Quad 16-Bit Voltage-/Current-Output DACs Save Space, Cost, and Power in Multichannel PLCs

By Colm Slattery

Overview

Programmable logic controllers (PLCs) use fast, deterministic functions, such as logic, sequencing, timing, counting, and arithmetic algorithms, to control machines and processes. They use analog and digital signals to communicate with *end nodes* (reading sensors and controlling actuators, for example). Typical methods of communication include current/voltage loops, Fieldbus,[1] and industrial Ethernet[2] protocols.

The industry has a continuing tendency to increase the number of sensor and control nodes in the remote area, causing a corresponding increase in the number of I/O module nodes in the controller—and some *distributed control systems* (DCS) can handle thousands of nodes. This concentration of nodes brings increased temperature-related challenges, especially for systems that implement the 4-mA to 20-mA loop communications standard.

Perhaps the biggest and most relevant challenge to the system designer is the need for greater efficiency and reduced power consumption, as the inefficiency of existing systems results in wasted power and increased operating costs. This article explains the challenges of designing such systems for greater efficiency and introduces the AD5755, a versatile, 4-channel, 16-bit digital-to-analog converter (DAC) as a more integrated solution to help resolve these issues.

System

The levels of communication in a typical industrial control system are shown in Figure 1. Until recently, the distributed input/output (remote I/O and PLC) would typically be connected using such open or proprietary protocols as Modbus,[3] PROFIBUS[4] (process field bus), or Fieldbus. Nowadays, there is an increasing interest in using PROFINET,[5] a form of industrial Ethernet protocol that is designed for the fast exchange of data between Ethernet-based devices.

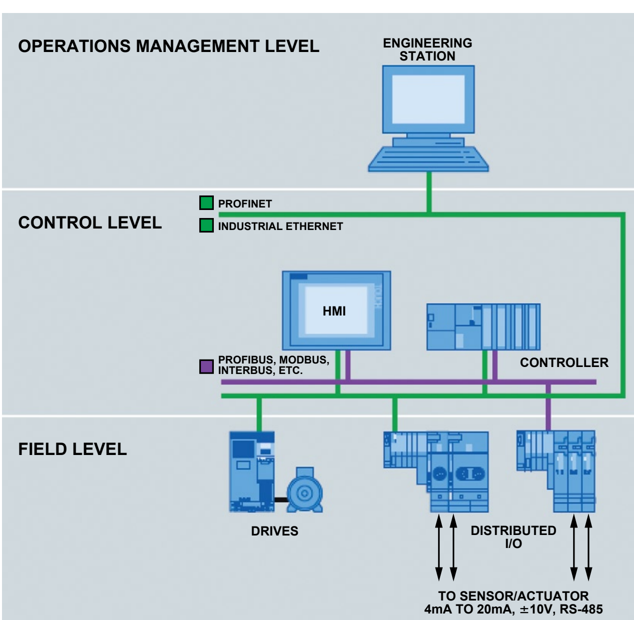

Figure 1. Hierarchy in a control system.

Some of the advantages of PROFINET are

- Increased speed, up from 9.6 kbps with RS-232 to 1 Gbps.
- Improved overall performance.
- Increased distance.
- Ability to use standard access points, routers, switches, hubs, cables, and optical fiber—which are immensely cheaper than the equivalent serial-port devices.
- Ability to have more than two nodes on link. This was possible with RS-485, but not with RS-232.

At the *field* level, field bus protocols, used to interconnect industrial drives, motors, actuators, and controllers to the PLC/DCS I/O systems, are numerous, including DeviceNet,™ CAN,[6] and InterBus,®[7] as well as the above-mentioned PROFIBUS and Fieldbus.

An input-output (I/O) controller connects to sensors and control actuators in a factory- or process environment; it communicates with multiple end nodes by analog and digital means, as noted above. Intrinsically safe systems connect via 4-mA to 20-mA current loops, and some use isolation. The control processor is typically an 8-bit to 32-bit processor with performance of up to 100 DMIPS (Dhrystone millions of instructions per second). Factory automation equipment is ruggedly constructed for fanless operation in a harsh industrial environment.

