2021 IEEE IAS Petroleum and Chemical Industry Technical Conference (PCIC) | 978-1-6654-0676-5/21/$31.00 ©2021 IEEE | DOI: 10.1109/PCIC42579.2021.9729013

INCIPIENT ELECTRIC CIRCUIT FAILURE DETECTION AND OUTAGE PREVENTION IN PETROCHEMICAL FACILITIES USING ADVANCED ELECTRICAL WAVEFORM MONITORING

Paper No. PCIC-2021-02

B. Don Russell
Life Fellow, IEEE
Texas A&M University
3128 TAMU
College Station, TX 77843
bdrussell@tamu.edu

Carl Benner
Fellow, IEEE
Texas A&M University238
3128 TAMU
College Station, TX 77843
carl.benner@tamu.edu

Jeffrey Wischkaemper
Member, IEEE
Texas A&M University
3128 TAMU
College Station, TX 77843
jeffw@tamu.edu

Karthick Muthu-Manivannan
Member, IEEE
Texas A&M University
3128 TAMU
College Station, TX 77843
karthick@tamu.edu

Abstract – Reliable and safe electric power is of critical importance in industrial facilities including field production facilities and plants. The best electric circuit protection and monitoring systems in use are not capable of failure prediction and incipient fault detection. Recent work demonstrates that early stages of apparatus, line, and cable failures can in some cases be detected and repaired, avoiding explosions and outages. The authors have developed a technology, which has become known as Distribution Fault Anticipation, which provides continuous health monitoring of circuits and real-time situational awareness of circuit activity. DFA monitors voltage and current signals to detect circuit abnormalities and failures. DFA utilizes intelligent algorithms to distinguish circuit events, including incipient failure signatures. This paper describes numerous examples of failing devices that were successfully detected, in early stages, thereby avoiding outages.

Index Terms — Fault anticipation, faults, incipient faults, situational awareness, electric power distribution, petrochemical facilities.

I. INTRODUCTION

From the beginning of electric power delivery, strong emphasis has been placed on responding to faults and other abnormal conditions by rapidly deenergizing circuits. In general, operational safety has been equated to implementing good fault protection systems. If we rapidly clear faults, then we have done our best to create a safe system. Protective relays protect but do not provide situational awareness of developing abnormal conditions that ultimately may result in an unsafe or hazardous condition. An unsafe condition may exist or be developing without a protective device operation or operator awareness.

Faults, whether in industrial facilities or on utility systems, can be explosive, produce arcing, or ignite fires, causing extreme hazards. Special risks exist where industrial processes are susceptible to ignition or line events can spark wildfire. Therefore, it is most important to detect circuit problems at the earliest possible stage and thereby reduce faults and other events.

There has been continued improvement in power system protection, culminating in the sophisticated digital relay devices that exist today. Rapid fault detection and sophisticated power restoration systems protect electrical infrastructure and minimize the duration of outages. But this approach to monitoring and protection of electric circuits has an obvious limitation, namely, that it does not provide awareness of developing, degrading conditions or device failures that ultimately can lead to faults, create outages, or result in unsafe conditions.

When a fault occurs and causes a protective relay to remove power from a circuit, operators are unaware that the condition that caused the fault may have begun developing days or weeks earlier. A protective relay rapidly clears a high-current fault but is blind to the time period preceding that fault. What if failure precursors exist and could be detected, enabling proactive repairs and thereby avoiding some of those future failures that otherwise would cause high-current faults?

Fig. 1 contrasts conventional electric operations with the potential for detecting precursors and enabling condition-based maintenance. With today's operating protocols, a circuit is considered "normal" until a fault event or outage occurs. Indeed, some events, such as those resulting from contact by foreign objects, occur without warning. In other cases, such as equipment degradation, however, failures may develop over time and exhibit electrical precursor signals. Detecting such precursors, thereby enabling repairs <u>before</u> catastrophic failures, is a central function of the distribution fault anticipation (DFA) technology. Proactive repairs are enabled by <u>awareness</u> of developing failures and in turn enable avoidance of some outages and dangerous events.

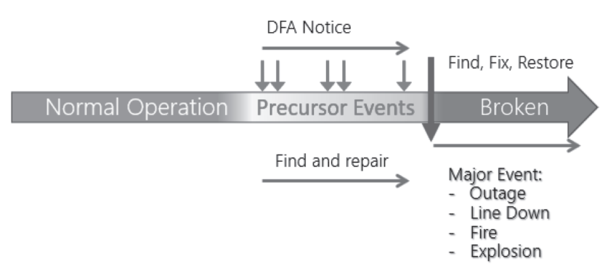

Fig. 1 Failure processes can produce detectable electrical precursors.

What has long been needed is a system that is predictive and diagnostic, capable of detecting an incipient failure condition at an early stage and enabling the ultimate catastrophic fault to be avoided. DFA technology uses advanced waveform analytics to provide continuous health assessment of electric circuits.

