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Automated Waveform Characterization for Providing Situational Awareness to Distribution System Operators

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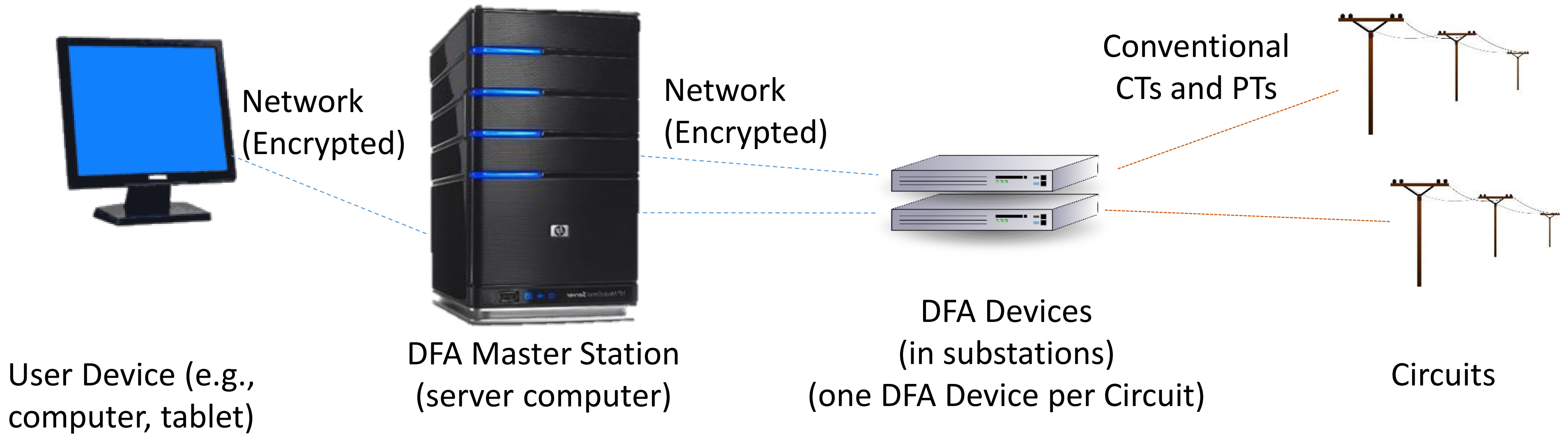
Presentation Outline

- Background on source of examples and data (DFA technology research and system)
- Two examples illustrating how the root cause of a fault can be far from where you find the initial evidence
  - Fault-induced conductor slap
  - Arrester failure caused by arcing internal to distant capacitor bank
- Conclusions

Background
DFA Technology

- Conventional distribution operations have limited awareness of circuit events and conditions.
- DFA technology, developed by Texas A&M Engineering, continuously monitors conventional CTs and PTs, with high fidelity, and automatically applies sophisticated waveform classification software to detect circuit events, including incipient failures. It reports them to personnel, giving them awareness and enabling action.
- Improved awareness (or visibility) enables improved circuit management and operations.

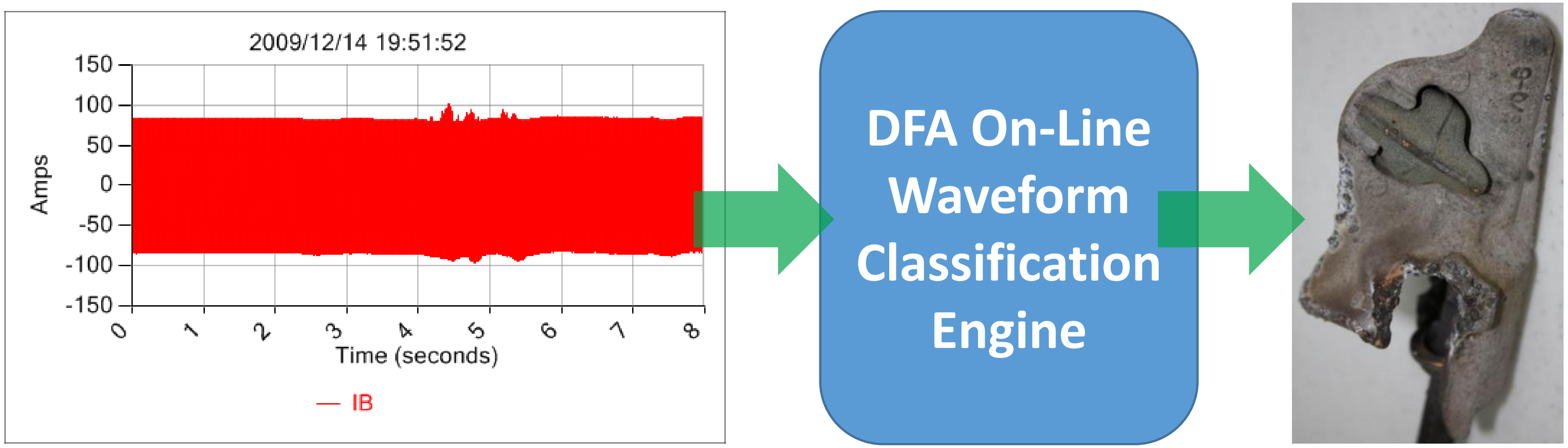
Background
DFA Monitoring Topology



Each substation-installed DFA Device runs waveform analysis and classification software and then sends results to a central DFA Master Station. Personnel access DFA results via browser connection to the DFA Master Station.

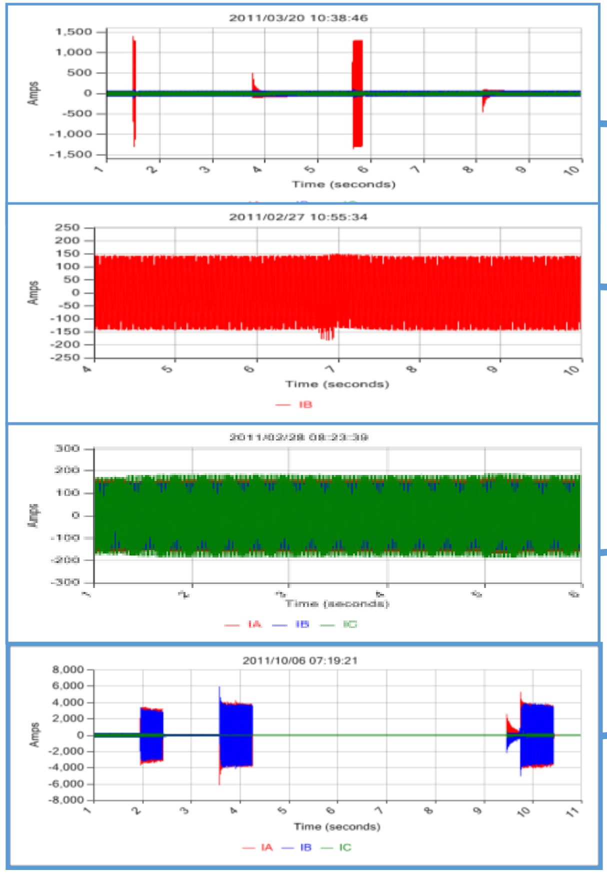
DFA Principle: Waveforms Contain Useful Information

- Graph shows line current during “normal” operations.
- DFA software reports this specifically as a failing clamp (which can persist for <u>weeks</u>, degrade service quality, and even burn down a line).