Examples of 8-channel analog I/O modules are featured in Figure 2. Because of their small size, they have limited power-dissipation capability, some even less than 5 W.

Figure 2. I/O modules.

Analog 4-mA to 20-mA current loops are commonly used for signaling in industrial process control, with 4 mA representing the low end of the range and 20 mA the high end. The key advantages of the current loop are that accuracy of the signal is not affected by voltage drops in the interconnecting wiring and the loop can supply up to 4 mA for powering the device. Even if the line has significant electrical resistance, the current loop transmitter will maintain the proper current, up to its maximum voltage capability.

The *live-zero* represented by 4 mA allows the receiving instrument to detect some failures of the loop (for example, 0 mA indicates an open loop, or 3 mA could indicate a fault condition on the sensor) and also allows *2-wire*-transmitter devices to be powered by the loop current. Such instruments are used to *measure* pressure, temperature, flow, pH, and other process variables and to *control* a valve positioner or other output *actuator*. The current in an analog current loop can be converted to a voltage input at any point in the loop with a series precision resistor. Since input terminals of instruments may have one side of the current loop tied to the chassis ground (earth), analog isolators may be required when connecting several instruments in series.

Power Dissipation Concerns

Figure 3 shows a system in which one channel is configured for 4-mA to 20-mA communications (in this case to drive an actuator load from a DAC). The termination resistance of the actuator determines the maximum compliance voltage needed across the loop. For example, a 100-Ω resistance would require at least 2 V at 20 mA. It is very common that today's systems must be able to drive loads of up to (and sometimes exceeding) 1 kΩ. With this load resistance, and a full-scale current of 20 mA, the supply would need to furnish at least 20 V. The power generated would be

$$P = V \times I = 20\text{ V} \times 0.02\text{ A} = 0.4\text{ W}.$$

If the load resistance was changed to 100 Ω, using the same supply (a valid condition), the power dissipated would still be 0.4 W, even though only 0.04 W is needed. In this case there is a 90% loss of efficiency in the system, with 360 mW being wasted.

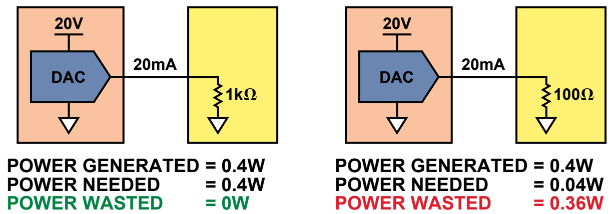

Figure 3. Power is wasted when full-scale output is much less than the power-supply voltage.

With an 8-channel module, the total power dissipation with a 20 V supply would be 3.2 W, of which as much as 2.88 W would be wasted in the module (if all loads are 100 Ω). In such cases, self heating, as well as the effect of the increased power budget, starts to become a consideration. Increased temperatures within the module can lead to increased system errors—the drift specs of the individual components need to be factored into the overall system error budget.

Designers may consider various ways to solve these problems:

- *Increasing the module size* allows more power dissipation, but the added cost makes this solution less competitive.
- *Heat sinking and/or fan control* can be used—an expensive solution that also increases space. Indeed, in some safety-critical applications, such temperature control devices are not allowed.
- *The maximum load resistance can be reduced* to limit the overall power dissipation in the circuit. This is a performance-limiting factor in some applications and is noncompetitive from a system marketing point of view.

In any event, the trend to provide an increased number of channels in a smaller space will cause further thermal power problems for many system designers.

One way to help solve this problem is to start with a 5-V supply. Monitor the output load voltage, then efficiently *boost* and regulate the output voltage as needed. The 5-V supply and an efficient dc-to-dc *boost converter* use *feedback control* to provide the appropriate output voltage, minimizing the on-chip power dissipation (Figure 4).

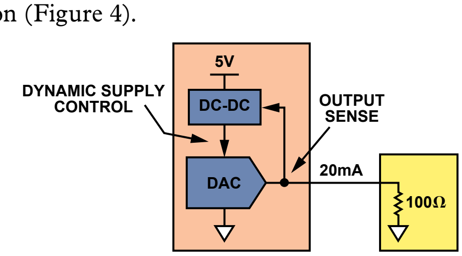

Figure 4. Dynamic supply control principle.