Operators often can be informed when circuits are unhealthy and need attention, before major hazardous conditions occur.

II. WAVEFORM ANALYTICS RESEARCH

Beginning in the mid-1970's, researchers, directed by the lead author, began investigations using advanced digital signal processing technologies with the goal of improving power system protection. At the time, the electric utility industry had named the detection of arcing downed powerlines as the most difficult problem in power system protection. Extensive experimental work documented the electrical behavior and characteristics of downed conductors, with specific emphasis on low-current arcing faults. This work resulted in the first practical algorithms for detecting high-impedance, arcing faults [1-3].

The arcing fault research effort led to analytical methods that became ever more sophisticated. Expanding research beyond downed conductors, the authors recognized that failing devices and apparatus on power circuits exhibited very low-grade electrical signatures that sometimes persisted for long periods before total failures occurred. Expert system and pattern recognition techniques had become quite advanced, but it was discovered that few high-fidelity recordings existed of naturally occurring failing devices on power circuits. To develop detection algorithms based on extracted features and the behavior of failing devices, a library of events with numerous examples of failures was required.

To meet the need for this event library, the research team conducted the longest running longitudinal study of naturally occurring device failures on power circuits, including overhead lines and cables. Scores of circuits were instrumented with advanced data capture equipment, some of which were monitored continuously for many years. The result was a library of tens of thousands of events. This data enabled researchers to create DFA detection algorithms [4-6].

Based on comparative studies of the event library more than 15 years of experience reviewing specific events from utility circuits during routine operations, the authors discovered key device failure characteristics on low-voltage and medium-voltage distribution power circuits.

1) The electrical signatures of failing devices often begin as low-amplitude arcing that occurs over a long period of time before evolving into full failures.
2) A failing device may have long periods of quiescence (i.e. no detectable incipient activity) only to repeatedly have the arcing activity return. The activity is aperiodic, and quiescent periods may last for hours or days.
3) For series arcing, such as occurs with hotline clamps and switches, the arcing current is a component of load current, but often there is no noticeable interruption of load until late in the failure process.
4) The low-level signals from an arcing device, such as a hotline clamp or connector, may cause a change of only a few amperes of primary line current, but can be detected by sensitive monitoring equipment at the substation head of the circuit.
5) Conventional current and potential transformers (CTs and PTs) have the bandwidth required to pass harmonic-rich failure signatures to monitoring equipment without excessive attenuation. Low-grade arcing of a few amps or tens of amps can be detected without special sensing devices.
6) Signature features and temporal behavior of failing devices are sufficiently unique that many devices can be specifically identified using sophisticated pattern recognition tools. For example, a failing hotline clamp creates a different signature than a failing arrester.

The extensive library of event failures, from years of monitoring dozens of real circuits during routine operations, enabled understanding of device failure characteristics and the research team's development of sophisticated failure detection algorithms. The research and development team worked closely with multiple utility companies to implement a system that provides real-time situational awareness for direct use by operators and engineers [7].

III. DISTRIBUTION FAULT ANTICIPATION (DFA)

DFA technology uses waveform analytics for the purpose of early detection of failures and abnormal conditions on electric distribution circuits. The main building blocks of the system for practicing DFA are DFA hardware monitors, applied one monitor per circuit, and a central DFA master station for gathering pre-processed reports from the fleet of DFA devices and making those reports available to users via web interface. The DFA monitor hardware platform records event waveforms in high fidelity (256 samples/cycle; 18 bits) and long data records (tens of seconds, rather than tens of cycles). Experience has shown that these longer-duration records are necessary for recognizing certain types of failure mechanisms. The recordings are processed automatically by sophisticated signal processing and pattern recognition software techniques that reside on each individual DFA monitor. DFA software uses analytic inference to identify circuit events and create reports that it sends to the central master station server, via encrypted network communications, for user access via secure login and web-based presentation.

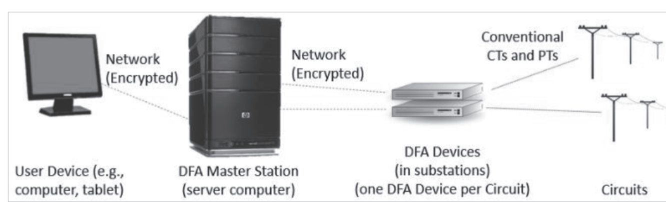

Fig. 2 System architecture for practicing DFA technology.

Fig. 2 shows the basic architecture of a DFA system. Each DFA monitor is a 19" rack-mount device, 1.5 rack units in height, with screw terminals to connect to conventional circuit CTs and bus or circuit PTs. All recording of waveform data, processing of that data by algorithms, and creation of reports is handled in the individual DFA monitor in a distributed processing architecture. When a DFA monitor creates a report, identifying a failure or other circuit activity, it delivers the reports, via network communications, to the master station for access by end users. Operators have real-time access to the reports as events occur. Unlike fault recorders or power quality monitors, the DFA system automates the waveform analysis process so that operators get actionable information without analyzing volumes of waveform data.

