# Improving the Reliability and Health of Distribution Circuits Using Real-Time Diagnostics and Incipient Failure Detection Preventing Outages, Fire Ignition and Safety Hazards

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# DFA Technology – A New Tool to Meet Utility Goals

- Utilities have multiple goals.
  - Improve service quality and reliability.
  - Improve operational efficiency.
  - Reduce wildfire ignition risk.
  - Avoid unsafe conditions, such as broken conductors.
- Most powerline failures affect all these goals.

<u>The point</u>: Each example in this presentation may emphasize a specific goal, but almost all examples affect all goals.

# DFA Technology – A Paradigm Shift

DFA technology represents a paradigm shift in distribution operations and requires a change in mindset, not just technology.

- Proactive
- Predictive
- Diagnostic
- Situational awareness
- Visibility
- Actionable recommendations
- Operator knowledge (not data!)

# Circuit Situational Awareness

- What do I know about my circuits?
  - The breaker is closed.
  - No one has reported an outage.
  - Therefore, circuits are presumed healthy.
- What do I not know about my circuits?
  - Circuit 12 has a burning clamp (that may drop a line next week).
  - Conductor slap in the same span has locked circuit 27 out three times in the past five years.
  - Intermittent vegetation contact on circuit 34 has caused three momentary interruptions in the past two weeks (but no one has reported the blinks).

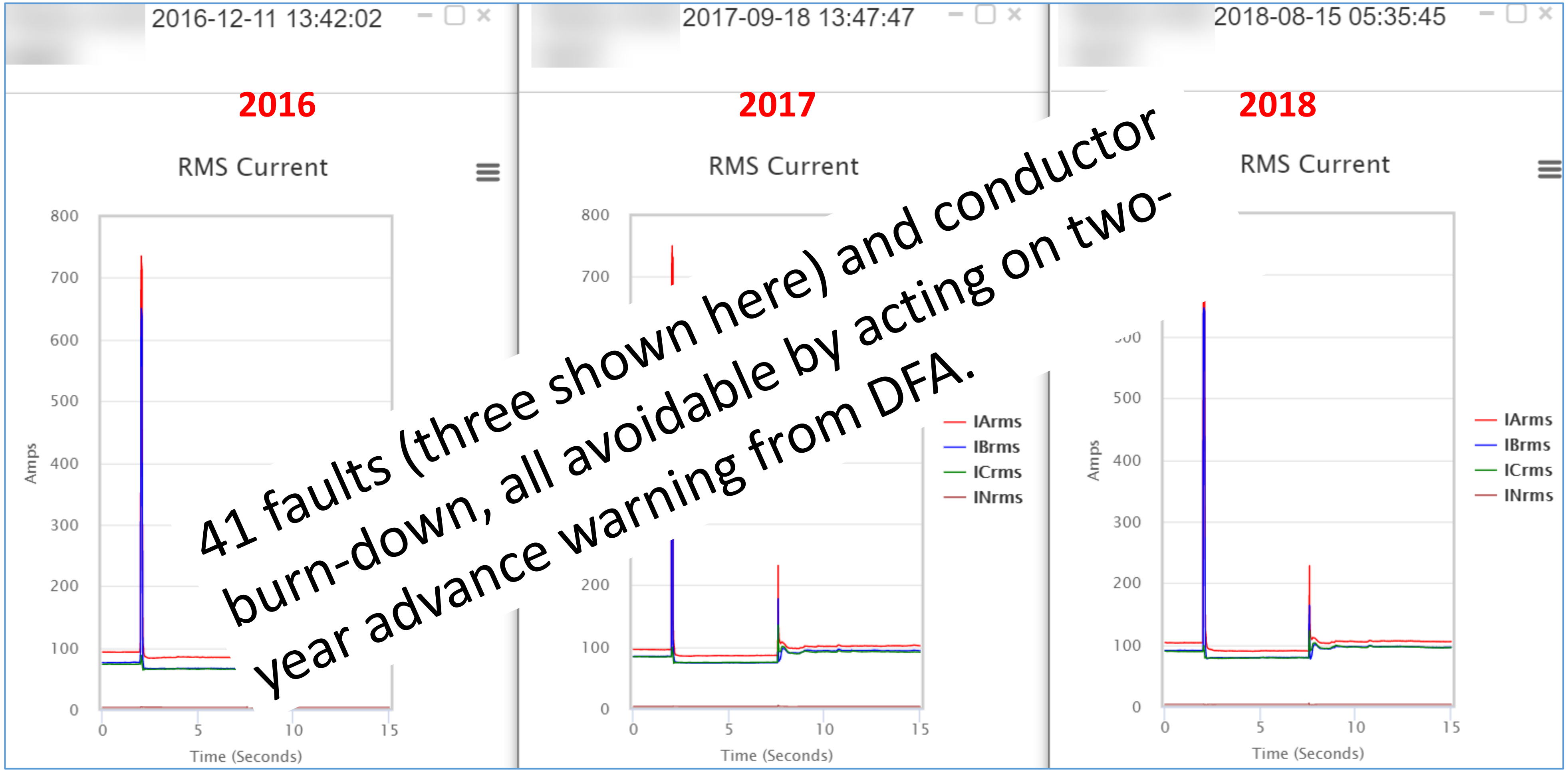
# Case Study for Consideration

<u>Note: Real case, DFA installation, routine circuit operations</u>

- Over a period of two years…
  - A single incipient failure condition caused 41 fully avoidable faults, the final one causing a broken conductor.
  - A communicating ACR operated (trip/closed) on every fault.
  - The utility took no action prior to the broken conductor.
- DFA reported the incipient failure condition, in real time, and enabled location.
  - It repeated the warning multiple times over the next two years.
- The utility had DFA in "blind study" mode – they did everything they would have done normally but withheld DFA reports from personnel.

<u>Thought question</u>: Would acting on the DFA report, thereby avoiding 41 faults and the broken conductor, constitute a valuable example of fault anticipation?

# Case Study for Consideration
(cont'd)



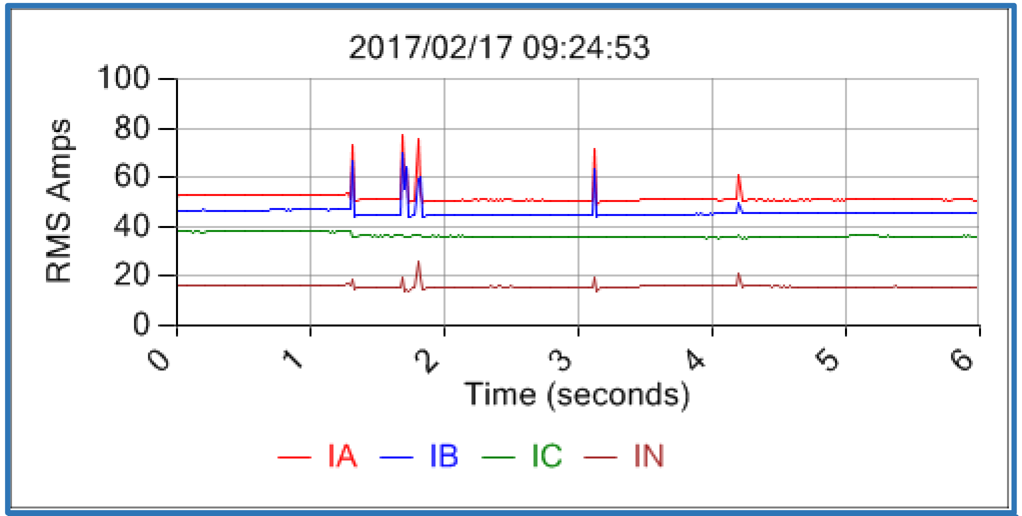
# Case Study for Consideration
(cont'd)

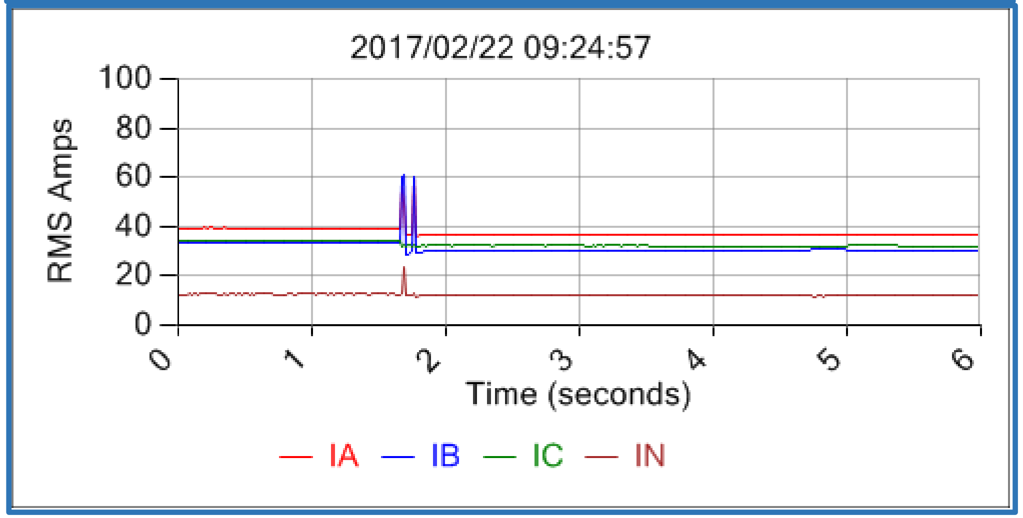
What we didn't tell you

- The incipient condition caused a total of 44 faults, not 41.
- The first fault provided the first electrical signal indicative of a problem.
- The second and thirds faults provided the electrical signal indicative of an incipient condition likely to cause ongoing faults and damage.
  - Truism: A incipient failure cannot be detected, based on electrical signals, before it produces any electrical signals (and repetitive things are not repetitive until they are).

