WHISKERLABS

A Survey of Fault Studies with a Large IOT Power Quality Sensor Network

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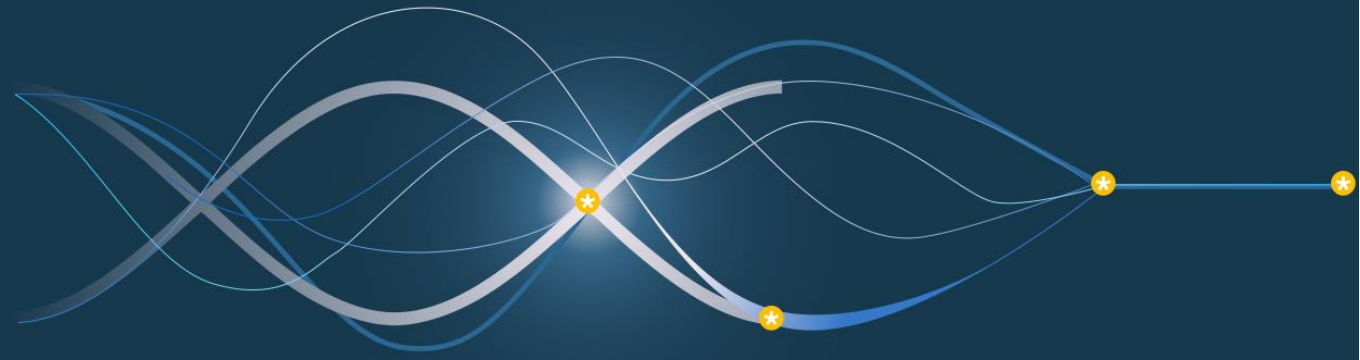


Agenda

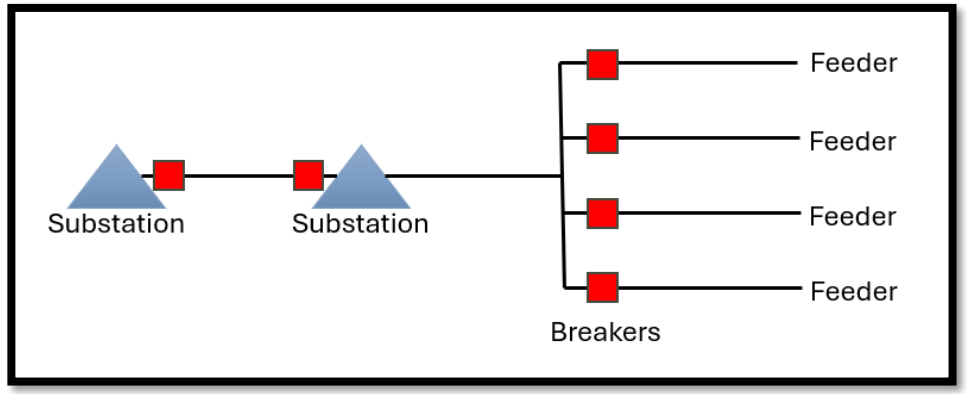
Prevention is our purpose

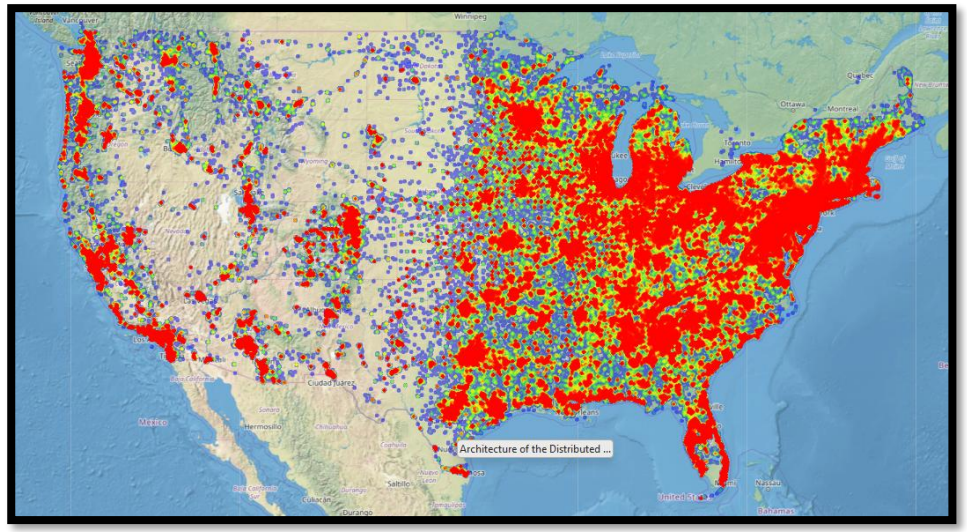
- Introduction
- Architecture of the Distributed Measurement Network
- Event Definitions and Disturbance Taxonomy
- Unique Signals from Time-Aligned, Distributed Service-Level Measurements
- Spatiotemporal Fault Correlation Methodology
- Case Studies
- Future Extensions
- Conclusions

Introduction

- Not Pictured
  - Midline Reclosers
  - CVR
  - FACTS
- More Complex Distribution Environment
- Different Measurement Approach Needed

Architecture of the Distributed Measurement Network

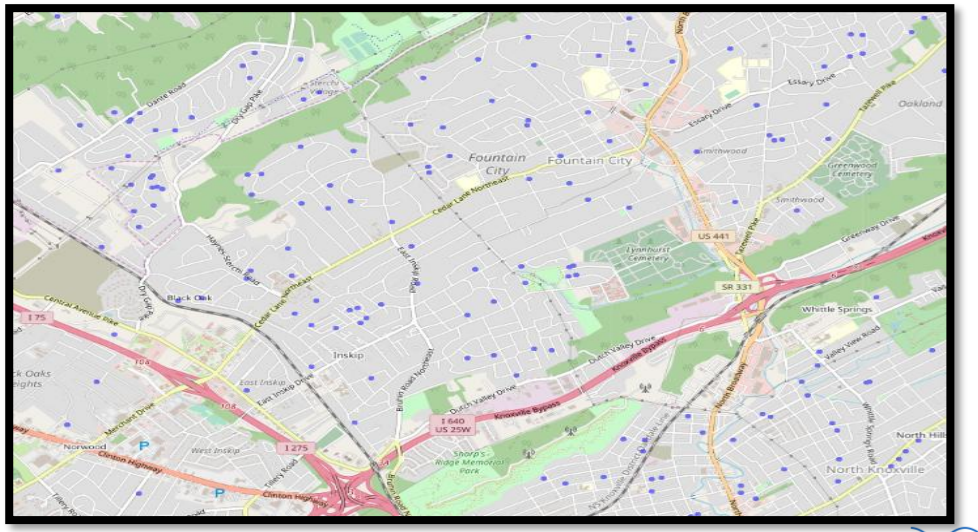




Continuous RMS Voltage, THD, and Frequency Measurement (30kHz sampling, 20Hz reporting)

Sags, Swells, Interruptions

Time Synchronized (5ms)



Event Definitions and Disturbance Taxonomy

Table 1 – Definition Comparison		
Term	Utility / IEEE Definition	Study Definition / Usage
Event	A known failure or fault condition either reported or recorded as a system event on the grid (e.g., protective device operation, equipment failure, outage). aka 'Incident'. [3]	The anchor point for analysis, with exact or approximate date, time, location provided by the utility. Used to align sensor data for retrospective analysis.
Fault	A grid condition severe enough to activate protective equipment (fuse, breaker, relay), causing a trip or isolation. [4]	A correlated disturbance pattern across sensors before, during, or after an Event, whether or not it triggered protective equipment. Includes conductor slap, vegetation contact, equipment degradation, etc.
Fault Analysis	Root-cause investigation of a trip or device operation after the fact. [5]	Broader analysis of sensor signals before, during, and after an Event. Distinguishes normal operations from abnormal precursors that may not trigger utility devices but contribute to failures or ignitions.

Event Definitions and Disturbance Taxonomy

A **voltage sag** is defined as a **reduction in RMS voltage** below a specified per-unit threshold for a duration exceeding a **minimum time** criterion. Sags are categorized by depth and duration to distinguish shallow disturbances from deeper, fault-associated depressions [6].