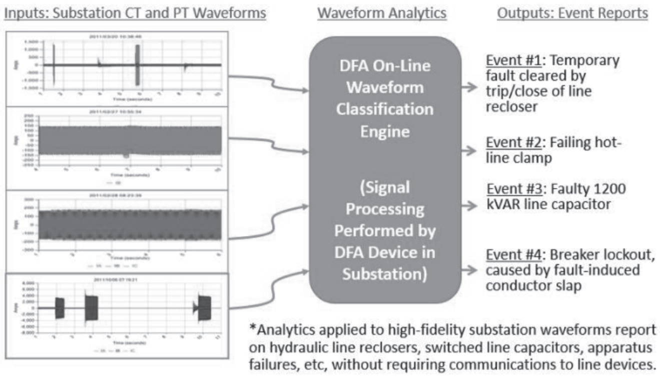

Fig. 3 Data capture and analysis inside each DFA monitor.

Figure 3 demonstrates the automated architecture of the DFA system. Waveforms of four specific circuit events shown on the left are recorded from conventional CTs and PTs and analyzed by a body of algorithms, known as the waveform classification engine. Reports are generated automatically and made available to operators for action, typically within one to three minutes of the occurrence of the underlying event.

Multiple stakeholders within a company have used DFA-generated reports, including personnel with responsibilities for operations, maintenance, asset management, system protection, and field repairs. The reporting system is web based and therefore able to share data and alerts as needed by stakeholders. DFA complements other smart grid and utility monitoring systems by providing high visibility of circuit activity.

IV. CASE STUDIES

Use of the DFA system is best understood through case studies of faults and device failures captured and analyzed from operating utility circuits. DFA monitors are installed on circuits at multiple utility companies. The following case studies detail events detected and recorded on DFA-monitored circuits.

Overarching point: The point of each case study is that the utility operator had opportunity to act only because the DFA system provided awareness of a problem. DFA monitoring has documented many cases where DFA information 1) was actionable and 2) provided the utility's only notice of the problem. Having notice is the without-which-nothing predicate to taking corrective action.

Important note regarding data plotted in figures: When DFA monitors record data, they record at a sample rate of 256 samples/cycle. Researchers and users have found, however, that the best initial, "big picture" understanding of an event often comes from viewing RMS quantities over the entire duration of an event recording. This is particularly true for records of long duration, such as those from DFA monitors. Most figures herein therefore display RMS quantities, but the reader should be aware that DFA software algorithms require and use the "sine waves" of the high-speed data recordings, which often contain subtleties not visible in the RMS data alone. RMS data shown herein has a granularity of one value per cycle and is calculated by DFA viewing software from the underlying data that is recorded at 256 samples per cycle. After the user views the RMS quantities, he may switch to plotting the high-speed waveforms, if he decides to do so based on the nature of the event.

A. Case Study: Repetitive, Incipient Network Cable Arcing

Cable failures represent a common class of incipient failure. It is not uncommon for failing cables, joints, and terminations to produce incipient signatures hours, days, or weeks in advance of catastrophic failure or notice by the utility or its customers.

From 2008-2012, the authors worked with a utility on a project that installed DFA monitors at multiple nodes of an underground, heavily interconnected low-voltage (120/208V) cable network [8]. This project demonstrated several important findings regarding the behavior of low-voltage cable failures and the potential for detecting such failures in their incipient stages. During the project period, DFA monitors recorded and researchers analyzed tens of thousands of arcing signatures associated with failing cables, developing a significant body of knowledge regarding the natural failure progression of arcing low-voltage cables. A key finding was that a failing cable section can experience arcing that is significant (hundreds or thousands of amperes) but sporadic, over long periods of time, without the utility's having any awareness of it. In several instances during the project period, utility personnel responded to DFA detection of arcing, located and repaired incipient failures, and avoided catastrophic events. The utility was unaware of those incipient failures, except for the information from the DFA monitors.

One such example occurred over a period of several weeks in March 2010. On March 13, two DFA monitors recorded significant bursts of arcing. The heavily interconnected nature of the network makes it common for an event at a single location to produce detectable activity at multiple network nodes. The initial arcing burst, recorded by one of the monitors, is shown in Fig. 4. Arcing continued over a period of almost seven hours, with a two-hour quiescent period in the middle. Then, for the next 21 hours, both data DFA monitors continued to record arcing, with alternating periods of arcing and quiescence measured in hours.

