Distribution Fault Anticipation

Improving Reliability and Operations by Knowing What Is Happening on Your Feeders

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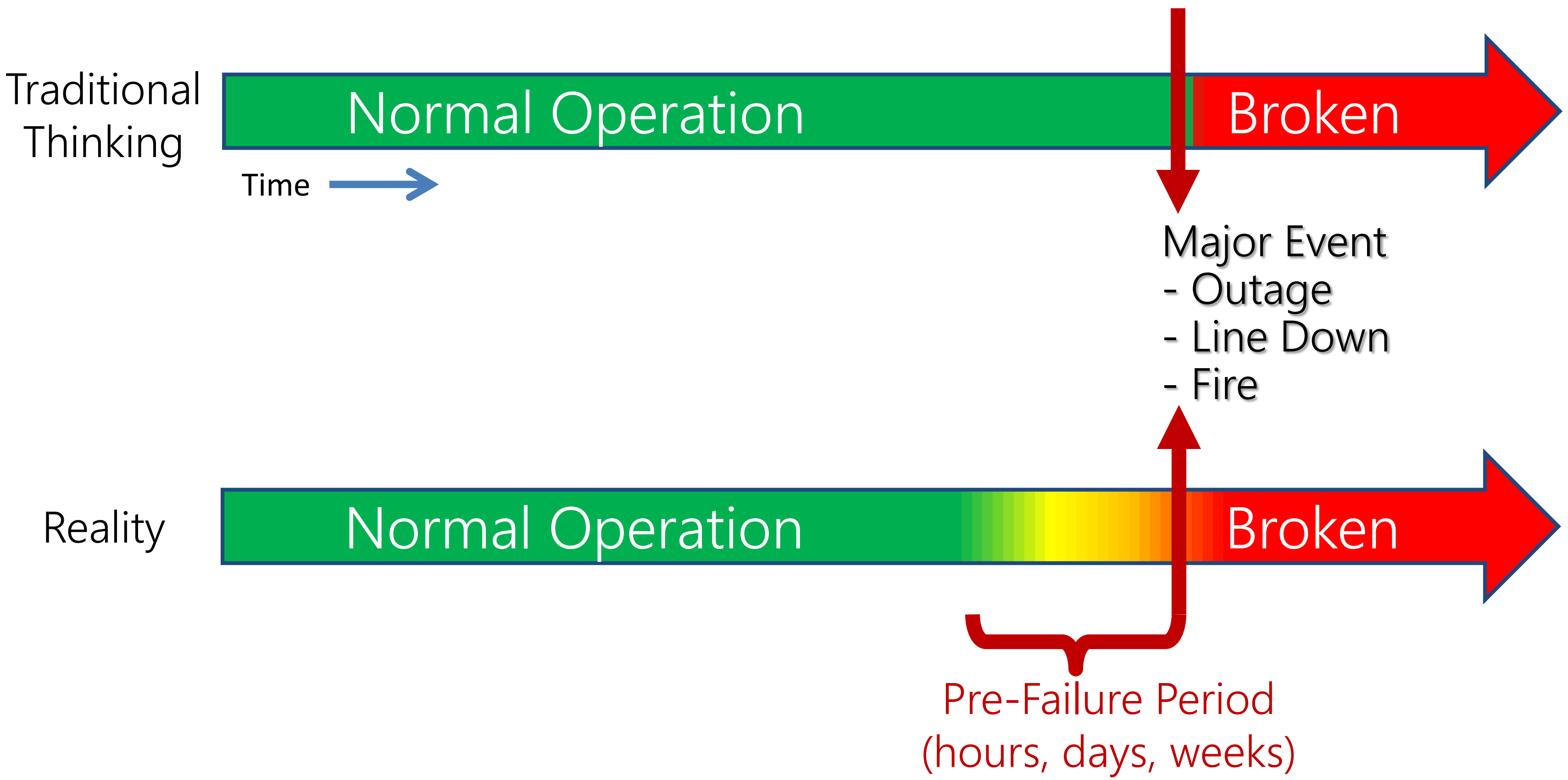
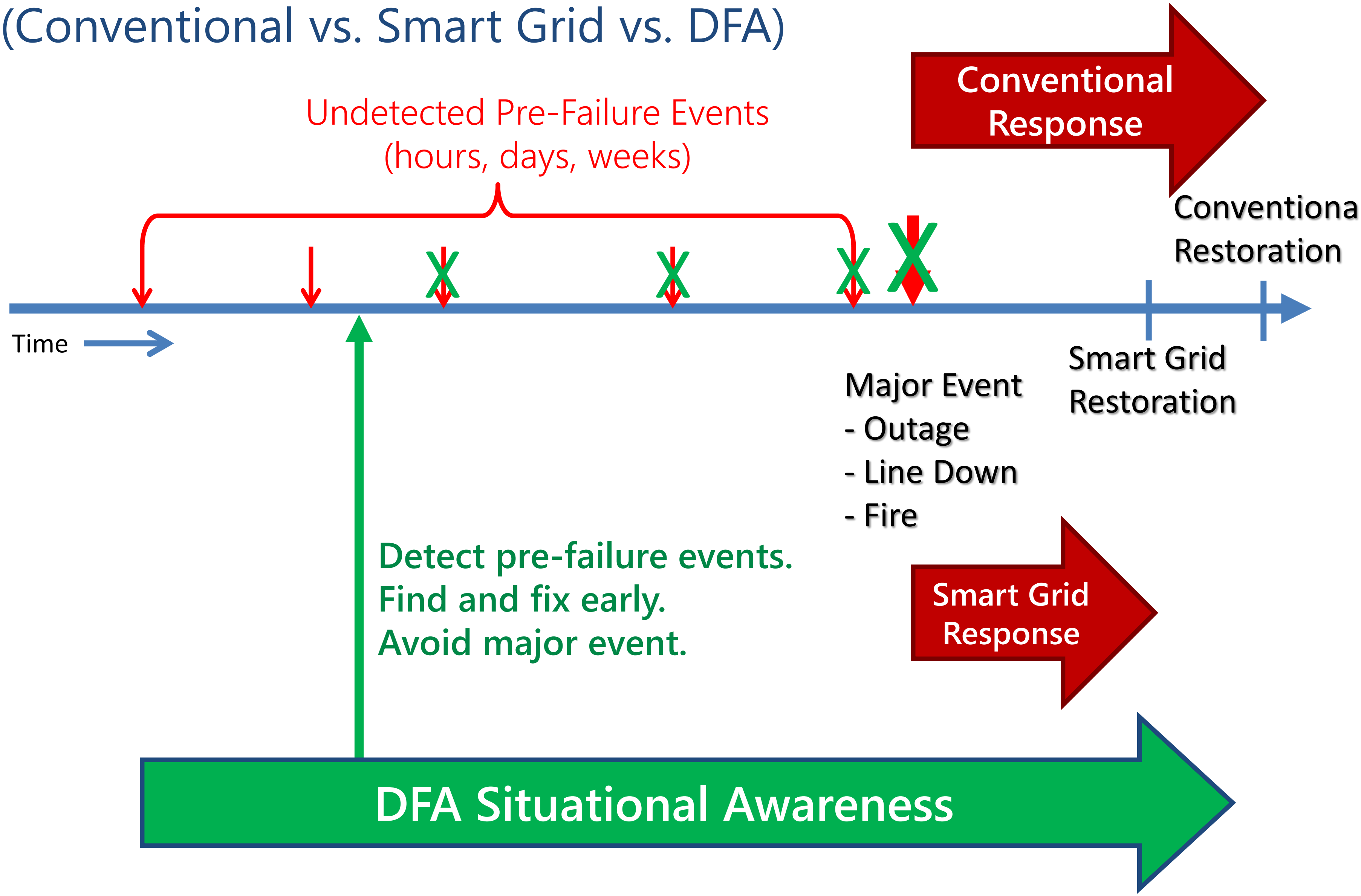
Electrical Feeder Operational Paradigms



Imagine detecting pre-failures and making repairs before major events occur.

Situational Awareness or "Visibility"

(Conventional vs. Smart Grid vs. DFA)



Fundamental Principles of DFA Waveform Analytics

- Feeder-level electrical waveforms represent feeder activity.
- Sophisticated waveform analytics, applied to waveforms of sufficient fidelity, can detect failures, pre-failures, and other feeder events.
  - PQ meters and relays have the same inputs (i.e., CTs and PTs) but do not record data of sufficient fidelity to support DFA functions.
- Waveform analytics also report operations of line devices (reclosers, capacitors, etc.), enabling oversight of those devices, without requiring communications to them.

With support from EPRI and others, Texas A&M has developed an on-line system of waveform analytics. This system, known as DFA Technology, provides a new level of situational intelligence that enables improvements in reliability, operational efficiency, and safety.

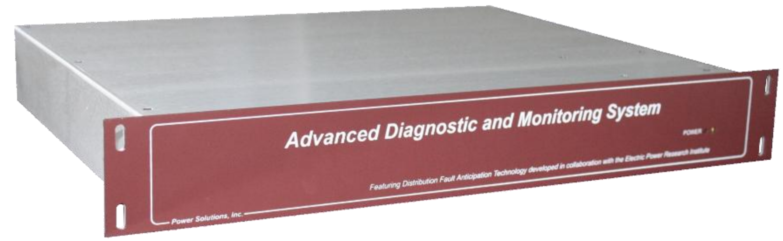
DFA Foundational Research

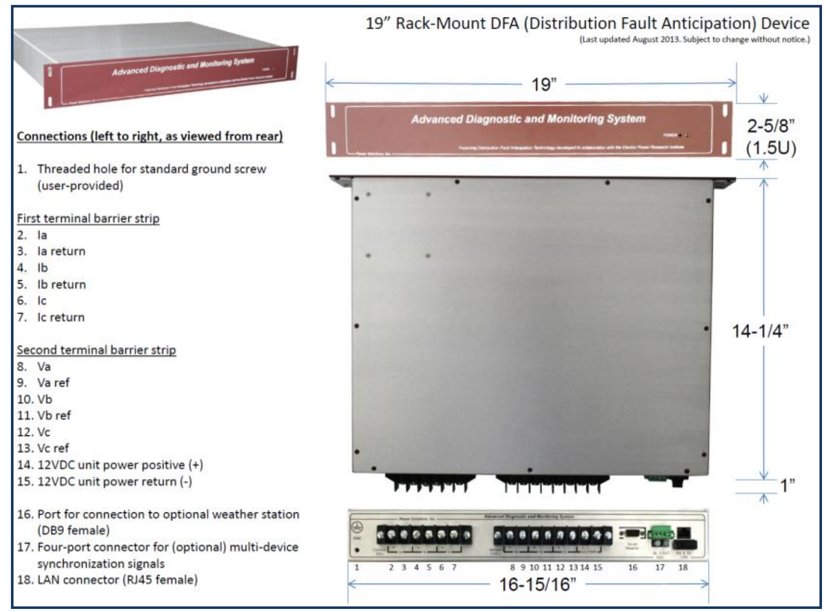
- A Decade of Field Research
  - Instrumented dozens of feeders at 10+ utilities
  - Created largest database of failure signatures in existence
  - Analyzed waveform anomalies and correlated with failure events
  - Discovered unique signatures for specific failures
  - Developed automated reporting to deliver actionable information
- Self-Imposed Constraints
  - Conventional sensors
  - Substation equipment only; distributed electronics not required
- Result: Improved power system reliability, operational efficiency, and safety enabled by advanced monitoring of electrical signals

