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(presented by Dr. Jeffrey Wischkaemper)

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Real-time Electric Circuit Diagnostics Using Waveform Analytics—Predicting Failures and Preventing Outages, Making the System More Reliable and Safe

TECHNICAL SESSION 3

SREDS19 · DOHA, QATAR · DEC. 1, 2019

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TEXAS A&M UNIVERSITY at QATAR

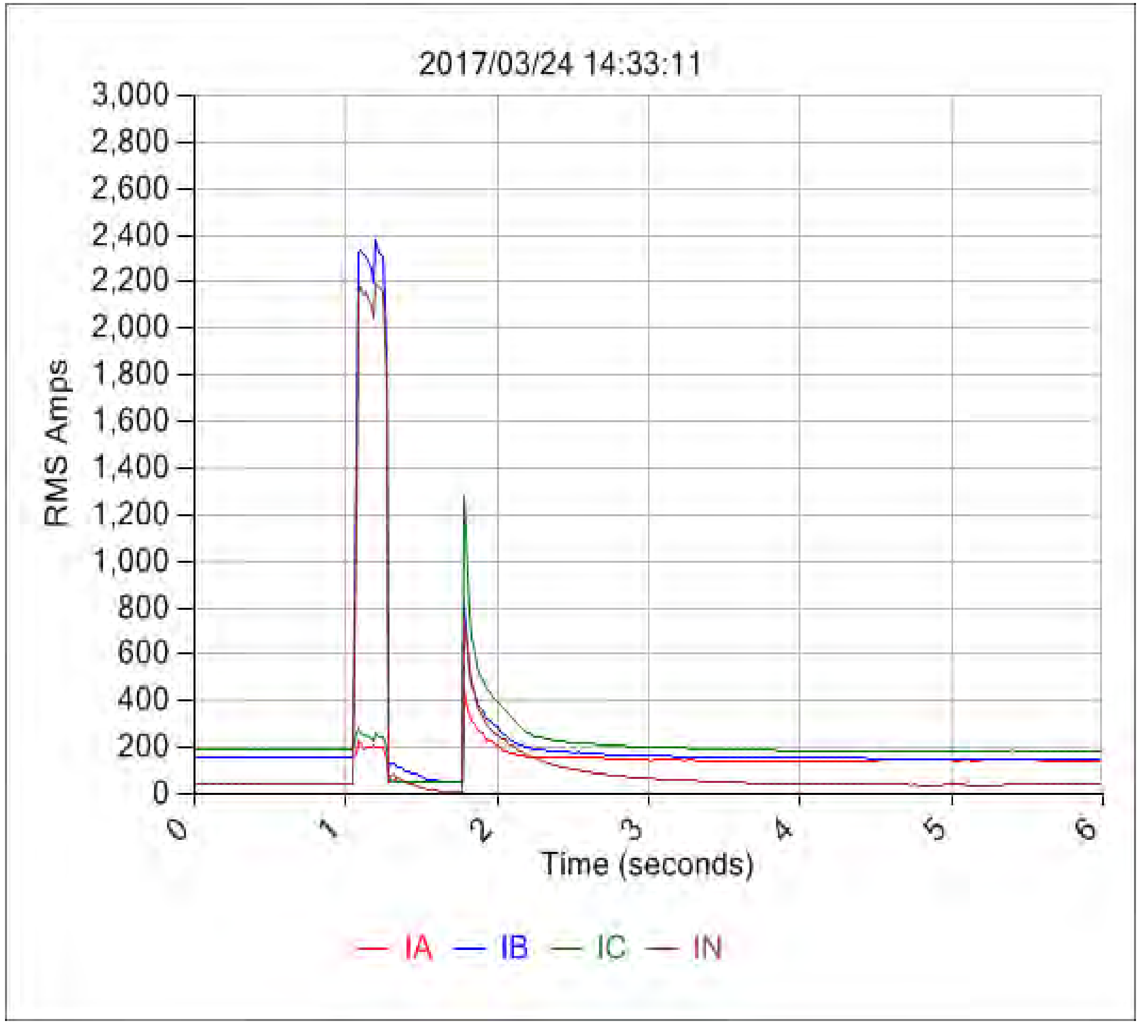
About the Speaker

- Distinguished Professor at Texas A&M University
- Director of the Power System Automation Laboratory
- Over 50 years of experience working with utility companies to develop solutions for real-world challenges facing the industry.

Circuit Situational Awareness

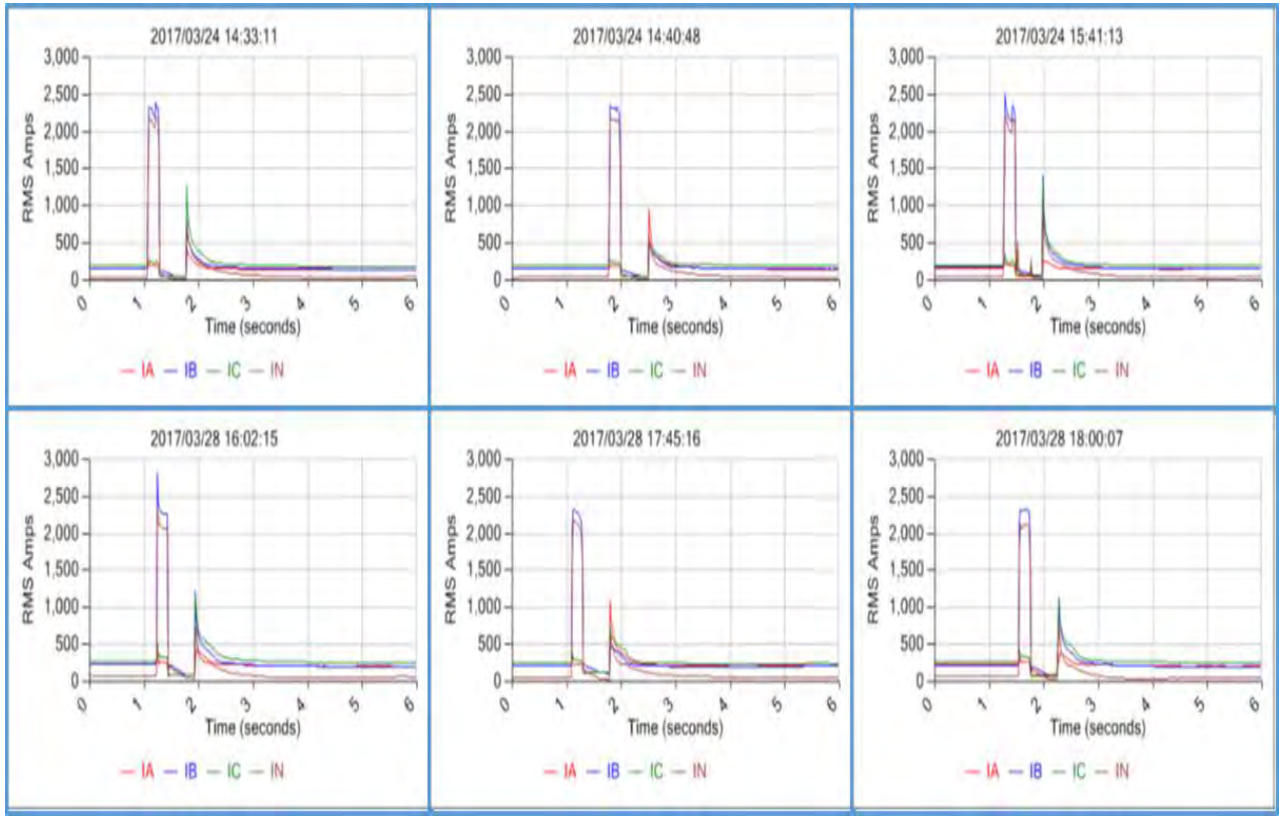
- How do I know that a circuit is healthy?
  - The breaker is closed.
  - Everyone has power.
  - No one has reported an outage.
  - Therefore, circuits are presumed healthy.
- What do I <u>not</u> know about my circuits?
  - An cable splice on circuit 6 is failing, and has caused seven self-healing faults over the last two months.
  - 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.

What Would You Do?



- Assume you know this fault occurred.
  - Downstream recloser trip/closed
  - No substation breaker operation
  - No outage
- What is the significance of this event?
- What would you do in response?

What Would You Do?



- Now assume six <u>identical</u> faults have occurred in four days.
  - Downstream recloser trip/closed
  - Still no outage

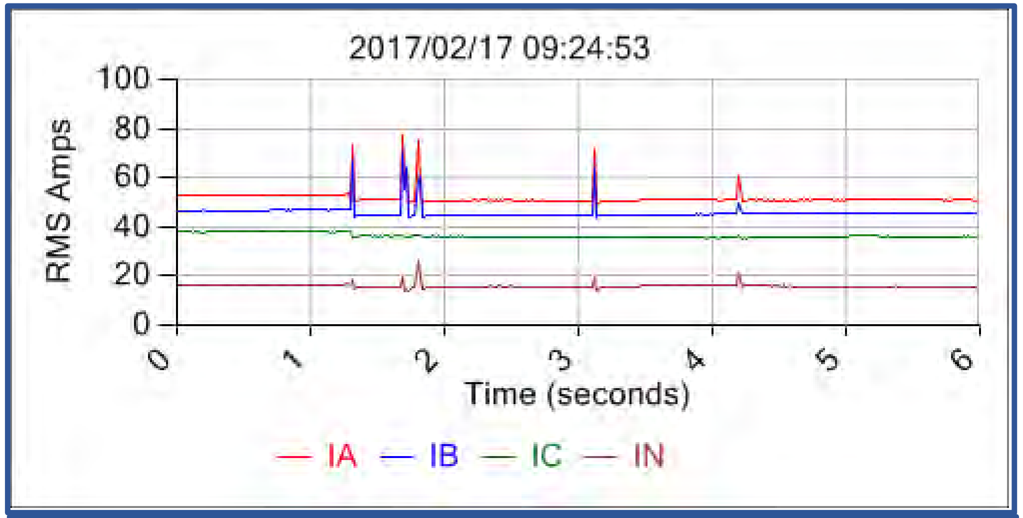
Possible recurrent fault	B	Three-Phase reclose, 2332 Amps	6 (4 days)

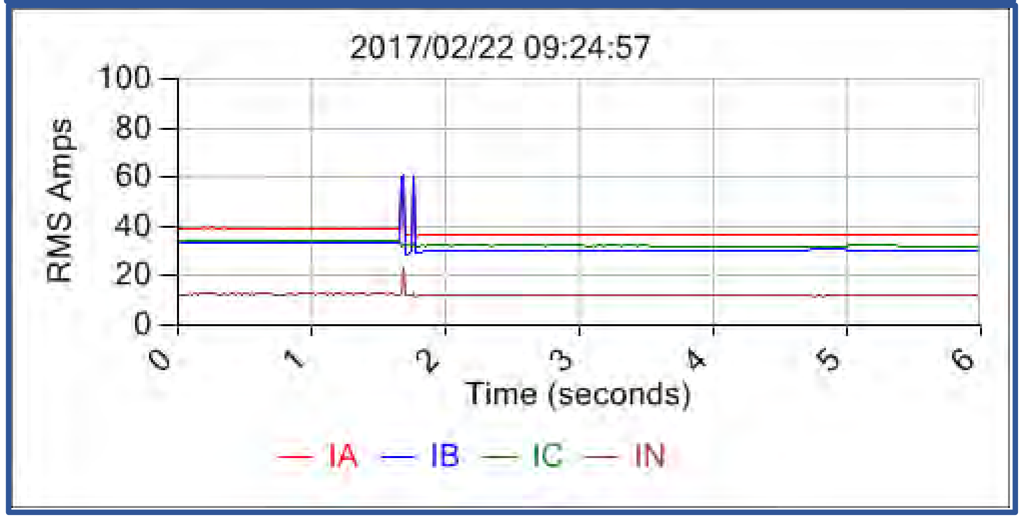
of the events?

- Now what would you do in response?