Thought question: If it is not possible to avoid the first 3 faults, is it still valuable to avoid the next 41 and the broken conductor?

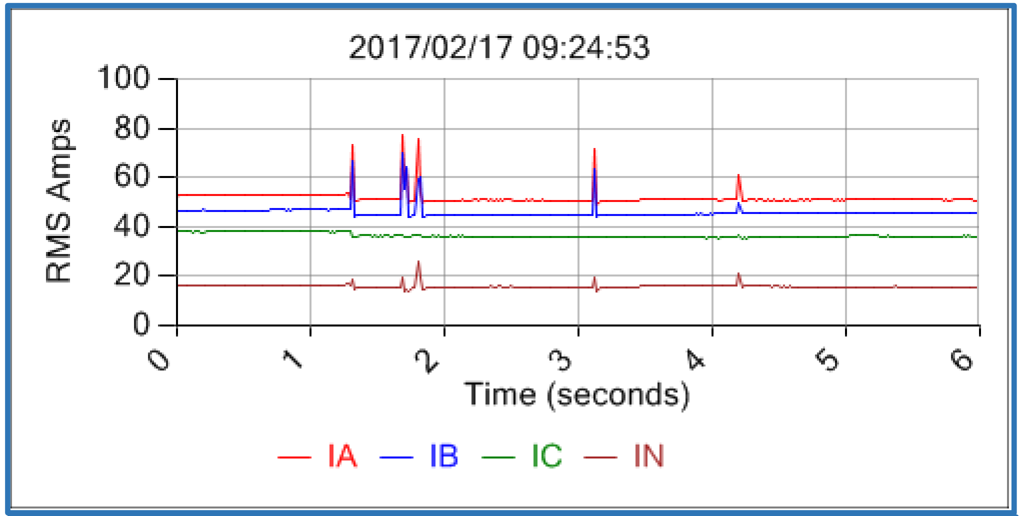
# Another “What Would You Do?”

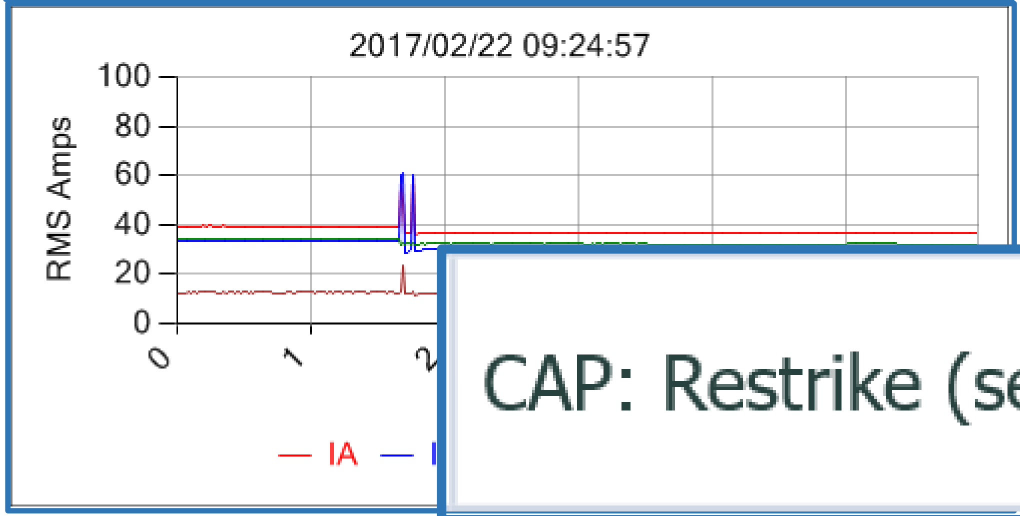



- Assume this activity is happening on one of your circuits.
- You have no way to know it is occurring.
- Even if you did know it was occurring, what does it mean, and what would you do?

# Another "What Would You Do?"




| | | | | | |
|---|---|---|---|---|---|
| CAP: Restrike (severe) | B | 191 | 194 | 190 | 02/22/17 09:24:57 |

- Now assume you know of the events and that you know they are severe restrikes in a 600 kvar capacitor switch.
- Now what is the significance of the events?
- Now what would you do in response?

# DFA Detects Incipient Events

- An incipient event predicts future events. Incipient is not synonymous with low-current. Incipient events can be low-current or high-current.
- Locating an incipient failure that causes high-current events usually is straightforward (with a circuit model), but only if one knows it exists.
  - Having devices that record faults (relays, reclosers) is not synonymous with having a system that makes you aware of incipient failures.
- Utilities have used DFA installations to correct numerous incipient conditions, based on DFA's recognition and clustering of high-current events (proximate trees, bushings, jumpers, …) and low-current events (failing clamp, failing switch, arcing capacitor).

# DFA Is a New Technology for the Toolbox

- DFA is a tool that provides unique information not provided by conventional systems…
- But optimal results come from synergistic use with other tools.
- DFA “sees” operation of non-communicating reclosers (including momentary and recurrent operations) and capacitors from substation.
- Synergy – smart meters/AMI/AMR can help locate events reported by DFA.
    - Pinging (location/confirmation of current outage)
    - Blink counts (location of recurrent momentaries)
    - Sags (location of series arcing) (early development of process)
- Synergy – use circuit models and distributed sensors for location.
    - DFA provides operator awareness of faults and accurate magnitudes for location.
        - DFA makes fault magnitudes and full SOE available in real-time without polling relays or human analysis of SCADA logs.
    - Two-step process to locate conventional faults (including recurrent faults; with or without outage)
        - Predict which protection device operated (for repeated momentaries); then use model to predict location.

# DFA and "Smart Grid"

- AMI and self-healing technologies …
  - Are important components in modernizing grid
  - But they are reactive to faults and outages
- DFA complements AMI and self-healing by providing visibility before, during, and after faults and outages.
  - Detects incipient faults
  - Diagnoses misoperating equipment
  - Reports operations of unmonitored devices, such as capacitors and reclosers
  - Identifies root cause of faults
  - Confirms effective repair

# Failing Substation Switch

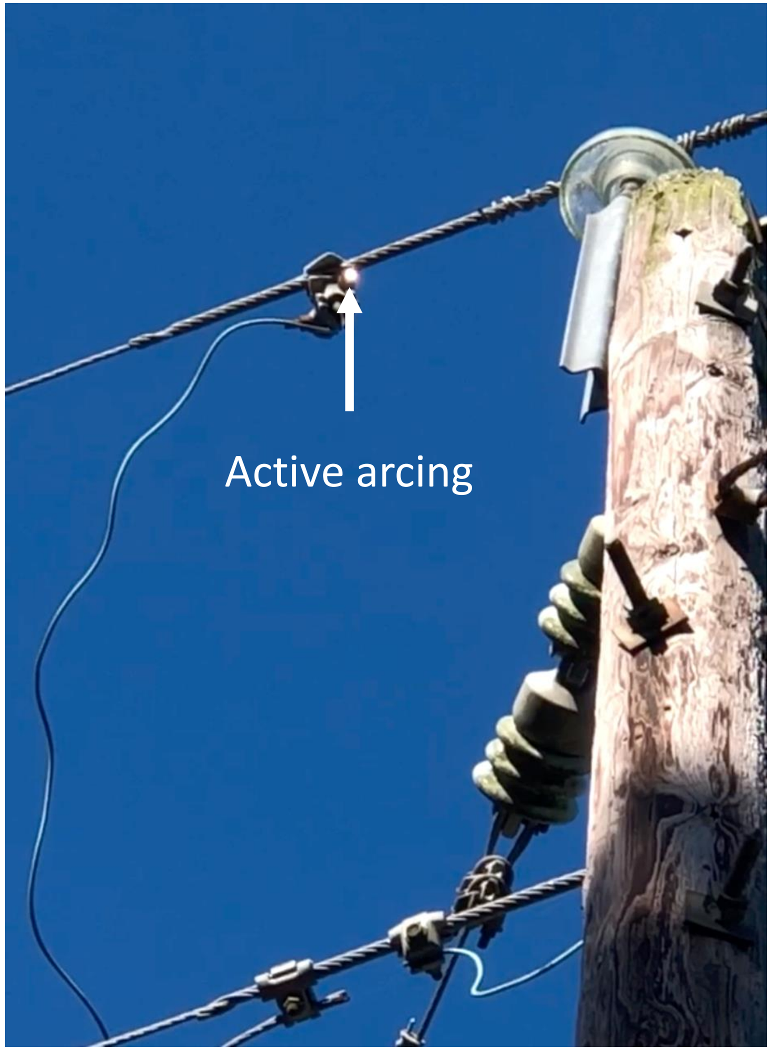
- 25 kV substation; 3 circuits; 2,000 customers
- Incipient failure
  - No outage, no customer calls
  - No problem indicated by SCADA or communicating reclosers
  - No problem indicated by smart meters (even when pinged after being alerted by DFA)
- DFA provided only notice.
- Utility located the failure and immediately initiated repairs.

