

**Circuits  
from the Lab®**  
Reference Designs

*Circuits from the Lab® reference designs are engineered and tested for quick and easy system integration to help solve today's analog, mixed-signal, and RF design challenges. For more information and/or support, visit <https://www.analog.com/CN0414>*

Devices Connected/Referenced	
<a href="#">AD4111</a>	Low Power, 24-Bit, Sigma-Delta ADC with $\pm 10$ V and 0 mA to 20 mA Inputs
<a href="#">AD5700-1</a>	Low Power HART Modem with Internal Oscillator
<a href="#">ADuM5411</a>	Quad-Channel Isolators with Integrated DC-to-DC Converters
<a href="#">ADuM3151</a>	3.75 kV, 7-Channel, SPI Isolator Digital Isolator for SPI
<a href="#">ADG704</a>	CMOS, Low Voltage, 4 $\Omega$ , 4-Channel Multiplexer
<a href="#">ADP2441</a>	36 V, 1 A, Synchronous, Step-Down DC-to-DC Regulator

## Quad Channel Analog Input with Open Wire Detection and HART Compatibility for PLC/DCS Applications

### EVALUATION AND DESIGN SUPPORT

#### Circuit Evaluation Boards

[CN-0414 Circuit Evaluation Board \(EVAL-CN0414-ARDZ\)](#)  
[ADICUP3029 Arduino Form-Factor Development Platform \(EVAL-ADICUP3029\)](#)

#### Design and Integration Files

[Schematics, Layout Files, Bill of Materials, Software](#)

### CIRCUIT FUNCTION AND BENEFITS

The circuit shown in Figure 1 provides a complete, fully isolated and highly flexible, 4-channel analog input system suitable for programmable logic controllers (PLCs) and distributed control system (DCS) applications that require multiple voltage inputs with open wire detection and HART-compatible, 4 mA to 20 mA current inputs, all protected from transient overvoltage or over-current events, suitable for the most harsh industrial environments.

Each channel is composed from one differential or two single-ended voltage inputs and one current input. All voltage channels benefit from a unique feature called open wire detection, which detects when an external sensor or source signal is disconnected from the system input. Preventing open wire situations simplifies diagnosing techniques by embedding the detection methods in the user application software without adding external circuitry, which reduces the system developing and maintenance costs, size, and complexity.

The analog input circuit accepts four voltages, supporting ranges of  $\pm 5$  V,  $\pm 10$  V, 0 V to +5 V, 0 V to +10 V, and four currents, supporting ranges of 4 mA to 20 mA and 0 mA to 20 mA. All inputs are referred to the input terminal blocks isolated ground and are galvanically isolated from the upstream host circuitry.

The HART compatibility of this module provides a complete field communications solution that is simple to use, low cost, and extremely reliable.

The circuit is powered from a standard 24 V bus supply, with on-board filtering and protection circuitry. Because many factories and industrial environments power their PLC/DCS from a 24 V standard bus line, this module is easy to integrate into any existing system. This module can also be powered from other standard supplies, starting from 12 V<sub>DC</sub> to 28 V<sub>DC</sub>.

#### Rev. 0

Circuits from the Lab® reference designs from Analog Devices have been designed and built by Analog Devices engineers. Standard engineering practices have been employed in the design and construction of each circuit, and their function and performance have been tested and verified in a lab environment at room temperature. However, you are solely responsible for testing the circuit and determining its suitability and applicability for your use and application. Accordingly, in no event shall Analog Devices be liable for direct, indirect, special, incidental, consequential or punitive damages due to any cause whatsoever connected to the use of any Circuits from the Lab circuits. (Continued on last page)

**CIRCUIT DESCRIPTION**

**Analog to Digital Converter**

The heart of the circuit is an **AD4111** low power, low noise, 24-bit,  $\Sigma$ - $\Delta$  analog-to-digital converter (ADC) with integrated  $\pm 10$  V and 20 mA analog front ends.

The **AD4111** is software configurable and allows four fully differential or eight single-ended voltage input channels with open wire detection, and four current input channels offering great flexibility via an internal crosspoint multiplexer.

The **AD4111** has internal calibration registers that can be programmed to provide offset and gain corrections for the full

input path, including external signal conditioning circuitry. This ADC comes in a small 6 mm  $\times$  6 mm LFCSP package, making it ideal where space is a premium.

The internal clock and precision 2.5 V reference minimize external components and result in additional space savings.

The two programmable general-purpose output pins (GPO0 and GPO1) control auxiliary circuitry without using additional control lines from the processor/controller.

**CN-0414** uses GPO0 and GPO1 to enable/disable **ADG704** multiplexers that allow a single **AD5700-1** HART modem to service all four current input channels.

