On-line Monitoring of Substation Waveform Data for Improved Asset Management and Circuit Operations

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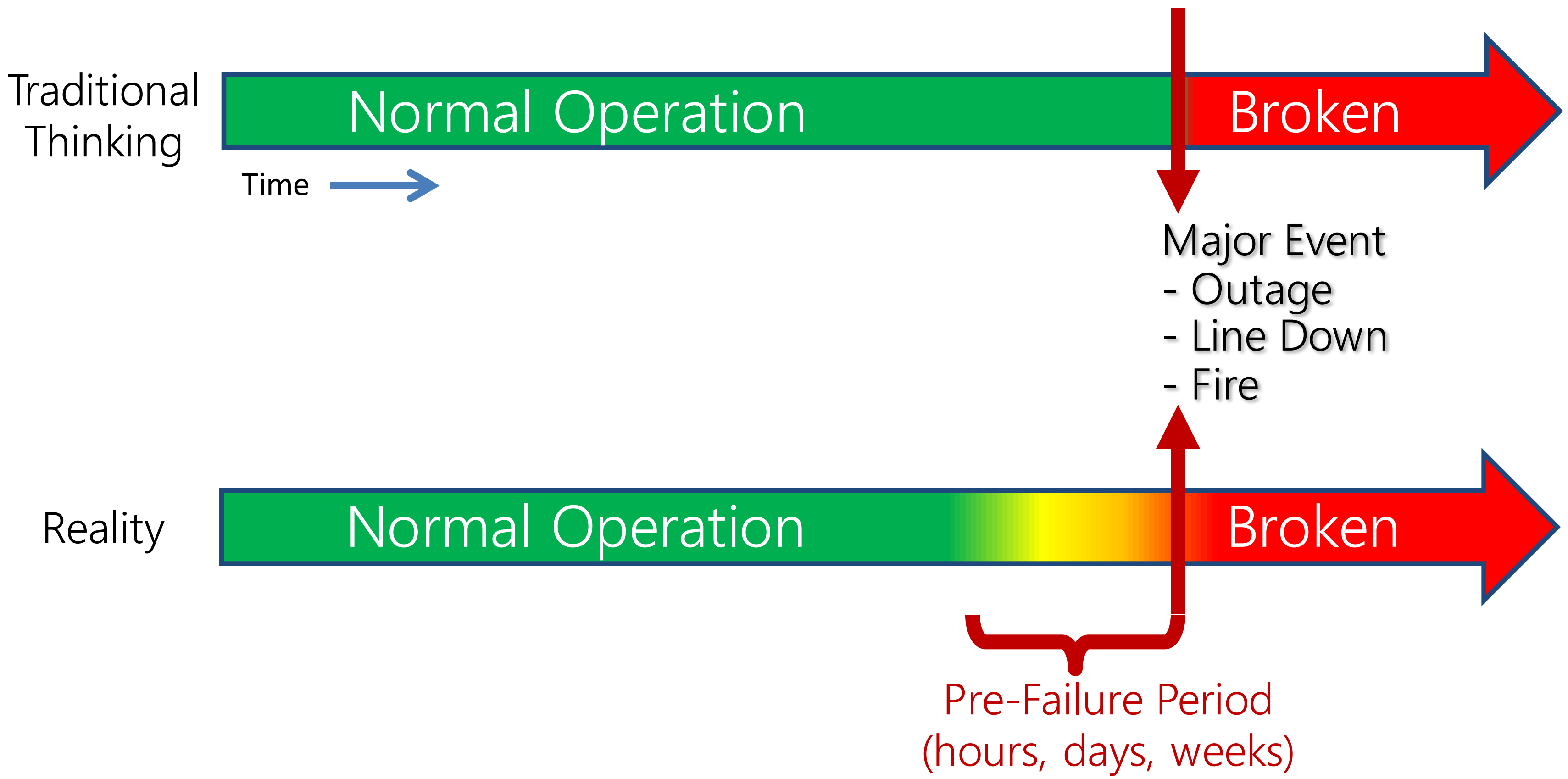
CIGRE Canada Conference 2015
1 September 2015
RBC Conference Center
Winnipeg, Manitoba, Canada.

Electrical Feeder Operational Paradigms



Imagine detecting pre-failures and making repairs <u>before</u> major events occur.

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.

