Industrial-strength design considerations to prevent thermal and EMI damage

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Introduction

Electronic controls and sensing in industrial applications enables or greatly improves many aspects of manufacturing, machining and production. However, electronics must survive within the harsh environments used to produce materials such as steel, petroleum products and chemicals, or in mines where the environment is extremely hot, dirty and humid. Careful considerations must be taken when designing any system that must endure these conditions that can include extremely strong electric and magnetic fields. Keeping these conditions in mind and designing for worst-case conditions will ensure that these systems continue to operate, regardless of the environment where they are installed. This article examines some of the key design obstacles and includes worst-case design techniques to achieve survivable solutions for industrial applications.

The Importance of Reliability

In our modern world of disposable phones and low-cost consumer electronics, why should engineers worry about periodic field failures on a factory floor? In reality, it is not the cost of the electronics and possibly not even the cost of maintaining the system. Rather, it very well could be safety or the loss of plant productivity that could dwarf the cost of the latter. Large-scale manufacturing plants can cost billions of dollars to build and millions more to run. A single shutdown event due to some system failure could take days to restart, costing potentially hundreds of thousands, if not millions of dollars, in lost revenue per day while off-line. Also, whenever human life is at stake, a failure that causes injury is unthinkable. In other words, failure in these facilities is not an option.

Electronic controls are often installed into areas that are inaccessible to humans during normal operation, such as near a furnace or behind a large piece of equipment. This means that to reach the control system, the production area must be shut down for access. Industrial systems are installed with the intention that they will operate for many years (sometimes for the lifetime of the facility) without ever failing or requiring maintenance. This is the true challenge for designers of industrial systems.

The challenge of thermal management

Heat is a byproduct of electronics due to the operation of transistors and other components. It must be well managed or rising temperatures will degrade or damage devices. To understand why, simply reviewing how semiconductors are fabricated illustrates the problem.

Integrated-circuit (IC) fabrication uses thermal processes such as diffusion and annealing to move material around and within structures. The atoms of the material migrates or forms crystal structures during these processes, which occur at fairly elevated temperatures (1200ºC or greater). However, unless the IC is held at absolute zero (0º K or –273.15ºC), thermal motion will continue the process of diffusion, although much slower than during fabrication.

A curiosity of silicon used to fabricate ICs is that it has a non-linear relationship to resistance and temperature. At room temperature, silicon shows an increase in resistance as the IC's operating temperature increases. However, as the temperature increases (above recommended limits), the resistance begins to decrease, resulting in a potential positive-feedback condition. This also can occur for various other systemic reasons inside an IC that may result in a thermal runaway condition. As more current flows, the resistance of the path decreases due to thermal heating, ultimately destroying the IC by thermal damage.

Many power ICs and voltage regulators employ thermal shutdown of the output stages to prevent this runaway condition from permanently destroying the IC. However, this is still a fault condition whereby the system will fail to continue operation. Even if an IC never reaches thermal shutdown, long term reliability suffers from elevated temperatures that can result in premature failure. ICs must be used in accordance with the datasheet's recommended operating conditions so that the temperature of the IC die inside the package is kept at a safe value.

To manage the operating temperatures in equipment, manufacturers often use fans to increase the airflow over heat-generating components. Unfortunately, fans are notoriously unreliable over long periods. Plus, industrial equipment is often sealed off from the environment, which prevents cooling with outside air. Heat must be carried away via a thermal path from the ICs to a point of lower temperature.

Starting with the die as a point of heat source, the thermal impedance specified in the IC datasheet must be used to calculate the thermal rise based on the rate the heat flows away from the device. The thermal impedance is given in degrees centigrade per watt of power dissipation of the IC along with the path the heat will travel. For instance, from the junction (die) to the IC's case is referred to as *Theta Junction to Case*, or θ_{JC} (pronounced theta sub JC).

