Practical Analytic Applications for Grid Reliability and Resilience

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SUMMARY

There is a fundamental link between the performance of electrical equipment and grid reliability and resilience. Equipment is exposed to new levels and types of system load, system transients, and an increasingly challenging environment. In the U.S. 31% of all distribution grid outages are related to the failure of equipment. Predictive maintenance programs can remove or repair equipment and avoid incipient outages but requires knowledge of the condition of the equipment. The monitoring of all distribution equipment is not practical due to the large number and types of equipment. This paper describes a pilot project where mobile, edge-computing, IIoT sensors and Artificial Intelligence combine to enhance grid reliability and resilience through the condition assessment of all distribution equipment enabling predictive maintenance and system enhancing analytics.

KEYWORDS

Mobile Edge Computing, Grid Resilience, Equipment Condition Assessment, Predictive Maintenance, Asset Management, IIoT Sensors, Analytics

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The Problem:

The reliability of the electric grid and the resilience of the grid to withstand the impacts of age and weather are most notably demonstrated by power outages. The transmission grid and its assets are well monitored and maintained and are designed with enough redundancy to avoid bulk transmission system outages. However, the roughly 5 million miles of the distribution grid is made up of hundreds of millions of assets that affect grid reliability and resilience. When these assets fail an outage occurs. It is estimated that the U.S. economy bears the $110 Billion impact of these outages annually. Grid maintenance costs utilities and their customers an estimated $52 billion annually. At the same time, there is an aging workforce issue. As the trained line workers leave their jobs, new grid analytics will augment less experienced line worker productivity.

There are 245 million power outages annually in the U.S. alone and 94% of these outages involve the 5 million miles of distribution grid. Power outages in the U.S. cause an annual $110 Billion economic impact on the nation's economy. [1] [2]

The miles of distribution grid and the dense distribution of assets makes monitoring grid to the device level with fixed sensors economically unfeasible. This has resulted in a run-to-failure grid maintenance strategy resulting in reactive outage management.

Distribution grid outages are increasing in frequency and duration. From 2015 through 2019 IEEE SAIFI for all utilities participating in the IEEE benchmark survey increased from 1.04 to 1.12. [3] Age of the grid, increased air contaminants, wear and tear, and weather impact distribution grid performance. Statistically, it is expected that 2/3 of outages will occur outside of the 8-hour workday.

Resolving the issues of grid performance resulting from incipient faults includes monitoring the distribution grid using fleet-vehicle mounted, edge computing sensors (MECS). The data from the sensors identifies the location of deteriorated equipment using stochastic resources enabling predictive maintenance. Employing a predictive maintenance strategy reduces unscheduled outages and grid repair lowering the utility maintenance costs and increasing worker productivity and safety.

The Pilot Project

A 2-year, 5,000 pole-mile Pilot Project including the deployment of sensors on sanitation trucks was started in 2020. The project addresses the monitoring and analysis of distribution grid hardware, the development of machine learning algorithms for grid reliability and resilience, and forecasting using deterministic models to predict future events and asset failures. The national distribution of deteriorated equipment findings on the grid are shown in Fig. 1. The confidence interval of ground truthed findings is more than 95%.