Waveform Classification – Behind the Scenes

Inputs: Substation CT and PT Waveforms



Waveform Analytics

DFA On-Line Waveform Classification Engine

(Signal Processing Performed by DFA Device in Substation)

Outputs: Event Reports

Event #1: Temporary fault cleared by trip/close of line recloser

Event #2: Failing hot-line clamp

Event #3: Faulty 1200 kVAR line capacitor

Event #4: Breaker lockout, caused by fault-induced conductor slap

*Analytics applied to high-fidelity substation waveforms report on hydraulic line reclosers, switched line capacitors, apparatus failures, etc, without requiring communications to line devices.

Waveform Classification – Behind the Scenes

DFA On-Line Waveform Classification Engine

(Signal Processing Performed by DFA Device in Substation)

DFA Device software technologies

- Multi-rate polyphase filter banks for phase drift compensation
- Fuzzy expert system for classification
- Fuzzy dynamic time warping for shape recognition
- Hierarchical agglomerative clustering for recurrent faults
- Finite state machine for fault SOE identification
- Shape-based and event-specific feature extraction
- Hierarchical classification architecture for feature space dimensionality reduction

The DFA on-line waveform classification engine uses sophisticated software to analyze waveforms and thereby identify circuit events.

Background
Texas Power Line-Caused Wildfire Mitigation Project

- Because many wildfires result from power line events, the Texas legislature established the Texas Power Line-Caused Wildfire Mitigation project, based on Texas A&M Engineering's DFA technology.
- Participants instrumented 60+ circuits with DFA circuit monitors.
  - Austin Energy
  - BTU (Bryan Texas Utilities)
  - Mid-South Synergy Electric Coop
  - Sam Houston Electric Coop
  - Bluebonnet Electric Coop
  - Concho Valley Electric Coop
  - Pedernales Electric Coop
  - United Cooperative Services
- Most DFA circuit monitors have been installed 2-3 years.
- Multiple participants are expanding deployments in 2018.

Background
Texas Power Line-Caused Wildfire Mitigation Project

Partial List of Events Detected and Corrected by Project Participants

- Detection and repair of substantial number of routine outages, without customer calls.
- Detection and location of tree branch hanging on line and causing intermittent faults.
- Detection and location of intact tree intermittently pushing conductors together.
- Detection and location of broken insulator that resulted in conductor lying on and heavily charring a wooden crossarm.
- Detection and location of catastrophically failed lightning arrester.
- Detection and location of arc-tracked capacitor fuse barrel.
- Detection and location of multiple problems with capacitor banks.
- Detection and location of multiple instances of fault-induced conductor slap (FICS).

Most events have potential for fire ignition and also affect reliability and service quality.

Case Study

Fault-Induced Conductor Slap

(or, How A Tree Caused A Fault Miles Away)

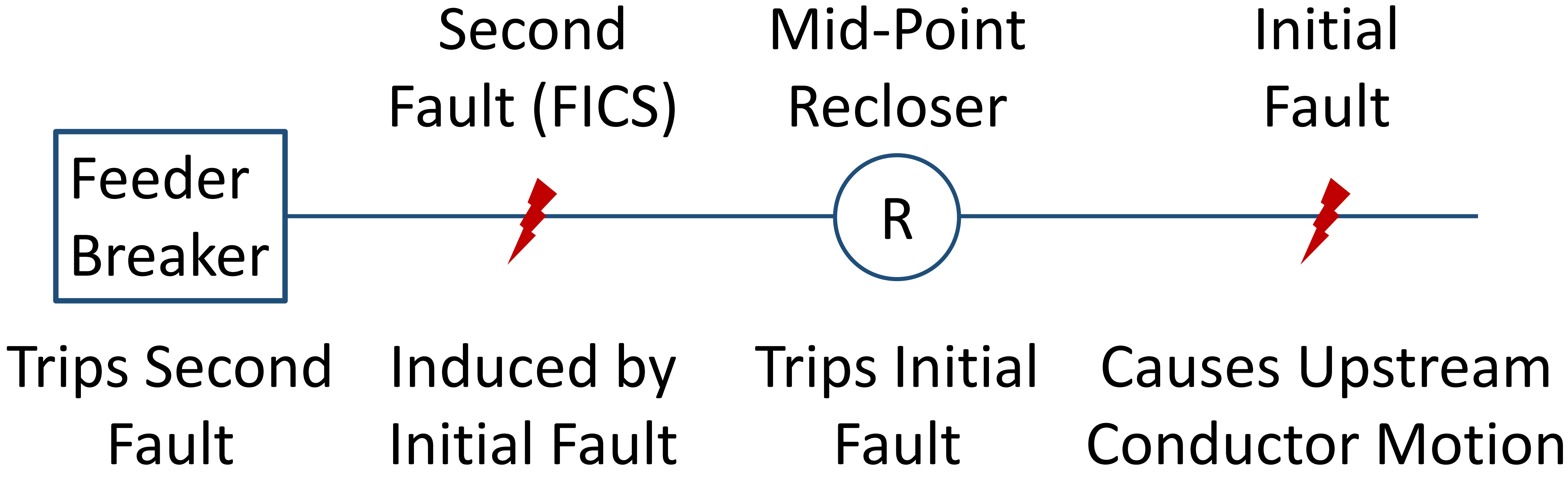
The Scenario (A Composite of Documented Field Cases)

- A tree three miles from a substation falls into a line and causes a fault.
- A mid-point recloser two miles from the substation locks out to clear the fault.
- But the substation circuit breaker also trips and locks out.
- Because the substation breaker tripped, the initial patrol focuses near the sub.
- The crew later expands the patrol, finds the tree, and restores service, but the outage was lengthened by the misdirected patrol.
- The utility notes apparent miscoordination of protection and investigates (retrieve and analyze data from all sources, test relay/breaker/recloser, …) but identifies no problem (other than the tree).
- The same sequence repeats a year later, by which time everyone has forgotten the first episode.

The Reason – Fault-Induced Conductor Slap (FICS)

- Recall electromagnetism theory: Currents in parallel conductors create magnetic forces between the conductors.
- Two-phase faults (opposite-direction currents) cause conductors to repel each other, displacing them from their neutral resting positions.
- Operation of a mid-point recloser instantaneously removes forces, and gravity pulls the conductors back toward their at-rest positions.
- Momentum causes them to pendulum through their at-rest positions.
- Under the right set of fault parameters (amplitude, duration) and line geometry, conductors may make contact and cause a second fault.
- The second fault trips upstream protection, often the substation.

