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Automated Power System Waveform Analytics for Improved Visibility, Situational Awareness, and Operational Efficiency

J. A. WISCHKAEMPER
C. L. BENNER
K. MANIVANNAN
B. D. RUSSELL
Texas A&M University
United States of America

SUMMARY

The proliferation of "smart" devices on distribution feeders in the past decade has resulted in a deluge of data. Most utilities recognize that recorded waveforms and other data contain information that could enable them to operate more effectively. In practice, however, most utilities find themselves confronted with an intimidating mountain of data, without tools or expertise to differentiate the important data from the pedestrian. Much data analysis continues to be performed manually, off-line, in response to specific perceived problems. That can provide forensic value, if the utility has the requisite expertise and the time necessary to identify and interpret the relevant data, but it provides little real-time system visibility or situational awareness that would enable operational improvements.

For multiple years, supported by EPRI and EPRI-member utility companies, Texas A&M researchers have used sensitive, high-fidelity waveform recorders to collect data from scores of feeders, using technology readily achievable with modern electronics. This has created the most comprehensive extant database of waveforms of incipient failures and feeder events. Based on that database and experience, they developed sophisticated waveform analytics and reporting methods. Dubbed distribution fault anticipation (DFA) technology, the system acquires high-fidelity waveforms from conventional CTs and PTs and then uses automated processes to apply analytics to those waveforms and thus report events and conditions. This provides personnel with real-time visibility of feeder events and conditions, including incipient failures. This newfound visibility, or awareness, enables improved reliability, improved operational efficiency, and true condition-based maintenance.

This paper explains general DFA concepts and then uses selected case studies to illustrate concrete operational benefits to utility companies.

KEYWORDS

Power system analytics; smart grid; Distribution Fault Anticipation; DFA; condition-based maintenance; incipient faults

Carl L. Benner: carl.benner@tamu.edu

Introduction

The past decade has seen widespread adoption of "smart-grid" technologies on distribution feeders, resulting in a dramatic increase in data. Utilities have invested heavily in electronics, communications, and enterprise databases to capture and archive data, but few have tools or expertise to turn that data into actionable information that can improve situational awareness and operational efficiency. [1] Even where such expertise exists, most analysis is done manually, on-demand, often as part of an investigation into a perceived problem or recent trouble. This type of analysis can provide forensic value, but it generally does not enable real-time assessment of feeder conditions.

Online waveform analytics can diagnose a variety of failures, including incipient failures, and also provide real-time visibility of feeder operations. In field demonstrations, reports from online analytics often provide utilities their only notice of a problem, thus enabling proactive repair of failing apparatus before outages occur. [2] Analytics also have assisted utilities by informing them when field repairs have *not* corrected a problem and by providing information on the true cause. Finally, analytics can aid crews diagnosing unusual conditions, such as when multiple line devices misbehave simultaneously.

DFA Waveform Analytics – Overview of Background and Status

For more than a decade, Texas A&M University researchers, with significant funding by EPRI and EPRI-member utility companies, have developed technology to detect failures, incipient failures, and misoperations on distribution feeders. This technology, which has become known as Distribution Fault Anticipation (DFA) technology, applies sophisticated online waveform analytics to high-fidelity waveforms from conventional CTs and PTs. The analytics identify signatures produced by: failing apparatus; failing control equipment; faults that cause repeated momentary interruptions without causing permanent outages; external intrusions into lines; and normal and abnormal feeder events. This provides awareness that enables utilities to address problems proactively.

DFA devices currently monitor several dozen distribution feeders across the United States. These devices are installed on a per-feeder basis and monitor waveforms from conventional feeder CTs and bus PTs. DFA devices do not require any communication with downstream line devices (e.g. reclosers, capacitors). Instead, embedded analytics infer, from CT and PT waveforms, the presence of unmonitored, downstream line devices as those devices operate.