The models will evaluate the grid continuously using grid condition assessment data from mobile edge computing sensors (MECS) mounted on fleet vehicles. These vehicles periodically traverse repeated routes near the grid and evaluate partial discharge emissions that are indicative of equipment deterioration and eventual failure. These emissions will:
- Predict the expected performance of distribution equipment at the asset level to maintain the operation of the distribution grid at the circuit level.
- Enable performance forecast of the entire grid as a system enabling proactive grid management, fault-tolerant operation, wide area reliability forecasts, reduction of outages, and preplanning to prepare for outage events.
- Enable predictive maintenance as an economic and proactive alternative to run-to-failure grid management.
- Establish a prediction layer to analyze the system based on forecast data of all system variables. Predicting and quantifying the energy deficiency can be considered and incorporated in any power system risk management case.
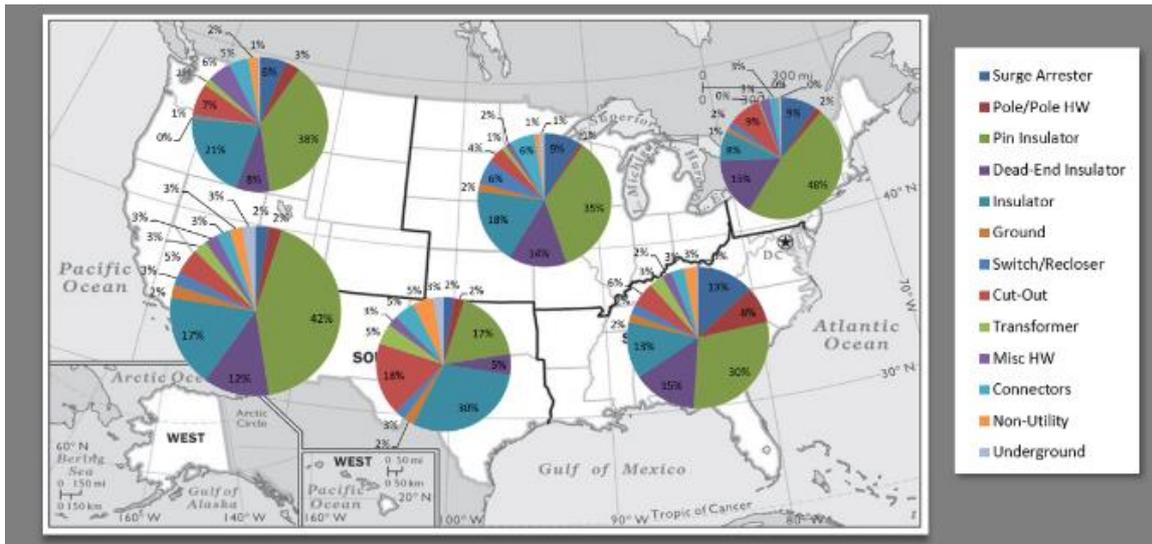
Figure 1: Regional Distribution of Deteriorated Equipment Findings in the U.S.

To illustrate the impact of improved grid performance, consider 1 deteriorated piece of electrical equipment for every 6 miles of the 5-million-mile grid. This represents 834,000 pieces of deteriorated equipment that will cause an outage. It will cost an estimated $834 million to replace these devices. However, $11 Billion annual savings is realized with a 10% improvement in grid performance.[3]

The Sensor Technology

As energized grid equipment deteriorates, Radio Frequency (RF) failure signature emissions are produced. Analyzing these emissions along with the motion of vehicles provides the location of deteriorated equipment. Sanitation trucks have been selected to create 52 weekly grid condition assessments per year for analysis. In field tests, the correlation of a Failure Signature capture and locating a deteriorated piece of energized grid equipment exceeds 90%.

To locate the issues on the grid for conditions-based maintenance, a low-cost, low-power, battery operated, weatherproof, mobile edge computing sensor (MECS) that includes the measurement of environmental conditions was designed and deployed.

A model of the sensor that includes the technology to evaluate RF emissions and discriminate partial discharge events in real-time is shown in the following figure along with the mixed error estimation integral process used in the analysis of the partial discharge emissions and Failure Signature correlation. A sample sanitation truck routing is also shown in Fig. 2. Notice that a given truck route does not cover the entire area. The analytics must aggregate the data from several fleet vehicles to develop a coverage map. This is an example of one truck on one day. The MEC sensor, Fig. 3 was piloted on 5,000 miles of grid for 18 months a demonstrated acceptable performance for the collection of the grid emission analytics. An AWS Cloud architecture Fig. 4 was implemented to provide secure storage, implement initial decoding of secure transmissions, preprocess data, and provide data access to all analytical systems. The entire distribution grid could be monitored by adding a MEC sensor to 20% of the existing 60,000 sanitation vehicle fleet that exist today.[4]
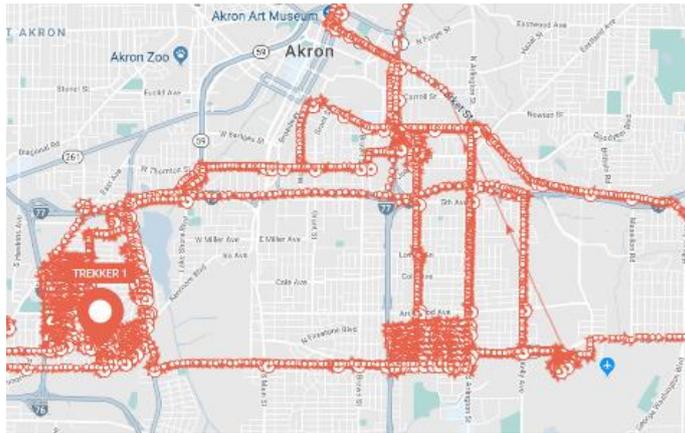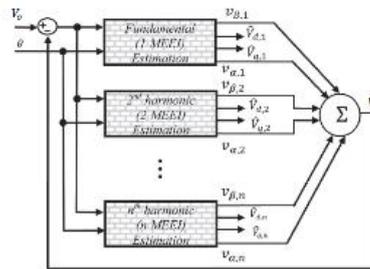
Figure 2: Sample Sanitation Truck Route