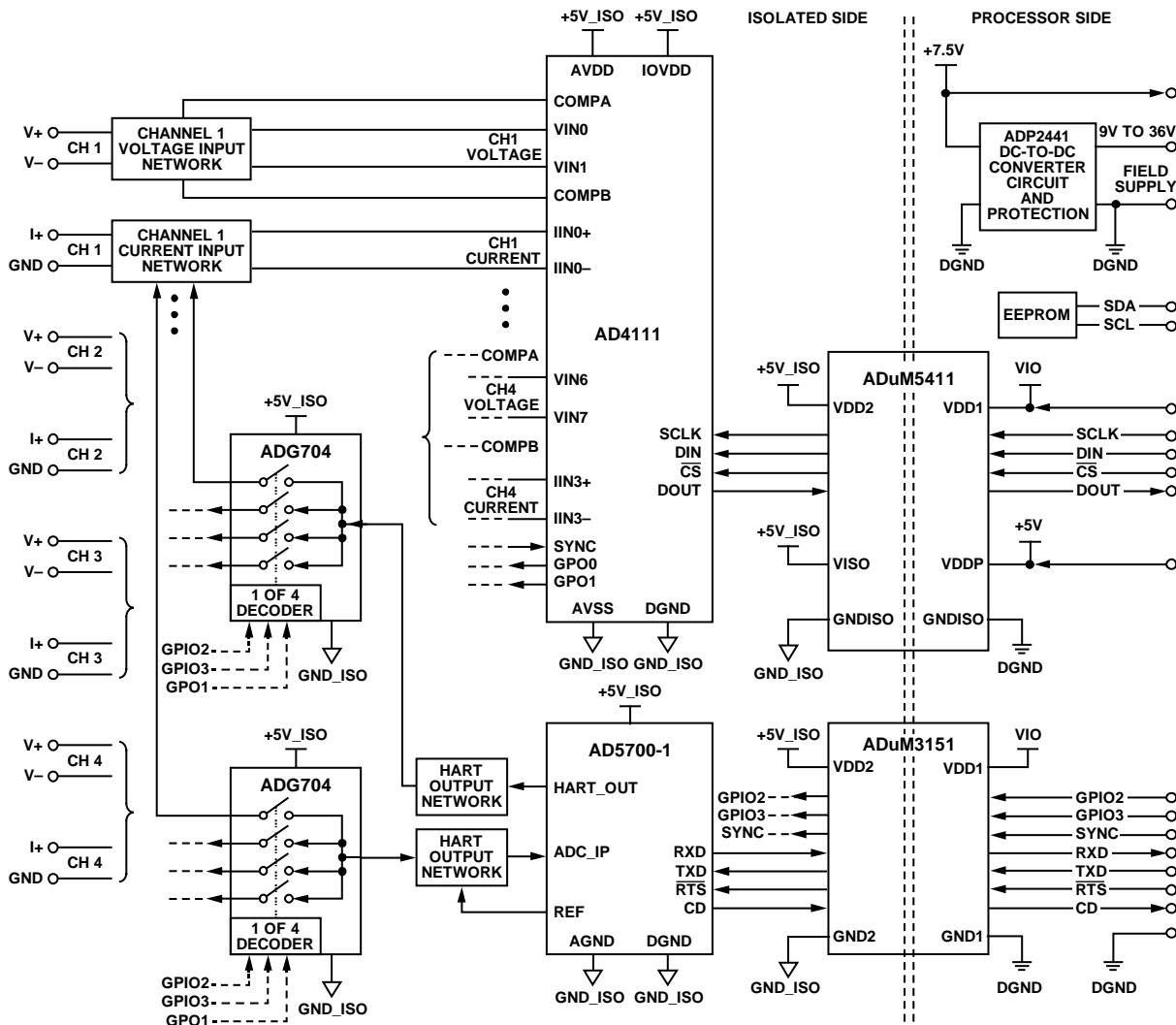


Figure 1. PLC/DCS Quad-Channel Voltage and Current Input Front End (Simplified Schematic: All Connections and Decoupling Not Shown)

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**Voltage Input Circuit**

Figure 2 shows the voltage input network for Channel 1.

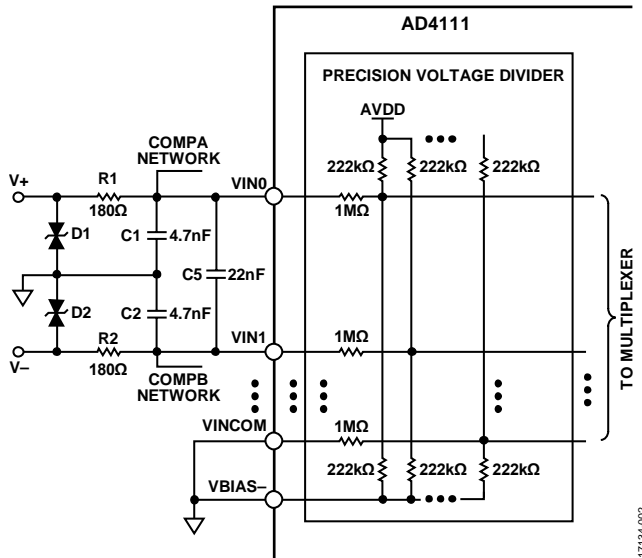


Figure 2. Voltage Input Equivalent Circuit (Simplified)

The circuit shown in Figure 2 has four differential inputs and supports an input range of up to ±10 V. The input impedance is guaranteed to be minimum 1 MΩ.