FICS Phenomenon – Conceptual Explanation



Recent Example of FICS – DFA-Generated Report

Possible conductor-slap	BC	Breaker trip F-(53.0c,1267A,BC)-T-(0,24,32)%-1.4s- F-(37.0c,2595A,BC)-T-2.3s-C-1.6s- F-(51.0c,1272A,BCN)-T-(0,32,34)%-3.8s- F-(37.0c,2581A,BC)-T-5.3s-C-1.5s- F-(58.0c,1256A,BCN)-T-(0,24,31)%-1.2s- F-(37.0c,2591A,BCN)-T	6 ops

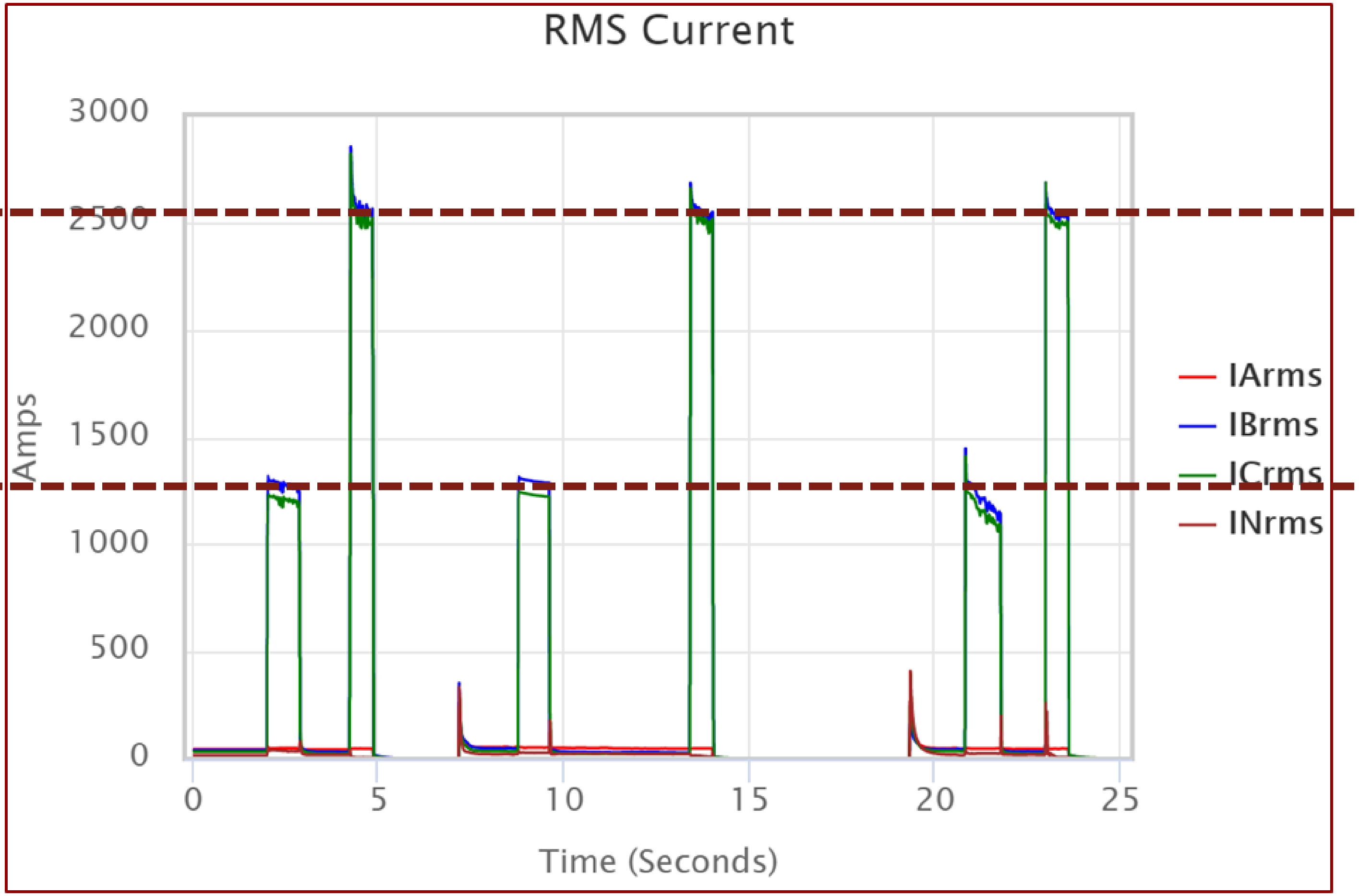
This is the report that the DFA system auto-generated and made available via website a few minutes after the event.

Recent Example of FICS – Summary of SOE

Element	Amps	Load Interrupted			Protection Device*
		A	B	C	
1	1267	0	24	32	Mid-Point Recloser
2	2595	All	All	All	Sub Circuit Breaker
3	1272	0	32	34	Mid-Point Recloser
4	2581	All	All	All	Sub Circuit Breaker
5	1256	0	24	31	Mid-Point Recloser
6	2591	All	All	All	Sub Circuit Breaker

* Protection Device is inferred from other SOE elements. Other columns are copied from SOE.

Recent Example of FICS – DFA Recording



Second Fault: 2590 amps

Initial Fault: 1260 amps

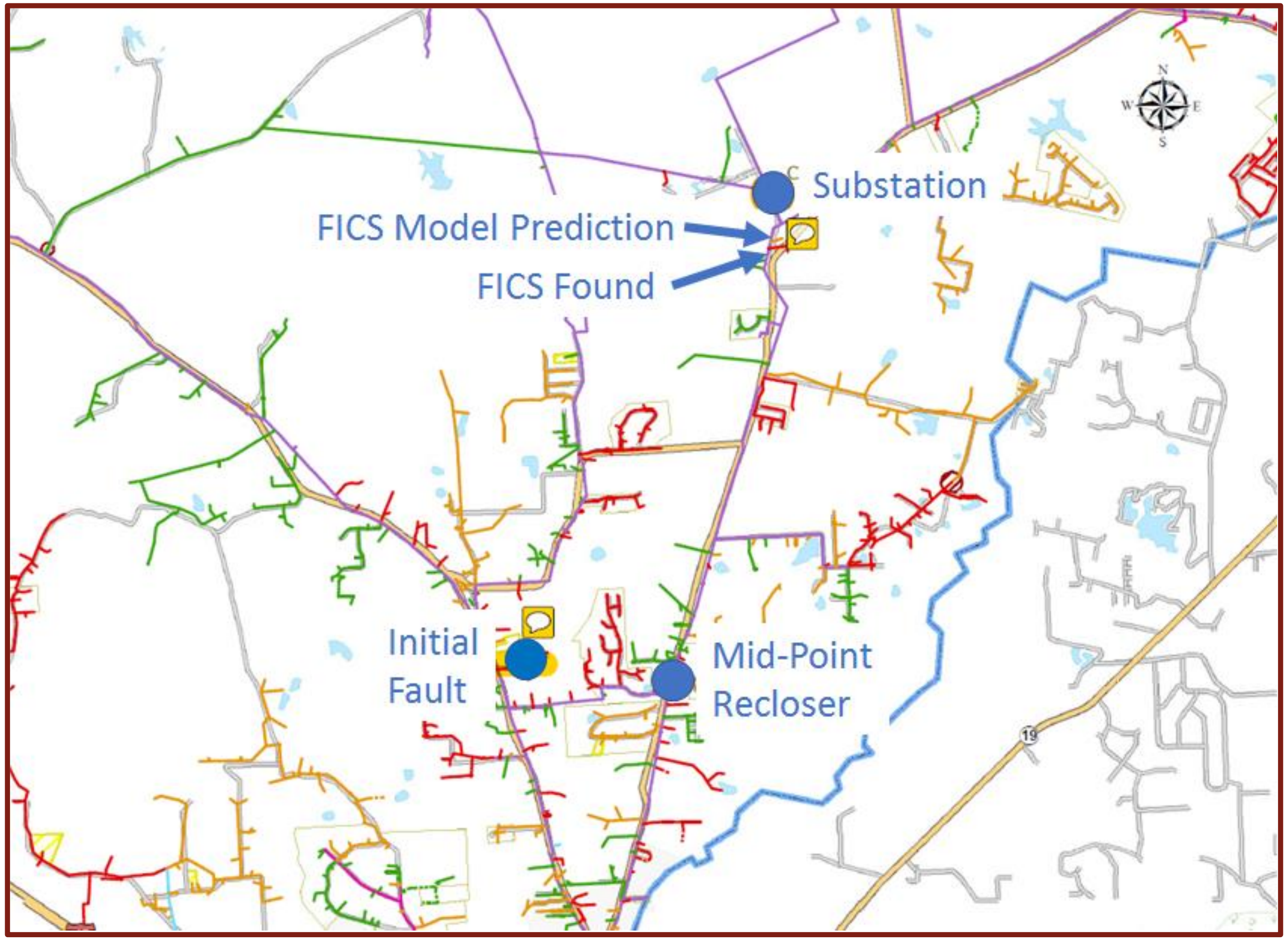
Note differing levels of load interrupted.