These values are extremely important. For example, a small linear regulator such as an LM340 in a SOT-223 package has a θ_{JA} (thermal impedance from the junction to the ambient air) of roughly 50ºC/W with an unlimited copper plane as the heat-sink. If the input voltage is 5 V, and the output voltage is 1.8 V (a common CMOS core voltage), with a 1-A load, the power dissipation of the regulator will be 3.2 W. This means that even with a large surface area on the PCB utilized as a heat-sink and the ambient air temperature is 20°C, the die's temperature still rises to 160°C. This greatly exceeds the device's normal operating temperature and could result either in a thermal shutdown or damage over time.

In this example, nothing could be done to make the heat flow away from the die unless a lower thermal impedance (other than copper) is tied directly to the case. The heat simply cannot flow away through the PCB copper fast enough to prevent the temperature from rising within the IC at that level of power. A solution here would be to use a more efficient method to convert the 5 V to 1.8 V (such as an LMZ10501 nano-module switching regulator). Another option is to use a package with much lower thermal impedance, which incidentally occupies more PCB surface area .

Thermal impedances, like their electrical cousin, can be summed in series to calculate the temperature rise. For example, $T_{Rise} = P_{Dissipated} \times (\theta_{JC} + \theta_{CA} + \theta_{AE})$ where the thermal impedances are θ_{JC} (junction to case), θ_{CA} (case to ambient) and θ_{AE} (ambient to environment or to the environment where the equipment resides). Selecting packages with very-low thermal impedances help transfer heat from the device. Also, adding aluminum heat sinks or heat pipes to the case can help provide a lower thermal-impedance path to the air. This reduces the operating temperature, which greatly improves long-term reliability.

Electromagnetic considerations

Managing thermal issues with equipment enclosed in an air-tight box is not the only problem. Now consider the equipment's electromagnetic (EM) environment and electromagnetic interference (EMI). Many engineers consider EMI susceptibility as damage caused by lighting or other voltage overstress condition—and they would be correct. However, that's not the only failure-inducing mechanism of extreme EM fields. More on this later.

Electrostatic damage mitigation is a reality that designers must address. If cables (including power) come into the chassis, then there is a path for large voltages to be present in that equipment, regardless of normal operating conditions. Power supplies often are protected intrinsically by design from large voltage spikes. The input stages might even have high-speed voltage monitors that clamp the input to prevent overvoltage related damage. However, when equipment is connected via wired networks, these connections provide a path with a means to store charge through the wire capacitance. It is not uncommon to find a thousand feet of wire between a sensor module (with active electronics) and a controller.

There are phenomena in nature that can destroy equipment, such as a direct lightning strike. However, there is another more-subtle effect known as cross striking. This phenomenon occurs when a highly-charged thunderhead slowly drifts over the network with long cabling and induces opposite charges on the wire (Figure 1). Normally, the charge is held in position by the charge high above in the cloud. However, if another cloud with an opposite charge drifts nearby, this can cause an electrostatic discharge (lightning) high above the network between the two clouds.