# Failing Substation Switch (cont'd)

- Switch was on bus side of breaker; failure would have interrupted all circuits (2,000 customers).
- A storm occurred the next day.
  - Wetting the weak switch could have caused final failure.
  - High current from a fault on the circuit likely would have failed the compromised switch.
  - Detection and repair were just in time.
- DFA notification allowed avoidance of an outage, catastrophic switch failure, or substation fire.
- Crews made repairs without time pressure inherent to large outage (crew safety).

# Arcing Line Clamp

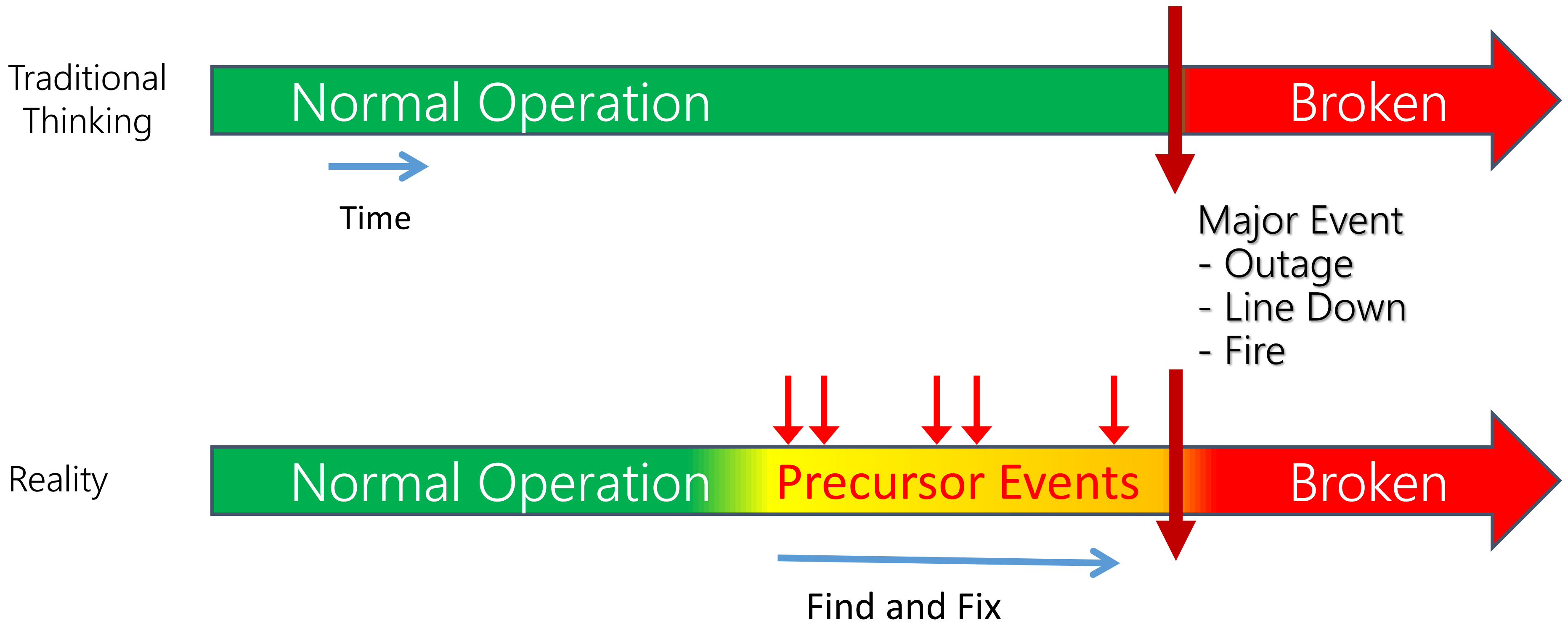
- DFA reported an arcing line clamp.
- The utility responded and found the burning clamp in a national forest.
- Continued arcing could have dropped hot particles or even burned down the line, both ignition sources.
- DFA provided the only notice (no outage, no SCADA information, no customer calls).
- Arcing is highly intermittent, so visual inspection likely would not find this.



# Distribution Operations – Current Status

- Operating personnel lack awareness of impending failures.
- Components run until failure and then are repaired or replaced.
- Consequences: Interruptions, outages, explosions, fires, safety hazards, PQ problems, …, some of which could be avoided if you knew of incipient failures as they were developing.

# Distribution Circuit Operating Paradigms




Conventional response starts <u>after</u> outage or other consequential event.

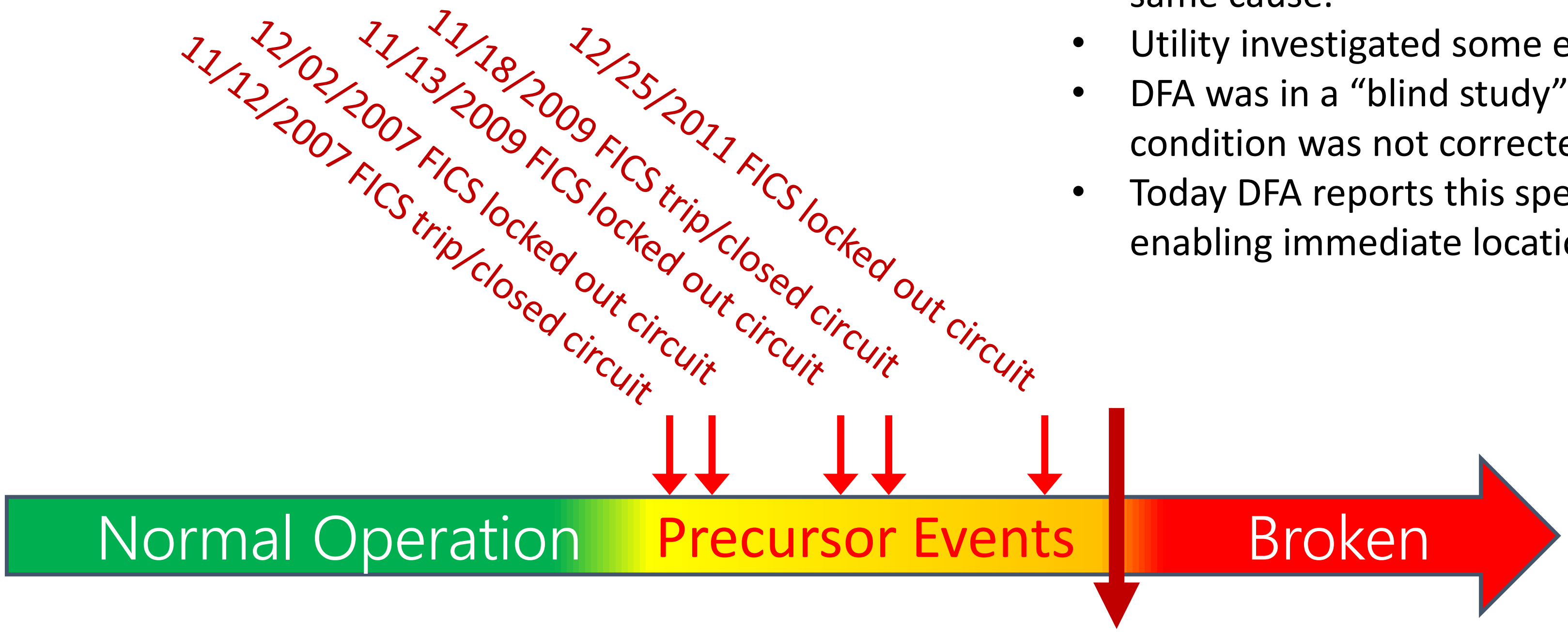
Smart grid response still starts <u>after</u> outage or other consequential event.

Key to better circuit management is <u>early awareness</u> of actual circuit activity.

