Automated Waveform Characterization for Providing Situational Awareness to Distribution System Operators

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Abstract

For two decades, Texas A&M Engineering researchers have worked in an area that has come to be known as Distribution Fault Anticipation, or DFA. The DFA research program installed specialized waveform recorders on dozens of North American circuits. Multi-year installations have resulted in what is believed to be the largest database ever created of high-resolution waveform recordings for failures and other events on distribution circuits under normal operating conditions (i.e., not simulations, staged failures, or accelerated aging). Based upon that database, researchers have identified waveform characteristics unique to multiple types of failures and incipient failures on electric power distribution circuits and have created and tested automated algorithms and a system for reporting failures via web in near real-time.

This paper overviews DFA technology background and current capabilities, such as automatic, web-based characterization and reporting of faults, incipient failures, and other circuit phenomena of interest. It details selected examples of complex events in detail, including those where transient activity at one location on a circuit causes sympathetic response and failure at a different location. For example, internal arcing of a line capacitor caused the failure of a lightning arrester farther down the circuit. Another example details how contact by a kite string at one position on a circuit induced a total of three faults on the circuit, including one that was five miles from the point of kite string contact.

Texas A&M Distribution Fault Anticipation (DFA) Technology

Distribution circuits consist of thousands of components and, as compared to transmission lines, have complex topologies. System operators have little visibility or awareness regarding circuit events or conditions. Consequently, with few exceptions, distribution circuits operate in a run-to-failure mode, with most corrective actions taken in response to customer outages or other trouble on the circuit.

Beginning in 1997, the Electric Power Research Institute (EPRI) sponsored a major research program, by Texas A&M Engineering, to investigate the feasibility of anticipating faults on distribution circuits. That research and the resulting technology have become known as Distribution Fault Anticipation (DFA).

Self-Imposed Constraints

To achieve a system that would be broadly practicable, the research project self-imposed a constraint to use only passive monitoring of conventional current and potential transformers (CTs and PTs) and avoid the use of exotic sensing technologies, active injection of signals, etc. The research project also self-imposed a constraint to require communications only to a central master station, where results could be accessed, and not require communications with line equipment (e.g., reclosers, capacitor banks).

Research and Development Methodology

Research and development methodology consisted of instrumenting a significant number of medium-voltage distribution circuits with high-capacity, high-fidelity waveform recorders configured with sensitive triggering thresholds. The research project began with a small-scale proof-of-concept demonstration involving three circuits and then expanded to major data-collection and -analysis project that instrumented 70 circuits at eleven EPRI-member utility companies. Over time there were multiple project phases and evolving hardware platforms used to collect the data and later to practice automatic algorithmic processing of waveform data to detect and characterize circuit events.

The industry had limited understanding of the progressive failure modes of line equipment. There was little understanding of how incipient failures progressed over time or manifested themselves electrically as they did so. It was postulated that the early stages of some incipient failures might cause only small changes in line currents and voltages. Researchers therefore used considerably more sensitive triggering than conventional recording approaches, attempting to discover some of the electrical manifestations that were too small to be recorded by more traditional monitoring and therefore previously unknown. This increased the probability of detecting early stages of failures. It also substantially increased the volume of waveform data recorded and necessitated automation in the process of recording, retrieving, managing, and processing the resulting data.

