Keywords: analog, output, 4 to 20mA, ESD, EMI, RFI, EMS, current loop, lightning, motor fault, voltage, TVS, gas discharge, ferrite beads, filters, Zener, diodes, DAC, reference, galvanic, isolation, switching power supplies, SPI

APPLICATION NOTE 6008

PROTECTION: HOW MUCH IS ENOUGH FOR AN ANALOG OUTPUT?

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Abstract: Analog outputs drive motors and actuators in factories and plants. They are the final control step in process logic controllers (PLC). The output amplifiers typically drive 0 to 10V and 4 to 20mA circuits. They need protection from high-voltage motor faults, electrostatic discharge (ESD), electromagnetic interference (EMI), electromagnetic susceptibility (EMS), and radio frequency interference (RFI). Many circuits are suggested to meet the application requirements.

Protection depends on what needs protecting and how valuable it is. It is a lot like money. Someone once told me, "No cash is petty, if it's yours." Experienced engineers know it is the little things that cause the biggest problems. It has been that way for a long time. The proverb, "In want of a nail" can be traced back to the early 1200s A.D., and even Benjamin Franklin published a version in 1758[1]. As engineers we understand we cannot always fix every single thing but sometimes people want to look up to engineers[2] and think we are super human, which makes the verse in **Figure 1** a bit comical.

The English "Knight" variant of the "nail" rhyme

For want of a nail the shoe was lost,
for want of a shoe the horse was lost,
for want of a horse the knight was lost,
for want of a knight the battle was lost,
for want of a battle the kingdom was lost.
So a kingdom was lost—all for want of a nail.

Figure 1. A proverb from "Justice League America: The Nail," a three-issue comic book[3].

The comic book series describes a world where Superman® does not exist. A nail punctures Ma and Pa Kent's truck tire, delaying them so they never find baby Superman's spaceship. This small change means the child does not grow to become Superman, and the world is forever in danger.

Sometimes analog output circuit protection feels this way because we are not Superman. We try to cover the vast majority of the situations but we are worried that the one little thing that causes failure will be noticed by the first customer the first time it is used. This really is a variation of Murphy's Law that everything that can go wrong will go wrong.

Analog Output with Alternative Transmission Means (Protection)

As the Industrial Revolution matured, multiple means became available to perform the same function. In Leonardo da Vinci's time, wooden gears and screws, rods, levers, and escapements made controlled movement possible. In the age of steam wheels, pistons, rods, levers, and speed governors enabled engineers to perform more tasks. In the 20th century, electric motors, actuators, and contactors (relays) started to be controlled by sensors and switches. Soon microprocessors became the brains of the control system, taking information from sensors and transforming the analog output into actions. A common equivalence became useful in controlling factories. To an engineer, a voltage from 0 to 10V was the same as 4 to 20mA current and this was the same as a 3 to 15 pounds per square inch (psi) pneumatic system. Recently, we have added other serial communication means, which includes wireless, to communicate between the analog output and the actuators.

Analog output circuit protection covers a wide variety of situations. Understanding the environment and the application helps us to decide what we should do to protect the analog output. Let's start by examining the first and easiest application.

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There is an output circuit and within a few feet of it is located a low-voltage actuator that it is going to control. They operate from the same power supply and are indoors, protected from the weather in a rather benign office environment. A second environment (still indoors) has an actuator a few hundred feet away in a temperature-controlled factory. At the far extreme, the output driver is physically separated from the actuator by about a kilometer (0.7 miles) of distance in an open field exposed to snow, high humidity summers, and lightning storms. For the inexperienced engineer, the worry is if there is enough or too little for protection for the device and if it is cost-effective.

A practical way to handle the three applications above, first the nearby indoor actuator could be controlled by 0 to 10V. Because it is close by, the amount of protection from electrostatic discharge (ESD), electromagnetic interference (EMI), electromagnetic susceptibility (EMS), and radio frequency interference (RFI) is likely minimized. In the second case, a distance of a few hundred-feet would be a candidate for a 4 to 20mA current loop because it minimizes EMI, RFI, and ESD pickup. The most difficult one would be where there is heat, snow, and lightning, which would probably lend itself to a hybrid approach. If there is a building nearby, a translator can be installed or a 4 to 20mA current loop can be installed as a conduit to the building. From there, a 3psi to 15psi pneumatic line to the actuator would allow control under inclement conditions including lightening.

