrity by its low on-state resistance, excellent on-state resistance matching, and total harmonic distortion (THD) performance. To prevent signal distortion while transferring a signal from one channel to another, the TS5A3359 also has a specified break-before-make feature. The device consumes very low power and provides isolation when $V_{CC} = 0$.
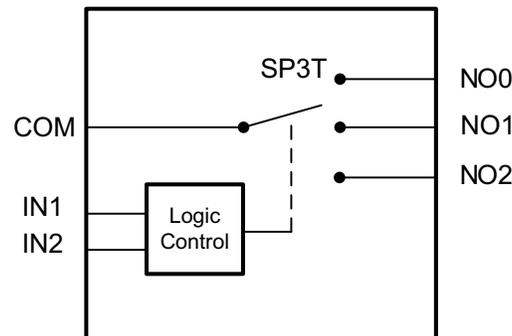
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Figure 4. TS5A3359 Functional Block Diagram

Key TIDA-00879 reference design related features:

- 1.65- to 5.5-V single-supply operation
- Low on-state resistance: 1 Ω
- Specified break-before-make switching

Find full device features and specifications at the TS5A3359 product folder.

3.1.4 TS3A24159—0.3-Ω 2-Channel SPDT Bidirectional Switch

The TS3A24159 is a 2-channel single-pole double-throw (SPDT) bidirectional analog switch that is designed to operate from 1.65 to 3.6 V. It offers low on-state resistance and excellent on-state resistance, matching with the break-before-make feature, to prevent signal distortion while transferring a signal from one channel to another. The device has excellent THD performance, low on-state resistance, and consumes very low power. These JESD 78, Class II features make this device suitable for a variety of markets and applications.
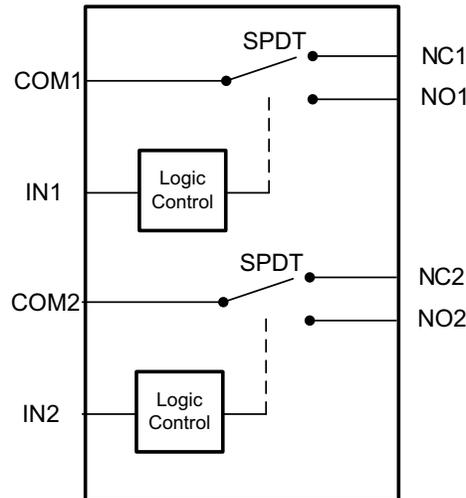
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Figure 5. TS3A24159 Functional Block Diagram

Key TIDA-00879 reference design related features:
• Specified break-before-make switching
• Low on-state resistance: 0.3 Ω (maximum)
• 1.65- to 3.6-V single-supply operation
• Control inputs are 1.8-V logic compatible

Find full device features and specifications at the TS3A24159 product folder.

3.1.5 OPA333—1.8-V, 17-μA, microPower, Precision, Zero Drift CMOS Op Amp

The OPA333 is a zero-drift, low-power, rail-to-rail input and output operational amplifier. This device operates from 1.8 to 5.5 V, is unity-gain stable, and is suitable for a wide range of general-purpose applications. The zero-drift architecture provides ultra-low offset voltage and near-zero offset voltage drift.

Key TIDA-00879 reference design related features:
• Low offset voltage: 10 μV (maximum)
• Zero drift: 0.05 μV/°C (maximum)
• 0.01- to 10-Hz noise: 1.1 μV_{PP} (10 μV, maximum)
• Quiescent current: 17 μA
• Single-supply operation
• Supply voltage: 1.8 to 5.5 V
• Rail-to-rail input/output
• microSize packages: SC70 and SOT23

Find full device features and specifications at the OPA333 product folder.

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4 System Design Considerations and Theory

Figure 6 shows the block diagram of the TIDA-00879 signal and measurement flow. Details of this process along with design considerations associated with each subsystem are described in the following subsections.
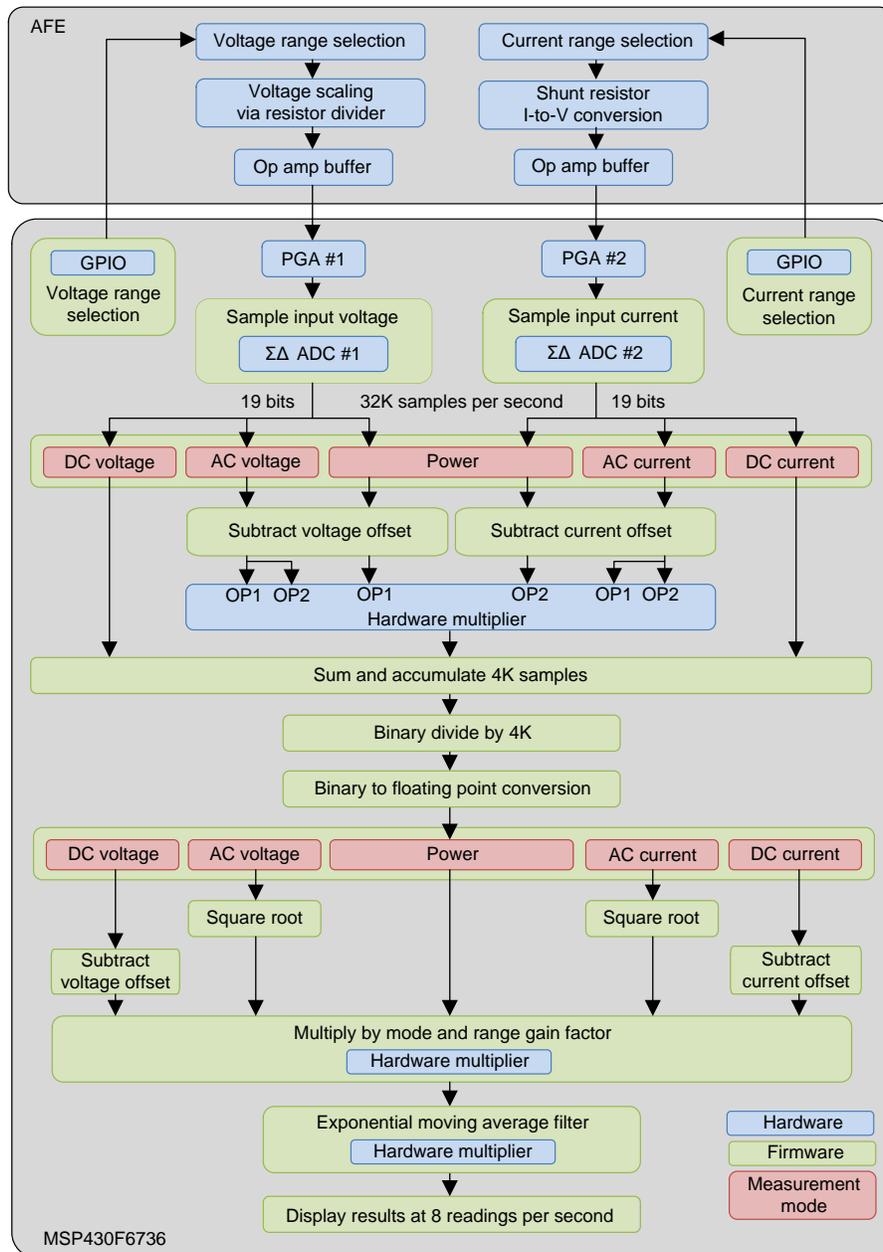
Figure 6. Block Diagram of TIDA-00879 Signal and Measurement Flow

4.1 AFE Subsystem

The AFE subsystem is detailed in the block diagram shown in Figure 7.
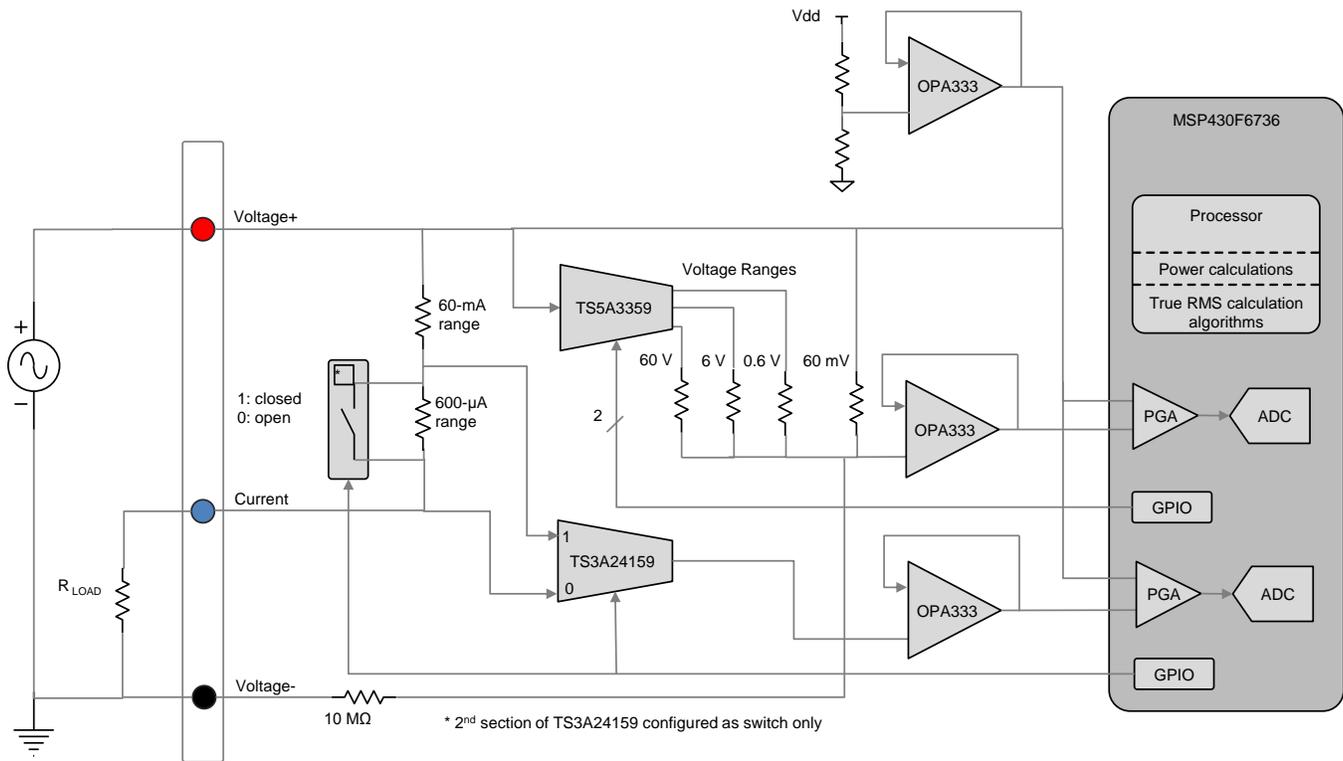
Figure 7. Block Diagram of AFE Subsystem

The AFE subsystem measures voltage by applying the external device-under-test (DUT) voltage between the voltage+ (red) and voltage– (black) terminals. 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 network controlled by a 1:3 TS5A3358 analog multiplexer. As shown in Figure 7, the TS5A3358 independently enables the 600-mV, 6-V, or 60-V divider resistors. These resistors work in parallel with the 60-mV resistor to establish the required divider ratio with the voltage terminal input resistor. The 60-mV range divider ratio is established with the 600-mV, 6-V, and 60-V resistors disabled. 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 resistor divider output is buffered through an OPA333 voltage follower to provide a low-impedance output for the MCU programmable gain amplifier (PGA). The OPA333 output voltages range is approximately ±60 mV, which corresponds to the signal level of the lowest (60-mV) voltage range. In this case, the voltage divider ratio is approximately 1.0.

