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Forensic Engineering Investigation of Electrical and Electronic Causes of an Industrial Equipment Failure

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Abstract

This case involved industrial equipment whose repeated, seemingly random failures resulted in the buyer of that equipment suing the seller. The failures had been isolated to a group of several transistors within electro-mechanical modules within the equipment, but the root cause of those transistors failing had not been determined. The equipment seller had more than 1,000 units in the field with no similar failures. And the electromechanical module manufacturer had more than 20,000 units in the field with no similar failures. Electrical contractors hired by the buyer had measured power quality, and reported no faults found in the three-phase power at the equipment terminals. This paper presents circuit analyses of the failing electro-mechanical module, basics of electrostatic discharge damage and protection, and the root cause of these failures — an electrical code-violating extraneous neutral-to-ground bond in a secondary power cabinet.

Keywords

Forensic engineering, electrical engineering, electronic engineering, troubleshooting, investigating, National Electrical Code, NEC, industrial equipment, power routing, grounding, neutral, bonding

Introduction

The industrial equipment investigated in this paper can be classified as medium-duty (1 to 10 tons), fully automated, electric motor-operated, consumer product packaging equipment (hereinafter referred to as “the equipment”)[1]. Featuring robotic functionality, including optical sensing, product handling, material handling, and basic quality control, the equipment automatically generates reports of operating and production status at regular intervals and issues alarms, triggering immediately when warranted.

Human operators load the somewhat fragile products onto a conveyor belt to be packaged as individual units. The equipment repositions the units on the conveyor belt with a higher degree of precision and spacing. Compressed air removes any dust from the units. The units are placed within packages, and then the packages are wrapped in plastic film. Hot air shrinks the plastic film. Printed labels are applied to the packages. The final packages, now much less fragile, are stacked onto pallets. Forklift operators move the pallets to loading docks or into the warehouse storage area.

The equipment’s optical sensing uses infrared, optical and UV light sources with corresponding photodetectors. Temperature sensors control the shrink-wrapping hot air blower, and there are physical position sensors, angle sensors, and rotation counters as well. Sensing is done at multiple points and times during the process. The sensors make the process observable to a control system microprocesser within the equipment. The microprocessor controls mechanical manipulators and tools, heaters, and blowers. The combination of observability and controllability results in a stable control system[2].

Three-phase 480VAC power enters the factory from a transformer mounted on a nearby utility pole and is distributed through a main panel and two sub-panels. The equipment has its own transformer, rectifiers, and power conditioners, delivering AC and DC of various voltages throughout the system.

Background

The seller manufactures and services the equipment. The buyer purchased and deployed a set of the equipment. The equipment control system first failed within two months of deployment. The seller repaired and returned it to the buyer’s facility. It failed again within two months.

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Except for frequent failures, the buyer was satisfied with the operation of the equipment. The buyer purchased and deployed a second unit within nine months of purchasing the first unit.

Failures continued to occur in both units every few months, and more frequently during the cold months — the heating season. Specifically, it was the physical position sensors, angle sensors, and rotation counters that failed (seemingly randomly). The seller replaced the various sensors eight separate times in less than a year. Each time, the equipment was out of service for days or weeks.

The seller claimed that the failures were caused by transient voltage fluctuations (a rapid voltage change in fundamental frequency voltages over several cycles) at the buyer's premises. The buyer's electrician tested for electrical abnormalities and reported normal readings that should not cause problems with the equipment.

After two years, the buyer was frustrated and purchased a set of similar packaging equipment from the seller's competitor. The buyer demanded a full refund for the two sets of the seller's equipment plus compensation for what the buyer had spent for ongoing repairs and lost revenue due to system downtime.

