PLC Evaluation Board Simplifies Design of Industrial Process-Control Systems

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Introduction

The applications for industrial process-control systems are diverse, ranging from simple traffic control to complex electrical power grids, from environmental control systems to oil-refinery process control. The intelligence of these automated systems lies in their measurement and control units. The two most common computer-based systems to control machines and processes, dealing with the various analog and digital inputs and outputs, are *programmable logic controllers*[1] (PLCs) and *distributed control systems*[2] (DCS's). These systems comprise power supplies, central processor units (CPUs), and a variety of analog-input, analog-output, digital-input, and digital-output modules.

The standard communications protocols have existed for many years; the ranges of analog variables are dominated by 4 mA to 20 mA, 0 V to 5 V, 0 V to 10 V, ±5 V, and ±10 V. There has been much discussion about wireless solutions for next-generation systems, but designers still claim that 4 mA to 20 mA communications and control loops will continue to be used for many years. The criteria for the next generation of these systems will include higher performance, smaller size, better system diagnostics, higher levels of protection, and lower cost—all factors that will help manufacturers differentiate their equipment from that of their competitors.

We will discuss the key performance requirements of process-control systems and the analog input/output modules they contain—and will introduce an industrial process-control evaluation system that integrates these building blocks using the latest integrated-circuit technology. We also look at the challenges of designing a robust system that will withstand the electrical fast transients (EFTs), electrostatic discharges (ESDs), and voltage surges found in industrial environments—and present test data that verifies design robustness.

PLC Overview with Application Example

Figure 1 shows a basic process-control system building block. A process variable, such as flow rate or gas concentration, is monitored via the input module. The information is processed by the central control unit; and some action is taken by the output module, which, for example, drives an actuator.

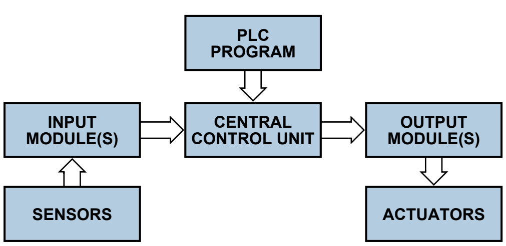

Figure 1. Typical top-level PLC system.

Figure 2 shows a typical industrial subsystem of this type. Here a CO_2 gas sensor determines the concentration of gas accumulated in a protected area and transmits the information to a central control point. The control unit consists of an analog input module that conditions the 4 mA to 20 mA signal from the sensor, a central processing unit, and an analog output module that controls the required system variable. The current loop can handle large capacitive loads—often found on hundreds-of-meters long communications paths experienced in some industrial systems. The output of the sensor element, representing gas concentration levels, is transformed into a standard 4 mA to 20 mA signal, which is transmitted over the current loop. This simplified example shows a single 4 mA to 20 mA sensor output connected to a single-channel input module and a single 0 V to 10 V output. In practice, most modules have multiple channels and configurable ranges.

The resolution of input/output modules typically ranges from 12- to 16 bits, with 0.1% accuracy over the industrial temperature range. Input ranges can be as small as ±10 mV for bridge transducers and as large as ±10 V for actuator controllers—or 4 mA to 20 mA currents in process-control systems. Analog output voltage and current ranges typically include ±5 V, ±10 V, 0 V to 5 V, 0 V to 10 V, 4 mA to 20 mA, and 0 mA to 20 mA. Settling-time requirements for digital-to-analog converters (DACs) vary from 10 µs to 10 ms, depending on the application and the circuit load.

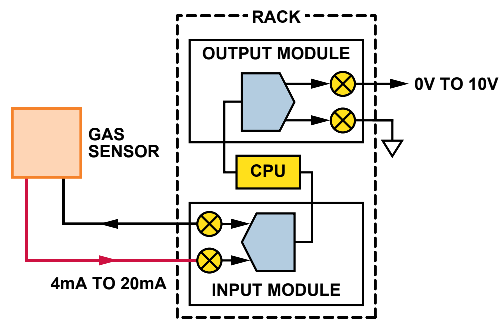

Figure 2. Gas sensor.

The 4 mA to 20 mA range is mapped to represent the normal gas detection range; current values outside this range can be used to provide fault-diagnostic information, as shown in Table 1.

Table 1. Assigning currents outside the 4 mA to 20 mA output range.

Current Output (mA)	Status
0.0	Unit fault
0.8	Unit warm up
1.2	Zero drift fault
1.6	Calibration fault
2.0	Unit spanning
2.2	Unit zeroing
4 to 20	Normal measuring mode
4.0	Zero gas level
5.6	10% full scale
8.0	25% full scale
12	50% full scale
16	75% full scale
20	Full scale
>20	Overrange

PLC Evaluation System

The PLC evaluation system[3] described here integrates all the stages needed to generate a complete input/output design. It contains four fully isolated ADC channels, an ARM7™ microprocessor with RS-232 interface, and four fully isolated DAC output channels. The board is powered by a dc supply. Hardware-configurable input ranges include 0 V to 5 V, 0 V to 10 V, ±5 V, ±10 V, 4 mA to 20 mA, 0 mA to 20 mA, ±20 mA, as well as thermocouple and RTD. Software-programmable output ranges include 0 V to 5 V, 0 V to 10 V, ±5 V, ±10 V, 4 mA to 20 mA, 0 mA to 20 mA, and 0 mA to 24 mA.