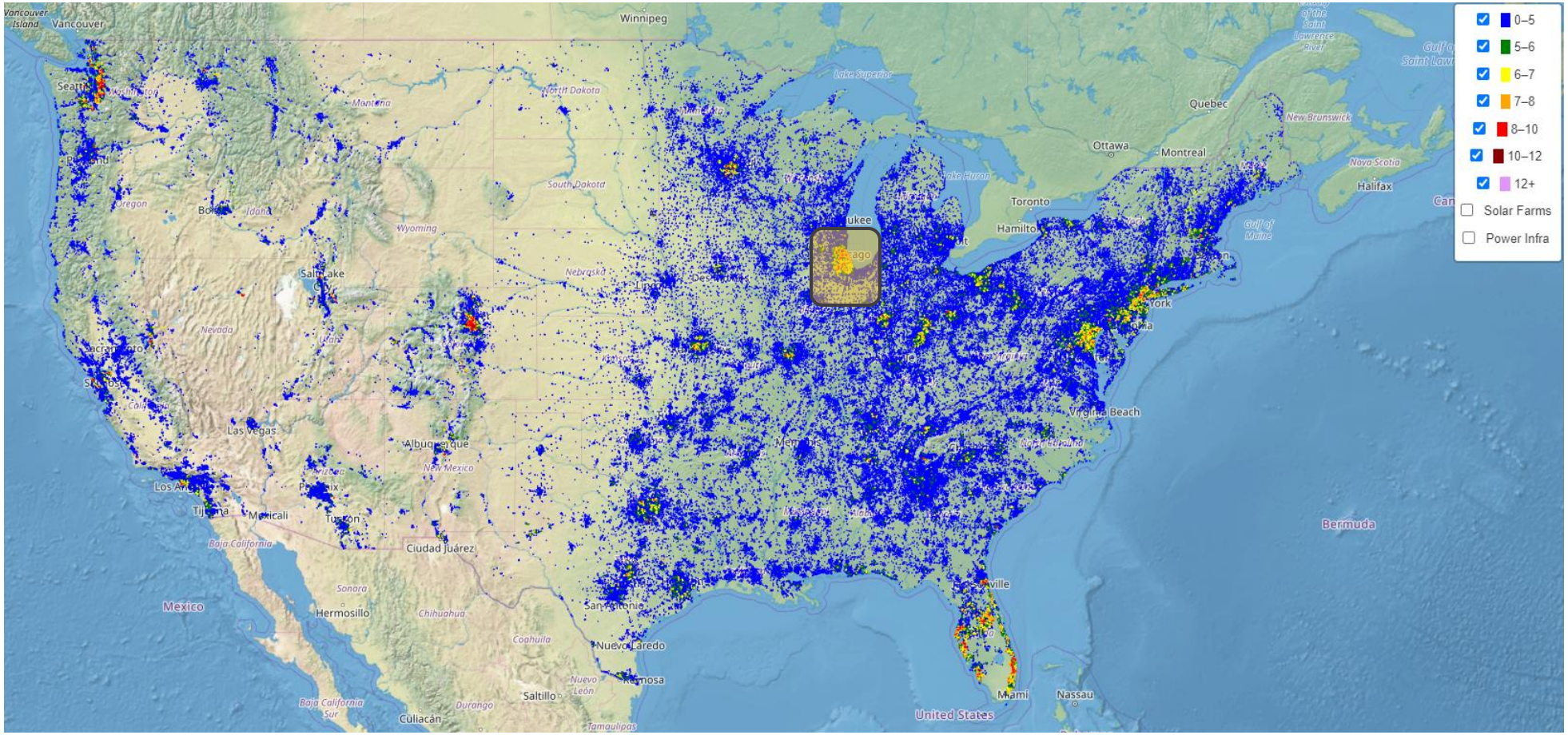
A **voltage swell** is defined as an **increase in RMS voltage** above nominal beyond a defined threshold and duration.

A **momentary interruption** is defined as **a near-zero voltage condition** consistent with protective device operation and **automatic reclosing**. These events are treated as cycle-capable during reconstruction.

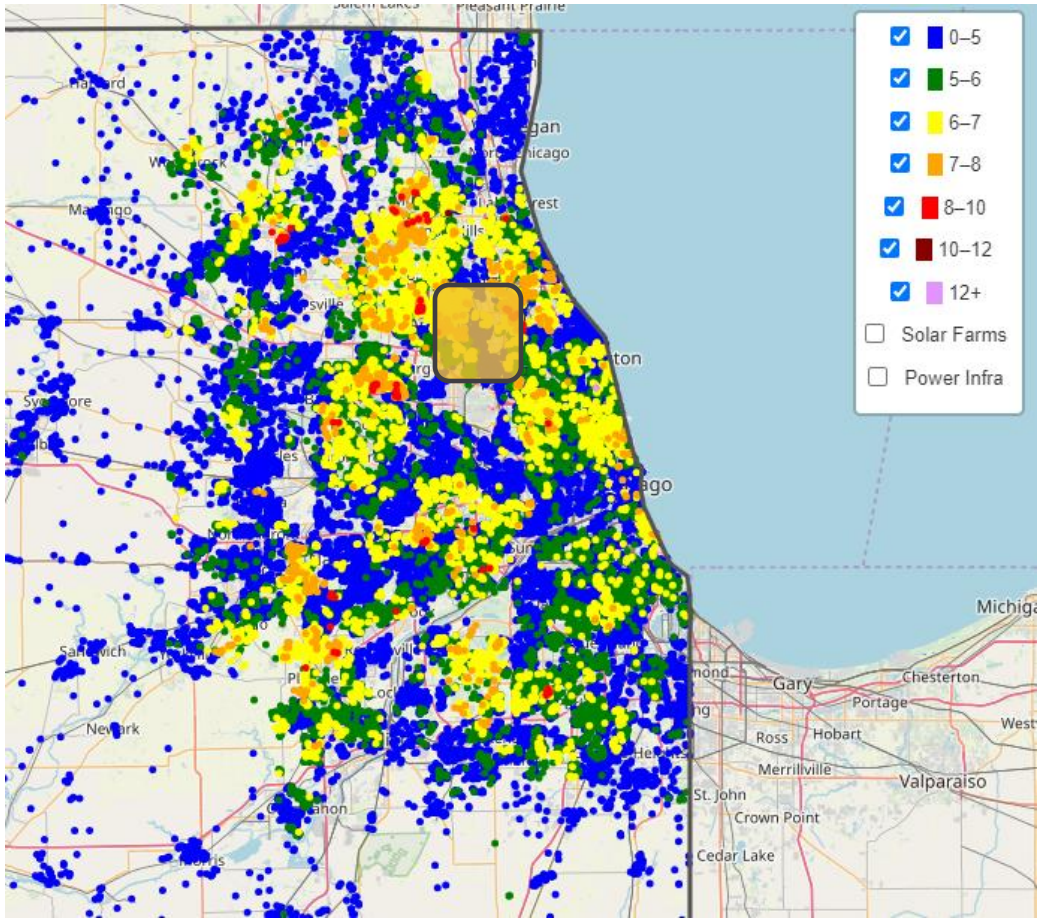
A **sustained interruption** exceeds the duration typically associated with reclosing attempts and indicates **extended de-energization or lockout**.

Multiple temporally proximate **events** at a **sensor** are treated as a **disturbance sequence**. Such sequences may represent **reclosing cycles**, intermittent vegetation contact, conductor movement, or progressive hardware failure.

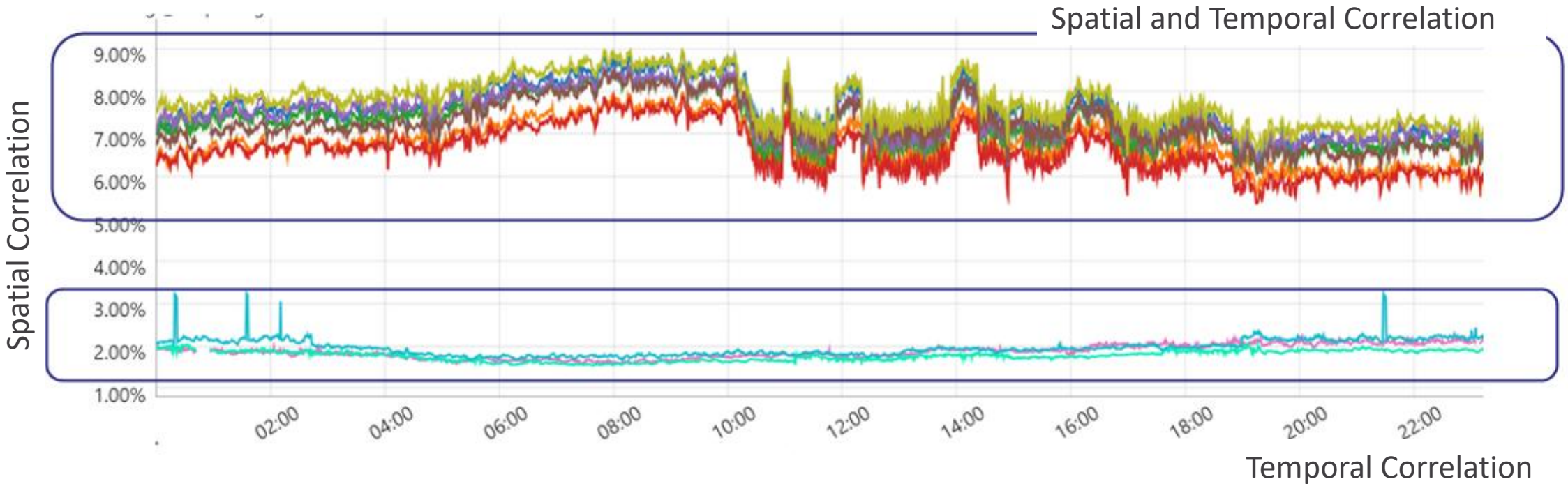
Unique Signals from Time-Aligned, Distributed Service-Level Measurements