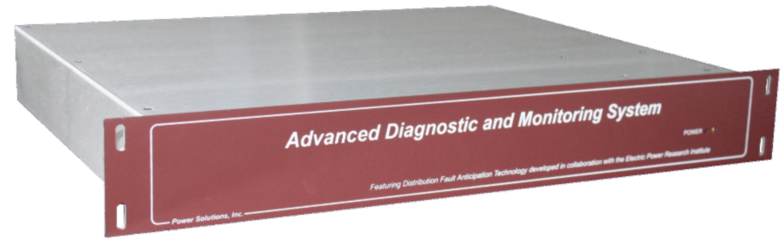
DFA Foundational Research

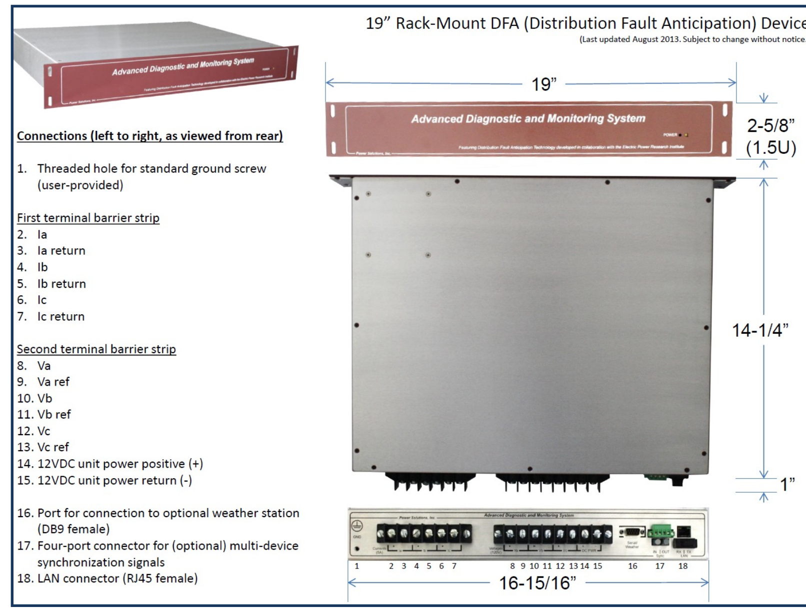
- A Decade of Field Research
  - Instrumented dozens of feeders at 10+ utilities
  - Created largest database of failure signatures in existence
  - Analyzed waveform anomalies and correlated with failure events
  - Discovered unique signatures for specific failures
  - Developed automated reporting 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