The voltage+ (red) terminal is used by both current and voltage functions. This terminal also represents the system reference voltage generated by the OPA333 at the midpoint of the add system voltage.

The current measurement section provides 600-µA and 60-mA current range settings as selected by the MCU. Two shunt resistors connected between the voltage+ (red) terminal and current (blue) terminal are used to convert the respective currents to voltage. Like the voltage section, 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 600-µA range shunt resistor when the 60-mA range is selected. The output of the TS3A24159 is buffered by an OPA333 voltage follower to provide a low impedance output for the MCU PGA. The OPA333 output voltage range is also approximately ±60 mV driven by the burden voltage requirement of 60 mV as shown in Table 1.

Power measurements are achieved by simultaneously measuring voltage and current in a "high-side" current configuration as shown in Figure 1. Although numerous power ranges are possible due to combinations of the four voltage and two current ranges, the TIDA-00879 firmware supports two ranges (3600 μW and 3600 mW). *Note that attempting to measure power in a "low-side" current measurement configuration creates a low impedance path between the positive and negative sides of the source voltage which could result in very high currents through the AFE shunt resistors.*

> **NOTE:** Because the TIDA-00879 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 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.

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 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, this reference design has an optional jumper setting not shown in Figure 7 to provide better noise and resolution performance at the low 60-mV range setting (see Section 5.1.3 for more details).

4.2   MSP430F6736 MCU Subsystem

Both voltage and current AFE outputs drive separate PGA and ADC peripherals in the MSP430F6736. The PGAs provide various gain options to amplify the input signal before input to the 24-bit sigma-delta ADC. Because the usable ADC input voltage range is approximately 1 V, a gain setting of 16 was chosen for both voltage and current modes. The next available gain option is 32, which would overdrive the ADC input range. Also, a common gain value for the voltage and current modes is required in order to maintain identical phase shifts for power mode measurements over frequency.

The MSP430F6736 24-bit sigma-delta ADCs have numerous adjustable parameters to optimize and tailor resolution, bandwidth, sampling rate, and power to specific application requirements. Details of the ADC features and performance can be found in the MSP430F6736 datasheet (SLAS731) and the *MSP430x5xx and MSP430x6xx Family User's Guide* (SLAU208).

The specific key ADC parameters selected for this handheld DMM application are a 2-MHz sigma-delta modulator frequency (F_M) with a 64 oversampling ratio (OSR). These setting provide 19 bits (18 bits + 1 sign bit), a basic ADC resolution, and a 32K sampling rate. The 32K sampling rate is required to achieve the targeted 1% accuracy at 2 kHz due to the low pass filter function required by the sigma-delta converter. The frequency response of the low pass SINC3 comb filter implemented in these ADCs is depicted in Figure 8.
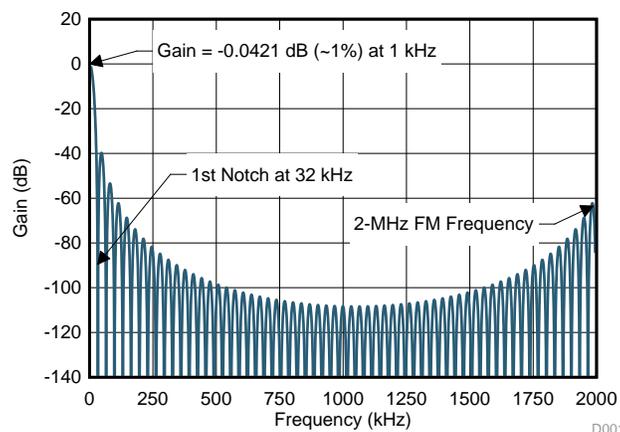
Figure 8. SINC³ Comb Filter Frequency Response

Referring to Figure 6, offset adjustments for power, AC voltage, and AC current modes must be made before the multiplication function for proper calculations. The mathematical equations and computations allow the voltage and current offset adjustment for the other measurement modes to be made later in the process for power saving purposes. These offsets are based on calibration constants acquired during calibration and can be different value for each signal channel and range setting.

After offset adjustments have been made, the remaining computational steps depends on the selected measurement mode based on the following equations:

$$V_{RMS} = Gain_V \sqrt{\frac{\sum_{k=0}^{N} V_{SAMPLE}^2(k)}{N}} \tag{1}$$

$$I_{RMS} = Gain_I \sqrt{\frac{\sum_{k=0}^{N} I_{SAMPLE}^2(k)}{N}} \tag{2}$$

$$P_{REAL} = Gain_V \times Gain_I \times \left(\frac{\sum_{k=0}^{N} V_{SAMPLE}(k) \times I_{SAMPLE}(k)}{N} \right) \tag{3}$$

$$V_{DC} = Gain_V \times \left(\frac{\sum_{k=0}^{N} V_{SAMPLE}(k)}{N} \right) \tag{4}$$

$$I_{DC} = Gain_I \times \left(\frac{\sum_{k=0}^{N} I_{SAMPLE}(k)}{N} \right) \tag{5}$$

where
- V_{SAMPLE} = offset adjusted voltage sample instance (k)
- I_{SAMPLE} = offset adjusted current sample instance (k)
- $Gain_V$ = active voltage range gain factor determined during calibration
- $Gain_I$ = active current range gain factor determined during calibration
- N = number of samples accumulated for each measurement

The AC current, AC voltage, and power measurement modes use the MSP430F6736 hardware multiplier to achieve the necessary system throughput performance and low power requirements. The hardware multiply function must be performed on every capture sample and within each sampling time interval (30.5 µs in this design). The DC voltage and DC current measurement modes do not require the multiplication step.

A 4K sample and accumulate quantity was selected for this implementation, which not only provides sufficient sampling periods for computing RMS and power across a wide range of frequencies, but also serves to lower the system noise to support the targeted resolutions and accuracy.

Up to this point in the process, all computations have been performed in binary format for performance efficiencies. The measured value is then converted to a single precision floating point format for subsequent calculations. Floating point calculations require many more CPU cycles, but these calculations are only required at an 8K/sec rate (32K ADC sampling divided by the 4K sum and accumulate process) and, therefore, has minimal impact on average power and battery life.

Per the equations previously mentioned, a square root function is required for AC voltage and AC current modes before applying the appropriate gain factors using the respective calibration constants for the various measurement ranges.

Finally, a simple exponential moving average filter is implemented to provide further smoothing as measurement results are displayed at a rate of eight measurements per second.

4.3 Power Supply Subsystem

As shown in Figure 1, a very simple, efficient, and cost effective power supply has been implemented in the TIDA-00879 reference design. The system operating voltage is selected to be 2.4 V, which is driven by the 2.4-V minimum voltage required by the sigma-delta ADCs. With an overall voltage range of approximately 2.4 to 4.8 V for the three AAA alkaline batteries, the TPS62740 DC-DC buck converter maximizes battery life.

Complete access to the four TPS62740 output voltage control pins were implemented in this design to allow easy system operating voltage. This output voltage control capability can be used to increase system operating voltage to support a higher MSP430F6736 operating frequency for DMM modes and functions that may require higher performance. For the TIDA-00879 reference design, all modes used 2.4 V.

The integrated load switch controlled by the MSP430F6736 MCU is also used to completely power down the AFE when the system enters a power down, off, or idle state to maximize battery life.

4.4 Test Subsystem

This TI Design has an isolated UART serial port to test, calibrate, and evaluate support. This port is activated when the TIDA-00879 firmware is placed in test or calibration mode (see Section 5.2.3 for more details).

Calibration mode streams the raw voltage and current ADC readings to the display and serial port. This mode can be used to determine voltage and current mode offset and gain factor for each DMM measurement mode and range setting. The calibration constants section of the TIDA-00879 firmware can then be updated with these calibration constants accordingly. The calibration procedure is described in more detail in Section 5.2.3.2.

An 8K × 8 serial SRAM is also included as part of the test block to capture actual ADC readings (at a 32-kHz sample rate), which are then transferred to a host environment for a detailed analysis if desired. However, the TIDA-00879 firmware does not support this device at this time.