Figure 3: MECS Sensor

Figure 4: Grid Emission Detection Deployment Example

Analytical Applications

The Deployment of MECS technology and the prognostic evaluation of future grid events provides an opportunity to evaluate asset operational risk and create a paradigm shift from run-to-failure to a proactive conditions-based grid management and maintenance strategy. The index metrics developed based on MECS technology will coexist with the risk and reliability, and risk assessment with new grid assets like renewables, energy storage, and control and protection units. In optimal power flow analysis, the economical justifications of the optimized solutions collide with the reliability requirements. This issue is more challenging when high levels of stochastic resources (e.g. renewable resources) are integrated in the power grid. The transient reliability in this case is more sensitive since the system energy margin required to supply the transient energy is extremely limited compared to the conventional power system.

Mathematically, steady state energy deficiency can be quantified based on the expected amount of electrical energy interrupted during specific periods due to external or internal conditions, where this interruption creates a deficit in the energy required by the load. Measuring the amount of transient energy deficiency requires precise attention. The system voltage and frequency are the direct measures that implicitly reflect any energy mismatch between the demand and the supply.

Therefore, predicting and quantifying the energy deficiency can be considered and incorporated in any power system risk management case. The energy index of reliability (EIR) which measures the energy served as a fraction of the total energy demand can be employed as an energy deficiency measure and provide direct Quality of Service (QoS) information.

The proposed work, maintaining a supply-demand balance and system reliability for grids with high levels of stochastic resources, aims to (a) represent the reliability level of the system using tangible short-term energy index of reliability to eliminate any expected energy deficiency, (b) provide optimal and reliable solution to the power flow problems such that the solutions are not only cost-effective but also reliable, and (c) (In case of storage battery is available) provide optimal battery scheduling at minimum cost with extended battery lifespan.

The solution structure, Fig. 5 illustrates transfer of MECS IIoT data streams and circuit information into a cloud environment where the data is aggregated, and quality checked. After pre-processing, advanced machine learning algorithms are applied to predict at-risk components, prioritize maintenance recommendations based on the number of customers served from at-risk components, and estimate both component and system health indices over time. With additional capacity and load information provided by the utility EIR can also be determined.