Design Approach

The design philosophy can take two radically different paths that depend on the application. Looking at **Figure 2**, path A takes the analog output board as is and provides zero protection. Or in path B, add all the analog protection circuits as shown. Some of the analog output protection circuits are alternatives "or" choices that will conflict with one another. Applications will usually take some middle ground and incorporate a subset of the Figure 2 protection.

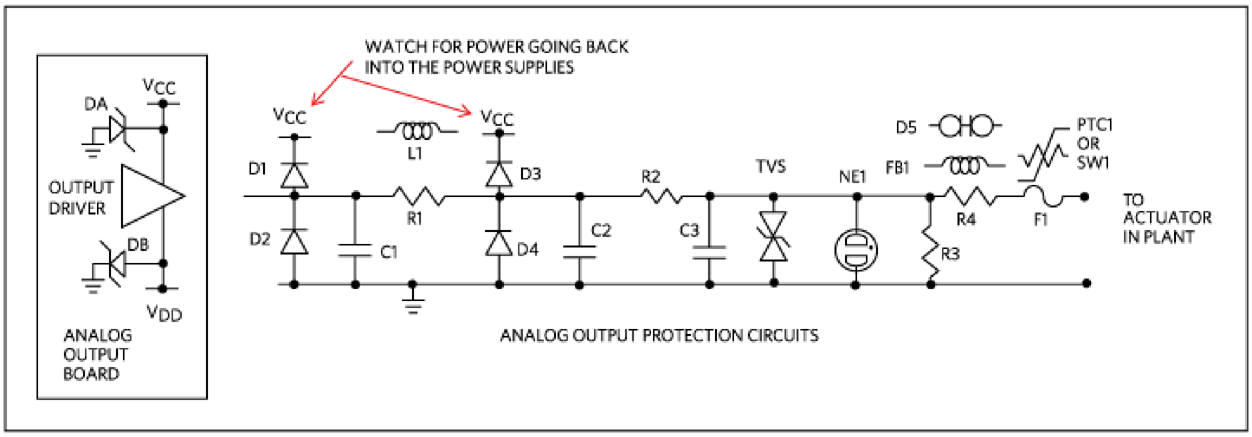

Figure 2. The 20%/80% interface circuit applied to an analog output circuit to protect against unwanted electrical vulnerabilities.

Why this is the case can be best illustrated by describing several applications. Two of many considerations of industrial equipment are "mean time before failure" (MTBF) and "mean time to repair" (MTTR). In the case of an integrated circuit manufacturer a desirable goal is to make a totally self-testing chip. In the factory and at power-up in the field, the part completely tests itself and turns on a little green light to say, "I'm good." That is a great idea but it may not be practical. For example, that extra test circuitry takes up five times more room than the circuit itself. Testing cost is saved but does the cost of extra silicon and the MTBF justify that cost? Is this a good return on investment? The answer is probably no. Having a circuit that fails five times more often may not be a good trade-off, but then in another application it may be fine. Compare circuits that no human can repair without huge costs, for example, space probes and satellites. Maybe a circuit is located on a mountaintop where snow prevents access for three months a year. Maybe a circuit is in a life-critical device such as an airplane or possibly the circuit is easily accessed by a human technician. In each case, a different level of redundancy-improved MTBF can be traded off with the MTTR.

To drill down to two industrial process logic control (PLC) applications, let’s discuss a case where circuit board A is in the control room with humans 24/7 and in the other case, circuit board B is isolated in a place that is too dangerous for a human. First, we decide in both cases to limit system instruction by digital isolation. In other words, all input and output ports contain isolated power supplies and digital isolation. This prevents a destructive high voltage on an output or input from propagating through and destroying the entire system. In case A, the MTTR is low by easily replacing the board. However, the MTBF may not support extensive protection circuits and causes early failure. In this case, zero or minor protection circuits may be warranted. There could be many self-healing protection circuits and even duplicates or triplicates of the circuit.Voting to choose the good circuit becomes important. Voting refers to redundancy in critical or life protection systems. For example, the US Space Shuttle was designed with three navigation computers to fire control rockets and thrusters. However, if one computer produced a different result, the two good computers would out-vote and ignore the faulty computer.