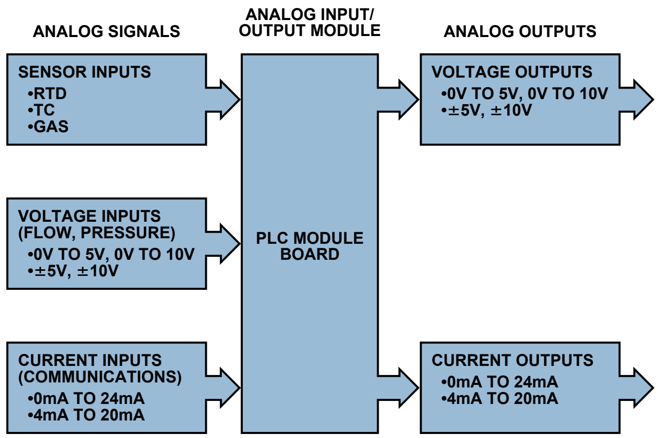

Figure 3. Analog input/output module.

Output Module: Table 2 highlights some key specifications of PLC output modules. Since the true system accuracy lies within the measurement channel (ADC), the control mechanism (DAC) requires only enough resolution to tune the output. For high-end systems, 16-bit *resolution* is required. This requirement is actually quite easy to satisfy using standard digital-to-analog architectures. Accuracy is not crucial; 12-bit integral nonlinearity (INL) is generally adequate for high-end systems.

Calibrated accuracy of 0.05% at 25°C is easily achievable by overranging the output and trimming to achieve the desired value. Today's 16-bit DACs, such as the AD5066,[4] offer 0.05 mV typical offset error and 0.01% typical gain error at 25°C, eliminating the need for calibration in many cases. *Total accuracy* error of 0.15% sounds manageable but is actually quite aggressive when specified over temperature. A 30 ppm/°C output drift can add 0.18% error over the industrial temperature range.

Table 2. Output module specifications.

System Specification	Requirement
Resolution	16 bits
Calibrated Accuracy	0.05%
Total Module Accuracy Error	0.15%
Open-Circuit Detection	Yes
Short-Circuit Detection	Yes
Short-Circuit Protection	Yes
Isolation	Yes

Output modules may have current outputs, voltage outputs, or a combination. A classical solution that uses discrete components to implement a 4 mA to 20 mA loop is shown in Figure 4. The AD5660 16-bit *nano*DAC® converter provides a 0 V to 5 V output that sets the current through sense resistor, R_S, and therefore, through R_1. This current is mirrored through R_2.

$$V_{DAC} / R_S = I_S = V_{R1} / R_1 = V_{R2} / R_2 = I_{R2}$$

$$I_{R2} = (V_{DAC} / R_S) \times R_1 / R_2$$

Setting R_S = 15 kΩ, R_1 = 3 kΩ, R_2 = 50 Ω and using a 5-V DAC will result in I_{R2} = 20 mA max.

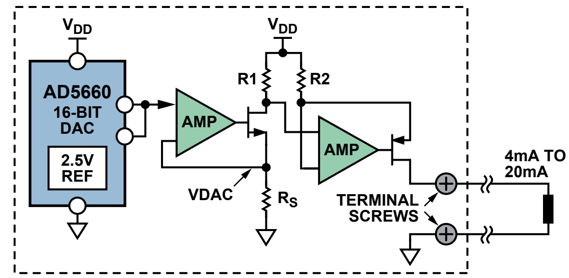

Figure 4. Discrete 4 mA to 20 mA implementation.

This discrete design suffers from many drawbacks: Its high component count engenders significant system complexity, board size, and cost. Calculating total error is difficult, with multiple components adding varying degrees of error with coefficients that can be of differing polarities. The design does not provide short-circuit detection/protection or any level of fault diagnostics. It does not include a voltage output, which is required in many industrial control modules. Adding any of these features would increase the design complexity and the number of components. A better solution would be to integrate all of the above on a single IC, such as the AD5412/AD5422 low-cost, high-precision, 12-/16-bit digital-to-analog converters. They provide a solution that offers a fully integrated programmable current source and programmable voltage output designed to meet the requirements of industrial process-control applications.

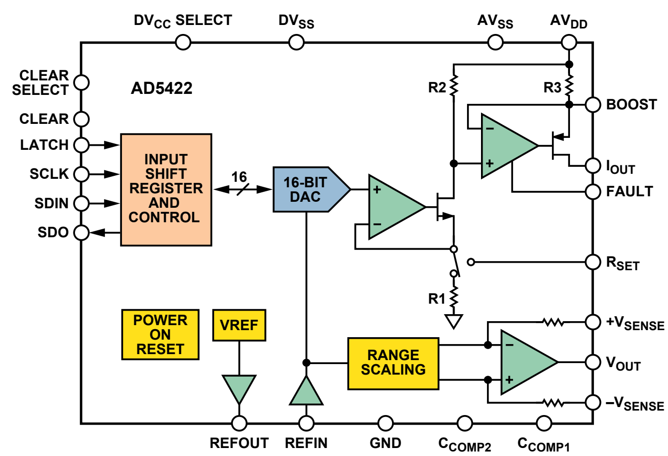

Figure 5. AD5422 programmable voltage/current output.

The output current range is programmable to 4 mA to 20 mA, 0 mA to 20 mA, or 0 mA to 24 mA overrange function. A voltage output, available on a separate pin, can be configured to provide 0 V to 5 V, 0 V to 10 V, ±5 V, or ±10 V ranges, with a 10% overrange available on all ranges. Analog outputs are short-circuit protected, a critical feature in the event of miswired outputs—for example, when the user connects the output to ground instead of to the load. The AD5422 also has an open-circuit detection feature that monitors the current-output channel to ensure that no fault has occurred between the output and the load. In the event of an open circuit, the FAULT pin will go active, alerting the system controller. The AD5750 programmable current/voltage output driver features both short-circuit detection and protection.