Data Requirements

Data requirements for performing the waveform analytics discussed herein are readily achievable with modern electronics, but they typically are not supported by commercial devices currently in widespread use. Requirements include:

- Triggering sensitivity – Digital fault recorders (DFRs) and power-quality meters (PQMs) typically trigger on large changes in current or voltage. Incipient failures of some line apparatus may cause current variations of only a few primary amperes and effectively no change in line voltage. DFRs and PQMs typically would not record these variations. Devices used for DFA waveform analytics intentionally trigger and record minor variations, so as to enable detection of these types of failures. Obviously, only with the data available can the analytics be performed.
- Record lengths – Most waveform recordings are measured in cycles or perhaps a few seconds. DFA research has found that longer records are necessary to characterize some failure modes. Devices used for DFA research record multiple seconds of full-fidelity waveforms, as a minimum, and multiple tens of seconds per record for some types of events.
- Data capacity – Memory and storage continue to improve in capacity and affordability. As noted above, waveform records to support analytics for subtle failure require sensitive triggering and relatively long records. These factors dictate appropriate capacity for acquisition of data and retention of that data until analysis can be performed.
- Range and resolution – Line voltages tend to have a relatively limited range, seldom exceeding about two per-unit. Line currents have much greater dynamic range. Waveform analytics require current signals of sufficient <u>range</u> to capture high-current faults (e.g., 100Arms secondary), so as to characterize those faults properly, but also of sufficient <u>resolution</u> to capture variations on the order of one ampere or less of primary current, so as to detect and characterize certain types of failures. The need to meet both the range requirement and the resolution requirement, simultaneously, challenges many commercial devices currently in widespread use.

- Sampling rate – The first question (sometimes the only question!) usually asked with regard to waveform-acquisition devices relates to sample rate. The sample rate that has been used for DFA research has been 15,360 samples/second (256 points/cycle). It is the authors' contention, however, that sample rate is not the most important specification. Sample rate clearly must be sufficient to represent phenomena of interest, but specification of sample rate should not overshadow consideration of other factors, such as those listed above.
- Data management and processing hierarchy – Most current system architectures consist of data-acquisition devices recording waveforms and delivering those recording to a central database for analysis. As noted above, some incipient-failure phenomena require sensitive triggering and relatively long records, equating to larger data volume than produced by conventional technologies. Texas A&M's system paradigm, therefore, distributes the analysis burden to the device level. In this architecture, the waveform recorder is an intelligent device that also executes the sophisticated analytics to characterize waveforms and provide "visibility" or "situational awareness." A central server retrieves predigested reports and makes them available to utility personnel. This approach lends itself to scalability and reduces time delays inherent to architectures that retrieve and process all data at a central location.

Case Studies

DFA installations have identified numerous incipient failures on feeders at multiple utility companies. Using examples that have occurred during routine feeder operations, the following case studies illustrate how waveform-based analytics can provide operational benefits by improving situational awareness and real-time visibility of feeder events and conditions.

Case Study 1: Difficult diagnosis caused by multiple, simultaneous malfunctions

The subject utility received low-voltage complaints on a portion of a long feeder. To troubleshoot, crews used line-voltage readings from meters at regulators along the feeder. Voltage readings behaved erratically, slowing the diagnostic process, which took more than four hours for multiple crews. Crews ultimately determined that a stuck phase on a voltage regulator was the cause of the original problem.

Coincident with the four-hour search for the low-voltage problem, the DFA system reported multiple episodes of unusual operation of a feeder capacitor. Figure 1, which shows 20 seconds of per-phase VARs during the first such episode, indicates that the feeder capacitor switched ON and OFF multiple times in that period. A properly operating controller should not allow repeated switching in such a short period. Furthermore, as the figure indicates, at the end of the 20-second period, one phase remained ON for an extended period, while the other two phases were OFF.