The test subsystem receives power through a 3-V output TPS78230 LDO directly from the battery voltage. The LDO output enable is controlled by the MSP430F6736 and is enabled when the board is configured for test mode as described in Section 5.2.3. *Even though flow control is not implemented from a data transfer standpoint, power is provided to the host side of the isolation barrier through the host RS-232 control signals (RTS and DTR), so the host must assert these signals for proper operation.*

5 Getting Started Hardware

Figure 9 highlights the various features of the TIDA-00879 hardware. These features are explained in the following subsections.
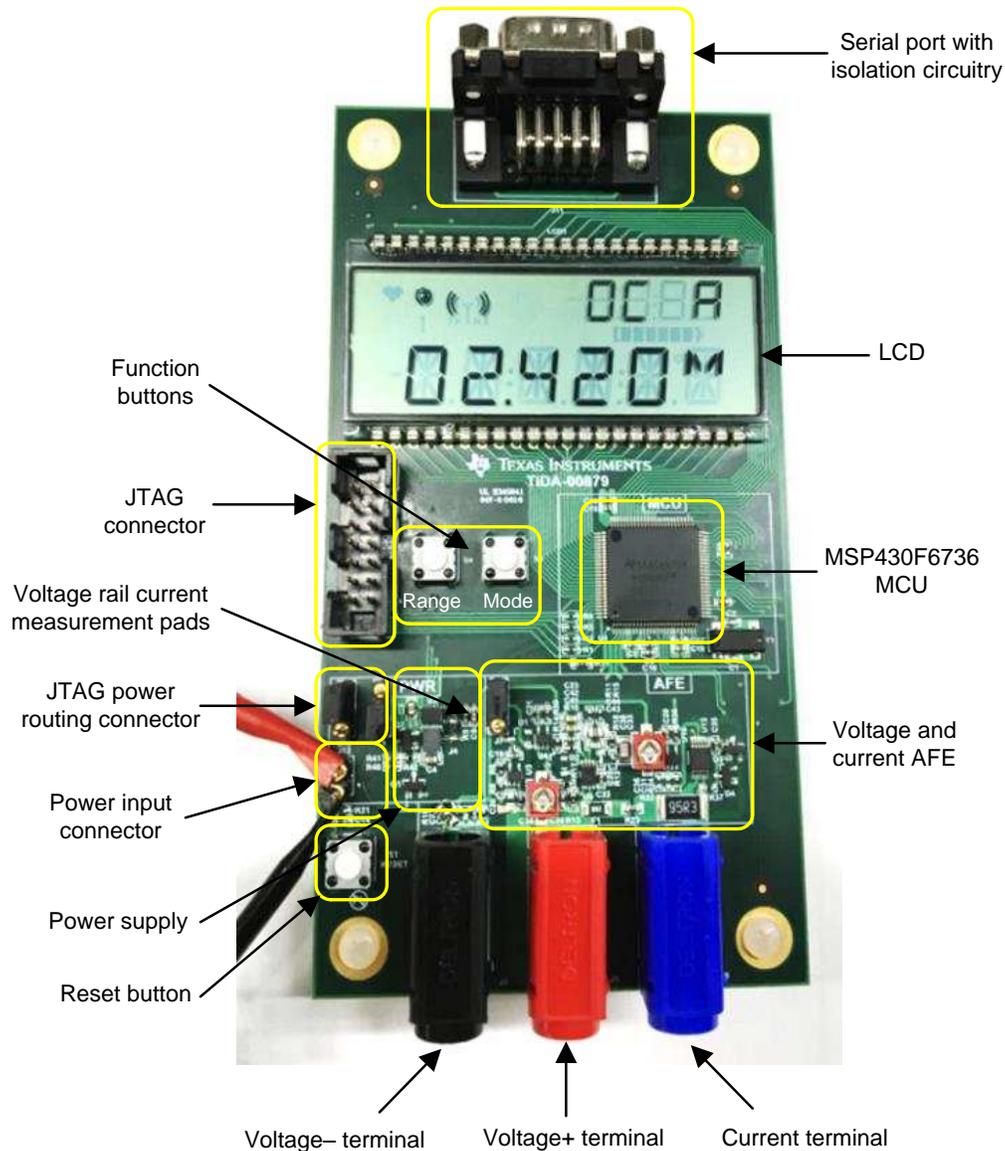
Figure 9. TIDA-00879 Board Features

5.1 Headers and Jumpers

All TIDA-00879 header and jumper locations are shown in Figure 10. See the following subsections for proper settings.
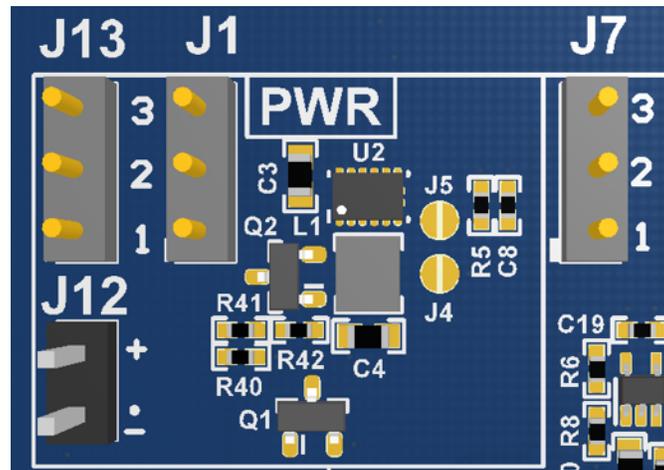
Figure 10. TIDA-00879 Board Jumpers

5.1.1 Board Power Supply Configurations

Table 2. Power Supply Jumper Settings

J12 VOLTAGE SOURCE	J13 HEADER POSITION	J1 HEADER POSITION	SYSTEM POWER CONFIGURATION
2.4 to 4.8 V[1]	2-3	1-2	System powered through external supply
X	2-3	2-3	System powered through JTAG port

[1] Ensure correct polarity is applied as shown in Figure 10.

5.1.2 Voltage Rail Current Measurement Pads

The two small round sets of PCB pads (J4 and J5) shown in Figure 10 are provided for inline current measurements for the AFE and digital voltage rails. J4 is the digital voltage rail and J5 is the AFE voltage rail. *Place solder bridges across each of these pad sets for normal operation.* The solder bridges can easily be removed and replaced with wires to connect multimeters for system current measurements.

5.1.3 60-mV Voltage Range Configuration Jumper

The J7 header shown in Figure 10 is used to physically control two different AFE range configurations for the 60-mV range setting. This option is included in the TIDA-00879 to evaluate improved resolution performance at the 60-mV range setting by lowering the resistor value in the voltage+ terminal to lower this resistor noise. See the schematics for configuration details. Note that the 10-MΩ input impedance requirement is still met in this case because the lower resistance values required for the higher range settings do not come into play with this configuration. This header switching basically emulates the rotator switch wheels found in many DMMs to support these lower range settings.

Table 3. Voltage Mode Input Impedance Jumper Settings

J1 HEADER POSITION	SYSTEM POWER CONFIGURATION
1-2	10-MΩ resistor setting
2-3	499-kΩ resistor setting

5.2 Functional Description

5.2.1 Measurement Mode and Range Selection

The mode button cycles through the various measurement modes in the following order:

- DC Voltage → AC Voltage → DC Current → AC Current → Power → OFF → Back to DC Voltage

The range button cycles through the various ranges for the active measurement mode as follows:

- DC and AC Voltage: 60 mV → 600 mV → 6 V → 60 V → Back to 60 mV
- DC and AC Current: Alternates between the 600-μA and 60-mA settings
- Power: Alternates between the 3600-μW and 3600-mW settings

The range states for the various measurement modes are saved when the mode is changed. The corresponding range setting is restored as the mode states are recycled.

5.2.2 Display Layout and Descriptions

Figure 11 highlights the various LCD features and indicators.
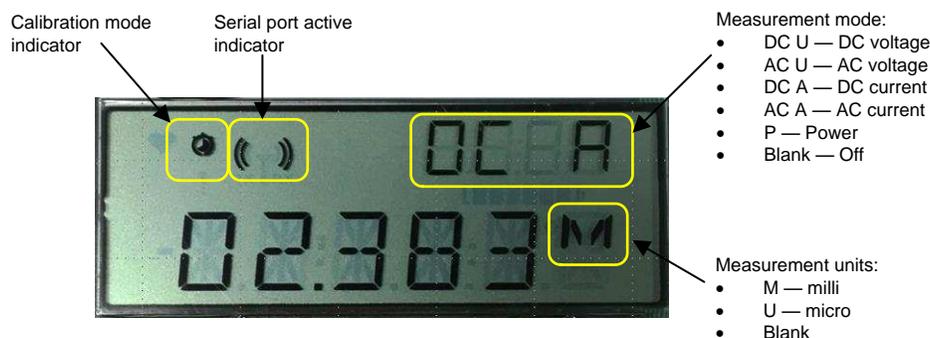
Figure 11. Display Layout and Descriptions

5.2.3 Test and Calibrate Modes

The test and calibrate modes as described in Section 4.4 can be accessed as described in the following subsections.

5.2.3.1 Test Mode

Pressing the "Mode" button while pressing and releasing the "Reset" button puts the board in test mode. This combination activates the serial port and streams the display readings for capture by a connected host system. All other board functions operate as normal after the board is reset and the "Mode" button is released.

The data format for the streamed data consists of two header bytes followed by four bytes that represent the measurement reading in single-precision floating point format with the most significant byte sent first. The TIDA-00879 firmware configures this port for 9600 baud, 8 data bits, 1 stop bit, no parity, and no flow control. LabView™ source code has been provided in the TIDA-00879 documentation as an example of a host environment for capturing these readings.

5.2.3.2 Calibration Mode

Pressing the "Range" button while pressing and releasing the "Reset" button puts the board in calibration mode. This combination activates the serial port and streams actual ADC readings for all measurement modes and associated ranges to a connected host system. These readings can then be captured for new calibration constant calculations. The TIDA-00879 LCD screen continues to display measurement values using the present offset and gain factor values.

The following three-point calibration procedure was used to calibrate the TIDA-00879 board. Note that the offset and gain factors for both voltage and current ADC channels will be different when operating in power measurement mode due to both channels being active in this mode and, therefore, requires unique calibration constants.