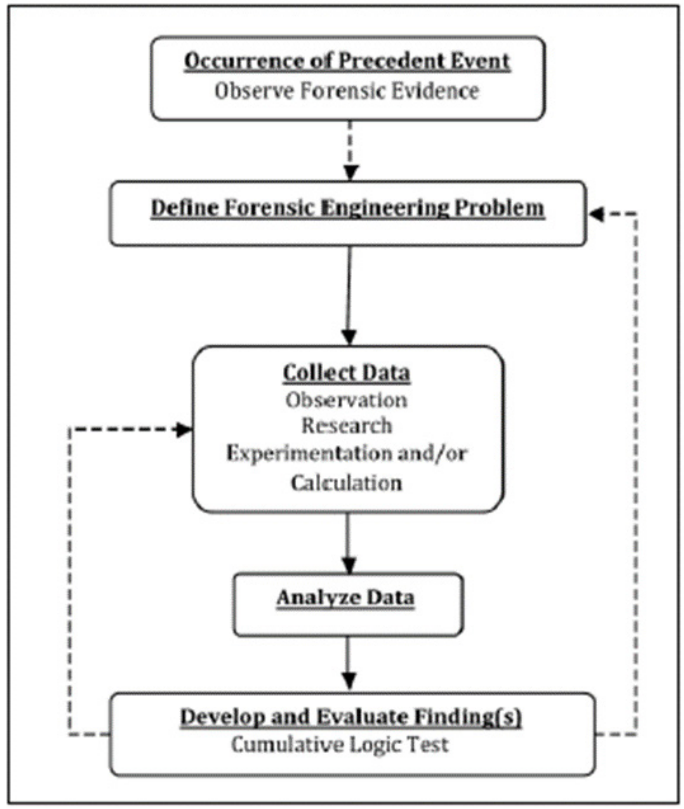

Figure 1
Flowchart illustrating forensic engineering method presented in "Forensic Engineering and the Scientific Method" by Liptai and Cecil.

Research and Hypotheses

For a complete description of the scientific method as it applies to forensic engineers, see "Forensic Engineering and the Scientific Method"[3]. From that article is **Figure 1**, a flowchart illustrating the forensic engineering method utilized in applied science or technology, which is an adaptation of the most general scientific method.

Three competing hypotheses (shown in **Figure 2**) were developed after reviewing the available documents. The hypotheses and their elements are discussed below:

1. *First hypothesis*: Although the buyer's electrician tested and reported normal readings that should not cause problems with equipment, the author's first hypothesis was that equipment failure was due to a fault in the three-phase power distribution. **Figure 3** on page 24 shows amplitude versus time plots of voltages and currents of the three phases. Plots of voltage and current on the neutral wire, referred to as ground, are not included. (Power quality testers, including three phases plus neutral, were available in March of 2019.) The current plots show current spikes of more than 5.6 kA and voltage excursions down to about 192.5V from 210V. That's less than 10%, and was considered acceptable by the electrician and the buyer. Plus, it was within the range required by the seller.

   Within the buyer's factory, the circuit powering the equipment also powers two chargers for lithium-ion battery powered forklifts. The current spikes occur when the battery is plugged in to the charger.

   Presenting a balanced load to the three-phase source is not a system requirement. The current and voltage fluctuations do not exceed specified limits required by the seller.

   Notice that there is no plot of the voltage and current of the neutral wire. With proper power distribution, if neutral voltage and current were plotted, the unbalanced current would appear in that plot — and a voltage plot would show only a few volts excursion. A high-impedance return path on the neutral wire could be problematic, causing higher voltage excursions. The author suspected a fault with the routing of neutral wires, which serves as the core of the first hypothesis.

2. *Second hypothesis*: Electrostatic discharge (ESD) was damaging the transistors. Provided documents isolated the failure to the output stage of the position sensors within the equipment. This push-pull output stage drives a digital signal through wire from the sensor to the microprocessor. A representative push-pull output stage is shown in **Figure 4** on page 24.

The output stage is a complementary metal oxide semiconductor (CMOS) inverter. It consists of a P-type metal oxide field effect transistor (MOSFET), abbreviated as a PFET, and an N-type MOSFET (NFET). The input signal is connected to both the PFET and the NFET. Both MOSFETS connect to the output. The "load" connected to the output symbolizes several meters of shielded cable connected to the input of a microprossesor within the equipment.

VDD is a DC voltage derived from one phase from the equipment's three-phase power. VSS is derived from the neutral wire of the three-phase power. The sensor's housing is connected to safety ground. The push-pull function is to drive a representative of signal "input" from the position sensor through a length of wire to the microprocessor.