03/28/17 18:00:07
03/28/17 17:45:16
03/28/17 16:02:15
03/24/17 15:41:13
03/24/17 14:40:48
03/24/17 14:33:11

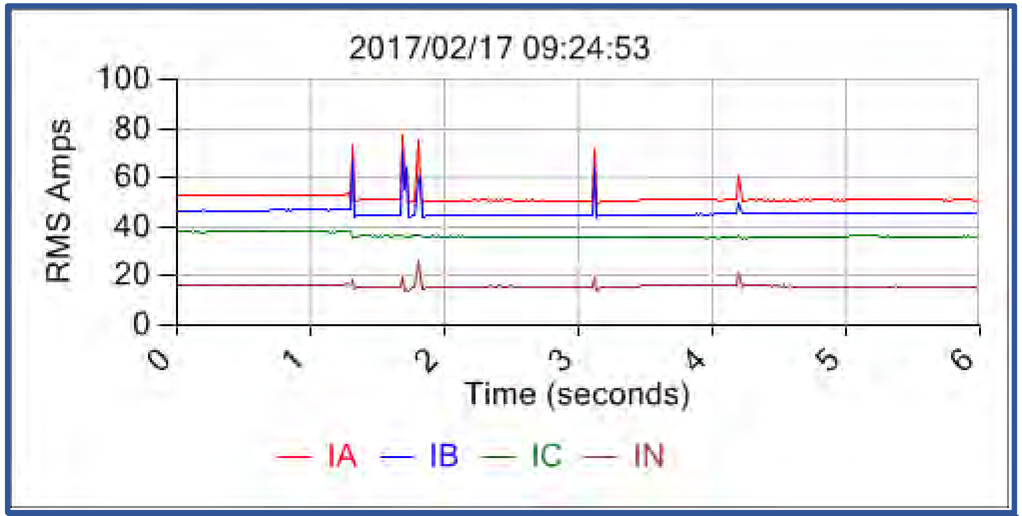
Another "What Would You Do?"

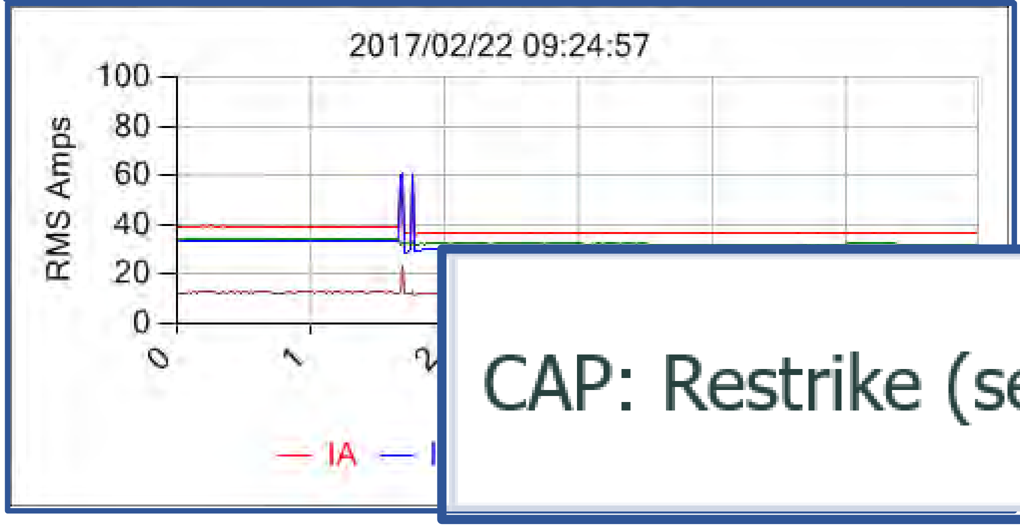




- Assume this activity is happening on one of your circuits.
- You have no way to know it is occurring.
- Even if you did know it was occurring, what does it mean, and what would you do?

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 Technology Background

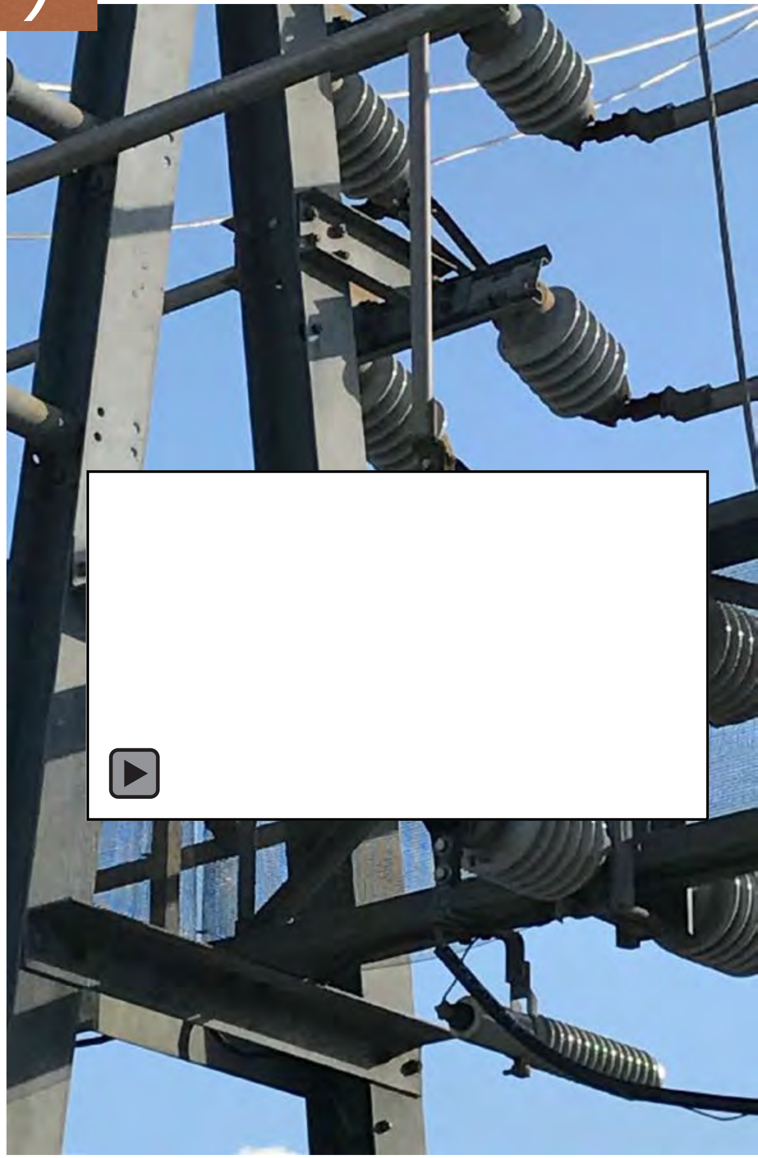
- Power System Automation Laboratory
  - Department of Electrical and Computer Engineering, Texas A&M University
  - Started waveform analytics research in 1978
  - Developed first commercial, HiZ arcing fault detector
- Distribution Fault Anticipation (DFA) technology R&D
  - DFA research sponsored by EPRI, starting in 1997
  - More than $10M invested by EPRI, the state of Texas, and utilities
  - Heavy involvement of more than a dozen utility companies
    - At present have instrumented over 200 circuits with specialized, Internet-based data recorders
    - Collected more than 1000 circuit-years of data and correlated results with field findings
    - <u>Result</u>: Largest existing database of electrical data from naturally occurring failure and misoperations events
  - Developed sophisticated suite of algorithms (a/k/a on-line waveform classification engine) for automatically identifying failures and other events

Failing Substation Switch

- 25 kV substation; 3 circuits; 2,000 customers
- Incipient failure
  - No outage, no customer calls
  - No problem indicated by SCADA
  - 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.

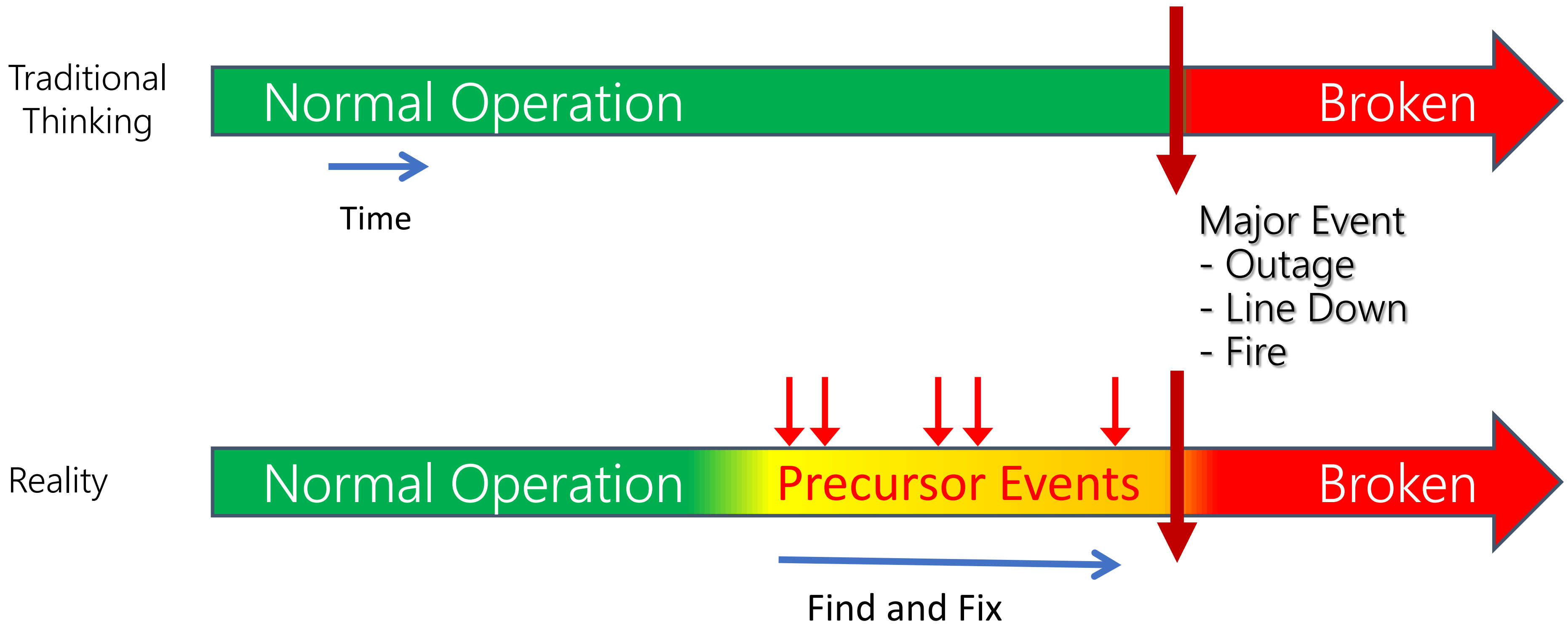
Maintaining Reliability and Circuit Health

- Distribution constitutes well over 90% of the line-kilometers in the US and causes most of the customer interruptions and outages.
- We must assume that there will be no mass replacement of aging distribution infrastructure in next 20-30 years.
- Resources are constrained and becoming more so.
  - Fewer people; less experience
  - Fewer dollars for maintenance and upgrades
- Periodic inspections and other preventative maintenance activities are resource-intensive and have limited effectiveness.

Distribution Operations – Current Status

- Operating personnel lack awareness of impending failures.
- Components run until failure and then are repaired or replaced.
- Consequences: Avoidable interruptions, outages, explosions, fires, safety hazards, PQ problems, …

Distribution Circuit Operating Paradigms



Conventional response starts after outage or other consequential event.

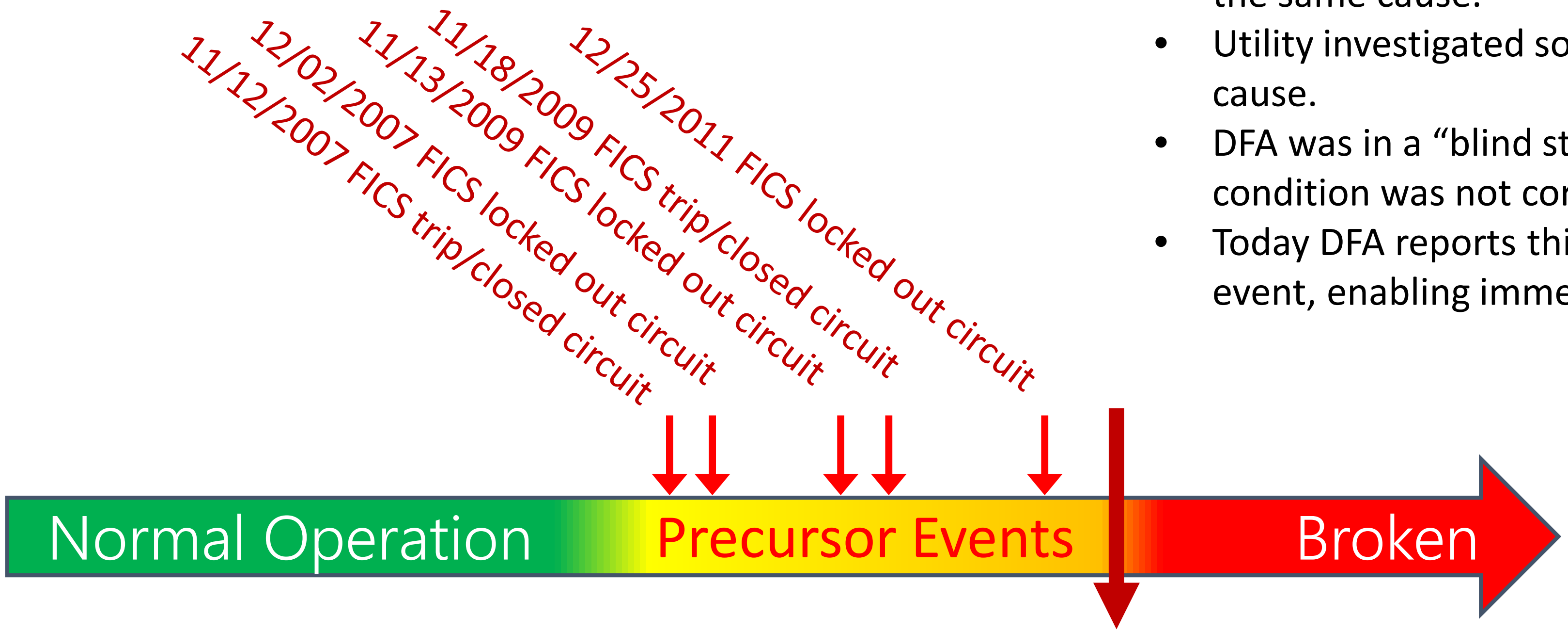
Smart grid response still starts after outage or other consequential event.