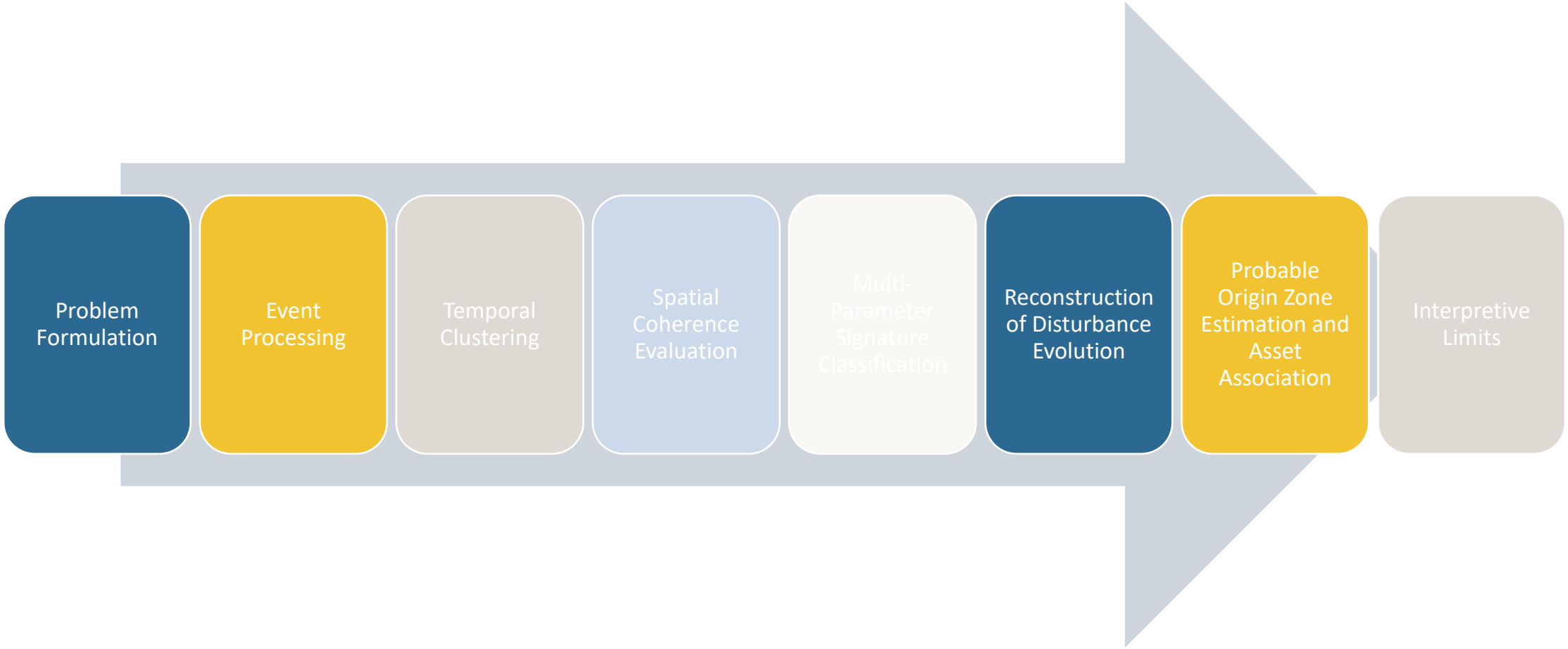
Unique Signals from Time-Aligned, Distributed Service-Level Measurements



Unique Signals from Time-Aligned, Distributed Service-Level Measurements

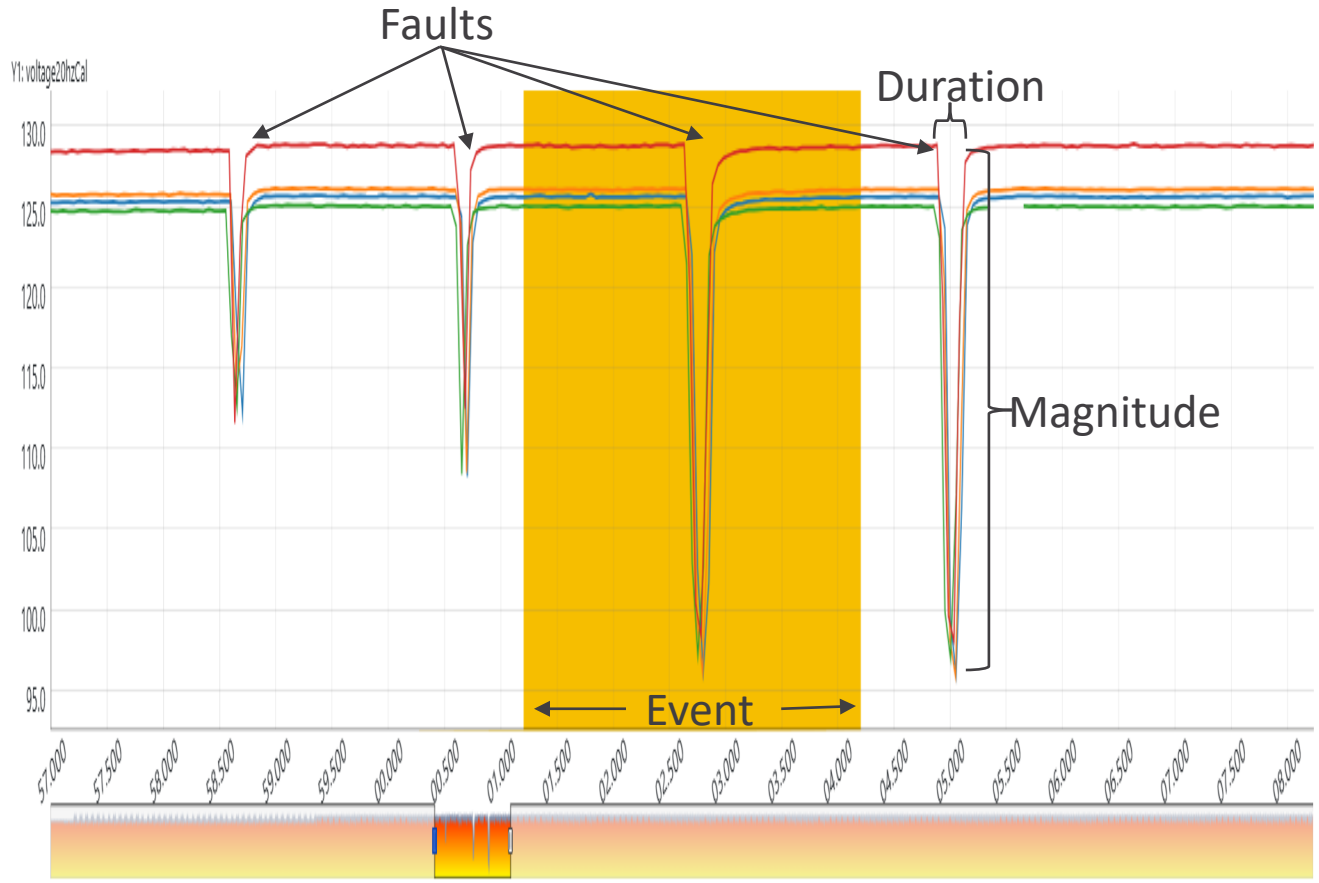


Spatiotemporal Fault Correlation Methodology



Spatiotemporal Fault Correlation Methodology

Problem Formulation



Each line represents the voltage measurement from a different sensor.