# Distribution Circuit Operating Paradigms

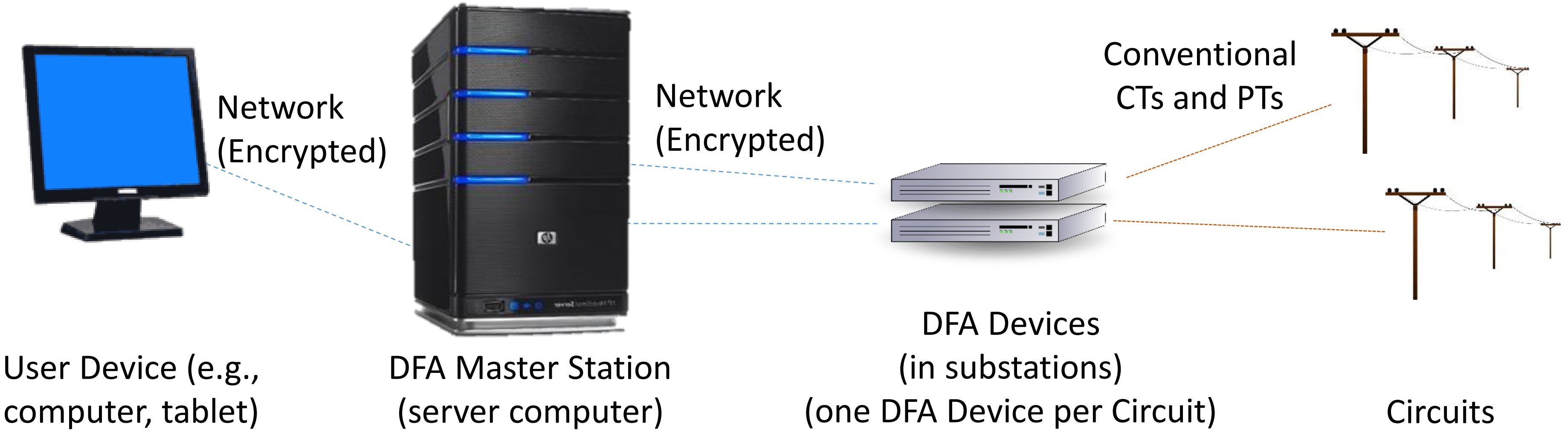
## Actual Example

- Five FICS events occurred at the same location and had the same cause.
- Utility investigated some events but failed to diagnose cause.
- DFA was in a “blind study” mode during first events, so condition was not corrected.
- Today DFA reports this specific condition, after first event, enabling immediate location and repair.




Repetitive FICS at the same location causes cumulative damage, fire hazards, and downed conductors.

# Background
# DFA Monitoring Topology




Each substation-installed DFA Device monitors an entire circuit 24x7 by analyzing conventional CT and PT waveforms with advanced software and sending results to a central DFA Master Station. Personnel access DFA results via DFA Web, a browser-based website provided by the DFA Master Station.

# Distribution Fault Anticipation (DFA) Hardware Device

Rack-Mount DFA Device
Case depth is 11-3/16”. Current, voltage, and unit power terminals on rear add 1” for total depth of 12-3/16”.
Connections to rear of each Device:
* Unit power, battery-backed, 12-60VDC
* (3) Current inputs, 5AAC nominal
* (3) Voltage inputs, 120VAC nominal
* Ethernet/Internet, RJ45 twisted-pair (Network port)
User is responsible for providing unit power, Internet service, CTs, PTs, and all cabling.

The Management Port on the front of the Device is for setup and diagnostic purposes only and is not intended to be connected during routine operation.


*DFA Device Drawings – December 2017. Subject to change.*
*Hardware platform by Power Solutions LLC*

# Distribution Fault Anticipation (DFA) Hardware Device

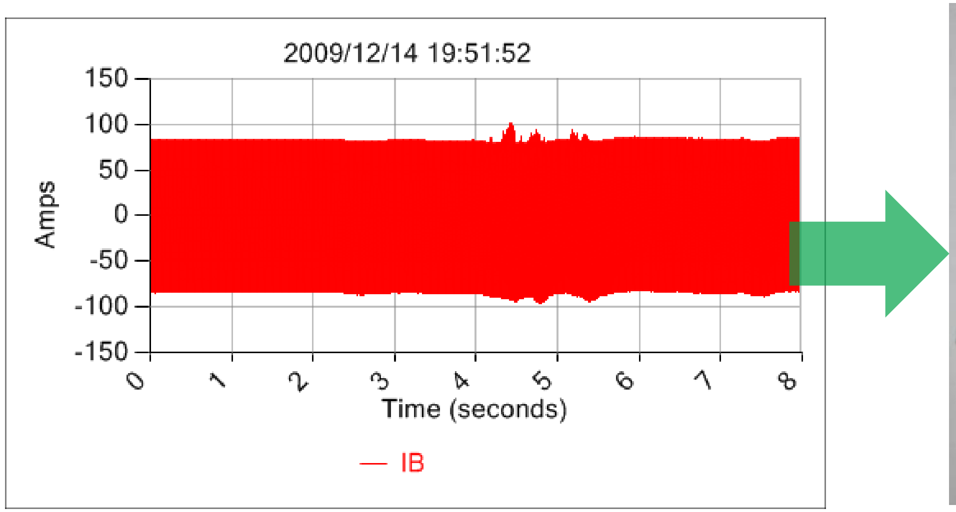
Rack-Mount DFA Device

- Each DFA device (one per circuit) monitors CT and PT signals 24x7, detects electrical anomalies, records and analyzes waveform files, and sends report to the central DFA Master Station, which provides access to the reports via secure browser-based login.
- Data acquisition specifications
  - 24-bit A/D converters with 18-19 effective bits of resolution
  - 256 samples/cycle (12,800/15,360 samples/second on 50/60 Hz systems)
  - DFA samples six channels (three current, three voltage) and calculates neutral/residual current for each sample point as IN=IA+IB+IC.
- Waveform Files
  - Sensitive triggering: The sensitive triggering necessary to detect some incipient phenomena results in multiple files per circuit per day, which requires automated real-time processing to achieve operational value.
  - Long-duration recordings: Recognition of some fault sequences and incipient failure signatures requires multiple seconds. With default configuration, the minimum DFA recording is 10 seconds, and continued electrical activity (i.e., repeated triggering) can result in 60-second files.
  - All waveform files are recorded at full sampling rate (256 samples/cycle) and stored using industry standard IEEE1519.3 (PQDIF) format, with PQDIF-standard data compression to reduce size.


*DFA Device Drawings – December 2017. Subject to change.*
*Hardware platform by Power Solutions LLC*

# DFA Principle: Waveforms Contain Useful Information

- Graph shows line current recorded during routine operations, with current modulated by a failing clamp signature.
- Conventional technologies do not detect such conditions, which can persist for weeks before catastrophic failure (e.g., line down).




# 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

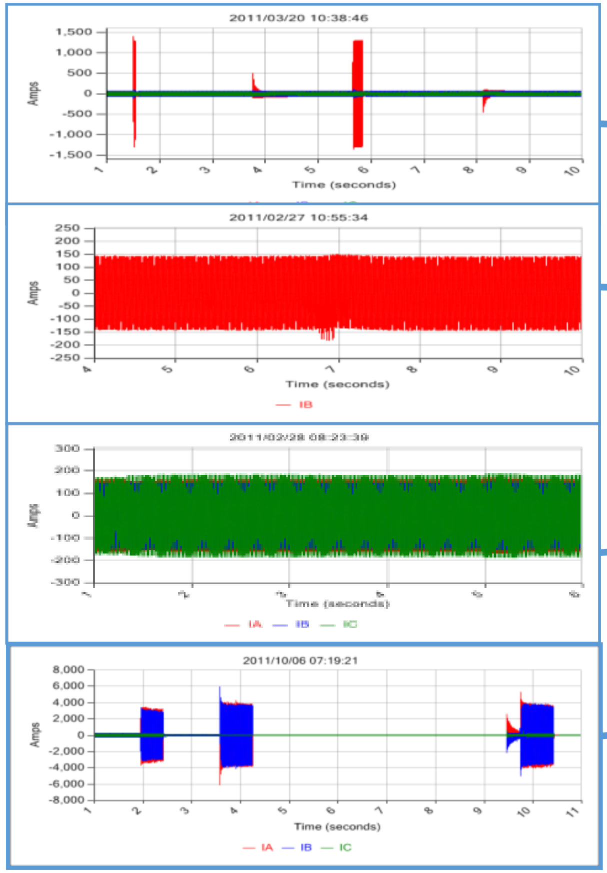
The DFA on-line waveform classification engine uses sophisticated software to identify circuit events. Software is improved regularly, with field units updated seamlessly via Internet.

# Where Did DFA Algorithms Come From?

- DFA algorithms were developed based on field data from naturally occurring device failures and faults on circuits under routine operation (i.e., not simulations or lab experiments).
- Working with 20+ utilities for 15+ years, Texas A&M researchers created a database of failure signatures. The database is the largest of its kind, having 1250 circuit-years of data and growing.
- Data came from internet-connected, high-fidelity waveform recorders, capturing long records, using sensitive triggering to capture low- and high-magnitude events. Data was sourced from conventional CTs and PTs.