Key to better circuit management is early awareness 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.

Distribution Operations – Paradigm Shift

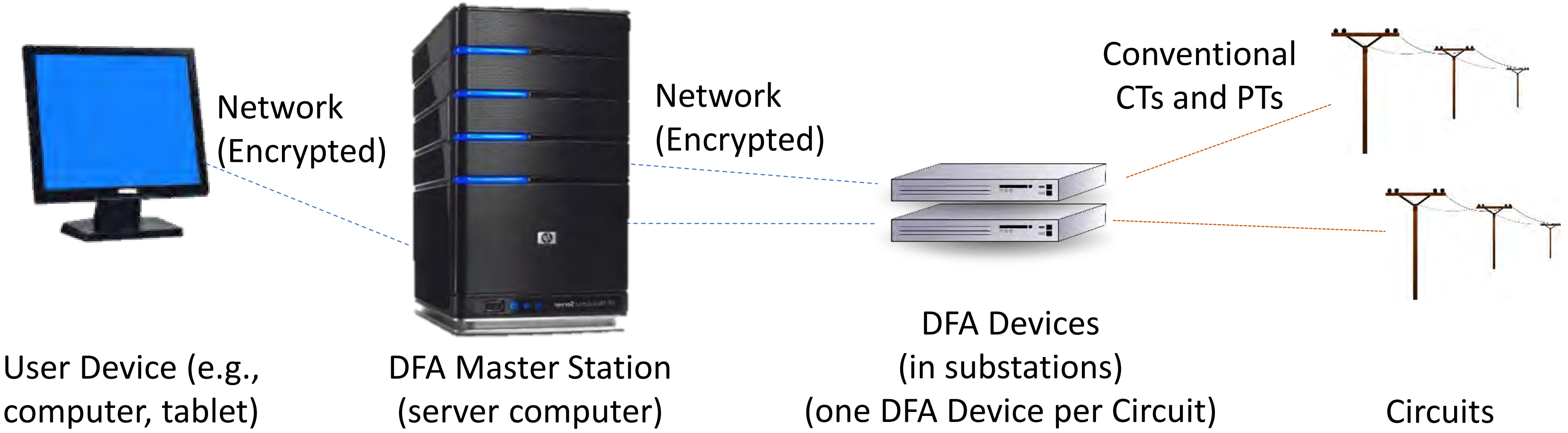
DFA technology represents a paradigm shift in distribution operations and requires a change in mindset, not just technology.

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

DFA and "Smart Grid"

- AMI and self-healing technologies
  - Important components in modernizing grid
  - Remain 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

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 Photos

DFA Device Drawings – December 2017. Subject to change.

<u>Rack-Mount DFA-Plus Device</u>

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)

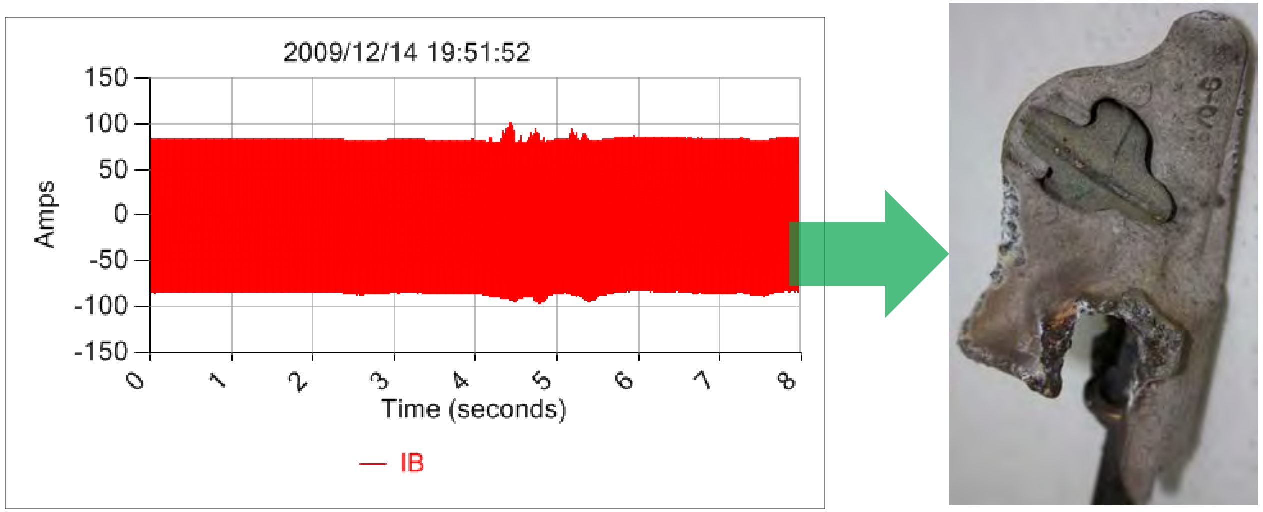
User is responsible for providing unit power, Internet service, CTs, PTs, and all cabling.

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

Hardware platform by Power Solutions LLC.

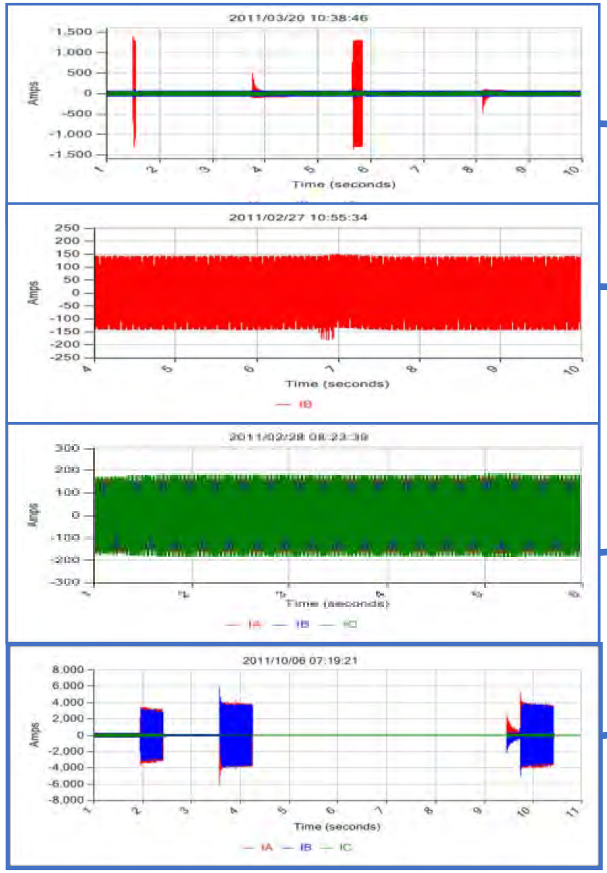
DFA Prianciple: Waveforms Contain Useful Information

- Graph shows line current during “normal” 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

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)

<u>DFA Device software technologies</u>

- 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.

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 and other labor impacts

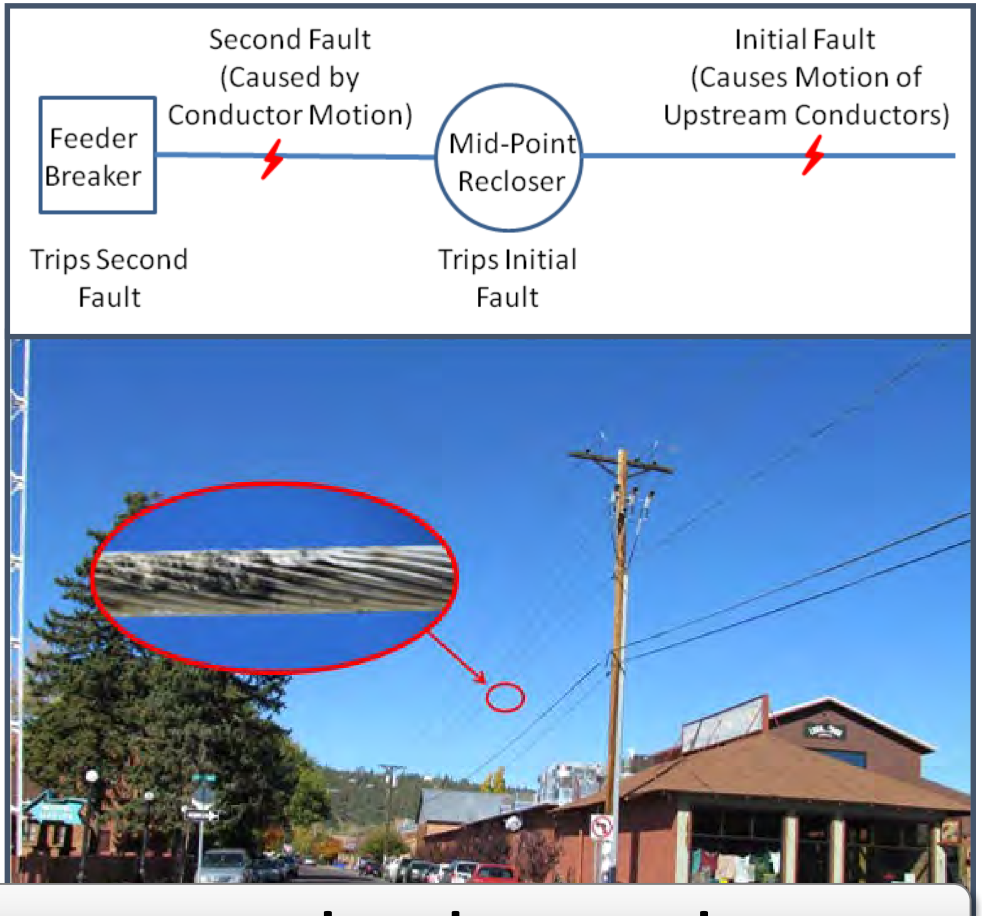
- Daylight, fair-weather, straight-time failure location and repairs
- Improved worker safety (fair-weather, daylight work)
- More efficient troubleshooting (e.g., fewer no-cause-found tickets)

Use Case Summaries

Use Case Summary

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.

Use Case Summary

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.

Use Case Summary

Crossarm Charred by Displaced Conductor

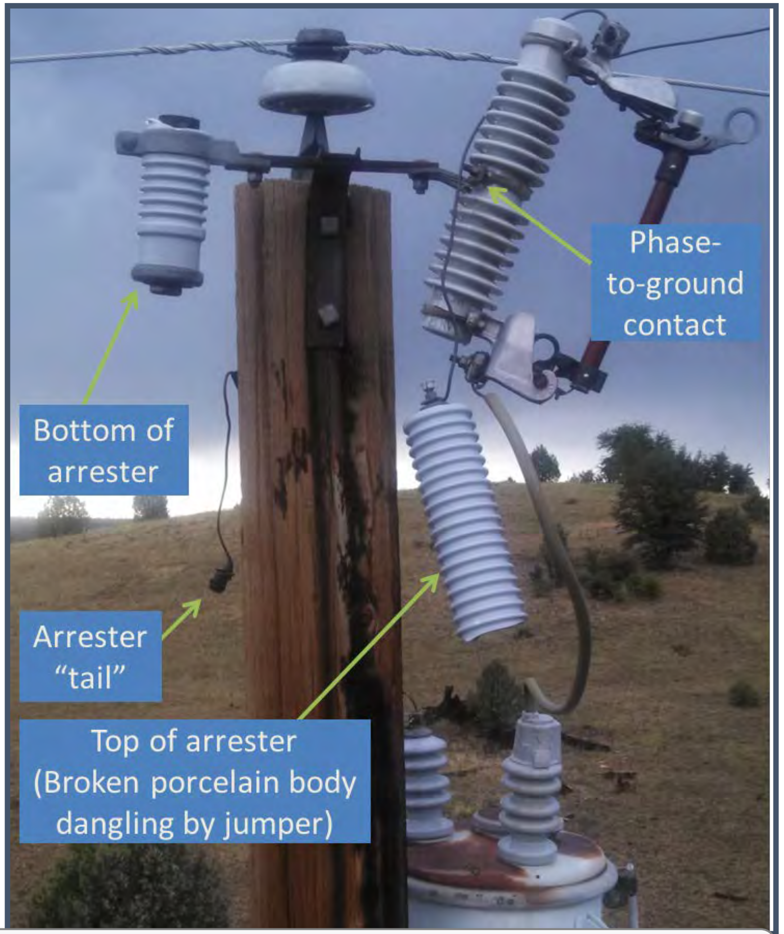
- Subject circuit has 175 km of exposure.
- During a routine review of DFA records, the utility noted two similar faults, one day apart.
- Putting DFA fault current into model-based fault location software identified two possible locations, on two major branches.
- The major branches have electronic 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.