Figure 6 shows the output module used in the PLC evaluation system. While earlier systems typically needed 500 V to 1 kV of isolation, today >2 kV is generally required. The ADuM1401 digital isolator uses *i*Coupler®[5] technology to provide the necessary isolation between the MCU and remote loads, or between the input/output module and the backplane. Three channels of the ADuM1401 communicate in one direction; the fourth channel communicates in the opposite direction, providing isolated data readback from the converters. For newer industrial designs, the ADuM3401 and other members of its family of digital isolators provide enhanced system-level ESD protection.

The AD5422 generates its own logic supply (DVCC), which can be directly connected to the field side of the ADuM1401, eliminating the need to bring a logic supply across the isolation barrier. The AD5422 includes an internal sense resistor, but an external resistor (R1) can be used when lower drift is required. Because the sense resistor controls the output current, any drift of its resistance will affect the output. The typical temperature coefficient of the internal sense resistor is 15 ppm/°C to 20 ppm/°C, which could add 0.12% error over a 60°C temperature range. In high-performance system applications, an external 2-ppm/°C sense resistor could be used to keep drift to less than 0.016%.

The AD5422 has an internal 10-ppm/°C max voltage reference that can be enabled on all four output channels in the PLC evaluation system. Alternatively, the ADR445 ultralow-noise XFET® voltage reference, with its 0.04% initial accuracy and 3 ppm/°C, can be used on two output channels, allowing performance comparison and a choice of internal vs. external reference, depending on the total required system performance.

Input Module: The input module design specifications are similar to those of the output module. High resolution and low noise are generally important. In industrial applications, a differential input is required when measuring low-level signals from thermocouples, strain gages, and bridge-type pressure sensors to reject common-mode interference from motors, ac power lines, or other noise sources that inject noise into the analog inputs of the analog-to-digital converter (ADCs).

Sigma-delta ADCs are the most popular choice for input modules, as they provide high accuracy and resolution. In addition, internal programmable-gain amplifiers (PGAs) allow small input signals to be measured accurately. Figure 7 shows the input module design used in the evaluation system. The AD7793 3-channel, 24-bit sigma-delta ADC is configured to accommodate a large range of input signals, such as 4 mA to 20 mA, ±10 V, as well as small signal inputs directly from sensors.

Care was taken to allow this universal input design to be easily adapted for RTD/thermocouple modules. As shown, two input terminal blocks are provided per input channel. One input allows for a direct connection to the AD7793. The user can program the internal PGA to provide analog gains up to 128. The second input allows the signal to be conditioned through the AD8220 JFET-input instrumentation amplifier. In this case, the input signal is attenuated, amplified, and level shifted to provide a single-ended input to the ADC. In addition to providing the level shifting function, the AD8220 also features very good common-mode rejection, important in applications having a wide dynamic range.

The low-power, high-performance AD7793 consumes <500 μA, and the AD8220 consumes <750 μA. This channel is designed to accept 4 mA to 20 mA, 0 V to 5 V, and 0 V to 10 V analog inputs. Other channels in the input module have been designed for bipolar operation to accept ±5 V and ±10 V input signals.

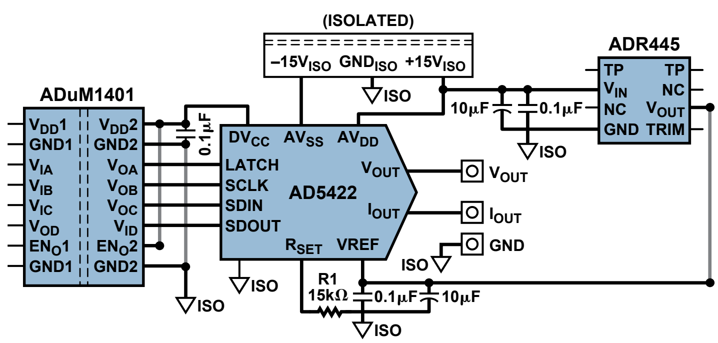

Figure 6. Output module block level.

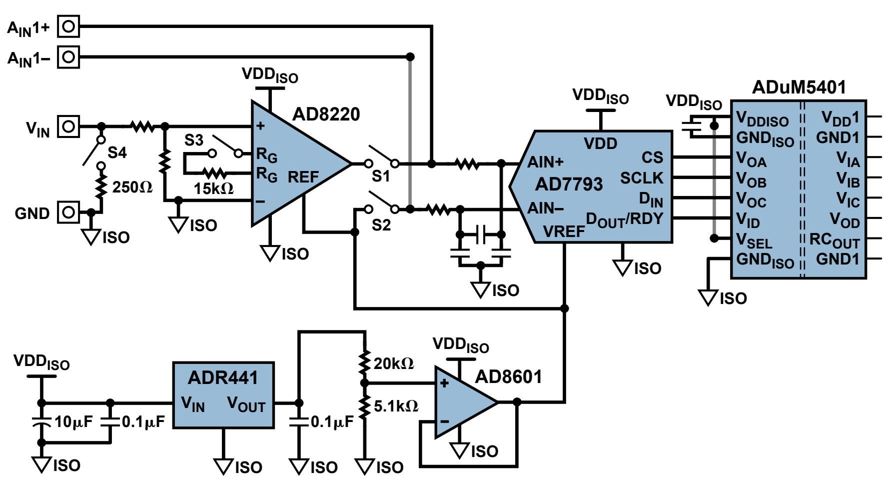

Figure 7. Input module design.

To measure a 4 mA to 20 mA input signal, a low-drift precision resistor can be switched (S4) into the circuit. In this design, its resistance is 250 Ω, but any value can be used as long as the generated voltage is within the input range of the AD8220. S4 is left open when measuring a voltage.