When the input voltage is below the threshold, the NFET "turns off" and does not conduct. The

	Hypothesis	Basis	Tests
1	Faulty three-phase power distribution	Although the buyer's electrician tested and reported normal readings that should not cause problems with equipment, this hypothesis is that equipment failure was due to a fault in the three-phase power distribution	1. Inspect 3-phase power from the transformer, through the main and sub-panels to the equipment, looking for proper configuration of three hot phases, neutral return, and ground connections
			2. If no faults found by visual inspection, perform a multi-day power quality measurement, including measuring of voltage and current on the neutral return line
2	Electro-Static Discharge damaged the output stage of the position sensors	Unwinding plastic film from a roll is a well-known generator of static build-up. Failures occurred more frequently during the winter months, when static build-up is more of a problem	1. Review the equipment design documentation to determine how ESD is intended to be mitigated
			2. Inspect the equipment for damaged shielded connectors and functionality of ESD mitigation subsystems
			3. Use a hand-held static-voltage meter to measure static voltage inside the equipment during operation
3	Radio Frequency Emission damaged the output stage of the position sensors	Microprocessors and electronic components operating at high switching frequencies emit electro-magnetic waves at radio frequencies. Metal surfaces and metal products being packaged and wrapped may reflect such waves. It's possible for non-linear elements within the equipment systems to amplify and shift the frequency, and be picked up and conducted into wires of the position sensors	1. Review the equipment design documentation to determine the specified grounding and shielding requirements
			2. Visually inspect the equipment for proper grounding, shielding, and any damage to grounding and shielding
			3. Use a hand-held static-voltage meter to measure electric field strength inside the equipment during operation

Figure 2
Hypothesis table.

PFET "turns on" and pushes current from the positive power supply "VDD," through the PFET, through the output, and through cable to microprocessor input — indicated as "load."

When the input voltage is above the threshold, the PFET "turns off" and does not conduct. The NFET "turns on" and pulls current back from the microprocessor input and cable, through the output, through the NFET, and to the negative power supply "VSS."

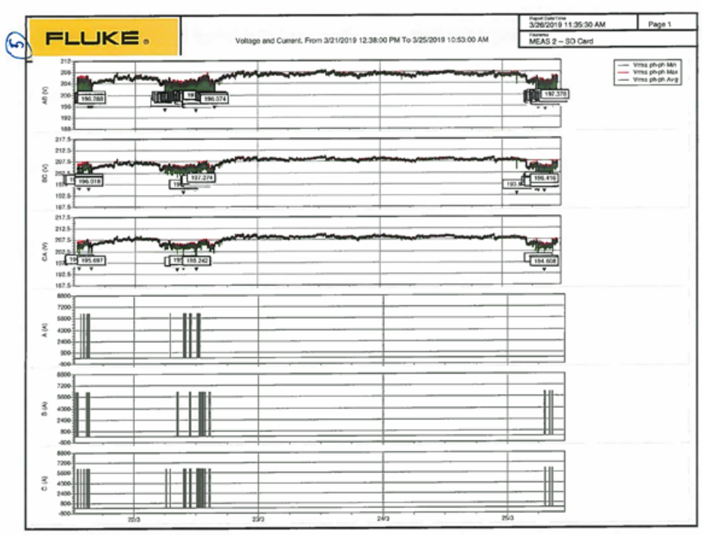

Figure 3
No problems with three hot-phase voltages appear in this voltage power quality plot.

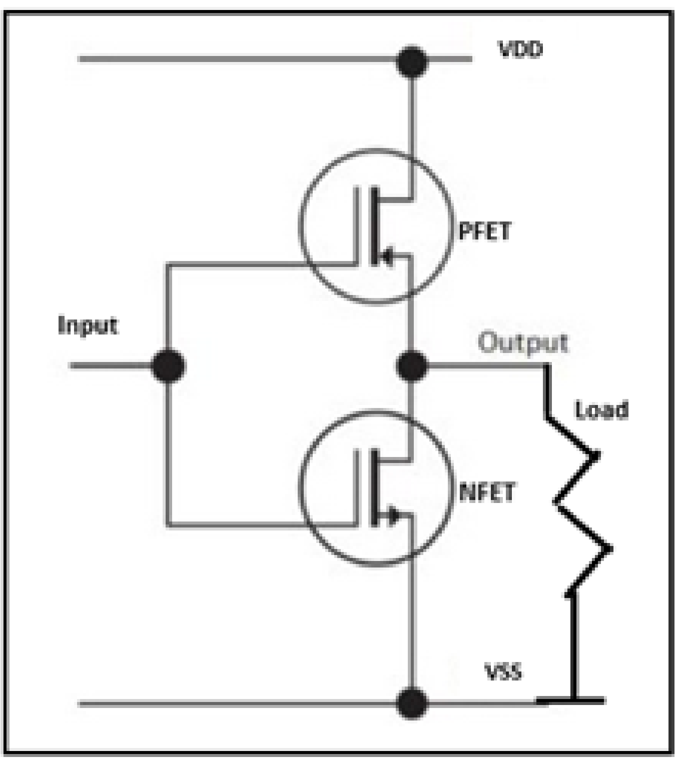

Figure 4
Typical CMOS push-pull output stage.