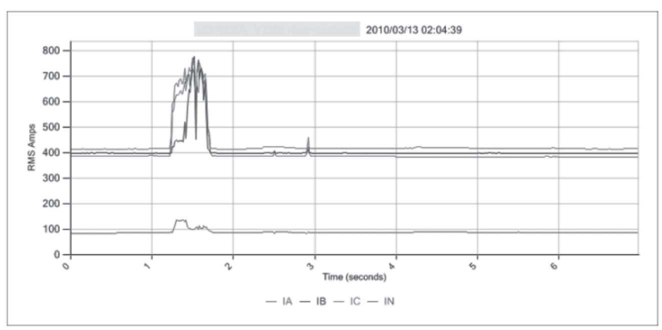

Fig. 4 Initial arcing recorded by a DFA monitor.

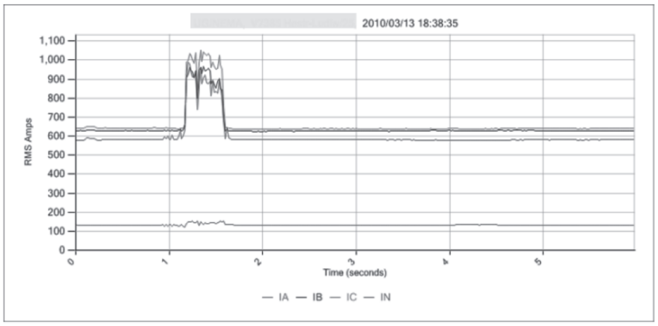

Fig. 5 Additional arcing, 16 hours after initial activity.

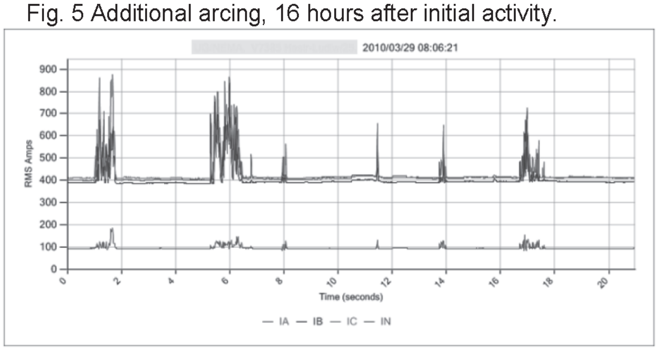

Fig. 6 Additional arcing, 16 days after initial activity.

Fig. 5 and Fig. 6 show arcing that occurred 16 hours and 16 days after the initial bursts. Then, no activity was recorded for the next five days. Additional episodes were recorded on March 19, March 23, March 29, and March 30.

On March 31, based on DFA measurements, the utility located several energized structures half a block from the DFA devices. A crew was dispatched and found significant damage to cables in proximate structures. Following repairs, no additional arcing episodes were detected, and the problem was considered resolved.

This case study shows that in some cases, arcing cables can continue over a period of weeks in an incipient state without operating overcurrent protection or generating enough evidence to indicate, by conventional means, that ongoing failure condition exists. In this particular case, it is not known how long the cables would have continued to arc without utility action, but it is certain that the condition persisted for at least 18 days.

B. Case Study: Repetitive, Incipient Non-Network Cable Arcing

This case study involved intermittent arcing of low-voltage cables, as did the previous case study, but with the following differences: 1) this case study involved direct-buried low-voltage cables; 2) the failure condition underlying this case study caused numerous complaints, including multiple outages, over the three-month timespan of the case; and 3) the electrical waveforms recorded by a DFA monitor came from conventional CTs, at the primary 13.2 kV distribution substation, as passed through the step-down customer service transformer (13.2 kV:240/120 V), not from CTs installed directly on the low-voltage cables.

This case persisted for three months, because of a communications outage. The communications outage had the benefit, from the perspective of documenting failure processes, of preventing personnel from having access to DFA information, which would have enabled earlier correction of the problem. The communications outage enabled documentation of conventional response processes and their shortcomings.

The first episode related to this case occurred on September 4, 2004 (Fig. 7) and caused an outage. The communications outage began shortly thereafter and persisted for many weeks. Field personnel responding to the outage found a completely self-protected (CSP) transformer breaker tripped. They checked for obvious damage to visible hardware and, finding none, closed the breaker. The breaker held, all customer voltage levels were appropriate and steady, and the crew left.

During the extended-duration communications outage, the DFA monitor detected and recorded numerous additional episodes (for example, Fig. 8) of the arcing caused by the failing cables. Some of the episodes caused outages; others did not. When outages occurred, field personnel again checked for obvious signs of damage, found none, reset the breaker, and left the scene, with all service voltages appearing normal. The case culminated when the cables went to final failure on December 7, 2004 (Fig. 9), almost three months after the first event. Figure 10 is a photograph of the buried cables that were exhumed following the final event and outage.

A key takeaway from this case study is that incipient failure conditions can be misdiagnosed, even if outages occur. The failure condition underlying this case study caused significant arcing, but only intermittently. Consequently field personnel responding to trouble calls had little evidence to make a correct diagnosis. If the communications outage had not persisted for so long, information from the DFA system would have enabled utility personnel to diagnose and correct this conditions weeks or months earlier, thereby avoiding multiple outages. Another takeaway is that arcing events on low-voltage, secondary service cables sometimes can be detected and identified from recordings from substation-based primary CTs.