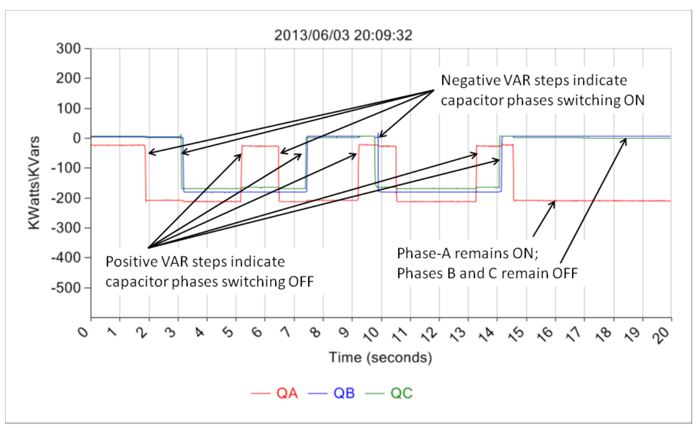

Figure 1: VAR flows when capacitor cycled ON and OFF repetitively in 20-second period

For the same episode, the upper portion of Figure 2 shows VAR flows for a longer period of time. It indicates that the third phase finally switched OFF, restoring balance, after about one minute. The lower portion of the figure shows the three phase voltages during that same period. It was the erratic behavior of the voltages that caused difficulty for the crews investigating the low-voltage problem.

The capacitor bank repeated this sequence eight times during the four-hour search for the low-voltage problem. Other than from the DFA system, operations personnel were unaware of the capacitor's misbehavior or that it was causing the erratic voltage readings that complicated the diagnosis of the regulator problem. Furthermore, after correcting the voltage problem, utility personnel remained unaware of the capacitor problem, except from the DFA system. Several conclusions can be drawn:

- Had operations personnel known the capacitor was behaving improperly and causing the erratic voltage readings, they could have switched it OFF. This would have enabled them to troubleshoot the low-voltage problem more efficiently, saving time.
- After the crew corrected the regulator problem, they had no conventional means to know that the capacitor controller had a problem.
- The regulator problem likely created the voltage condition necessary to cause the capacitor controller to malfunction. Correcting the voltage problem caused the capacitor controller to resume normal operation. Ironically, the next time the capacitor controller would misoperate likely would be during the next feeder voltage problem.

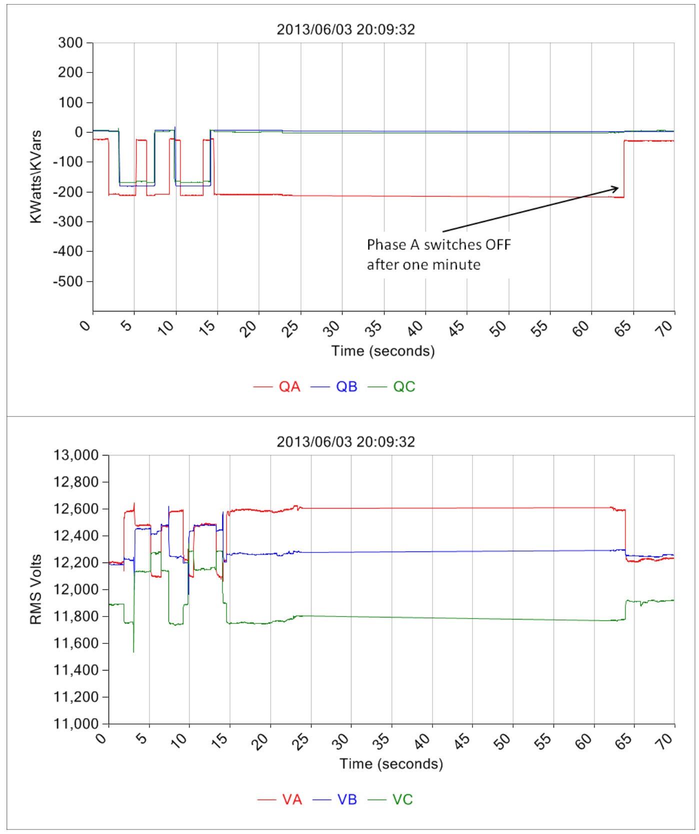

Figure 2: VAR and voltage fluctuations over 70-second interval

- Operations personnel were not deficient in their response to the problem. Rather, they lacked tools that would provide situational awareness that would enable them to respond more effectively.
- Because the capacitor controller problem occurs only in the presence of abnormal feeder voltage, conventional capacitor maintenance would fail to detect this problem. This capacitor was maintained and tested less than 60 days before the subject event, with no problem detected. Furthermore, subsequent maintenance cycles likely would continue to miss the problem.