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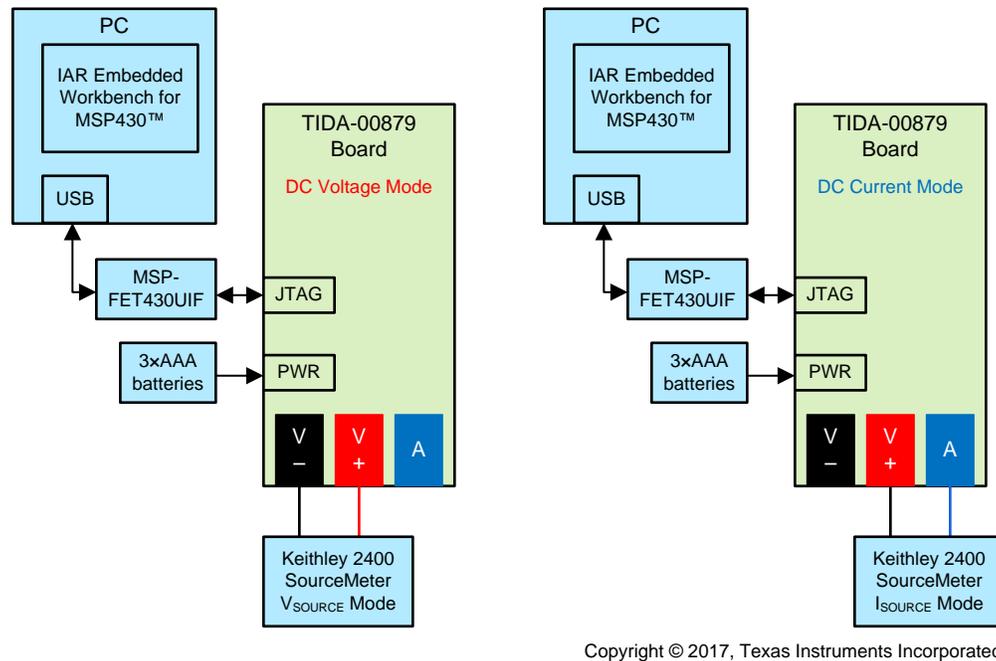
Figure 12. Calibration System Configurations

To calibrate voltage measurements:

1. Configure the system as shown in Figure 12.
2. Select the TIDA-00879 Voltage Measurement Mode (where "DC U" appears in the upper right corner of display).
3. Select the desired voltage range.
4. Capture the TIDA-00879 voltage readings versus the Keithley 2400 voltage readings at full range negative voltage, 0 V, and full-range positive voltage settings.
5. Perform a linear regression on these three data points and record gain (that is, the slope in terms of volts/LSB) and offset (or the intercept in terms of LSB) values.
6. Repeat Steps 3 through 5 for the remaining voltage ranges.
7. Modify the calibration constants in the firmware source code (see Section 6.1), recompile, and download the updated firmware.

To calibrate current measurements:

1. Configure the system as shown in Figure 12.
2. Select the TIDA-00879 Current Measurement Mode (where "DC A" appears in the upper right corner of display).
3. Select the desired current range.
4. Capture the TIDA-00879 current readings versus the Keithley 2400 current readings at full-range negative current, 0 A, and full range positive current settings.
5. Perform a linear regression on these three data points and record gain (that is, the slope in terms of amps/LSB) and offset (or the intercept in terms of LSB) values.
6. Repeat Steps 3 through 5 for remaining current range.
7. Modify the calibration constants in the firmware source code (see Section 6.1), recompile, and download the updated firmware.

To calibrate power measurements:

1. Configure the system as shown in Figure 12 to calibrate voltage measurements.

2. Select the TIDA-00879 Power-Voltage Measurement Mode (where "P U" appears in the upper right corner of display).

3. Select the 6-V voltage range.

4. Capture the TIDA-00879 voltage readings versus the Keithley 2400 voltage readings at full-range negative voltage, 0 V, and full-range positive voltage settings.

5. Perform a linear regression on these three data points and record gain (that is, the slope in terms of volts/LSB) and offset (or the intercept in terms of LSB) values.

6. Repeat Steps 3 through 5 for the 60-V voltage range.

7. Configure the system as shown in Figure 12 for current measurement mode calibration.

8. Select the TIDA-00879 current measurement mode (where "P A" appears in the upper right corner of display).

9. Select the 600-µA current range.

10. Capture the TIDA-00879 current readings versus the Keithley 2400 current readings at full-range negative current, 0 A, and full range positive current settings.

11. Perform a linear regression on these three data points and record gain (that is, the slope in terms of amps/LSB) and offset (or the intercept in terms of LSB) values.

12. Repeat Steps 9 through 11 for the 60-mA current range.

13. Modify the calibration constants in the firmware source code (see Section 6.1), recompile, and download the updated firmware.

A snapshot of the source code calibration constants found in the dmm_00879_defines.h file described in Section 6.1 is shown in Figure 13.

```
21   //Voltage Mode Gain Factor and Offset Constants
22   #define VOLTAGE_60mV_GAIN          (2.77041E-7)          // Volts per LSB
23   #define VOLTAGE_60mV_OFFSET        2797                  // LSBs
24
25   #define VOLTAGE_600mV_GAIN         (2.99970E-6)          // Volts per LSB
26   #define VOLTAGE_600mV_OFFSET       2550                  // LSBs
27
28   #define VOLTAGE_6V_GAIN            (3.02517E-5)          // Volts per LSB
29   #define VOLTAGE_6V_OFFSET          3270                  // LSBs
30
31   #define VOLTAGE_60V_GAIN           (3.02917E-4)          // Volts per LSB
32   #define VOLTAGE_60V_OFFSET         2917                  // LSBs
33
34   //Current Mode Gain Factor and Offset Constants
35   #define CURRENT_600uA_GAIN         (2.87524E-9)          // Amps per LSB
36   #define CURRENT_600uA_OFFSET       2430                  // LSBs
37
38   #define CURRENT_60mA_GAIN          (5.47478E-7)          // Amps per LSB
39   #define CURRENT_60mA_OFFSET         2423                 // LSBs
40
41   //Power Mode Gain Factor and Offset Constants
42   #define POWER_MODE_6V_GAIN         (3.02517E-5)          // Volts per LSB
43   #define POWER_MODE_600uA_GAIN      (2.87524E-6)          // Amps per LSB
44   #define POWER_MODE_6V_OFFSET       2657                  // LSBs
45   #define POWER_MODE_600uA_OFFSET    2150                  // LSBs
46
47   #define POWER_MODE_60V_GAIN        (3.02917E-4)          // Volts per LSB
48   #define POWER_MODE_60mA_GAIN       (5.47478E-4)          // Amps per LSB
49   #define POWER_MODE_60V_OFFSET      2917                  // LSBs
50   #define POWER_MODE_60mA_OFFSET     2423                  // LSBs
```

Figure 13. TIDA-00879 Source Code Calibration Constants

6 Getting Started Firmware

The IAR Embedded Workbench for the MSP430, version 6.40.1 was used to develop the TIDA-00879 firmware. This software development environment along with the MSP-FET430UIF USB Debug Interface is required to program and debug the TIDA-00879 hardware. See Section 5.1.1 to ensure that the power configuration jumpers are properly installed before connecting the MSP-FET430UIF system.

6.1 Firmware Module Descriptions

The firmware can be downloaded from http://www.ti.com/tool/DESIGNNUMBER. The names and brief descriptions of the TIDA-00879 firmware source code modules are as follows:

- dmm_00879_main.c: This module includes the main control, event handling, and user interface code, including mode and range control, system event handling, display interface, and procedures to power down and up.
- dmm_00879_processing.c: This module handles all of the processing and mathematical calculations associated with the various measurement modes.
- dmm_00879_hw_setup.c: This module contains the MSP430F6736 initialization code.
- dmm_00879_defines.h: This module includes all of the define statements for the project. This file also contains the calibration constants as described in Section 5.2.3.2.

The streamed data format and protocol consists of two header bytes (0xAA55) followed by four bytes that represent the measurement reading in a single-precision floating point format with the most significant byte sent first. The host system can poll the ongoing data stream for the 0xAA55 header and then capture the next four bytes representing the transmitted measurement reading. LabView source code has been provided in the TIDA-00879 documentation as an example of a host environment for capturing these readings.

7 Test Setup

The following test equipment was used in the various characterization tasks to capture, report, and evaluate the performance of the TIDA-00879 reference design:

- Agilent E3631 DC power supply
- Agilent AFG3021B function and waveform generator
- Agilent 34401A multimeter
- Keithley 2400 source and measurement unit
- Keithley 2001 multimeter
- Serial-to-USB interface
- GPIB-to-USB interface
- PC laptop

8   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.*

The specific test configurations for each characterization activity are as follows:

- Voltage Measurement Resolution (see Section 8.1)
- Current Measurement Resolution (see Section 8.2)
- Voltage Measurement Accuracy and Linearity (see Section 8.3)
- Current Measurement Accuracy and Linearity (see Section 8.4)
- Frequency Response for AC Voltage Measurement (see Section 8.5)
- AC Current Measurement Frequency Response (see Section 8.6)
- Power Measurement Resolution (see Section 8.7)
- Power Measurement Frequency Response (see Section 8.8)
- System Power Measurements and Battery Life Calculations (see Section 8.9)

8.1   Voltage Measurement Resolution

Figure 14 shows the test setup for characterizing voltage measurement resolution performance. DC Voltage Mode was used for these measurements.
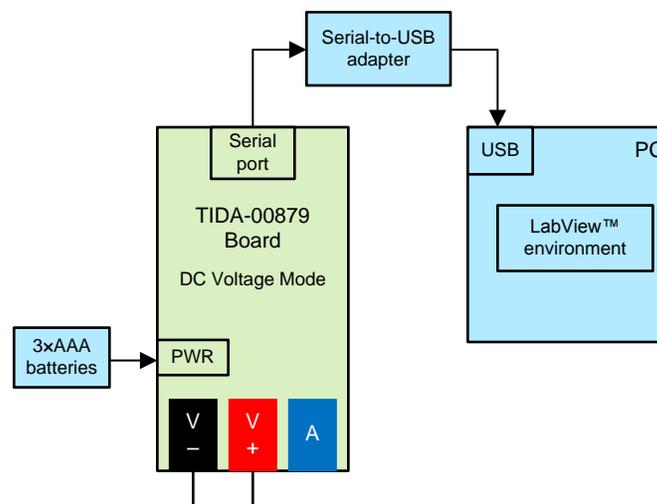

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Figure 14. Test Configuration for Voltage Measurement Resolution

Test procedure:

1. Short the V+ and V– terminals.
2. Power up the TIDA-00879 board in Test Mode.
3. Select the TIDA-00879 DC Voltage Mode.
4. Select the desired TIDA-00879 voltage range.
5. Capture and plot 1000 readings through the serial port and host environment (such as LabView).
6. Repeat for all four TIDA-00879 voltage ranges.