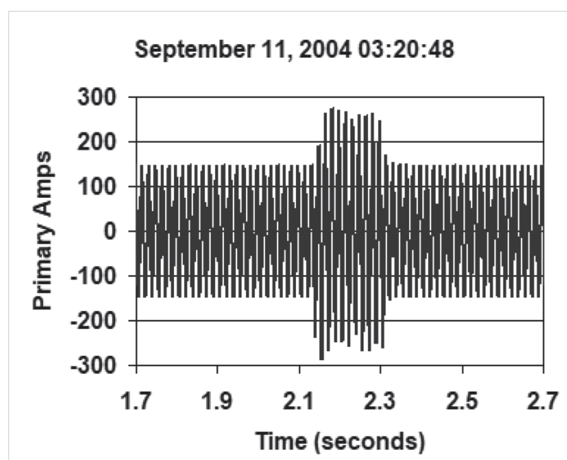

Fig. 7 First recorded episode of this cable arcing series

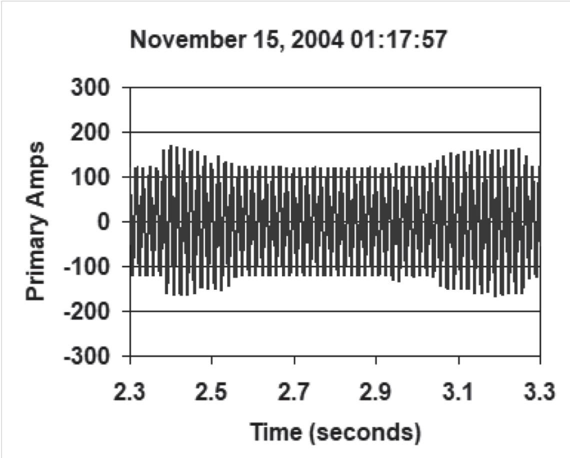

Fig. 8 Episode two months later. Multiple other episodes occurred between the first episode and this one.

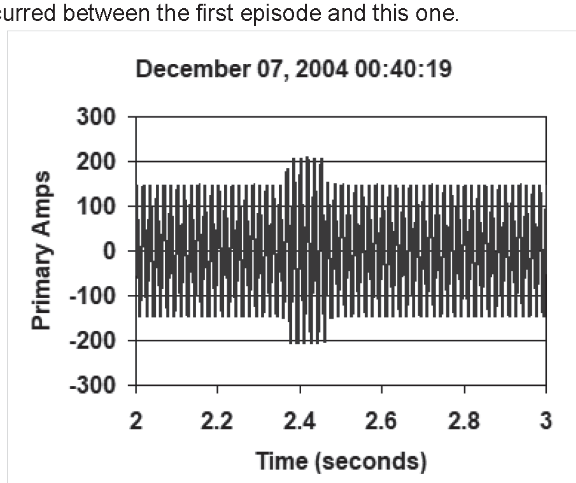

Fig. 9 Final episode of arcing, which resulted in a sustained outage.

Figure 10. Failed cables that had arced and caused intermittent outages for three months.

C. Case Study: Medium-Voltage URD Cable Failure

Conventional wisdom generally holds that any fault involving medium-voltage cable is a permanent fault. Study of field data by the authors and others, however, shows that incipient failures may occur in medium-voltage cable systems, particularly in discontinuities such as splices and elbows, without immediately causing permanent faults or outages. This case study details an example in which an initial fault was not truly permanent and for which true situational awareness could have prevented an outage of extended duration.

The timeline of this case study is as follows: a high-current fault (Fig. 11) on a 15 kV-class URD cable loop caused a fuse to blow and resulted in an outage; the responding troubleman saw no obvious damage and therefore replaced the fuse, which held without blowing, without making any repair to the cable; in the following hours, the degraded cable caused multiple additional recognizable high-current events (Fig. 12shows one episode) but not a sustained fault or an outage; on the third day, final failure of the cable (Fig. 13) resulted in an eight-hour outage.

A DFA monitor recorded these events as they occurred, but the DFA system was not available to operations personnel and therefore not used. In strict observance of Murphy's Law, the final failure occurred in the middle of the night (2:24 a.m.).

DFA information makes such conditions fully actionable: the cable-failure signatures in the hours after the fuse replacement gave clear indication that the problem was a cable, that the problem still existed, and that the problem likely would evolve into a permanent fault and outage within hours or days; and identification of the which of the circuit's URD loops was known based on the initial outage. Had this information been used operationally, the failure point could have been pinpointed, using conventional cable fault location tools, and the unplanned eight-hour could have been avoided or significantly reduced.