This kind of closed-loop dynamic power capability can be found in the AD5755 family of 4-channel, 16-bit, serial-input, voltage- and current-output DACs (see Appendix—Figure A). Because each of its four channels can individually furnish either current or voltage with 16-bit resolution, with output powered by an individual dc-to-dc converter under dynamic power control, the device provides the equivalent of four low-dissipation nodes in a very compact 9-mm × 9-mm × 0.8-mm package.

The simplified circuit of Figure 5 shows how the dynamic power control works, using an inductive boost circuit. Each channel is capable of providing a boosted output voltage greater than 30 V. The dynamic power control mechanism uses feedback to regulate the output voltage, which is divided down by a resistive voltage divider and compared to the reference voltage in an internal error amplifier to create an error current. At the beginning of the switching cycle, the MOSFET switch is turned on and the inductor current ramps up. The MOSFET current, converted to a voltage, is measured. When the current-sense voltage is greater than the error voltage, the MOSFET is turned off and the inductor current ramps down until the internal clock initiates the next switching cycle. A similar scheme is used to regulate the output compliance voltage in current mode. In this case a feedback error current is used.

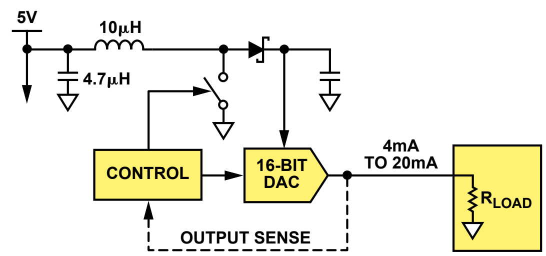

Figure 5. Voltage boost with power control.

The user has the option to switch the frequency and phase of each channel's dc-to-dc converter switching signals to allow for circuit and component optimization.

Programmable Switching Frequency: Offers the ability to change dc-to-dc switching frequencies, allowing for system optimization and more flexible choices of external components	**Programmable DC-to-DC Clock Phase:** Offers the ability to change the phase of the clock edges of individual dc-to-dc blocks, allowing for system optimization
• 333 kHz • 400 kHz • 500 kHz • 667 kHz	• All four channels clock on same edge • ChanA and ChanB clock on one edge, ChanC and ChanD clock on opposite edge • ChanA and ChanC clock on one edge, ChanB and ChanD on opposite edge • ChanA, ChanB, ChanC, and ChanD clock 90° out of phase from each other (0°, 90°, 180°, and 270°)

The dynamic power control on the output driver is designed to minimize package power dissipation. Typical ICs can operate at internal junction temperatures (T_{JMAX}) up to 125°C. Assume the ambient temperature, T_A, in the system is 85°C. The thermal impedance, θ_{JA}, for the LFCSP package is typically 28°C/W.

To calculate the allowable on-chip dissipation we can use the following analysis.

$$\frac{T_{JMAX} - T_A}{\theta_{JA}} = \frac{125° - 85°}{28°C/W} = 1.42\ W$$

Without dynamic power control, assuming a 24-V supply, the worst-case power dissipation (per channel) can be calculated to be

$$\begin{aligned} \textit{Power Dissipation} &= \textit{Supply Voltage} \times \textit{Max Current} \\ &= 24\ V \times 20\ mA \\ &= 0.48\ W \end{aligned}$$

Four channels would dissipate nearly 2 W under similar conditions; this would cause problems for both the module and the semiconductor circuitry. By enabling the dynamic power feature, the AD5755 regulates the supply to minimize the on-chip power dissipation. Figure 6 shows a comparison of the power dissipated per channel with dynamic power enabled and disabled (fixed supply).