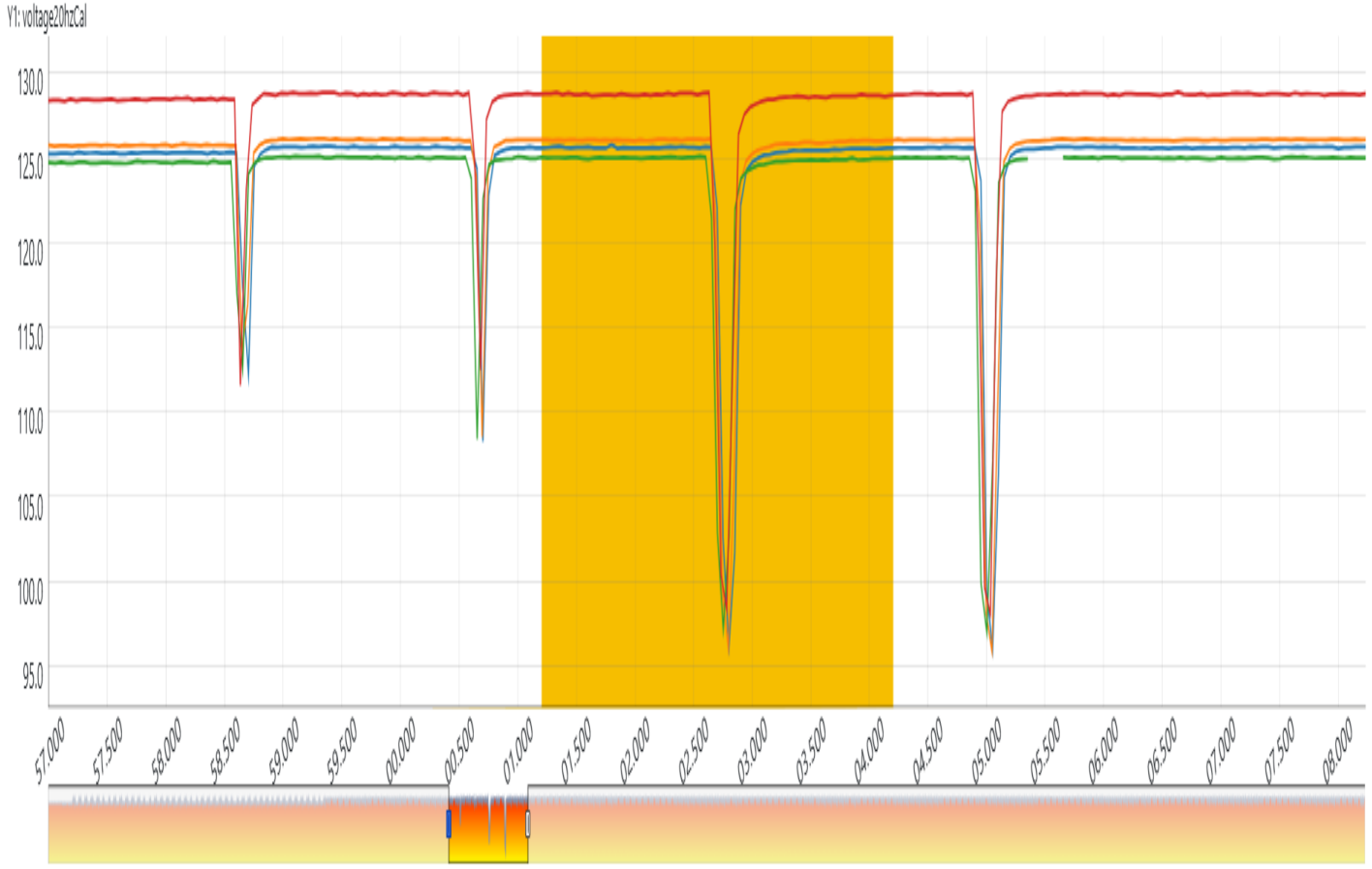
The measurement from each sensor is timestamped.

The magnitude and duration for each fault is captured.

The event type is tagged.

In this case voltage, but can be used with other measured parameters (e.g., Frequency, THD)

Spatiotemporal Fault Correlation Methodology



Data is normalized for analysis.

Per unit conversion of measurements.

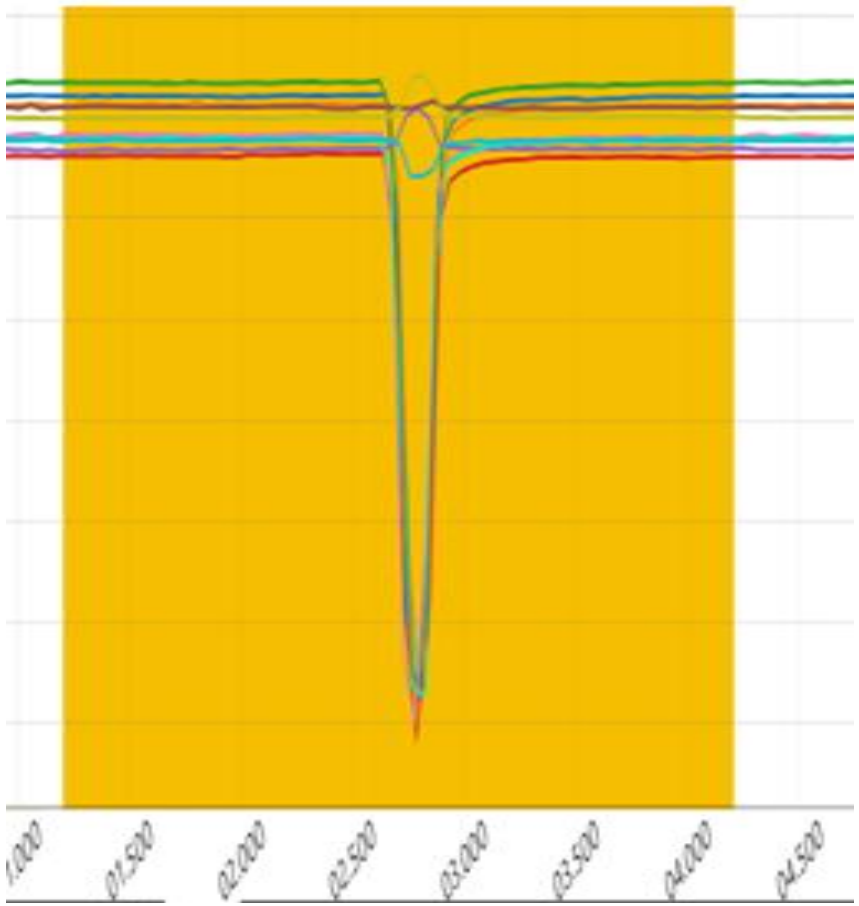
Time alignment.

Filtering below minimum thresholds.

Spatial indexes are built.

Spatiotemporal Fault Correlation Methodology

Temporal Clustering



A sliding time window groups events occurring within defined temporal proximity.