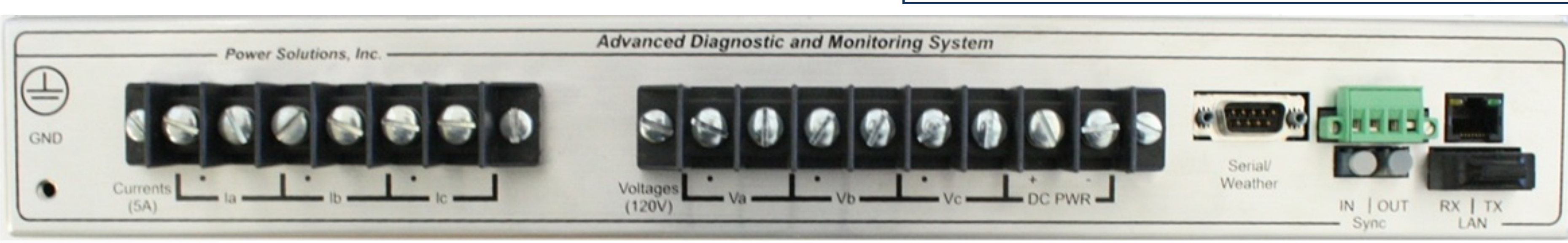
Research Partners

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

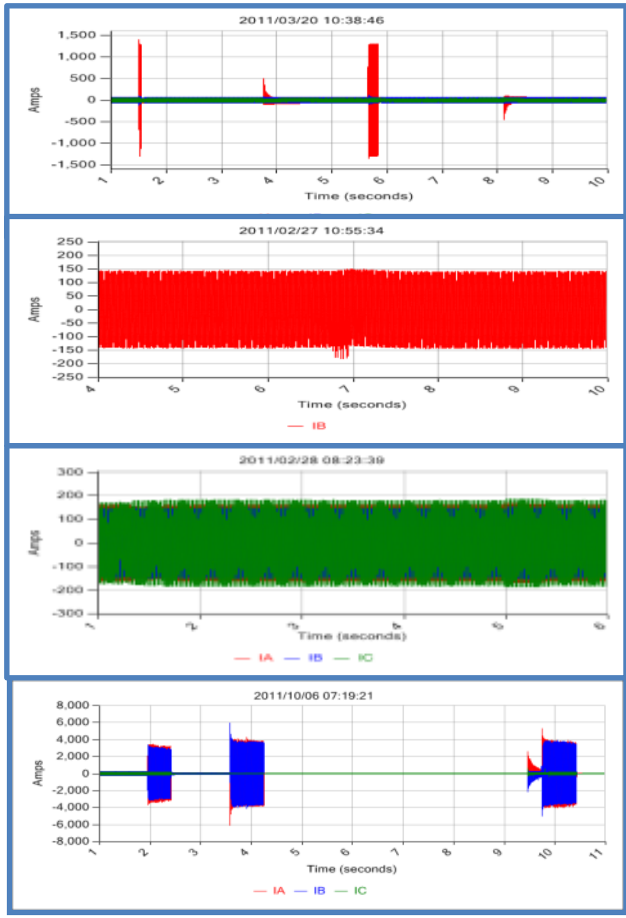






Waveform-Based Analytics – Behind the Scenes

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

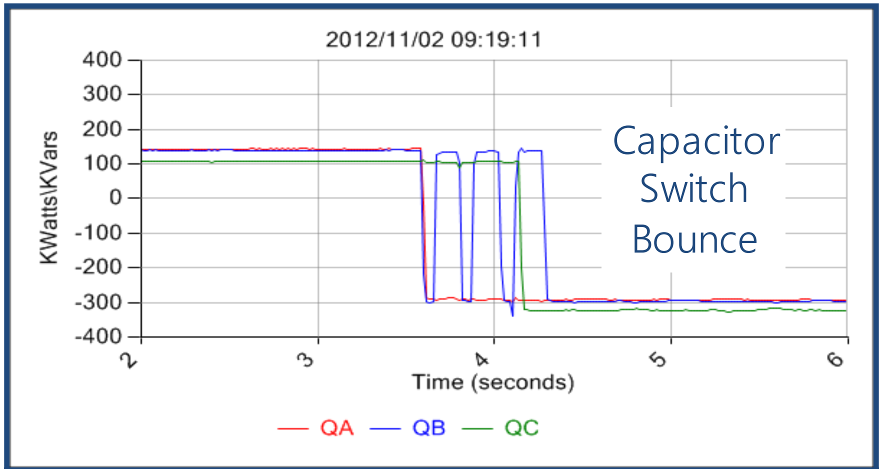
Certain failure types have been seen many times and are well understood. Others have been seen fewer times. DFA system architecture anticipates and accommodates updates to analytics as new events are encountered, analyzed, and documented.

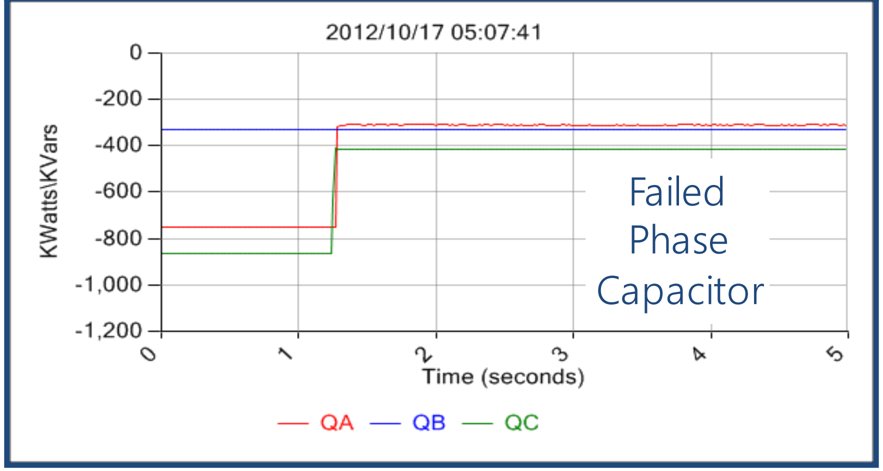
USE CASE SUMMARIES

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).