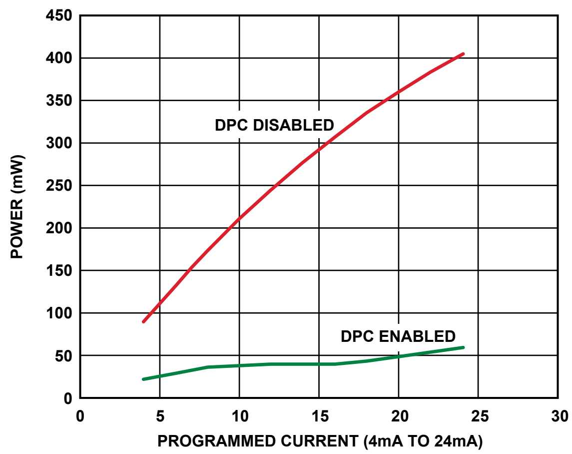

Figure 6. Dissipation comparison with and without dynamic power control.

When the dynamic power capability is enabled, the on-chip power dissipation is about 50 mW with output current of 24 mA vs. 400 mW with no regulation. This ability to control the on-chip power dissipation is of great value to the system designer because the number of channels in the system can be increased while minimizing module dissipation. It thus eliminates the need to consider extensive (and expensive) methods to control system temperatures.

System Error Checking and Diagnostics Under Fault Conditions:

For industrial applications, it is important to be able to monitor and report system-level faults and critical to have as much control as possible over the system under a fault condition. The AD5755 includes many on-chip diagnostic features that provide the user with system-level error checking.

One serious consideration is where the MCU/DSP that controls the DAC goes when a fault condition occurs. With no ability to control the output, the user would lose complete control of the system. The AD5755 has a watchdog timer (with programmable timeouts) that sets an alert flag (active *high*) if it has not received a command over the SPI interface within the timeout period. If desired, this alert pin can be directly connected to the CLEAR pin (also active high) to set the outputs into a known safe condition (Figure 7). Each channel on the AD5755 has a 16-bit programmable clear code register, giving the user flexibility to clear the output to any code.

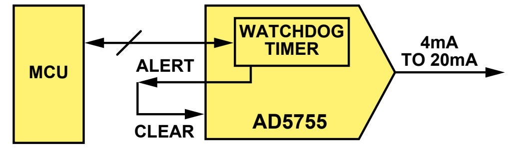

Figure 7. Watchdog timer flags loss of control signal and returns DAC to clear setting.

Even with the MCU operating normally, communications signals can become corrupted in noisy industrial environments. For dealing with this possibility, the AD5755 has an optional *packet error-checking* (PEC) function, which implements a CRC8 polynomial routine. This can be enabled or disabled through software to ensure that the output is never incorrectly updated.

Miswiring on the output can often lead to open- or short-circuit connections, potentially damaging the system. (Even if no damage occurs, the problem can often be difficult to diagnose. The AD5755 has open- and short-circuit detection, immediately setting a fault flag to alert a technician of the problem). In addition, short-circuit protection limits the output current in the event of a short circuit. All faults can be communicated via the SPI interface or through a hardware fault pin, allowing the user to take immediate action.

Flexible Output-Range Programmability

To deal with the required variety of voltages and currents, the AD5755 has many programmable ranges available for each channel, including: 4 mA to 20 mA, 0 mA to 24 mA, 0 mA to 20 mA, 0 V to 5 V, 0 V to 10 V, ±5 V, ±10 V, and ±12 V. It is also possible for the user to digitally program the gain and offset of each range on individual channels. These gain- and offset registers have 16-bit resolution. For example, to set a 0-V to 10.5-V output range (as in Figure 8), first select the 0-V to 12-V range, then program the gain code to trim the gain to 10.5 V. Once the gain trim is complete, the output range will be 0 V to 10.5 V, with 16-bit resolution. The offset can be programmed in a similar manner.

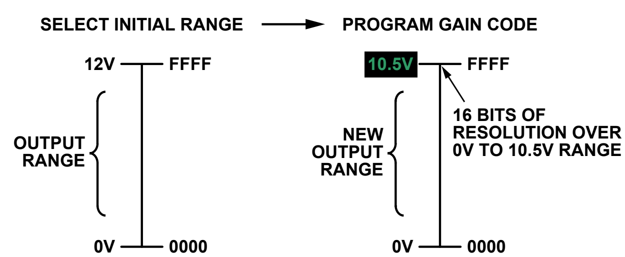

Figure 8. Arbitrary range scaling.