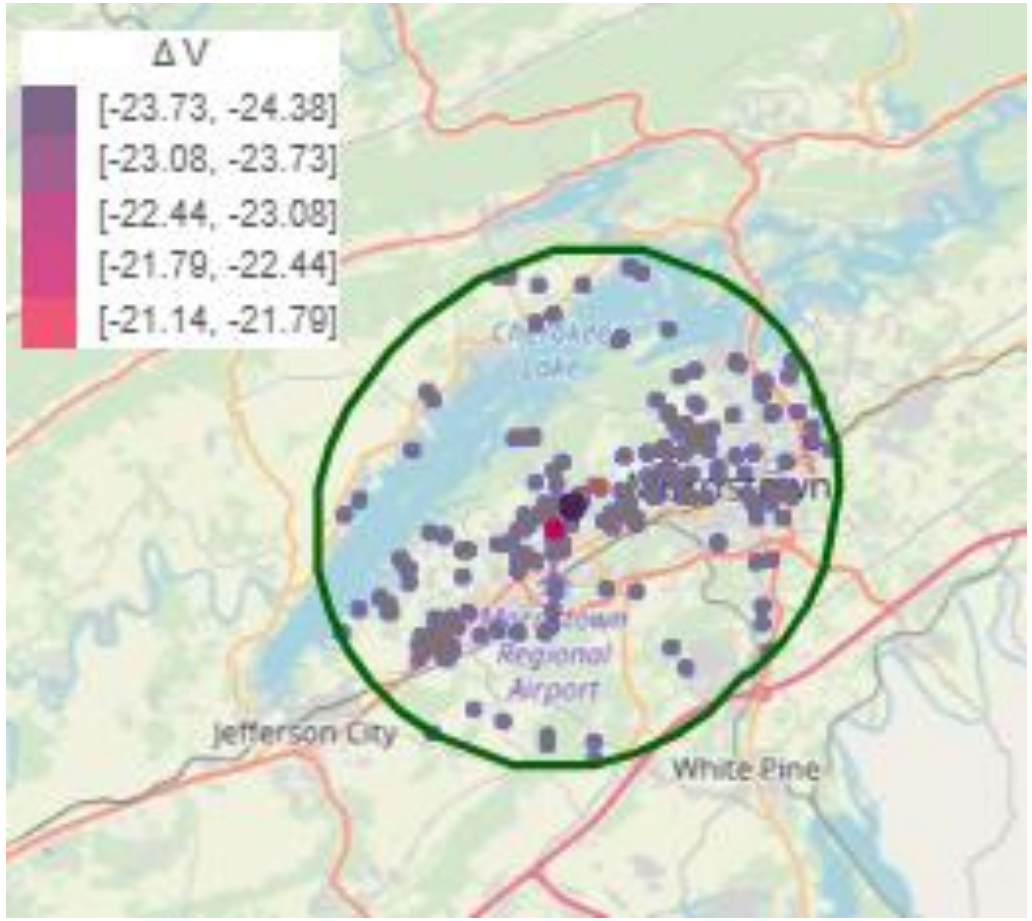
Candidate disturbance clusters are formed when event density exceeds a threshold relative to the geographic region represented.

Temporal clustering incorporates simultaneity of voltage deviations and, where present, coincident frequency or harmonic anomalies.

Repeated clusters separated by characteristic dead time are treated as potential protection sequences.

Spatiotemporal Fault Correlation Methodology

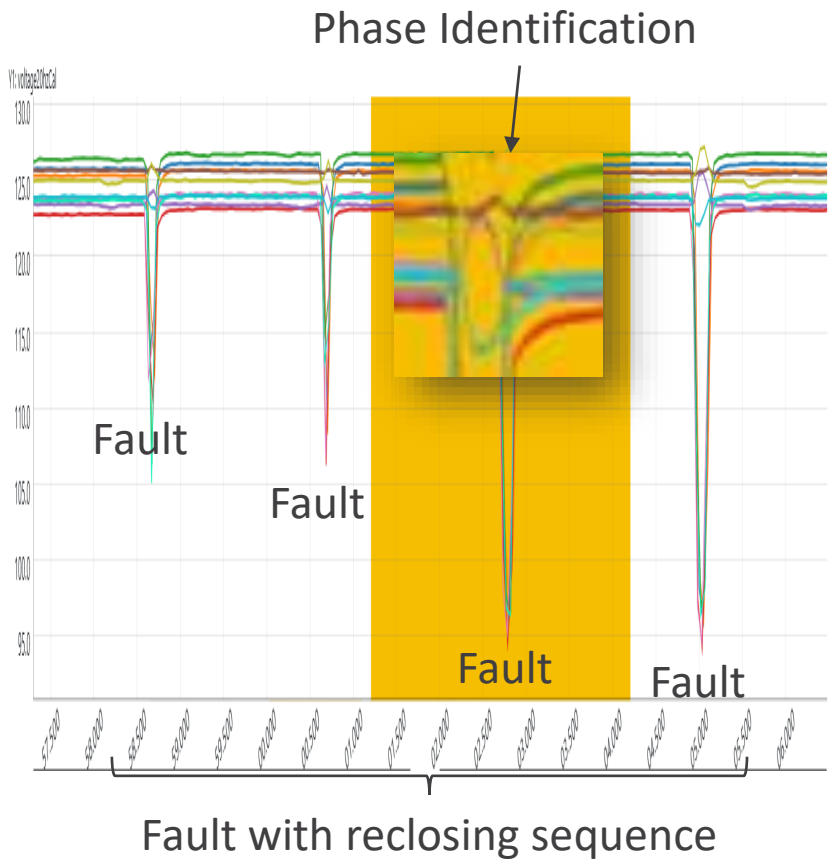
Spatial Coherence Evaluation



Each candidate temporal cluster is evaluated for spatial coherence using geographic contiguity, cluster diameter constraints, and spatial gradients in disturbance magnitude or related parameters.

Fault-driven disturbances often exhibit measurable gradients across space, while upstream disturbances may produce broader, more uniform signatures.

Spatiotemporal Fault Correlation Methodology



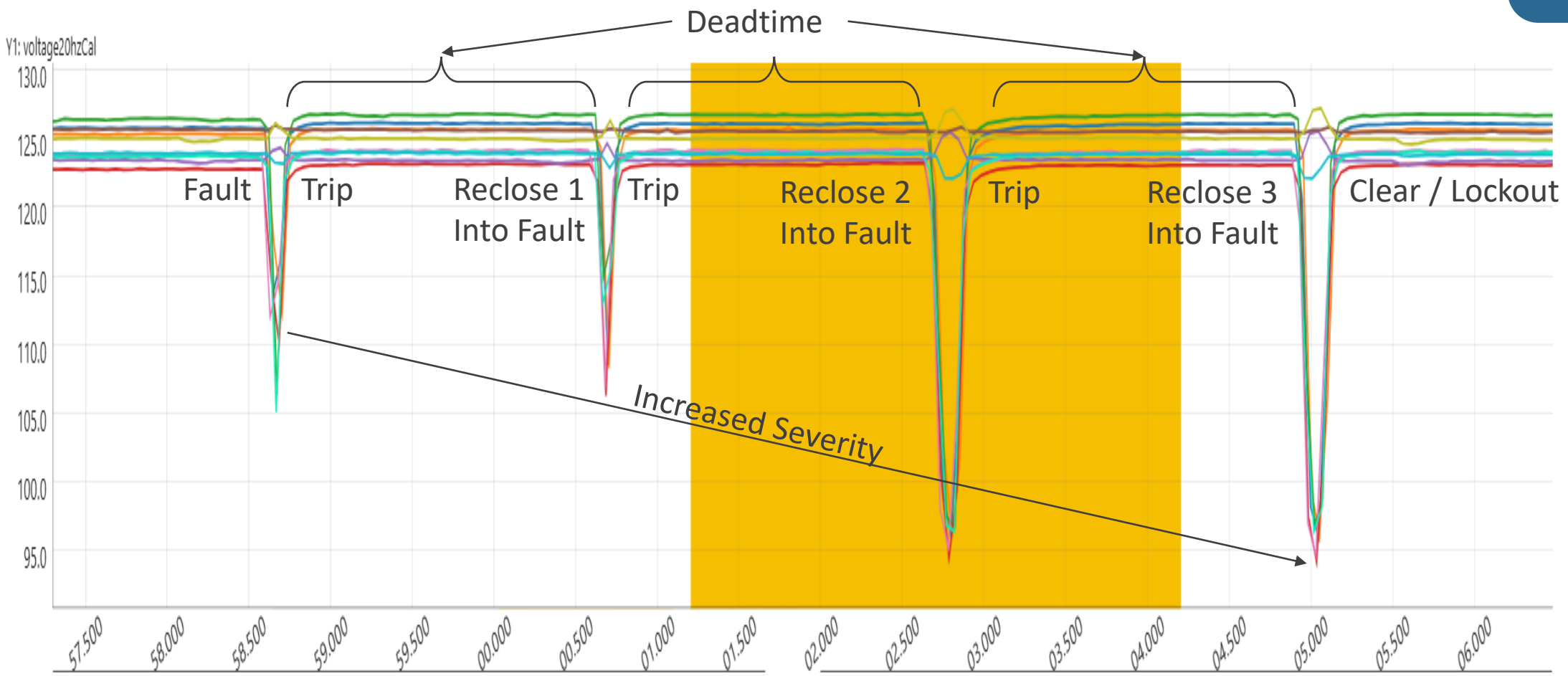
Clustering into categories:

- Fault
- Fault with reclosing sequence
- Switching operation
- Transmission-side disturbance
- Localized anomaly