The following graphs show the results from all four voltage ranges. The light green plot lines represent the targeted resolution accuracy limits shown in Table 1.
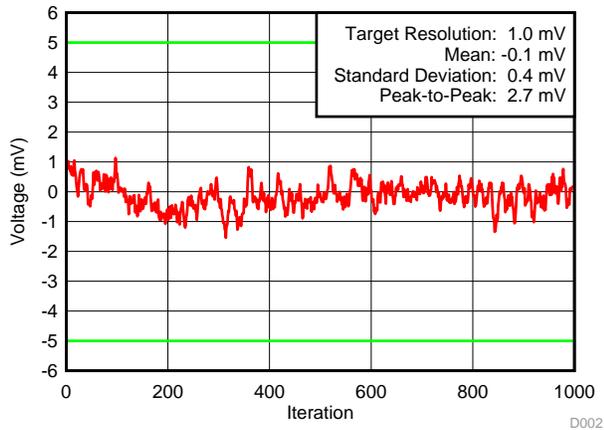
Figure 15. DC Voltage Mode, 60-V Range, 0-V Input
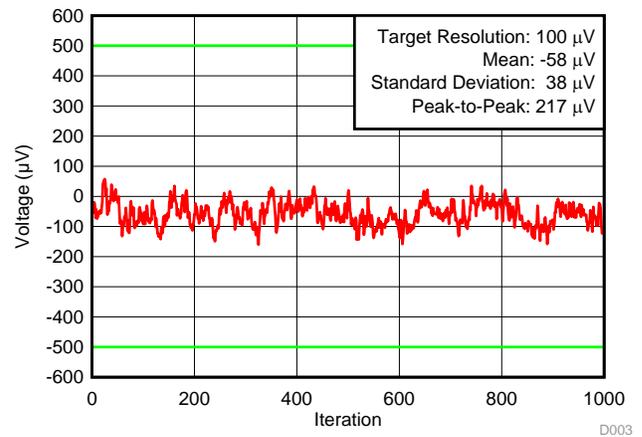
Figure 16. DC Voltage Mode, 6-V Range, 0-V Input
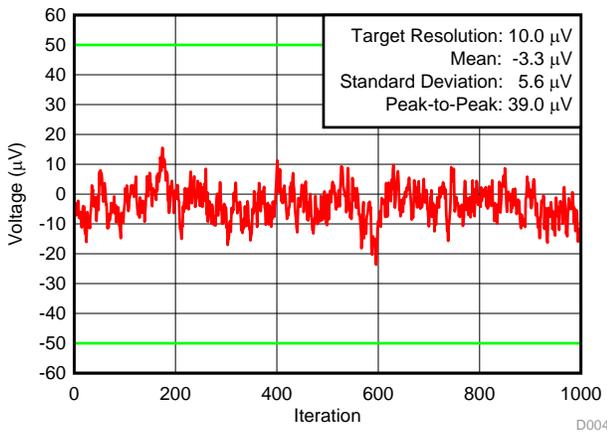
Figure 17. DC Voltage Mode, 600-mV Range, 0-V Input
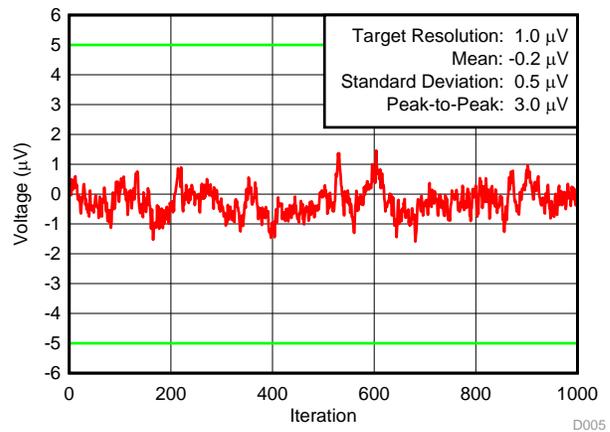
Figure 18. DC Voltage Mode, 60-mV Range, 0-V Input

8.2   *Current Measurement Resolution*

Figure 19 shows the test setup for characterizing current measurement resolution performance. DC Current Mode was used for these measurements.
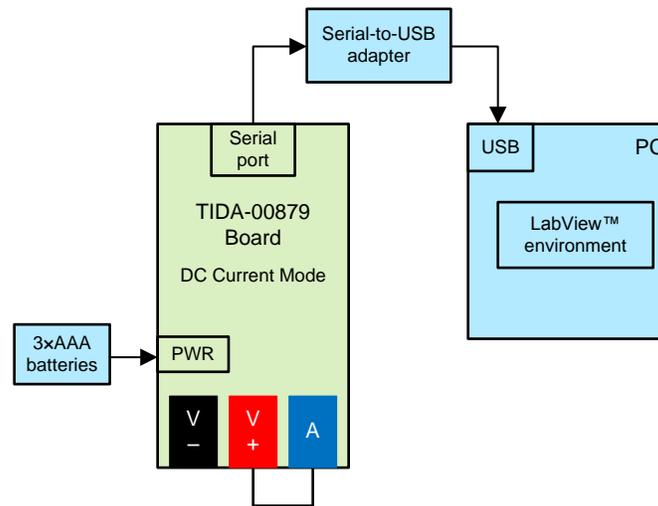
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Figure 19. Test Configuration for Current Measurement Resolution

Test procedure:

1. Short the V+ and V– terminals.
2. Power up the TIDA-00879 board in Test Mode.
3. Select the TIDA-00879 DC Current Mode.
4. Select the desired TIDA-00879 current range.
5. Capture and plot 1000 readings through the serial port and host environment (such as LabView).
6. Repeat for both TIDA-00879 current ranges.

The following graphs show the results for both current ranges. The light green plot lines represent the targeted resolution accuracy limits shown in Table 1.
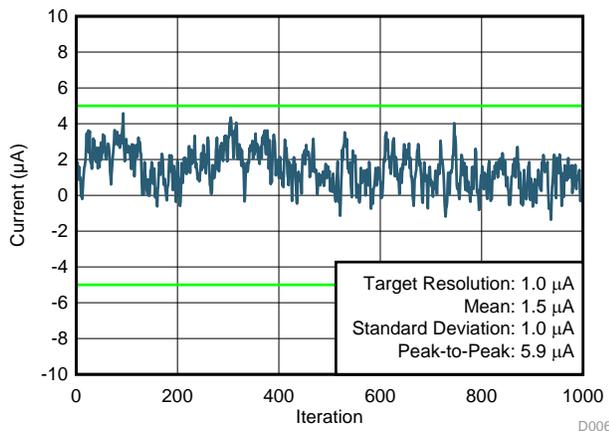
Figure 20. Noise Floor, 0-V Input, 60-mA Range
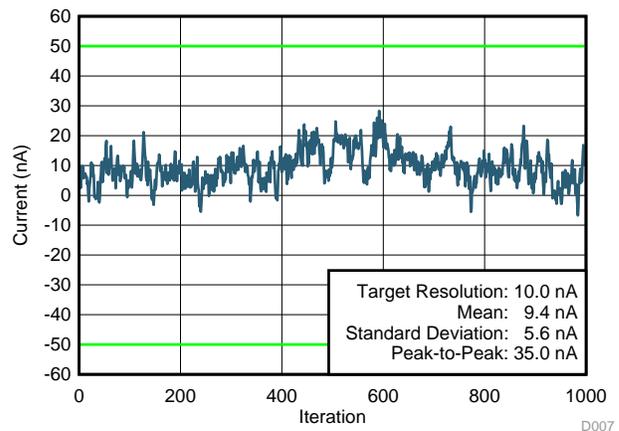
Figure 21. Noise Floor, 0-V Input, 600-µA Range

8.3 Voltage Measurement Accuracy and Linearity

Figure 22 shows the test setup for characterizing voltage measurement accuracy and linearity. DC Voltage Mode was used for these measurements.
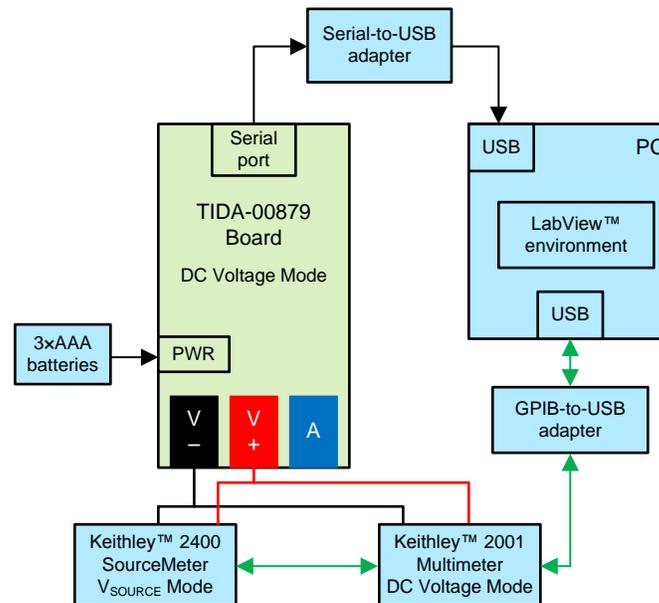
Copyright © 2016, Texas Instruments Incorporated

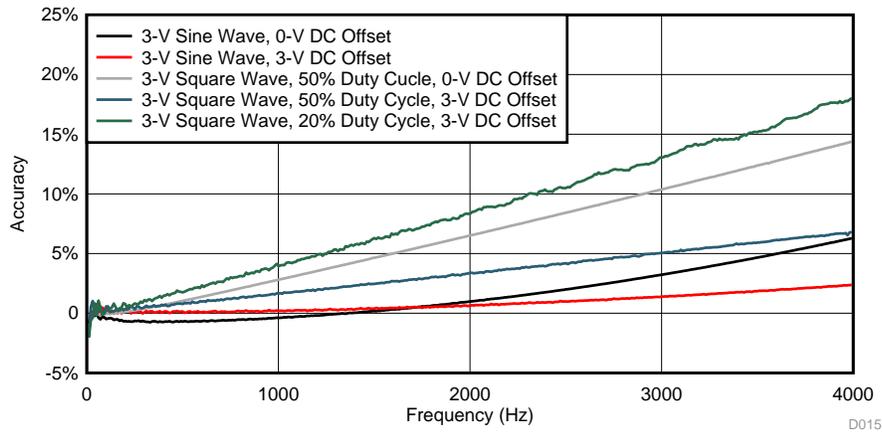**Figure 22. Test Configuration for Voltage Measurement Accuracy and Linearity**
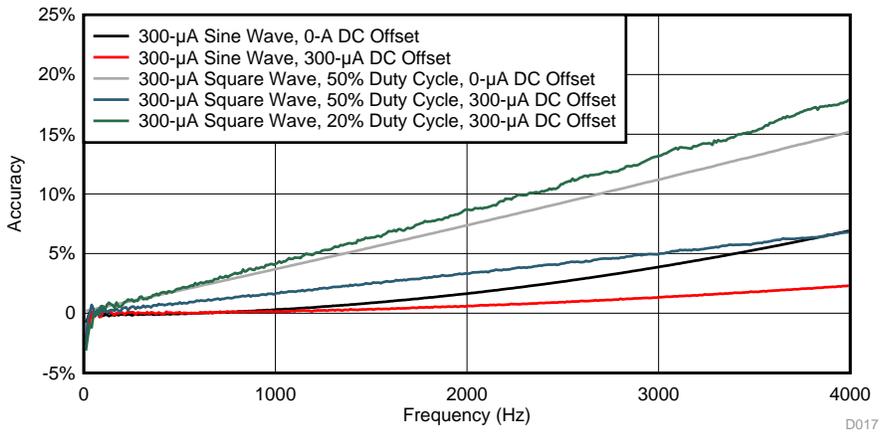
Test procedure:

1. Connect the test equipment to the TIDA-00879 board as shown in Figure 22.
2. Power up the TIDA-00879 board in Test Mode.
3. Select the TIDA-00879 DC Voltage Mode.
4. Select the TIDA-00879 desired voltage range.
5. Set the Keithley 2400 to V_{SOURCE} Mode.
6. Set the Keithley 2001 to DC Voltage Mode.
7. Sweep the Keithley 2400 SourceMeter DC Voltage from the minimum range voltage to maximum range voltage for 600 steps.
8. Capture the TIDA-00879 readings and Keithley 2001 Multimeter (V_{DC}) readings through the host system.
9. Plot the error voltage (TIDA-00879 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 light green plot lines represent the targeted resolution accuracy limits shown in Table 1.
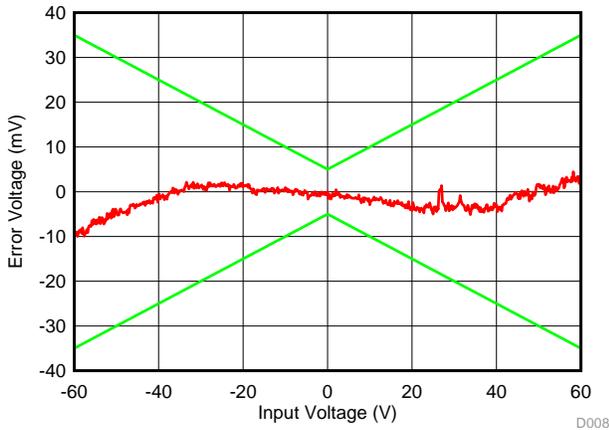
Figure 23. Linearity Plot, 60-V Range
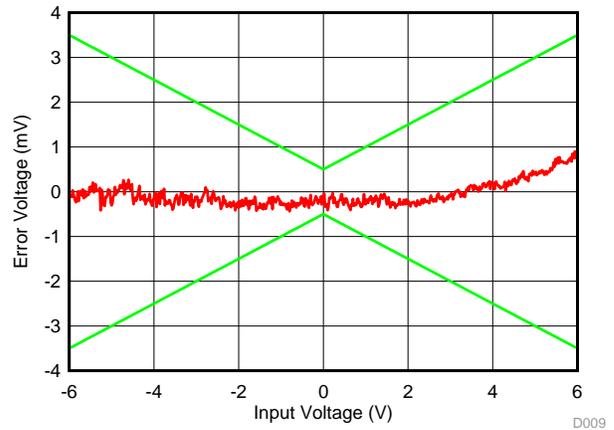
Figure 24. Linearity Plot, 6-V Range
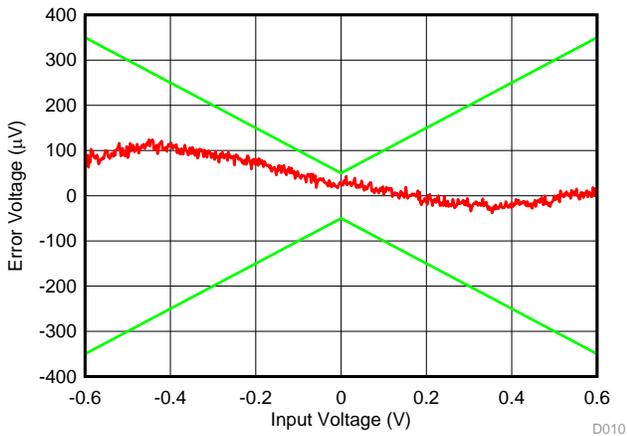
Figure 25. Linearity Plot, 600-mV Range
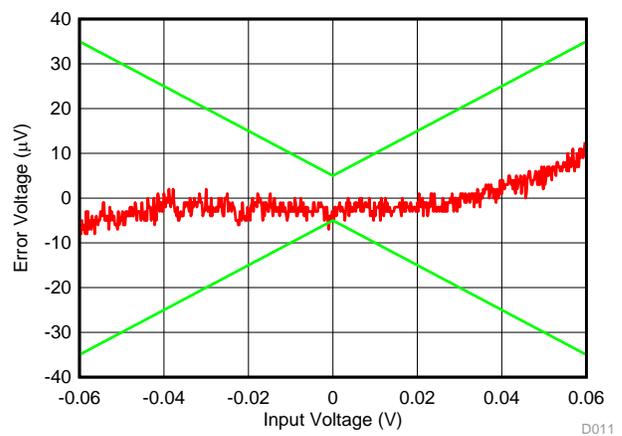
Figure 26. Linearity Plot, 60-mV Range

8.4 Current Measurement Accuracy and Linearity

Figure 27 shows the test setup for characterizing current measurement accuracy and linearity. DC Current Mode was used for these measurements.
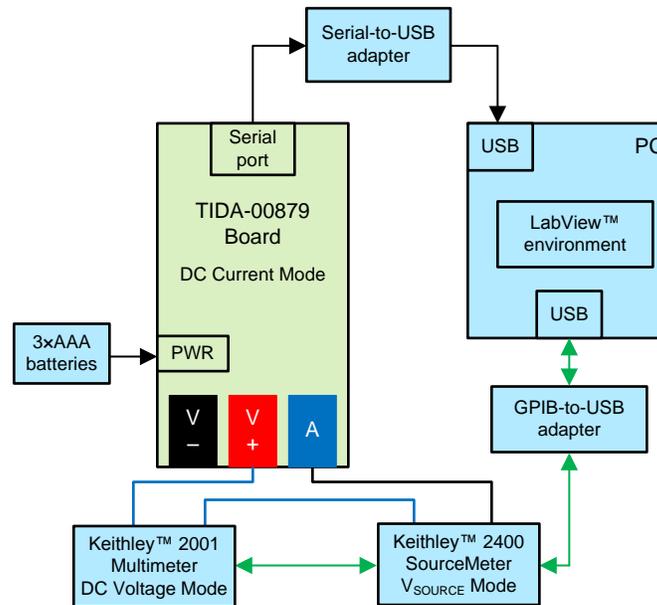
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Figure 27. Test Configuration for Current Measurement Accuracy and Linearity
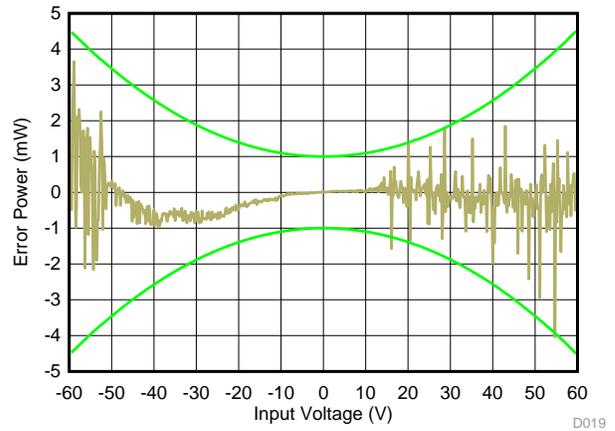
Test procedure:

1. Connect the test equipment to the TIDA-00879 board as shown in Figure 27.
2. Power up the TIDA-00879 board in Test Mode.
3. Select the TIDA-00879 DC Current Mode.
4. Select the desired TIDA_00879 current range.
5. Set the Keithley 2400 to I_{SOURCE} Mode.
6. Set the Keithley 2100 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-00879 readings and Keithley 2001 Multimeter (I_{DC}) readings through the host system.
9. Plot the error voltage (TIDA-00879 value minus the I_{DC} value) versus the I_{DC} values.
10. Repeat Steps 4 through 9 for both current ranges.

The following graphs show the data taken from both current ranges. The light green plot lines represent the targeted resolution accuracy limits shown in Table 1.
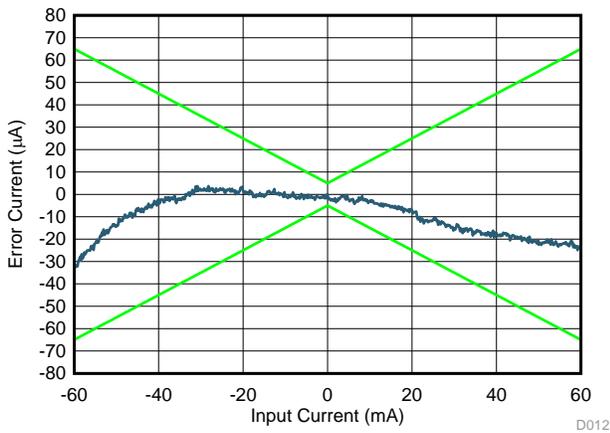
Figure 28. Linearity Plot, 60-mA Range
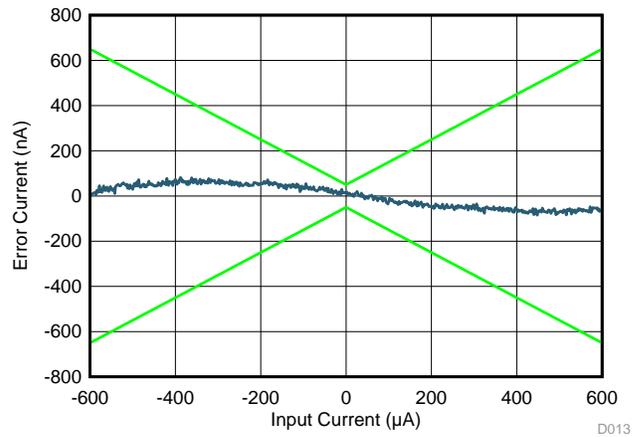
Figure 29. Linearity Plot, 600-µA Range