# 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

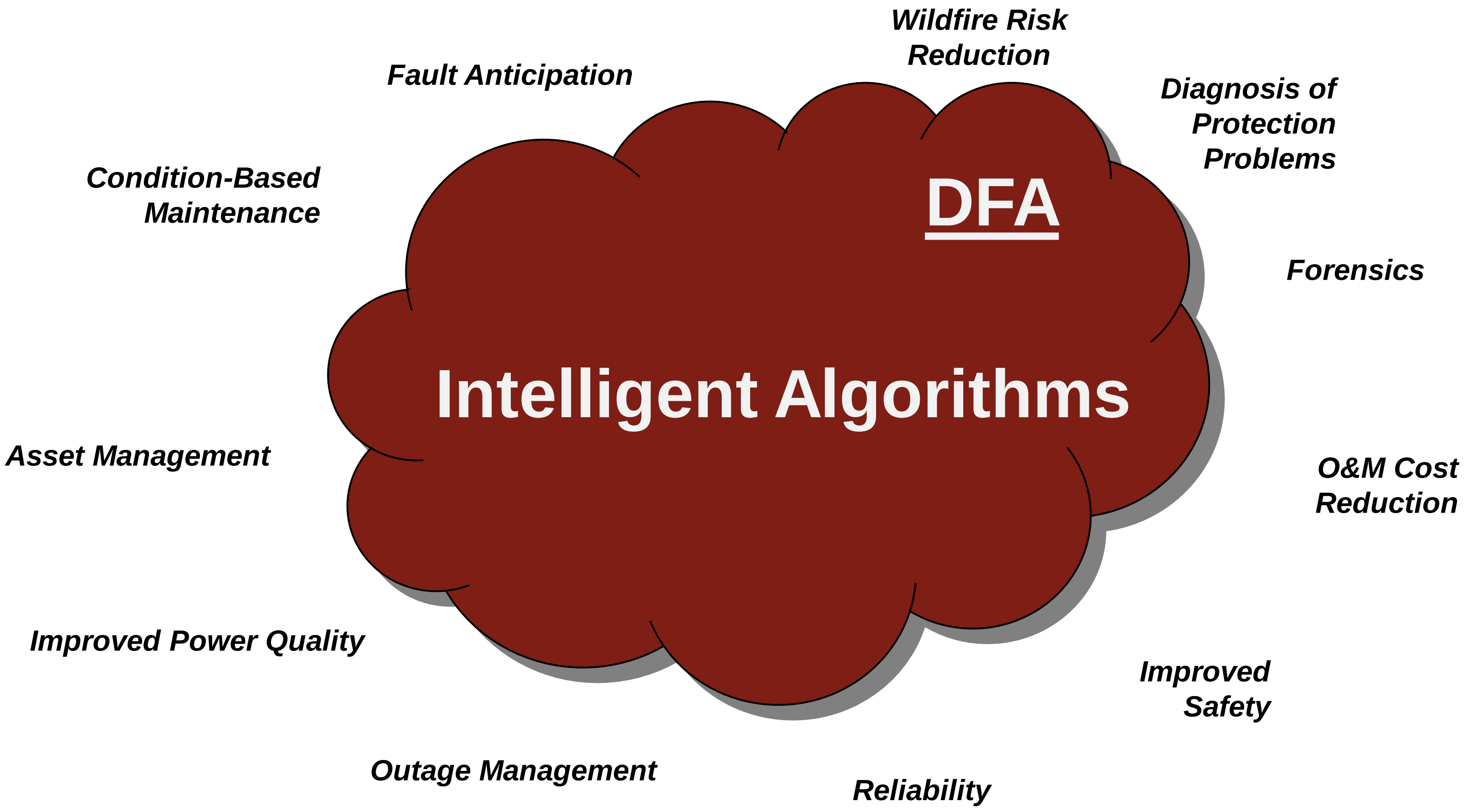
Event #2: Failing hot-line clamp

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.

# DFA Stakeholders



# Documented Failures

- Voltage regulator failure
- LTC controller maloperation
- Repetitive overcurrent faults
- Lightning arrester 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 pad mount 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 the on-line waveform classification engine, as new events are encountered, analyzed, and documented.**

# Benefits of Incipient-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, cost reduction, and other labor impacts

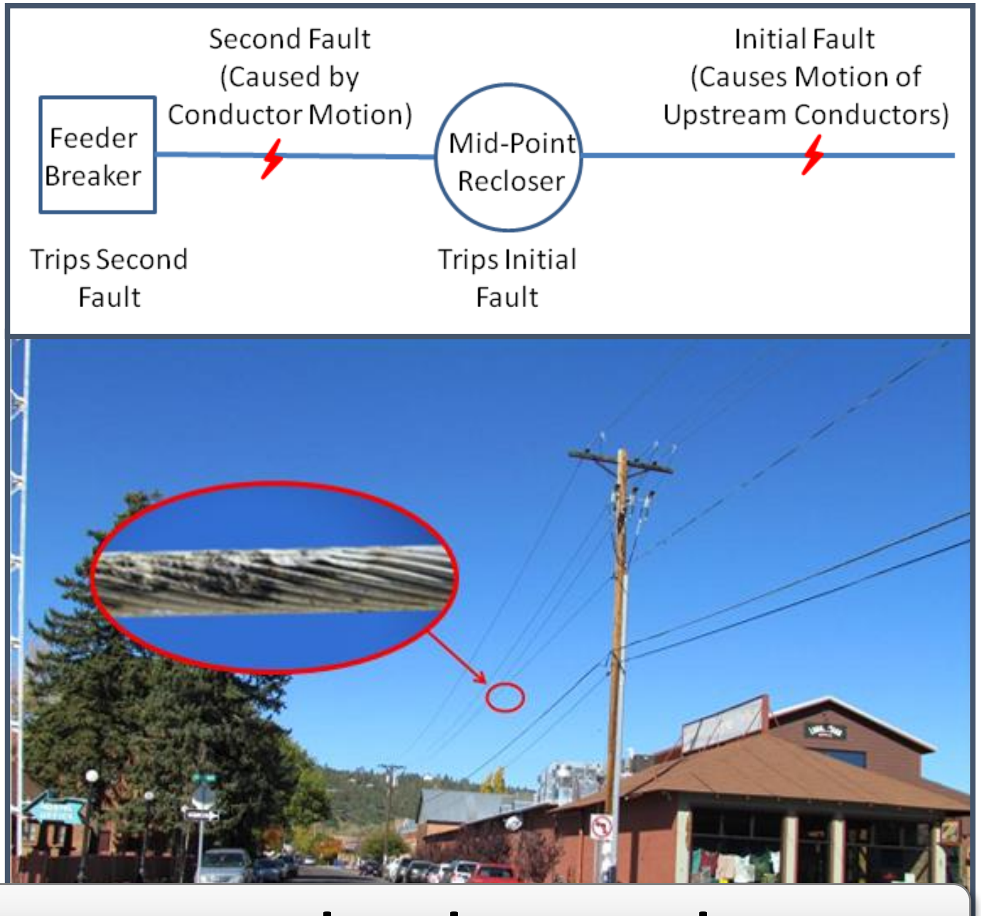
- Daylight, fair-weather, straight-time failure location and repairs
- Improved worker safety (fair-weather, daylight work)
- More efficient troubleshooting (e.g., fewer no-cause-found tickets)
- Effortless access to real-time pre-interpreted fault reports, including magnitudes

Remember: Incipient failures can have low-current or high-current manifestations. The important thing is that they predict a future bad thing.

# Use Case Summaries

# Circuit Lockout (4,000 Customers)

- Fault-induced conductor slap (FICS) locked out a 4,000-customer circuit.
- 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 FICS as the cause and provided location parameters.
- FICS recurs in susceptible spans. Knowing that FICS has occurred avoids future circuit trips, system stresses, and outages.




**Improved reliability; improved safety; reduced manpower; reduced system damage.**

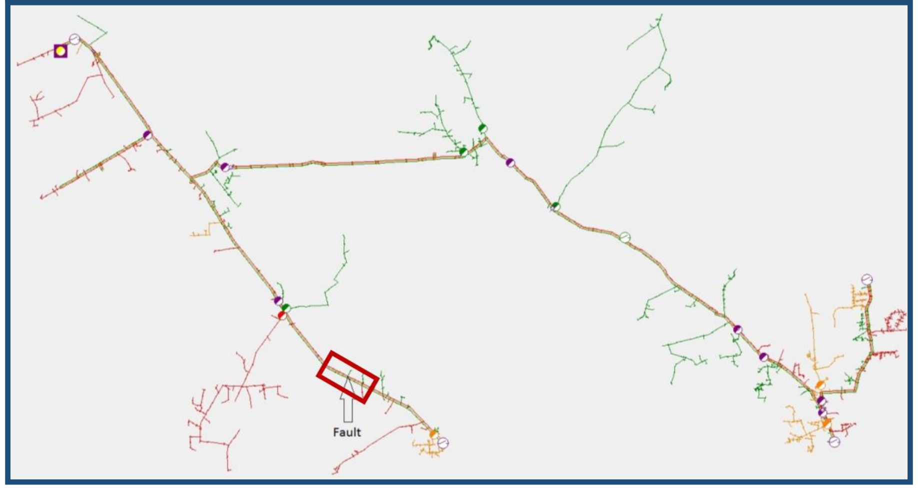
# Repeated Vegetation-Caused Circuit Trips

- Two momentary substation breaker operations occurred during storms three weeks apart.
- DFA provided utility's only notice that the two incidents were the same fault. (This is the key.)
- DFA also provided information to locate the cause: branches pushing phases together.
- Note progressive conductor damage (broken strands) in photo.
- Targeted trimming prevented additional momentary operations, circuit lockouts, line damage, and potential burn-down.