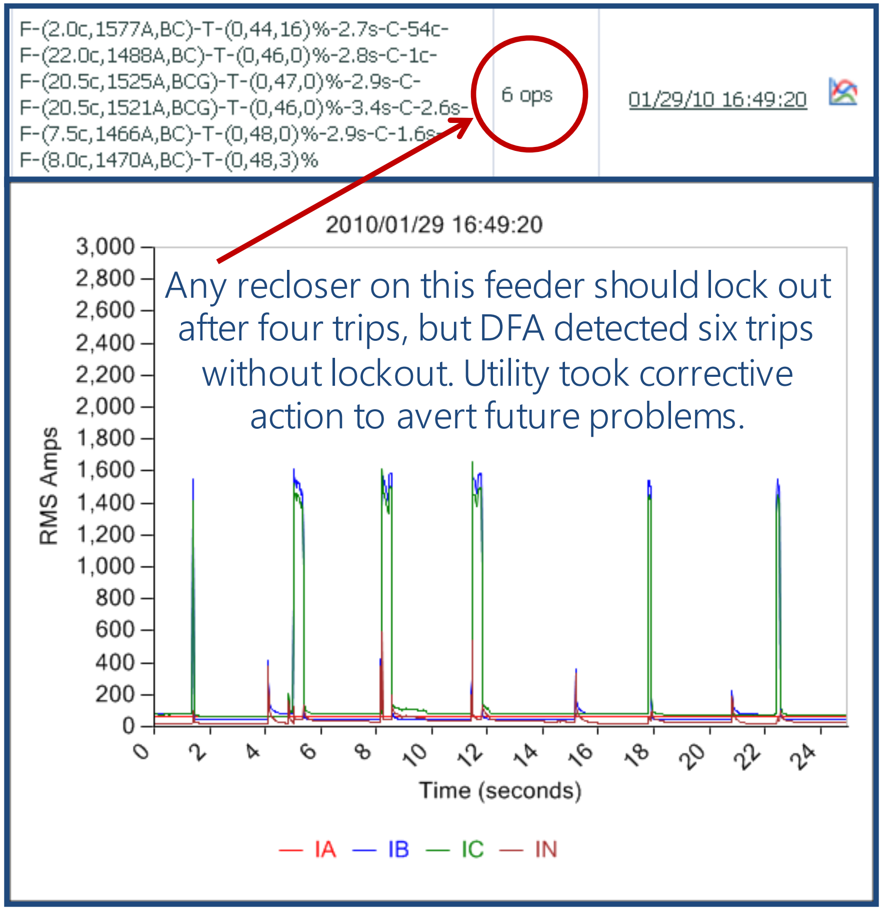


<u>Benefits</u>: Improved maintenance efficiency; better, faster detection of failures; and improved PQ.

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.



Benefits: Notice of latent problems; improved protection; improved operations; and improved safety.

DETAILED USE CASES

CenterPoint Energy Project

- Began DFA trial in 2012
- Instrumented four feeders
  - Two 12.5 kV feeders
  - Two 34.5 kV feeders
- Has detected multiple events
  - Repetitive tree-induced conductor clash that severely damaged conductors
  - Failing line switch
  - Capacitor restrikes
  - Multiple pre-failures of capacitor vacuum switches
  - Note: This is a partial list

Detailed Use Case

Capacitor Vacuum Switch Pre-Failure

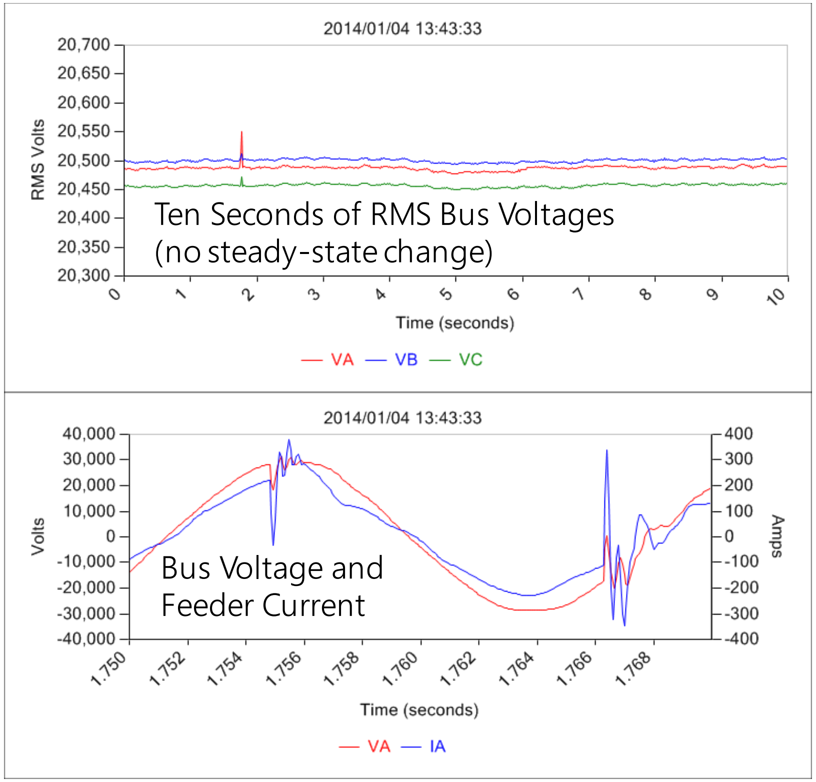
- CenterPoint uses one-way paging to switch feeder capacitors. After each page, the system monitors substation VARs to verify 1) that the bank has switched and 2) that it is balanced.
- On 11/29/2013, a DFA device began detecting unusual transients suggesting pre-failure of a capacitor bank.
- Trouble tickets indicated no problem. CenterPoint and Texas A&M continued to monitor.
- The transient occurred 500 times over the next 2-1/2 months.
- 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>