The microprocessor interprets the pattern of voltages developed at its input as digital logic signals and uses them in its control algorithm for the system.

The push-pull output stage is robust when there is proper connectivity to VDD, VSS, and safety ground at all points. However, if for some reason VSS even momentarily reaches a significantly higher voltage than the output, current from VSS can overpower the normal operation of the NFET, burst through its electronic "barrier," and flow upward from VSS to the output. If VSS reaches a voltage significantly higher than VDD, current from VSS can overpower the normal operation of both the NFET and the PFET and flow through both up to VDD.

Either event can generate enough heat to damage the semiconductor junctions of one or both MOSFETs. Even after VSS voltage returns to normal, the damaged MOSFETs can allow current to leak from VDD through the PFET and NFET to VSS — no matter the state of the input. The leakage current generates heat, which further increases the leakage current and generates more heat. This is known as thermal runaway, and eventually melts the active areas of the MOSFETs. One cause of such a catastrophic failure is ESD.

Static electricity is called static because it does not move through wires; however, if enough builds up, it will jump from one object to another[4]. The hypothesis to be investigated is that static charge built up somewhere in the equipment and jumped to VSS in **Figure 4**, resulting in high enough voltage between VSS and the output or between VSS and VDD to damage the NFET, the PFET, or both.

Components such as the position sensors that failed are designed for self protection from ESD during manufacture, test, and installation. Protection from ESD in operation is the responsibility of the equipment designer (that is, the seller). It is the buyer's responsibility to repair any damage to the equipment that compromises protection, such as loose grounding wires or straps. To be investigated was whether or not the ESD protection of the equipment was adequate.

A typical static electrical charge buildup in electrical equipment occurs when plastic material (such as plastic shrink wrap) is unwound from a roll. Multiple solutions can be used to mitigate this tribological effect[5].

Ionization can neutralize static charges in a matter of seconds[6]. Ionizers create positively and negatively charged ions, which are distributed by fans through the system to be protected. A solution promoted in "Solutions for Static Buildup on Process Rollers"[5] includes conductive graphite in mechanical rollers within the system.

The observation by both the buyer and seller that failures occurred more frequently during the winter months points to ESD as a potential cause of the failures. Heated inside air in the winter has lower relative humidity than inside air from ventilation in spring and fall or chilled air in the summer. Low relative humidity increases the likelihood of electrostatic charge buildup, as intuitively known by getting static shocks after walking across a carpet in winter and touching a metal doorknob.

Industrial systems, such as the equipment, are designed to be robust against ESD using techniques of "Solutions for Static Buildup on Process Rollers"[5] and When Do You Need Ionization?"[6] or others. The position sensors and other components within the system have installation requirements, including the use of shielded cables to guard against static charge "jumping" onto the wires from charged surfaces within the equipment.

3. *Third hypothesis*: Radio frequency interference (RFI) damaged the output stage of the position sensors. The microprocessor and control system for the equipment include components that may emit high-frequency radiation. A design fault or system failure could possibly lead to high-frequency radiation coupling into a wire, such as VSS in **Figure 4** and damaging the junction of the NFET or PFET in a similar way as ESD.

   Typically, such systems are designed for robustness against RFI, but this was a hypothesis to be tested and ruled out.

Given the "zero failure rate" claimed by the seller and the manufacturer of the position sensors, the author planned to investigate only these three hypotheses.

Protocol for Site Visit

The following protocol was requested and accepted:

1. View and photograph the three-phase service, including the transformer mounted on the utility pole, the service drop wires to the service entrance, and electric meter.

2. To observe and photograph while the seller's representative or the buyer's representative:

   a. Demonstrates and operates the systems.

   b. Explains their operation.

   c. Points out their components and their function.

   d. Points out the failing components and explains their failure modes.

3. For the buyer's or the seller's qualified representative to show where and how the power quality test instruments were connected, so that the author may view and photograph.

4. Direct the licensed electrician (subcontracted by the author) to probe for high voltage on neutral wire due to wire damage and the large unbalanced load current it carries when, for example, the forklift charger is operated. This would involve measuring the voltage on the neutral wire near the same location where the power quality probes were attached. Note: An electrical engineer — even a licensed professional forensic engineer like the author — is not necessarily an electrician. Therefore, it is important to delegate certain tasks accordingly.