- Others as the clustering algorithm identifies new categories

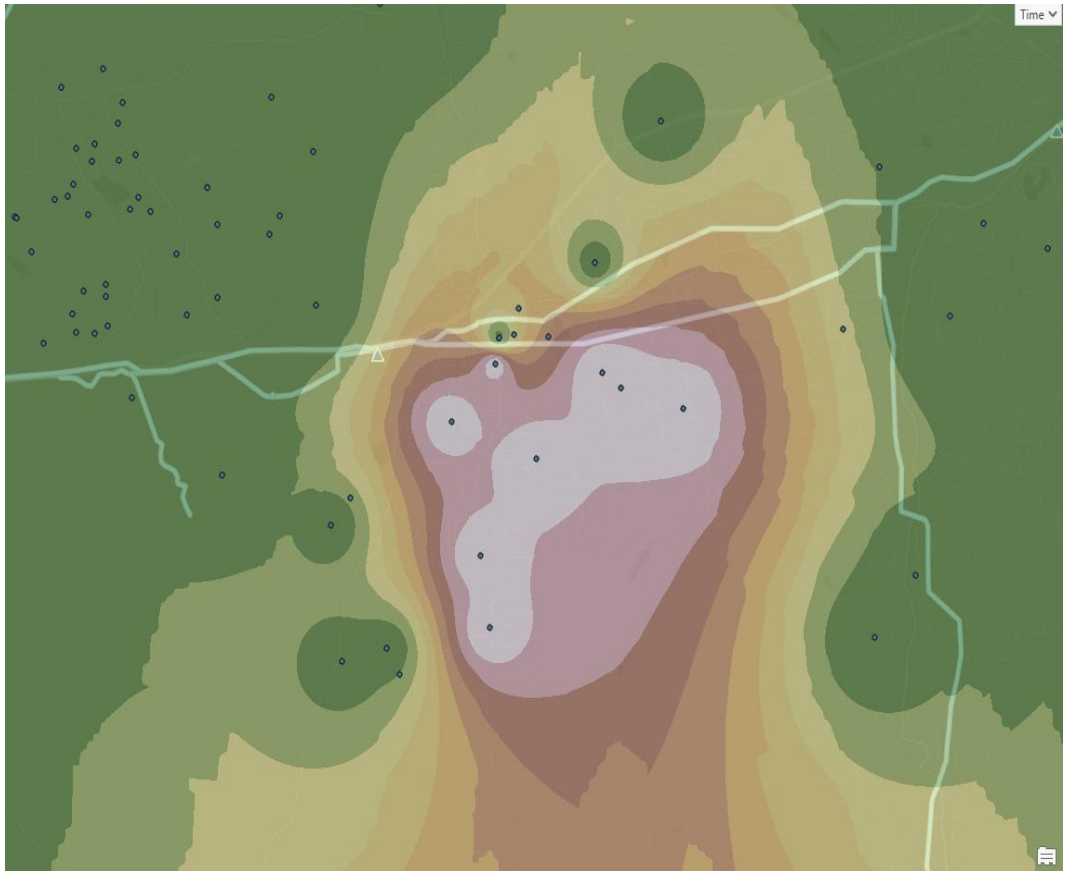
Spatiotemporal Fault Correlation Methodology

Reconstruction of Disturbance Evolution

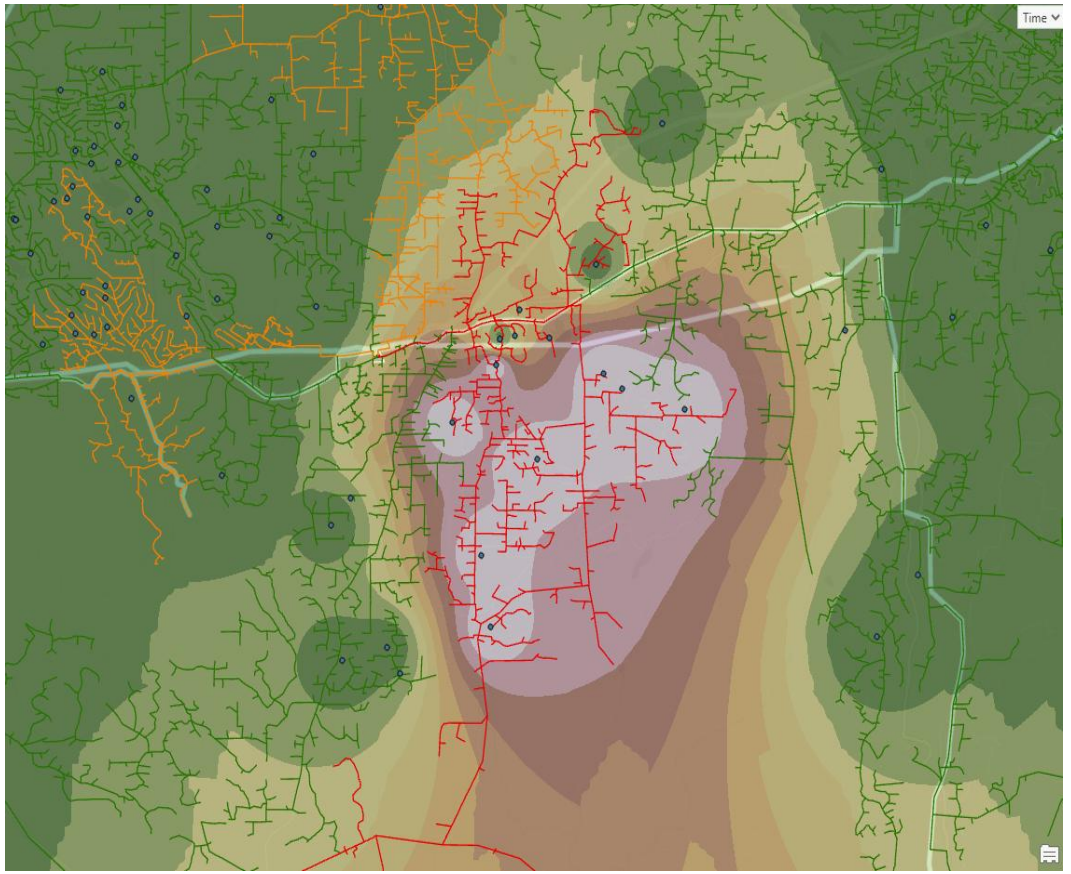


Spatiotemporal Fault Correlation Methodology

Probable Origin Zone Estimation and Asset Association



In an Area



On a Feeder

Spatiotemporal Fault Correlation Methodology

The methodology assumes **sufficient sensor density** to resolve spatial gradients.

Geographic proximity does not always correspond to **electrical proximity**, and transmission-level events may mask distribution-level behavior.

The absence of direct current measurement **limits precision** relative to impedance-based methods but **provides** complementary **spatial observability** not otherwise available.

