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Predictive Maintenance (PdM) Integration for Electrical Distribution Safety and Reliability

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Introduction

Electricity and its uninterrupted and clean distribution through our nation, facilities and lives are inescapable requirements and the backbone of progress in today's society. The resurgence of U.S. commerce is not possible without it. Safe and reliable electrical distribution systems typically start out as being well engineered with bright futures provided they receive regular, adequate maintenance and periodic testing.

Over time, electrical infrastructure changes, facilities expand, load requirements increase and equipment becomes degraded with age or lack of maintenance. It's not uncommon to find functioning electrical distribution equipment that hasn't been maintained and tested, is obsolete, or is well beyond its design service life. Electrical systems that were appropriate for the loads and incoming power when they were installed may now expose employees to life-threatening hazards. Often, there is no indication of a potential problem until a fault occurs and the overcurrent protective device fails to operate, resulting in injury or damage to equipment and property. U.S., Canadian and EU authorities regularly track and report on hundreds of electrically caused facility fires, explosions, injuries and deaths all caused by poorly implemented and reactive "layers of protection."

Safety, maintenance and reliability professionals can proactively change this scenario and enhance these protections and sustainability of their electrical systems by deploying an integrated condition monitoring strategy with predictive maintenance (PdM) technologies. The unlimited potential and stakeholder buy in for reliability-based safety programs is unleashed once this condition monitoring data is centralized and users have access to a dashboard of analysis tools highlighting safety, reliability and ROI information. The paper is broken down into the following sections:

- Just a Few Numbers
- Layers of Protection (LOP)
- Failure / Hazard Recognition
- Condition Monitoring with PdM Tool Box
- Facility Survey High Points
- The Big Close
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Just a Few Numbers

Reviews of insurance/risk statistics and every day media headlines remind us of the extreme failures and unfortunate circumstances caused by the mismanagement of electrical distribution systems. For example:

- FM Global statistics identify that between 1992 and 2001 electricity was leading cause of fires and explosions causing nearly 1,400 insurance losses. Total gross loss caused due to electrical fires and explosions was approx $788MM.[1] ($950MM in 2008)

- Zurich Insurance Risk Engineering reports that 25-30% of all large loss fires are caused by electrical failures.[2] Using NFPA's 2007 Large Loss figures (properties)[3], this is estimated to have had an impact of $127MM.

- Canada's Ministry of Labor (MOL) reviewed a decade of electrical incident records to find that 50% of the 1,200 electrocution deaths and critical and minor arc flash injuries came from performing basic maintenance and repair on or around energized equipment. An interesting statistic is that 79% of the fatalities involved occupations outside of traditional role of electricians. These included maintenance workers, millwrights, apprentices, laborers, heat, ventilation and air conditioning (HVAC) technicians, equipment operators, supervisors and drivers."[4]

These catastrophic and deadly events seem to get attention and focus efforts towards ensuring that the most current type of incident does not occur in our facilities. Instead of isolated improvement initiatives or narrow reactions to specific events, organizations must recognize that achieving excellence in one area is progress but will not create a sustainable safety culture. Additionally, not every electrical incident or near miss results in death or catastrophic loss but does produce significant ripple effects:

Injuries & Deaths	Fires
Explosions	Lawsuits, Fines and litigation
Business Interruption	Property Damage
Insurance Claims	Spoilage
Supplier Bottlenecks	Lost Orders
Energy Losses	Production Interruption
Shareholder Dissatisfaction	Poor Morale

Figure 1. Electrical Incident Ripple Effects

Layers of Protection (LOP)

Just as there are many ripples resulting from an incident, there may be more than one primary root cause and often there is a complex chain of events or secondary contributing causes. These events are a mix of management and human errors and equipment failures which deteriorate, weaken and create gaps in the "barriers" or layers of protection. Two examples highlight these problematic challenges.

Example 1: Barrier Analysis "Near Miss" Case Study.[5] Using Figure 2, a work order is authorized and barriers are penetrated to allow for the possibility of an undesired event (possible personal injury from working on an energized circuit). Barriers related to safety requirements (tagout), communications and procedure failed, but the barrier established by training resulted in averting an injury.

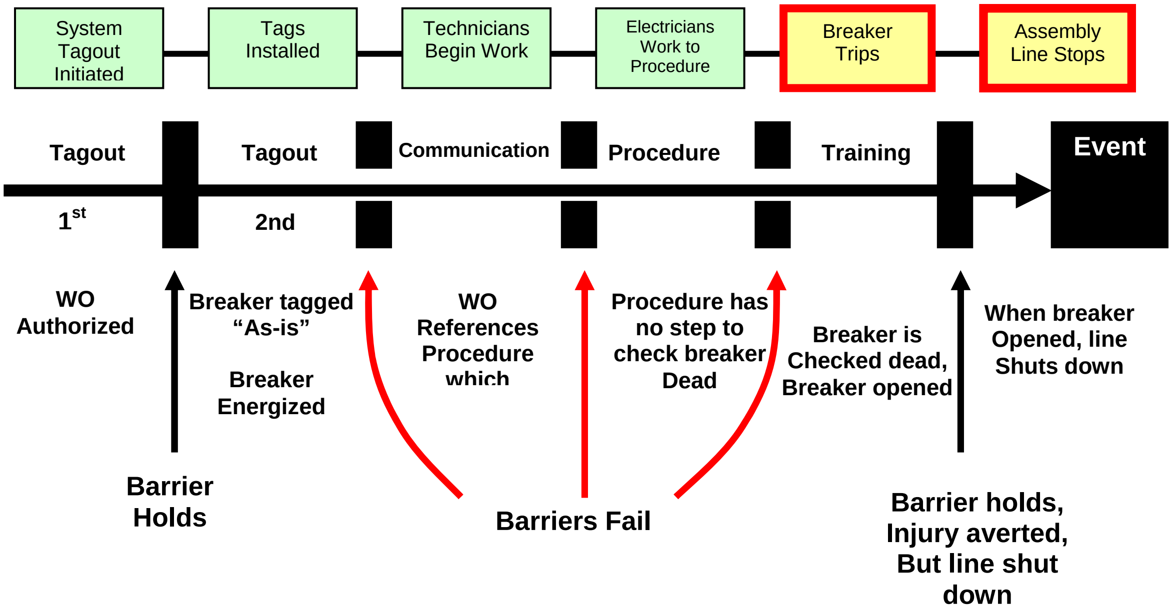

Figure 2. Barrier Analysis of a "Near Miss"

Example 2: "Human Error and Disregard for Safety" [6] - February 2001, an operator made an "Extraordinary attempt" to close a molded case circuit (MCC) breaker to start 100 HP, 480 volt, 3 phase power roof vent. The operator received a massive "arc" flash and burns to unprotected parts of hands, arms, and face. Injuries were aggravated due to the fact that the operator had opened the module door to gain access for applying added force for closing the breaker after attempts from outside failed due to apparent linkage binding.