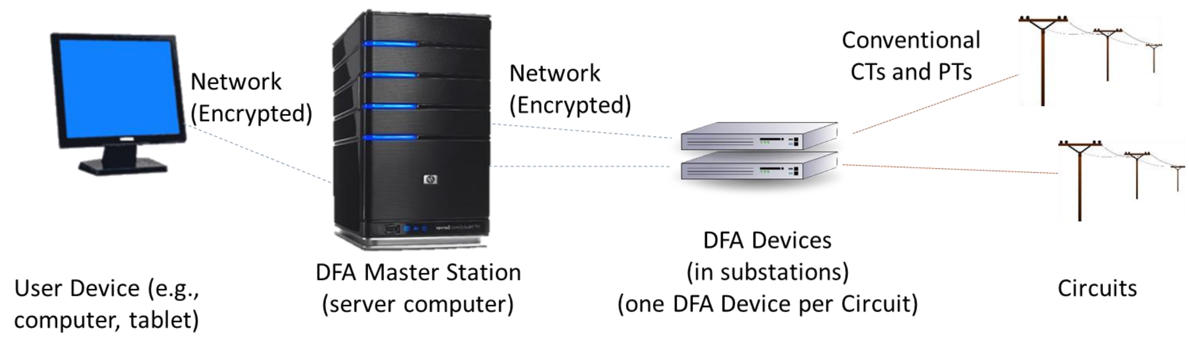
The other key component of the research methodology was feedback from utility company personnel, including field personnel. Researchers analyzing recorded data contacted the utility company for feedback from system operators and line crews when unrecognized anomalies were noted in recorded data. In cases where personnel knew of circuit events around the time of the anomaly, detailed information about the specifics of the event were sought. This enabled researchers to correlate electrical signatures with field findings. Where a specific type of event manifested specific waveform characteristics, researchers became adept at inferring the type of event based on analysis of electrical waveforms. As they gained more experience, they developed algorithms to automate the process of analyzing, recognizing, and characterizing multiple types of failures and other line phenomena.

Extended Focus

In the process of analyzing the many waveform anomalies recorded by field installations, researchers could recognize events that were not incipient failures but that nonetheless represented potentially operationally useful information, and they developed algorithms for those events. For example, many circuits have unmonitored line reclosers and unmonitored line capacitors. DFA algorithms can report temporary faults that operate fuses and reclosers, along with parameters such as fault current amplitude and duration and the timing sequence (e.g., trip/close/trip/close) of unmonitored reclosers. They also can detect multiple problems with switched capacitors, including routine failures, such as inoperative phases, and more subtle issues, such as switch bounce and restrike.

System Architecture

The sensitive triggering employed by DFA results in data volume that makes it infeasible for personnel to perform full analysis of all data. In addition, knowledge of some events can be operationally useful, but only if reported in a timely way. A system architecture was adopted to automate the end-to-end processes of detecting waveform anomalies, recording those anomalies, applying sophisticated software to classify and characterize line events, reporting those events to a central master station, and making the information available to operators and other personnel via password-protected, browser-based login. The system architecture is illustrated in the diagram below.



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

Case Studies

DFA installations have documented a wide variety of circuit anomalies. The following is a select list of events that utilities have used the DFA system to detect and address.

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

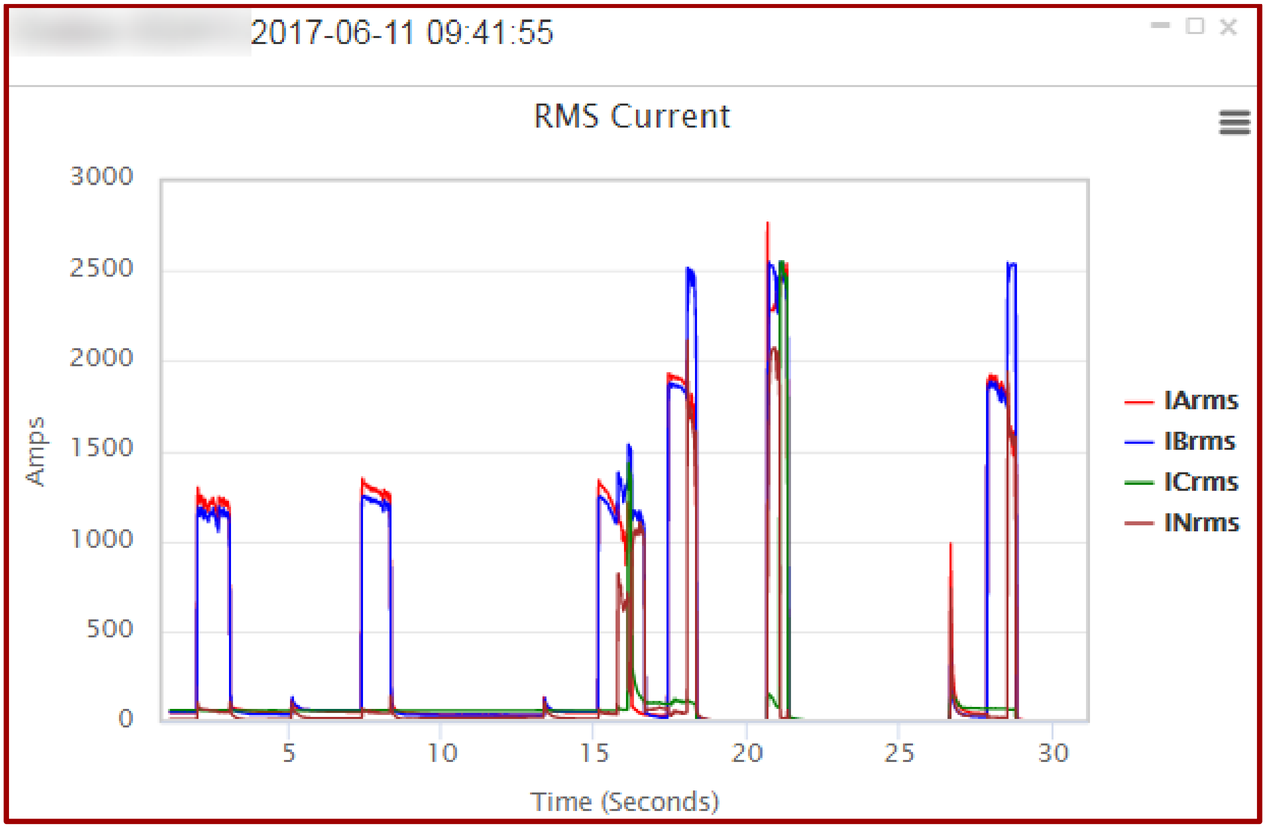
The remainder of this section will detail two particularly interesting events. DFA records current and voltage waveforms at 256 samples per cycle. Events that have durations longer than one or two seconds often are best understood by first getting the "big picture." Graphs used herein therefore present RMS quantities, calculated at a rate of one value per cycle, instead of the higher-speed pseudo-sinusoids that are recorded at 256 samples per cycle.