Isolation is required for most input-module designs. Figure 7 shows how isolation was implemented on one channel of the PLC evaluation system. The ADuM5401 4-channel digital isolator uses *iso*Power®[6] technology to provide 2.5-kV rms signal and power isolation. In addition to providing four isolated signal channels, the ADuM5401 also contains an isolated dc-to-dc converter that provides a regulated 5-V, 500-mW output to power the analog circuitry of the input module.

Complete System: An overview of the complete system is shown in Figure 8. The ADuC7027 precision analog microcontroller[7] is the main system controller. Featuring the ARM7TDMI® core, its 32-bit architecture allows easy interface to 24-bit ADCs. It also supports a 16-bit *thumb* mode, which allows for greater code density if required. The ADuC7027 has 16 kB of on-board flash memory and allows interfacing to up to 512 kB external memory. The ADP3339 high-accuracy, low-dropout regulator (LDO) provides the regulated supply to the microcontroller.

Communication between the evaluation board and the PC is provided via the ADM3251E isolated RS-232 transceiver. The ADM3251E incorporates *iso*Power technology—making a separate isolated dc-to-dc converter unnecessary. It is ideally suited to operation in electrically harsh environments or where RS-232 cables are frequently plugged in or unplugged, as the RS-232 pins, Rx and Tx, are protected against electrostatic discharges of up to ±15 kV.

Evaluation System Software and Evaluation Tools: The evaluation system is very versatile. Communication with the PC is achieved using LabView.[8] The firmware for the microcontroller (ADuC7027) is written in C, which controls the low-level commands to and from the ADC and DAC channels.

Figure 9 shows the main screen interface. Pull-down menus on the left side allow the user to choose active ADC and DAC channels. Under each ADC and DAC menu there is a pull-down range menu, which is used to select the desired input and output ranges to be measured and controlled. The following input and output ranges are available: 4 mA to 20 mA, 0 mA to 20 mA, 0 mA to 24 mA, 0 V to 5 V, 0 V to 10 V, ±5 V, and ±10 V. Small signal input ranges can also be accommodated directly on the ADC by using its internal PGA.

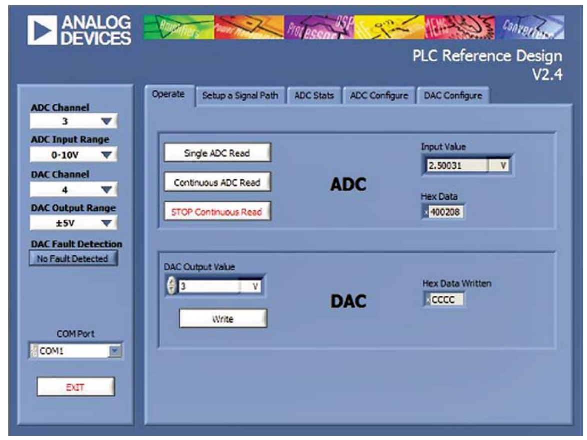

Figure 9. Evaluation software main screen controller.

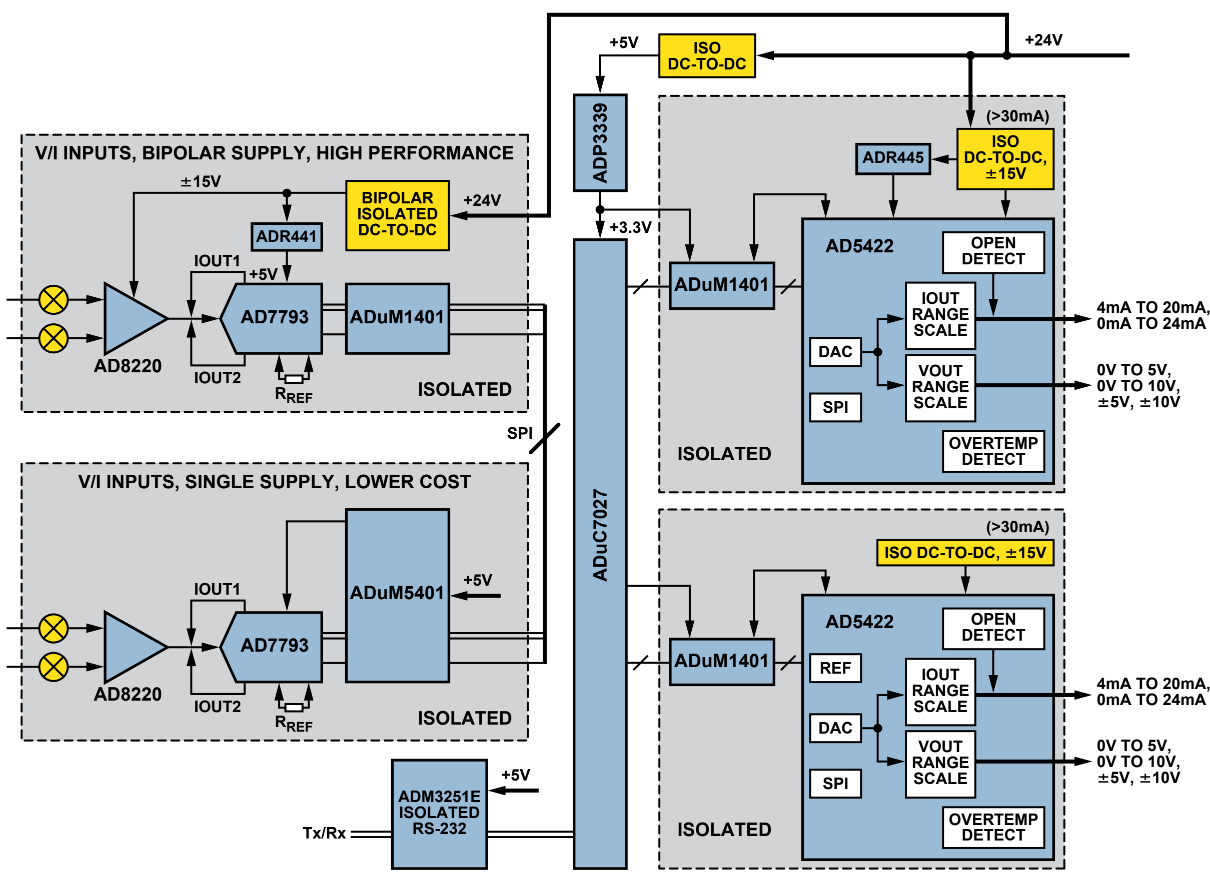

Figure 8. System-level design.