Some of the Missing LOPs:

- Existing PM to "inspect and clean" not applied to this module
- Failing Motor known to have a low resistance-to-ground condition and correction planned but not scheduled
- Circuit wasn't tagged out of service

Both examples involved physical protections and human variable programs that only worked as well as the people applying their common sense. Alternativley, only a small amount of information (training) was needed to prevent mistakes leading to the hazard. The problem isn't bad people or lack of competency – it's that the systems governing equipment integrity aren't rigorous enough to ensure the required reliability.

It's essential to take a proactive approach – not just monitoring for behaviors, errors and failures that are known root causes for electrical safety incidents but also identifying improvement opportunities to counter this accumulation of barrier breaches and minimize risk. Therefore, to counteract the

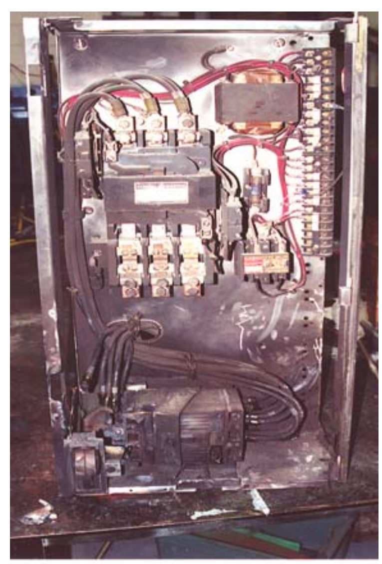

Figure 3. The Damaged circuit breaker and cubicle

unknown, managers should rely on a strategy of multiple independent LOP to strengthen safety. This is where the growing acceptance and using predictive maintenance (PdM) technologies to monitor equipment conditions for failures. Before you run out to “PdMs R Us” of reliability toys, a little homework is needed.

Industry didn’t wake up yesterday saying “hey, maybe I should be more careful around electricity.” Many smart people have used over 100 years of lessons learned from near misses, injuries, deaths, technological advances as well as the following resources to build a very robust set of possible barriers or LOP.

- Standards and Best Practices from Trade Associations (EASA, IEEE, EPRI, etc.)
- Testing / Listing Agencies (FM, UL)
- Government (OSHA)
- Consultants / Service Providers
- Manufacturers
- Codes / Standards (NFPA/NEC, OSHA) for proper:
  - System engineering, installation and maintenance
  - Personnel training, procedures, PPE
  - Industry Best Practices
  - Shock Hazard Assessments and Arc Flash Studies
  - House keeping and Documentation

These LOP can be distilled down to 2 very fundamental but simple rules:

1. **Don’t let equipment fail and/or hurt people** (i.e. electrical shock, burns from contact, arcs, or flashes and impact from blasts)
2. **Don’t let people do things to degrade equipment performance and/or electrically hurt themselves**

Failure and Hazard Indicators

Using “the two rules”, the questions become “Can we get better at identifying conditions that cause equipment failures and if the condition is negatively affecting the asset, are there early indicators that can be identified to prevent failure or warn employees of a potential hazard? The use of various root cause analysis (RCA) and failure modes effects analysis (FMEA) platforms help us determine a few by focusing on “what happened?” and “how did it happen?” Additionally, the author researched Predictive Service (PSC) database of condition monitoring services, analysis and reporting which is summarized in the “Big Close” section. This information is referenced in various areas of this document.

Secondary Contributing Factors

Numerous factors can affect the proper operation of electrical assets. These conditions include excessive, dust, dirt, debris, high or low ambient temperature, humidity, corrosive atmospheres, water, vibration, high-resistance connections / contacts, overloading, uninterrupted faults, lack of maintenance and countless other processes / procedures failures.

Primary Contributing Factors / Key Hazards

If left unchecked, the secondary-contributing factors create primary effects which include the following "Key Hazards." Ultimately, these lead to equipment damage, malfunctions, failure, losses, injuries and deaths. On the "up side", most of these generate early warning signals from the abnormal heat, visual, sounds, voltage/amperage anomalies and vibration. The Key Hazards are as follows but keep in mind that many can be affected by other hazards and in turn cause other hazards:

- **Electrical Arcing** – Occurs in all voltages. Arcing produces a stream of vaporized metal between conductors and through air or bulk insulation systems destroying electrical equipment. Arcing can cause overloads, defective contacts, uninterrupted faults and overheating.
- **Tracking** is often referred to as "baby arcing" and follows the path of damaged or dirty insulation across component surfaces. Tracking occurs most often in medium to high voltage equipment 1,000 volts (1kV or greater).
- **Overheating** is caused by high resistance within a conductor or at over-tightened or loose connections (line or load side), uninterrupted fault currents, build up of excessive dust, dirt, water, wet and corrosive atmospheres.
- **Uninterrupted Fault Current** – The enormous amperage rapidly heats components to very high temps that destroy insulation, melt metal, start fires and event cause an explosion if arcing occurs. These are caused when a circuit breaker, relay or fuse unsuccessfully interrupts current.
- **Voltage Irregularities** are caused by unstable utility supply, line surges, lightning strikes, transient voltage, unbalanced loads and harmonics.
- **Corona** is the partial discharge, electrical stress or leakage of 1000 volt (1kV) or more at sharp points along an electrical path. The leakage ionizes the surrounding air producing faint sparks, cracking, hissing, humming, frying noises, radio/TV interference, conductor vibration and ozone. In case of visible corona, the conductor will with a glow blue or green light.