5. With assistance from the licensed electrician, measure the harmonic content on the three power phases, which may reach high levels while the forklift charger is operated.

6. Evaluate the static electrical charge build-up of

the environment inside the equipment system — that is, measure the strength of static electric field along the product path. This needs to be done with actual product being processed.

7. Evaluate the strength of radio frequency fields within the environment inside the packaging equipment while it is processing product.

Site Visit

Along with the master electrician and his assistant, the author viewed and photographed the three-phase transformers on the utility pole, the ground rod at the foot of the utility pole, and the service-drop cable package — three hot phases and neutral cable — from the transformers to the service entrance. All was well with the electric utility-owned system.

Inside the premises, the electricians removed the cover from the main breaker panel (service disconnect) for the building. This 400A service panel was owned by the buyer.

Figure 5
Panel 1, showing proper configuration of three fuses and neutral-to-ground bonding point.

The bonding point of neutral to ground for the building can be seen to the left of **Figure 5**. All of the neutral return lines within the building should be isolated from ground until they reach this bonding point within Panel 1. One can see that panel cabinet is also bonded to this ground point.

Earth grounding is established by a grounding rod penetrating the foundation into the earth as shown in **Figure 6** (pointed out by the author's foot). This earth-ground is bonded to the node shown in **Figure 5**.

The electricians verified all phase-to-phase and phase-to-neutral voltages. Since earth-ground and neutral are bonded inside Panel 1, ground to neutral is zero volts by construction at this point.

Panel 2 is mounted on the same exterior wall, a few meters from Panel 1. Panel 2, shown in **Figure 7**, limits the available current to 200A. Three hot phases, neutral, and ground wires can be seen. As is proper, neutral and ground are isolated from each other by insulating fittings. This isolation and the bonding between the cabinet of Panel 2 and ground can be seen more readily in **Figure 8**.

Verifying all phase-to-phase and phase-to-neutral

Figure 6
Service ground is established by a steel rod penetrating the foundation into the earth.

voltages within Panel 2, the electrician also confirmed 0V between neutral and ground within Panel 2.

Panel 3 is mounted on an interior wall, about 100 meters from Panel 2. The electrician opened Panel 3, shown in **Figure 9**. Hot phase wires are red, blue, and yellow. To their right is the white connector for neutral.

The close-up of Panel 3 interior in **Figure 10** (on page 28) shows a green screw attached to a bonding clamp on the white (neutral) wire. By convention, this green screw indicates bonding of neutral to ground.

The electricians verified proper voltages between all phases and phases to neutral. Because of the bond, neutral to ground voltage is 0V. Bonding of neutral to ground anywhere other than the main service entrance (Panel 1) violates the *National Electrical Code* (NEC)[7]. The ramifications of this will be discussed later.

Panel 3 is the first panel upstream from the equipment and is shown on the upper right of **Figure 11** (on page 28). Panel 3 supplies power to the two chargers for the

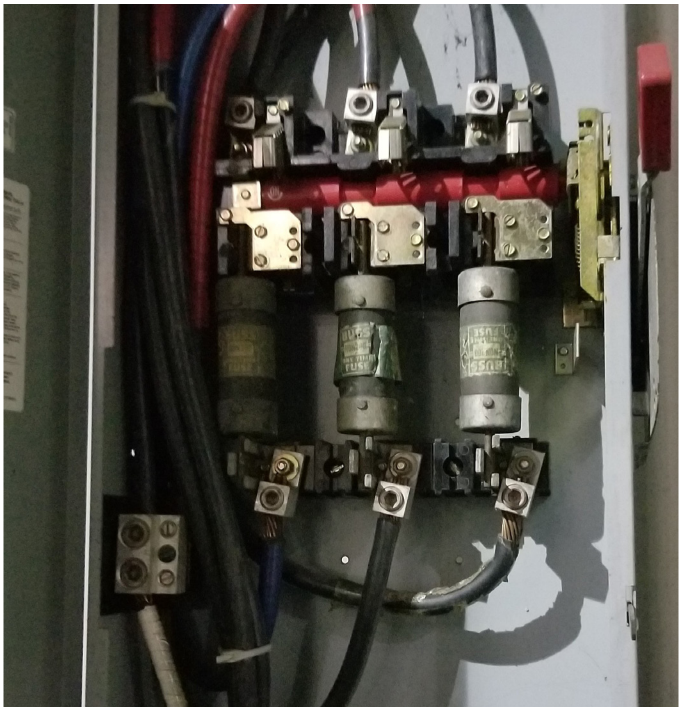

Figure 8
Close-up showing neutral isolated from ground within Panel 2.