Use Case Summary

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-kilometers 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.

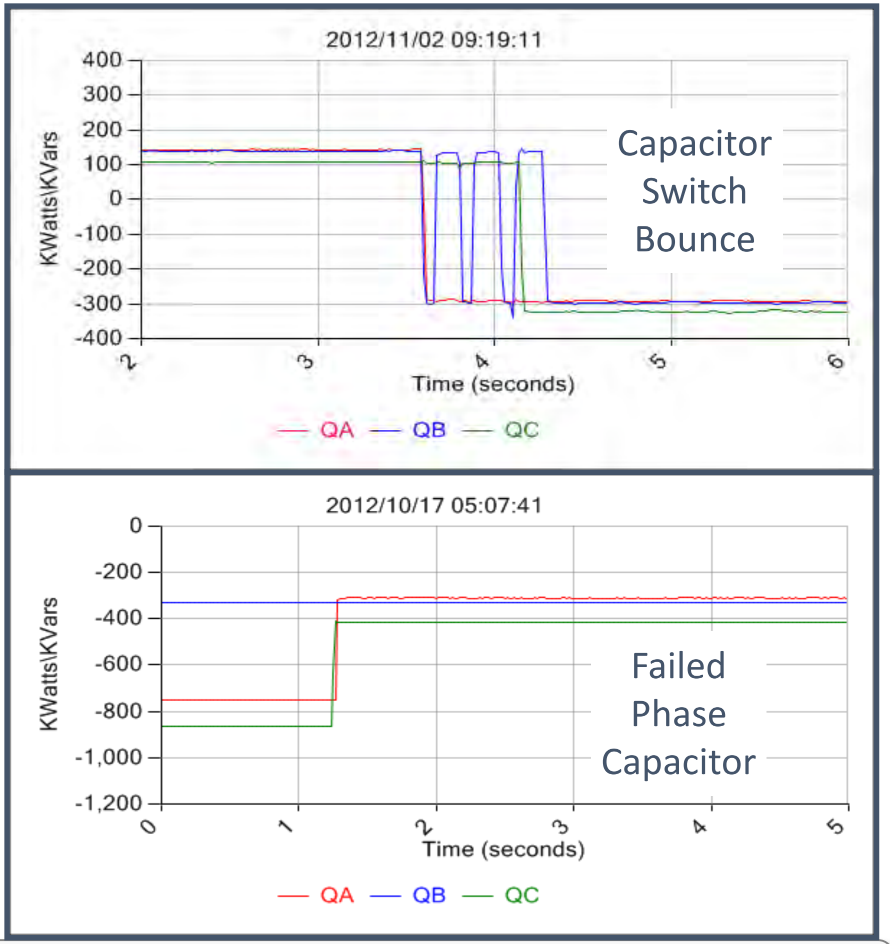


Reduced manpower; fewer close-to-test attempts; quicker restoration.

Use Case Summary

Management of Line Capacitor

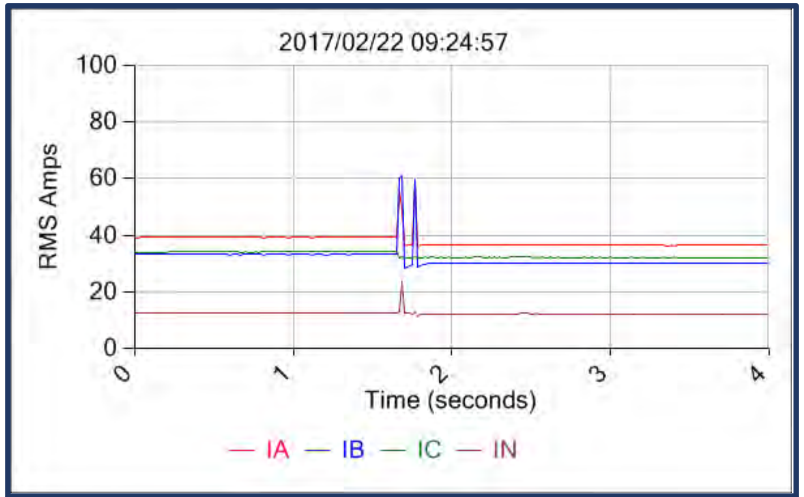
- Traditional maintenance of switched line capacitors is labor-intensive and somewhat ineffective.
- Using waveform analytics, DFA reports failures of switched line capacitors …
  - without communicating with them.
  - without being configured to know they are even present.
- DFA detects types of capacitor 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.

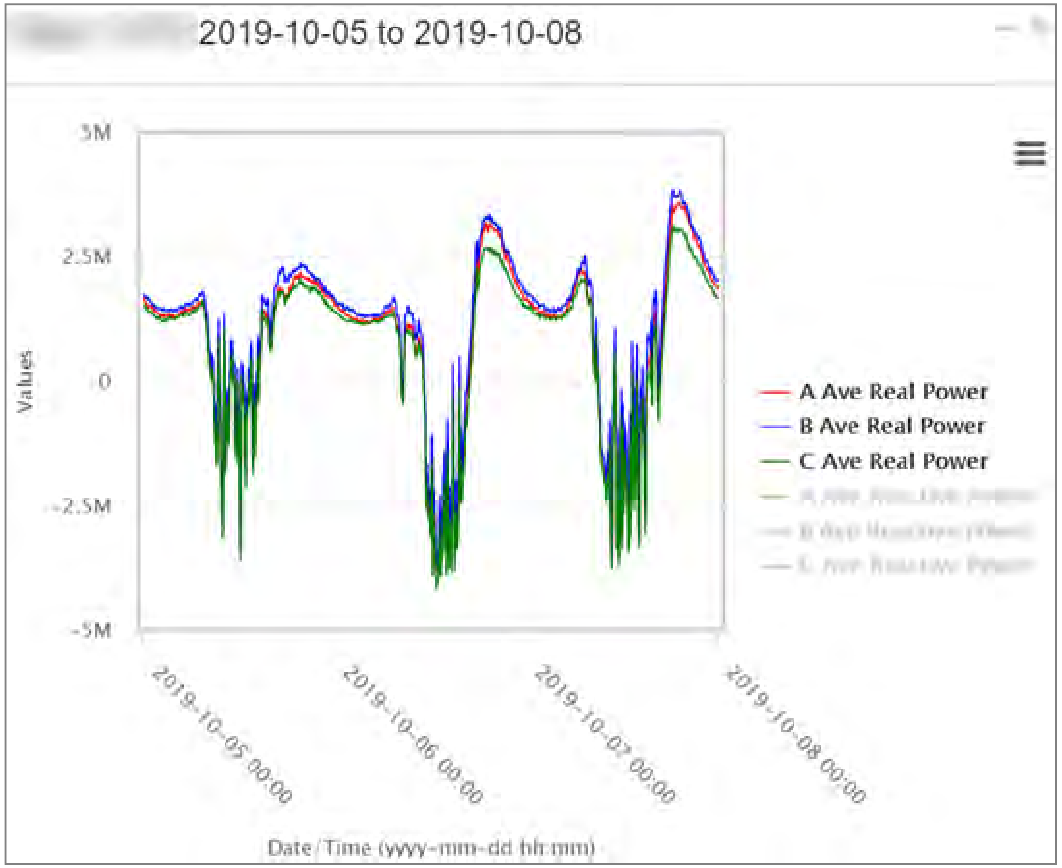
Partial Loss of Vacuum in Capacitor Switch

- 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



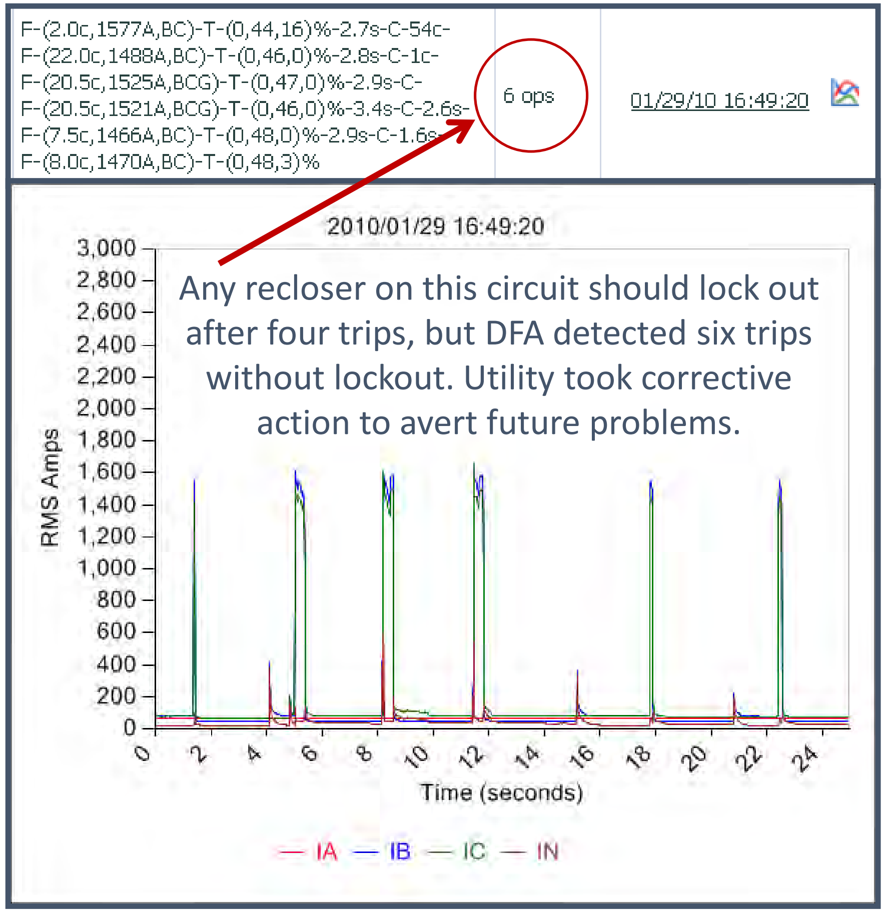
- DFA provides instantaneous, trending, and archival information for circuits.
- For example, DER adds complexity to distribution, which can be monitored as shown in this graph.

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 swings and diurnal cycles of positive and negative power flow.