8.5 *Frequency Response for AC Voltage Measurement*

Figure 30 shows the test setup for characterizing AC voltage measurement accuracy as a function of frequency. Five AC waveform types were chosen for demonstration purposes. The first waveform was a basic sine wave with no DC offset component. The second waveform adds a DC component to the sine wave to illustrate the AC+DC RMS measurement capability. The third, fourth, and fifth waveforms are variations of a square wave, which includes DC offset and duty cycle variations. These square waves pose the greatest RMS measurement challenges due to their significant harmonic content extending well above the targeted 1K bandwidth specified in Table 1. The AC Voltage Mode was used for these measurements.
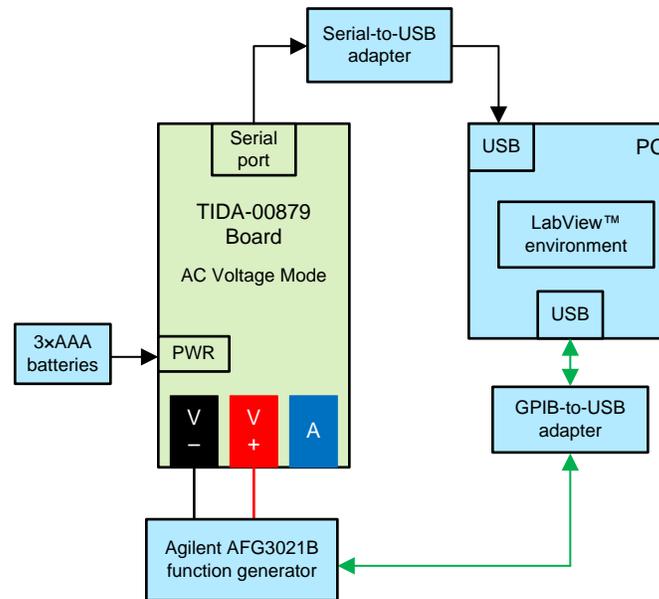
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Figure 30. Test Configuration for AC Voltage Frequency Response

Test procedure:

1. Connect the test equipment to the TIDA-00879 board as shown in Figure 30.
2. Power up the TIDA-00879 board in Test Mode.
3. Select the TIDA-00879 AC Voltage Mode.
4. Select the TIDA-00879 6-V range setting.
5. Set the Agilent AFG3021B to sine wave mode with 3-V amplitude and 0-V DC offset voltage.
6. Sweep the Agilent AFG3021B from 1 Hz to 4 kHz in 10-Hz increments.
7. Capture and plot the TIDA-00879 readings versus frequency.
8. Repeat Steps 5 through 7 for the following settings:
    (a) Sine wave, 3-V amplitude, 3-V DC offset
    (b) Square wave, 3-V amplitude, 50% duty cycle, 0-V DC offset
    (c) Square wave, 3-V amplitude, 50% duty cycle, 3-V offset
    (d) Square wave, 3-V amplitude, 20% duty cycle, 3-V offset

The following graphs show the results from these measurements.
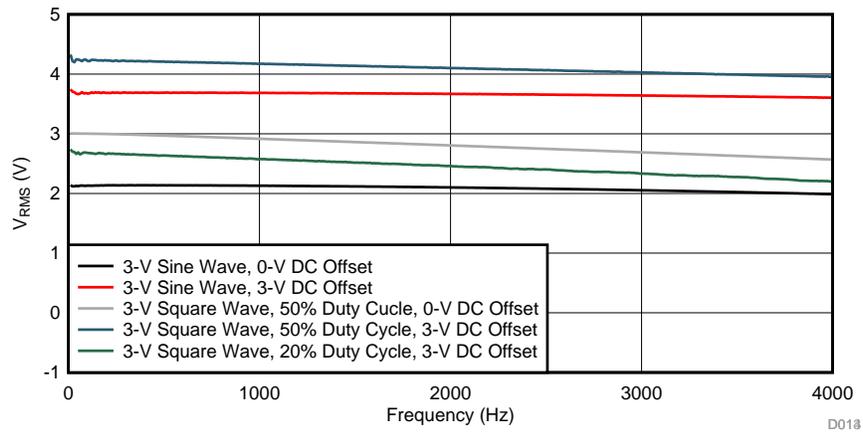
Figure 31. AC Voltage Frequency Response, 6-V Range (V_RMS)

Figure 32. AC Voltage Frequency Response, 6-V Range (Accuracy)

8.6 Frequency Response for AC Current Measurement

Figure 33 shows the test setup for characterizing AC current measurement as a function of frequency. AC Current Mode was used for these measurements.
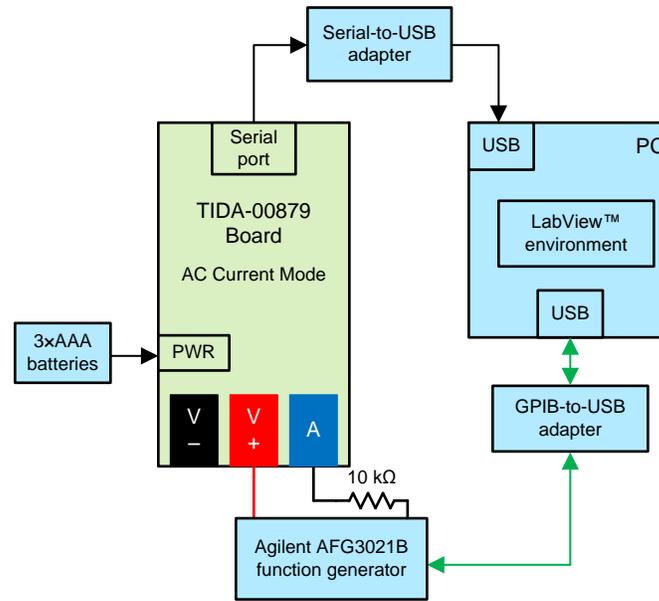

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Figure 33. Test Configuration for AC Current Measurement Frequency Response

Test procedure:

1. Connect the test equipment to the TIDA-00879 board as shown in Figure 33.
2. Power up the TIDA-00879 board in Test Mode.
3. Select the TIDA-00879 AC Current Mode.
4. Select the TIDA-00879 600-µA range setting.
5. Set the Agilent AFG3021B to sine wave mode with 3-V amplitude and 0-V DC offset voltage.
6. Sweep the Agilent AFG3021B from 1 Hz to 4 kHz in 10-Hz increments.
7. Capture and plot the TIDA-00879 readings versus frequency.
8. Repeat Steps 5 through 7 for the following settings:
    (a) Sine wave, 3-V amplitude, 3-V DC offset
    (b) Square wave, 3-V amplitude, 50% duty cycle, 0-V DC offset
    (c) Square wave, 3-V amplitude, 50% duty cycle, 3-V offset
    (d) Square wave, 3-V amplitude, 20% duty cycle, 3-V offset

The following graphs show the data taken from both current ranges.
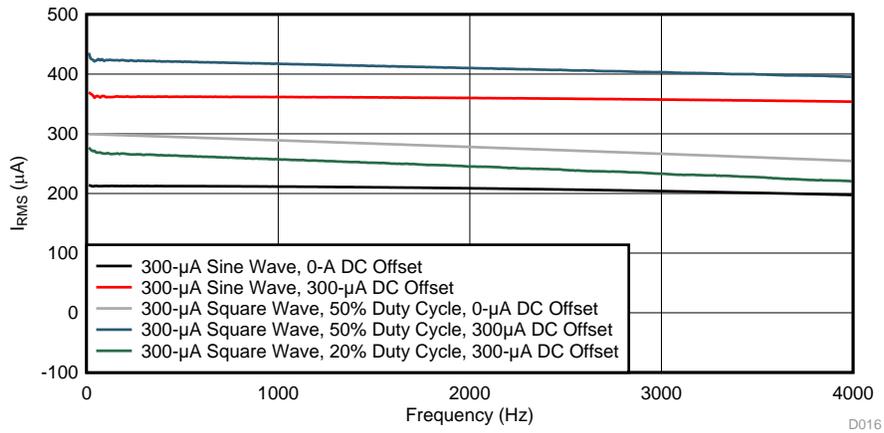
Figure 34. AC Current Frequency Response, 600-µA Range (I$_{RMS}$)

Figure 35. AC Current Frequency Response, 600-µA Range (Accuracy)

8.7 Power Measurement Resolution

Figure 36 shows the test setup for characterizing power measurement accuracy and linearity. DC Voltage Mode was used for this test.
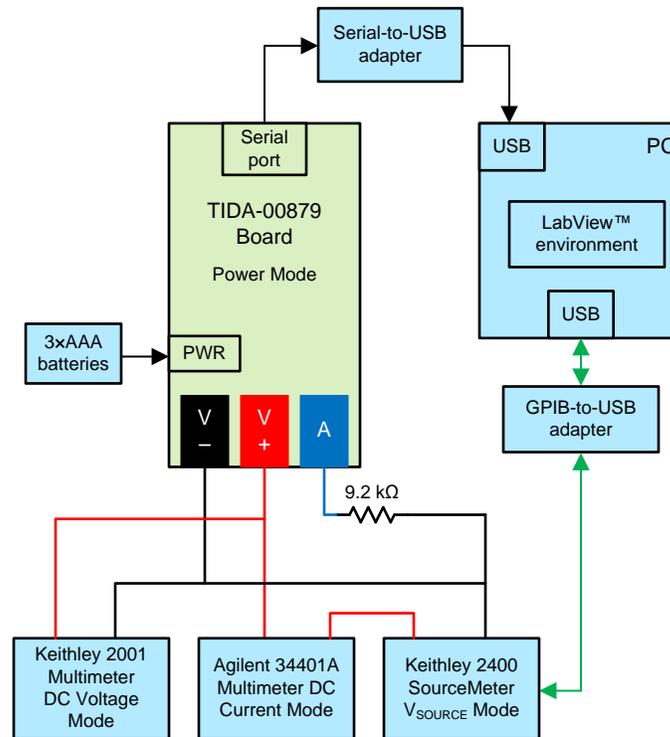
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Figure 36. Test Configuration for Power Measurement Resolution

Test procedure:

1. Connect the test equipment to the TIDA-00879 board as shown in Figure 36.
2. Power up the TIDA-00879 board in Test Mode.
3. Select the TIDA-00879 Power Mode.
4. Select the TIDA-00879 3600-µW range setting.
5. Sweep the Keithley 2400 SourceMeter DC Voltage from –6 V to 6 V in 600 steps.
6. Capture and plot the TIDA-00879 readings and Keithley 2001 Multimeter (V_{DC}) readings.
7. Plot the error voltage (TIDA-00879 value minus the V_{DC} value) versus the V_{DC} voltage.