Case Study 1: Balloon Causing Three Faults, including Fault-Induced Conductor Slap

The subject event involved a balloon contacting an overhead, three-phase primary distribution circuit and causing a circuit-wide outage. It seemed improper to have a circuit-wide outage, because the circuit had two reclosers between the site of the fault and the substation circuit breaker. In the following event narrative, the reclosers are designated as R1 and R2, with R2 the one farther out on the circuit. Each was a bank of three single-phase reclosers with single-phase tripping capability.

Findings by the responding line crew provided a partial explanation. They found a jumper between R1 and R2 burned in two, presumably because the initial fault current had passed through it. A second fault initiated at the point of the burn jumper. This required R1 to operate but should not have caused the substation circuit breaker to operate.

The complex event occurred over a period of about 30 seconds. The DFA system recorded the line currents and voltages continuously for this period. The figure below shows the RMS currents.



DFA software automatically analyzed the recorded current and voltage waveforms and created a report of "Breaker Trip – Possible Conductor Slap," with the sequence of events shown below:

<u>DFA Web Grid Event Report</u>

Breaker Trip – Possible Conductor Slap	F-(64.5c,1219A,AB)-T-(-,-,-)%-4.3s-C- F-(56.5c,1278A,AB)-T-(12,21,0)%-6.8s-C- F-(91.5c,1495A,ABCN)-T-(38,59,0)%-0.8s-C F-(55.5c,2488A,ABN)-T-2.3s-C- F-(40.0c,2522A,ABCN)-T-5.3s-C-1.2s F-(56.5c,2522A,ABN)-T

A Necessary Aside: Understanding Fault-Induced Conductor Slap (FICS)