Case Study 2: Recurrent fault caused by broken strand in long span

DFA analytics have detected numerous cases of incipient apparatus failures that manifest themselves by causing high-current flashovers under specific environmental and/or mechanical conditions. For example, a cracked transformer bushing may flash over only when moisture accumulates on its surface. A reclosing device, often a sectionalizing recloser, typically performs a momentary interruption, which "cures" the fault until conditions again become conducive to flashover. Flashovers may recur numerous times, over periods of weeks, with the utility company remaining unaware of the problem until it escalates to a sustained outage.

Most recurrent faults involve single-phase events. By contrast, the subject case study involved phase-to-phase faults. This eliminated from consideration many common causes, including single-phase insulators and cracked bushings. As an aside, single-phase apparatus can cause multi-phase faults. This occurs when a single-phase device initiates a single-phase fault, but the fault's ionized arc path migrates to involve other phase(s). In the subject case, however, each fault episode involved two phases from inception. This eliminated common single-phase failure modes from consideration.

The second episode of the subject fault caused an outage. A crew restored service but was unable to determine a clear cause. About two hours later, the fault occurred twice more, each time causing a momentary operation of an unmonitored line recloser, but no outage. The utility company dispatched a crew, who found and replaced a set of compromised dead-end bells. This diagnosis did not seem consistent with the phase-to-phase nature of the faults, however, because failure of dead-end bells typically would be expected to initiate single-phase faults.

Although failing dead-end bells seemed an unlikely cause, faults did not recur for approximately two weeks, and the problem appeared resolved. Sixteen days later, the fault did recur. DFA analytics matched the new fault with the previous ones. Based on the updated information, the utility again patrolled the feeder. Running through rough, rural terrain, the subject feeder contains a span of more than 300 meters (1,000 feet). In that span, the utility crew found a phase conductor with a broken strand, partially unwound and protruding laterally approximately 30 centimeters (one foot) in the direction of an adjacent phase conductor. The crew found arc pitting on the adjacent conductor, consistent with arcing contacts, and concluded that conductors in this long span were swinging close to one another during windy conditions, with the protruding strand contacting the adjacent phase. The absence of significant wind activity during the two-week hiatus explained the lack of incidents in that time period. After the span was repaired, the recurrent faults ceased.

This case illustrates the value of waveform analytics for knowing when field repairs have not corrected the right problem. The phase-to-phase initiation of the faults (as opposed to faults which begin single-phase and then evolve to phase-to-phase) indicated that the failing dead-end bells were not likely the cause of the repeated faults. Also, when the fault recurred two weeks later, the analytics system recognized that fault had the same characteristics as the earlier episodes, prompting a renewed search and identification of the true problem.

Case Study 3: Multiple outages caused by conductor slap

Fault-induced conductor slap (FICS) typically occurs when a phase-to-phase fault induces magnetic forces that push line conductors away from each other, followed by operation of midpoint protection, which abruptly removes the magnetic forces and allows the conductors to swing back toward their resting points. Momentum causes conductors to over-swing and possibly contact one another. If contact occurs in an energized span, a second fault, having higher magnitude than the first, occurs. [3] DFA systems have detected FICS on multiple feeders at multiple utilities. Experience indicates that FICS does not tend to occur randomly, but rather that susceptible spans experience FICS repeatedly.