Communicating Additional Information Over the 4-mA to 20-mA Current Loop

The disadvantage of a pure 4-mA to 20-mA current loop is its unidirectional communication of a single process variable, an annoying limitation in modern industrial control systems. The development of the *highway-addressable remote transducer* (HART) standard opened up new possibilities for 4-mA to 20-mA communication lines.

HART provides for a digital two-way communication scheme that is compatible with 4-mA to 20 mA current loops. A 1-mA peak-to-peak *frequency-shift-keyed* (FSK) signal is superimposed on the 4-mA to 20-mA analog current signal. The two frequencies used are 1200 Hz (Logic 1) and 2200 Hz (Logic 0), based on the BELL 202 communications standard (Figure 9).

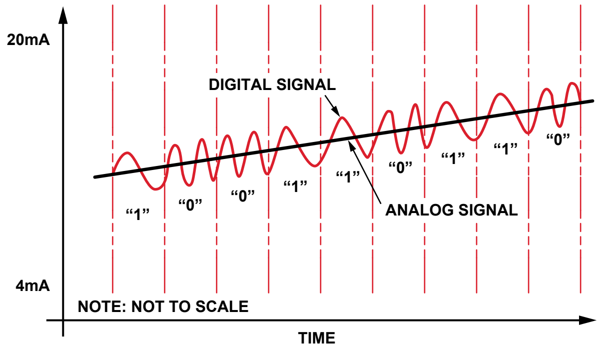

Figure 9. HART signal riding on an increasing loop current.

The AD5755 can be configured to transmit a HART signal with only two external components. The output of the HART modem is attenuated and ac-coupled at the CHART pin of the AD5755; this results in the modem output being modulated on top of the 4-mA to 20-mA analog current without affecting the "dc" level of the current. The circuit in Figure 10 shows how the AD5755 can interface to a HART modem to embody this dual form of communication.

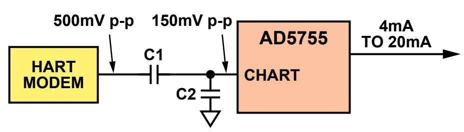

Figure 10. The AD5755 in HART communication.

The HART specification requires that the maximum rate of change of analog current not interfere with HART communications. Obviously, step changes in the current output can disrupt HART signaling. Fortunately, the AD5755 has controllable slew rate, which, when enabled, allows the user to digitally limit the slew rate of the current output.

AD5755 Complete Solution

Figure 11 shows a typical setup using the AD5755. (One HART modem channel is shown in the diagram, but four HART inputs are available—one per channel). When enabled, the dynamic power control feature requires four external components per channel: an inductor with a saturation current of the order of 1 A, a switching diode, and two capacitors having low *equivalent series resistance* (ESR). With a minimal number of external components, the AD5755 provides an integrated high-performance system capability on a single chip. The total unadjusted error (TUE), including all gain and offset errors at 25°C, is typically 0.01%.

Conclusion

As both the required number of channels and the density of channels per module increase, a number of problems present themselves to systems designers: How can I increase the number of channels while keeping the form factor of the module small? How can I increase the number of channels and design an energy-efficient system, while minimizing self-heating effects and drift errors within the system? How can I offer the most flexibility to my customer in terms of programmability of the outputs? What safety features and diagnostics can I provide to ensure robust systems in which problems can be easily tracked?

As a 4-channel device in a 9-mm × 9-mm CSP package, the AD5755 dramatically helps reduce board area while increasing channel density. With dynamic power control, the on-chip power dissipation is regulated and module power dissipation is minimized. The addition of on-chip diagnostics, including watchdog timers, PEC error checking, and open-/short-circuit detection and protection gives the end user higher confidence that the robust design is capable of working in harsh industrial environments. The AD5755 is a true system-on-a-chip solution.