D1 and D2 protect the input during high voltage transient events.

Input common-mode noise filtering is provided by  $R1 || R_{IN\_ADC} / C1$  and  $R2 || R_{IN\_ADC} / C2$ , and is approximately 190 kHz. Differential noise filtering is provided by  $R1 || R_{IN\_ADC}$ ,  $R2 || R_{IN\_ADC}$ , and C5, and is approximately 18 kHz.

Table 1 summarizes the parameters and performance of the four voltage input channels.

**Table 1. Voltage Input Circuit Parameters**

Parameter	Value	Unit	Test Conditions/Comments
Input Impedance	>1	MΩ	
Input Range	±10	V	
Offset Error	±.15	mV	25°C, uncalibrated
Offset Drift	±7	μV/°C	
Gain Error	±0.05	% of FS	Internal full-scale calibration, 25°C
Gain Drift	±1	ppm/°C	
Input Filter	18	kHz	Differential
	190	kHz	Common mode

**Current Input Circuit**

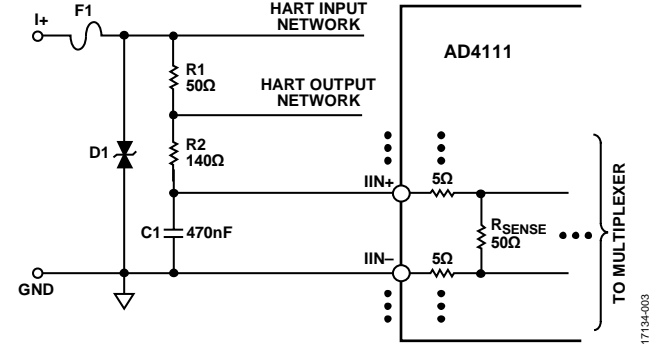


Figure 3. Current Input Equivalent Circuit (Simplified)

The circuit shown in Figure 3 has four current input channels, supporting a maximum input range of 0 mA to 24 mA. The input impedance of the circuit is 250 Ω (60 Ω internal to the AD4111), and the input is referenced to ground.

D1 and F1 protect the input during any high voltage or high current transient events.

An internal 50 Ω current sense resistor is used so that a 24 mA input produces 1.2 V, which is within the 2.5 V full-scale range of the ADP2441 (using the internal 2.5 V voltage reference).

The input path allows signals up to the full input bandwidth of the Σ-Δ ADC. It is also possible to use the internal sinc filters to reject the 1.2 kHz and 2.2 kHz HART frequencies. A filter model for AD4111 is provided in the **Tools & Simulations** section link on the AD4111 product page. **From the Tools & Simulations** section, reference **Design Tools** to find the best solution to reject HART frequencies.

Table 2 summarizes the parameters and performance of the current input channels.

**Table 2. Current Input Circuit Parameters**

Parameter	Value	Unit	Test Conditions/Comments
Input Impedance	250	Ω	Referred to ground
Offset Error	±2	μA	
Offset Drift	±3	nA/°C	
Gain Error	±0.02	% of FS	Internal full-scale calibration, 25°C
Gain Drift	±10	ppm/°C	
Input Filter	5.6	kHz	

**Open Wire Detection**

Open wire detection is a system level diagnostic that detects when an external sensor or source signal is disconnected from the system input. The AD4111 incorporates a unique feature that enables open wire detection on ±10 V voltage inputs while operating on a 5 V or 3.3 V single power supply, which in existing designs requires a supply greater than ±10 V.

The open wire detection feature is supported in user software. An open wire on an input is detected by comparing the absolute difference between the two channels associated with an input to a threshold. The suggested threshold is 300 mV input referred. If the difference is greater than this threshold, an open wire must be flagged by the user software.

The provided software source code exemplifies how to actually implement the open wire detection feature described in the AD4111 data sheet—a feature that simplifies the hardware and software design in terms of costs, size, complexity, and development time.

Figure 4 shows the voltage input setup necessary to detect an open wire event for Channel 1 for single-ended or differential configurations.

As an example, to detect an open wire event for a single-ended input configuration, in this case Channel 0 (VIN0) and Channel 15 (VINCOM), it is necessary to enable data, status, open wire detection, input buffers, mode, and reference source in the corresponding registers and then calculate the voltage difference between Channel 0 and Channel 15. If these two inputs are left floating, a voltage difference greater than 300 mV appears and an open wire is flagged. Otherwise, if a sensor or a signal source is connected, the voltage difference is lower than 300 mV and an open wire is not flagged.

For an open wire detection event in a differential input configuration, the algorithm is the same, the only difference being that the voltage difference that needs to be calculated is between Channel 1 (VIN0) and Channel 2 (VIN1).

When open wire detection is used, it is necessary to assign two channels per measurement for each voltage input. Voltage inputs must also be assigned to specific channel pairs to ensure that open wire detection measurements work correctly.