The following graphs show the data taken from the 3600-µW and 3600-mW ranges. The light green plot lines represent the targeted resolution accuracy limits shown in Table 1.
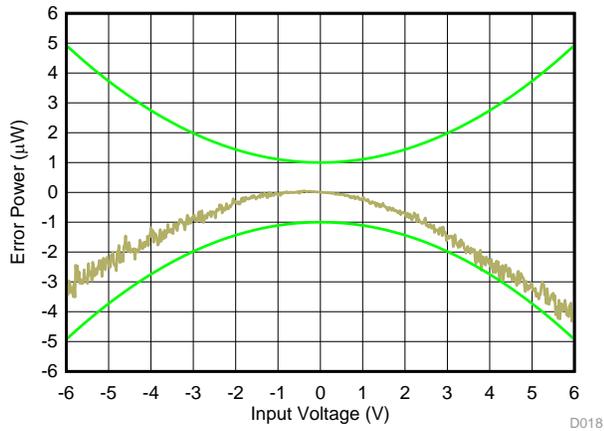
Figure 37. Linearity Plot, 3600-µW Range

Figure 38. Linearity Plot, 3600-mW Range

8.8 *Frequency Response for Power Measurement*

Figure 39 shows the test setup for characterizing AC current measurement as a function of frequency. AC Current Mode was used for these measurements.
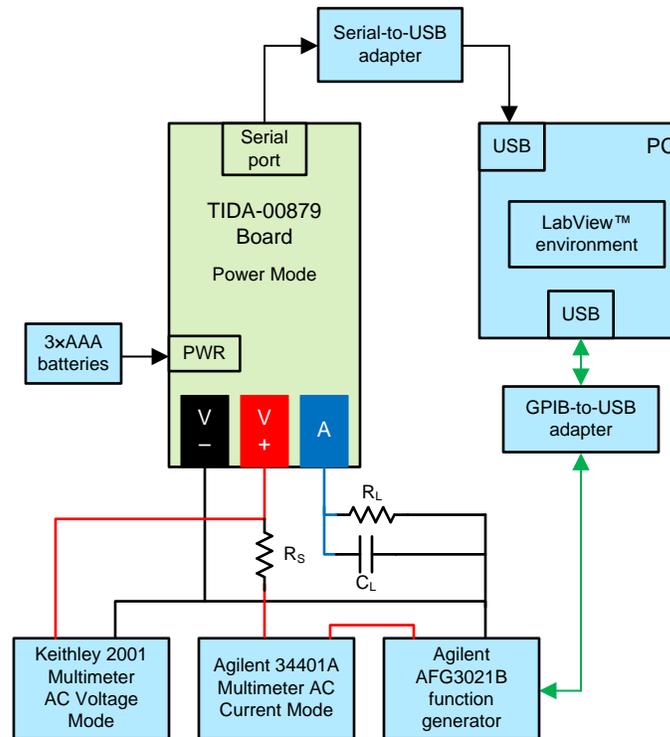
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Figure 39. Test Configuration for Power Measurement Frequency Response

Test procedure:

1. Connect the test equipment to the TIDA-00879 board as shown in Figure 39 with R_S = 0 Ω, R_L = 9.2 kΩ, and C_L = 0 pF.

2. Power up the TIDA-00879 board in Test Mode.

3. Select the TIDA-00879 Power Mode.

4. Select the TIDA-00879 3600-µW range setting.

5. Set the Keithley 2001 Multimeter to AC Voltage Mode.

6. Set the Agilent 34401A Multimeter to AC Current Mode.

7. Set the Agilent AFG3021B to sine wave mode with 6-V amplitude and 0-V DC offset voltage.

8. Sweep the Agilent AFG3021B from 1 Hz to 4 kHz in 10-Hz increments.

9. Capture and plot the TIDA-00879 readings versus frequency.

10. Repeat Steps 8 through 9 for R_S = 9.2 kΩ, R_L = 24.2 kΩ, and C_L = 6800 pF

The following graphs show the data taken for the real load and complex load configurations described in this section.

NOTE: Real load: R_L = 9.2 kΩ, R_S = 0 Ω, C_L = 0 pF
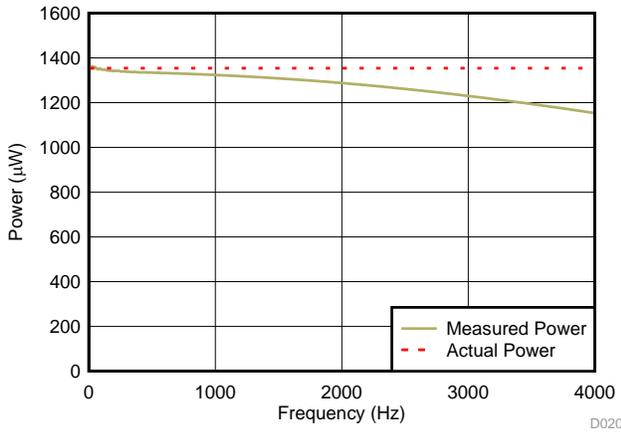
Figure 40. Power Measurement Frequency Response, 3600-µW Range (Power)
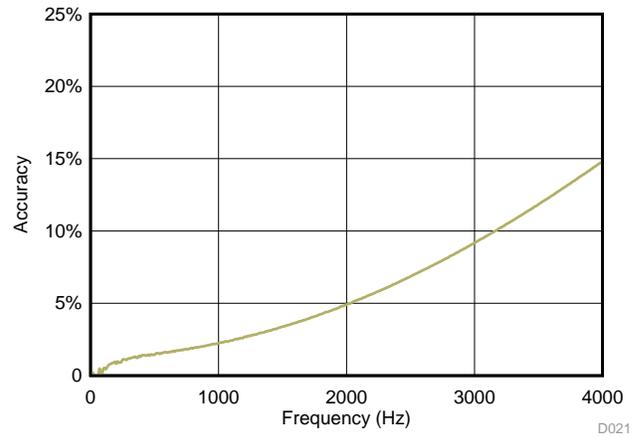
Figure 41. Power Measurement Frequency Response, 3600-µW Range (Accuracy)

NOTE: Complex load: R_L = 24.2 kΩ, R_S = 9.2 Ω, C_L = 6724 pF
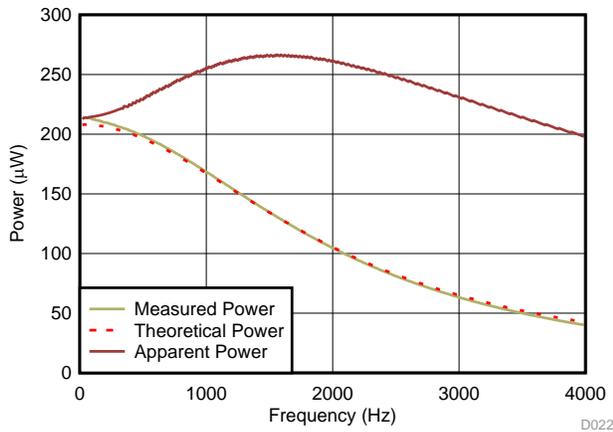
Figure 42. Power Measurement Frequency Response, 3600-µW Range (Power)
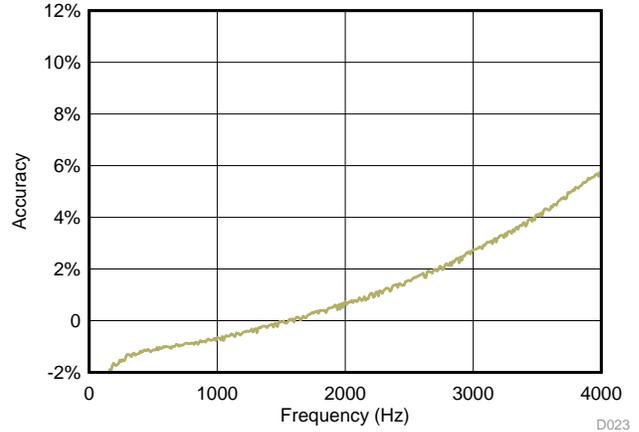
Figure 43. Power Measurement Frequency Response, 3600-µW Range (Accuracy)

8.9 *System Power Measurements and Battery Life Calculations*

Table 4 shows the current consumed by each TIDA-00879 measurement mode. These measurements were taken at a 3.6-V input, which represents a nominal voltage of a 3×AAA alkaline battery source over its entire operating voltage range of 2.4 to 4.8 V.

Table 4. System Power Measurements and Battery Life Calculations

MEASUREMENT MODE	CURRENT CONSUMPTION (mA)	% USAGE
DC voltage	1.610	35%
DC current	1.730	35%
AC voltage	1.700	10%
AC current	1.800	10%
Power	2.550	10%
Off	0.013	0%
Average current	1.770	100%

The average current of 1.77 mA is based on the assumed associated usage factor shown in Table 4.

Using a nominal 3×AAA battery source capacity of 1200 mAh, the estimated battery life of this TIDA-00879 system is *approximately 676 hours of actual operating time*.

Note that this reference design also supports 3×AA batteries with approximately a 3000-mAh capacity. This alternate source results in battery life of approximately 1690 hours of actual product operating time.

9   Design Files

9.1   Schematics

To download the schematics, see the design files at TIDA-00879.

9.2   Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00879.

9.3   Layout Prints

To download the layer plots, see the design files at TIDA-00879.

9.4   Altium Project

To download the Altium project files, see the design files at TIDA-00879.

9.5   Layout Guidelines

See the individual IC component datasheets for PCB layout considerations and recommendations.

9.6   Gerber Files

To download the Gerber files, see the design files at TIDA-00879.

9.7   Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00879.

10   Software Files

To download the software files, see the design files at TIDA-00879.

11   References

1. Texas Instruments, *MSP430x5xx and MSP430x6xx Family User's Guide* (SLAU208)
2. Texas Instruments, *Mixed Signal Microcontroller*, MSP430F6736 Datasheet (SLAS731)

11.1   Trademarks

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12   About the Author

RUSS ROSENQUIST is a systems designer at Texas Instruments Inc. where he is responsible for developing reference design solutions for the industrial segment. Russ has 33 years of experience in embedded product design. Russ earned his bachelor of science in electrical engineering (BSEE) from Texas Tech University.