The *ADC Configure* screen, shown in Figure 10, is used to set the ADC channel, update rate, and PGA gain; to enable or disable excitation currents; and for other general-purpose ADC settings. Each ADC channel is calibrated by connecting the corresponding DAC output channel to the ADC input terminal and adjusting each range. When using this method of calibration, therefore, the offset and gain errors of the AD5422 dictate the offset and gain of each channel. If these provide insufficient accuracy, ultrahigh-precision current and voltage sources can be used for calibration if desired.

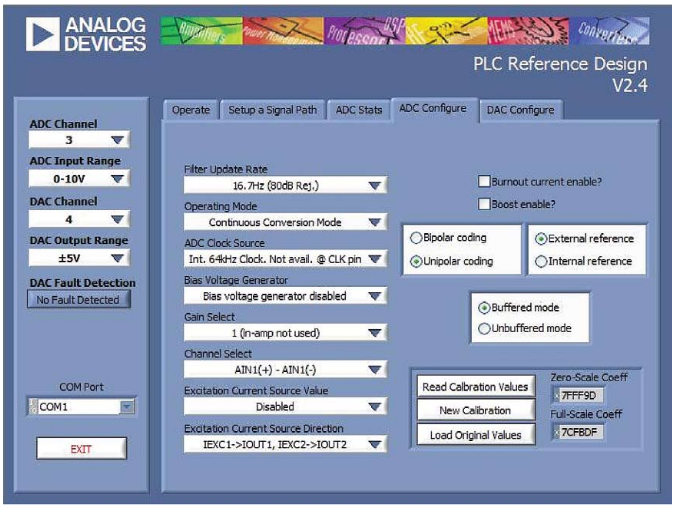

Figure 10. ADC Configure screen.

After selecting the ADC's input channel, input range, and update rate, we can now use the *ADC Stats* screen, shown in Figure 11, to display some measured data. On this screen, the user chooses the number of data points to record; the software generates a histogram of the selected channel, calculates the peak-to-peak and rms noise, and displays the results. In the measurement shown here, the input is connected through the AD8220 to the AD7793: gain = 1, update rate = 16.7 Hz, number of samples = 512, input range = ±10 V, input voltage = 2.5 V. The peak-to-peak resolution is 18.2 bits.

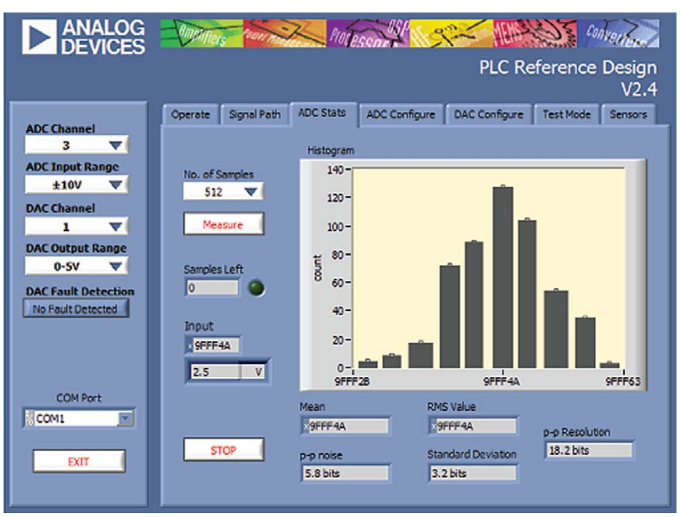

Figure 11. ADC Stats screen.

In Figure 12, the input is connected directly to the AD7793, bypassing the AD8220. The on-chip 2.5-V reference is connected directly to the AIN+ and AIN– channels of the AD7793, providing a 0-V differential signal to the ADC. The peak-to-peak resolution is 20.0 bits. If the ADC conditions remain the same but the 2.5-V input is connected through the AD8220, the peak-to-peak resolution degrades to 18.9 bits for two reasons: at low gains, the AD8220 contributes some noise to the system; and the scaling resistors that provide the input attenuation result in some range loss to the ADC. The PLC evaluation system allows the user to change the scaling resistors to optimize the ADC's full-scale range, thereby improving the peak-to-peak resolution.

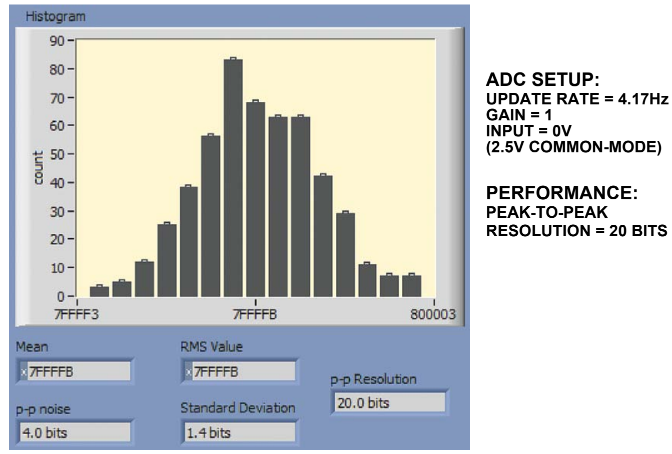

Figure 12. AD7793 performance.