For single-ended input, open wire detection measurements, the channel pairings that must be used are as follows:

- Channel 15 and Channel 0
- Channel 1 and Channel 2
- Channel 3 and Channel 4
- Channel 5 and Channel 6
- Channel 7 and Channel 8
- Channel 9 and Channel 10
- Channel 11 and Channel 12
- Channel 13 and Channel 14

For differential input, open wire detection measurements, the channel pairings that must be used are as follows:

- Channel 1 and Channel 2
- Channel 5 and Channel 6
- Channel 9 and Channel 10
- Channel 13 and Channel 14

Additionally, for differential inputs, the inputs must be set up in the following differential pairs to ensure correct operation:

- VIN0 and VIN1
- VIN2 and VIN3
- VIN4 and VIN5
- VIN6 and VIN7

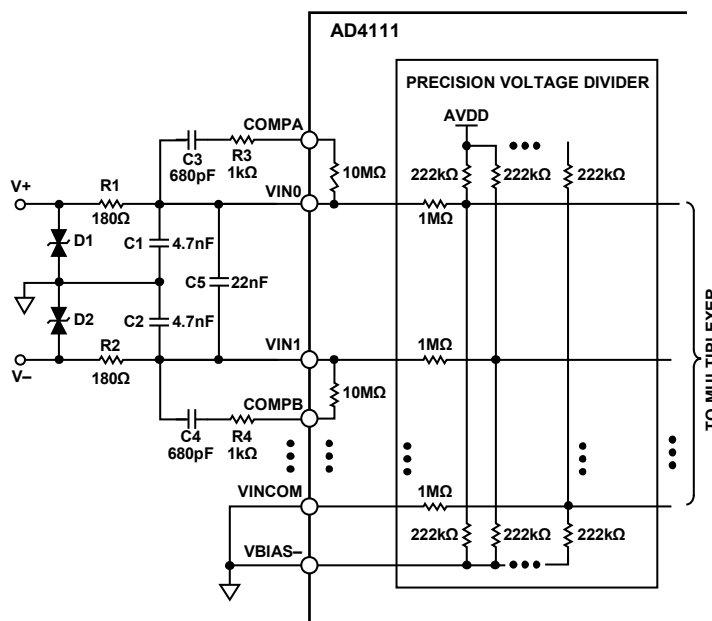


Figure 4. Voltage Input Equivalent Circuit with Open Wire Complete Setup



**Power Supply Circuit**

The board is powered by a 9.5 V to 36 V dc power supply and uses an on-board switching regulator to provide the 7.5 V supply to the system, as shown in Figure 6 and Figure 7. In the test setup, the 7.5 V powers the EVAL-ADICUP3029 board. The EVAL-ADICUP3029 board then provides a regulated 3.3 V for the V<sub>IO</sub> (IOREF pin in Figure 7) voltage and 5 V to the remaining circuitry.

The ADP2441 36 V, step-down, dc-to-dc regulator accepts an industrial standard 24 V supply, with wide tolerance on the input voltage. The ADP2441 steps the input voltage down to 7.5 V at 1 A for the platform board and 5 V power for the remainder of the EVAL-CN0414-ARDZ, utilizing the 5 V regulator typically present on Arduino-compatible platforms. The circuit also includes filtering and protection on the 24 V supply terminals.

The high switching frequency of the ADP2441 allows minimal output voltage ripple even when small inductors are used.

Selecting the size of the inductor involves considering the trade-off between efficiency and transient response. A smaller inductor results in larger inductor current ripple, which provides excellent transient response but degrades efficiency. Due to the high switching frequency of the ADP2441, using shielded ferrite core inductors is recommended because of their low core losses and low electromagnetic interference (EMI).

In the Figure 6 circuit, the switching frequency is approximately 550 kHz with the 162 kΩ external resistor. The inductor value of 33 μH is chosen from the ADP2441 data sheet. The circuit is connected to the field supply of 9.5 V to 36 V (12 V to 28 V usually) using screw terminals. The EARTH terminal can be connected to an external earth connection or to the GND terminal if an external earth connection is not used.

Power inductors, varistors, a power diode, and a 1.1 A fuse provide additional input protection against high voltage transient events.

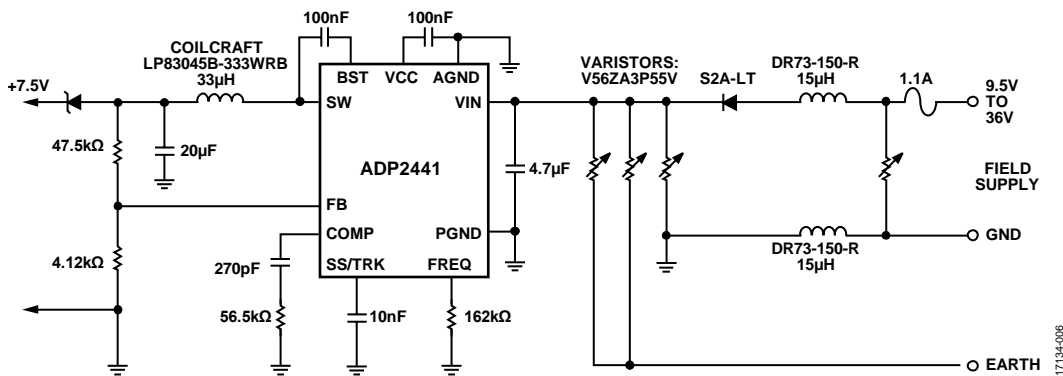


Figure 6. Power Supply Circuit (Simplified Schematic: All Connections Not Shown)