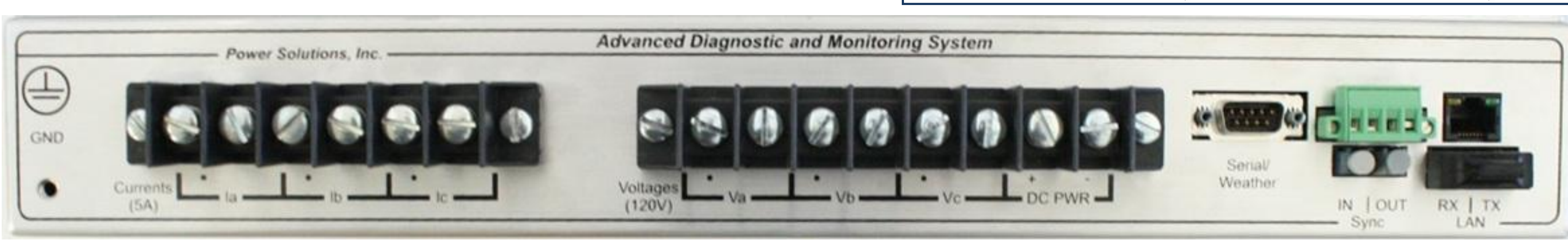
Research Partners

Hardware Description

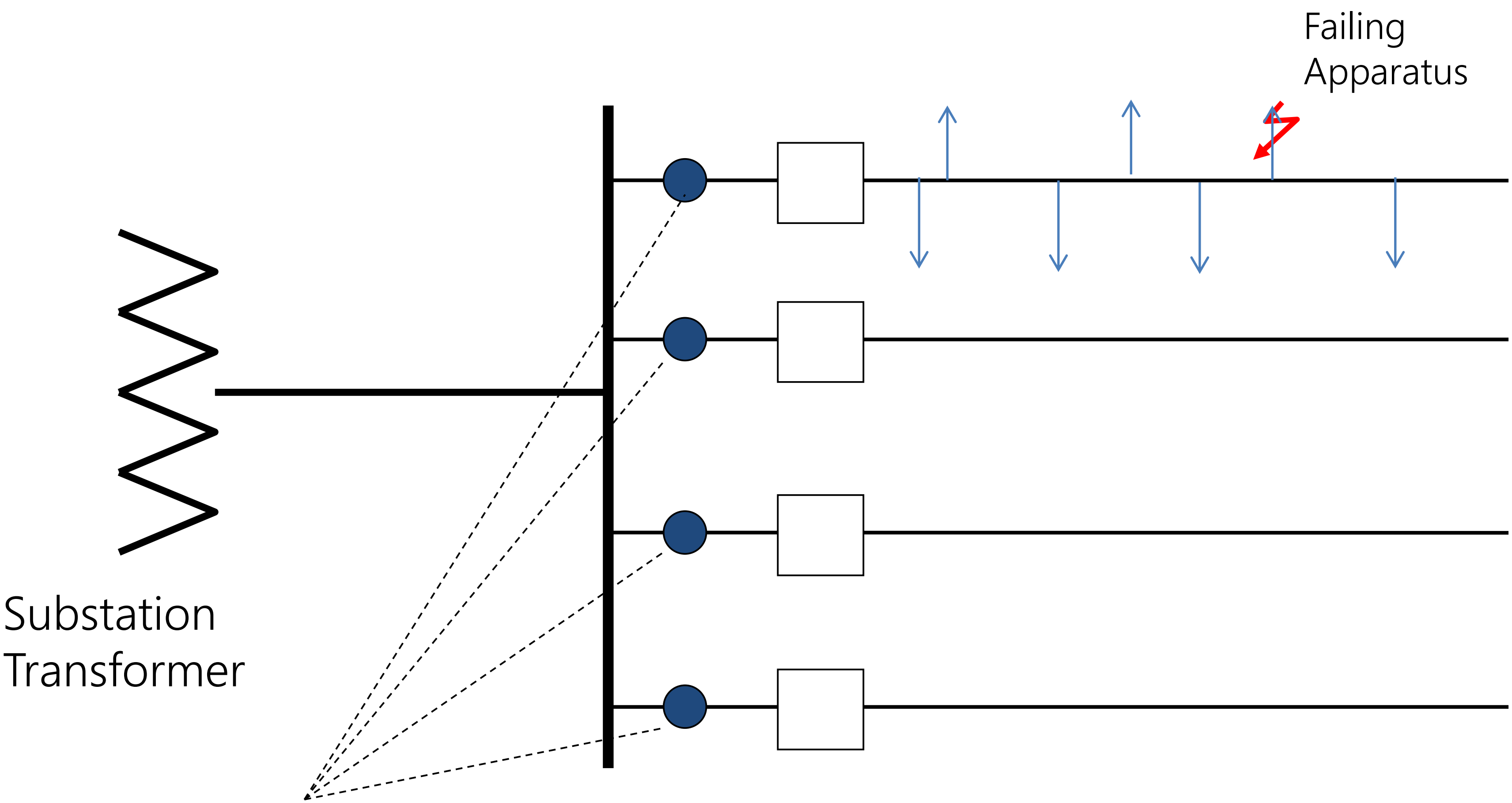
- Standard 19" rack-mount substation equipment
- One device per feeder
- Uses conventional CTs and PTs
- No distributed electronics or communication required
- Communicates with master station via Internet







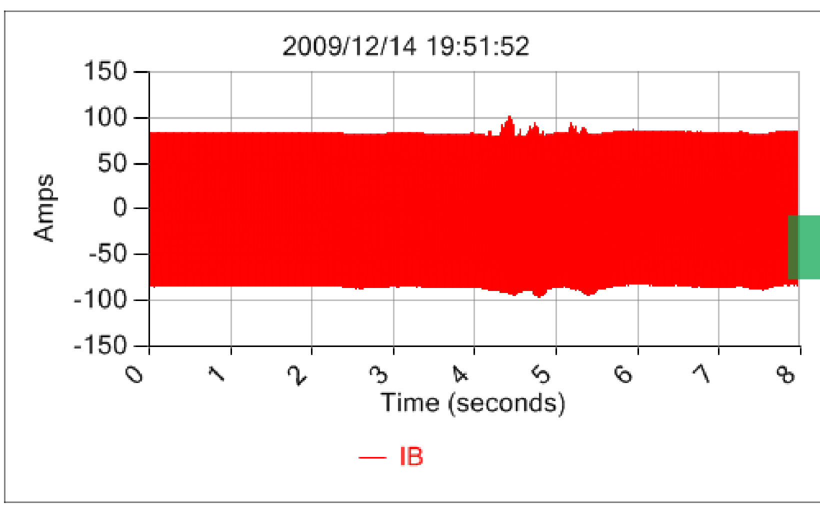
Monitoring Topology

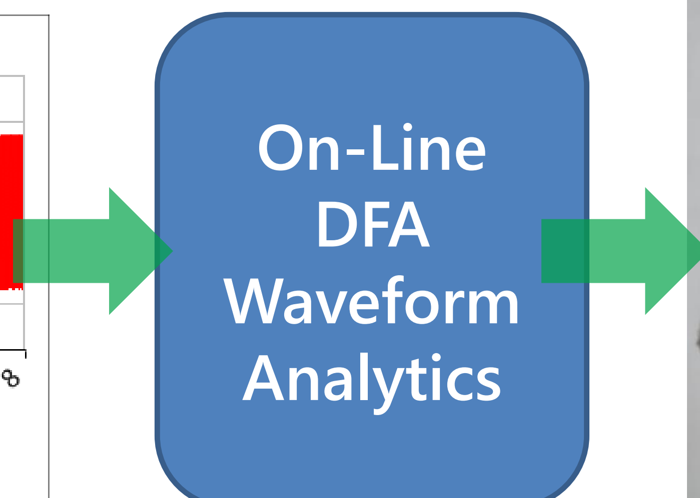


High-fidelity DFA devices, connected to conventional CTs and PTs, one per feeder.

Fundamental Principle – An Illustration

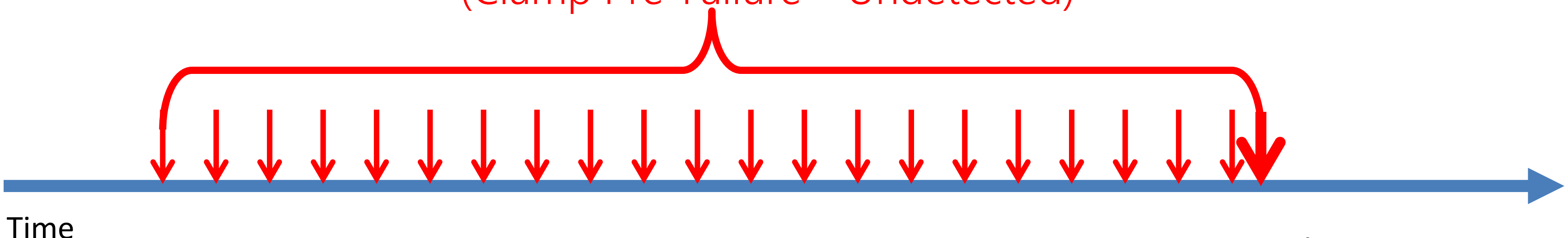
- Graph shows current during “normal” feeder operations.
- Conventional technologies do not detect pre-failures such as this one.
- Waveform analytics recognize this specifically as a pre-failure clamp waveform signature. Pre-failure clamps can degrade service quality, drop hot metal particles, and in extreme cases burn down lines.





Example Scenario

2,333 Events in 21 Days
(Clamp Pre-Failure – Undetected)



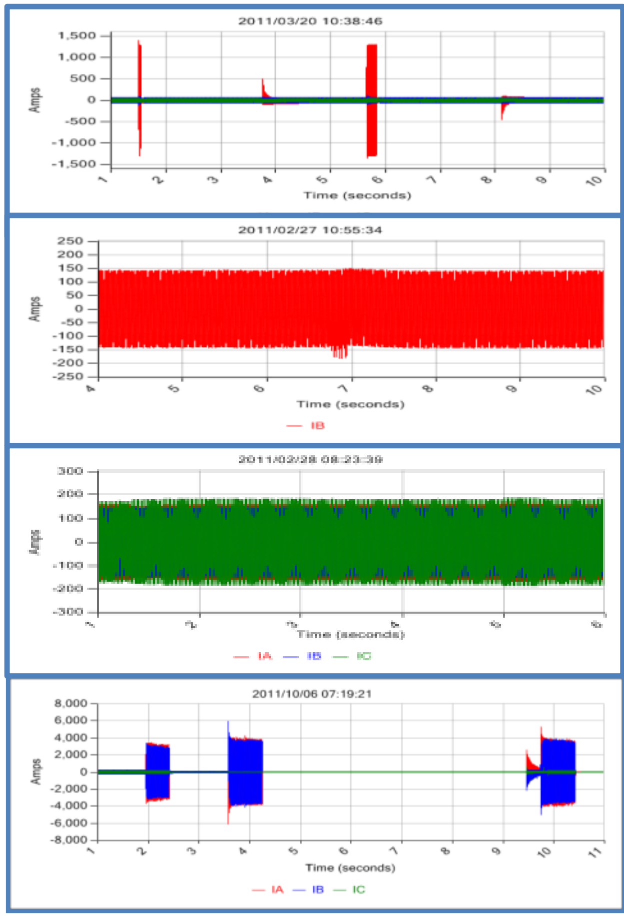
Major Event
- Outage
- Line Down

With conventional technology, utility companies learn of the major event but are unaware of the pre-failure activity. DFA provides "awareness" of feeder events, including pre-failures.

