systems with intelligence

The Evolution of Substation Maintenance:
From Manual Inspections to Autonomous Monitoring

Discover the practical realities and the roadmap toward fully automated substations that will define the industry's future.

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Executive Summary

The utility industry stands at a transformational inflection point where traditional calendar-based maintenance approaches are giving way to AI-powered autonomous monitoring systems. This shift, driven by aging infrastructure, workforce constraints, and technological advancement, promises significant improvements in safety, reliability, and operational efficiency while reducing maintenance costs by up to 50%.

The U.S. Department of Energy's Grid Modernization Initiative validates this potential, targeting a 50% reduction in outages over the next decade through digital substations, with a goal of achieving $13 billion in energy savings annually by 2030 through streamlined operations and reduced maintenance costs. [1]

Operations & Maintenance professionals are leading this evolution by implementing continuous monitoring solutions that replace routine manual inspections with intelligent, sensor-driven strategies. The transition represents more than technological change, it's a reimagining of how utilities ensure grid reliability, moving from reactive maintenance to predictive analytics that identify failures weeks in advance.

A major U.S. utility serving over 7 million customers demonstrated this transformation by reducing transformer failures by 48% and achieving over $40 million in annual economic value after implementing predictive maintenance across 10,000 transformers and 22,000 circuit breakers. [2]

This white paper explores the practical realities of this transformation, examining real-world implementations, quantifiable benefits, and the roadmap toward fully automated substations that will define the industry's future.

From Calendar-Based to Condition-Based Maintenance

Utilities worldwide are rapidly abandoning time-based inspection schedules in favor of condition-based maintenance strategies powered by continuous monitoring technologies. This fundamental shift occurs once Touchless™ monitoring systems prove their reliability, typically within weeks of deployment. The transformation delivers immediate economic benefits through reduced truck rolls and enables Operations & Maintenance teams to move from scheduled to event-driven maintenance. Rather than dispatching crews regardless of actual equipment condition, utilities now respond to real-time data that indicates genuine maintenance needs.

Edgar Sotter, Senior Director of Business Development and Innovation at Systems With Intelligence, observes this change firsthand: "We have a customer in Arkansas, a cooperative with small numbers of people working for them. For small utilities, it's very critical to save money and maintain costs at a certain level. They were able to do a whole storm recovery assessment without having to send people even during the storm."

The validation process follows a predictable pattern across utility implementations. Initial skepticism from thermographers and field personnel gives way to confidence as the technology proves its accuracy. The typical validation cycle spans just two to three weeks, during which experienced technicians compare remote sensor readings with traditional handheld thermal cameras. Once this validation completes, utilities quickly recognize that continuous monitoring provides capabilities impossible with periodic inspections.

The economic impact extends beyond simple cost avoidance. Utilities report that continuous monitoring enables purposeful visits rather than routine patrols. When an Arkansas utility received neighbor reports about sparks at a substation, the dispatcher immediately accessed remote cameras, identified the precise issue, and dispatched crews with specific instructions and photographic evidence. This targeted approach eliminates unnecessary site visits while ensuring crews arrive prepared for the actual conditions they'll encounter.

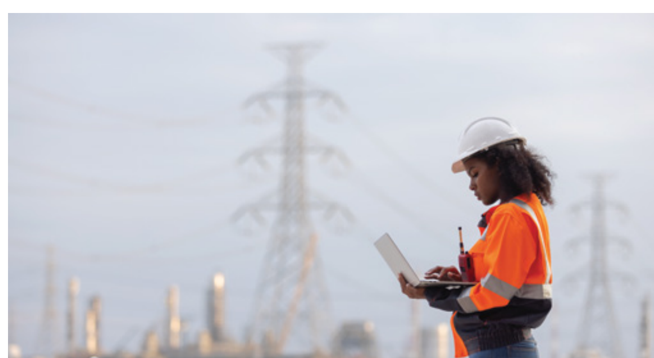
"The shift of mentality of automating the system is a whole evolution in the industry," Sotter explains. "They can quickly see that there was some sort of periodicity on the issue, they could track exactly where it is. Those things, you cannot do with a remote thermal scan unless you put a tent beside the radiator and start monitoring."