  Corona also forms ozone (O3) which will conduct current and can follow a direct path to ground, resulting in catastrophic results, especially in enclosed switchgear. Corona also produces nitrogen oxides and in an aqueous form nitric acid which further destroys the insulating material and metal components causing possible thermal problems.
- **Partial Discharge (Corona)** is commonly explained as being intermittent unsustained arcs which are shot off of the conduction material like a stream of electrons. It occurs inside electrical components such as transformers and insulated busbars. It is affected by and causes insulation deterioration.

Equipment: For purposes of this paper, a typical facility distribution system includes medium voltages (MV) at a property's substation or pole/pad mounted transformer on down to 120 volt branch circuits. This voltage range covers hundreds of system types but for simplicity, the equipment and PdM concepts are segmented into five key equipment categories.

1. Cables and Busbars
2. High- and Medium-Voltage Service Lines, Connections, Bushings, Arrestors and Switchgear
3. Oil-filled and Dry transformers
4. Circuit Breakers, Fuses and Disconnects
5. MCCs and Motors

Any device involving electrical current can overheat and spark a fire. The good news is that we can use known causal factors or failure modes to focus safety and reliability efforts on the worst “bad actors.” Based upon a review of fires caused by failed electrical components, 70-90% was due to lack of maintenance (Figure 4).[7]

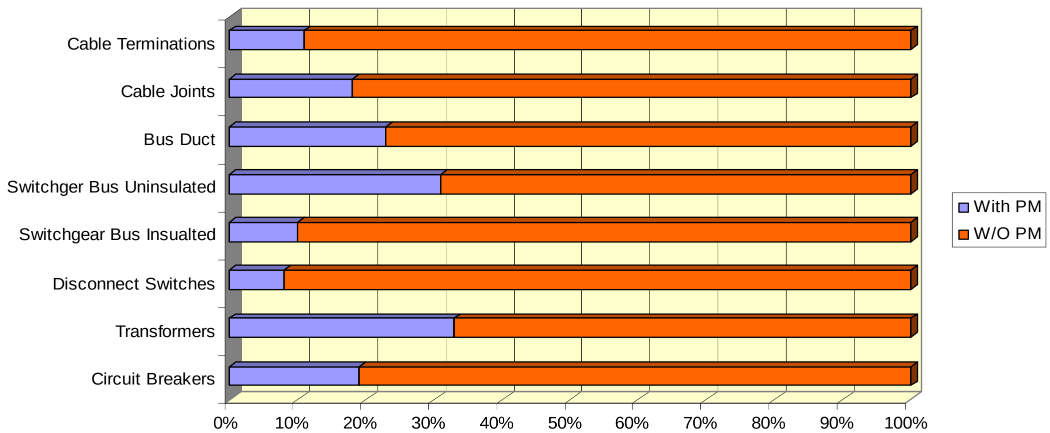

Figure 4. Equipment Failures caused by lack of Preventive Maintenance

Condition Monitoring with the Integrated PdM Tool Box

Condition monitoring with predictive maintenance (PdM) is an important maintenance strategy management of components in the distribution system. This early warning system only triggers maintenance activities based upon trends/forecast of ailing machine heath. This allows maintenance and reliability managers to identify maintenance priorities, plan work assignments, schedules, arrange for outside services and order necessary parts and materials and make repairs on a controlled outage basis. Thus, it typically extends the interval between successive maintenances and therefore incurs less cost. From a safety perspective, this equals fewer times to have personnel to be on or near energized equipment.

Based upon our progress, we know the typical contributing factors/failure modes and the equipment categories affected the most. The next step is to determine which condition monitoring technologies are the best at capturing equipment failure modes / indicators. Best-in-class maintenance organizations rely on complimentary condition monitoring data from multiple technologies (i.e. there is no silver bullet) to make informed decisions about asset health. There are five key PdM layers of protection discussed: Common Senses, Infrared Thermography, Ultrasound, Oil Analysis and Motor Circuit Analysis. These tools are only a few of the many required troubleshooting and testing instruments used to monitor and diagnose. The following sections provide a brief introduction to each non-destructive technology; the conditions monitored and then, are applied during a systematic walk-down of a typical facility.

<u>Making Sense of the Situation</u>

The first and probably the most important, immediate, and accurate tools in a facility’s PdM tool box are each person’s god-given common senses (o.k., I know common sense isn’t that common, but work with me). From a reliability perspective, these include seeing, hearing, smelling, touching, and common sense, but probably not tasting, unless you like the taste of dirt and oil. Merge the senses with a little awareness training and they can identify general early warning indicators in up to 70% of all safety and reliability problems. When it comes to identifying potential OSHA and NEC violations and fines, these low cost senses are unmatched by any hardware and software system. Most of the fines carry a minimum possible fine of $2,000 each.

The findings are very apparent and are a great indicator about a site's safety and reliability culture. For example, the PSC research identifies that compliance to thermal electrical issues carries a 2.6:1 ratio. A higher percentage of code compliance gaps correlate to an increase in electrical system faults and findings. The inverse is also true.

The following lists basic physical conditions easily identified with other senses:

- Discoloration of bus connections, terminations and live parts in the air switches
- Poor wiring conditions such as burnt and cracked wires, mismatched components, missing covers, "rats nest" of loose wires
- Broken skirts on insulators and pot heads
- Excessive vibration denoted by noise and usually will cause loose connects to appear on live parts, laminations and improperly supported buses inside transformer housings. For example, vibration guys love to put their hand on every motor they walk by. Additionally, "ouch" is good thermal indicator
- Gray powder on outside of cable indicating corona or arcing
- Sounds of arcing are indications of corona, which leads to ozone
- Ozone smells which puts a sharp taste in the back of your throat (There, taste now in the senses tool box). Note: OSHA has limits on ozone - somewhere around 20 parts per billion (ppb) which is far below level where can easily be smelled.
- Poor Housekeeping – Excessive dirt, grease dust, fibers on components. The surrounding area should be evaluated for accumulation of trash or combustible storage, clearance violations, component integrity, poorly sealed panels allowing dust ingress, etc.