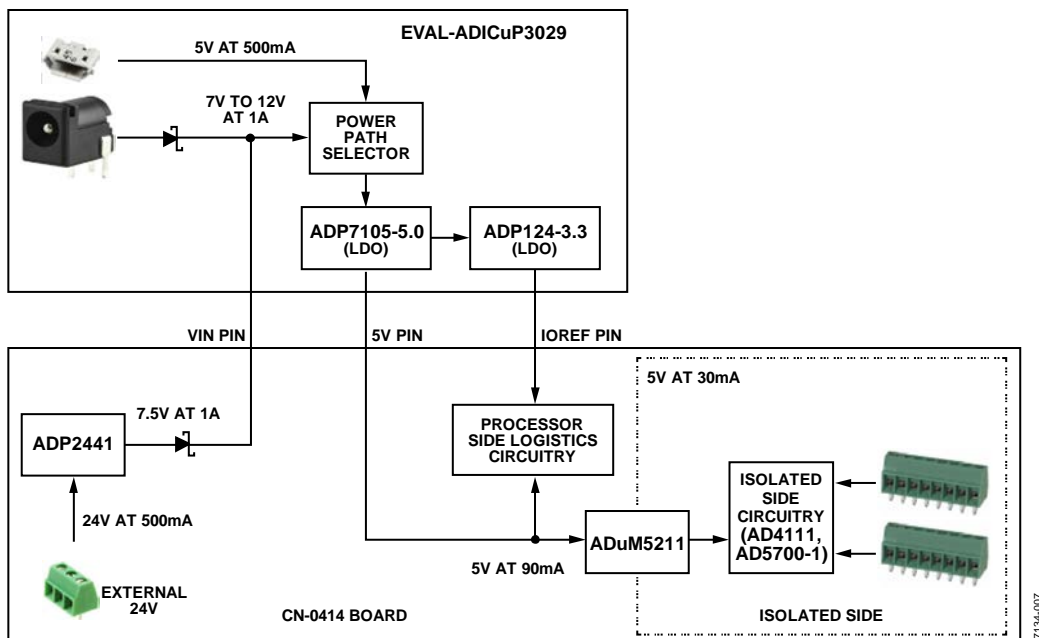


Figure 7. Power Tree and Configurations for CN-0414 Board

The [EVAL-CN0414-ARDZ](#) can be powered in three ways, as shown in Figure 7 and described in Table 3. In any case the [EVAL-CN0414-ARDZ](#) is powered from [EVAL-ADICUP3029](#) or any other compatible Arduino base board.

There is a priority between power sources if more are connected to the [EVAL-CN0414-ARDZ](#) or [EVAL-ADICUP3029](#). The highest voltage value is the selected power source.

**Table 3. CN-0414 Power Options**

Power Source	USB Power <sup>1</sup>	Barrel Jack Power <sup>1</sup>	Terminal Block Power <sup>1</sup>
<a href="#">ADICUP3029</a> USB (5 V)	Connected	Connected for data only	Connected for data only
<a href="#">ADICUP3029</a> Barrel Jack (7 V to 12 V)	N/A	Connected	N/A
<a href="#">CN-0414</a> Terminal Block (12 V to 28 V)	N/A	N/A	Connected

<sup>1</sup> N/A means not applicable.

**Isolation**

The [ADuM5411](#) isolates the SPI interface (SCLK, SDI, SDO, CS) and also provides the isolated 5 V supply via integrated *isoPower*® technology, whereas the [ADuM3151](#) SPIisolator® provides isolation for HART interface and control signals. These isolators offer significant space savings over discrete transformer-based solutions. For more information, check out the *Analog Dialog* article, “[PLC DCS Analog Input Module Design Breaks Barriers in Channel-to-Channel Isolation and High Density.](#)”

**Noise Test**

The [CN-0414](#) software running on the [ADICUP3029](#) platform includes a function for capturing a number of samples. Most terminal programs have the ability to log received data to a file. This received data can then be imported into a spreadsheet or other program for analysis.

Evaluate the system noise by shorting the input terminals for each channel, which results in a zero differential voltage for the voltage input channels and grounded input for the current input

channels. Gather the data with the inputs shorted, and compute the code spread and noise-free code resolution from the set number of samples.

The rms noise of the ADC input can be calculated by taking the standard deviation of a large number of samples. The code spread and noise-free code resolution of each channel can be obtained, and the data displayed in a histogram. Figure 8 and Figure 9 each show a histogram from sample data gathered from the voltage input and current input of Channel 1.