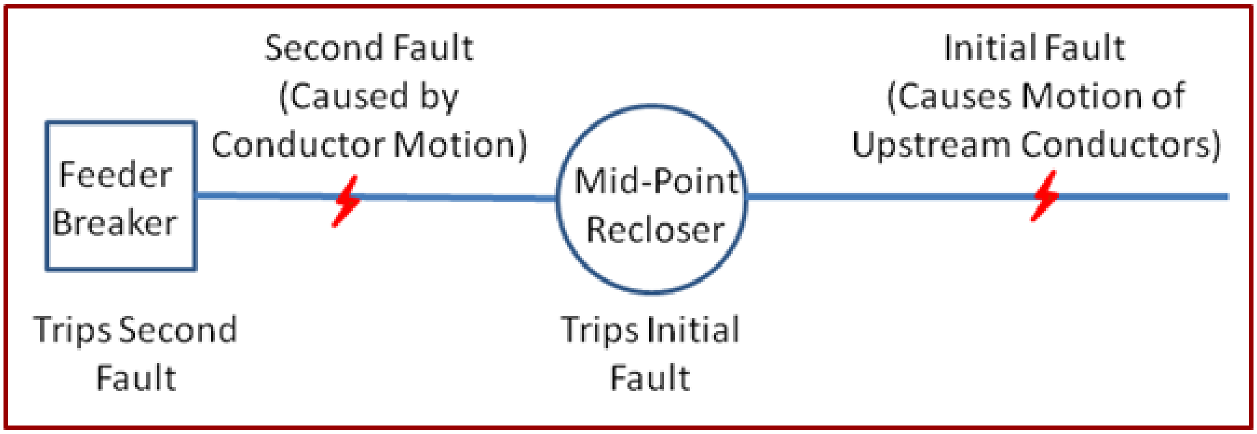
Understanding the relevance of this information requires a brief discussion of the phenomenon known as fault-induced conductor slap (FICS), a phenomenon which has been analyzed, modelled, and described well by Ward.[1]

The following diagram facilitates an explanation of the FICS phenomenon. FICS occurs when an initial fault at one location on a circuit induces motion of upstream conductors and results in a second fault, sometimes distant from the initial fault. Often there is a mid-point recloser between the initial fault and the second fault. Most typically FICS results from an initial fault between two phases. A phase-to-phase

[1] Daniel J. Ward, "Overhead Distribution Conductor Motion Due to Short-Circuit Forces," IEEE Transactions on Power Delivery, vol. 18, no. 4, October 2003, pp. 1534-1538.

fault causes fault current to flow in two parallel phase conductors, with opposite polarity. Magnetic forces result and push the two conductors away from each other. After some time, the mid-point recloser interrupts the fault current. This suddenly removes the magnetic forces, and the conductors begin to move back toward their at-rest positions. Momentum can cause them to swing through their resting positions, however, and, under the right line geometry, contact one another.

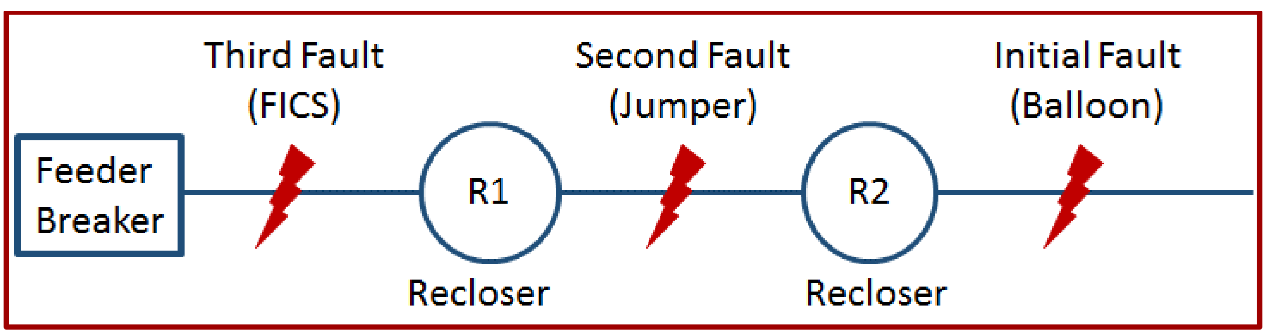
Because the second fault occurs upstream of the initial fault, it draws more fault current. Because it occurs upstream of the mid-point recloser, it must be cleared by an upstream device, often the substation circuit breaker.



FICS in the Subject Event

There is clear evidence of FICS in the data recorded during the subject event. The graph of currents shows initial fault currents on the order of 1200-1500 amps and later fault currents on the order of 2500 amps. Based on the DFA-generated FICS report, the utility performed a follow-up patrol, specifically looking for evidence of FICS and guided by the following parameters.

- The FICS (usually referred to as the “Second Fault” but in the subject event referred to as the “Third Fault”) must be in the path between the substation and the initial fault. This is because it was the initial fault (or, in this case, perhaps the second fault) that caused the fault current, which caused the conductor motion, which caused the Third Fault.
- The final fault was ABCN and drew approximately 2500 amps. This information can be entered into model-based software to predict location.