**Improved reliability; reduced system damage; fair-weather repairs; improved safety.**

# Crossarm Charred by Displaced Phase Conductor

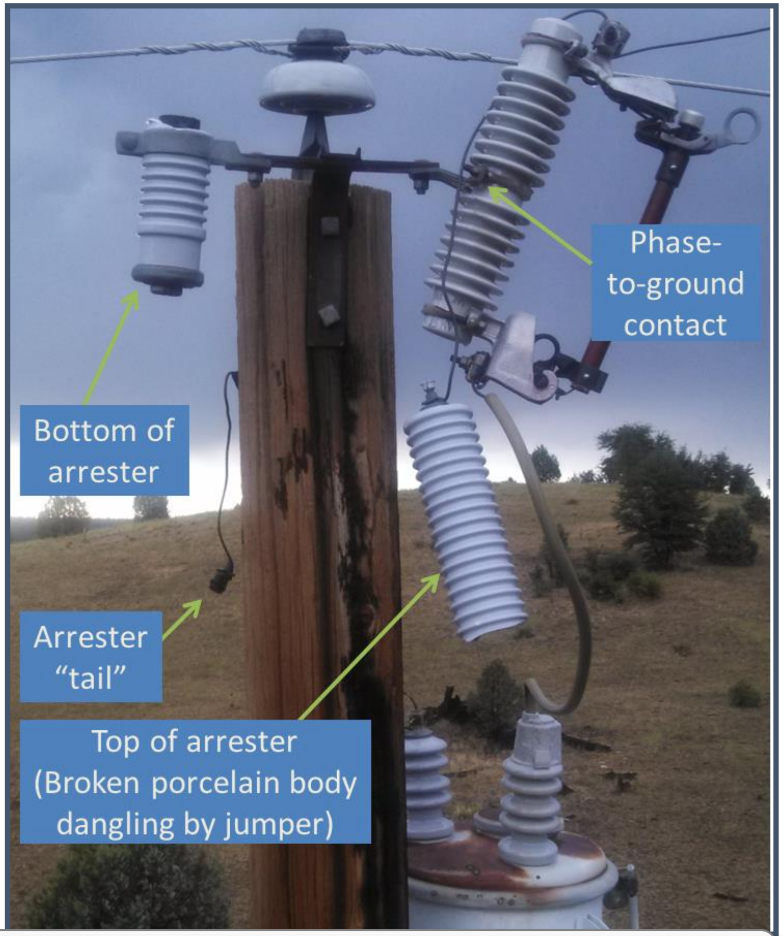
- Subject circuit has 109 miles of exposure.
- During a routine review of DFA records, the utility noted two similar faults, one day apart.
- Putting DFA fault current into model-based fault location software identified two possible locations, on two major branches.
- The major branches have electronic reclosers. One had “seen” the faults; the other had not.
- The problem was six spans from the prediction.
- Because of a broken insulator, a phase conductor was lying on and charring a wooden crossarm.




**Improved reliability; reduced system damage; fair-weather repairs; improved safety.**

# Failed Line Apparatus

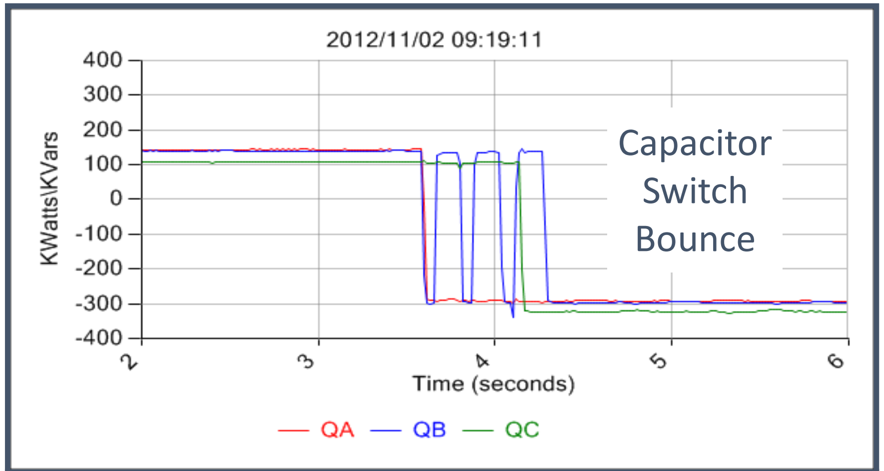
- A blown arrester caused an outage in a hard-to-patrol area.
- DFA data provided fault current and suggested that a blown arrester was the cause.
- The subject circuit has many line miles past the tripped device. Knowing the fault current reduced search time substantially.
- Crews typically must look for broken apparatus, tree contacts, downed lines, …. Knowing the cause, from DFA, further shortened the search.

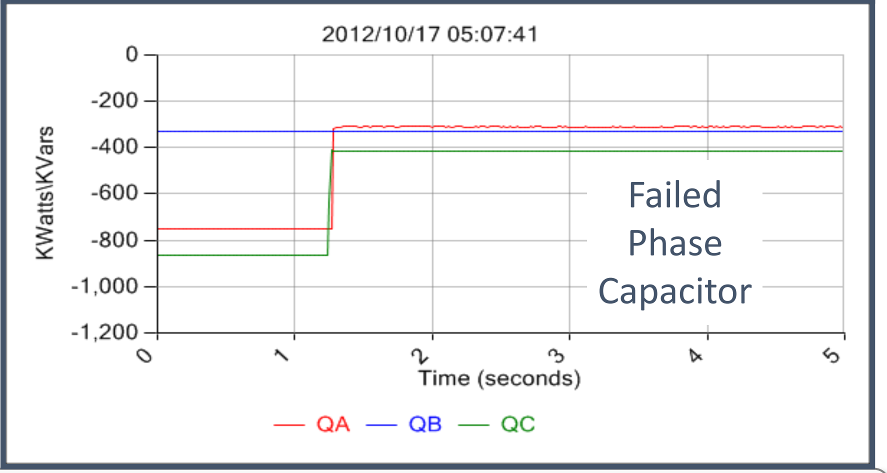



**Reduced manpower; fewer close-to-test attempts; quicker restoration.**

# 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).

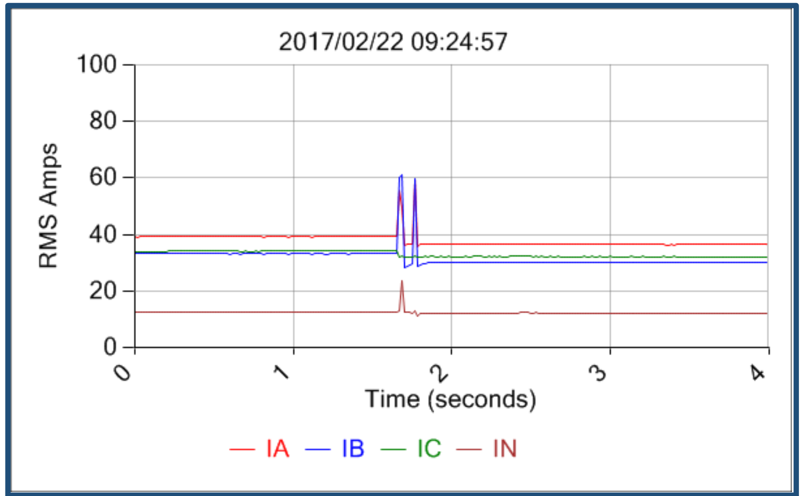



**Improved maintenance efficiency; better, faster detection of failures; improved PQ.**

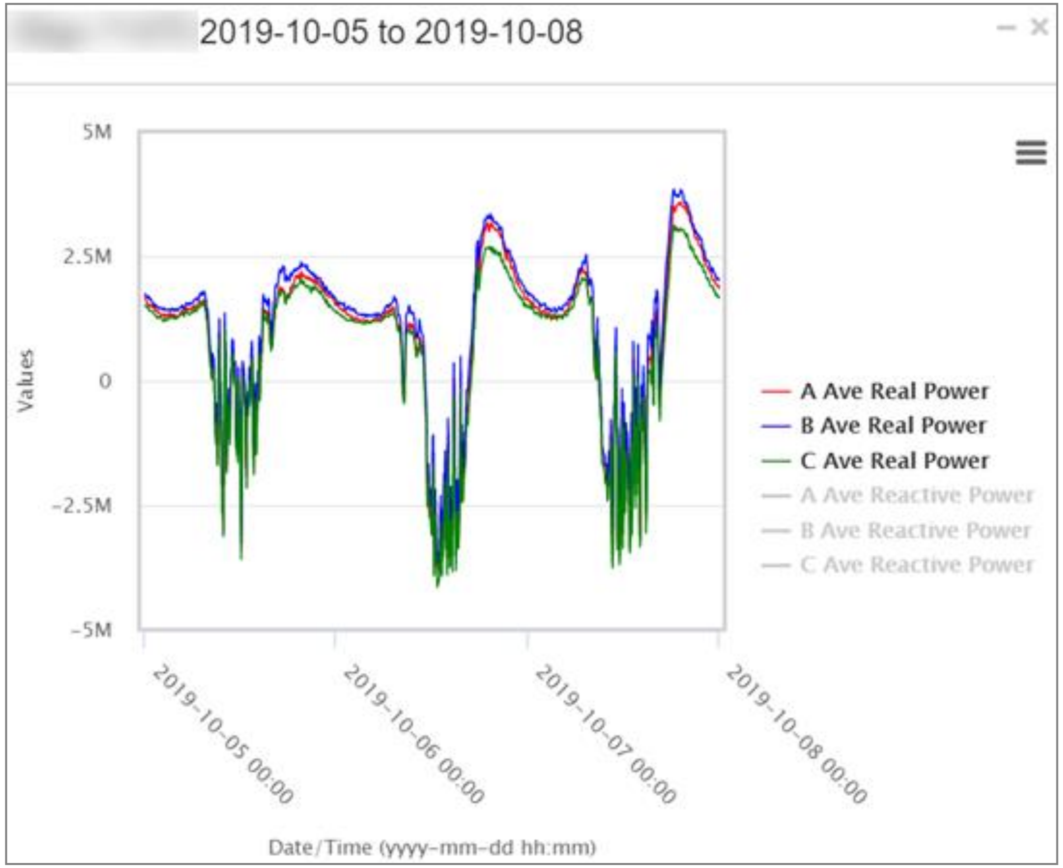
# Partial Loss of Vacuum in Capacitor Switch