Locating FICS in General

- Once FICS is known to have occurred (without which, nothing), information is available to guide a patrol for the offending span.
- Repairs have been made, so the location of the initial fault is known.
- The mid-point recloser was tripped, so its location is known.
- FICS must lie between the substation and mid-point recloser.
- Putting fault amplitude into circuit model gets crew within a few spans.
- The offending span usually will have an unusual attribute (extra slack, extra long, transition span, closer-than-normal spacing, …) and will exhibit pitting and "bright spots."

Recent Example of FICS – Location

- Model predicted location close to substation.
- FICS evidence (pitting) was found five spans from prediction, in a transition span.
- FICS was 4.2 miles upstream of recloser.
- Absent DFA report, utility would have been unaware of this FICS.
- This is one of a number of similar examples detected by DFA.



Why Does It Matter?

Question: The FICS fault already caused the outage. Why does it matter that I know what caused it?

- Misdirected patrols
  - Information available in the immediate aftermath of the outage leads crews to patrol close to the substation, far from the actual fault.
  - This wastes man-hours and prolongs outages.
- Unproductive investigation
  - The most obvious initial evidence suggests miscoordination of protection.
  - An investigation proceeds under a false premise (miscoordination), wastes time pulling data, analyzing curves, testing breakers, etc., and results in "cause UNK."
- Recurrence – A susceptible span will experience FICS again.

Recurrent FICS

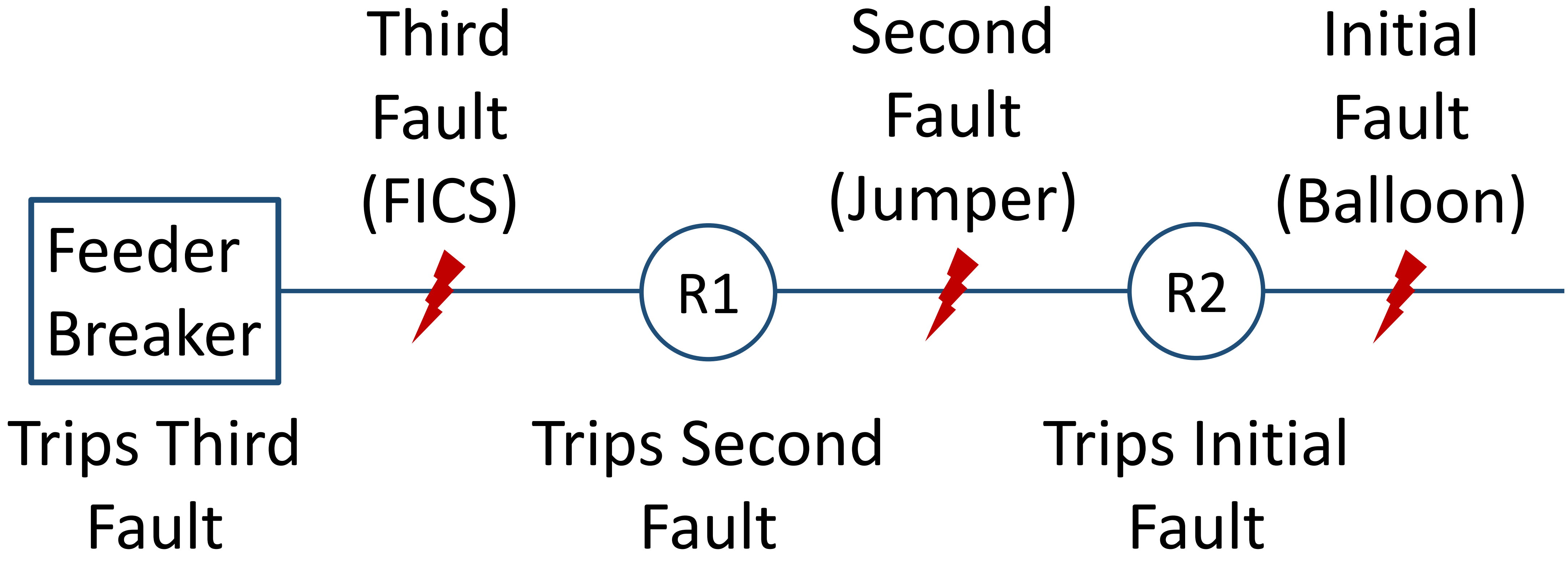
- 11/12/2007 – FICS trip/close
- 12/02/2007 – FICS lockout
- 11/13/2009 – FICS lockout
- 11/18/2009 – FICS trip/close
- 12/25/2011 – FICS lockout

<u>Summary</u>

- Five FICS events in four years
- Three lockouts, two momentaries
- All in a single span

- An FICS-susceptible span can experience repeated episodes.
- But those episodes may be separated by long periods of time, so the utility does not correlate them mentally.
- In addition to causing outages, recurrent FICS causes cumulative conductor damage, which ultimately could cause a broken conductor.

FICS – An Even More Complex Case (See Paper for Details)