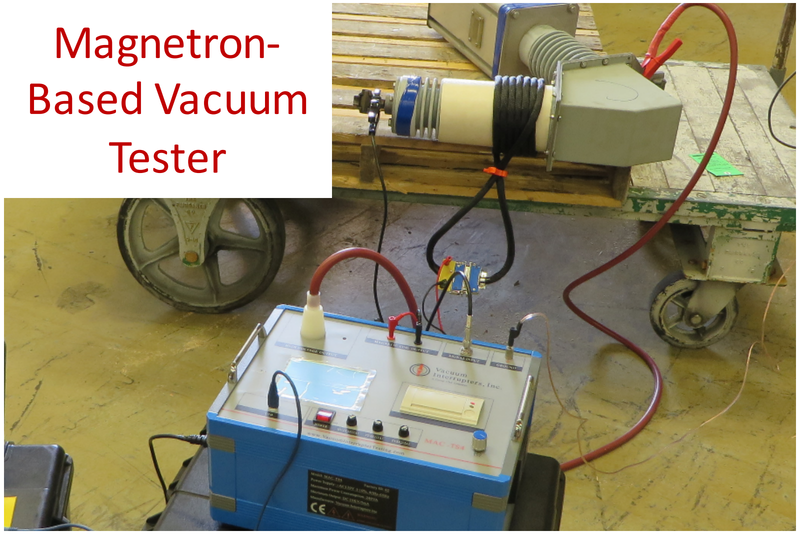
- Normal capacitor switching causes two phenomena.
  - A short-lived high-frequency transient
  - A step change in voltage (yes, even at the bus!)
- Each subject event caused a transient, but no step change.
  - This indicates the events were not during switching.
- Each event caused a high-frequency 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)

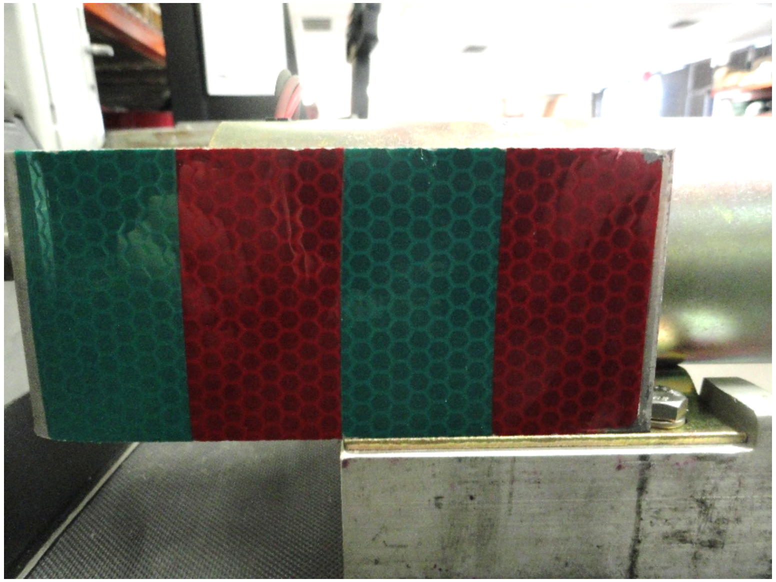
- On February 14, the utility decided to open the fuses of all five of the feeder's banks to confirm the "pre-failure capacitor bank" diagnosis.
- A crew found an anomaly at the first bank.
  - The bank's "closed" current should be 30 amps.
  - The paging system showed the bank as "open."
  - A hot-stick meter showed 0.7 amps through the "open" switch.
  - First bank's fuses were pulled.
  - Other four banks were left in service.
  - DFA system was watched for five days. Absence of additional transients validated diagnosis.
- The pre-failure switch failed a hi-pot test. A vacuum interrupter expert performed a root cause analysis.