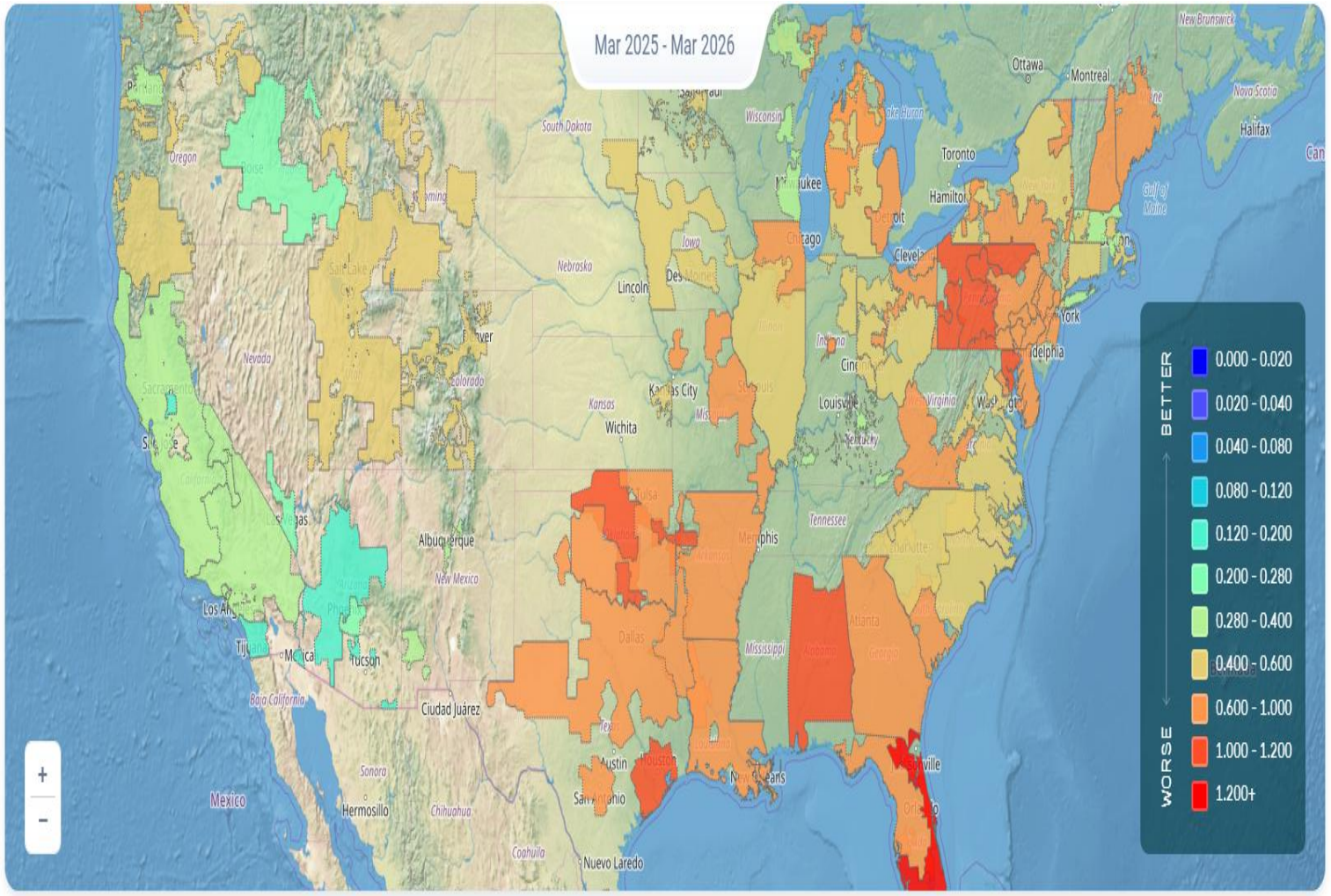
Case Studies

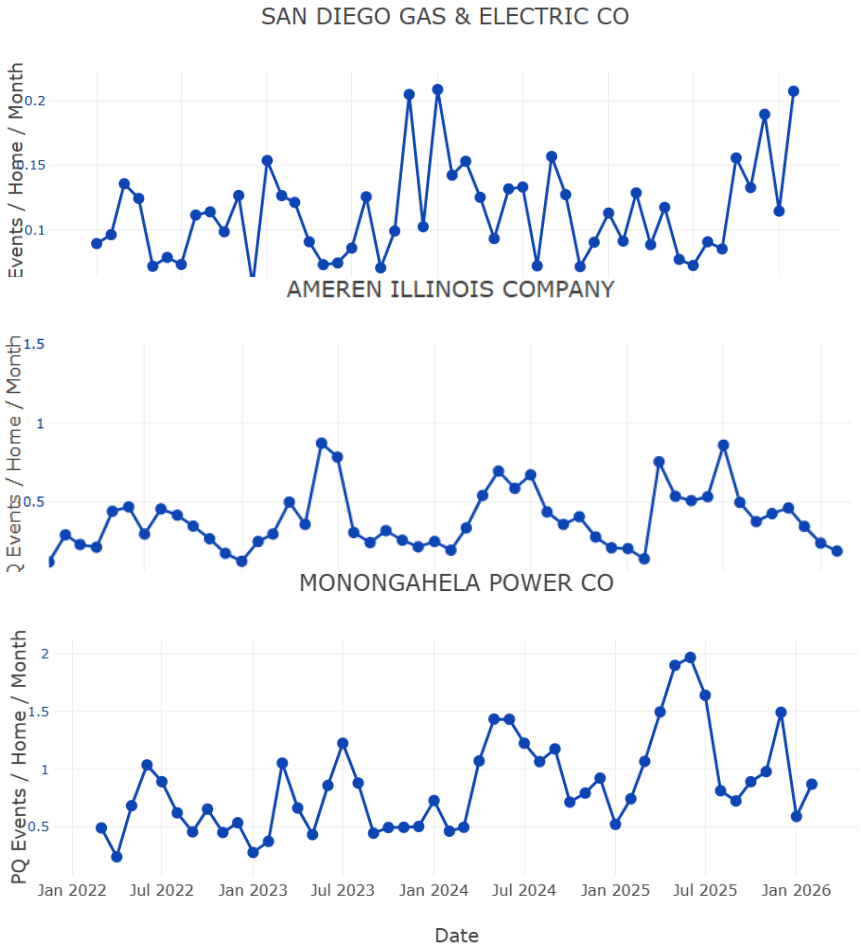
Grid Events Overview

Mis-Operating Capacitor Bank

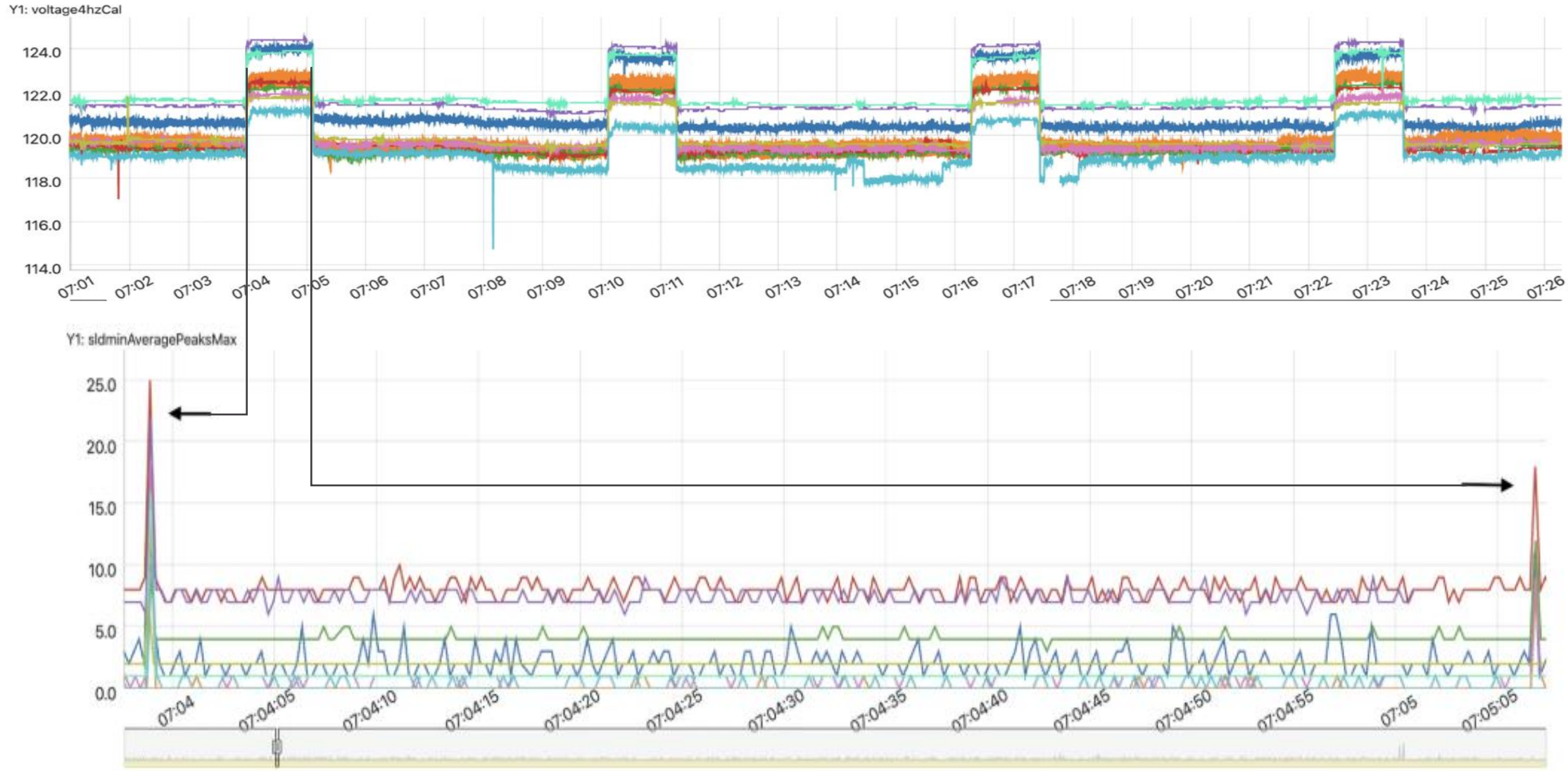
Fault Correlation

Grid Events Overview

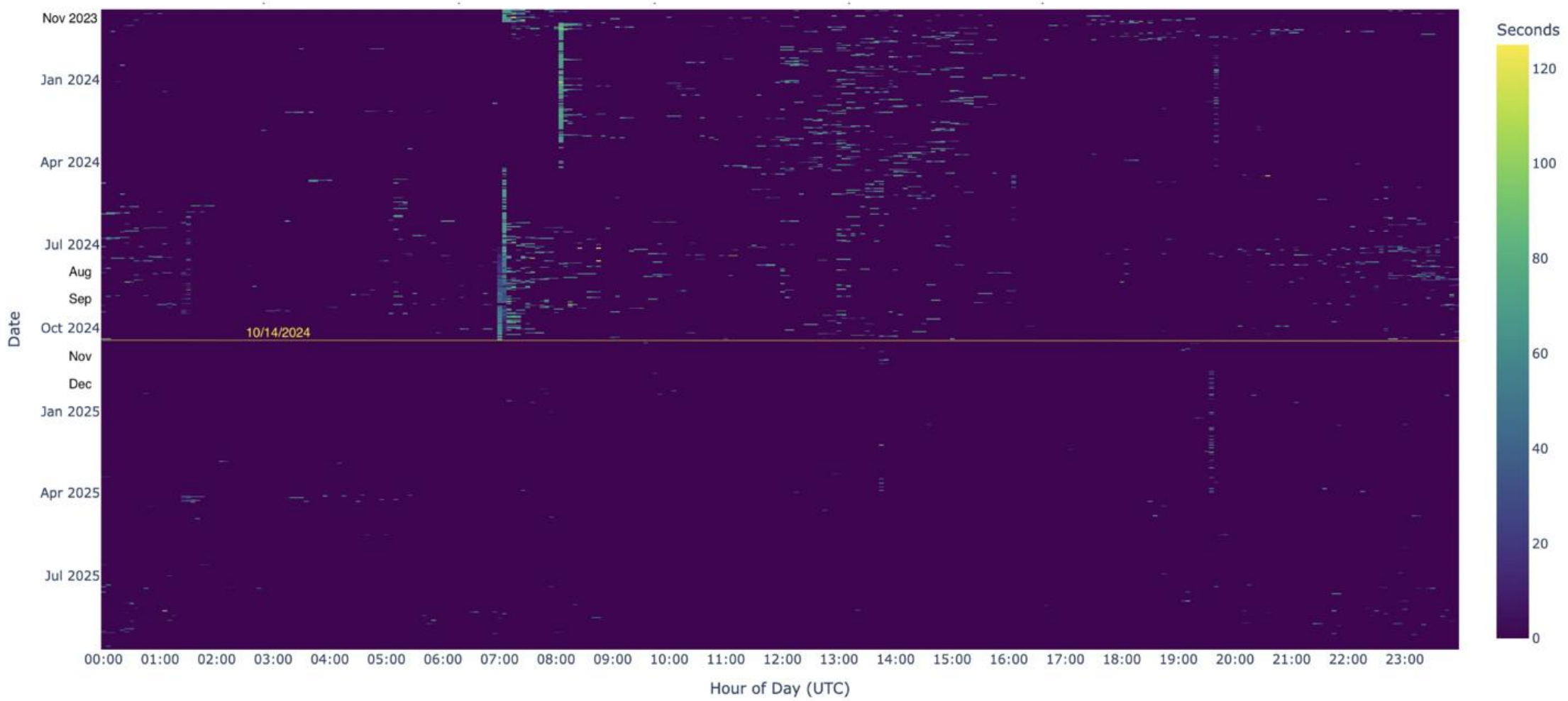




Mis-Operating Capacitor Bank



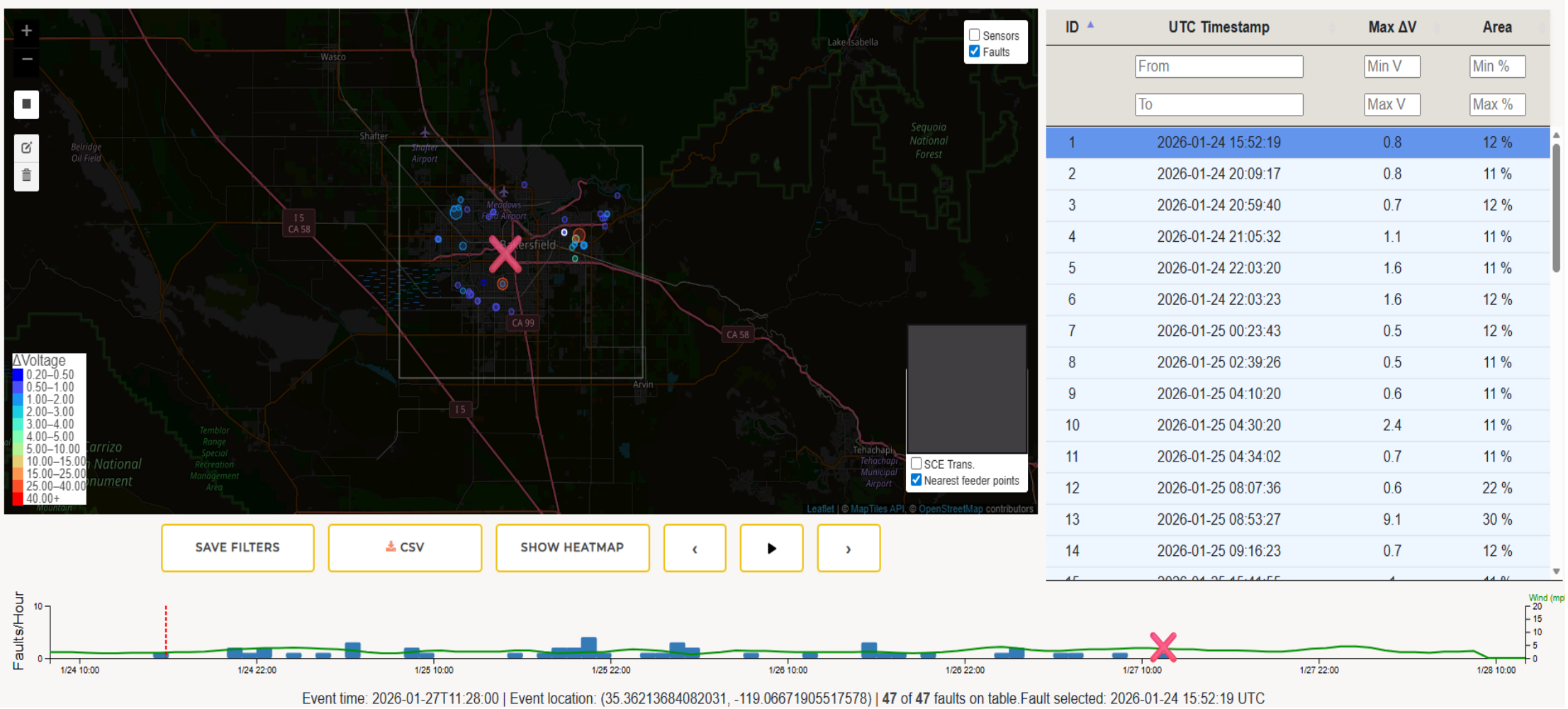
Mis-Operating Capacitor Bank



Fault Correlation

Faults 72h	48h	24h	12h	3h	1h	Total	Fault Heatmap
-	-	-	-	-	-	-	
48	34	14	6	1	0	49	
5	3	3	3	3	2	10	
8	6	4	4	3	2	18	
2381	1921	677	276	268	230	3847	
1	1	1	1	0	0	14	
142	142	142	142	100	38	1466	

Fault Correlation



ID	UTC Timestamp	Max ΔV	Area
	From	Min V	Min %
	To	Max V	Max %
1	2026-01-24 15:52:19	0.8	12 %
2	2026-01-24 20:09:17	0.8	11 %
3	2026-01-24 20:59:40	0.7	12 %
4	2026-01-24 21:05:32	1.1	11 %
5	2026-01-24 22:03:20	1.6	11 %
6	2026-01-24 22:03:23	1.6	12 %
7	2026-01-25 00:23:43	0.5	12 %
8	2026-01-25 02:39:26	0.5	11 %
9	2026-01-25 04:10:20	0.6	11 %
10	2026-01-25 04:30:20	2.4	11 %
11	2026-01-25 04:34:02	0.7	11 %
12	2026-01-25 08:07:36	0.6	22 %
13	2026-01-25 08:53:27	9.1	30 %
14	2026-01-25 09:16:23	0.7	12 %

Future Extensions

The framework is extensible to additional synchronized measurements including **frequency excursions**, **harmonic distortion behavior**, and **high-frequency transient** features indicative of arcing behavior.

Integration of these features may further improve **disturbance classification** and **precursor identification** capabilities.