Case Study

Arcing Capacitor Causing Failure of a Downstream Arrester

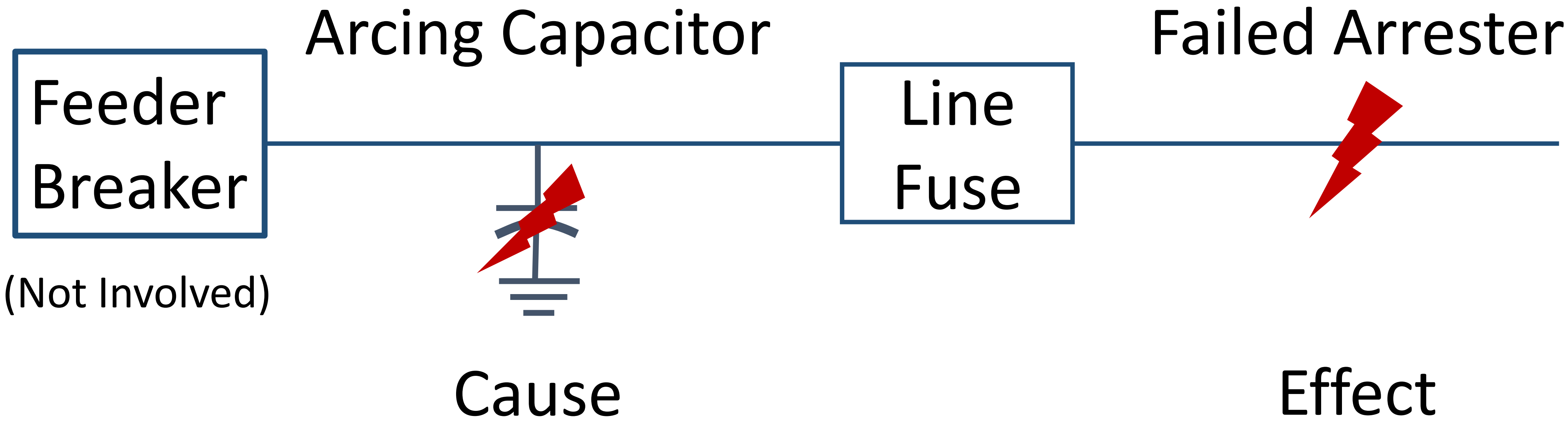
The Beginning

- Utility received customer report of outage and found a blown line fuse.
- After an initial patrol, the utility replaced the fuse, but it blew again.
- Subsequent patrol identified blown arrester as cause. Case closed, right?

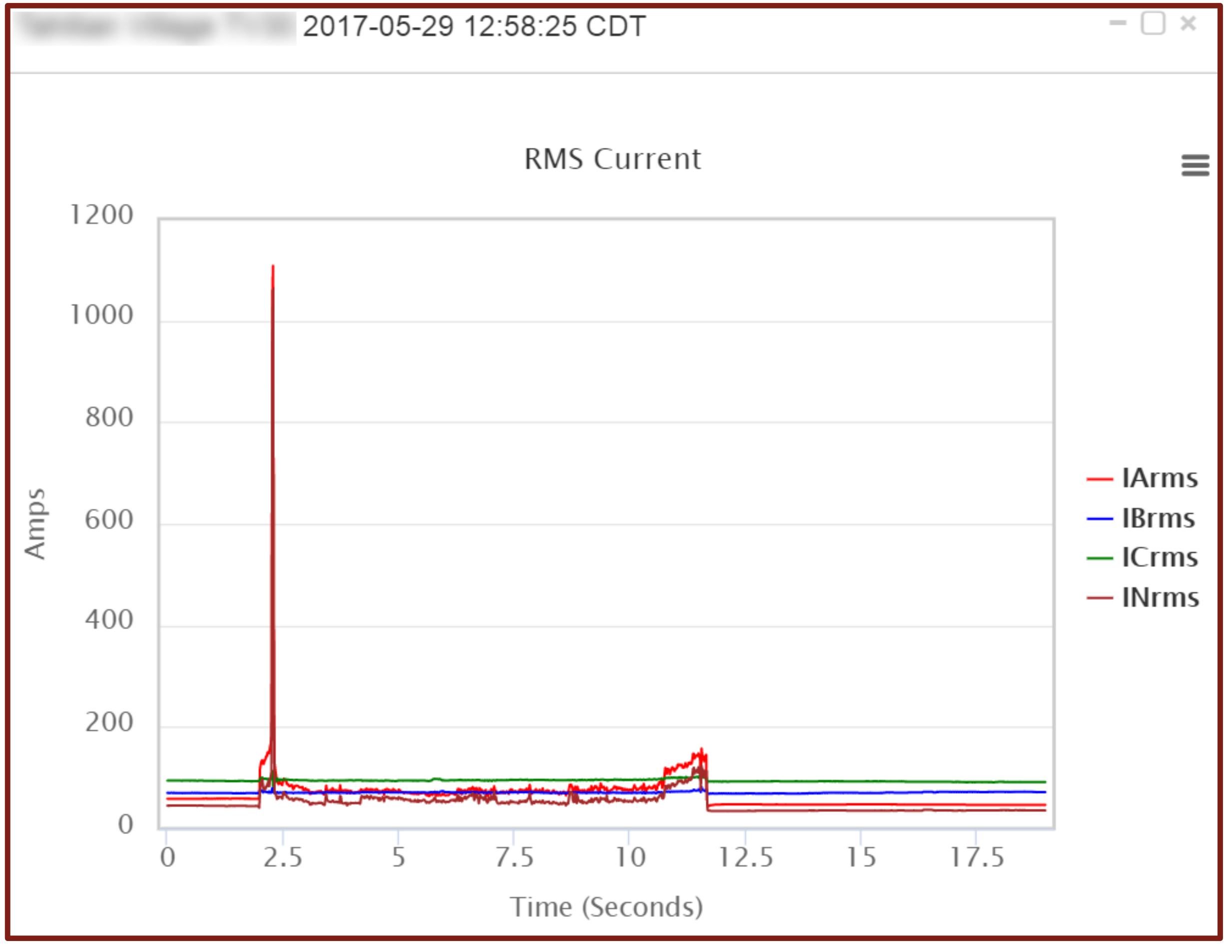
The Next Day

- Utility received customer report of outage and found a blown line fuse.
- After an initial patrol, the utility replaced the fuse, but it blew again.
- Subsequent patrol identified blown arrester as cause. Case closed, right?
- Next-day analysis of DFA recording indicated:
  - Capacitor arcing right before the high-current fault (arrester failure).
  - Continued arcing for nine seconds after the high-current fault blew the line fuse.
  - Loss of about 150 kvar, on faulted phase, when capacitor arcing ceased.
- Conclusion: arcing capacitor precipitated arrester failure, blowing fuse, and then burned capacitor open.