Power Supply Input Protection: The PLC evaluation system uses best practices for electromagnetic compatibility (EMC). A regulated dc supply (18 V to 36 V) is connected to the board through a 2- or 3-wire interface. This supply must be protected against faults and electromagnetic interference (EMI). The following precautions, shown in Figure 13, were taken in the board design to ensure that the PLC evaluation system will survive any interference that may be generated on the power ports.

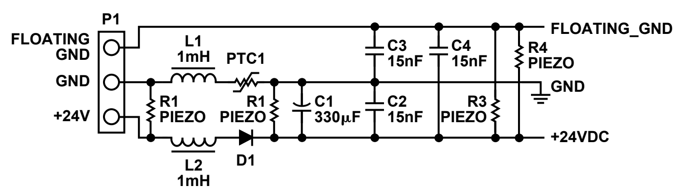

Figure 13. Power supply input protection.

- A piezoresistor, R1, is connected to ground adjacent to the power input ports. During normal operation, the resistance of R1 is very high (megohms), so the leakage current is very low (microamperes). When an electric current surge (caused by lightning, for example) is induced on the port, the piezoresistor breaks down, and tiny voltage changes produce rapid current changes. Within tens of nanoseconds, the resistance of the piezo resistor drops dramatically. This low-resistance path allows the unwanted energy surge to return to the input, thus protecting the IC circuitry. Three optional piezoresistors (R2, R3, and R4) are also connected in the input path to provide protection in cases when the PLC board is powered using the 3-wire configuration. The piezoresistors typically cost well under one US dollar.
- A positive temperature coefficient resistor, PTC1, is connected in series with the power input trace. The PTC1 resistance appears very low during normal operation, with no impact to the rest of the circuit. When the current exceeds the nominal, PTC1's temperature and resistance rapidly increase. This high-resistance mode limits the current and protects the input circuit. The resistance returns to its normal value when the current flow decreases to the nominal limit.

- *Y capacitors* C2, C3, and C4 suppress the common-mode conductive EMI when the PLC board operates with a floating ground. These safety capacitors require low resistance and high voltage endurance. Designers must use Y capacitors that have UL or CAS certification and comply with the regulatory standard for insulation strength.
- Inductors L1 and L2 filter out the common-mode conducted interference coming in from the power ports. Diode D1 protects the system from reverse voltages. A general-purpose silicon or Schottky diode specifying a low forward voltage at the working current can be used.

Analog Input Protection: The PLC board can accommodate both voltage and current inputs. Figure 14 shows the input structure. Load resistor R5 is switched in for current mode. Resistors R6 and R7 attenuate the input. Resistor R8 sets the gain of the AD8220.

These analog input ports can be subjected to electric surge or electrostatic discharge on the external terminal connections. Transient voltage suppressors (TVS's) provide highly effective protection against such discharges. When a high-energy transient appears on the analog input, the TVS goes from high impedance to low impedance within a few nanoseconds. It can absorb thousands of watts of surge power and clamp the analog input to a preset voltage, thus protecting precision components from being damaged by the surge. Its advantages include fast response time, high transient power absorption, low leakage current, low breakdown voltage error, and small package size.

Instrumentation amplifiers are often used to process the analog input signal. These precision, low-noise components are sensitive to interference, so the current flowing into the analog input should be limited to less than a few milliamperes. External Schottky diodes generally protect the instrumentation amplifier. Even when internal ESD protection diodes are provided, the use of external diodes allows smaller limiting resistors and lower noise and offset errors. Dual series Schottky barrier diodes D4-A and D4-B divert the overcurrent to the power supply or ground.

When connecting external sensors, such as thermocouples (TCs) or resistance temperature devices (RTDs), directly to the ADC, similar protection is needed, as shown in Figure 15.

- Two quad TVS networks, D5-C and D5-D, are put in after the J2 input pins to suppress transients coming from the port.
- C7, C8, C9, R9, and R10 form the RF attenuation filter ahead of the ADC. The filter has three functions: to remove as much RF energy from the input lines as possible, to preserve the ac signal balance between each line and ground, and to maintain a high enough input impedance over the measurement bandwidth to avoid loading the signal source. The –3-dB differential-mode and common-mode bandwidth of this filter are 7.9 kHz and 1.6 MHz, respectively. The RTD input channel to AIN2+ and AIN2– is protected in the same manner.

Analog Output Protection: The PLC evaluation system can be software-configured to output analog voltages or currents in various ranges. The output is provided by the AD5422 precision, low-cost, fully integrated, 16-bit digital-to-analog converter, which offers a programmable current source and programmable voltage output. The AD5422 voltage and current outputs may be directly connected to the external loads, so they are susceptible to voltage surges and EFT pulses.

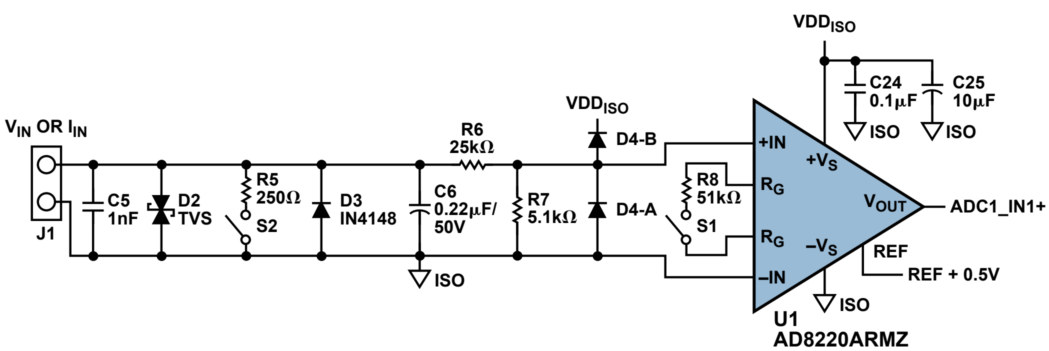

Figure 14. Analog input protection.