Figure 7
Internal view of Panel 2 shows neutral isolated from ground.

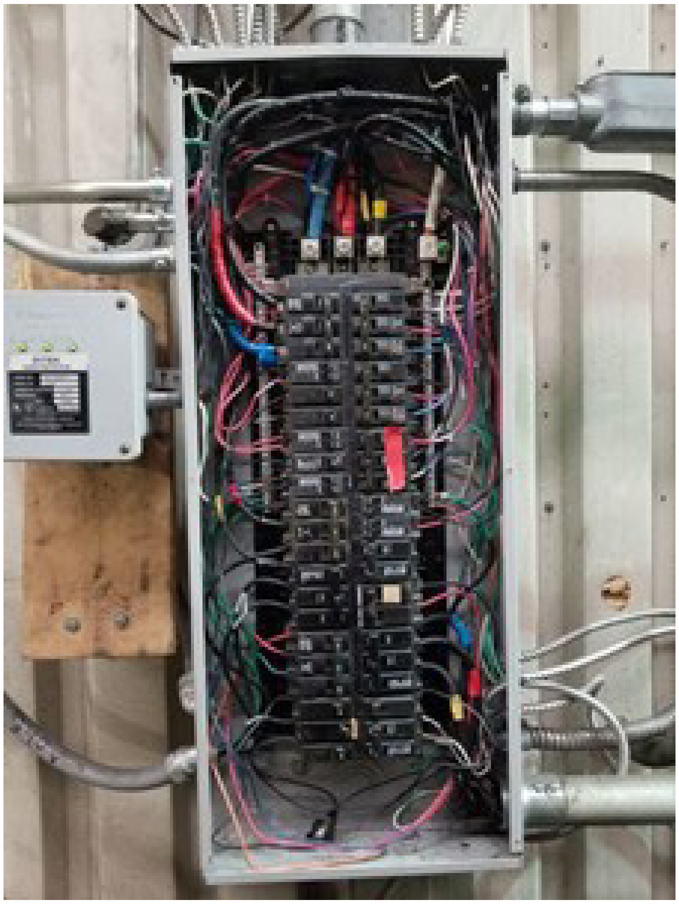

Figure 9
Interior view of Panel 3.

lithium-ion batteries of electric-powered forklifts on the floor beside Panel 3 — and to the subject equipment in a large factory room across the wall from Panel 3.

Continuing on to the subject equipment, **Figure 12** shows one of the position sensors that failed regularly. The green collar attaches the cable to the output stage of the sensor — that is, the push-pull driver shown in **Figure 4**. The green collar also bonds the cable's shielding to the sensor's housing.

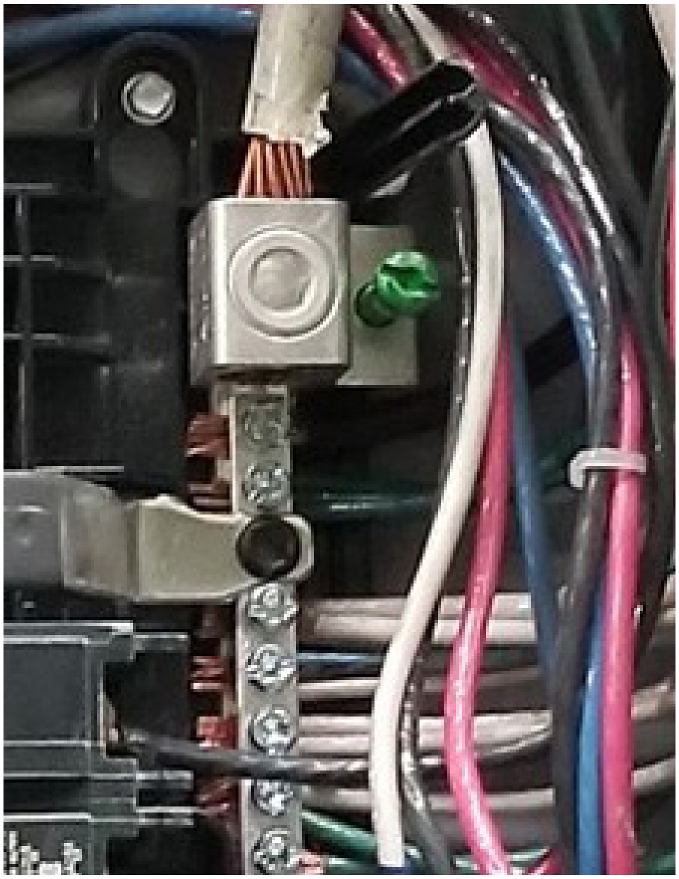

Figure 10
Close-up within Panel 3, showing
improper bonding of neutral to ground.