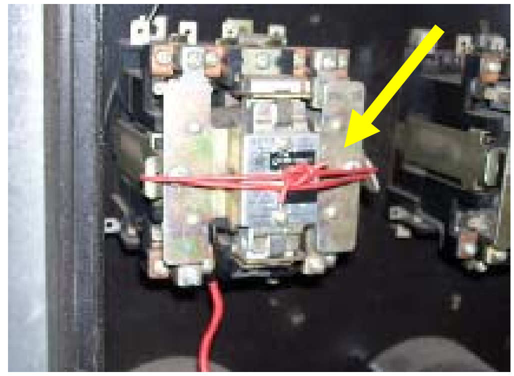

Figure 5. Component held in place with wire knot. (NEC 110-12) Not Installed in Workman-like Manner

Figure 6. Exposed Wires OSHA 1926.403(e)

- Poor Operating Environment - Hot room temperatures, corrosive atmospheres, cable penetrations through walls should be sealed with fire retardant material to prevent fire from spreading and water is not allowed to penetrate / enter the room.
- Lack of Documentation – Missing spec sheets, OEM manuals, service logs and outdate drawings (if you can find them).

<u>Infrared Thermography</u>

A rule of thumb is that 70% (72% PSC Statistics) of thermal anomalies are due to loose connections. Infrared thermography is the premier tool for capturing overheating due to high resistance, overloading, phase imbalance and loose connections that are likely to fail and are wasting energy. Infrared is fast, accurate and can detect problems quickly, without interrupting service. This significantly reduces unscheduled power outages. Completing surveys helps facilities comply with insurance company recommendations and is a recommended best practice by NFPA.

Another Rule of Thumb: "Heat is a Real Equipment Killer" - All electrical equipment, conductors and insulation have maximum allowable rises in temperature above ambient which is typically 72°F (40°C). Every 18°F (10°C) rise above the nameplate operating temperature will reduce the component's operating and insulation life by 50%!

Ultrasound

Ultrasound detection systems, which compliment infrared, are extremely valuable for inspections of medium and high voltage electrical systems. Loose connections and the deterioration of high voltage insulation, cables, broken sheds or contaminated porcelain produce an electrical leakage known as corona, tracking or partial discharge. The system receives ultrasound waves, which cannot be detected by the human ear, and modulates them so they can be heard by the lucky guy with the head sets. Additionally, when operational or safety factors prevent the use of infrared on enclosed, energize electrical equipment, ultrasound is deployed to scan around door seals and air vents helping to detect the presence of arc flash hazard potentials (electrical leakage).

Transformer Oil Analysis

Oil is used to cool and insulate the internal components of transformers and certain types of switches. Because it bathes every internal component, the oil contains a great deal of diagnostic information. Just as a blood test provides a doctor with a wealth of information about the health of a patient, a sample of transformer oil can tell a great deal about the condition of a transformer. This includes advanced warning of developing conditions such as tap changer arcing, overloading, partial discharge (corona), liquid overheating and break down of insulation.

Key Gases	Most Likely Cause
Hydrogen (H2)	Partial Discharge (Corona)
Methane (CH4)	Overheating
Acetylene (C2H2)	Arching
Ethylene (C2H4	Localized Overheating
Ethane (C2H5)	General Overheating
Carbon Monoxide (CO)	Cellulose Overheating
Carbon Dioxide CO2	Oil and/or Cellulose Overheating

Figure 7. Dissolved Gases and Probable Causes

The analysis is broken into two parts. 1) The oil is reviewed for contaminants and degradation of its dielectric (insulation) strength and 2) dissolved gas analysis (DGA) looks for certain gas quantities, combinations and the likely cause (Figure 7).

Motor Circuit Analysis

Motor circuit and motor current analysis (universal "MCA") evaluates the integrity of the cabling and insulation starting at the motor control center (MCC) components on down to the motor's rotor and stator windings and grounding. Defects and faults include developing shorts, resistive unbalances and insulation to ground faults, cable defects and rotor defects. MCA can be applied to any size or voltage motor covering over 50% of all potential electrical and mechanical motor faults

Facility Survey Highlights

This approach targets "local" power distribution equipment everything "inside the fence" of a typical end-user's property or downstream of the utility's meter. Additionally, local distribution systems are the responsibility of shop electricians and maintenance workers and fall under NEC rules. "Typical" applies to commercial, institutional, government, industrial, foods, education or anyone that uses electricity. The PdM tools and systems being targeted include:

PdM Tool Box	Primary Equipment Targets				
	HV / MV Service	Cables / Busbars	XFMR	CB / Fuses	MCC / Motors
Senses	X	X	X	X	X
Infrared Thermography	X	X	X	X	X
Ultrasound	X	X*	X	X*	X*
Motor Circuit / Current Testing					X
Transformer Oil Analysis			X	X**	

* Ultrasound can be applied to all assuming 1kV or more

** Oil analysis is applicable to certain MV / HV CB

Figure 8. PdM and Electrical Equipment Matrix

<u>Main Medium-Voltage Incoming Service</u>

A facility's main serve is comprised of equipment that transfers high- or medium voltages to lower voltages used within the facility. This equipment includes bushings, insulators, steel support structures, high voltage lines, step-down transformers, and switch gear (interrupting, control, metering protective and regulating devices and assemblies). Once inside this includes panelboards and switchboards. This equipment is designed to be outdoors either directly or in weatherproof housings. **The Integrated PdM Tool Box** should include Common Sense Surveys, Infrared and Ultrasound.

Typical issues include dirt, dust, debris, salt residue (gulf cost region) coating connects and lines increasing the chances of corona, tracking, and arcing. Partial discharge accounts for the largest percentage of disruptive failures of medium voltage switchgear. Look for broken bushings, insulators, arrestors, vandalism and weather damage.

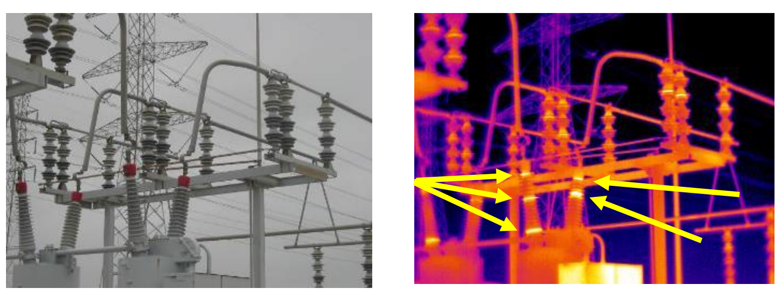

Figure 9. IR Image of Tracking on HV Insulators

Lights Out during Peak "Sold Out" Production - In this example, mist from cooling towers caused the pole insulators to become dirty, in turn causing arcing and tracking across the insulators. The pole caught fire which weakened the transmission line supports. The top "T" section tipped 90 degrees causing phase-to-phase shorting. The plant was in a "sold-out" condition and was down for 8 hours and didn't get full production for over 24 hours. Harsh Midwestern weather prevented IR and airborne ultrasound for 6 months. New procedure is for quarterly IR and ultrasound with semi-annual PMs to have qualified contractors clean the insulators live.