Utility personnel patrolled in the area that met the above criteria and found the “bright spots” typical of conductor arcing, as shown in the photograph that follows. They determined that this span measured 366 feet, which exceeds the 300-foot standard for this type of conductor. Interestingly, while personnel were on site, a customer who happened to be at that location told them that he had witnessed a “shower of sparks” at this location on multiple occasions.

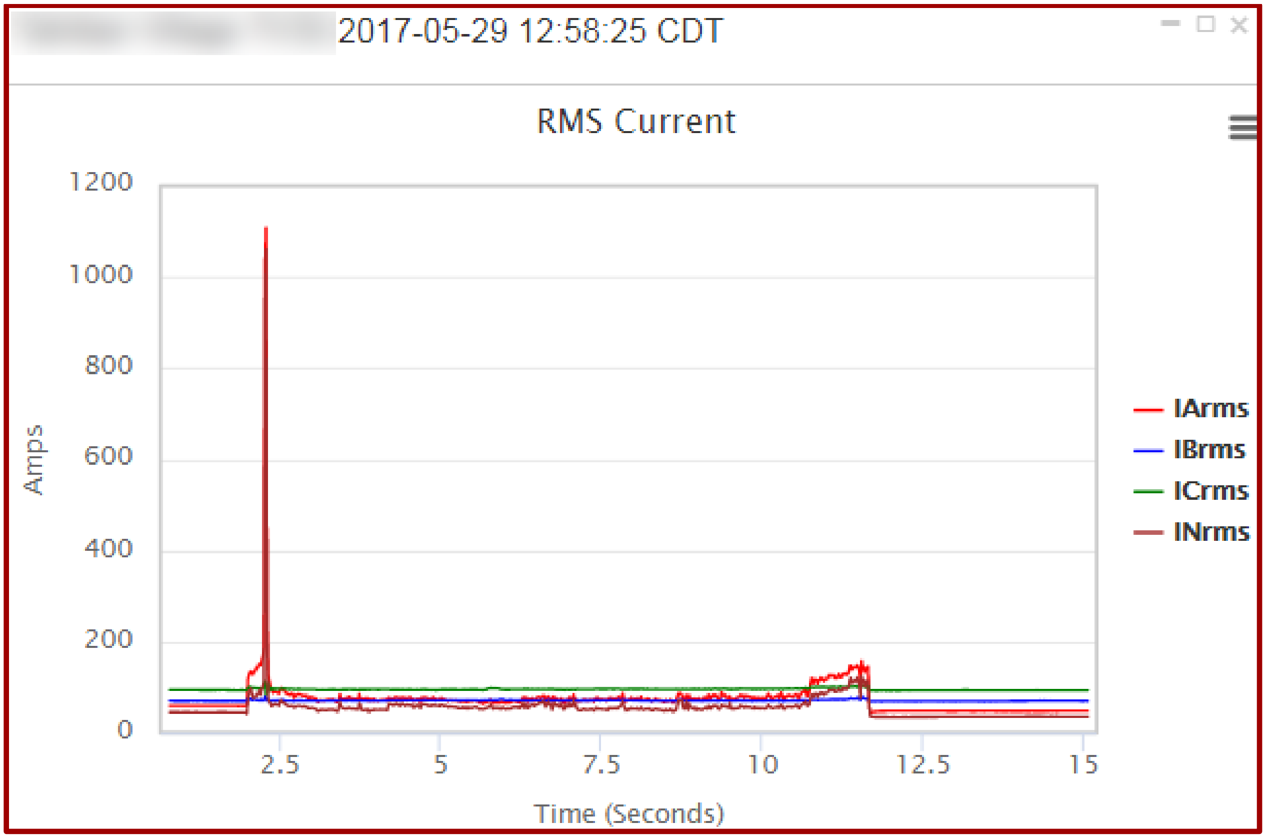
Identification of fault-induced conductor slap is important for multiple reasons.