Figure 11
Panel 3 and two forklift battery chargers.

The opposite end of the green cable connector is shown in **Figure 13**, along with the connecting fixture to the microprocessor. Cable and connector include shielding. Outside of connector is connected to shield and makes electrical contact with the encoder housing. Shielded point to point connectivity to grounded metal housings provides protection from ESD and RFI damage. The author observed similar proper grounding and shielding techniques throughout the equipment, making hypotheses

Figure 12
One of the position sensors that regularly
failed shows intact cabling and shielding.

Figure 13
Opposite end of the cable of **Figure 10**
where it attaches to the microprocessor.

2 and 3 unlikely causes of the repeated failures.

Hypothesis 1 — that equipment failure was due to a fault in the three-phase power distribution — is the most likely of the three hypotheses. The fact that an NEC violation is present adds to that likelihood, and creates an urgent obligation that the buyer be informed of this safety hazard immediately.

Discussion

The unwanted bonding from neutral to ground in Panel 3 was the most important finding and is a safety hazard as well as the most likely cause of the repeated failures. The safety hazard can be explained with these quotations from the NFPA 70, *National Electrical Code Handbook*[7].

> ***250.5 (4) Path for Fault Current:***
>
> *"The earth shall not be considered as an effective fault-current path."*
>
> *"The two reasons for grounding are as follows:*
>
> *1. To limit the voltages caused by lightning or by accidental contact of the supply conductors with conductors of higher voltage*
>
> *2. To stabilize the voltage under normal operating conditions (which maintains the voltage at one level relative to ground, so that any equipment connected to the system will be subject only to that potential difference)"*
>
> *...*
>
> ***250.24(a)(5)***
>
> ***(5) Load-Side Grounding Connections.***
>
> *"A grounded conductor shall not be connected to normally non–current-carrying metal parts of equipment, to equipment grounding conductor(s), or be reconnected to ground on the load side of the service disconnecting means except as otherwise permitted in this article."*
>
> *...*
>
> *"Section 250.24(A)(5) prohibits re-grounding of the grounded conductor on the load side of the service disconnecting means. This correlates with the requirement of 250.142(B), which is a general prohibition on the use of the grounded conductor for grounding equipment.* ***This prevents parallel paths for neutral current on the load side of the service disconnecting means. Parallel paths could include metal raceways, metal piping systems, metal ductwork, structural steel, and other continuous metal paths that are not intended to be current-carrying conductors under normal conditions."***
>
> ***(Author's emphasis added)***
>
> ***250.30 (A)***
>
> *"Installing a system bonding jumper at both the source and the first disconnecting means* ***can result in establishing an unintended parallel path for current that would otherwise utilize the grounded conductor. Exposed normally non–current-carrying metal components are often included as part of this parallel path and can present an unintentional safety hazard. This type of installation is prohibited*** *..."*

A plain English explanation is posted as an answer to a frequently asked question[8].

> *"**Frequently Asked Question:** Why do the grounds and neutrals need to be separated in a sub-panel? What happens if they aren't?*
>
> ***Answer:*** *Though the neutral doesn't have significant voltage, it does carry current. Remember, it's current that kills, not voltage. In a 2-wire circuit, the neutral carries just as much current as the hot conductor. If the neutral and ground are connected in a sub-panel, that current will travel on other paths, such as bare ground wires, equipment enclosures, and metal piping systems, on its way back to the service panel. One problem created by this condition is possible shock hazards, the severity of which depends on the locations of the equipment and the person touching the enclosure or piping system. Another problem is magnetic fields that do not cancel themselves out. Since the return current has multiple paths, the current remaining in the neutral will not counterbalance the*

current in the hot wire. The resulting imbalance creates a magnetic field that can interfere with sensitive electronic equipment. In a metal conduit system, the imbalance will induce current into the conduit, which could cause the conduit to overheat."

NEC Expert Mike Holt, of Mike Holt Enterprises, explains this even more bluntly and directly in his online Code forum[9].