Composite of Actual Events

Waveform-Based Analytics – Behind the Scenes

Inputs: Substation CT and PT Waveforms



Waveform Analytics

On-Line Signal Processing and Pattern Recognition Analytics

(Performed by DFA Device in Substation)

Outputs

- Line recloser* tripped 8% of phase-A load twice, but reclosed and did not cause outage
- Failing hot-line clamp on phase B*
- Failed 1200 kVAR line capacitor* (phase B inoperable)
- 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.

Documented Failures

- Voltage regulator failure
- LTC controller maloperation
- Repetitive overcurrent faults
- Lightning arrestor failures
- Switch and clamp failures
- Cable failures
  - Main substation cable
  - URD primary cables
  - URD secondary cables
  - Overhead secondary cables
- Tree/vegetation contacts
  - Contacts with primary
  - Contacts with secondary services
- Pole-top xfmr bushing failure
- Pole-top xfmr winding failure
- URD padmount xfmr failure
- Bus capacitor bushing failure
- Capacitor problems
  - Controller maloperation
  - Failed capacitor cans
  - Blown fuses
  - Switch restrike
  - Switch sticking
  - Switch burn-ups
  - Switch bounce
  - Pack failure

Certain failure types have been seen many times and are well understood. Others have been seen fewer times. DFA system architecture anticipates and accommodates updates to analytics as new events are encountered, analyzed, and documented.

Benefits of Pre-Failure Detection

(Partial List)

Power quality and reliability

- Improved SAIDI and SAIFI (avoided outages)
- Improved PQ (avoided momentary interruptions, sags, etc.)
- Improved customer satisfaction
- Better support of economic development

System stresses and liability

- Reduced stress on line equipment (e.g., transformers, lines, connectors, switches, reclosers)
- Reduced damage and liability from catastrophic failures (e.g., conductor burn-down, fire, transformer explosion)

Operational efficiency and other labor impacts

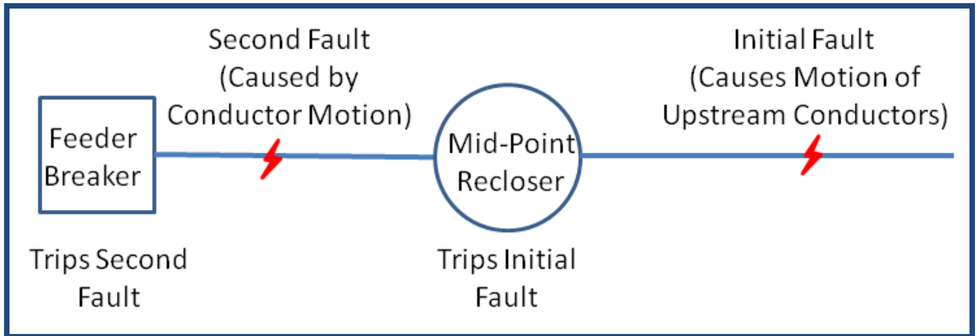
- Daylight, fair-weather, straight-time failure location and repairs
- Improved worker safety (fair-weather, daylight work)
- More efficient troubleshooting (e.g., fewer no-cause-found tickets)

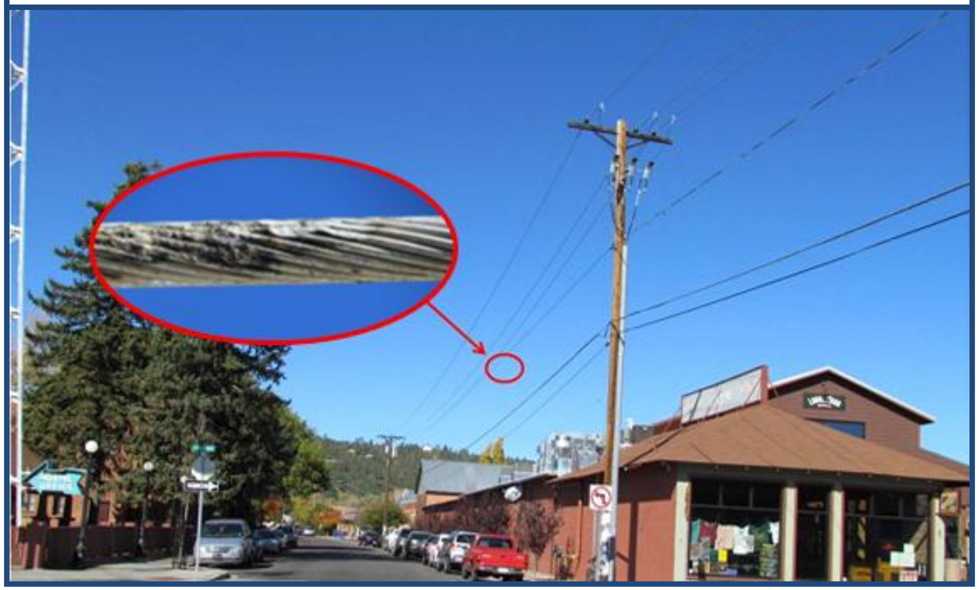
USE CASE SUMMARIES

Use Case Summary

Feeder Lockout (4,000 Customers)

- Fault-induced conductor slap (FICS) locked out 4,000-customer feeder.
- FICS is a complex phenomenon. Investigations are manpower-intensive and often conclude with "no cause found."
- Within minutes of the subject lockout, the DFA system reported the cause and the location parameters.
- FICS recurs in susceptible spans. Knowing that FICS occurred and finding the offending span enables remediation, so as to avoid future feeder outages.



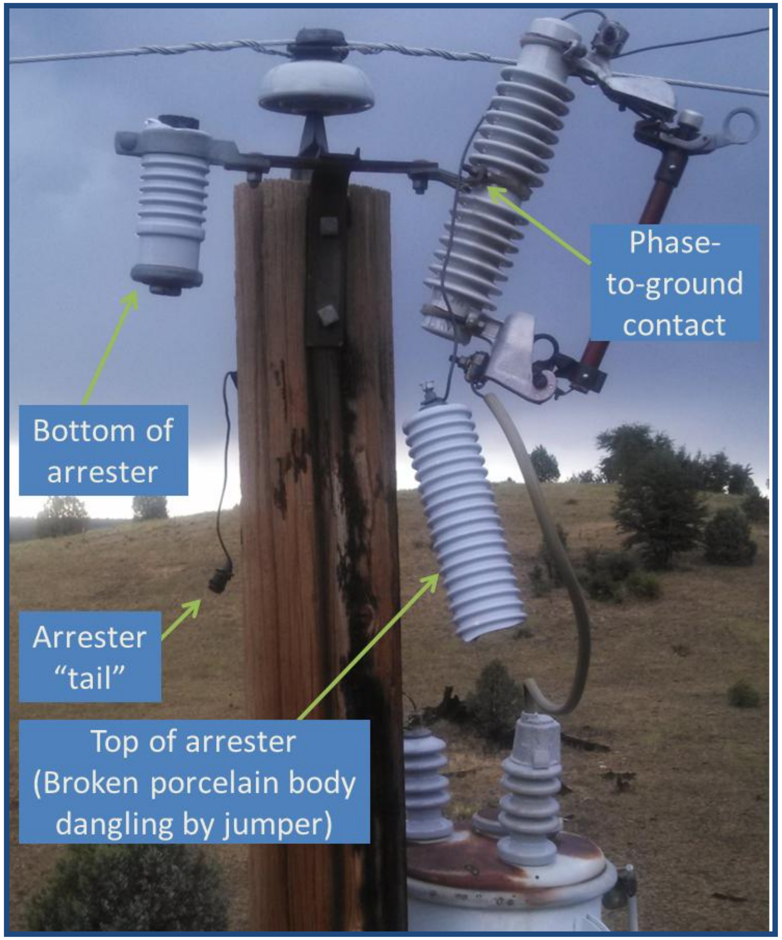


<u>Benefits</u>: Reduced manpower and improved reliability.

Use Case Summary

Diagnosis of Failed Line Apparatus

- Blown arrester caused outage in (very) hard-to-patrol area.
- DFA data provided fault current and suggested blown arrester.
- Feeder has many miles past the tripped device. Knowing the fault current reduces search time substantially.
- Crew typically must look for broken apparatus, tree contacts, downed lines, …. Knowing cause, from waveform analytics, speeds search.



<u>Benefits</u>: Reduced manpower; fewer close-to-test attempts; reduced effects on customers; and quicker restoration.

Use Case Summary

Repeated Vegetation-Caused Feeder Trips

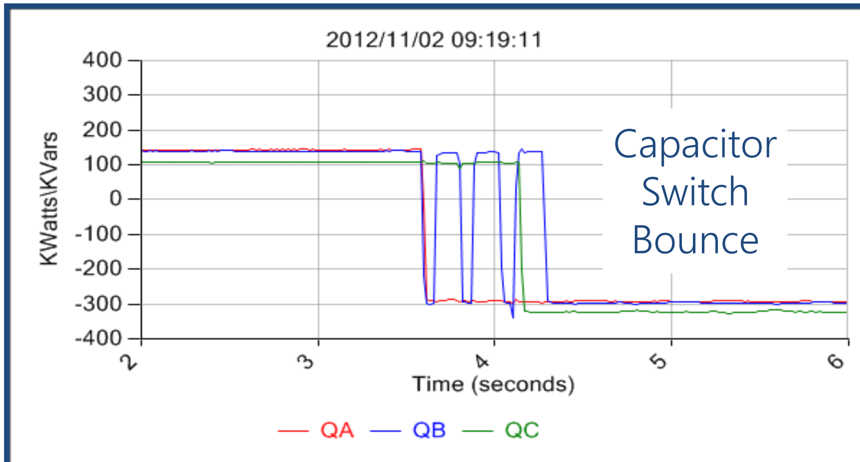
- Momentary breaker operations occurred during storms three weeks apart.
- DFA provide notice that both incidents were the same fault.
- DFA also provided information to locate branches pushing phases.
- Trimming prevented future consequences, including momentary operations, feeder lockouts, line damage, and potential burn-down.

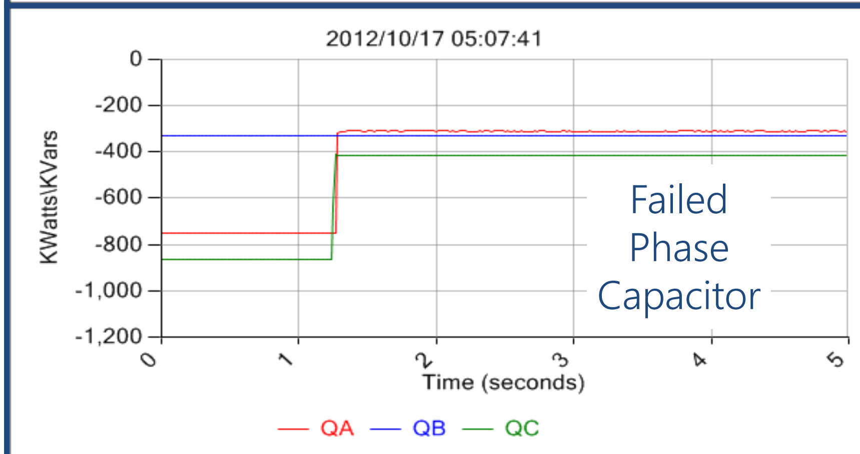
<u>Benefits</u>: Improved reliability; reduced damage; scheduled, fair-weather repairs; and improved personnel and public safety.

Use Case Summary

Management of Line Capacitors

- Traditional maintenance of switched line capacitors is labor-intensive and somewhat ineffective.
- Using waveform analytics, DFA reports failures of switched line capacitors …
  - without communicating with them.
  - without being configured to know they are even present.
- DFA detects types of capacitor failures that electronic controls…
  - do detect (e.g., blown fuses).
  - do not detect (e.g., restrike, switch bounce, arcing switch).