Figure 10. Tracking and Arching cause Pole Fire

What's Behind HV Door Number One? - IR cameras require line of site and, unlike Superman, can not see through cabinets to scan the targeted components. Thermographers are put at risk by opening cabinets and doors to gain access which conflicts with NFPA 70E requirements. This can be overcome with the strategic installation of viewing panes that allow scanning of internal components without opening the panels. Current trends limit installations to more critical HV systems, switch gear and transformers since they require significant planning and downtime to be opened up for installation. Don't forget about ultrasound as a short-term backup.

Transformers

Facilities use dry-type or oil-filled transformers step-up or step down voltages to meet the specific needs of a site. Step-down transformers are comprised of insulated primary windings (higher voltage) and secondary windings (lower voltage) which are in close proximity, iron core laminations, tap changers, bushings, and connections but typically no mechanical moving parts. The physical design of transformers presents the potential for primary-to-secondary shorts from insulation failure. **The Integrated PdM Toolbox** should include Common Sense Surveys, Oil Analysis, Thermography, and Ultrasound.

Transformers run hot and require proper air and/or fluid circulation to ensure they don't overheat. Transformers have an estimated 20-30-40 life expectancy under normal operating conditions but as they age this ability diminish. The National Electric Code (NEC) Section 450 is one of many resources which establishes requirements aimed at keeping transformers cool and away from people. Additional stresses such as being exposed to mechanical vibration, switch surges, line surges and limited short circuits also reduce life expectancy.

Transformer Loss Data - Transformers are one of the more expensive pieces of equipment used in a power system, and the potential consequences of failure can be quite damaging. Loss of a critical transfer can cost facility weeks of down time before getting back on line. For example a study of 6,453 industrial transformers (2.5-35 kV, liquid filled) failed at a rate of 1/ 200 per year and the average repair time was 308.9 hours.[8] Recent trends in steal and iron prices and international demand have driven up the price of replacements, repairs and wait times. Additionally, these economic drivers are delaying new installations and requiring sites to get more out of their aged, overloaded and possibly problematic transformers[9]. Basically, you are stuck if an incident occurs since you just can't go to Home Depot pick up a replacement.

Oil-filled Transformers - Oil-filled transformers have radiators, cooling fins filled with mineral oils or insulating fluids. The windings are wrapped in a pressboard paper and have spacers to provide physical dielectric clearance distances to withstand movement. The insulating fluids are circulated and cooled by fans and/or ambient air which ensures dielectric strength and preserve transformer paper and windings. The preservation of windings, load tap changers, and accessories is crucial to transformer performance but still end up 50% of all failures and insurance losses based upon a review of 4 major transformer studies[10].

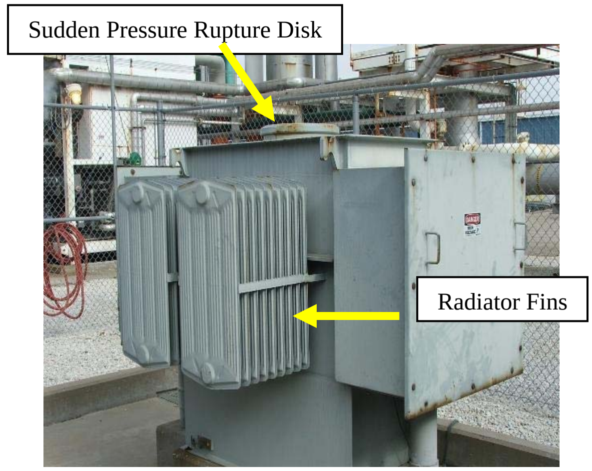

Figure 11. Oil-filled Transformer

Concerns - When the oil is exposed to a combination of heat, oxygen and core and coil components a chemical reaction occurs. The oxidation forms acids and polar compounds which breakdown mineral oils and the paper insulation to form sludge. The sludge will then coat heat transfer surfaces on the core/coil and tank/radiators, reducing the heat transfer capacity of the system. The operating temperatures are increased, accelerating the degradation of the oil. The sludge traps heat, accelerating paper destruction. Given enough time, the paper spacing narrows and eliminates the winding-to-winding barriers and eventually flashes over. IEEE defines a transformer's end of life when paper has lost 75% of tensile strength. Beyond this point the transformer may not reliably withstand the next surge load or short circuit. Moisture is another major concern as it reduces the insulating effectiveness of oil. The craft paper will absorb moisture negatively creating power factor issues.

Figure 12. Unwanted Rodent

Oil-filled transformer issues - Make a through inspection of the transformer and the surrounding area, looking for indicators such as animal carcasses, bulged tank or cover, discolored tank, fallen tree limbs, vandalism, discolored tank, oil leaks, burnt oil aroma, flashed or broken bushings and any short circuits in the secondary or service-side. Check and record oil level and temperature gauges, and OEM nameplate for recommended operating temperature ranges. Once recorded, reset high temperature limit. Additional information to consider includes extreme weather conditions (storms, lightning, snow, ice, outdoor temp and air humidity), contamination, vegetation, animals, humans, excessive loads, lack of maintenance, ageing, wear out and design.

Figure 12. Combustible Dirt and Debris

Mineral oils are the most common insulating fluids and present the greatest fire hazard due to its flammability. Incipient faults, internal arcing and overheating produce explosive gases (Figure 7.) such as acetylene or ethylene, increasing the probability of tank rupture which could lead to an ignition of transformer insulating fluid.