- This utility controls line capacitors via radio and monitors kvars to confirm switching.
- DFA reported ‘severe restrike’ during switching 17 February 2017 and again five days later.
- The utility had no other indication of a problem.
- Utility used radio dispatch to determine the offending bank and then dispatched a crew.
- The bank’s suspect vacuum switch was tested and determined to have lost partial vacuum.
- The vacuum switch was replaced prior to failure.




**Improved power quality; avoided catastrophic failure of vacuum switch; scheduled, fair-weather repairs; improved personnel and public safety.**

# Visibility and Awareness – An Example



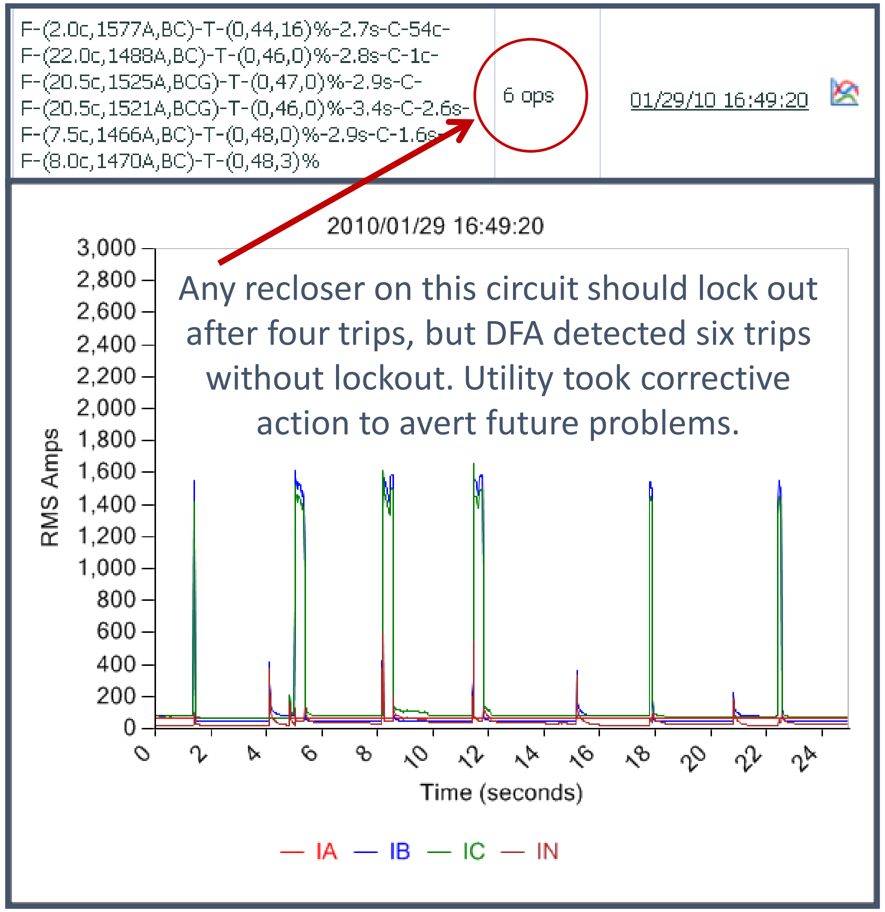

- DER adds complexity to distribution, which can be monitored as shown in this graph.
- DFA provides instantaneous, trending, and archival information for circuits.

Graph shows power profile, recorded by an active DFA installation, on a distribution circuit with a large solar farm and several MW of normal distribution load. Note dynamic short-term swings and diurnal cycles of positive and negative power flow.

Use Case Summary

# Management of Unmonitored Line Reclosers

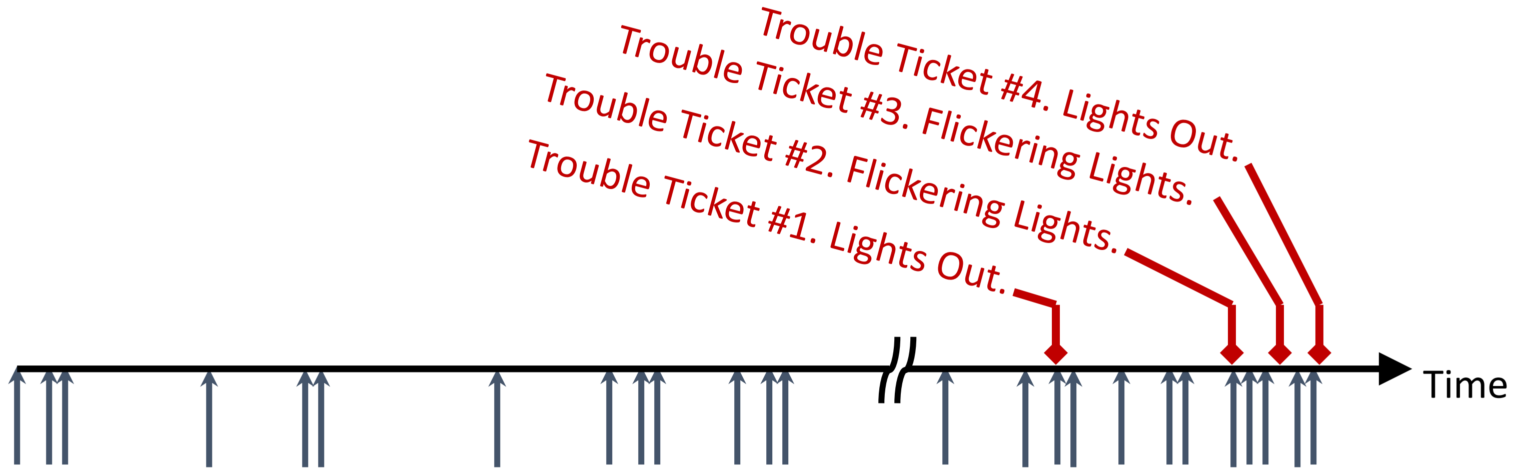
- Intelligent, communicating reclosers are available, but a large population of unmonitored reclosers remains in service for the foreseeable future.
- DFA reports recloser operations, in detail, based on substation waveforms.
- DFA has revealed multiple cases of reclosers operating incorrectly.
  - Excess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