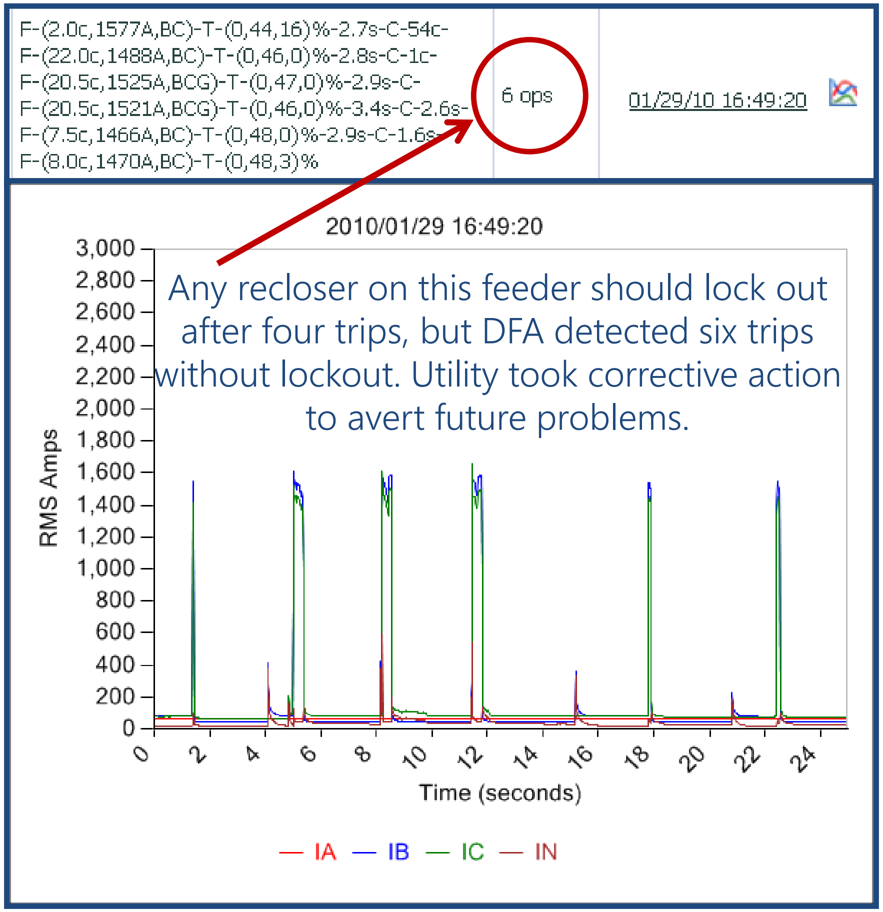


<u>Benefits</u>: Improved maintenance efficiency; better, faster detection of failures; and improved PQ.

Use Case Summary

Management of Unmonitored Line Reclosers

- Intelligent, communicating reclosers are available, but a large population of unmonitored reclosers remains in service for the foreseeable future.
- DFA reports recloser operations, in detail, based on substation waveforms.
- DFA has revealed multiple cases of reclosers operating incorrectly.
  - Excess operations before lockout.
  - Failure to complete sequence.
- DFA provides visibility of recloser operations, particularly for utilities that test reclosers irregularly.

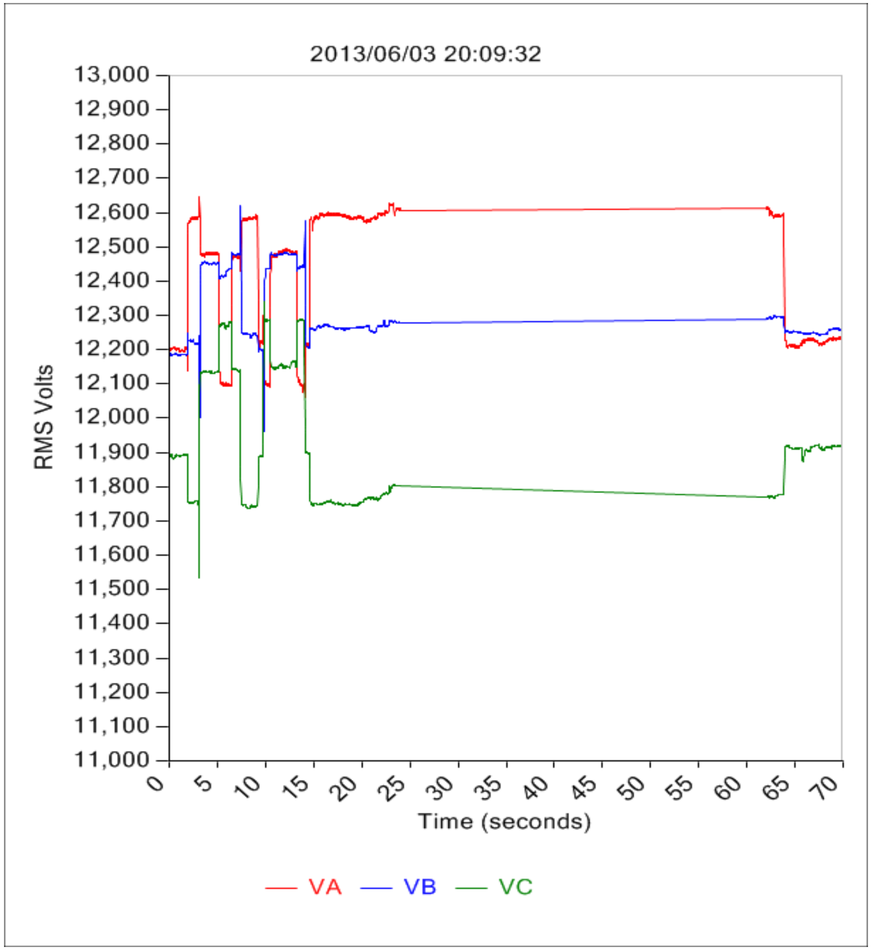


<u>Benefits</u>: Notice of latent problems; improved protection; improved operations; and improved safety.

Use Case Summary

Troubleshooting Complexity and Inefficiency

- Customers reported low voltage.
- Two interrelated problems existed.
  – A four-hour, multi-crew search identified a bad regulator.
  – A misbehaving capacitor slowed that search process by creating erratic line-voltage readings.
- If the crew had been aware of the capacitor problem, they could have turned it OFF and found the faulty regulator more efficiently.
- Routine maintenance does not find this kind of capacitor problem.



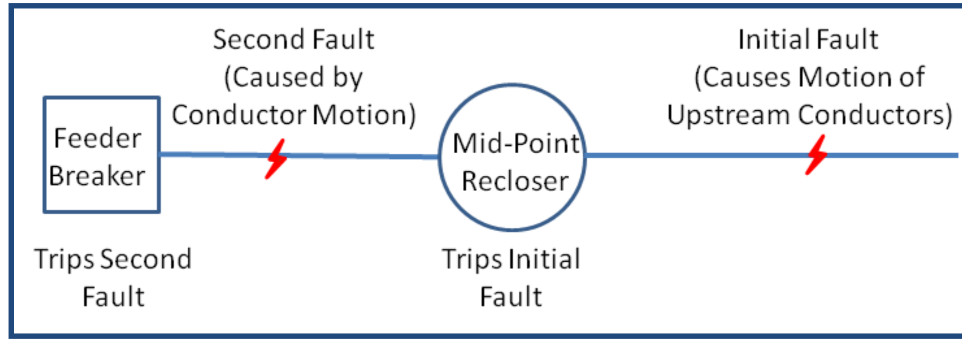
<u>Benefits</u>: Improved operational visibility; improved efficiency; improved power quality; and reduced manpower.

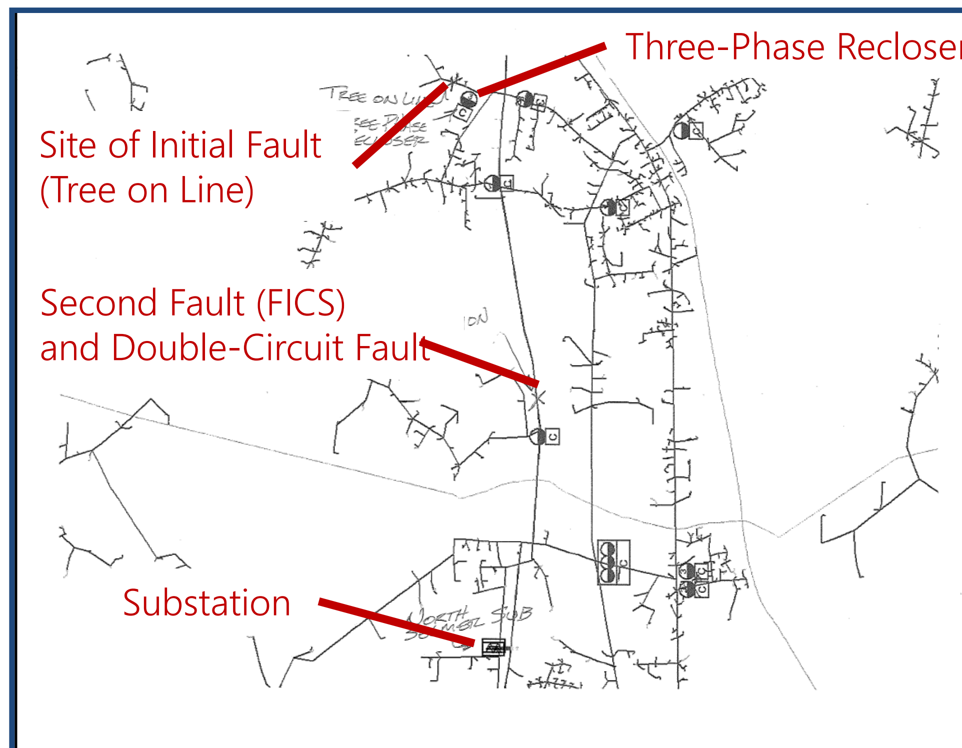
DETAILED USE CASES

Detailed Use Case

Double-Circuit Fault Resulting from Fault-Induced Conductor Slap (FICS)

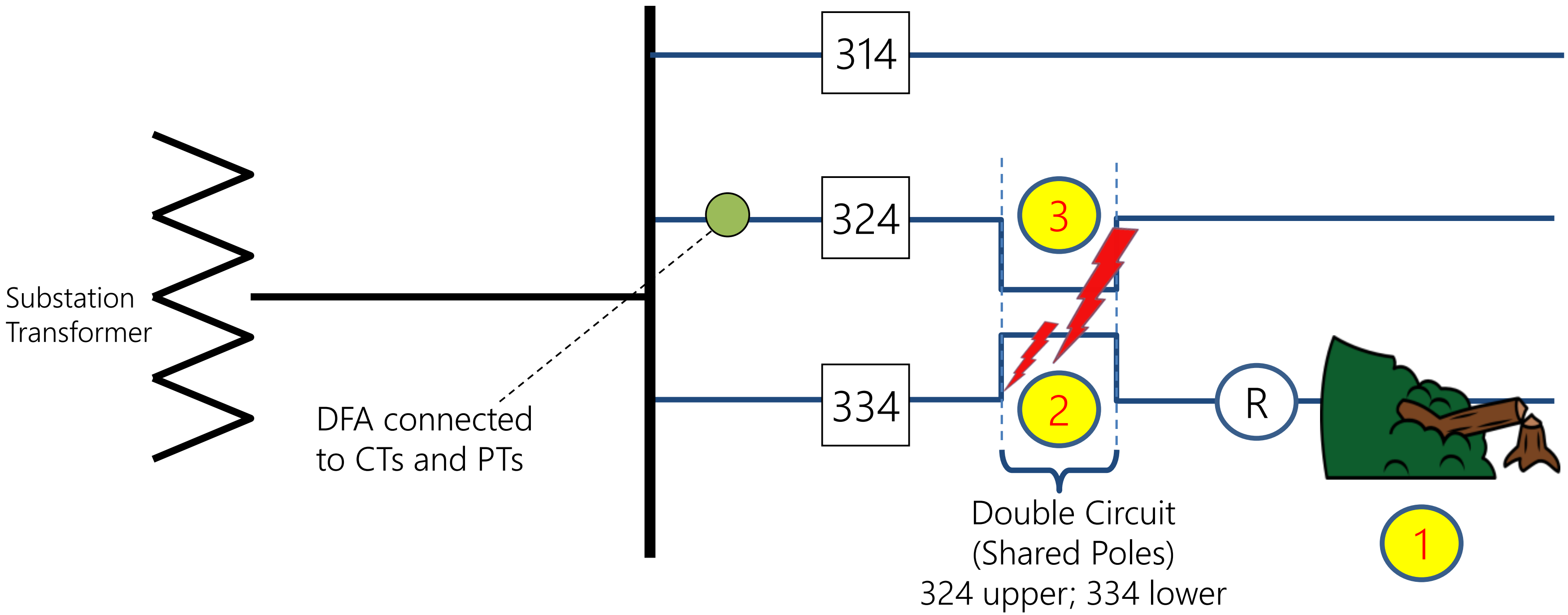
- A previous example described the FICS phenomenon.
- This current example details an episode of FICS that further evolved into a circuit-to-circuit fault.
- DFA recordings on the "second" circuit helped us diagnose this complex event.