Use Case Summary

Management of Unmonitored Line Reclosers

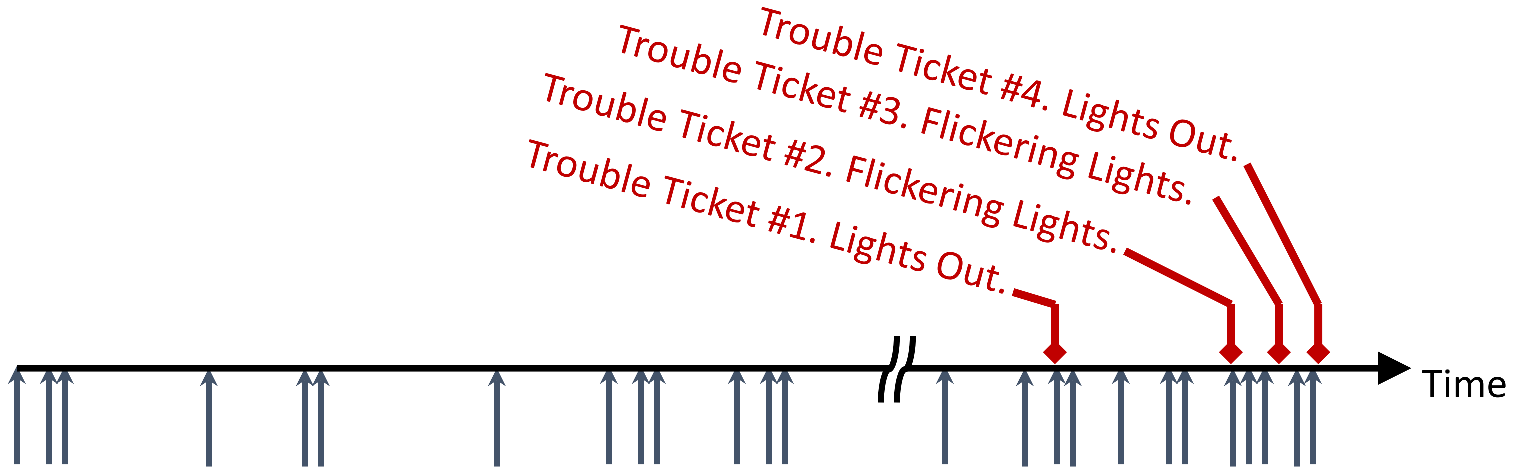
- Intelligent, communicating reclosers are available, but a large population of unmonitored reclosers remains in service for the foreseeable future.
- DFA reports recloser operations, in detail, based on substation waveforms.
- DFA has revealed multiple cases of reclosers operating incorrectly.
  - Excess 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.

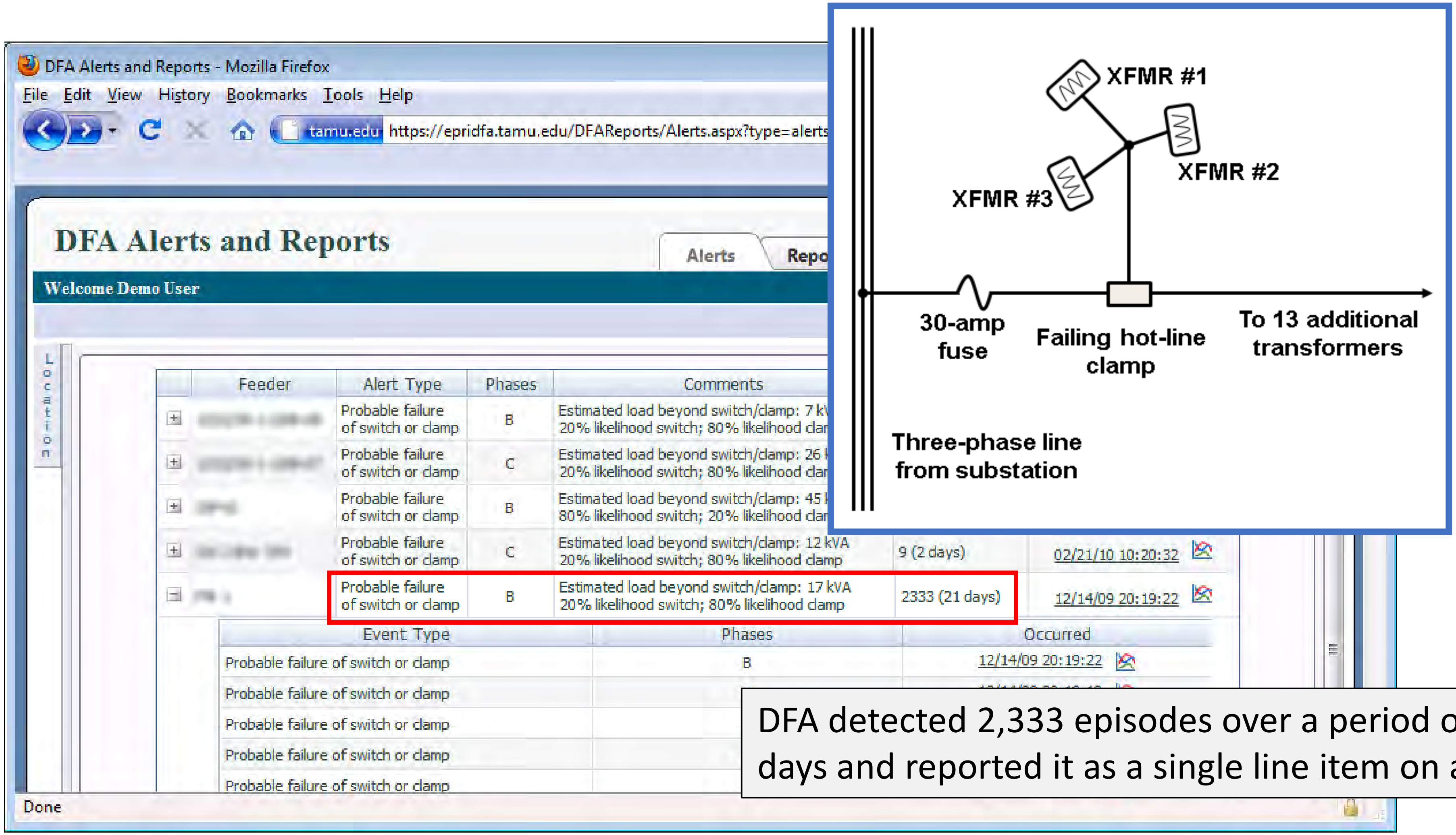
Improving Operational Efficiency

- 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.
- **Result**: A single failing clamp "cost" four trouble tickets, four truck rolls, and two transformer replacements, all on overtime and mostly unnecessary.



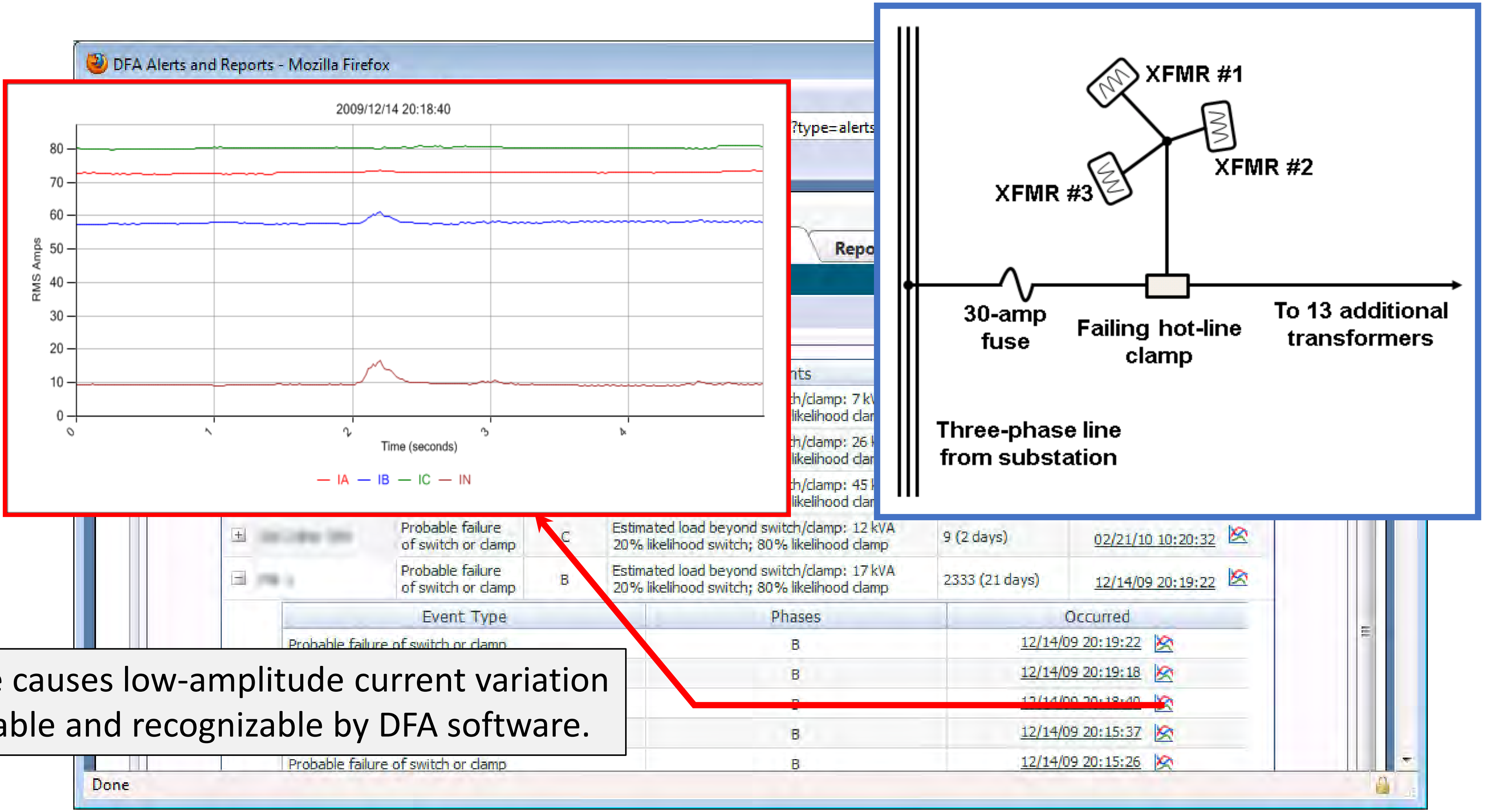
Failing-Clamp Detections by DFA (2,333 Episodes over 21-Day Period)

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.

Detailed Use Case – Capacitor Switch Failure

Incipient capacitor switch failure

- Because the DFA monitors quite sensitively, it not only detects events on the monitored circuit ("downstream events"), but also events that are "upstream" – that is to say, on adjacent feeders, the bus, or on the transmission system.
- For example, a fault on one feeder in a substation will often trigger recordings on all monitored feeders:

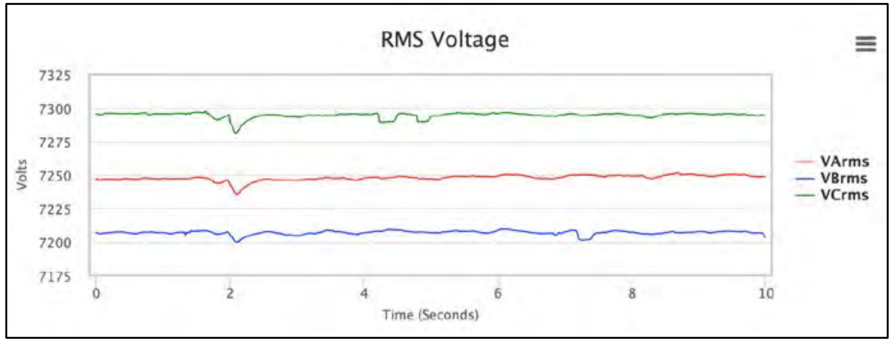
Circuit	Classification	Phases	Downstream	Time
22SY11 Herbert	Overcurrent fault	AN	No	2018-03-27 13:08:34 ACST
22SY04 Dundee	Overcurrent fault	AN	Yes	2018-03-27 13:08:34 ACST
22SY02 McMinns	Overcurrent fault	AN	No	2018-03-27 13:08:34 ACST
22SY12 Noonamah	Overcurrent fault	AN	No	2018-03-27 13:08:34 ACST
22SY15 Darwin River	Overcurrent fault	AN	No	2018-03-27 13:08:34 ACST
22SY03 Virginia	Overcurrent fault	AN	No	2018-03-27 13:08:34 ACST

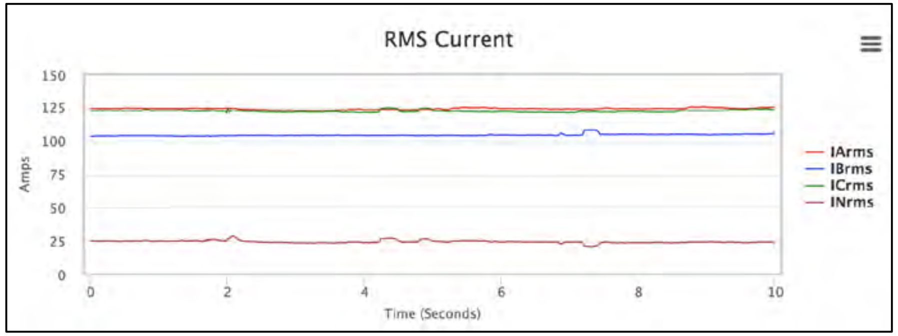
Incipient capacitor switch failure

- In July 2017, a DFA detected a signature associated with an arcing capacitor switch “upstream” of the unit.