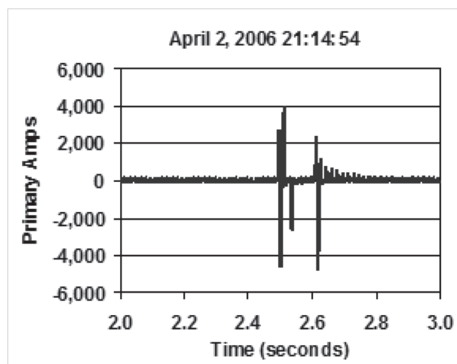

Fig. 11 Initial failure (blown fuse) of MV URD cable.

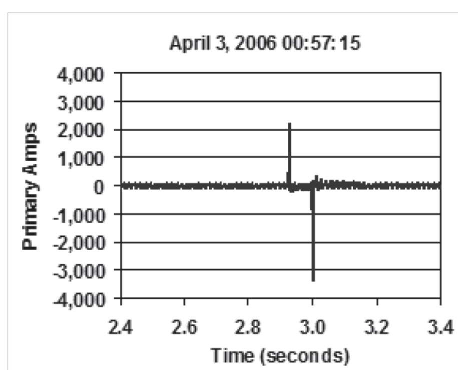

Fig. 12 Signature recorded hours after the fuse was replaced (cause of blown fuse unknown to the troubleman at the time), indicative of the unresolved incipient failure. Note: The event

represented by this signature self-cleared without causing an outage.

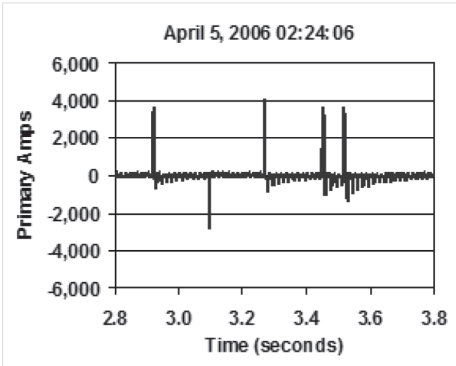

Fig. 13 Final catastrophic failure of cable, which occurred three days after the initial fault. Note: This final failure caused eight-hour outage that could have been avoided.

D. Case Study: Incipient Arcing Failure of Substation Switch

The term “arcing” often denotes shunt arcing, where unintended contact or compromised insulation enables current to flow in an unstable way through an unintended path. Another type of arcing is series arcing. Unlike shunt arcing, series arcing does not involve current in an unintended path. On the contrary, it represents a restriction of normal current flow because of a “hot spot” developing in a load-carrying device, such as a hotline clamp or switch. This “modulates” the voltage to loads served downstream of the failing device, resulting in distinct, low-amplitude current variations that are detectable via substation-based CTs and PTs. As such a condition develops, it can remain unnoticed by users for a long period of time, or it can cause symptoms such as mysterious protection operations or flickering lights. The DFA research program has documented multiple cases in which series arcing is electrically detectable for hours to weeks prior to being detected by any conventional technology or conventional means.

The case study reviewed here involved a blade switch that carried the full load of a 25 kV distribution circuit serving hundreds of primarily rural electric customers. The photograph of Fig. 14 shows the “hot spot” that the DFA system reported as series arcing, but that was not detected by any conventional means.

Fig. 14 Incipient series arcing (hot spot) visible in contacts of substation switch.

The timeline of this case study is as follows. DFA detected and reported series arcing mid-morning on a Saturday. Utility personnel were dispatched shortly thereafter. The circuit has more than 100 miles of exposure and numerous switches and hotline clamps, but the utility was able to use DFA information to target their search to the portion of the circuit at or near the substation. Upon arriving at the substation, a crewman knew that he had found the problem, because he could hear buzzing and see arcing in the substation switch.

The utility deemed this condition to be sufficiently urgent that they called in crews and made repairs that Saturday evening. This response was timely, because the area experienced thunderstorms the next day. Wetting the switch could have precipitated its final failure. Also, the storm caused miscellaneous faults on the circuit, and passage of fault current through the weak switch likely would have precipitated its final failure. Had the switch gone to final failure, it would have, at minimum, caused an outage of extended duration for up to 2 000 customers, and at maximum, caused a fire in the substation.

The key takeaway from this case study is that preemptive repair of this serious incipient condition was possible only because the DFA-based monitoring system made the utility aware of it.

E. Case Study: Incipient Arcing Failure of Hotline Clamp

As was the case for the previous case study, the condition involved in this present case study is series arcing, a “hot spot” that affects the flow of load current. In this present case, a DFA monitor at the substation head of a 25 kV distribution circuit detected series arcing and reported it as a probable failure of a hotline clamp. The monitoring system estimated that only a small portion of the circuit load was being served through the failing device. Pinpointing location therefore was more challenging than it had been for the substation switch, where DFA information directed the crew to search at or near the substation. In addition, incipient failure signatures in the present case were much more intermittent than they had been for the switch, probably because of the smaller amount of load current being conducted.