Results are delivered in accordance with utility specifications. This may include direct delivery of files to the utility's native maintenance management system together with state-of-the-art dashboards and visualizations. These can help to identify areas which may benefit from larger capital improvement projects like circuit-rebuilds as opposed to component-by-component maintenance.
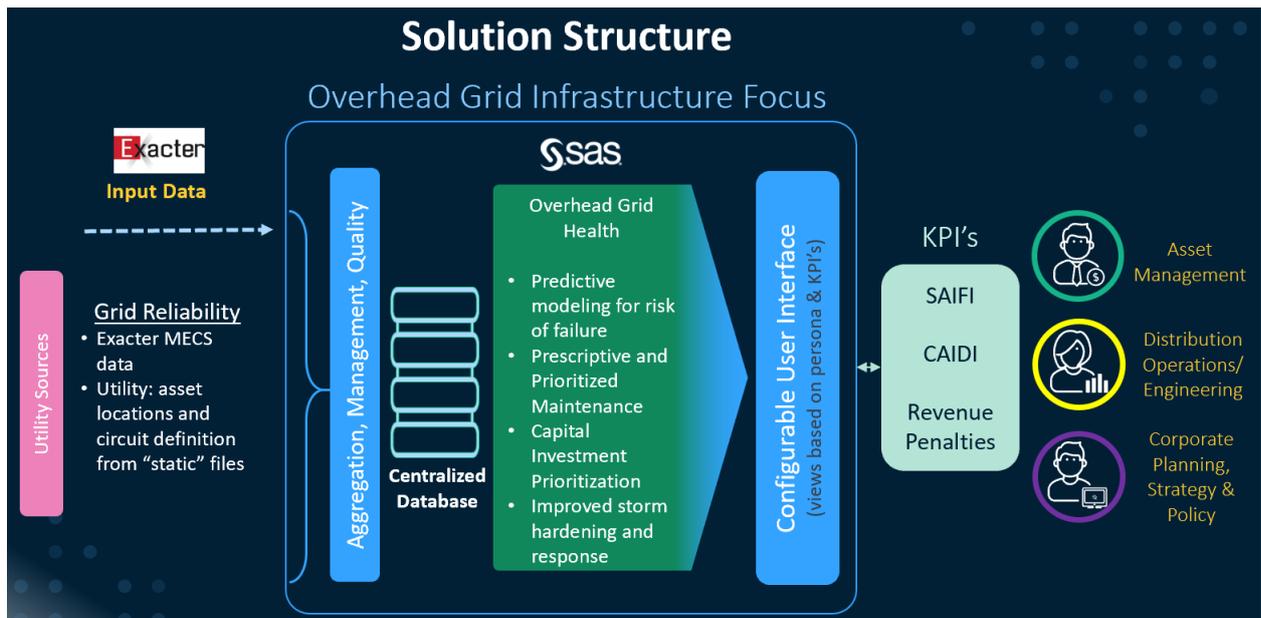
Figure 5: Solution Structure

Several direct and indirect benefits accrue to the utility from this technology. Most importantly, the solution helps employees work safer. There are two reasons for this. First, the solution predicts failures. This allows utilities to plan maintenance instead of reacting to unplanned failures. And planned maintenance is safer than reacting to unplanned failures. The second reason this solution helps utility employees work safer is that it can reduce worker fatigue through reductions in overtime. This prevents injuries. One study shows that employees who perform work without reliance on overtime schedules can cut their injury hazard rates by 38%. [5]

Another direct benefit of this solution is that it can help eliminate high crew overtime costs for repairing failed equipment. Again, the solution predicts which equipment is going to fail. And these predictions allow utilities to schedule maintenance during normal working hours instead of working overtime to repair unexpected failures. This means that premium-rate overtime hours can be shifted to regular time hours paid at the normal rate, which typically corresponds to a 33% reduction in associated cost.

Among the indirect benefits are higher customer satisfaction and cost savings for C&I customers resulting from avoided interruptions. Furthermore, if a utility is subject to performance-based regulations on distribution reliability, then lower SAIFI and CAIDI values which result from fewer equipment failures can help meet reliability performance goals. These benefits are summarized in Fig. 6.
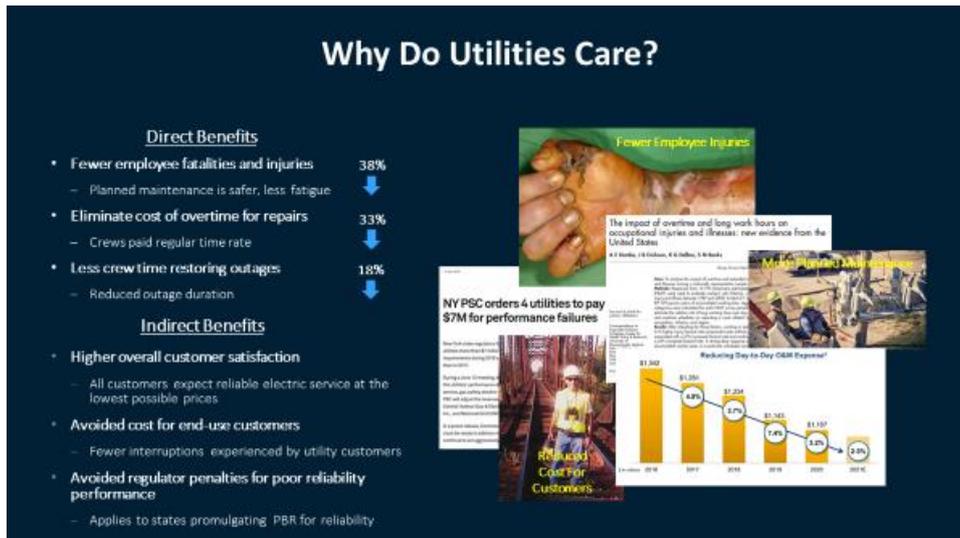
Figure 6: Direct and Indirect Benefits of Grid Reliability and Resilience Improvements