Dry Transformer Hazard Indicators - Dry-types use ambient air and convection currents (sometimes fans) to keep laminated windings cool. Check to make sure maximum ventilation air flow by ensuring air intake grates / screening are free of obstructions and not blocked by walls. Observations of dust, dirt and debris on windings, which prevent cooling could combust causing a fire. Corrosive atmospheres can break down the insulation producing arcing and potential fires.

Figure 13. Dry Transformer Blocked with Dryer Lint

Infrared Thermography - Similar to the switchgear, use the thermography to examine high- and low-voltage external bushing connections, as well as external surfaces such as cooling tubes, fans, and pumps. IR testing is great for identifying low and high temperature areas caused by fault, bad oil or foreign materials blocking cooling passages in an oil-filled transformer. If left unchecked, heat can rise to a point that connections melt and break the circuit; as a result, explosions and fires may occur.

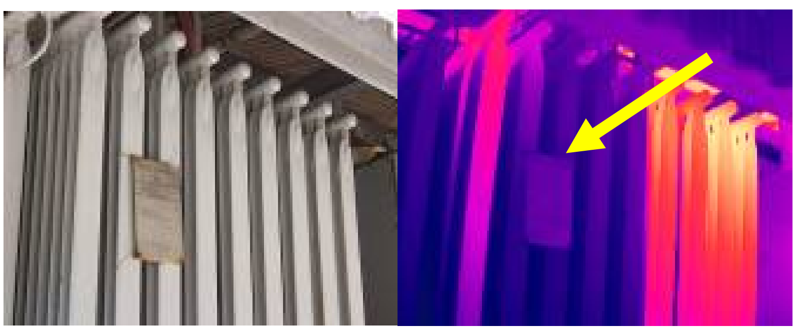

Figure 15. Infrared Image of Blocked Cooling Passages

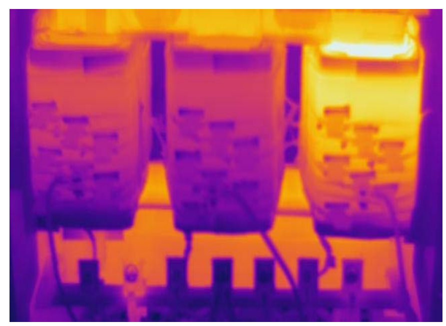

Figure 16. Overheating of C Phase Coil (Dry-type)

<u>Conductors (Cables and Bus bars)</u>

Cables and bus bars are the crucial superhighways of power distribution in facilities as they quickly and efficiently carry power throughout a facility to do useful work. Power can only be distributed safely through conductors with tight and clean connections and proper insulation or metal clad covers. The main conductor hazards are poor connections and insulation breakdown. **The Integrated PdM Toolbox** should include The Common Sense Survey, Infrared and Ultrasound.

Connections, terminations and splices usually are the weakest points in cable and bus bar systems. Loose or corroded connections and will generate high resistance and heat which are great candidates for infrared.

Insulation is King - The insulation is rated to have a specific dielectric strength or (insulating value which is the ability to keep the flow of current from the conductor outward, thus insulating current from us and us from it. Premature insulation failures are due to absorption of moisture, dirt, dust, grease, excessive heat, sunlight, vibration/abrasion, loose connections, oily deposits, loss of polyvinyl chloride (PVC) oil and compounds, power surges, overvoltage and aging. These contributing factors cause insulation to become brittle and crack which allows current to have a low resistance path or short to ground. Insulation failure in all types of cables is usually following by arcing and overheated because of excessive electric current. Moisture and dirt allow tracking and even flash over.

The arcing can ignite the combustible insulation under the sheath. The PVC insulation provides fuel for the fire and continues to burn even though the initial arc may be stopped by the operation of the over current device. Research has shown that even heat generated by faults in low voltage signal wiring may generate damaging off-gases and burn adjacent combustible materials[11] and horizontal cable trays[12].

Figure 18. MCC Feeder Rubbed and Shorted

Additionally, one of the off gases is hydrogen chloride which when mixed with water forms hydrochloric acid. This highly corrosive acid damages sensitive relays, instruments, control apparatus, copper bus bars and the base metals such as iron, brass, aluminum or zing and alloys. It can cause significant fire and non-thermal damage.

Manufacturing deformities during insulation manufacturing process creates high electric filed stresses and causes insulation failure . . . ionizes air particles around the conductor . . . produces corona . . . heats up insulation . . . produces ozone . . . deterioration and flashover . . .you get the picture.

Figure 17. Burnt Wire
Min. Possible Fine: $2,000

Figure 19. 1 wire per terminal (NEC 110-14a)

Circuit Breakers / Fuses / Disconnects

A circuit breaker (CB) is a protective device that carries load and if it senses a higher circuit load than the established setting, it rapidly opens the circuit interrupting the flow of electricity to / or within electrical equipment (i.e. transformers, motors, switchgear, etc.). It can be reset. CBs come in many types, sizes and voltage ratings.

Ranking	Voltage	Types / Components	Sensing of Abnormal Situation	Typical Clearing Cycles
Low	< 1kV	Molded Case Circuit Breakers (MCCB)	Self Sensing	3-8
Medium	1kV – 69kV	Air magnetic, air blast, oil sulfur (S6) hexafluoride and vacuum	Uses protective relays, current transformers, the control power (battery) and the interconnecting wires	Relays can add 3-4 cycles
High	69kV			

Figure 21. Circuit Breaker Ratings

Concerns - Typical CBs are installed, sit in place supplying power and forgotten for years. This is contrary to the regular maintenance requirements OEM, NFPA 70, IEEE and National Electric Manufacturers Association (NEMA). Several studies by IEEE show that low voltage CB failed within 5 years if not maintained will have a 50% failure rate. Most power system failures caused by short circuit.

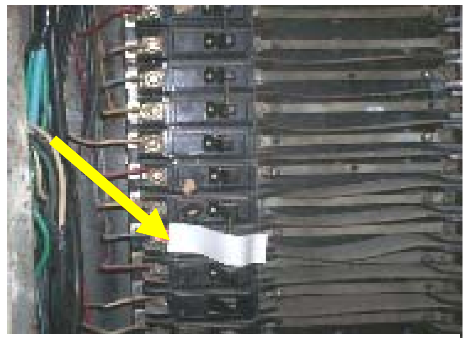

Figure 22. Taped Over Breaker (NEC 240-80)

When the warnings signs of an aging or faulty power distribution system occur such as breaker nuisance tripping or main breaker failure, it's a message that repairs, replacements or upgrades are needed. The problem is that after high level fault, "it is not always clear to investigating electricians what damage has occurred inside encased equipment."[13] As mentioned earlier, they can be reset which is what typically occurs. Again, there are many authorities having jurisdiction (AHJ) like OSHA who no longer allows resetting CB 3-4 times since numerous burns resulted from explosions (OSHA 29 CFR 1910.33 4 (b) (2).