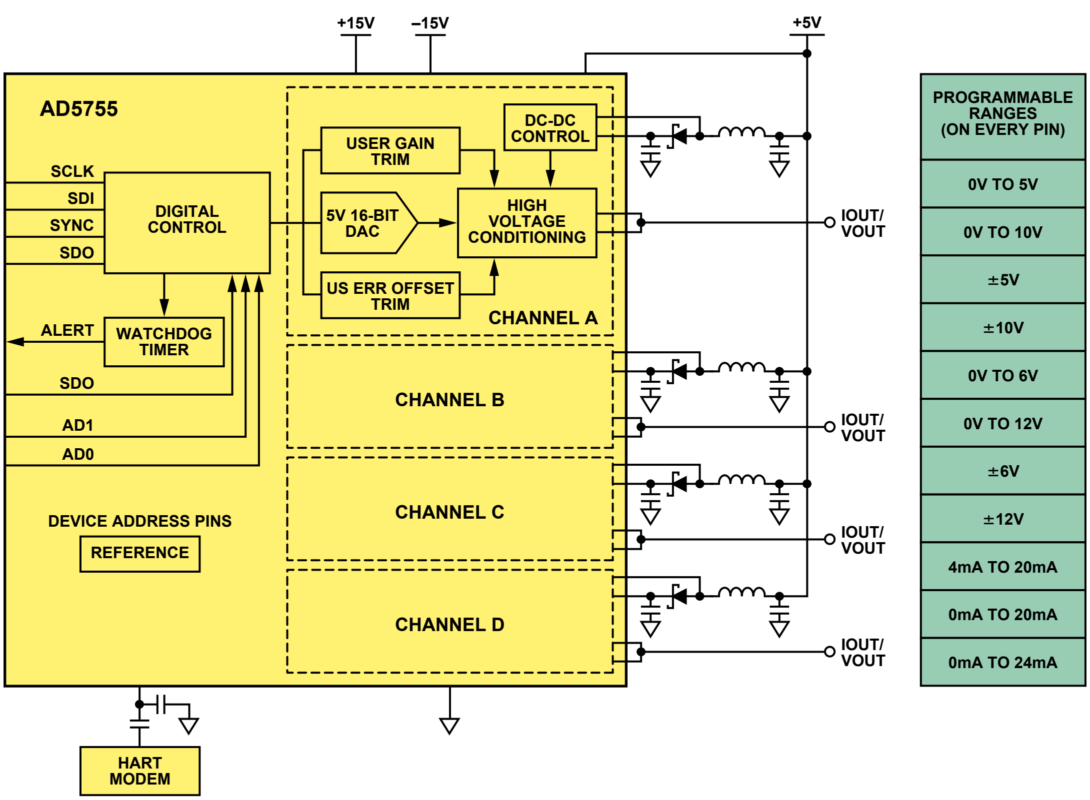

Figure 11. AD5755 setup.

APPENDIX

More About the AD5755 Quad DAC

The AD5755[8] quad voltage- and current-output DACs operate with a –26-V to +33-V power supply. On-chip dynamic power control minimizes package power dissipation in current mode by regulating the voltage on the output driver between 7 V and 30 V.

The AD5755 uses a versatile 3-wire serial interface that operates at clock rates up to 30 MHz and is compatible with standard SPI,® QSPI,™ MICROWIRE,™ DSP, and microcontroller interface standards. The interface also features optional CRC-8 packet error checking, as well as a watchdog timer that monitors activity on the interface.

The AD5755 features 16-bit resolution and monotonicity, voltage or current output on the same pin, user-programmable offset and gain, on-chip diagnostics, an on-chip 5 ppm/°C max voltage reference, and a –40°C to +105°C operating temperature range. Available current-output ranges are 0 mA to 20 mA, 4 mA to 20 mA, and 0 mA to 24 mA ± 0.05%; available voltage ranges are 0 V to 5 V, 0 V to 10 V, ±5 V, ±10 V, ±6 V, and ±12 V ± 0.05%.

References

[1] www.fieldbus.org.

[2] www.cisco.com/web/strategy/docs/manufacturing/industrial_ethernet.pdf.

[3] www.lammertbies.nl/comm/info/modbus.html.

[4] www.profibus.com.

[5] www.anybus.com/technologies/profinet.shtml.

[6] www.interfacebus.com/Design_Connector_CAN.html.

[7] www.interfacebus.com/INTERBUS_Field_Bus_Description.html.