DFA reported the subject condition for a time, and then the condition became quiescent. Lacking clear guidance as to location, the utility therefore put the circuit on a "watch list." The subject utility had prior experience with DFA-based detection of series arcing and was aware that the arcing signature could become quiescent temporarily but then return. The incipient failure signature indeed resumed three days later. The utility, which uses a powerline-carrier based system for reading meters, noted a temporary communications failure coincident with the resumed activity. Specifically, communications to seven residential meters, in one geographic location, had failed temporarily, and that communications problem coincided in time with the DFA system's report of resumed series arcing.

Using knowledge of the specific type of incipient failure, from the DFA system, and location clues, from the communications anomaly, a targeted search in the area of the seven aforementioned meters readily identified low-grade series arcing in the jaws of a hotline clamp (Fig. 15). The failing device happened to be in a national forest and therefore represented an elevate risk of wildfire ignition. A similar case of series arcing, in a hotline clamp, caused the broken primary conductor of Fig. 16. Such a failure was averted in the present case study. Notification from the DFA monitoring system was the only actionable notice the utility had of the incipient failure.

Key takeaways from this case study include: 1) conventional monitoring systems do not detect most incipient failures; 2) sophisticated pattern recognition algorithms, applied to high-fidelity waveforms from conventional CTs and PTs, can detect incipient conditions; 3) DFA monitoring is one tool in an overall suite of tools available to circuit operators, and synergistic use of multiple tools (in this case, DFA monitoring and the PLC-based meter system) can provide optimal results; and 4) knowledge of incipient failures enables proactive repairs that avoid interruptions, power quality problems, and dangerous situations.

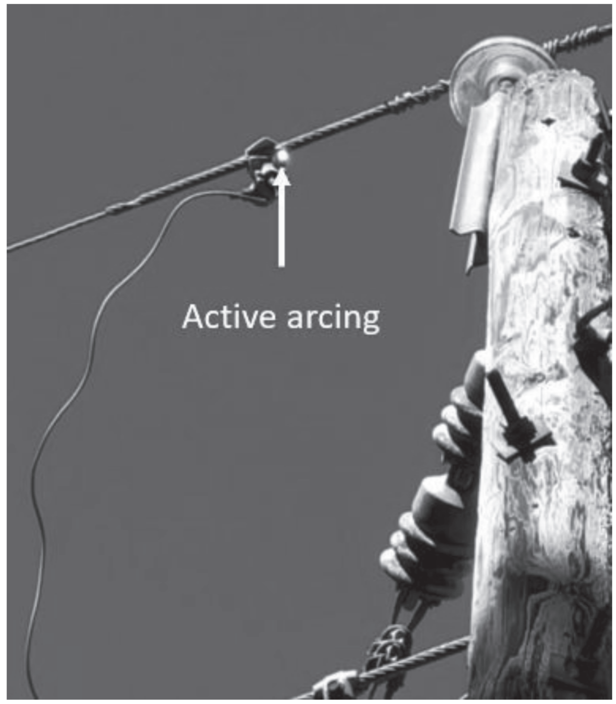

Fig. 15 Series arcing of hotline clamp in national forest, detected by DFA monitor in substation miles away.

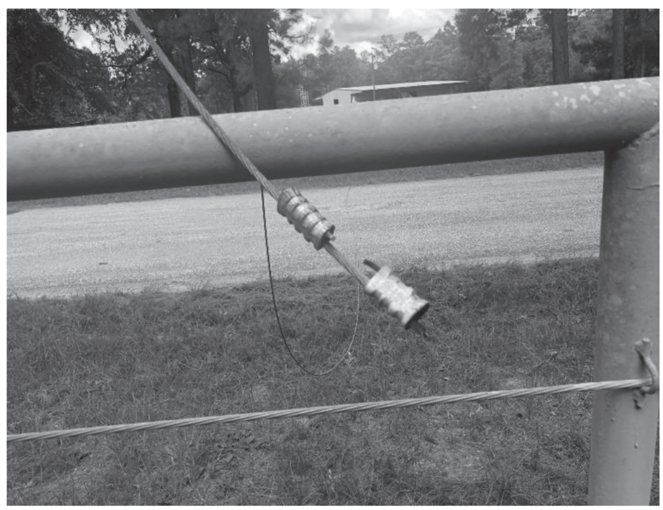

Fig. 16 Primary conductor that broke as a result of series arcing in a connector.

V. CONCLUSIONS

Many faults and failure conditions exhibit precursor signals for significant periods of time prior to catastrophic failures. The authors have developed a monitoring technology, known as DFA, which has the capability of informing operators of developing problems so that field crews can find and fix incipient conditions.

DFA technology is applied utilizing conventional voltage and current transformers that already exist to provide inputs to protective devices. Operators are provided actionable information without having to wade through data or analyze waveforms.