Key metrics driving adoption include cost reduction, windshield time minimization, and risk mitigation. O&M costs directly impact utility bottom lines, with some cooperatives achieving up to 50% reduction in travel costs with documented cases showing transformational results. One major utility's shift from time-based to predictive maintenance achieved an estimated $800,000 in annual savings in operations and maintenance costs, while monitoring 10 years of historical data from 12 disparate sources [3]. Windshield time encompasses both transit time and on-site exposure hours, representing a comprehensive safety and efficiency metric. Risk mitigation extends beyond costs, as every truck roll and site entry presents potential safety hazards.

Alarm Quality and Operator Workload

The challenge of maintaining high-quality alerts while preventing operator overload represents a critical success factor for continuous monitoring systems. Modern Operations & Maintenance teams face the dual requirement of catching every genuine issue while avoiding alarm fatigue that could compromise response effectiveness. Advanced monitoring platforms address this challenge through multi-layered approaches that combine administrative rule-based filtering with machine learning algorithms that adapt to site-specific conditions and operational patterns.

"We are working on machine learning techniques to filter noise," Sotter notes. "The first type of filters were more administrative—you just put rules like 'this is noise, this is not.' Now we're putting another layer of machine learning, which is more data-driven and model-driven type of filtering."



Modern alarm management incorporates several key strategies. Temporal persistence requirements ensure alerts must sustain for 30 to 60 minutes before triggering notifications.

Advanced implementations now incorporate AI orchestrator systems using prompt-based workflow policies for automated alarm processing, with digital twin architectures providing predictive insights for asset maintenance and remaining useful life calculations that integrate directly with SCADA platforms. [4]

Machine learning pattern recognition allows AI algorithms to learn normal operational patterns and flag only genuine anomalies. SCADA integration with priority polling enables critical alerts to receive higher priority routing and faster response protocols. Context-aware filtering considers environmental conditions, operational status, and historical patterns when evaluating potential alarms.

Future developments in alarm quality management focus on predictive capabilities that identify potential issues before they manifest as operational problems. Machine learning algorithms analyze thermal image backgrounds to highlight persistent hot spots that weren't present in previous time periods, alerting customers to investigate areas outside their normal monitoring zones.

"We are leveraging machine learning techniques to improve alarm quality by being able to see the whole background of a thermal image and highlight potential issues—identify things that were not there the day before and tell the customer 'I can see a persistent hot spot there that wasn't there last week. Can you check that?'"

Edge Intelligence vs. Backhaul Limits

The architectural tension between edge processing capabilities and cloud analytics potential represents a fundamental design challenge for continuous monitoring systems deployed in utility environments. Substation-hardened equipment must operate reliably in extreme conditions without cooling systems, limiting onboard processing power while bandwidth constraints in rural locations restrict cloud connectivity options. This technical reality requires careful balance between local intelligence and centralized analytics to deliver effective monitoring solutions.

Edge devices face deliberate hardware constraints designed to ensure reliability in harsh utility environments. Without fans or active cooling systems, processing capabilities remain intentionally limited compared to consumer electronics.

As Sotter explains: *"My PlayStation probably has a bigger processor than what the DVS has. My phone probably has a bigger processor than what the DVS has. This is done on purpose—it's not that we don't want to put a big processor. It's just that if we put a bigger processor, we will need a cooling mechanism, and that will impact the reliability of the system."*

The cloud computing advantage lies in scalability, advanced processing capabilities, and surprisingly, enhanced security. Major cloud providers offer security infrastructure that exceeds most utility IT departments' capabilities. However, utility reluctance to place operational data outside their networks continues to influence deployment architectures. This cultural resistance shapes technical decisions even when cloud solutions provide superior technical and security benefits.

"The cloud is way more secure than what you can have on premises. Google, Amazon, Microsoft—they have really strict security levels, way more than any IT department in any utility can provide. But there is still the challenge of utilities not trusting when their data is outside," Sotter observes.

Renewable-Driven Load Cycling

High renewable energy penetration fundamentally alters substation operating conditions, creating unprecedented thermal cycling patterns and bidirectional power flows that stress conventional equipment.

NERC's 2024 Long-Term Reliability Assessment documents how these bidirectional power flows affect Essential Reliability Services that substations must provide, particularly as renewable generation creates operational patterns that traditional equipment wasn't designed to handle, with assessments covering 10-year periods to evaluate equipment reliability under these new conditions [5].