*"At the service panel (**ONLY AT THE SERVICE PANEL - HUGELY IMPORTANT**) the neutral bus bar is bonded to ground. You should see the ground lead and neutral tied to the same bus (the neutral bus bar).*

*However, any sub-panel after the primary service from there **MUST** have an isolated neutral. **DO NOT DO NOT DO NOT bond neutral to ground in a sub-panel**.*

Why is this?

When you tie neutral to earth ground in a sub-panel, you create a potential parallel path for current to return via earth (ground). In the event of a fault, your ground conductor has assumed the role of the return path for current and now everything that you've grounded (sub-panel, appliances, metal fixtures, etc.) to that sub-panel is now hot.

All it takes is a preexisting fault, one rainstorm, or wet feet, whatever... and you touching something energized - and you're doing the 60 cycle shuffle."

Conclusions

From readings and observations during the site visit, the author discarded the second and third hypotheses as unsupportable. Proper grounding and shielding were designed into the equipment. The likelihood of ESD or RFI damaging the output stages of the various sensors used throughout the system was negligible. A summary of case and root causes are shown in **Figure 14**.

	Hypothesis	Findings	Significance
1	Faulty three-phase power distribution	Faulty installation of an electrical sub-panel was found by visual inspection. In the sub-panel powering the equipment and the battery chargers, there was an unexpected and dangerous bonding between the neutral busbar and safety ground	1.This extraneous bond violates National Electric Code 250.5 and others, and creates a safety hazard.
			2. In terms of electrical performance, this extraneous bond enables a ground loop which under certain circumstances can cause transient voltages on the neutral line (and VSS within the sensor), large enough to damage the sensor output transistors
2	Electro-Static Discharge damaged the output stage of the position sensors	The author visually inspected the equipment and found no damaged shielded connectors or other obvious damage that would affect ESD susceptibility	Author had reviewed the documentation prior to visiting the site to understand the ESD mitigation intent. Finding all systems in place and intact, author decided ESD damage was a far less likely failure cause than the discovered extraneous ground bond.
3	Radio Frequency Emission damaged the output stage of the position sensors	The author visually inspected the equipment and found no damaged shielded connectors or other obvious damage that would affect Radio Frequency Interference susceptibility	Author had reviewed the documentation prior to visiting the site to understand the RFI prevention intent. Finding all systems in place and intact, author decided RFI damage was a far less likely failure cause than the discovered extraneous ground bond.

Figure 14
Summary of author's findings.

Consider the thousands of installations worldwide and hundreds of installations within the United States. Two machines repeatedly fail. Both are owned by the same customer, operate inside the same building, and are powered from the same improperly wired sub-panel. What is different about this customer and their facility causing the failures? The improper wiring is a likely difference.

The root cause is not due to a single overriding fault, but rather several shortcomings, including the electrical transients that were conducted through the inadvertent ground loop, which combine to the observed failure mode. There is a strong likelihood that fixing the Code violation will make the other contributing causes insignificant.

1. The mistaken bonding of neutral wire to ground at Panel 3, which services the equipment and also the forklift chargers, creates multiple parallel current return paths where there ought to be a single path from all loads within the building facility back to the transformer outside the building.

    a. This dangerous condition can cause injury. Fixing it is not optional: It must be fixed as soon as possible for safety reasons if nothing else.

    b. It is a violation of NEC Section 250.

    c. It can cause voltage fluctuations on the ground and neutral wires within the equipment.

2. Battery chargers next to Panel 3, when used, cause large unbalanced current to flow in the neutral-ground combination that can interfere with the power supplies of the position sensors within the equipment. Removing the illegal bond will allow this unbalanced current to divide and flow properly through the neutral and hot phases without disturbing the ground voltage.

3. Misleading clue #1. Failure Mode Analysis of the position sensors indicated their output stage was burnt out. This pointed to ESD or RFI as a possible cause, especially because failures occur during the heating season when humidity is low and static charge buildup is high. However, the system was designed to be robust against electrostatic discharge.

4. Misleading clue #2. The buyer is the only (known) customer of the seller using the equipment to wrap large all-metal products. If static charge were borderline high, the antenna effect of the ungrounded metal products could be exacerbating the postulated ESD effect. However, the sealer is designed and built to allow processing all-metal products.

Given the danger from this Code violation, the author advised the buyer to fix the violation immediately — before any further investigation of the equipment failures. Once the ground-neutral bond was repaired to Code specifications, it appeared to have fixed the conditions that caused the failures.

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