One of most common hazards is the failure of a circuit breaker or fuse to operate and open the circuit during overload, electrical fault or other abnormal operating condition. If it can not interrupt the fault it may fail, destroying the enclosure and creating a hazard for anyone working near equipment. In some instances, arcing can occur and ignite combustible materials due to the delay. The combustible insulation tied to CBs and oil inside certain HV CBs become a fuel sources for a fire which can spread to adjacent circuit breakers, fuses or other combustibles.

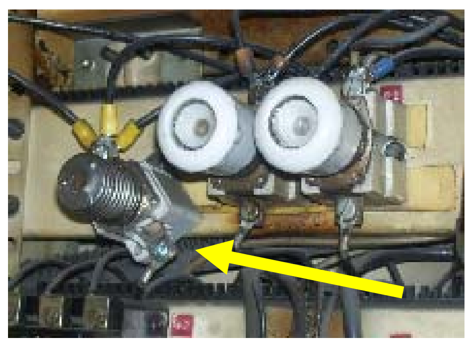

Figure 23. Broken Fuse (NEC / OSHA)

Failure to operate and clear the fault is often a combination of following:

- Loose connections which cause increased resistance and generation of heat
- Corroded Connections
- Contaminations by liquids such as rain water
- Overheating caused through excessive loading (operating above rated capacity)
- Mechanical malfunction of circuit breaker or relay caused by poor maintenance
- Inadequate sizing of circuit breaker for fault condition

Fuses & Disconnects - Fuses and fused disconnects are common electrical protection devices and provide overload and/or short circuit protection. Fused disconnects provide short circuit protection. The fuses are secondary protection in the event circuit breaker contacts don't trip. If a fuse shows up hot on a thermal scan, it might be at or near its current capacity. However, not every problem shows up as hot. A blown fuse, for example, exhibits a cooler than normal temperature.

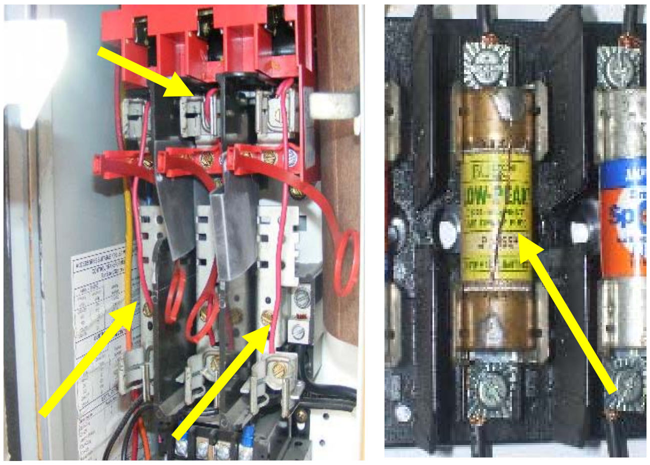

Figure 24. Wires for Fuses / Jumpered Fuse
Lack of Component Integrity (NEC 110-12c)

Motor Control Centers and Motors

Motor control centers (MCC) house the control and protective devices for motors that drive equipment. The electrical condition of plant equipment is as important as their mechanical condition. **The Integrated PdM Tool box** should include Common Sense Surveys, Infrared and Motor Circuit Analysis. Using these PdM tools collect and analyze separate parameters to determine motor condition as well as working "downstream" of the associated MCC devices and conductors.

Motor Control Centers (MCC) - To evaluate a motor control center under load, open each compartment and compare the relative temperatures of key components: bus bars, controllers, starters, contactors, relays, fuses, breakers, disconnects, feeders and transformers. It is important to measure the amperage load of each phase at the time of each scan, so that you can trend and evaluate your measurements against normal operating conditions. At this point, use all of the Key Hazards and PdM tools to identify issues.

Motors - Motors are electrical rotating equipment that convert electrical energy into mechanical energy. Magnetism is the basis of their principles of operation. General purpose motors range from fraction horse power (HP) of ¼ hp to 2,000 – 3,000 hp and generally rotate as slow as 100 revolutions per minute (RPM) up to tens of thousands RPMs. Motors and associated windings and insulation are typically classified based on enclosure type, speed, efficiency and service factor. Motors are typically AC or DC. This discussion uses AC induction motors (squirrel cage and synchronous) as reference.

Motor Concerns - Analyzing insurance related motor failure and loss data from 1989 to 2005 indicated that 65% of the failures and 71% of the losses were related windings and electrical connections.[14]

Damaged part	% Losses	% Loss $
conductor	1%	1%
stator Winding	55%	46%
Rotor Windings	5%	23%
Contacts Electrical	4%	1%
	65%	71%

Figure 25. Motor Failure and Loss Data

Infrared thermography of MCC and motors is a great tool since it can be applied to all types of motors to detect problems such as poor connections in the motor terminal box and overheating windings, bearings, and motor couplings.

- Poor electrical connections in the motor terminal box, overheated bearings and often signals active breakdown and potential failure. Thermography accurately pinpoints which areas of the motor overheating and how much.
- Regular reference temperatures or comparison of the operating temperatures of like equipment performing similar functions, to OEM requirements and previous readings on that unit
- Overheating is caused by inadequate air flow caused by clogged air intake grills (Figure 27). Fault current motors may experience single-phase ground faults which increase temperatures and go undetected (Figure 26). The intake screen was plugged because oil from the bearing got on it and collected dirt. Over time it clogged and overheated the motor and windings.
- Unbalanced voltages or overloading are usually caused by high resistance connection in the switchgear, MCC or disconnect.
- IR, troubleshooting tools and/or motor circuit tester which can perform power diagnostics and quality analysis and pinpoint the issues.