[8] www.analog.com/pr/AD5755.

Author

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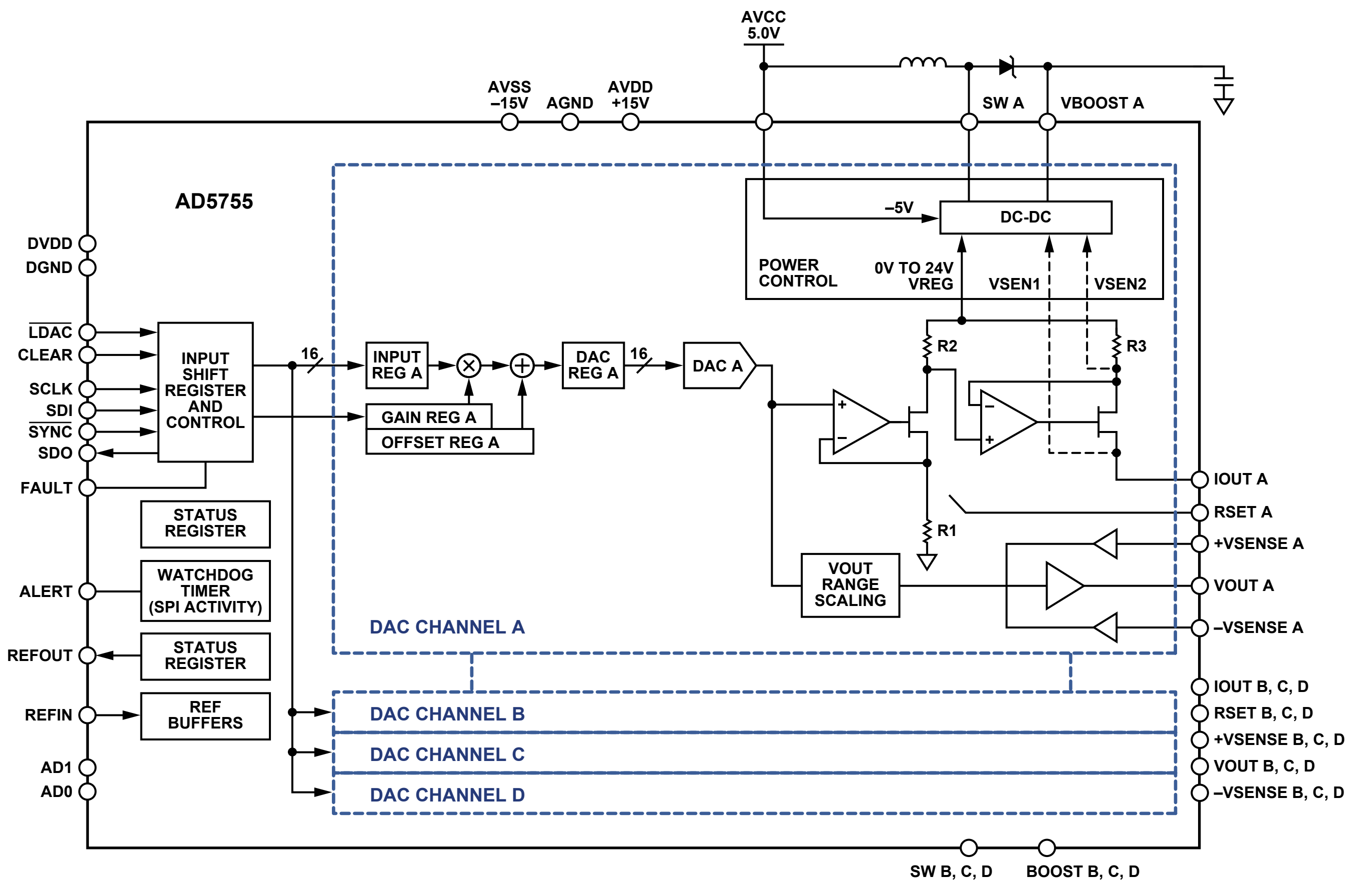

Figure A. Functional block diagram of the AD5755 quad DAC. All four channels are identical.