Continuous monitoring reveals these previously invisible operational stresses, enabling Operations & Maintenance teams to develop new strategies for asset protection and optimization. The integration of wind and solar generation introduces rapid load swings and reverse power flows that traditional maintenance schedules cannot adequately address, making real-time monitoring essential for reliable operations.

"Basically anything that deals with load creates heat, no matter what it creates heat. So we are leveraging our thermal imaging portfolio to address renewable applications as well," Sotter explains. "Either if it's just to monitor the performance of transformers and breakers on the flow of electricity, or the cycles for batteries and how they charge and discharge."

The regulatory compliance aspect proves particularly valuable for renewable operators. Ontario's Independent System Operator requires proof that solar panels remain snow-free during winter months to maintain generation capacity commitments. Automated camera systems capture and transmit this evidence without requiring site visits, reducing operational costs while ensuring regulatory compliance.

Extreme-Weather Resilience and Safety Gains

Climate extremes increasingly test both utility equipment and monitoring systems, making operational resilience a critical requirement for continuous monitoring solutions.

Comprehensive power system resilience studies reveal that 75% of interruptions stem directly from weather events, with elevated temperatures drastically reducing equipment lifespan and escalating the probability of line-to-line faults, requiring monitoring systems to operate reliably beyond standard operational temperatures of -30°C to 40°C [6].

Modern monitoring platforms must maintain reliable operation across temperature ranges from minus 40 degrees Celsius in northern Canada to extreme heat in Middle Eastern deployments, while providing clear visibility during smoke, storms, and other adverse conditions that make traditional inspections impossible or dangerous. This operational resilience enables utilities to maintain situational awareness precisely when conditions are most challenging and traditional inspection methods fail.

Ruggedized monitoring systems undergo deliberate design choices that prioritize reliability over raw performance specifications.

The fundamental philosophy centers on long-term operational capability in harsh environments rather than maximum technical performance. Field deployments spanning 10 to 15 years in extreme conditions validate this approach, with systems continuing to operate reliably across diverse climate zones.

"We are built for that," Sotter emphasizes regarding extreme weather operation. "We have systems deployed in really bad conditions, and they've been working for already 10, 12, 15 years. Those are cameras that are out there, minus 40 in Ontario, in Alberta. We have cameras deployed in the Middle East as well."[2]

The concept of "windshield time" encompasses both transit risks and on-site exposure, representing a comprehensive safety metric that utilities use to evaluate monitoring system benefits. Every truck roll involves multiple risk factors: vehicle accidents during transit, slip and fall hazards at facilities, electrical contact risks, and confined space dangers in vaults or manholes. Remote monitoring eliminates many routine exposures while providing enhanced intelligence for necessary site visits.

"Windshield time is the time that the crew is driving, and the time that the crew is also on the site. That has an impact on cost, yes, but also has a risk. Anytime you put a crew on a truck, things could happen. Anytime you send a crew to the substation, things could happen," Sotter explains regarding comprehensive safety considerations.

Workforce Evolution and Cybersecurity Integration

The utility workforce faces unprecedented transformation as traditional manual inspection skills evolve to encompass data interpretation, edge device maintenance, and AI system stewardship. This evolution occurs against a backdrop of significant generational transition, with experienced workers nearing retirement while new technicians enter an industry increasingly dependent on digital technologies. Operations & Maintenance teams must navigate this transition while maintaining operational excellence and building capabilities that bridge traditional electrical expertise with modern data analytics competencies.

"There is a huge gap that is happening now in utilities. Many people are retiring, people with experience. It's hard for newer people to catch up. Systems like this one will reduce the experience gap in ways that experienced people by common sense would imagine and probably avoid situations. This type of system can complement that," Sotter observes.

Training programs must address resistance to change while demonstrating how technology augments rather than replaces human expertise. *Industry data validates this observation, showing that 56% of utility employees now have less than 10 years of service, with both non-retirement and total attrition at their highest levels since 2006, according to a survey representing 41 utilities with 315,000 jobs* [7]. Effective approaches emphasize practical applications where monitoring data enables better decision-making rather than replacing judgment entirely. Success stories where experienced technicians used monitoring data to solve complex problems help build confidence and acceptance.