Detailed Use Case

Double-Circuit Fault Resulting from Fault-Induced Conductor Slap (FICS) (cont'd)

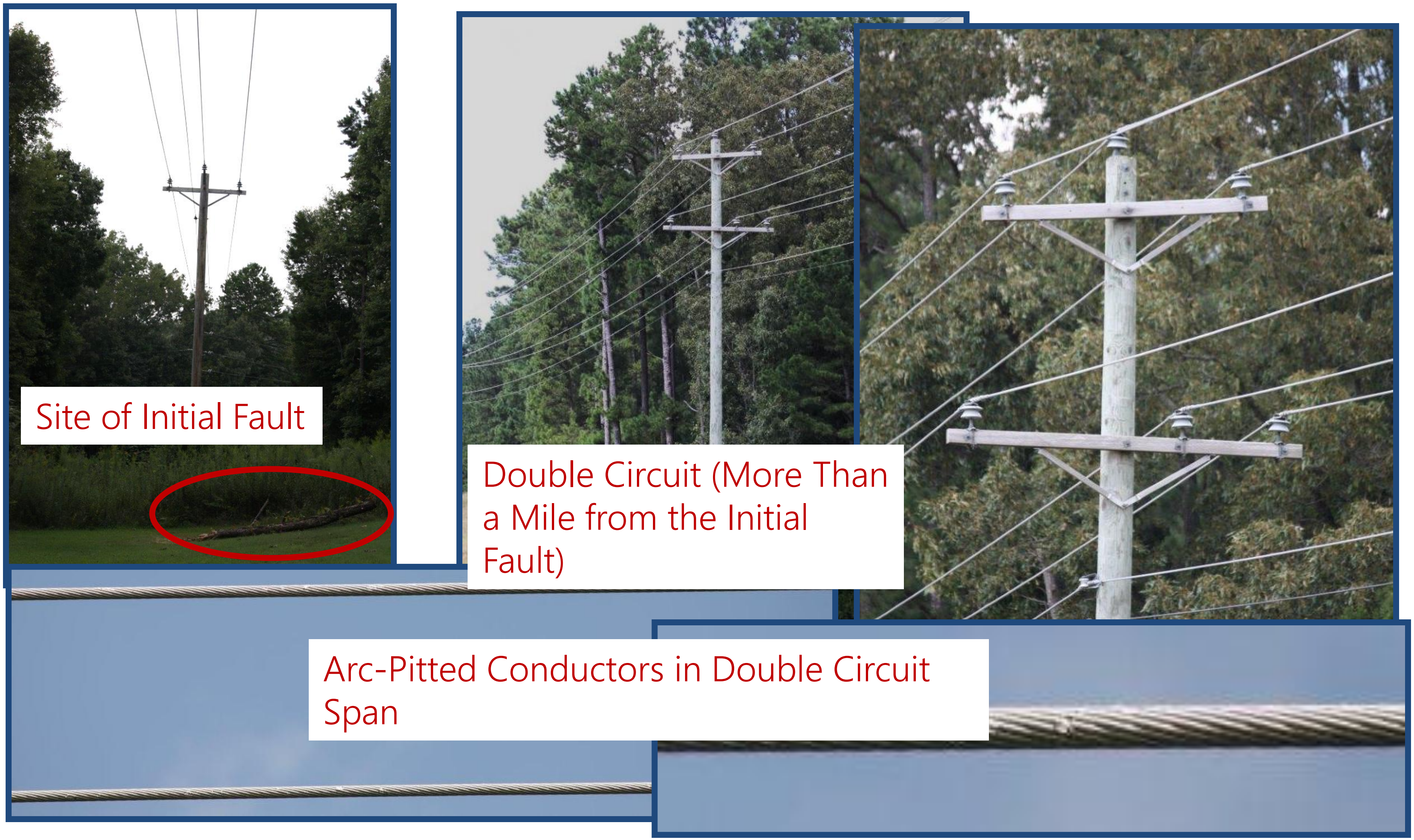


Sequence of Events

1. Tree fell into line, tripping recloser R.
2. Fault-induced conductor slap (FICS) occurred upstream of R, tripping breaker 334.
3. Plasma from fault 2 rose into 324, causing double-circuit fault. Both circuits tripped.

Detailed Use Case

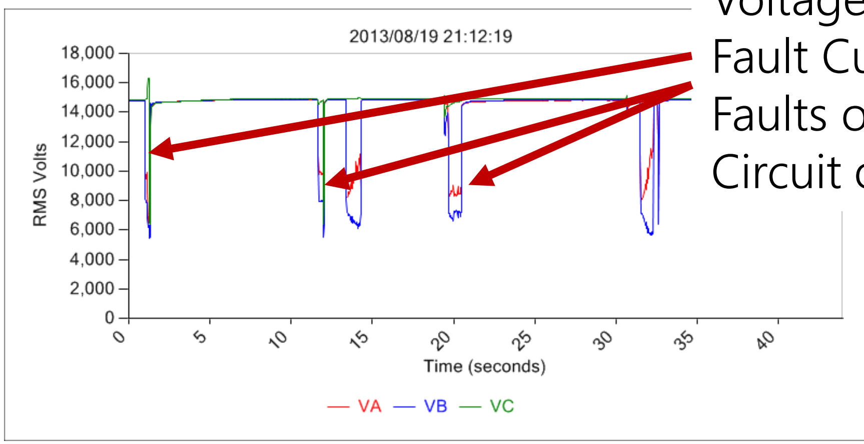
Double-Circuit Fault Resulting from Fault-Induced Conductor Slap (FICS) (cont')



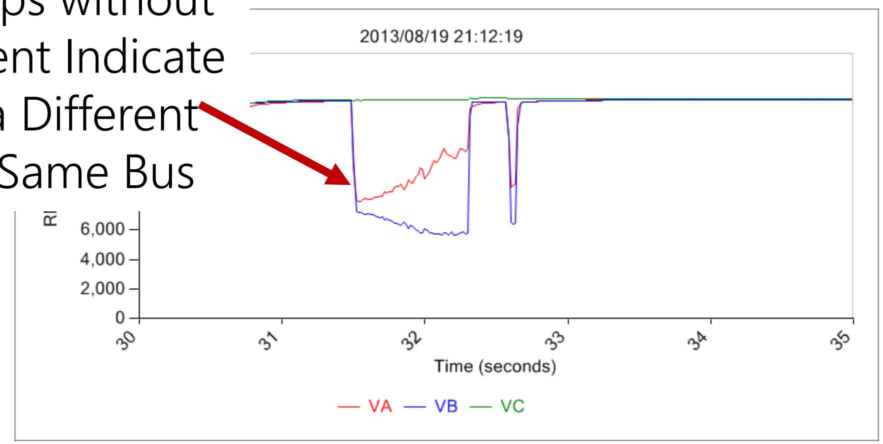
Detailed Use Case

Double-Circuit Fault Resulting from Fault-Induced Conductor Slap (FICS) (cont')

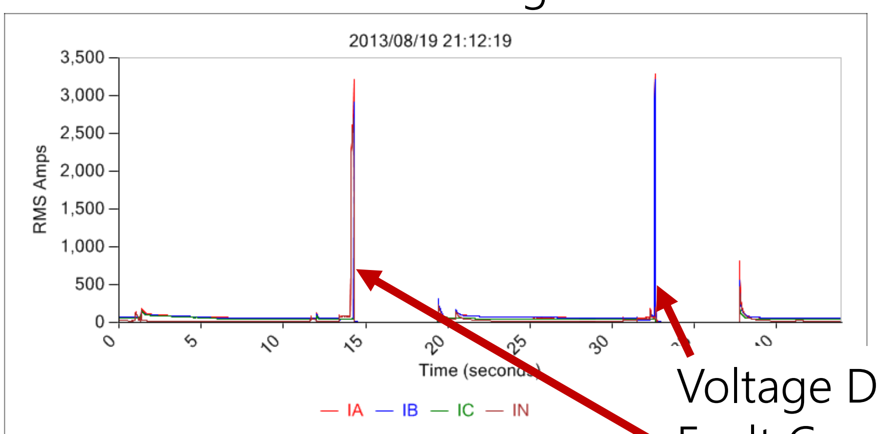
Voltage Dips without Fault Current Indicate Faults on a Different Circuit on Same Bus

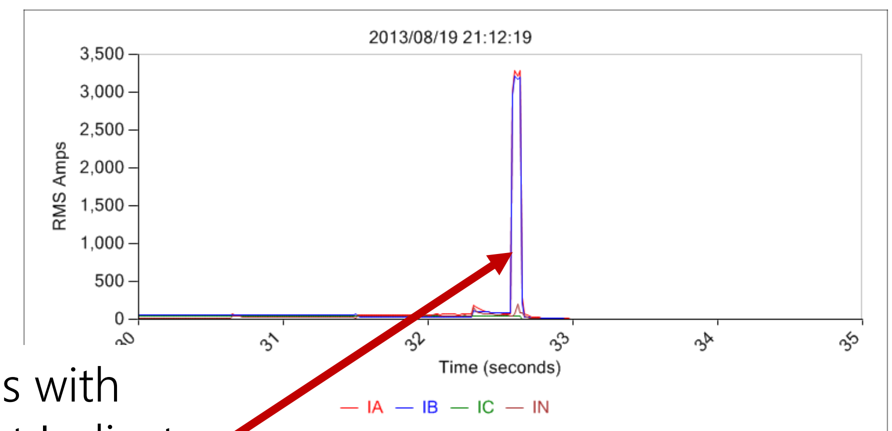


44-Second DFA Recordings



"Zoom" of Seconds 30-35



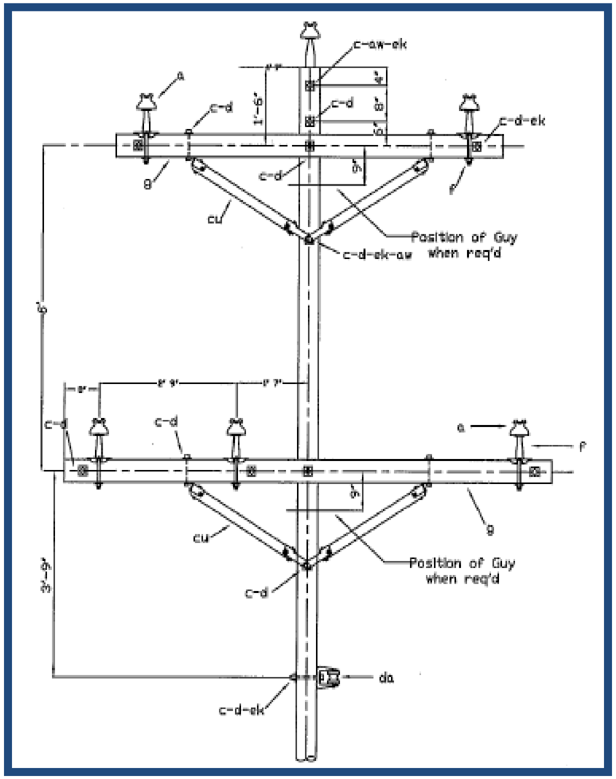


Voltage Dips with Fault Current Indicate Faults on DFA Circuit

Detailed Use Case

Double-Circuit Fault Resulting from Fault-Induced Conductor Slap (FICS)