Diagnosis Theorized Based upon Analysis of Data

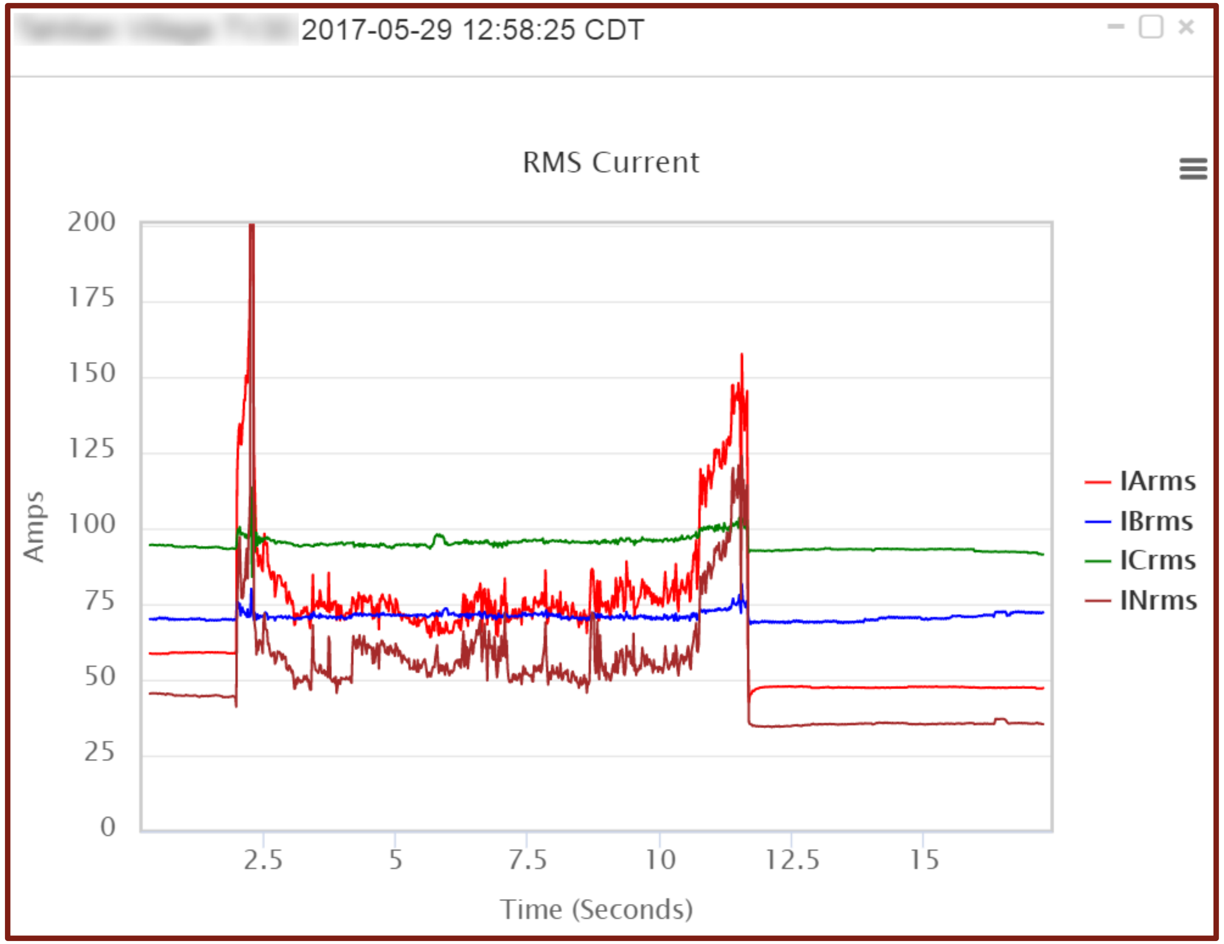


Capacitor Arcing and Lightning Arrester Failure



- The next six slides review the data recording used for the diagnosis.
  - Low-amplitude capacitor arcing occurred before and after the high-current fault blew the line fuse.
  - Circuit lost 150 kvar of reactive power at the end of the event.
- Crew found blown fuse on 150 kvar capacitor.

Capacitor Arcing and Lightning Arrester Failure



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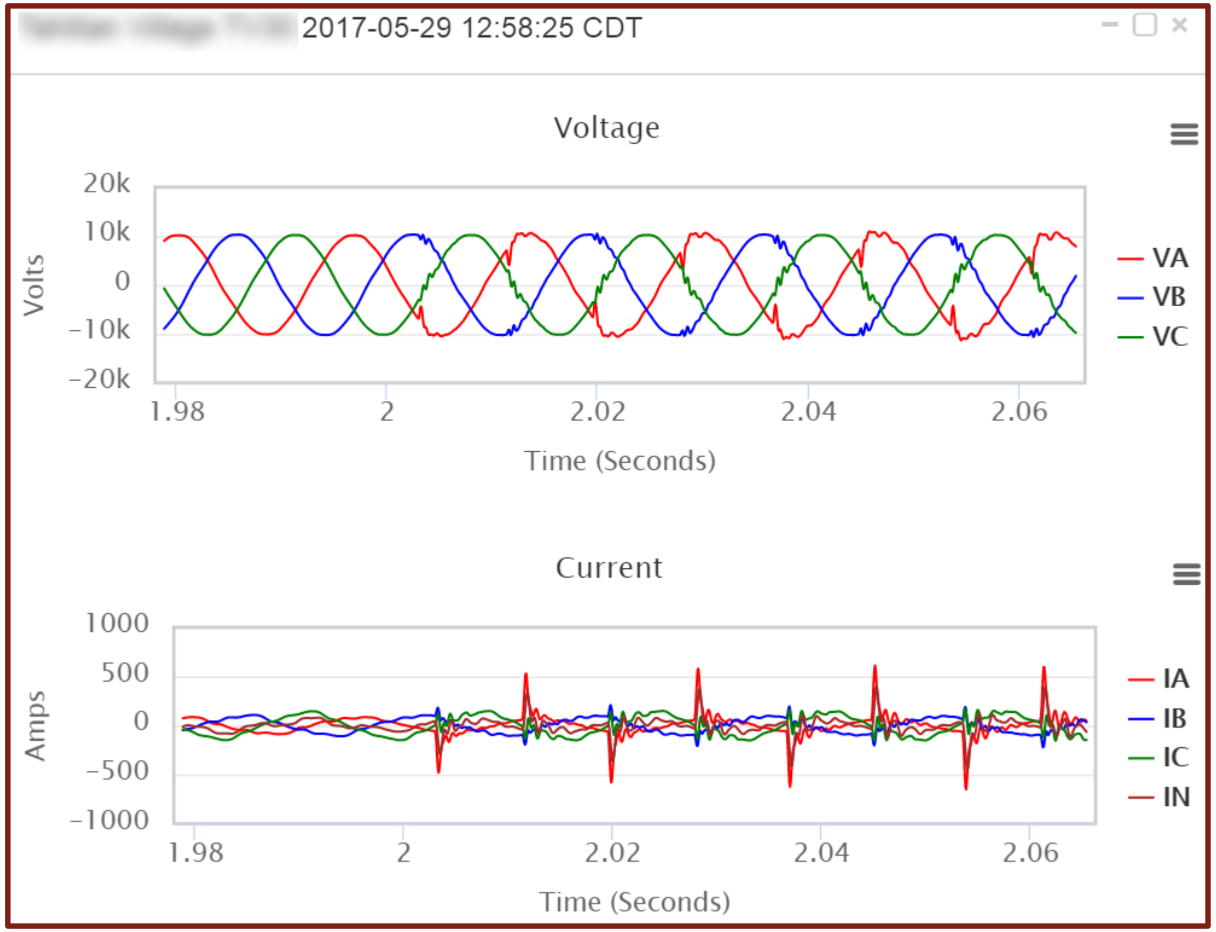