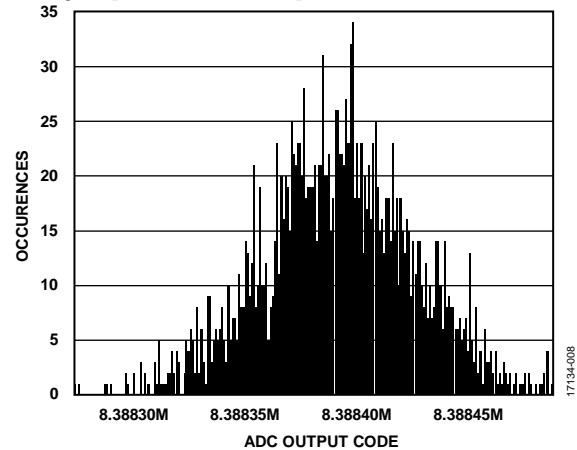


Figure 8. Channel 1 Voltage Input, Inputs Shorted, 31.25 kSPS, Sinc5 + 1 Filter, 2000 Samples

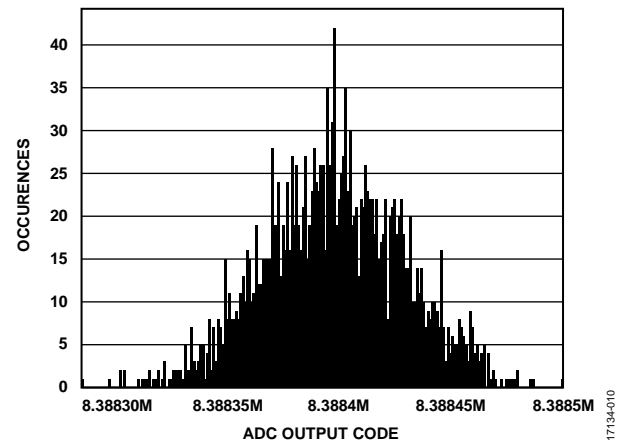


Figure 9. Channel 1 Current Input, Inputs Shorted, 31.25 kSPS, Sinc5 + 1 Filter, 2000 Samples

Table 5 shows a comparison on noise performance between the AD4111 noise as reported in the data sheet and the actual determinate noise by using the CN-0414 board.

**Table 4. CN-0414 Performances for ±10 V Voltage Input RMS Noise Resolution vs. ODR Using a Sinc5 + Sinc1 Filter**

Output Data Rate (sps)	Data Sheet (µV)	Channel 1 (µV)	Channel 2 (µV)	Channel 3 (µV)	Channel 4 (µV)
31,250	106	108.52	122.15	132.7	111.8
15,625	94	96.59	108.42	116.42	95.76
10,417	82	84.3	92.27	86.64	81.91
5208	62	60.95	63.09	65.31	61.7
2597	47	54.98	56.65	55.12	54.26
1007	27	30.08	31.06	30.55	29.37
504	21	21.46	21.65	21.25	20.75
381	17	18.43	18.1	18.36	17.86
200.3	13	13.17	13.54	13.23	13.26
100.2	8	9.6	9.77	9.74	9.94
59.52	7	8.21	8.04	7.52	8.3
49.68	7	6.95	7.08	7.59	7.09
20	4	5.2	5.5	4.95	6.49
16.67	4	5.18	4.92	4.88	4.6
10	3.7	3.65	4.52	5.32	4.58
5	3.4	5.47	5.36	3.76	4.13
2.5	2.4	3.38	3.6	3.77	3.75
1.25	2.3	3.6	5.03	3.27	4.14

**Table 5. CN-0414 Performances for 0 mA to 20 mA Current Input Noise and Resolution vs. Output Data Rate Using a Sinc5 + Sinc1**

Output Data Rate (sps)	Data Sheet (µV)	Channel 1 (µV)	Channel 2 (µV)	Channel 3 (µV)	Channel 4 (µV)
31,250	155	188.07	190.23	188.82	183.33
15,625	136	162.33	165.41	164.15	166.78
10,417	113	138.19	145.44	140.42	137.43
5208	84	105.15	103.63	105.9	108.61
2597	75	89.44	91.07	90.6	91.4
1007	43	53.12	51.21	51.23	51.76
504	29	34.4	35.32	36.91	34.39
381	21	30.46	29.61	30.48	30.82
200.3	18	22.18	22.12	22.03	22.47
100.2	13	15.27	15.51	15.4	15.48
59.52	10	11.77	11.72	11.87	11.83
49.68	9	10.83	10.78	11.05	11.04
20	6	6.86	6.8	6.82	7.5
16.67	5.3	6.8	6.71	6.84	6.82
10	4.6	4.88	5.32	5.16	5.33
5	3	3.73	3.74	3.65	3.94
2.5	2.8	2.95	2.83	2.67	3.1
1.25	2.7	2.29	2.13	2.34	2.29



### HART Test

The HART functionality was tested according to the HART physical layer test specification (HCF-TEST-2). More details on the HART specifications can be obtained directly from the HART Communication Foundation and in the [Flexible Bandwidth 4 mA to 20 mA Current Input with Easy HART Compatibility](#) technical article.

A physical layer HART compliance test verifies the wave shape, carrier start/stop/decay, carrier start/stop transient, output noise during silence, impedance measurements, noise sensitivity, carrier detect level, carrier detect start/stop, and others.