- To prevent recurrence – FICS often occurs in a specific span because there is something unusual or even deficient about that span. Examples include spans that are longer than normal, such as in the subject case, spans with excess slack, spans with closer-than-normal conductor spacing, and spans transitioning between horizontal and vertical construction. A span susceptible to one FICS episode is susceptible to additional FICS episodes. In the subject case, the customer’s observation that he had seen showers of sparks on multiple occasions is consistent with repeated conductor slaps at this location. Another DFA field installation, operating in a “blind study” mode, documented a span that experienced five FICS episodes over a period of four years. Each episode caused either a momentary interruption or a permanent outage for the entire circuit. Knowing that FICS has occurred is the key to investigating, locating, and correcting the underlying problem and avoiding future episodes in the same span.
- To reduce wasted manpower – FICS often appears to have caused operation of a substation circuit breaker for a fault that should have tripped only a mid-point recloser, which would constitute miscoordination of protection. The utility sometimes takes note of and investigates this apparent miscoordination. DFA field research has documented cases in which utility companies have investigated such cases by pulling records from the substation relay and other available recording devices, analyzing those records, testing breakers, etc., only to finish the investigation with “no cause found.” This wastes considerable effort, in addition to failing to identify and correct the underlying problem. Knowing that FICS is the root cause, before beginning an investigation, saves valuable manpower and correctly diagnoses the problem.

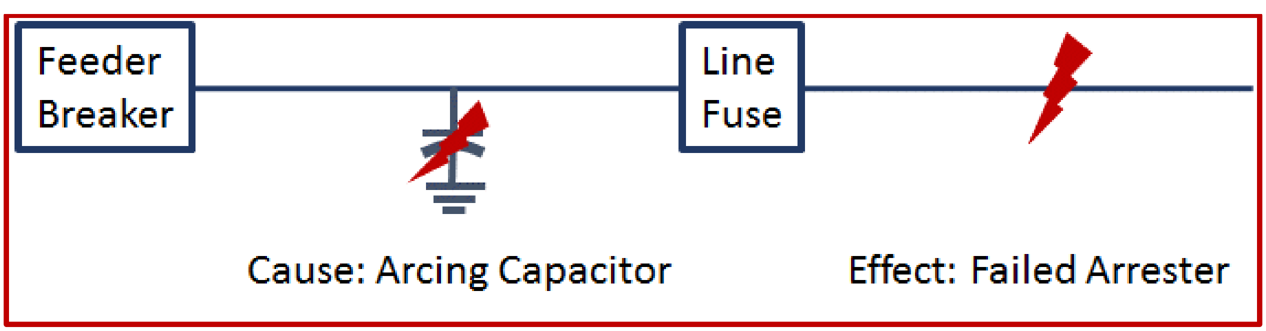
Case Study 2: Arcing Capacitor Causing Failure of a Downstream Arrester

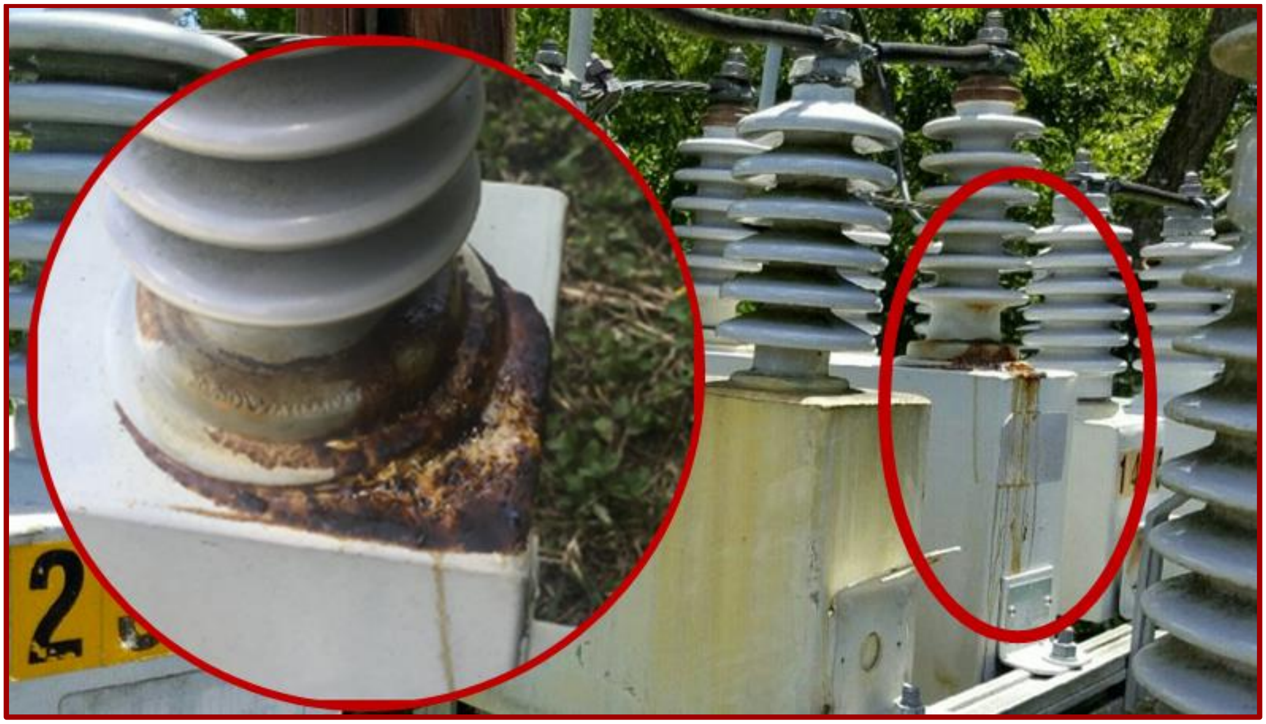
Responding to a partial-circuit outage, the utility in question found a blown line fuse. They replaced the fuse, but it blew again. Additional patrolling identified a catastrophically failed MOV-type lightning arrester. After replacing the arrester, they replaced the line fuse again, and it held.