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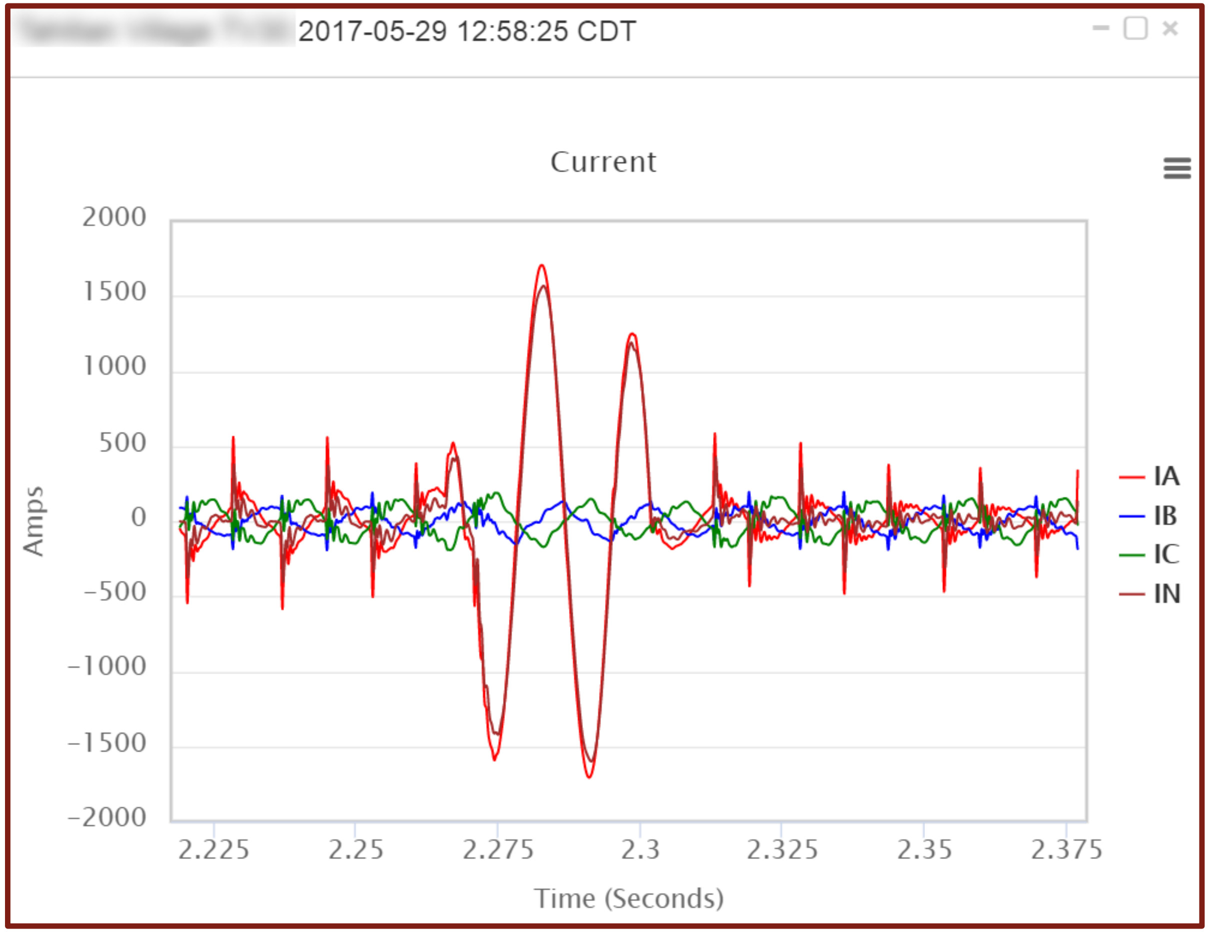

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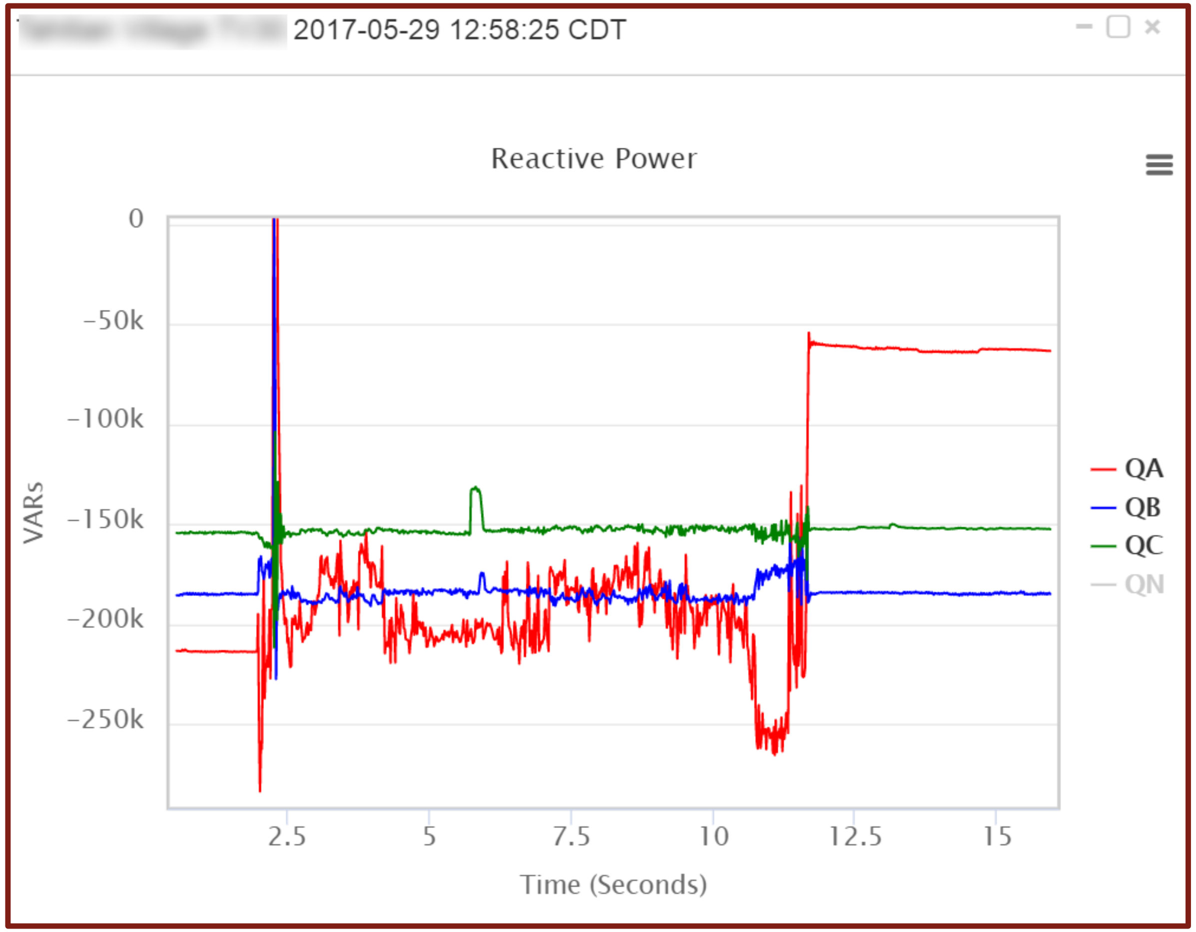