- Diagnosing the FICS and the circuit-to-circuit fault told us know why both circuits tripped.
  - FICS often is not recognized with conventional analysis, particularly when faults are miles apart.
  - Where a span is susceptible to FICS, it likely will recur in that span again in the future.
- Digital relays sometimes provide data that could be used to diagnose FICS.
  - Doing so requires development of expertise.
  - It also requires spending time doing the analysis.
  - DFA flags FICS and other issues automatically and provides data in a convenient format for analysis.
- DFA provides extended recordings that enable analysis of complex events.
- Another consideration: Awareness of these kinds of events enables us to assess whether our standards might need revision.



Detailed Use Case

Capacitor Vacuum Switch Pre-Failure

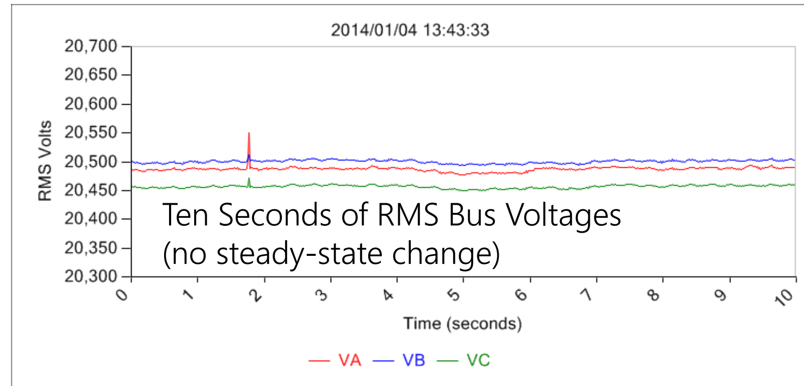
- On 11/29/2013, a DFA device began detecting unusual transients suggesting pre-failure of a capacitor bank.
- The transient occurred 500 times over the next 2-1/2 months.
- Experience shows that outage logs, trouble tickets, etc. generally have nothing for this type of pre-failure. Exception: The transients can cause complaints from sensitive customers, such as industrial facilities with numerical controllers.
- After 2-1/2 months, increasing event activity suggested the problem might be accelerating toward failure, prompting corrective action.

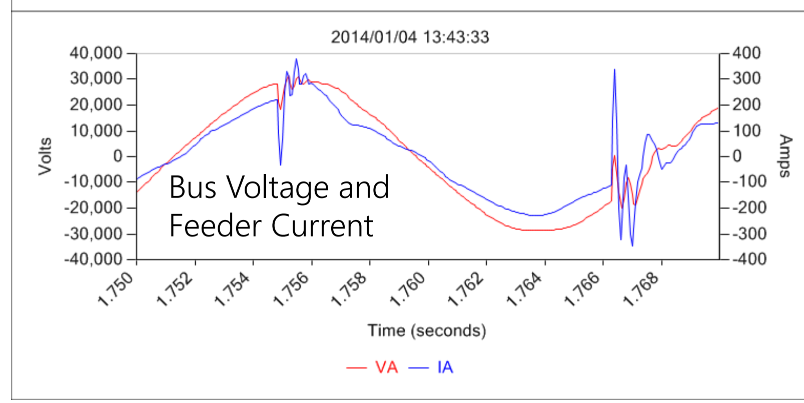
Detailed Use Case

Capacitor Vacuum Switch Pre-Failure (cont'd)

<u>Theory and Analysis</u>

- Normal capacitor switching causes two phenomena.
  - A short-lived high-frequency transient
  - A step change in voltage (even at the bus!)
- Each subject event caused a transient, but no step change.
  - This indicates the events were not during switching.
- Each event caused a high-frequency spike in current and voltage.
  - The current and voltage spikes had the same polarity (i.e., when voltage spiked up, current spiked up).
  - This indicated a "reverse" event. For "forward" events, voltage and current spikes have opposing polarities.
  - From the DFA's perspective, a "reverse" event is one occurring on a different feeder or on the bus itself.

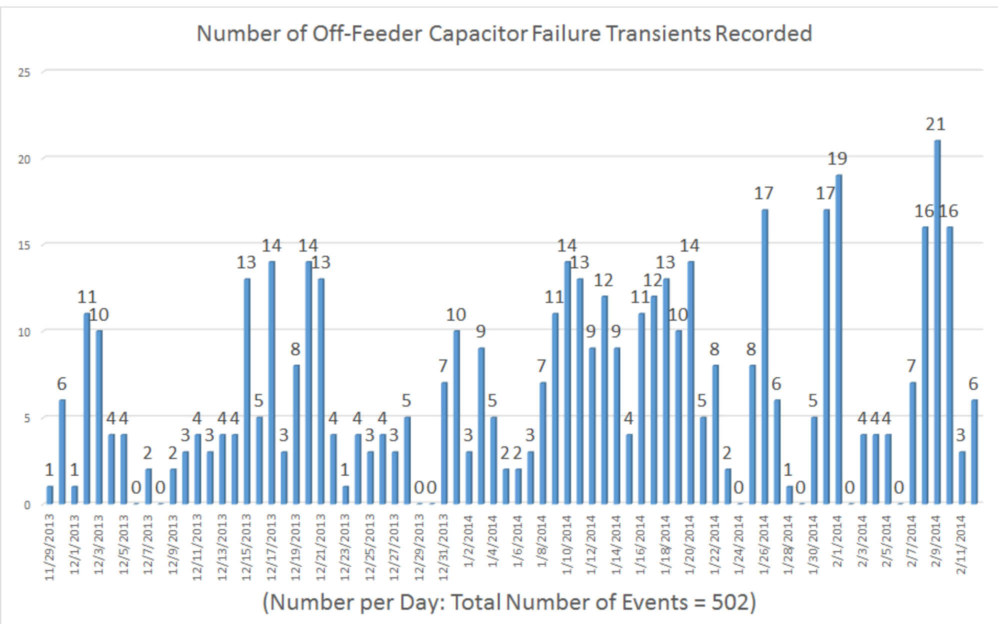




Detailed Use Case

Capacitor Vacuum Switch Pre-Failure (cont'd)

Statistical Analysis #1: Number of transient events recorded per day, during 75-day period.

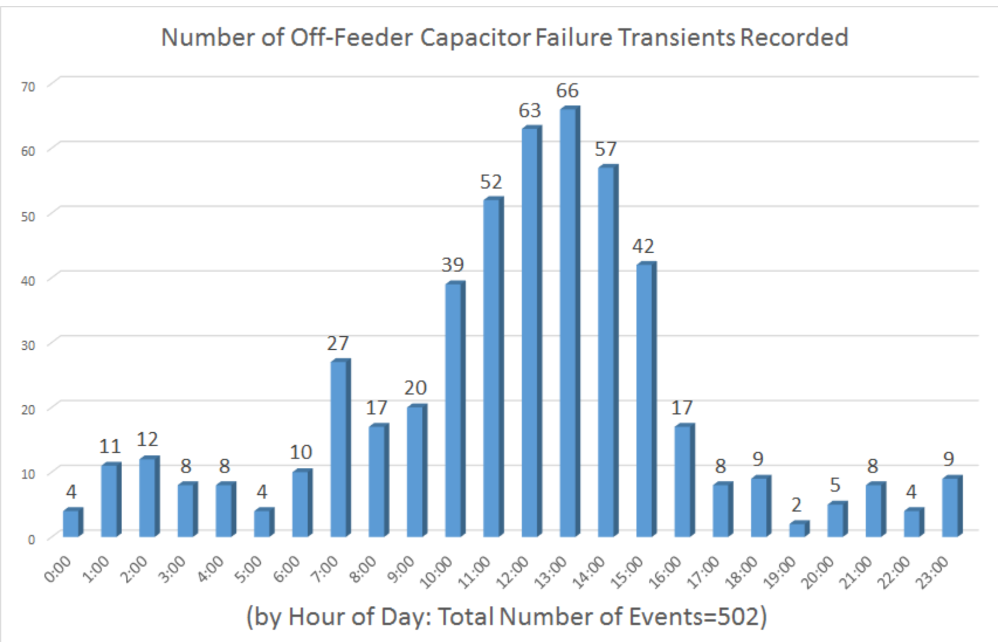


- Graph shows the number of events on each day (11/29/2013 – 2/12/2014)
- There is no definitive trend.
- "Peaks" weakly suggest a slight increase in activity over time.

Detailed Use Case

Capacitor Vacuum Switch Pre-Failure (cont'd)

<u>Statistical Analysis #2</u>: Number of transient events recorded as a function of time of day.



- Graph shows the frequency of events as a function of time of day, cumulatively for the 75-day period.
- Events occur at all times of day but most frequently during the middle of the day.
- 64% occur during 25% of day. (319 of 502 events between 10:00 and 16:00)
- 47% occur during 17% of day. (238 of 502 events between 11:00 and 15:00)

Detailed Use Case

Capacitor Vacuum Switch Pre-Failure (cont'd)

- On February 14, utility decided to pull fuses from all five of the feeder's capacitor banks, to "make sure" the waveform-based diagnosis was correct.
- At the first bank, before opening fuses, crew used hot-stick meter and found 0.7 amps through suspected pre-failure phase, despite the switch controller's "open" status.
  - First bank's fuses were pulled.
  - Other 4 banks were left in service.
  - Monitoring DFA system for five days confirmed that the transients had stopped.
- Full evaluation of switch, by vacuum interrupter expert, is scheduled next week.

Post Mortem Photos Coming Soon!

Detailed Use Case

Capacitor Vacuum Switch Pre-Failure (cont'd)

- A utility company usually learns of vacuum switch failures only during routine maintenance or when switch fully fails (sometimes spectacularly!)
- DFA recorded pre-failure signature for 2-1/2 months. It is not known when switch would have had full failure.
- 500+ high-frequency transients can have adverse effects on sensitive customers.
  - Without DFA, complaints are difficult to diagnose, because the transients are 1) not continuous and 2) not correlated with capacitor switching.
- Detection of pre-failure enabled scheduled, fair-weather location and repairs.
- Knowledge of pre-failure signatures, plus evaluation by expert, help researchers and industry better understand failure processes.

Post Mortem Photos Coming Soon!