A complete design support package for the [EVAL-CN0414-ARDZ](#) board, including schematic, bill of materials, and layout can be downloaded from [www.analog.com/CN0414-DesignSupport](http://www.analog.com/CN0414-DesignSupport).

### COMMON VARIATIONS

The [AD4112](#) can be used if open wire detection in voltage input mode is not a requirement. A less integrated solution can also be used, such as shown in [CN-0364](#), which would consume larger area but could be optimized to operate at higher input bandwidths.

When high channel data rates are required, the [AD7175-2](#) ADC can be used. The [AD7175-2](#) supports data rates of up to 250 kSPS, with channel switching rates of up to 50 kSPS. The [AD7175-2](#) can achieve a resolution of 17.2 noise-free bits at the 250 kSPS data rate. Aside from the higher data rates, the features of the [AD7175-2](#) are similar to those of the [AD7173-8](#).

For applications that require more than 150 mW of isolated power, the [ADuM5400](#) family (including [ADuM5400](#), [ADuM5401](#), [ADuM5402](#), [ADuM5403](#), and [ADuM5404](#)) or [ADuM3470](#) family (including [ADuM3470](#), [ADuM3471](#), [ADuM3472](#), [ADuM3473](#), and [ADuM3474](#)) can be used. The [ADuM5400](#) family uses *isoPower* technology to supply up to 500 mW of isolated power. The [ADuM3470](#) family drives an

external, discreet transformer to supply up to 2 W at up to 70% efficiency.

### CIRCUIT EVALUATION AND TEST

The circuit shown in Figure 10 uses the [EVAL-CN0414-ARDZ](#) evaluation board and the [EVAL-ADICUP3029](#).

The [CN-0414](#) software communicates with the [EVAL-ADICUP3029](#) to configure and capture data from the [EVAL-CN0414-ARDZ](#) evaluation board.

The provided software targets the [EVAL-ADICUP3029](#) platform, but it is designed to be easily portable to other microcontroller platforms.

When porting to other platforms, be sure to thoroughly review hardware compatibility, including voltage levels and functionality.

### Equipment Needed

- PC with a USB port and Windows® 7 (32-bit) or higher
- Serial terminal program such as Tera Term or Putty
- [EVAL-CN0414-ARDZ](#) circuit evaluation board
- [EVAL-ADICUP3029](#) evaluation board or any compatible Arduino board
- Micro USB cable
- [CN-0414](#) software or prebuilt hex file
- A power supply: 9.5 V to 36 V dc at 1 A
- Precision voltage and current source (for input)

### Getting Started

Install the [CN-0414](#) software. Then, follow the wiki instructions from [https://wiki.analog.com/resources/eval/user-guides/eval-adicup3029/tools/cces\\_user\\_guide](https://wiki.analog.com/resources/eval/user-guides/eval-adicup3029/tools/cces_user_guide) to install and use the software. For more information and complete details on setup, please reference the [CN-0414 user guide](#).

### Functional Block Diagram

Figure 10 shows a function block diagram of the test setup.