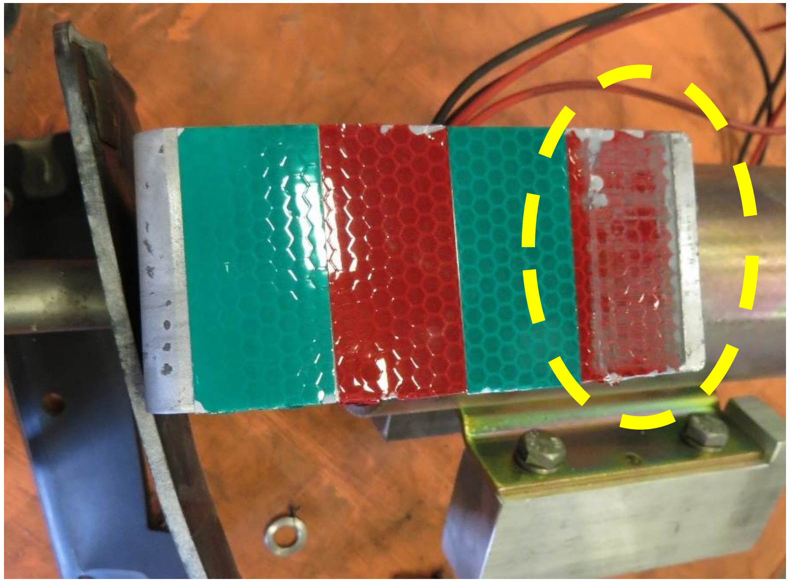
Magnetron-Based Vacuum Tester

Detailed Use Case

Capacitor Vacuum Switch Pre-Failure (cont'd)