Circuit	Classification	Phases	Downstream	Time
DMD-08	CAP: Arcing switch, can or connection	CAN	No	2017-07-15 11:03:41 EDT

- The signature itself is quite subtle, but DFA analytics correctly identified it:





Incipient capacitor switch failure

- Over the next several weeks, the DFA continued to register notifications of this event on a more-or-less daily basis:

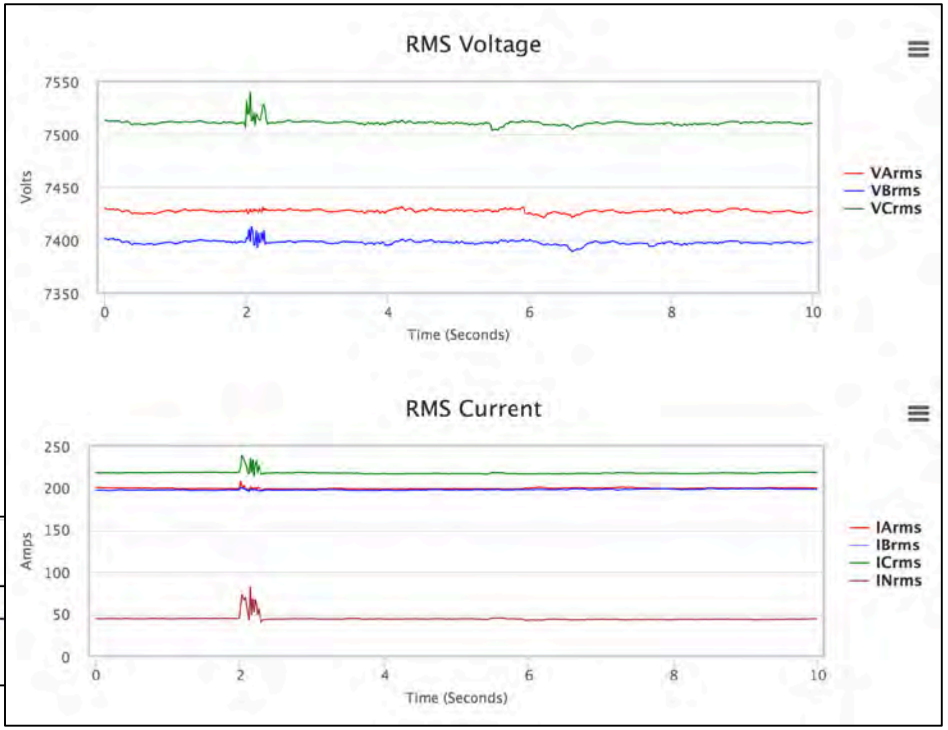
DMD	DMD-08	CAP: Arcing switch, can or connection	CN	No	2017-08-10 12:54:52 EDT
DMD	DMD-08	CAP: Arcing switch, can or connection	CN	No	2017-08-08 11:14:43 EDT
DMD	DMD-08	CAP: Arcing switch, can or connection	CN	No	2017-08-07 09:47:18 EDT
DMD	DMD-08	CAP: Arcing switch, can or connection	CN	No	2017-08-04 11:13:47 EDT
DMD	DMD-08	CAP: Arcing switch, can or connection	CN	No	2017-08-03 10:51:25 EDT
DMD	DMD-08	CAP: Arcing switch, can or connection	CN	No	2017-08-03 10:50:21 EDT
DMD	DMD-08	CAP: Arcing switch, can or connection	CN	No	2017-08-02 11:36:29 EDT
DMD	DMD-08	CAP: Arcing switch, can or connection	CN	No	2017-07-31 11:43:40 EDT
DMD	DMD-08	CAP: Arcing switch, can or connection	CN	No	2017-07-30 14:48:17 EDT

Incipient capacitor switch failure

- Analysis of the waveforms suggested the events occurred when a capacitor switched on, but did not suggest a definitive location (e.g., adjacent feeder, transmission system, etc.).
- In late August, the number of events appeared to be accelerating, and TEES notified the utility on 25 August.
- A cursory check of capacitor logs did not indicate any banks with problems, and no banks on the adjacent circuit or transmission system switched at the times arcing was observed.
- The utility in question has a FLISR system widely installed on their circuits, including the circuit where the DFA was installed.

Incipient capacitor switch failure

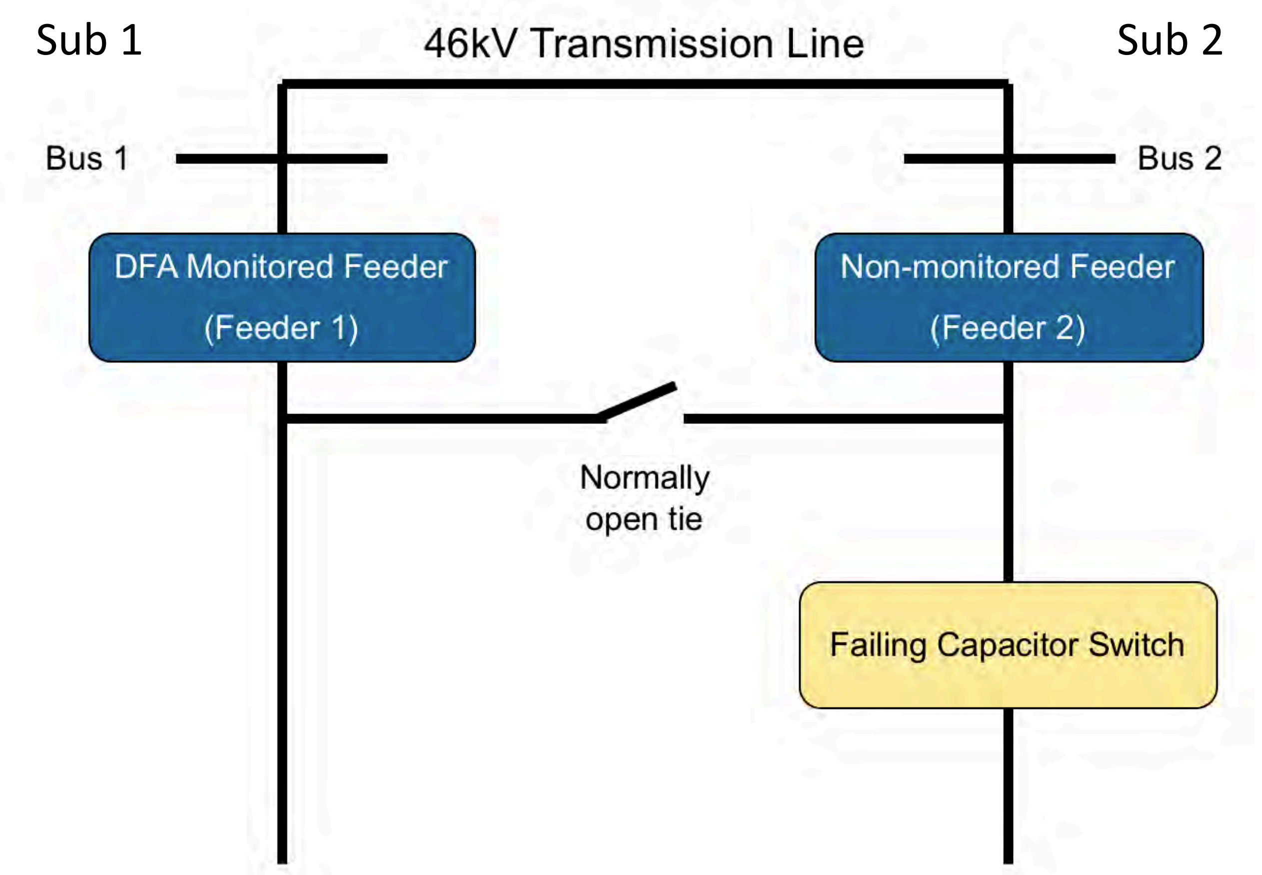
- On September 1, while the circuit was abnormally switched, the DFA registered a capacitor arcing *downstream*.
- Switching times from the bank in question matched precisely, and the switch was scheduled to be taken out of service.



Circuit	Classification	Phases	Downstream	Time
DMD-08	CAP: Arcing switch, can or connection	BN	Yes	2017-09-

Incipient capacitor switch failure

- Simplified one line circuit diagram:



Incipient capacitor switch failure

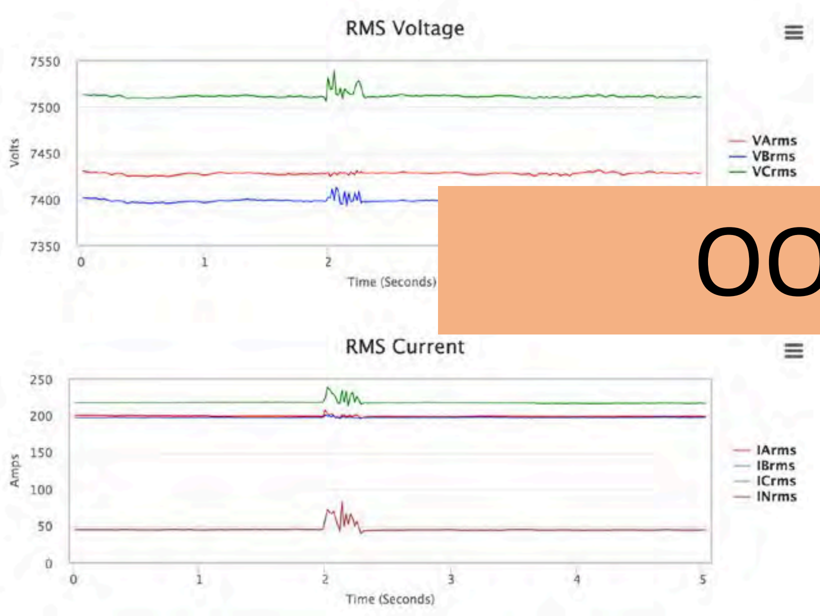
- A repair was scheduled for early October.
- Coincidentally, the crew that repaired the switch was also the crew that installed the capacitor bank – in July 2017.
- The crew mentioned that they had difficulty installing the bank because the controller "kept tripping out because of an imbalance," but eventually they managed to get it working.
- The dispatchers also noticed a "brief imbalance on one phase" every time the capacitor switched on, but thought nothing of it.

Capacitor bank,
faulty switch on front right

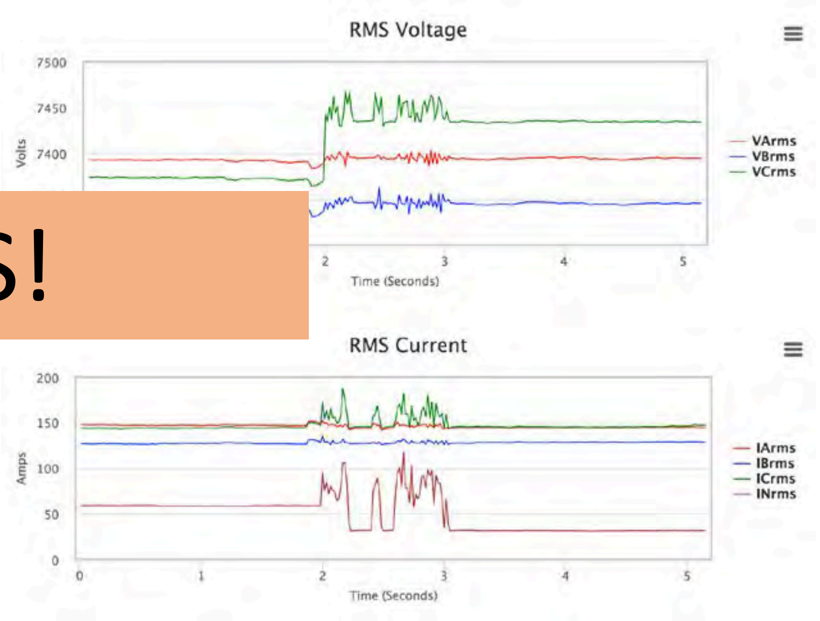
Incipient capacitor switch failure

- After switching out the problematic bank, TEES researchers wanted to show the linemen the before / after waveforms to show how the problem had been fixed:

Before replacement



After replacement

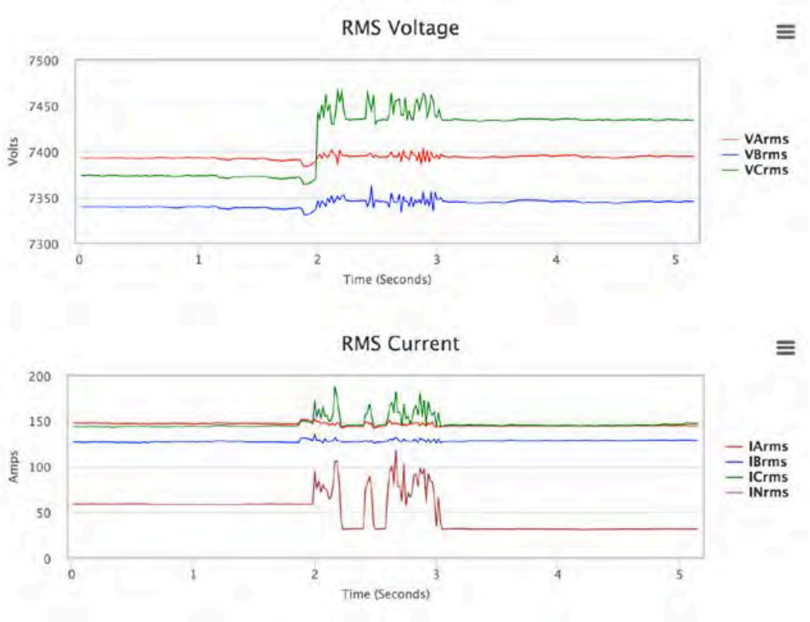


OOPS!