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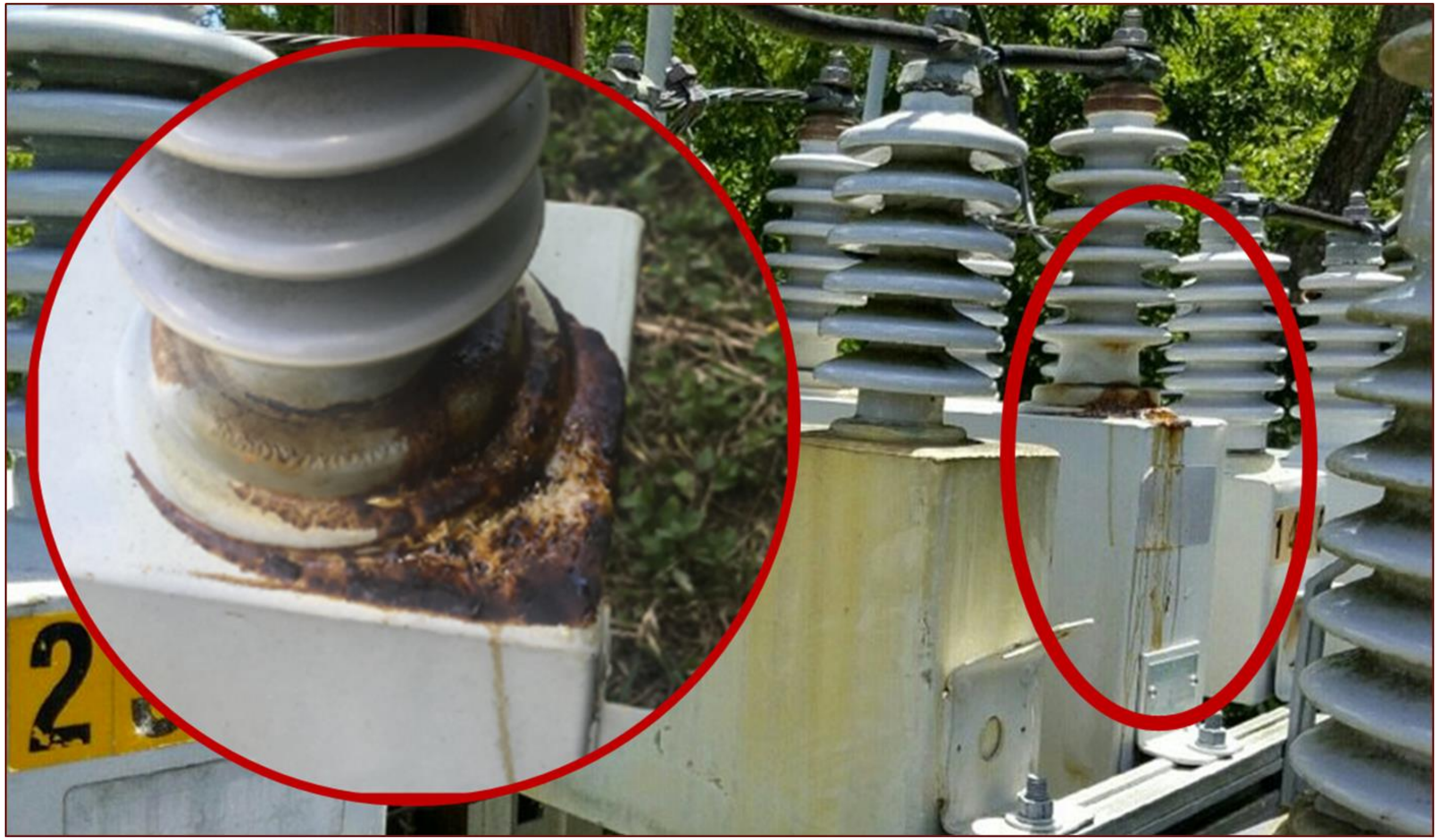
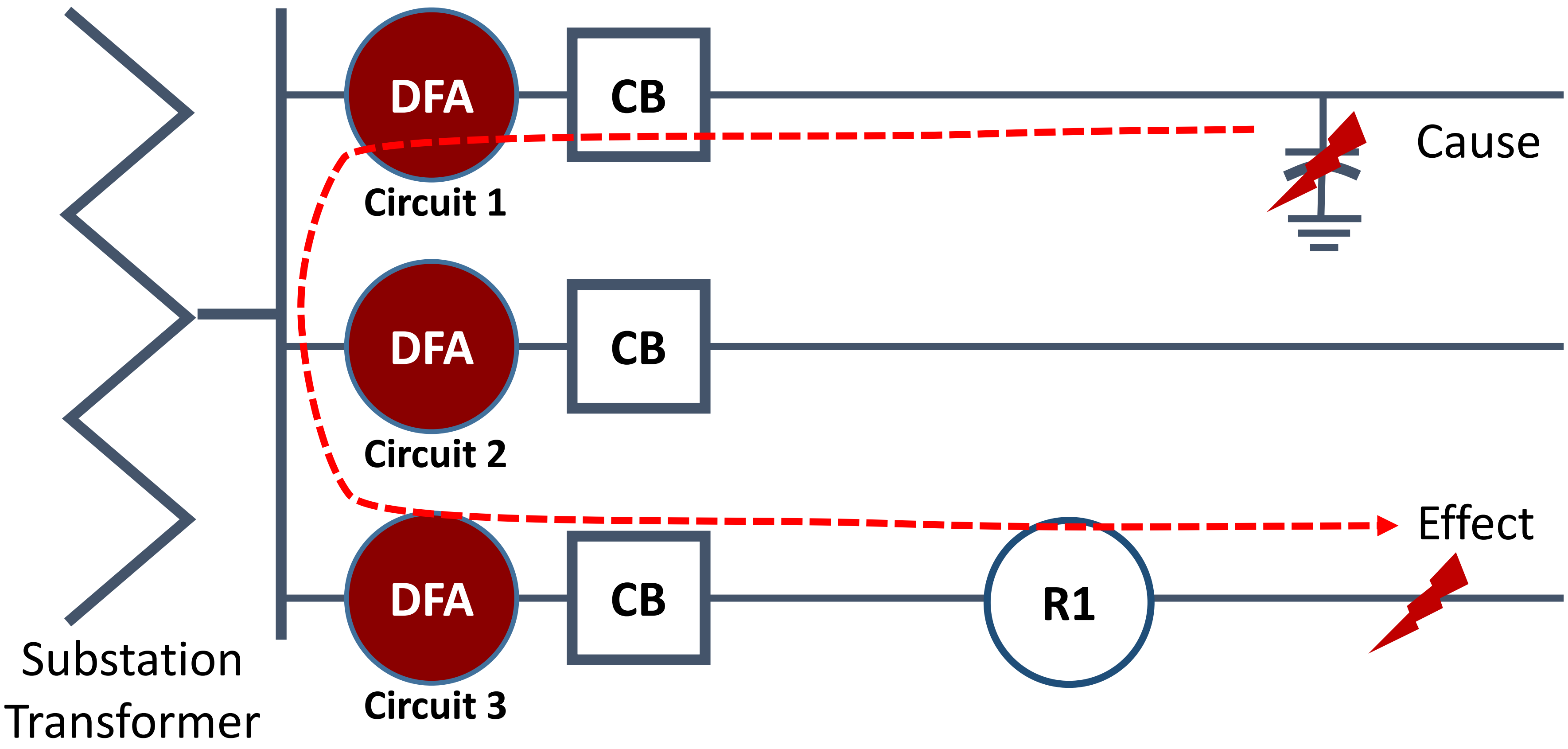
The Finding – Internally Arced Capacitor

- Easy find: Inspected 450 kvar (150 kvar per phase) capacitor upstream of blown line fuse.
- Found blown capacitor phase fuse and evidence of leakage.



Capacitor Arcing and Lightning Arrester Failure
(Another Example)



Conclusions

- The root cause of an event is not necessarily near the fault or near the location where the first evidence is found.
- Waveform data contains information that in some cases is the only way to diagnose what really happened.
- Some phenomena (e.g., FICS) are poorly understood by the industry, seldom diagnosed properly, and occur more frequently than appreciated. Automatic analysis and reporting are key to improved detection and correction of such problems.