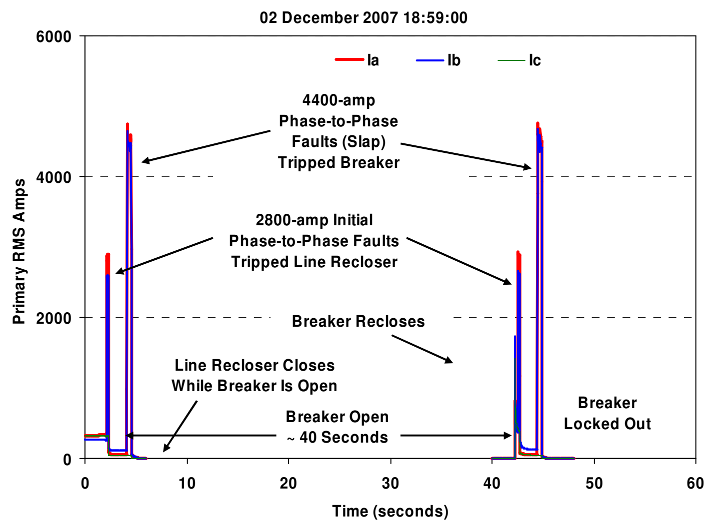

Figure 3: Breaker lockout caused by FICS

In 2007, before DFA analytics could recognize FICS, a DFA-monitored feeder locked out because of FICS. Figure 3 shows RMS line currents during the FICS event. An initial 2,800-ampere fault occurred and tripped a midpoint recloser. This recloser trip was followed by a higher, 4,400-ampere fault which locked out the substation breaker. This caused an outage for all 4,000 of the feeder's customers, whereas the initial fault should have tripped only the midpoint recloser.

The utility company recognized that the initial fault should have been sectionalized by the midpoint recloser, without operating or locking out the feeder breaker. They expended substantial time and effort collecting and analyzing available data, but that effort resulted in "no cause found."

Two years later, FICS occurred in the same span of the same feeder, again resulting in an outage to all of the feeder's 4,000 customers. Five days later, FICS occurred in the same span, causing the substation breaker to trip but not lockout. In the two years since the original incident, DFA analytics had advanced and now could detect FICS. Based on a DFA report, utility personnel learned FICS was occurring and identified the offending span.

The utility did not take immediate action to correct the problem. In late 2011, FICS in the same span again locked out the feeder breaker and resulted in an outage for all 4,000 customers.

Several observations can be made from this example:

- FICS causes predictable patterns in waveform data, and these patterns can be recognized.
- FICS occurs more frequently than widely understood.
- Spans susceptible to FICS tend to experience it repeatedly.
- Utility personnel may recognize when a particular fault should have been sectionalized by midpoint devices, such as fuses or reclosers, but instead tripped feeder breakers, perhaps even causing them to lock out. Ensuing investigations often involve substantial time and effort, by highly skilled personnel, to retrieve and analyze data from a variety of sources. In the end, however, either the paucity of data or the lack of knowledge of complex phenomena such as FICS often prevents the utility company from determining the true cause.
- Although FICS tends to recur in susceptible spans, substantial time (e.g., months, years) may pass between episodes. As a result, personnel may not recognize the recurring nature of the problem.

Conclusion

The proliferation of smart grid devices in the last decade has created significant data-management problems. Many utilities are investing in smart devices, communication systems, and enterprise databases to collect and store data. Most utilities recognize that the data contains information valuable for improving system operations, but they lack resources to analyze the voluminous data and differentiate the important data from the inconsequential. Data therefore remains severely underutilized. Utility operators have more data at their fingertips than ever, but they cannot make full use of it, with the result that the status quo for utility operations has changed only incrementally, particularly with regard to awareness of feeder health and real-time situational awareness.

Sophisticated, on-line analytics, as embodied by DFA technology, offer utilities the potential to utilize waveform data to improve feeder maintenance and operations. By providing high-fidelity, real-time information about the health and status of feeder components, as well as advance indication of future problems, waveform analytics relieve utility personnel of the burden of finding the "needle in the haystack" of data, and therefore provide the visibility that enables them to work more efficiently and fix failing apparatus and incipient faults before they impact system reliability.

In addition to the case studies presented in this paper, waveform analytics can diagnose a broad range of adverse feeder events and provide feeder visibility and situational awareness to utility personnel. Field installations of DFA systems have shown that they often provide a utility's only notice of a problem or failure. They also have shown that integrating results of waveform-based analytics into operational procedures can enable utility companies to reduce manpower, schedule repair of failing equipment during daylight hours, shorten outage restoration times, and prevent momentary interruptions from becoming sustained outages.

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