**Notice of latent problems; improved protection; improved operations; improved safety.**

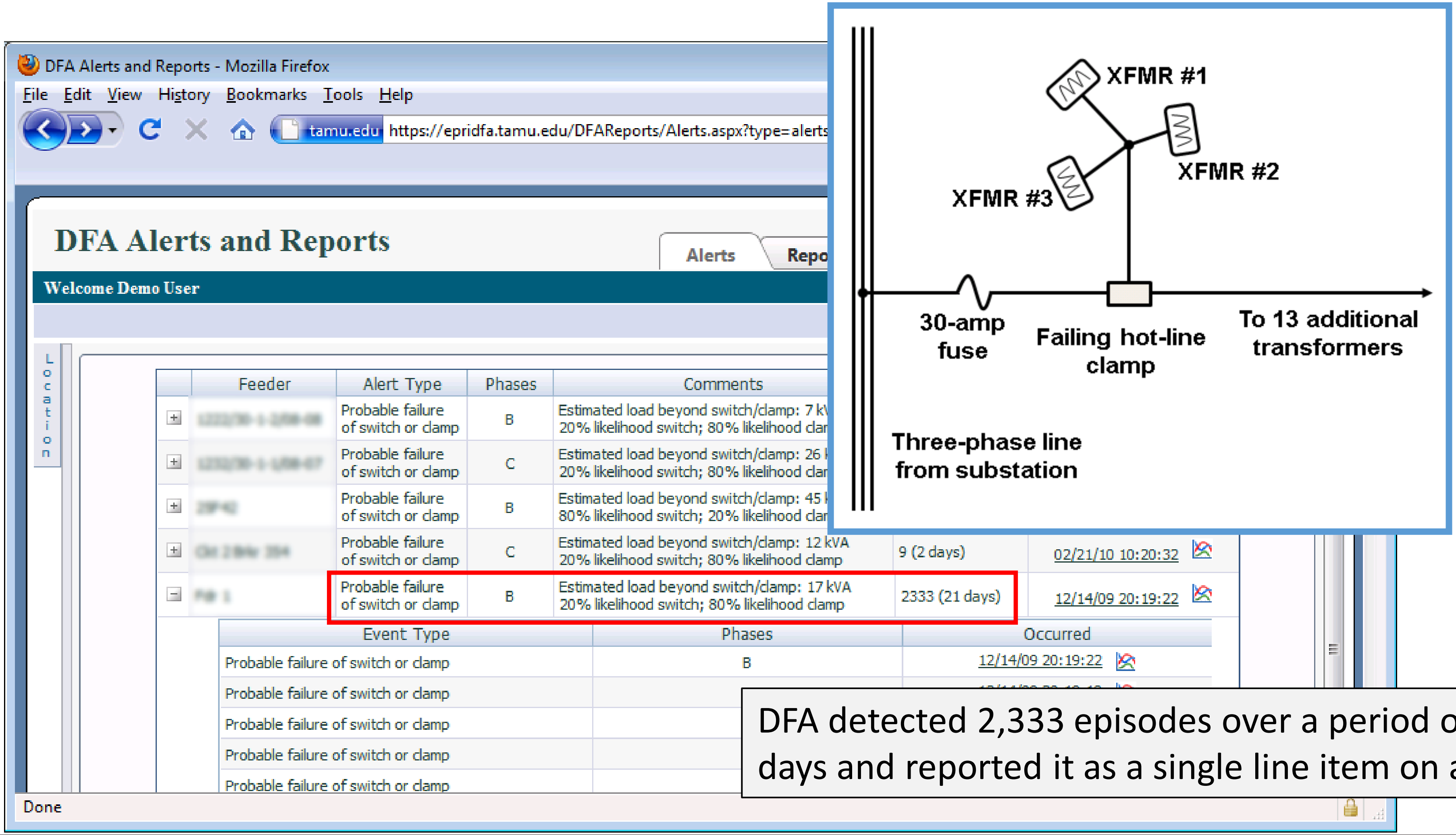
# Operational Inefficiency Using Conventional Practices

- DFA detected incipient failure of a single clamp repeatedly for three weeks.
- At the end of the three-week period, a group of customers experienced trouble four times over a period of 40 hours, necessitating four crew trips.
- DFA was operating in “blind study” mode. Utility crews responded using conventional processes and had difficulty identifying the root cause.
- **<u>Result</u>**: A single failing clamp “cost” four trouble tickets, four truck rolls, and two transformer replacements, all on overtime and mostly unnecessary.



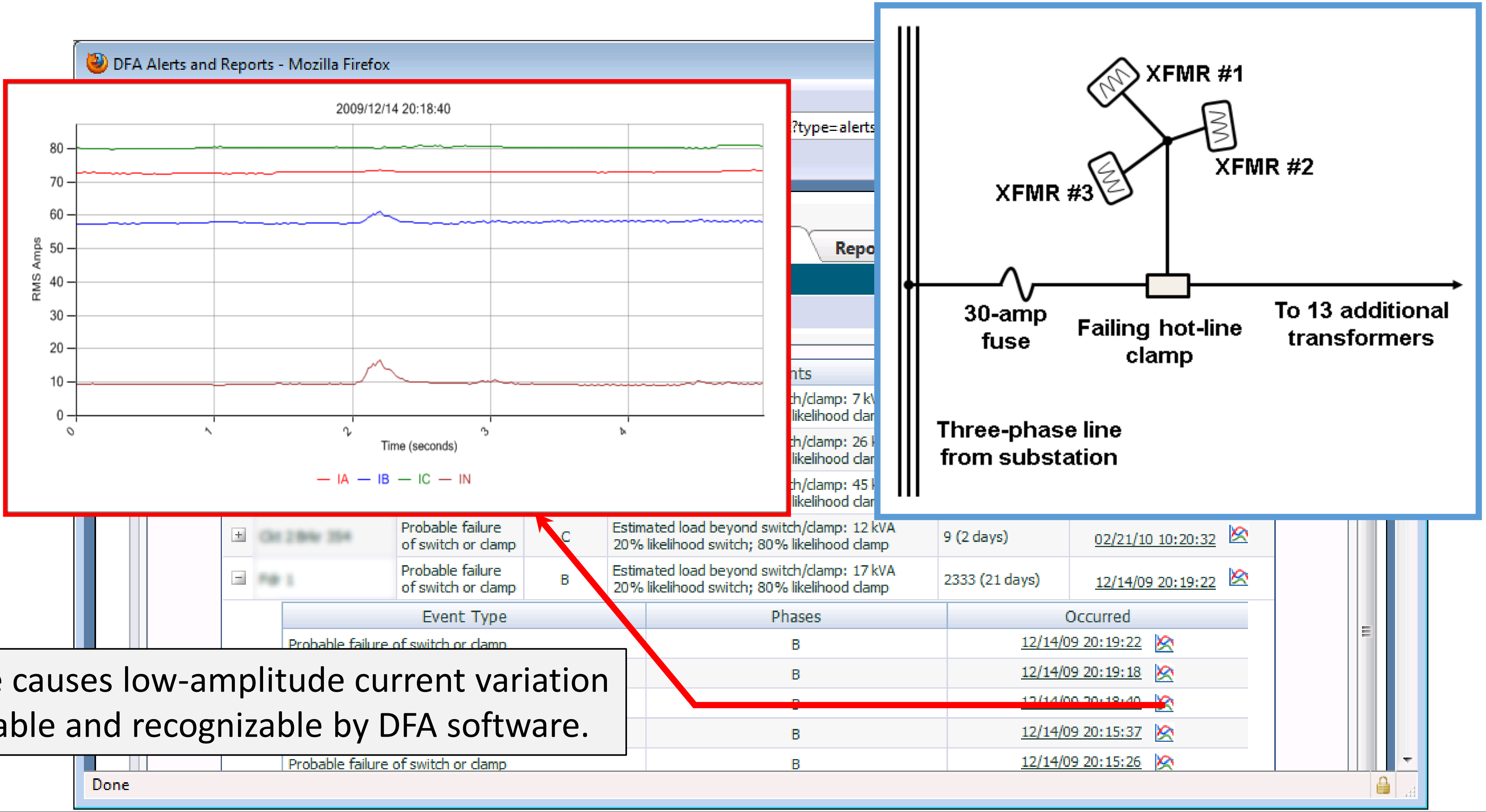

Failing-Clamp Detections by DFA (2,333 Episodes over 21-Day Period)

# Operational Improvement Using DFA




DFA detected 2,333 episodes over a period of 21 days and reported it as a single line item on a report.

# Operational Improvement Using DFA




Clamp failure causes low-amplitude current variation but is detectable and recognizable by DFA software.

# Special Focus
# Fires and Other Safety Issues

# How Do Power Lines Cause Unsafe Conditions?


Downed Conductors


Clashing Conductors


Vegetation


Failing Apparatus

# Example #1: Preventable Events that Can Cause Unsafe Conditions

- Branch hung on a phase conductor, sagging it near an underbuilt earth wire.
- This caused multiple faults, over a 24-hour period, and burned the line down.
- The utility learned of the problem only when customers called after the line broke.
- Each fault represented the potential for ignition. The final fault dropped an energized line and a smoldering limb on the earth.

| | |
|---|---|
| 11/2/2004 | 6:57:47 |
| | 7:58:33 |
| 11/3/2004 | 0:09:06 |
| | 0:16:48 |
| | 0:40:38 |
| | 0:40:53 |
| | 1:10:51 |
| | 1:12:37 |
| | 1:15:30 |
| | 3:24:47 |
| | 4:19:39 |
| | 4:30:36 |
| | 5:51:01 |
| | 6:19:45 |

13 precursors in 24 hours

Identify, Find, and Fix

Avoid Future Faults, Outages, Broken Wire, and Potential Ignition

The utility asserts that, if they had had DFA technology in operation, they believe they would have prevented multiple fault episodes and the burn-down.

# Example #2: Preventable Events that Can Cause Unsafe Conditions

- 11/12/2007 – Fault

Identify, Find, and Fix

- 12/02/2007 – Same Fault
- 11/13/2009 – Same Fault
- 11/18/2009 – Same Fault
- 12/25/2011 – Same Fault

Avoid Future Faults, Outages, and Potential Ignition Events

Over a period of four years, these five faults all occurred from the same root cause, at the same location, but conventional utility processes did not identify the problem or its root cause. Each episode causes arcing and represents the potential for ignition. Texas A&M's DFA technology determined the root cause, enabling location and repair, to avoid future episodes.

# Conclusions

DFA technology offers a deep level of knowledge about circuit operations and health in near real-time.

- Proactive
- Predictive
- Diagnostic
- Situational awareness
- Visibility
- Actionable recommendations
- Operator knowledge (not data!)

# Improving the Reliability and Health of Distribution Circuits Using Real-Time Diagnostics and Incipient Failure Detection Preventing Outages, Fire Ignition and Safety Hazards

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