Now let’s fall back on some well known principles for circuit protection, which provide multiple overlapping concepts to be used in analog output protection. Looking at Figure 2, the ESD, EMI, EMS, and RFI devices[4, 5] can be grouped in three categories:

1. Voltage-limiting devices: gas discharge arrestors, metal oxide varistors, suppressor diodes, triacs, diacs, and switches.
2. Current-limiting and switching devices: fuses, circuit breakers, and thermal cutouts
3. Filters, rise-time reducers: resistors, inductors, coils, ferrite beads, and capacitors, all of which slow the rise time of a transient and spread the impulse over time, thereby allowing other protection devices time to function. The lowpass filters also act as reconstruction filters for the output of the DAC. The working voltage and self-resonance point of each capacitor needs to match the application's frequency and bandwidth. Each of these networks is reciprocal; they protect a system from the outside world (EMS) and protect the outside world from any unintentional signal (EMI) that a device might radiate.

With this in mind, let us study Figure 2. Working backwards, start at the output on the right and toward the input on the left. Figure 2 is drawn to protect a unipolar system where the voltages go from ground to high voltage. If the output driver can handle a bipolar output, voltage above and below ground, Figure 2 can be repeated by turning it upside down and connecting the two grounds to protect both above and below ground.

F1, the protection fuse, indicates a fuse, self-resetting circuit breaker or thermal cutout. Alternatives for F1 are PTC1 (Positive Temperature Coefficient) polymeric or ceramic devices (do not forget that they need current to work), or a SW1, which is a high-voltage signal-line protector. This is a switch that senses high voltage, turns off the series switch, and then turns on a clamp to reduce the amount of voltage at the amplifier. D5 is a current-limiting diode that looks like a JFET with the source and drain terminals tied together. R4 and R5 are resistors that attenuate high-fault voltages to protect the output driver. FB1 reduces the pulse rise time and widens the pulse in time to reduce EMI and ESD.

NE1 is a neon lamp and can be replaced or augmented with gas-discharge arrestor tubes or a transient voltage suppressor (TVS), which is a specialized diode that clamps the voltage to a known value. Other voltage-limiting devices, metal oxide varistors (MOV), zener suppressor diodes, triacs, and diacs can also be used.

Capacitors are part of the filtering function. C1, C2, and C3 shunt high frequencies to ground RFI and integrate ESD pulses, thus reducing their rise time. Resistors and capacitors that form better RC lowpass reconstruction filters (with additional poles) include R2 and C3, R1 and C2). When an inductor L1 replaces R1, L1 and C2 (2-pole) or L1, C1, and C2 (3-pole), it produces a lowpass reconstruction filter with additional attenuation. R1 and R3 act as filter termination resistors.

Diodes D1–D4 are ESD-protection diodes that clamp the amplifier input to the power supplies. D3 and D4 are silicon clamp diodes (0.6V to 0.7V forward voltage). The high-speed signal diode is used for low currents, and the larger, silicon clamp diodes are general-purpose rectifiers for larger currents (watch the voltage and power ratings). Diodes D1 and D2 are Schottky clamp diodes with 0.25V to 0.3V forward voltage to clamp more closely to the power rail. Resistors R1, R2, R3, and R4 limit current in the ESD clamp diodes listed above.

Note the warning above the ESD diode's D1 and D3. The ESD voltage through the diodes will try to raise the power-supply voltage. That extra energy must go somewhere, if the load is relatively large, the power-supply regulator will momentarily reduce its current contribution. This allows the load to dissipate the energy. Other power supplies may be capable of both sourcing current and sinking current so they can have an active role in keeping the power-supply voltage at the right level. Notice the power supply on the analog output board output driver, the zener DA will forward bias when the power from the supply current of the ESD diodes D1 and D3 keeps the VCC or power rail from going too high. Diode DB of the analog output board will serve the same purpose for the negative power rail.

In the end, the application, circuit cost, reliability, ease of circuit board replacement, and design philosophy will determine how much protection is applied. We are not super humans and we cannot call on a superhero for help. At best we want to provide a laundry list of possibilities to aid the thought process and help ensure the most probable conditions will be considered. Making a conscious decision to include or exclude a circuit element is far better than being surprised at a later time because something was not thought of in advance.

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