Sample Results of Predictive Maintenance Analysis
The first level deliverable of the MECS data analysis is to identify deteriorated equipment on the grid for replacement. Small study areas of 2 sq miles were geofenced to evaluate the effectiveness of the study. In these areas, equipment that was identified by the MECS analysis were confirmed by evaluating arc emissions with ultrasonic acoustic measurement equipment. This equipment is very sensitive to the pressure waves developed during arcing or partial discharge events and precisely shows the point of the emission source.

In one study area, made up of about 120, circuit-miles there were 30, deteriorated devices located (one every 4 circuit-miles) that were creating PD emissions. Fig.7 shows a typical field report. Fig. 8 shows the distribution of types of equipment. The distribution follows the quantity of each device type closely.
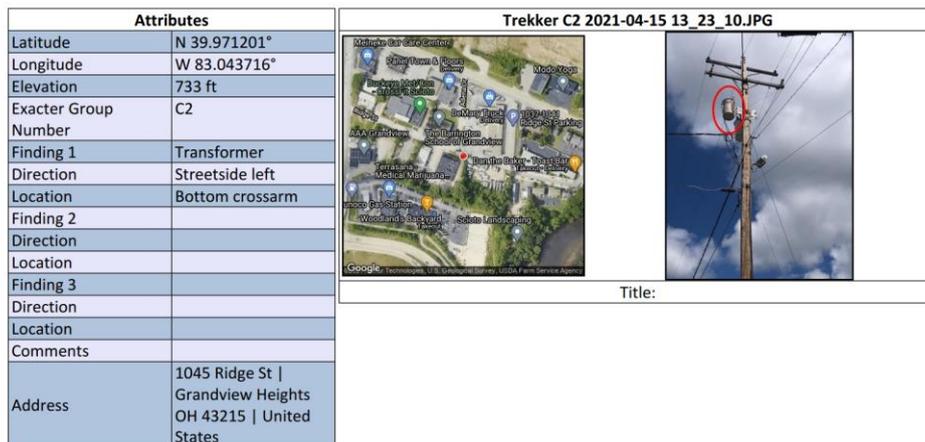
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Longitude	W 83.043716°	
Elevation	733 ft	
Exacter Group Number	C2	
Finding 1	Transformer	
Direction	Streetside left	
Location	Bottom crossarm	
Finding 2		
Direction		
Location		
Finding 3		
Direction		
Location		Title:
Comments		
Address	1045 Ridge St | Grandview Heights OH 43215 | United States	

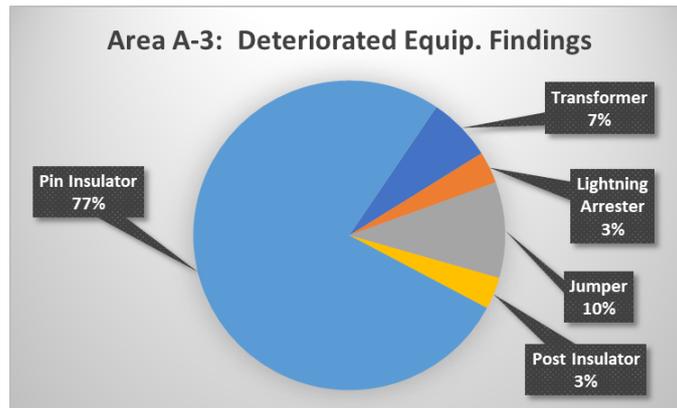Figure 7: Sample Trekker Field Report

Figure 8: Deteriorated Equipment Findings on 120 Circuit Miles Identified

Conclusions

A mobile, edge-computing sensor (MECS) that receives RF emissions from deteriorated electrical equipment was designed and piloted for 18 months. The result of the weekly survey of 5,000-miles of electric grid was accomplished with 12-sensors mounted on residential trash collection trucks. The trucks moved the sensors throughout the entire the overhead grid every week providing data on how the grid reacted to weather and load events. The data is being used to develop advanced analytics that address grid reliability and resilience, and to assist it the deployment of capital budgets for grid hardening and improve worker and public safety.

The improvement of grid financial performance will be evaluated as the entire system is expanded and its application deployed.

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