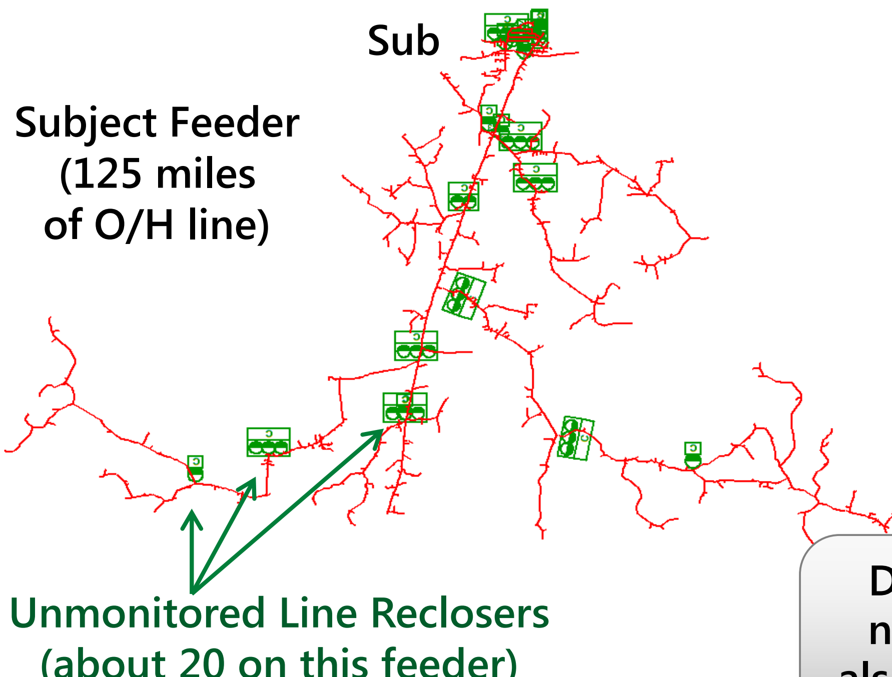
Detailed Use Case

Unreported Intermittent Faults

Possible recurrent fault	C	Single-Phase reclose, 510 Amps	2 (18 days)	09/28/11 13:45:22

Change page: 1 Change page: 1 Go Page size: 2 Change Displaying page 1 of 1, items 1 to 2 of 2.

Event Type	Phases	Comments	Occurred
Single-Phase reclose	C	F-(3.0c,510A,CG)-T-(0,0,19)%-2.1s-C	09/28/11 13:45:22
Single-Phase reclose	C	F-(3.0c,510A,CG)-T-(0,0,21)%-2.0s-C	09/10/11 14:19:25



- Distribution feeder; conventional overhead construction; 125 miles; numerous reclosers
- Normal operating conditions; no active customer complaints; fair weather.
- 9/28/2011: On-line DFA waveform analytics detected that the "same" fault had occurred twice in the past 18 days. The system responded by generating the line-item report shown above.
- Drilling down into the report provided details of the two fault events.

DFA waveform analytics often provide the only notice of these recurrent "blinks." The analytics also provide location information – even for faults that have not caused outages yet.

Detailed Use Case

Unreported Intermittent Faults (cont'd)

Possible recurrent fault	C	Single-Phase reclose, 510 Amps	2 (18 days)	09/28/11 13:45:22

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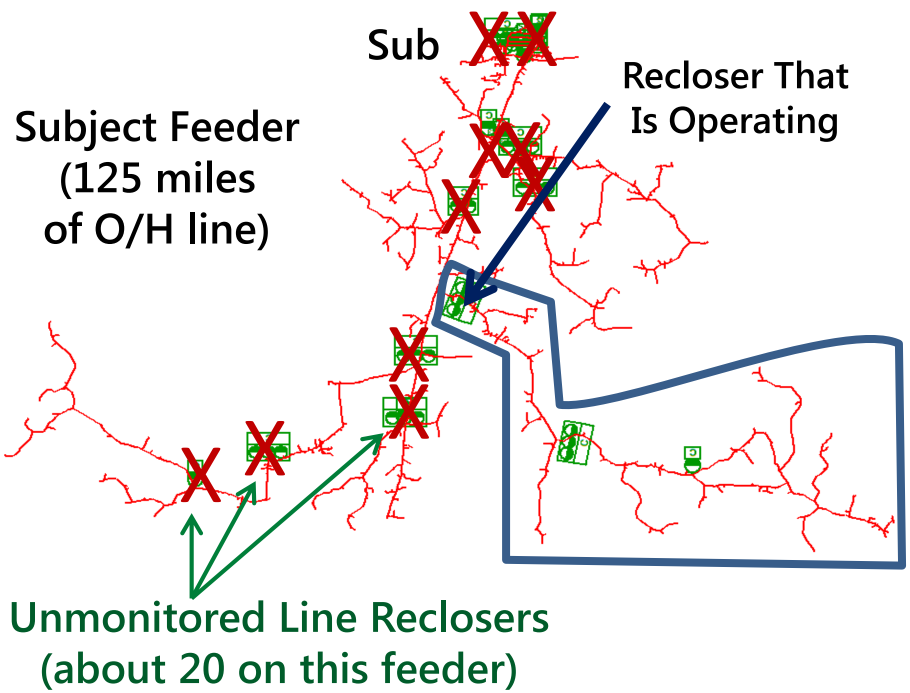

<u>To Locate Fault</u>: Compare analytics outputs to model

- Faults were on phase C.
  - ➢ Eliminate segments w/o phase-C.
- Operations were single-phase.
  - ➢ Eliminate three-phase reclosers.
- First-shot open intervals: 2.0s and 2.1s
  - ➢ Eliminate reclosers with first-shot open intervals other than 2 seconds.
- Momentary load loss: 21% and 19%
  - ➢ Eliminate reclosers carrying much different load.
- This process identifies which recloser is operating, replacing the time-consuming practice of checking counters. In this particular case, this reduced the search area by 76%.

Detailed Use Case

Unreported Intermittent Faults (cont'd)

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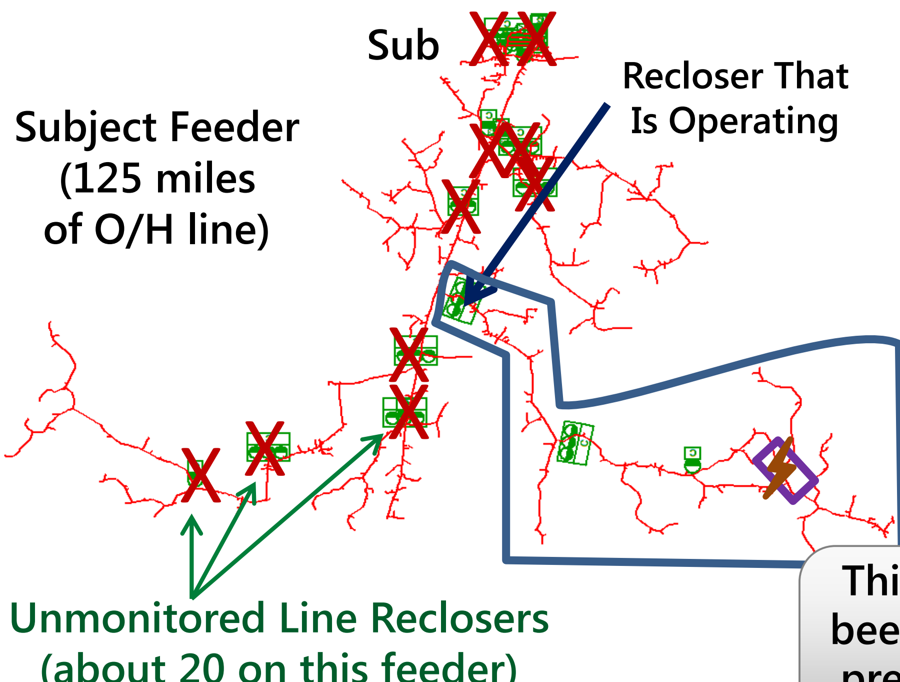


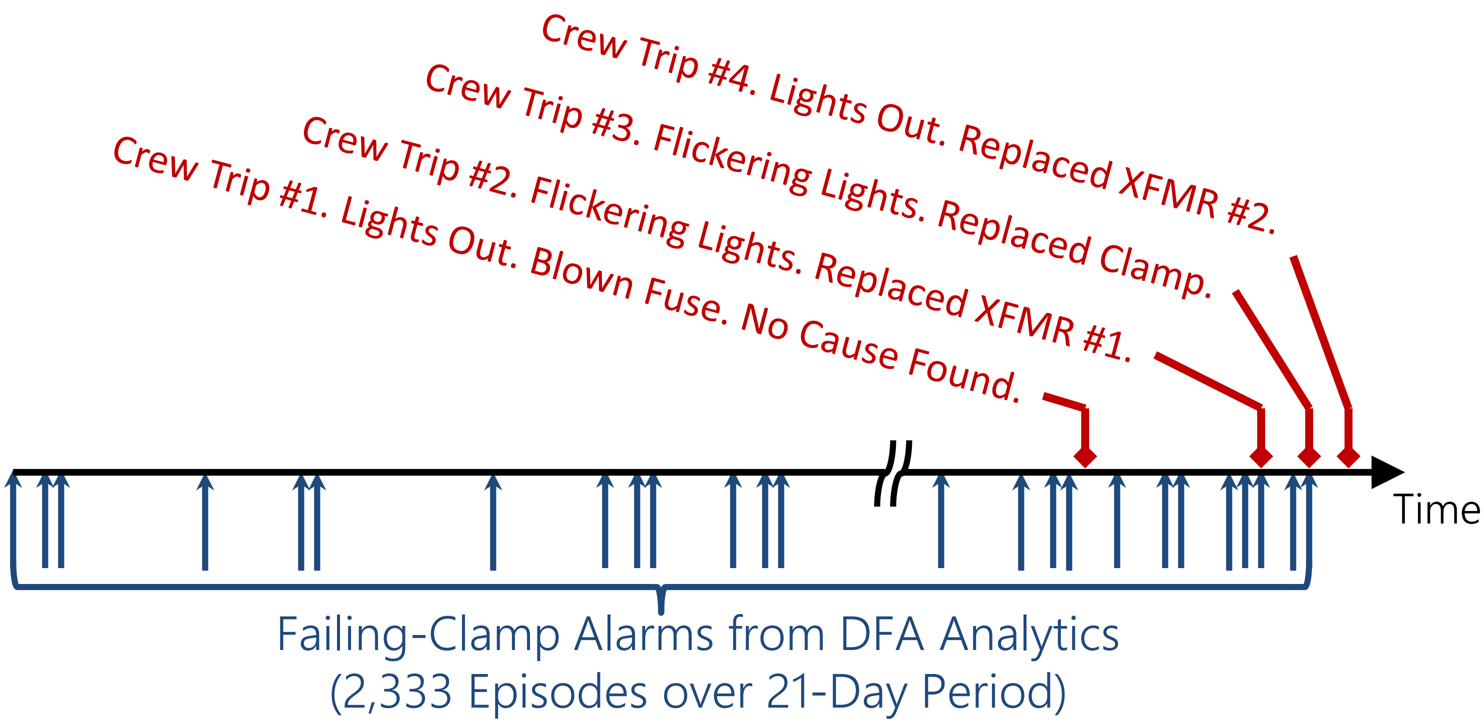
- Now compare analytics-generated fault currents (510A) to the feeder model. (Measured fault currents commonly match within ~1% between episodes.)
- Looking only downstream of the previously identified recloser, fault-magnitude analysis targets a small search area (purple rectangle).
- Crew found failing arrester within 4 spans. Future 53-customer outage was averted.

This is not an isolated case. On-line analytics have been used <u>multiple</u> times to 1) detect and 2) locate pre-failures. Remember that these are pre-failures that have <u>not</u> caused outages.