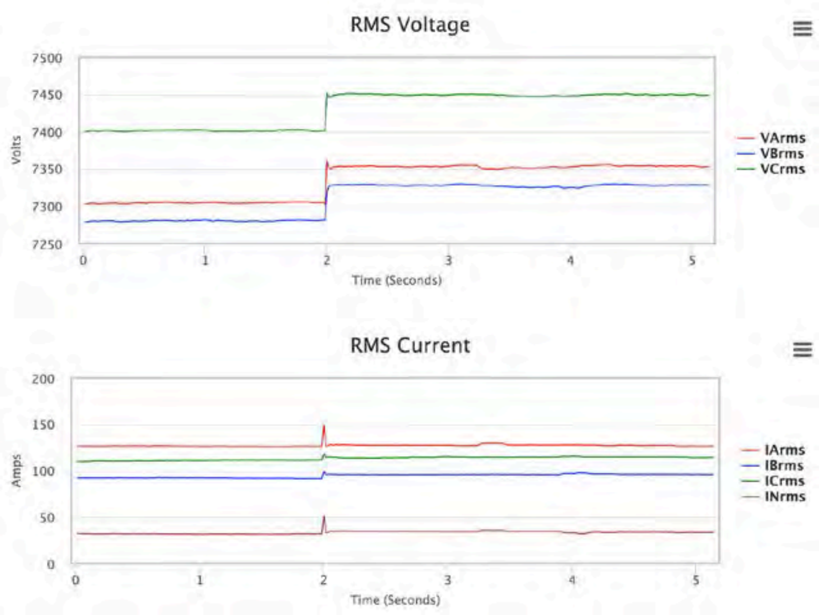
Incipient capacitor switch failure

- A phasing issue caused us to swap out the wrong switch!
- After swapping the correct switch:

Before replacement

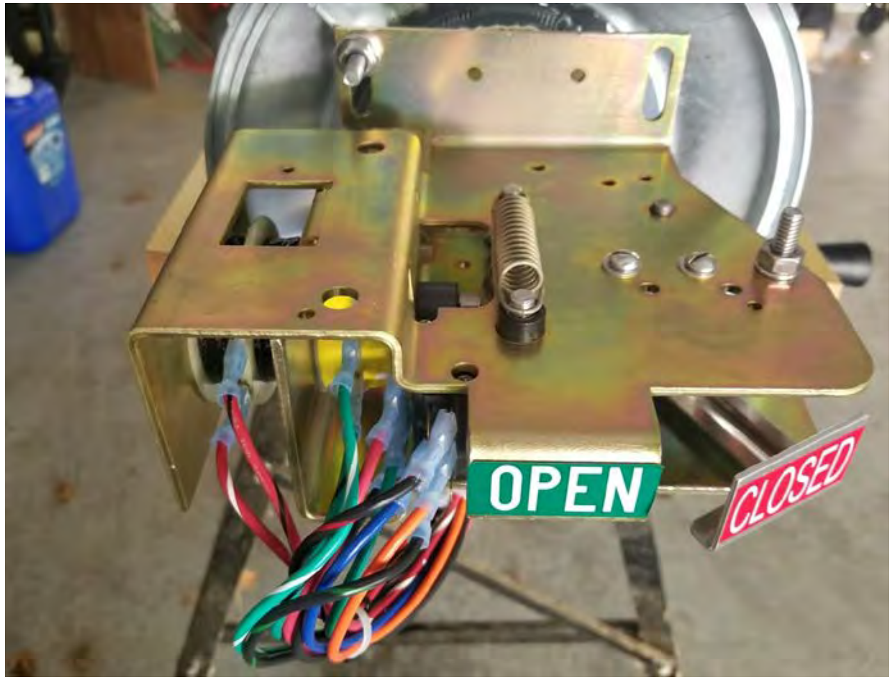


After Replacement



Incipient capacitor switch failure

- After removing the switch from service, it tested “open” in the closed position.
- A hi-pot test at 1,000V still showed several MΩ of impedance.
- It is believed that the vacuum switch was not making solid contact on close, but eventually the 7.2kV potential would arc and create a conductive path (until the switch opened).

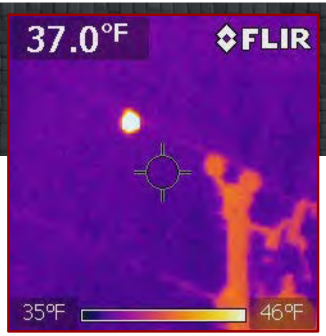


Incipient capacitor switch failure

- Lessons learned:
  - DFA detected the incipient signatures of a failing capacitor switch located on a circuit served out of a different substation connected by a 46kV transmission line.
    - Not an isolated incident!
  - The capacitor switch was almost certainly faulty when installed.
    - Both the line crew and dispatchers had information that suggested there was a problem, but the pieces didn't fit together in a way that pointed to the switch.
  - Access to data in the field can help crews know when they *haven't* successfully fixed a problem.
    - The ability to pull up the switching event *immediately* confirmed that we'd changed the wrong switch.
  - The ability to reconfigure circuits is both a challenge an an opportunity.
    - Events "move" from one circuit to another, but intentional switching can help locate hard-to-find failures.

Detailed Use Case – Series Arcing

Series Arcing Phenomenon



- Series arcing occurs when a current-carrying device develops a “hot spot” and represents incipient failure of the device.
  - Contacts of clamps, switches, and cutouts (many documented by DFA program).
  - Maybe splices, but these have not been documented by DFA program.
- Whereas conventional faults cause current to flow in unintended paths, series arcing interferes with current flow in an intended path.
- Field experience with DFA demonstrates that series arcing often occurs for hours to weeks before a device fully fails and causes an outage.
- Before final failure, series arcing may cause intermittent, hard-to-diagnose issues, including blown fuses, momentary trip/closes, flickering lights, ...

Case Study
31-Day Series Arcing (Incipient Clamp Failure)

Subject circuit

- 25 kV
- Conventional four-wire overhead
- 430 km of exposure, 72 km furthest extent
- 427 active meters
- Almost entirely oilfield load
- RF-based AMI across entire system

Failing Switch/Clamp Report from DFA

Probable failure of switch or clamp | B | Estimated load beyond switch/clamp: 194 kVA 80% likelihood switch; 20% likelihood clamp | 496 transients (31 days)

	[illegible]	[illegible]	Single-phase fault	C	Short-lived fault	N/A	2017-10-25 08:50:11
	[illegible]	[illegible]	Multi-phase trip	BC	F-(1.5c,417A,BCN)-T-(4,6,4)%	1 op	2017-10-24 10:59:58
+	[illegible]	[illegible]	Probable failure of switch or clamp	B	Estimated load beyond switch/clamp: 194 kVA 80% likelihood switch; 20% likelihood clamp	496 transients (31 days)	2017-10-24 10:07:15
	[illegible]	[illegible]	Single-phase fault	C	Short-lived fault (May affect fault current accuracy) (Experimental) Possible Causes: 80% Animal, 15% Arrester F-(15ms,491A,CN)	N/A	2017-10-23 00:52:52

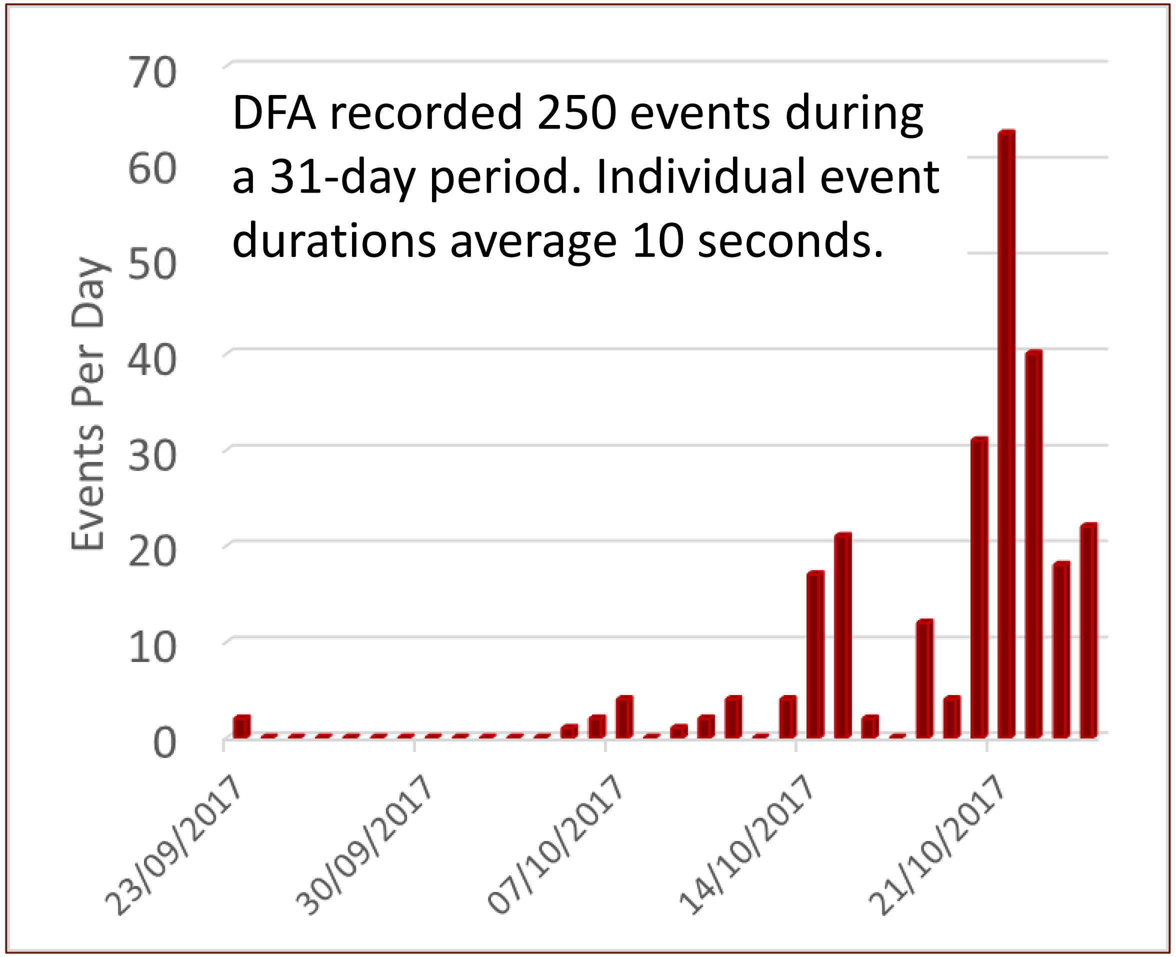
Failing Switch/Clamp Report from DFA

Expand	Substation	Circuit	Event Type	Phases	Comments	Count	Last Occurred
-	[illegible]	[illegible]	Probable failure of switch or clamp	B	Estimated load beyond switch/clamp: 194 kVA 80% likelihood switch; 20% likelihood clamp	496 transients (31 days)	2017-10-24 10:07:15

Export   Show 200 entries   Search:

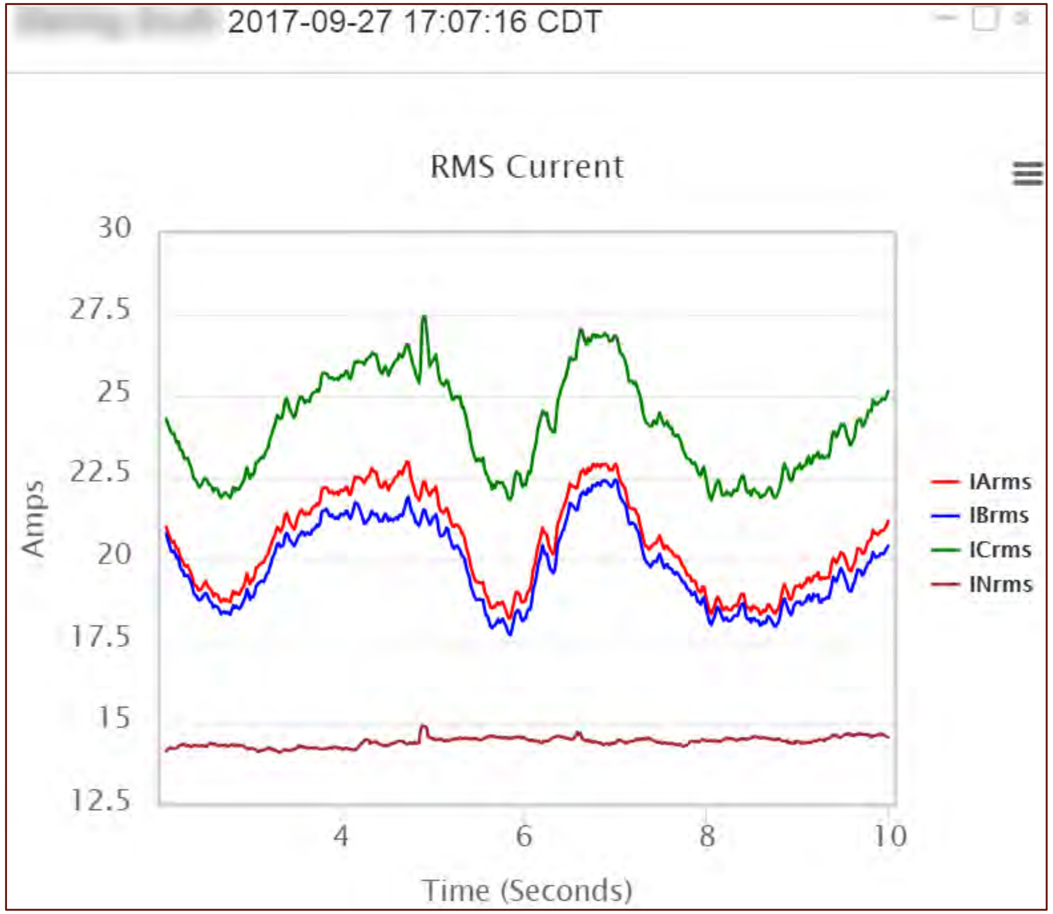
Event Type	Phases	Phase A Amps	Phase B Amps	Phase C Amps	Transients	Last Occurred
Probable failure of switch or clamp(C)	B	14	108	10	1	2017-10-24 10:07:15
Probable failure of switch or clamp(S)	B	10	64	8	6	2017-10-24 09:41:26
Probable failure of switch or clamp(I)	B	9	70	8	3	2017-10-24 09:11:26
Probable failure of switch or clamp(I)	B	5	57	6	2	2017-10-24 06:52:43
Probable failure of switch or clamp(I)	B	8	37	7	1	2017-10-24 06:51:30
Probable failure of switch or clamp(I)	B	8	102	8	1	2017-10-24 06:50:21
Probable failure of switch or clamp(I)	B	7	91	10	2	2017-10-24 06:45:25
Probable failure of switch or clamp(I)	B	8	45	6	1	2017-10-24 06:44:54
Probable failure of switch or clamp(I)	B	7	50	6	1	2017-10-24 06:36:18
Probable failure of switch or clamp(I)	B	10	101	8	1	2017-10-24 06:35:39

Intermittency of Series Arcing



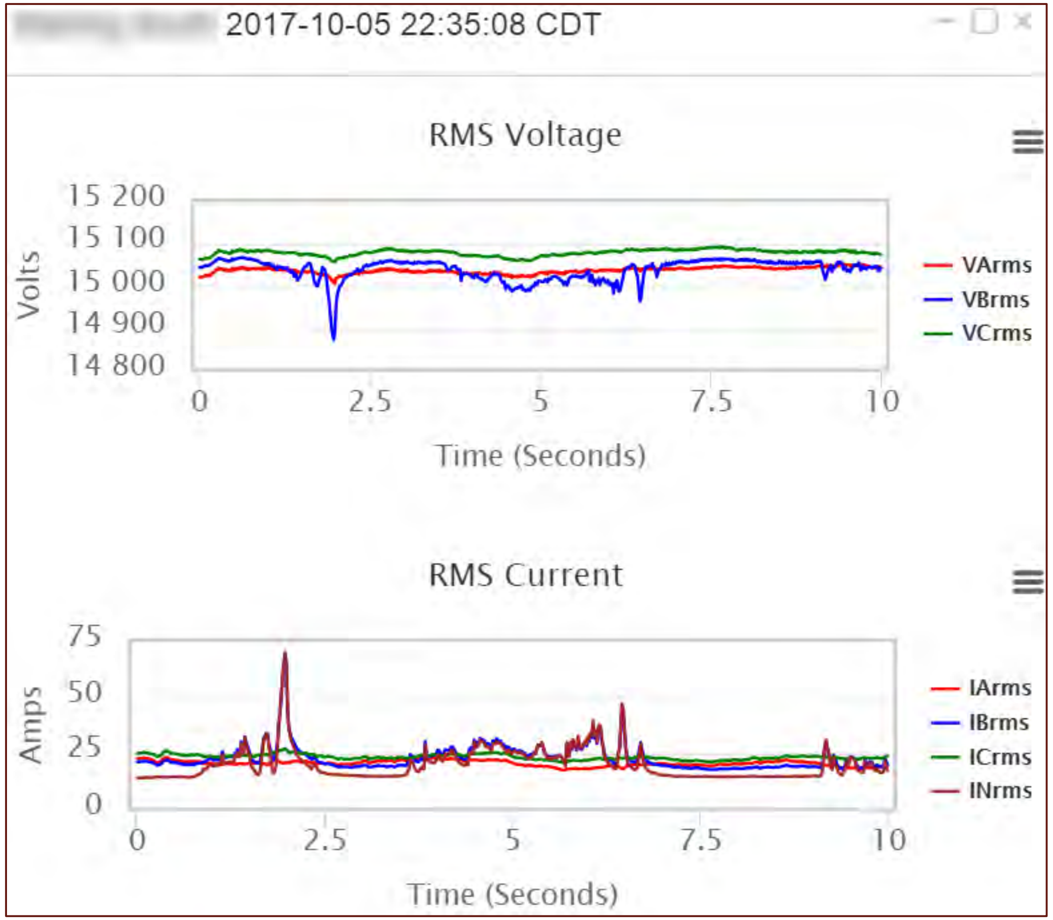
- DFA recorded 250 events in 31 days.
  - 174 were during the final five days.
  - Days 2-12 registered no events.
  - Peak activity was 63 events on day 28.
  - Activity generally increased over time, but not steadily or predictably.
- Most of the total period was quiescent.
  - (250 x 10)/(31 x 24 x 60 x 60) = 0.1%.
  - No activity was recorded 99.9% of time.
- Intermittency makes location with RF, thermal imaging, … difficult.

Subject Circuit – Normal Load



- Graphs come from DFA recordings, which come from conventional circuit CTs and bus PTs at substation.
- Most DFA recordings are 10+ seconds at 256 samples/cycle.
- RMS (one value per cycle) is shown to give "the big picture."
- Subject circuit is mostly oilfield load.
- Variability shown in this graph is normal for this circuit.

Line Current and Voltage During Series Arcing Event



- Voltage variations are < 1 %.
- Current variations:
  - Peaks of several tens of amperes
  - Highly unstable and intermittent.
  - Magnitudes similar to large loads and inrush events.
- Peaks have sufficient magnitude to trip sensitive overcurrent protection, but limited duration.
- Event signature is subtle.

Challenges of Locating Series Arcing

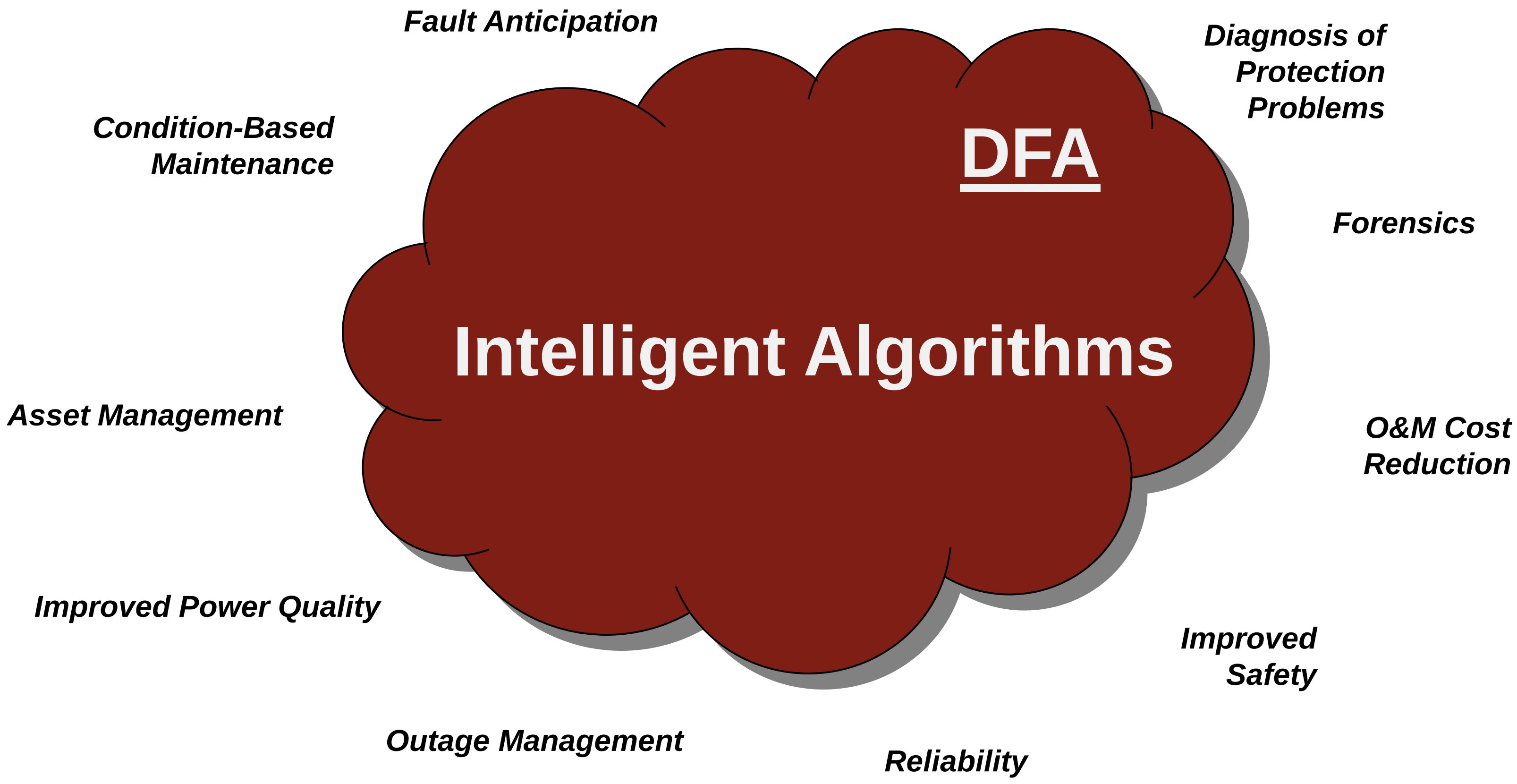
- For series arcing, current amplitude is largely a function of connected kVA capacity downstream of the failing device, rather than line impedance. Therefore impedance-based fault location methods are ineffective.
- RF and thermal diagnostics might be effective if applied during an active flare-up, but flare-ups occur only a tiny percentage of the time.
- Clamp failures may operate protection in the path upstream or downstream of the failing device. (The "downstream" part is counterintuitive, but it is readily explained by theory and has been documented multiple times by DFA field installations.)

Search Process and Learnings

- This was the utility's first attempt to locate series arcing.
- Circuit model identified 18 circuit locations that fit DFA parameters.
- Murphy's Law was in full force – clamp was at last location.
- (Murphy cont'd) Conductor burned in two, ending series arcing, right before Concho arrived to check that location. AM radio got a "hit."
- Clamp was on phase B on the source side of a hydraulic E recloser.
  - Bank of three single-phase reclosers, type E, 50A pickup, 2A2B.
  - Since last check, operations counters had incremented by 3 (A), 27 (B), and 2 (C). It is believed that many of the phase-B "counts" resulted from the clamp.
- The utility expected that the AMI system would have data relevant to location of a clamp, but in this case it did not.

The Culprit

DFA Stakeholders



Thank You ⊿

Feedback and Interest Survey ⊿

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