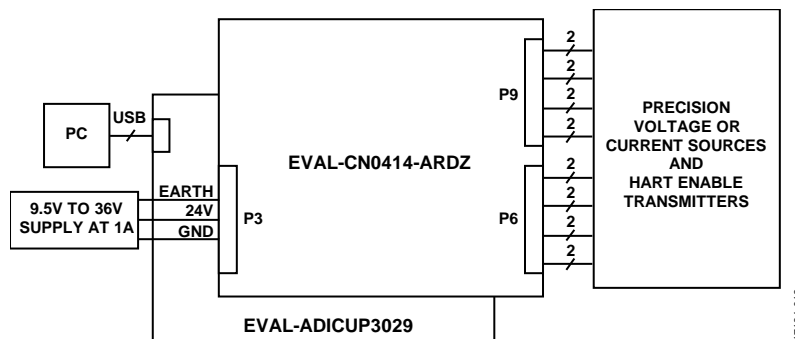


Figure 10. Test Setup Functional Block Diagram

Setup

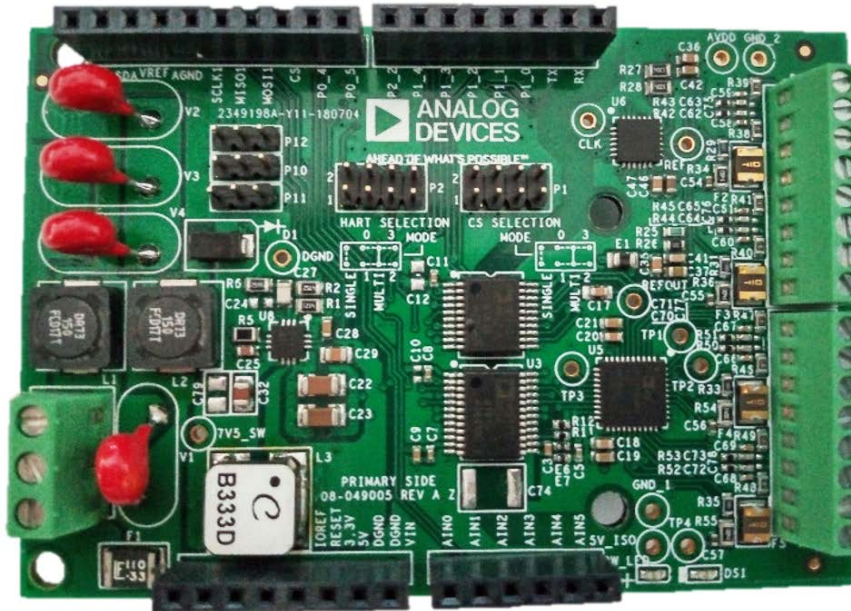


Figure 11. Photograph of EVAL-CN0414-ARDZ Evaluation Board

The CN-0414 software and the EVAL-ADICUP3029 board allow the data to be captured and analyzed using a PC.

Figure 11 shows a photo of the EVAL-CN0414-ARDZ evaluation board.

The following are the basic steps for setup:

1. If the jumpers are not already mounted, mount the jumpers provided in the box in the same configuration as shown in Figure 12.



Figure 12. EVAL-CN0414-ARDZ Default Jumper Position/Connection

2. Connect the EVAL-CN0414-ARDZ evaluation board to the EVAL-ADICUP3029 in the same configuration as shown in Figure 13.



Figure 13. EVAL-CN0414-ARDZ Connected to EVAL-ADICUP3029

3. Connect a signal source. Precision voltage and current sources can be used as input to the analog front end to evaluate system performances. In Figure 14, a constant current source is connected on Channel 1 current input and a voltage source is connected on Channel 4 voltage inputs to measure a differential voltage.

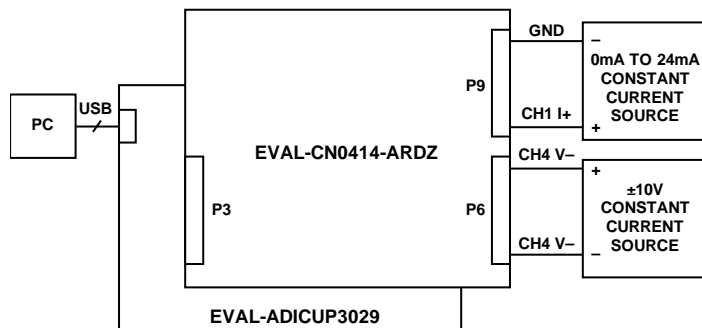


Figure 14. Analog Input Setup Example

- Connect a HART signal source. The [CN-0267](#) circuit (a complete 4 mA to 20 mA loop powered field instrument with HART interface) can be connected as shown in

Figure 15 to easily test the HART physical layer functionality. The [CN-0267](#) hardware responds to the HART commands available in the [CN-0414](#) software.

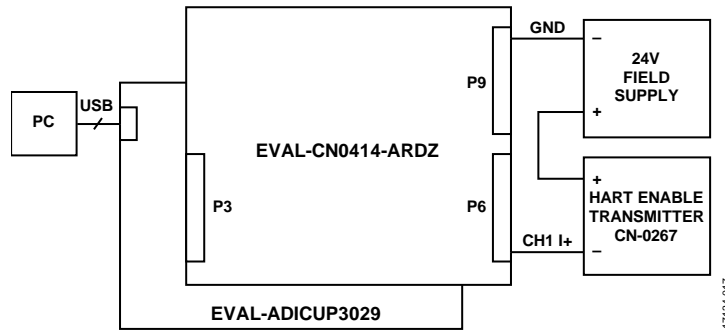


Figure 15. HART Setup Example

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**LEARN MORE**

CN-0414 Design Support Package.

CN-0267 Circuit Note, *Complete 4 mA to 20 mA Loop Powered Field Instrument with HART Interface*, Analog Devices.

CN-0270 Circuit Note, *Complete 4 mA to 20 mA HART Solution*, Analog Devices.

CN-0278 Circuit Note, *Complete 4 mA to 20 mA HART Solution with Additional Voltage Output Capability*, Analog Devices.

CN-0321 Circuit Note, *Fully Isolated, Single Channel Voltage and 4 mA to 20 mA Output with HART Connectivity*, Analog Devices.

CN-0328 Circuit Note, *Completely Isolated 4-Channel Multiplexed HART Analog Output Circuit*, Analog Devices.

Mark Cantrell, *Recommendations for Control of Radiated Emissions with isoPower Devices*, Application Note AN-0971, Analog Devices.

**Data Sheets and Evaluation Boards**

CN-0414 Circuit Evaluation Board (EVAL-CN0414-ARDZ)

ADuCM3029 Development Platform (EVAL-ADICUP3029)

AD4111 Data Sheet

AD5700-1 Data Sheet

ADuM3151 Data Sheet

ADuM5411 Data Sheet

ADG704 Data Sheet

ADP2441 Data Sheet

**REVISION HISTORY**

3/2019—Revision 0: Initial Version

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