The following graph shows the RMS current recorded by DFA during the fifteen-second period at the time of the initial fault. As in the previous case study, the DFA records high-speed (256 samples/cycle) waveforms for phase currents and voltages, but the graph presents RMS values, having one-cycle resolution, because such presentation tends to give the best big-picture perspective of the event.



The day after the outage, the DFA recording was analyzed. The high-current fault lasted two cycles before presumably blowing the line fuse. The graph, however, contains considerable transient activity for several cycles just before the high-current fault and for nine seconds after it. Detailed analysis of the cycles before the high-current fault revealed high-frequency transients indicative of internal capacitor arcing, followed by an electrical signature indicative of a failure of an MOV-type arrester. Analysis of the period following the high-current fault indicated that internal capacitor arcing continued for nine seconds. DFA system graphing capability enables viewing of real and reactive power. In the subject case, that indicated that the event resulted in the loss of 150 kvar of reactive power on the same phase as the fault. This led to a conclusion that the failure began when a capacitor started arcing internally. Such arcing generates high-frequency voltage transients sufficient to cause an arrester, particularly if already weak, to go into conduction and fail catastrophically. In this case the arrester failed and caused the line fuse to blow, resulting in the outage. The internal capacitor arcing continued after the fuse blew, indicating that the capacitor is upstream of the fuse. The following diagram represents the relative positions of the subject capacitor, line fuse, and arrester.





A subsequent field patrol identified the failed capacitor shown in the photograph above. Key benefits of the analysis in this case included 1) a better understanding of how events on one portion of a circuit can precipitate failures elsewhere on the circuit and 2) identification and expedited repair of the failed capacitor.

DFA research has documented multiple cases in which capacitor transients have precipitated events well distant from the capacitor, including:

- A case in which capacitor arcing on one circuit caused a fault on another circuit that was served by the same substation bus.
- A case in which switching of a capacitor on the 138 kV transmission side of substation A precipitated failure of an arrester on a 12 kV distribution circuit served by substation B, several miles away.

In each of the cited cases, the presence and analysis of electrical waveform recordings conclusively proved the cause and sequence of the event.

Conclusions

Line currents and voltages contain information indicative of incipient failures and other operationally significant events on distribution circuits. Taking advantage of the information requires having the appropriate data, knowing how to interpret it, and having automated processes that allow near real-time reporting of events of interest. The DFA research program has identified signatures of multiple failures, incipient failures, and other circuit events of interest. It also has implemented a system architecture to address the need for automated processing and delivery of information to personnel. This enables personnel to respond to events of which they otherwise have no awareness. Having the real-time and historical database of waveform activity also enables use of that data for study and forensic evaluation, leading to better understanding of complex events.