Detailed Use Case

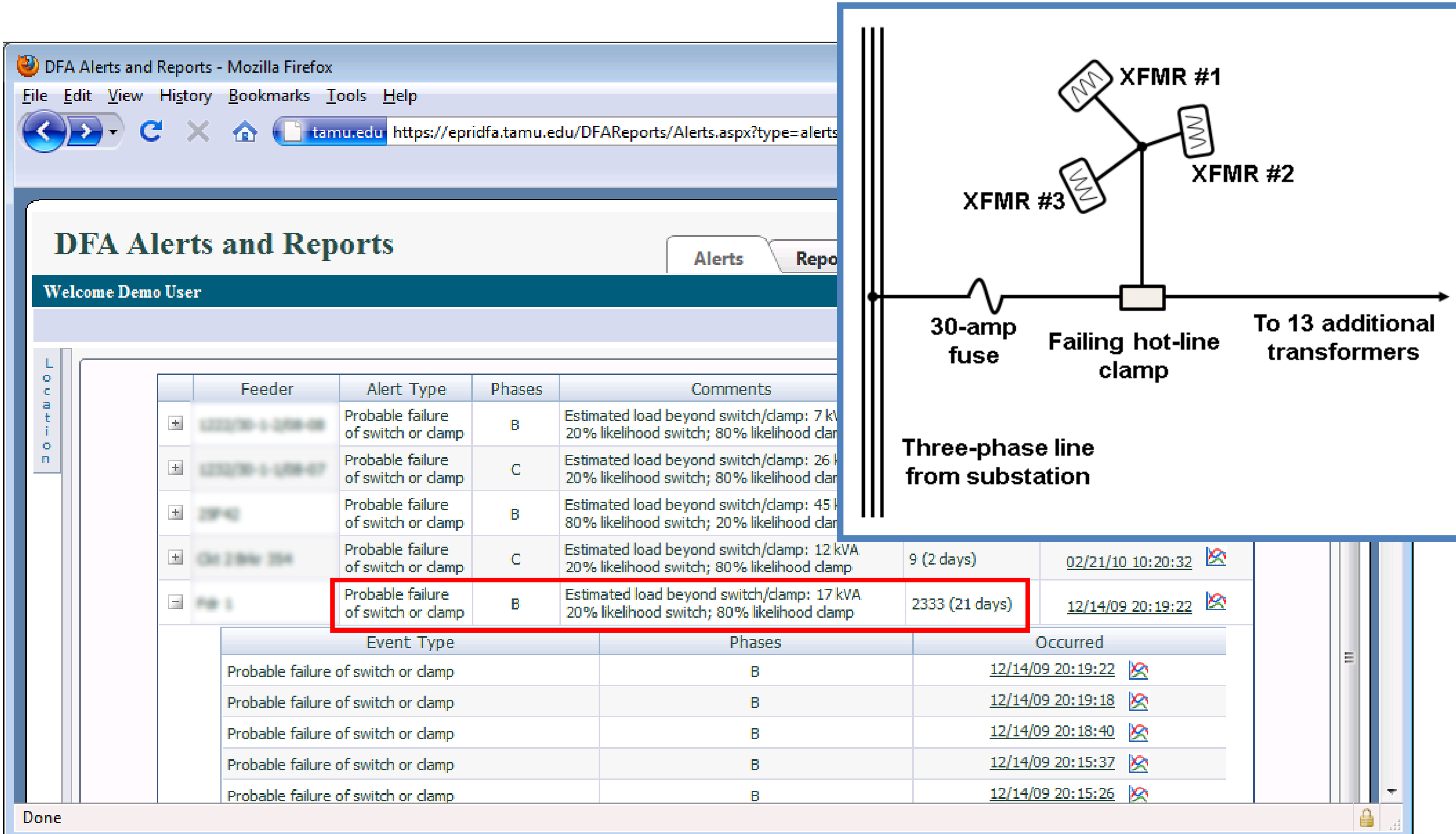
Hard-to-Diagnose Trouble

- Customers on a lateral experienced service trouble (e.g., lights out, flicker) four times in a 40-hour period.
- This "cost" the utility four complaints, four truck rolls, and two transformer replacements – all on overtime and mostly unnecessary.
- DFA analytics detected and reported the cause ("failing clamp") weeks before the first customer complaint. Crews were unaware of the DFA report, however, so their response was conventional.



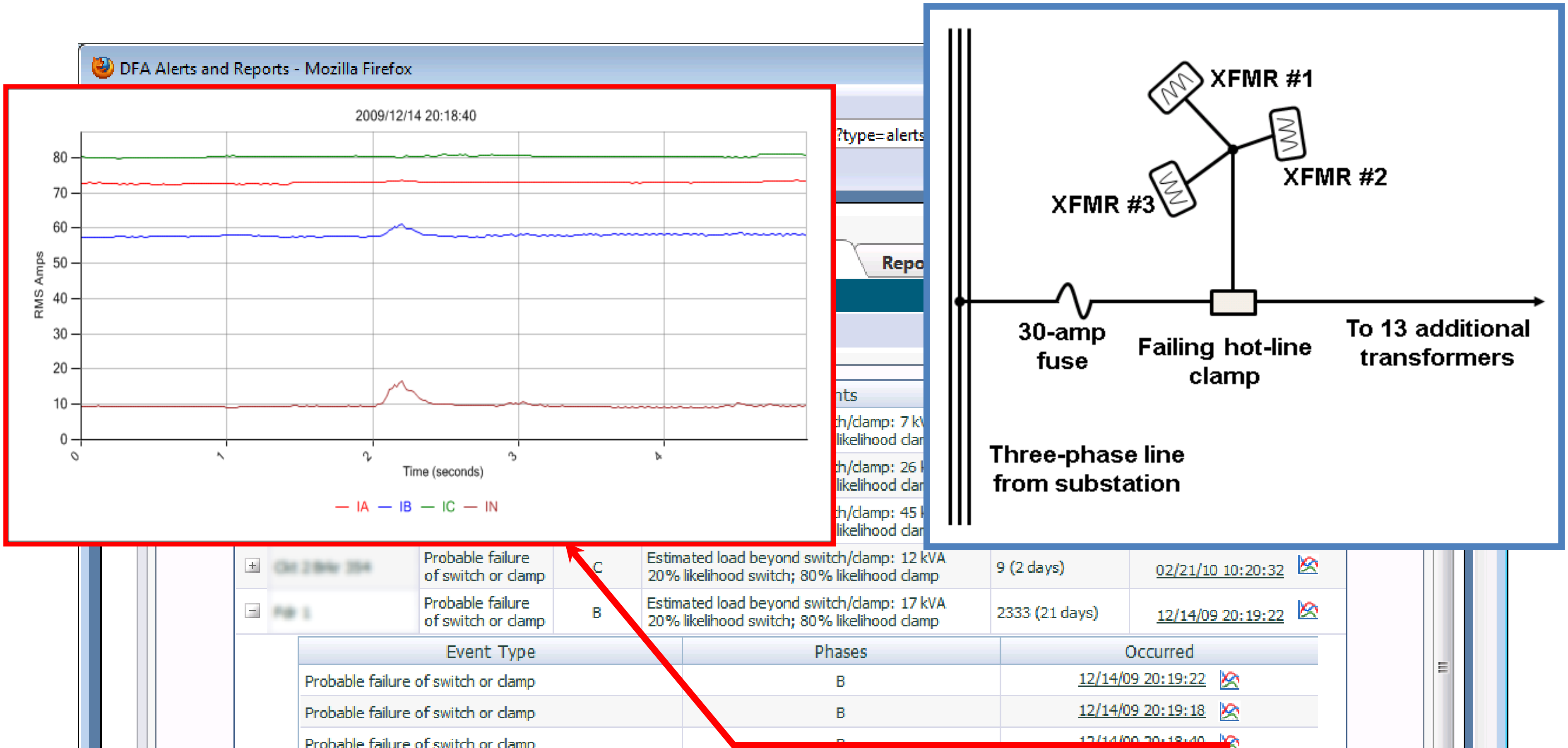
Detailed Use Case

Hard-to-Diagnose Trouble (cont’d)



Detailed Use Case

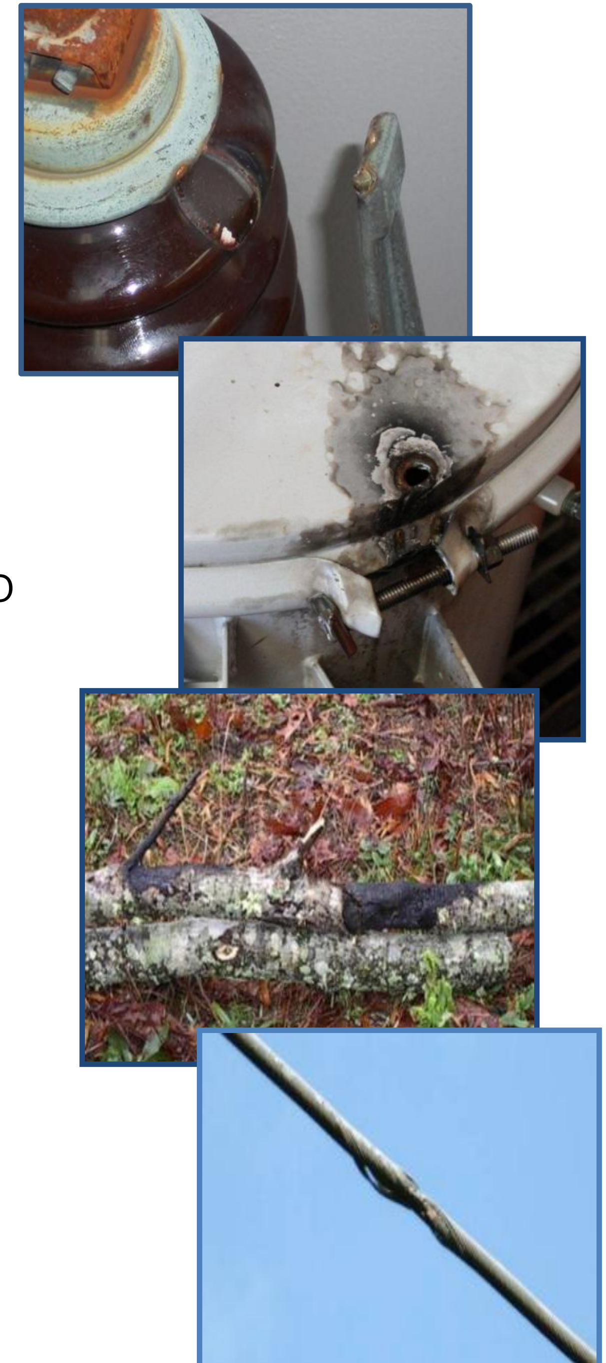
Hard-to-Diagnose Trouble (cont'd)



Electrical variations caused by the clamp failure were minor, but on-line analytics diagnosed them properly. A crew knowing to look for a clamp failure can respond more efficiently and effectively and fix the right problem the first time.

Summary

- DFA technology applies sophisticated waveform analytics to high-fidelity CT and PT waveforms, to provide heightened visibility, or awareness, of feeder conditions. This enables improved reliability, operational efficiency, and safety.
- The DFA system automates the analytics process, so as to deliver actionable intelligence, not just data.
- DFA is a data-driven technology that embodies multiple functions.
- The March 2013 *T&D World* has a related story by Arizona Public Service and Pickwick Electric.
- CRN is formulating a project in which about 10 co-ops will test DFA on their systems.
- Utility companies have used DFA to demonstrate the avoidance of outages and improvements in operational efficiency.



Distribution Fault Anticipation

Improving Reliability and Operations by Knowing What Is Happening on Your Feeders

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