Figure 1. Conditions for cross-striking when oppositely-charged clouds float by

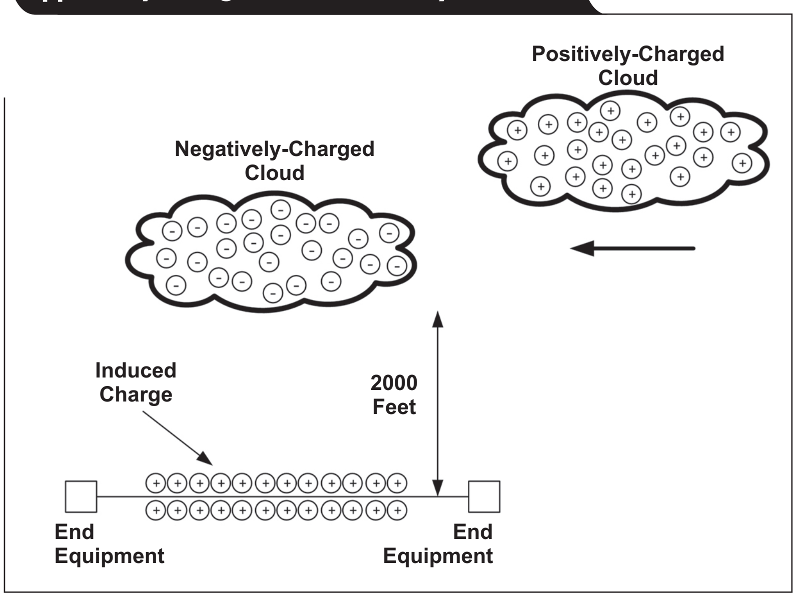
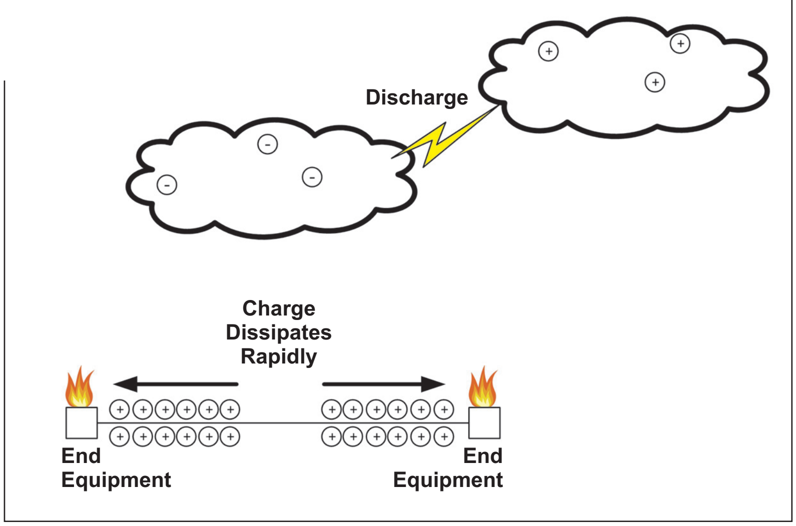


Figure 2. A cross-strike event may result in damage to end equipment



Once the charge in the cloud directly above has dissipated, the induced charge on the wire must also dissipate. As the charge rapidly drains from the wire, extremely large voltages appear at both ends of the cable. If left unchecked, the voltage potentially can destroy whatever is located on either end of the wire (Figure 2). To mitigate this type of damage, arc tubes or spark gaps along with electrostatic discharge (ESD) protection diodes are located in the end-equipment cable termination, providing the charge a path to ground. Otherwise, the path will be through cable drivers or transceivers, which most likely will not survive.

As mentioned earlier, the other type of EMI doesn't directly destroy ICs. Instead, it causes them to shift their operating points; or cause drift from specified limits. Many manufacturing facilities now use microwave heaters or other RF sources in the process. These large RF fields can induce currents into various parasitic diodes and active components found within an IC. If the IC was not designed to handle these fields, internal bias points may shift, changing the circuit's operating point.

A common nonindustrial EMI problem can be observed in many speaker phones. Amplifiers are often susceptible to RF sources such as cell phones. If the speaker phone is in use, often times a buzzing can be heard on a call while holding the cell phone close. The RF energy from the cellular transmitter is parasitically demodulated inside the amplifier chain and is heard audibly through the speaker.

However, in an industrial-control application, this phenomenon can be far more serious. It often manifests itself as an offset in precision measurements. That could mean a temperature-sensing error of several degrees or other measurement errors with remote sensors. Many processes must be held to extremely tight tolerances. Any deviation may result in either a catastrophic failure of the production process, or at a minimum substandard quality.

To address the problem, designers need to use RF-hardened components (not to be confused with radiation-hardened ICs). ICs such as the LMP2021 (single) and LMP2022 (dual) operational amplifiers are designed specifically for precision performance in the presence of high-level RF fields. Using ICs like these will mitigate errors in precision applications caused by the presence of RF interference.

Conclusion

The industrial environment is harsh and unforgiving to electronic systems. Designers must take into account the conditions of elevated temperatures as well as other sources of damage and interference. Much of the heavy lifting is now done by the ICs themselves because they are designed to handle extreme conditions. Ultimately, however, it is the designer's decisions that will result in a system that operates continuously for years without failure.

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