Many unsafe conditions, including explosions and arcing faults, can be prevented. Long outages that occur after damaging faults can be avoided, minimizing operational interruptions and loss of production. DFA detects low-amplitude arcing, which differs substantially from traditional partial-discharge monitoring.

DFA represents a transformational tool that supplements existing protection and monitoring systems, providing previously unavailable real-time visibility and awareness of circuit activity.

Key takeaways of case studies described herein include: 1) conventional technologies leave operations personnel "blind" to a great deal of circuit activity, including incipient failure activity; 2) awareness of the activity is the sine qua non (without which, nothing) to proactive repairs; 3) continuous monitoring and intelligent algorithms, applied to high-resolution electrical waveform data, and a fully automated system for delivery of reports can enhance awareness; 4) in many cases, intelligent algorithms also can identify the specific failure mechanism and provide information to enable location; and 5) response enabled by such information can reduce service interruptions, reduce collateral damage, improve power quality, and improve safety.

VI. REFERENCES

[1] Benner, C., Carswell, P., Russell, B.D., "Improved Algorithm for Detecting Arcing Faults Using Random Fault Behavior," Electric Power Systems Research, Vol. 17, No. 1, July 1989, pp. 49-56.

[2] Russell, B.D., Benner, C.L., "Performance of High-Impedance Fault Detection Algorithms in Long-Term Field Trials, "Electric Power Systems Research, Vol. 31, No. 2, November 1994, pp. 71-77.

[3] Russell, B.D., Benner, C.L., "Arcing Fault Detection for Distribution Feeders: Security Assessment in Long Term Field Trials," IEEE Transactions on Power Delivery, Vol. 10, No. 2, April 1995, pp. 676-683.

[4] "Distribution Fault Anticipation," Technical Report prepared for the Electric Power Research Institute (EPRI), Palo Alto, California, EPRI Publication #1013824, December 2007.

[5] Benner, C.L., Russell, B.D. "Intelligent Systems for Improved Reliability and Failure Diagnosis in Distribution Systems," IEEE Transactions on Smart Grid, Vol. 1, No. 1, June 2010, pp. 48-56.

[6] Wischkaemper, J. A., Benner, C. L., Russell, B. D., and Manivannan, K., "Automated Power System Waveform Analytics for Improved Visibility, Situational Awareness, and Operational Efficiency," CIGRE USNC Grid of the Future Symposium, October 2013.

[7] Wischkaemper, J. A., Benner, C. L., Russell, B. D., and Manivannan, K., "Application of Waveform Analytics for Improved Situational Awareness of Electric Distribution Feeders," Smart Grid, IEEE Transactions on, vol. 6, pp. 2041-2049, 2015.

[8] Wischkaemper, J. A., "Electrical Characterization of Arcing Fault Behavior on 120/208V Secondary Networks," Ph. D. dissertation, Dept. of Electrical Engineering, Texas A&M University, College Station, TX, USA, 2011.

VII. VITAE

Dr. B. Don Russell is Regents Professor in the Department of Electrical and Computer Engineering at Texas A&M University, where he directs the research activities of the Power System Automation Laboratory. For more than 35 years, he has investigated advanced signal processing and waveform analysis techniques applied to distribution system faults and device failures. He is best known for work, beginning in the 1970's, that scientifically characterized the behavior of arcing faults and for developing the first algorithms to detect high-impedance faults. These techniques were commercialized and are incorporated today in utility relay platforms. Dr. Russell is past president of the IEEE Power and Energy Society and Vice President and Managing Secretary of United States CIGRE. He is a Fellow of five professional societies and a member of the National Academy of Engineering.

Carl Benner holds B.S. and M.S. degrees in Electrical Engineering from Texas A&M University. Since the late 1980's, he has performed applied research at Texas A&M, where he currently serves as Research Professor in the Department of Electrical and Computer Engineering. He developed algorithms used in the first commercial system for detecting high-impedance, downed-conductor faults. His continuing work focuses on using continuous monitoring and automated systems that apply advanced waveform analytics to improve the reliable and safe operation of power distribution systems. Mr. Benner is a registered Professional Engineer in the state of Texas. He is a Fellow of IEEE and a member of the IEEE Power and Energy Society, the IEEE Industry Applications Society, and CIGRE.

Dr. Jeffrey Wischkaemper received his Ph.D. from Texas A&M University in 2011. He is a Research Assistant Professor and a member of the Power System Automation Laboratory at Texas A&M University. Dr. Wischkaemper's research includes a focus on the characterization of electrical events, including high-impedance faults, and the application of waveform analytics to new power system problems.

Dr. Karthick Manivannan received his Ph.D. from Texas A&M University in 2012. He is a Research Assistant Professor and a member of the Power System Automation Laboratory in the Department of Computer and Electrical Engineering at Texas A&M University. His current research interests include waveform analytics, developing algorithms for automatic classification and reporting of power system events, application of signal processing and pattern recognition techniques and efficient algorithm design.