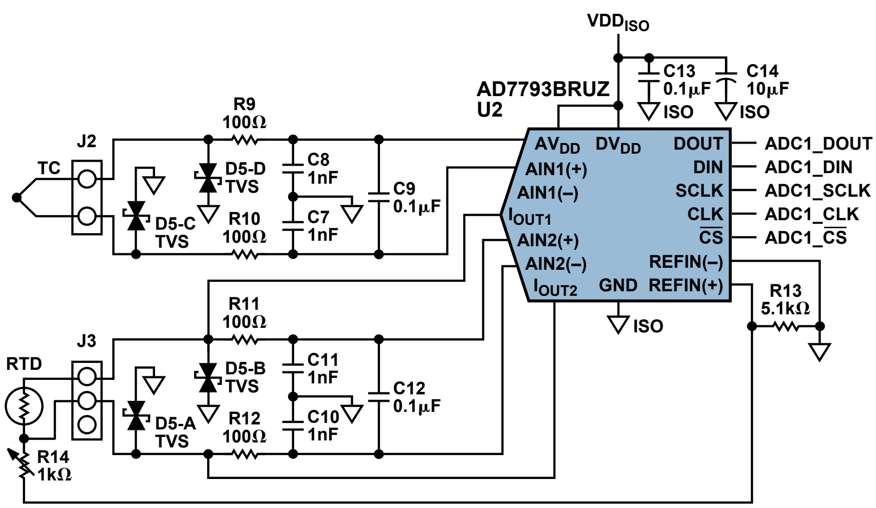

Figure 15. Analog input protection.

The output structure is shown in Figure 16.

- A TVS (D11) is used to filter and suppress any transients coming from port J5.
- A nonconductive ceramic ferrite bead (L3) is connected in series with the output path to add isolation and decoupling from high-frequency transient noises. At low frequencies (<100 kHz), ferrites are inductive; thus, they are useful in low-pass LC filters. Above 100 kHz, ferrites become resistive, an important characteristic in high-frequency filter designs. The ferrite bead provides three functions: localizing the noise in the system, preventing external high frequency noise from reaching the AD5422, and keeping internally generated noise from propagating to the rest of the system. When ferrites saturate, they becomes nonlinear and lose their filtering properties. Thus, the dc saturation current of the ferrites must not go over their limit, especially when producing high currents.
- Dual series Schottky barrier diodes D9-A and D9-B divert any overcurrent to the positive or the negative power supply. C22 provides the voltage output buffer and the phase compensation when the AD5422 drives capacitive loads up to 1 µF.
- The protection circuitry on the current output channel is quite similar to that on the voltage output channel except that a 10-Ω resistor (R17) replaces the ferrite bead. The current output from the AD5422 is boosted by the external discrete NPN transistor Q1. The addition of the external boost transistor will reduce the power dissipated in the AD5422 by reducing the current flowing in the on-chip output transistor. The breakdown voltage BV_{CEO} of Q1 should be greater than 60 V. The external boost capability is useful in applications where the AD5422 is used at the extremes of the supply voltage, load current, and temperature range. The boost transistor can also be used to reduce the amount of temperature-induced drift, thus minimizing the drift of the on-chip voltage reference and improving the device's drift and linearity.
- A 15-kΩ, precision, low-drift current-setting resistor (R15) is connected to R_{SET} to improve stability of the current output over temperature.
- The PLC demo system can be configured to provide a voltage output higher than 15 V when the AD5422 is powered by an external voltage. A TVS is used to protect the power input port. Diodes D6 and D7 provide protection from reverse biasing. All the supplies are decoupled by 10-µF solid tantalum electrolytic and 0.1-µF ceramic capacitors.

IEC Tests and Results: The results in Table 3 show the deviations of the DAC output that occurred during the testing. The output recovered to the original values after the tests were completed. This is generally referred to as Class B. Class A means that the deviation was within the allowed system accuracy *during* the test. Typical industrial control system accuracies are approximately 0.05%.

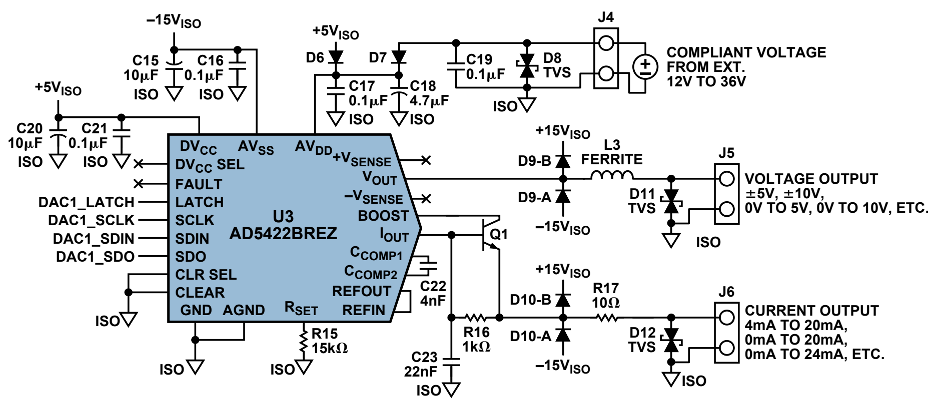

Figure 16. Analog output protection.