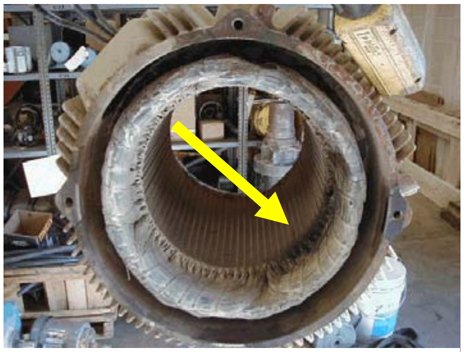

Figure 26. IR Identified Hot Damaged Motor Shorted to Ground

- IR is also great for identifying mechanical issues such as bearing failures and alignment issues.

Electric Motor Testing provides both offline (Motor Circuit Evaluation) and online (Motor Current Analysis) testing of the motor and circuits to determine the health and identify any potential operational concerns. Typical tests performed include resistance and capacitance to ground, phase resistance and inductance to ground, current and power quality analysis, voltage unbalance and total harmonic distortion.

The Big Close

Since you came this far, you might as well listen to how we can pull all this together with a nice bow on it.

The advancements in electric power systems, power transmission and distribution grids are critical for a nation's growth and development. However, they are comprised of a large number of highly distributed and capital-intensive physical assets that can fail in catastrophic ways.

As an industry, we face many challenges navigating through aging and changing electrical distribution systems with the variability of the "human element." Even without catastrophic losses, the "ripple effects" from the untold near misses can erode the best safety, reliability and sustainability initiatives. Many safety, maintenance and reliability professionals have added the powerful condition monitoring strategies and integrated PdM toolbox as a way to add another barrier or layer of protection.

The challenge for many is that apply integrated PdM programs generate an enormous amount of data. Much of this is delivered in word processing documents, PDFs and spreadsheets, proprietary software and hard copies which slow a Leader's ability extract information for making empowered and proactive decisions. The question becomes, how do you manage the mountains of data that get generated with this type of initiative to get your message out?

My focus was/is to spark greater interest and support by using risk-based approach:

1. Showing Potential Impact of Losses
2. Understand the Hazard (put areas impacted on the map)
3. Appreciate the magnitude of the risk by publishing failure scenario data (creates a need for risk models)
4. Comprehend the numbers involved (how much value is at risk)

There are many examples of how data and statistics strewn throughout this message to compare, contrast and support various topics. Additionally, I used the Predictive Service (PSC) database and some simple MS Excel "elbow grease" to analyze the data. You can too. Additional summary tables precede the References section.

Total Years of Data in Sample	4 Years (2004 –2008)

Equipment Inspected	637,976	
Thermal Anomalies	42,869	6.7% *
Compliance Gaps	16,607	2.6% *

Anomaly Category	**%**
Poor Connection	72%
Internal Flaw	18%
Overload	6%
Misc: Items	4%
	100%

* % of equipment Inspected

Figure 27. Summaries of PSC Database

If that doesn't seem too easy, you do have a few options.

1. Do it For Me (DIFM) - Hire outside experts and resources who can jumpstart or round out your initiatives. This works for a majority but can not be relied upon solely.
2. Help Me Do It (HMDI) – Build a hybrid program of in-house and third-party expertise and resources
3. Buy software and do it all in-house – Depending upon your level of sophistication and layers of protection, managing a program yourself with some third-party or old fashioned spreadsheets may be an option. Keep in mind that trying to find some super, all encompassing enterprise safety, asset management, maintenance and reliability platform may be difficult. I am not sure it exists but if you do find something, don't get caught up in all of the bells and whistles or do nothing because you are forever waiting for the software to kick-out perfect information and results

Regardless of your strategy, you have to be engaged.

For those of you just starting out to get your hands around this situation, I recommend applying the KISS (Keep It Super-Simple) principal of data management. If you have good data in a safety, computer maintenance management systems (CMMS) or an enterprise asset management (EAM) system, use them. On the other hand, don't blinded by their bells and whistles and effort required to input and extract information. Even if you have robust software platforms and "mountains" of data, these systems create a belief that "we must wait for the software to kick out perfect information before making a decision."

Today's recessionary pressures prevent many maintenance leaders from affording this software luxury and or the possible stagnation of efforts. Instead they should rely on "keeping it super simple", small, accurate and manageable. Remember if this is a pilot project and in the early stages the approach requires building a case for targeted equipment, personnel and PdM opportunities with the best and highest probability success. Maintaining the data in a centralized and organized system is crucial for transforming it into usable information which drives the programs and your success.

With a little hard work, there is unlimited potential, stakeholder buy-in, cultural support and true safety achievements for reliability-based safety programs that can be unleashed once this condition monitoring data is centralized and users have access to a dashboard of analysis tools highlighting safety, reliability and ROI information.

Additional PSC Inspection Database Summaries follow and should be a reference points as you move through you PdM Integration for Electrical Distribution Safety and Reliability.

Good Luck, and don't hesitate to call if you have questions or comments.

Rank	Equipment	% of Total
1	Bucket	22%
2	Panelboard	22%
3	Disconnect Fused	13%
4	Control Cabinet	10%
5	Transformer Dry Type	4%
6	Starter	4%
7	Switchboard (1 Sec. Only)	4%
8	Distribution Panel	4%
9	Breaker	3%
10	Disconnect Nonfused	3%

Figure 28. Top All Equipment Inspected

Rank	Equipment	% of Total
1	Panelboard	29%
2	Bucket	24%
3	Disconnect Fused	14%
4	Control Cabinet	12%
5	Distribution Panel	4%
6	Switchboard (1 Sec. Only)	4%
7	Starter	2%
8	Disconnect Nonfused	2%
9	Switchboard (Multi Sections)	2%
10	Breaker	1%

Figure 29. Top 10 Thermal Issues by Equipment Type

Rank	Equipment	% of Total
1	Panelboard	64%
2	Disconnect Fused	10%
3	Bucket	4%
4	Distribution Panel	4%
5	Control Cabinet	3%
6	Transformer Dry Type	3%
7	Switchboard (1 Sec. Only)	2%
8	Starter	2%
9	Contactor	2%
10	Disconnect Nonfused	1%

Figure 30. Top 10 Compliance Issues by Equipment Type

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