Red/Green Indicator
on Normal Phase

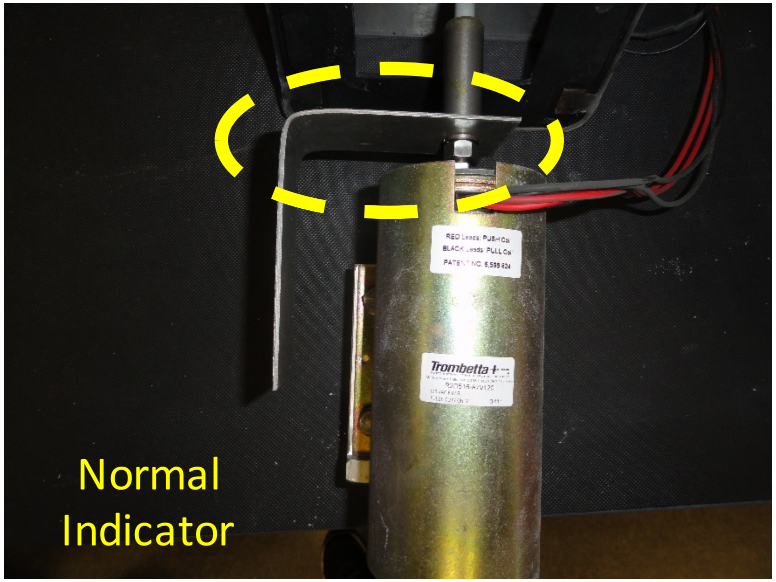


Red/Green Indicator
on Pre-Failure Phase

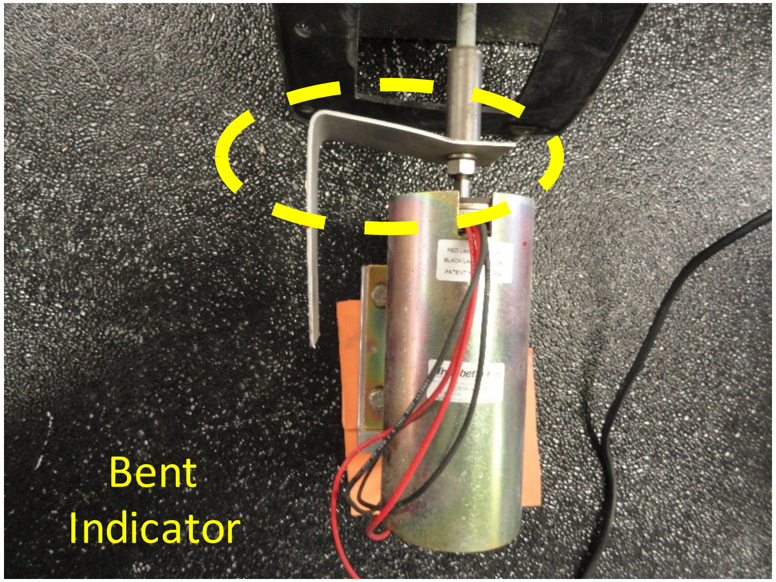
The switch has a sight window with a red/green position indicator. The pre-failure switch's indicator had clear signs of rubbing against the mechanism housing.

Detailed Use Case

Capacitor Vacuum Switch Pre-Failure (cont'd)



Indicator on
Normal Phase

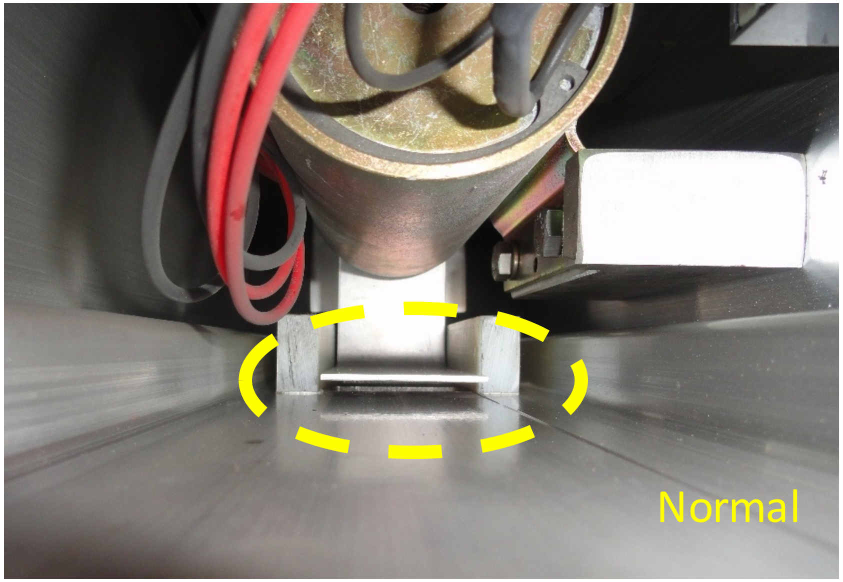


Indicator on
Pre-Failure Phase

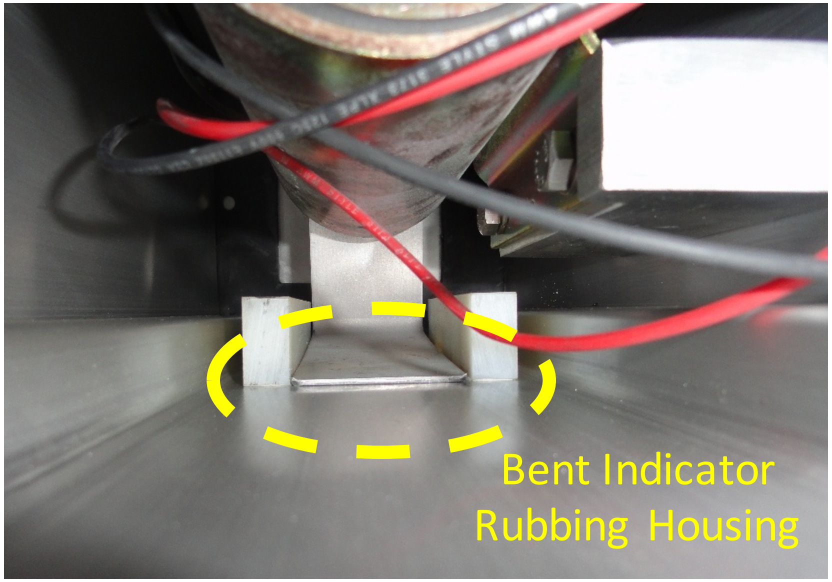
The indicator on the normal phase has an intentional 90-degree bend. The indicator on the pre-failure phase clearly is deformed.