Table 3. IEC test results.

Test Item	Description	Result
EN and IEC 61000-4-2	Electrostatic discharge (ESD), ±4 kV VCD	Max deviation 0.32% for CH3 Class B
	Electrostatic discharge (ESD) ±8 kV HCD	Max deviation 0.28% for CH3 Class B
EN and IEC 61000-4-3	Radiated immunity 80 MHz to 1 GHz 10 V/m, vertical antenna polarization	Max deviation 0.09% for CH1, 0.30% for CH3 Class B
	Radiated immunity 80 MHz to 1 GHz 10 V/m, horizontal antenna polarization	Max deviation –0.04% for CH1, 0.22% for CH3 Class B
	Radiated immunity 1.4 GHz to 2 GHz 3 V/m, vertical antenna polarization	Max deviation 0.01% for CH1, –0.09% for CH3 Class B
	Radiated immunity 1.4 GHz to 2 GHz 3 V/m, horizontal antenna polarization	Max deviation 0.01% for CH1, 0.09% for CH3 Class B
EN and IEC 61000-4-4	Electrically fast transient (EFT) ±2 kV power port	Max deviation –0.12% for CH3 Class B
	Electrically fast transient (EFT) ±1 kV signal port	Max deviation –0.02% for CH3 Class A
EN and IEC 61000-4-5	Power line surge, ±0.5 kV	No board or part damage occurred, passed with Class B
EN and IEC 61000-4-6	Conducted immunity test on power cord, 10 V/m for 5 minutes	Max deviation 0.09% for CH3 Class B
	Conducted immunity test on input/output cable 10 V/m for 5 minutes	Max deviation –0.93% for CH3 Class B
EN and IEC 61000-4-8	Magnetic immunity horizontal antenna polarization	Max deviation –0.01% for CH3 Class A
	Magnetic immunity vertical antenna polarization	Max deviation –0.02% for CH3 Class A

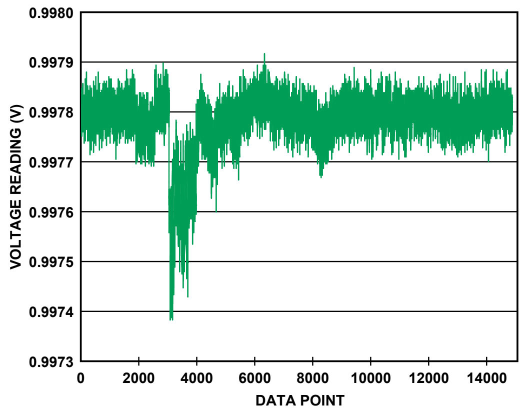

Figure 17. DAC channel dc voltage output. Radiated immunity 80 MHz to 1 GHz @ 10 V/mH.

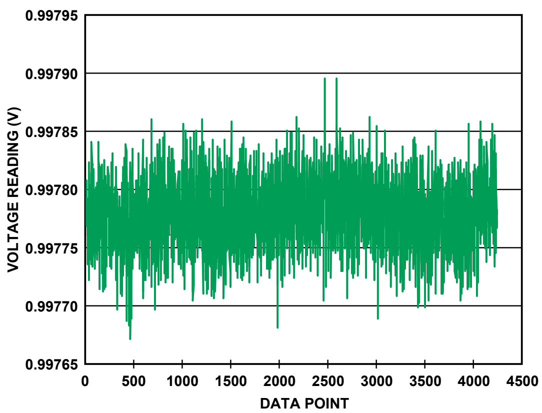

Figure 18. DAC channel 1 dc voltage output. Radiated immunity 1.4 GHz to 2 GHz @ 3 V/mH.

Typical System Configuration: Figure 19 shows a photo of the evaluation system and how a typical system might be configured. The input channels can readily accept both loop-powered and nonloop-powered sensor inputs, as well as the standard industrial current and voltage inputs. The complete design uses Analog Devices converters, isolation technology, processors, and power-management products, allowing customers to easily evaluate the whole signal chain.

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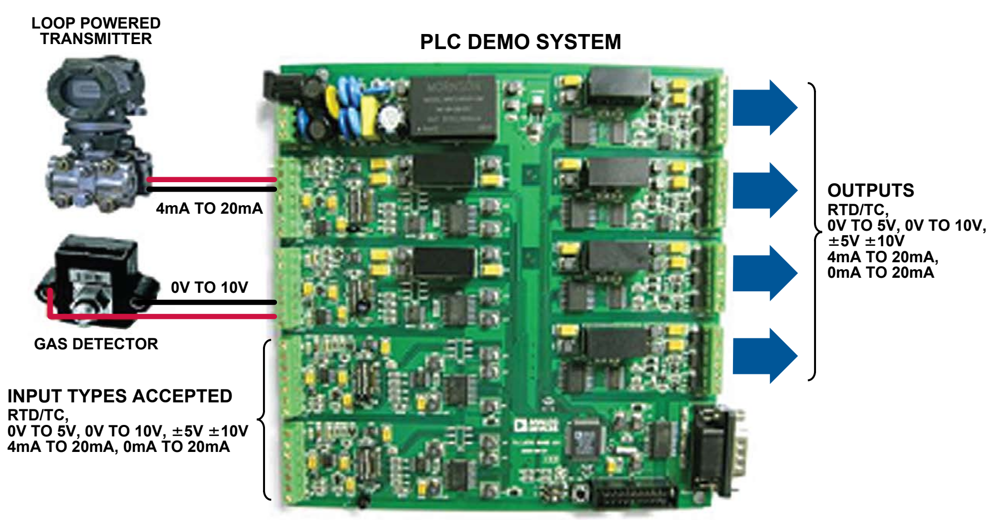

Figure 19. Industrial control evaluation system.