The data classification challenge represents a fundamental aspect of security integration. Monitoring systems collect operational data distinct from protection and control information, creating opportunities for different security treatment based on criticality levels. Visual and thermal monitoring data resembles information that technicians traditionally transmitted via text messages or email, suggesting less stringent security requirements than mission-critical control systems.

"The type of data that we provide is not protection and control, which is the real critical stuff. We just take temperature readings. It's the same as when you send your thermographer, and that guy is sending you the data to your cell phone via text messages," Sotter explains regarding data sensitivity classification.

This distinction aligns with NERC CIP-015-1 standards for Internal Network Security Monitoring, which mandate different data classification levels based on impact to bulk power system reliability, applying to over 1,636 U.S. entities and specifically distinguishing between operational data monitoring versus protection and control systems [8]

Roadmap to Fully Automated Substations

The trajectory toward fully automated substation operations spans the next decade, with clear technological milestones marking progress from current monitoring capabilities to comprehensive autonomous management systems. The five-year vision encompasses systems that automatically identify equipment, diagnose problems, and generate work orders without human intervention. This progression involves systematic capability building rather than revolutionary technology deployment, ensuring reliability and regulatory acceptance throughout the evolution.

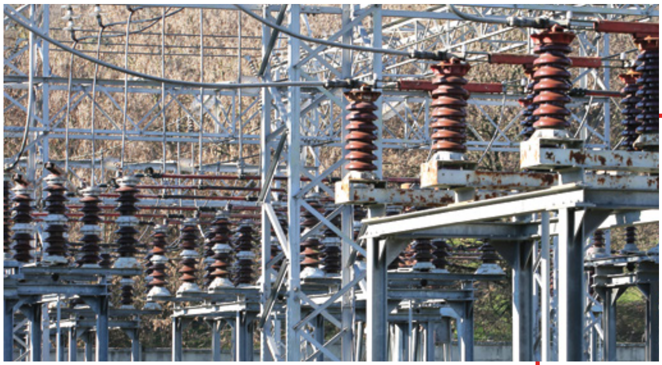
"Our goal, probably five years from now, is to be able to deploy the system, and the system will automatically identify transformers, will automatically identify breakers, so no need for someone to configure everything. The system already can tell you something is wrong or not, and not only that, but we already integrate with your SAP and create the work order to go and check it out," Sotter describes the ultimate automated maintenance vision.

Near-term milestones include component auto-identification where systems recognize major equipment types without manual configuration. Automated anomaly flagging allows AI to detect "something different" conditions requiring human investigation. Reduced setup time streamlines commissioning processes minimizing manual system configuration. Enhanced predictive capabilities enable pattern recognition identifying potential issues before failure manifestation.

The intermediate development phase focuses on practical capabilities that provide immediate value while building toward more sophisticated automation. Machine learning algorithms will evolve from rule-based detection to model-driven analysis that understands normal operational patterns and flags deviations automatically. This progression enables systems to identify issues in areas not specifically monitored while providing operators with actionable intelligence.

Long-term capabilities encompass multi-modal sensing integration where UV, acoustic, chemical, and electromagnetic sensors provide comprehensive equipment awareness. Predictive maintenance orchestration involves AI systems scheduling interventions based on failure probability analysis. Autonomous response coordination creates self-healing capabilities that isolate problems and reconfigure systems automatically. *Digital twin optimization enables virtual system models for predictive operations and scenario analysis. Digital twin technology is already proving transformational, with NERC noting it as 'a game changer for security,' providing virtual representations that enable predictive maintenance and scenario testing while offering unprecedented control from virtually any location* [9]

Early adopter utilities play crucial roles in validating autonomous technologies and influencing development priorities. Pilot programs and beta testing partnerships enable utilities to shape vendor roadmaps while gaining early experience with emerging capabilities. These collaborative relationships ensure that automation development addresses real operational needs rather than theoretical possibilities.



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About Systems With Intelligence

Systems With Intelligence (SWI) is the trusted global leader in Touchless™ Monitoring solutions for electric utilities and industrial applications. Founded over 15 years ago, SWI pioneered real-time thermal imaging for substations and has deployed thousands of monitoring systems worldwide. The company's sensor networks and analytics platforms enable utilities to achieve dramatic O&M savings while building the data foundation for grid modernization and autonomous operations.