Detailed Use Case

Capacitor Vacuum Switch Pre-Failure (cont'd)



Red/Green Position Indicator
Mechanism on Normal Phase



Red/Green Position Indicator
Mechanism on Pre-Failure Phase

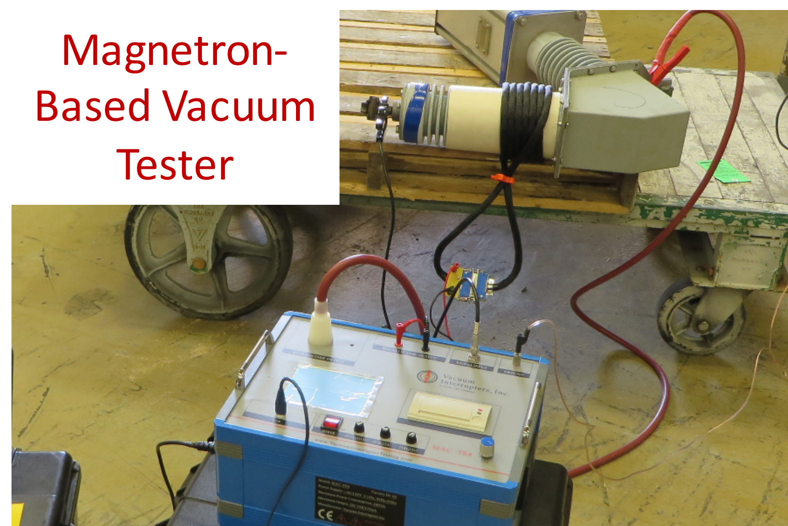
The root cause of the pre-failure was the indicator rubbing and binding, preventing the switch contacts from parting fully. Current (0.7A) flowing through the gap is believed to have caused progressive internal damage to the vacuum interrupter.

Detailed Use Case

Capacitor Vacuum Switch Pre-Failure (cont'd)

Summary and Conclusions

- Vacuum switch failures have multiple potential consequences.
  - Least severe: unbalanced capacitor operation
  - Most severe: rupture of switch or capacitor
- This pre-failure example persisted 2-1/2 months before intervention.
  - Normal operational practices did not and do not detect this kind of pre-failure.
  - Pre-failure detection provided time (in this case, 2-1/2 months) to correct the condition and preempt full failure.
- Waveform analysis provided only notice and opportunity to correct proactively.



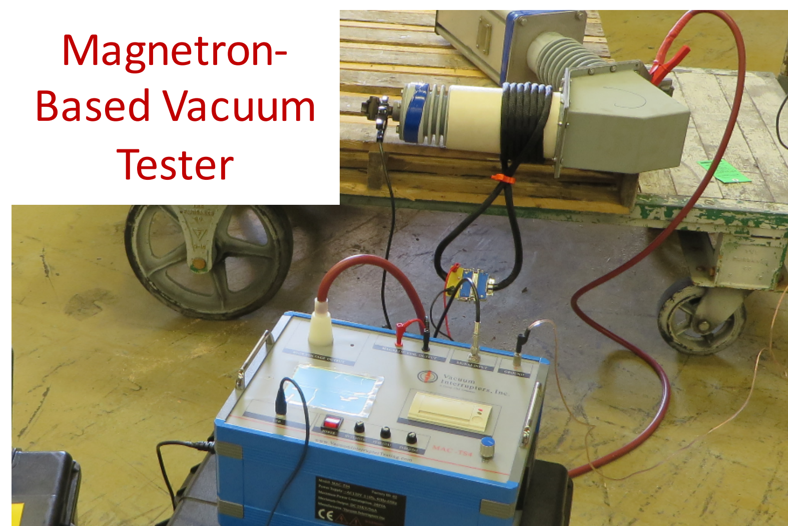
Magnetron-Based Vacuum Tester

Detailed Use Case

Capacitor Vacuum Switch Pre-Failure (cont'd)

<u>Post-event Follow-up:</u>

- One year later, an almost identical case occurred on a DFA-monitored circuit (detailed in paper).
- A lineman was dispatched to visually inspect all three banks on the monitored circuit, but no obvious problems were found.
- CenterPoint suspected there *might* be a problem with one of the banks on the circuit, because they had lost communication to it.
- Investigation with DFA-provided waveforms escalated the problem, and allowed CenterPoint to remove the failing switch from service before it catastrophically failed.



Magnetron-Based Vacuum Tester

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.
- Utility companies have used DFA to demonstrate the avoidance of outages, better asset management, and improvements in operational efficiency.

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