21, rue d'Artois, F-75008 PARIS
http://www.cigre.org

CIGRE US National Committee
2022 Grid of the Future Symposium

Detecting and Responding to Incipient Failures on Distribution Circuits

C.L. BENNER, B.D. RUSSELL, J.A. WISCHKAEMPER, K. MANIVANNAN
Texas A&M University
USA

SUMMARY

Failures of line apparatus can degrade service reliability and quality. They also present safety risks, including the risk of ignition. Some failures occur precipitously, but many failures have incipient periods, of short or long duration, during which they manifest detectable electrical anomalies. Working with more than 20 distribution companies for more than two decades, researchers of Texas A&M's Power System Automation Laboratory have compiled a database of more than 1700 circuit-years of data from distribution circuits, during routine operations. The database has enabled development, and continues to enable enhancement, of sophisticated software that recognizes line events, including incipient failures. A hardware/software system for practicing this technology has become known as Distribution Fault Anticipation, or DFA.

Some incipient failures manifest relatively high-magnitude electrical anomalies, but others only low-magnitude. Detecting low-magnitude anomalies requires more sensitive triggering and signal fidelity than conventional measurement systems can provide. The purpose-designed DFA platform, now monitoring some 500 circuits, samples high-fidelity signal waveforms from conventional, substation-based current and potential transformers (CTs and PTs), triggers sensitively, runs event-recognition software, and sends reports to a central repository. All processes run automatically, without human intervention. DFA installations routinely identify incipient failure conditions.

Detection of incipient failures provides circuit operators with a new category of situational awareness. Taking advantage of this newfound awareness requires development of new best practices. Meaningful use requires three distinct steps: detection, targeting of search, and field response. Ongoing collaborative projects between Texas A&M and multiple circuit operators indicate that best practices are necessarily bespoke, because of each company's unique mix of available tools. These projects also demonstrate that modifications to operational procedures may be necessary, to enable sufficiently timely field response and avoid business-as-usual outcomes.

KEYWORDS

Incipient failures, incipient faults, reliability, power quality, risk reduction, ignition reduction, circuit health, feeder health.

carl.benner@tamu.edu

INTRODUCTION

A typical electric power distribution circuit consists of thousands of interconnected components, spanning significant geography and operating under rugged environmental conditions. Despite this, circuits generally provide service for decades with minimal trouble. That said, failures occur from time to time. Failures have a wide range of consequences, from minor inconvenience to serious hazards, such as electrocution or fire ignition.

Some apparatus failures occur precipitously, without warning. The most obvious example is external assault to the system, such as when a car strikes a pole, or when an off-right-of-way tree falls and tears a line down. These cannot be detected electrically in advance, because there is no electrical anomaly until the final, catastrophic event. In other cases, a line device experiences a period of incipient degradation, during which it continues delivering service, without gross malfunction. Incipient failure periods can range from minutes to months, occasionally even longer. During that period, the circuit operator and customers may perceive no change in service, but there may be changes in the electrical characteristics of the failing device, and thus in line currents and voltages.

Researchers with Texas A&M University's Power System Automation Laboratory have conducted applied research into the discovery and exploitation of electrical changes in circuit electrical parameters, to enable detection of line events and conditions, including incipient failures. The overarching focus is improving circuit operators' awareness of circuit condition circuits and thus enablement of improved service quality and reliability and lower risk of catastrophic failure.

TIMELINE OF RESEARCH AND DEVELOPMENT

Texas A&M's efforts in advanced monitoring begin in the 1970's, with efforts to detect high-impedance, arcing faults, such a fault defined practically as a conductor arcing to the ground or to a grounded object, with insufficient current magnitude and duration to trip conventional overcurrent protection. The approach used continuous monitoring of conventional current and potential transformer (CT and PT) signals, generally on a per-circuit basis from a substation, and application of signal processing and other software techniques to recognize patterns unique to high-impedance, arcing faults. The work progressed through stages of laboratory experiments, field experiments, electrical characterization of arcing faults, development of detection algorithms, field testing on circuits during routine operations, and licensing of the technology to a commercial manufacturer.

Beginning in the 1990's, efforts broadened beyond high-impedance faults. The methodology continued to use continuous monitoring of substation-based circuit CT and bus PT signals, coupled with sensitive triggering and purpose-designed software algorithms to recognize patterns in line currents and voltages. The spectrum of events of interest broadened to include generalized recognition of line events, with particular focus on incipient failures of line apparatus. The expanded effort began with instrumentation of three proof-of-concept circuits and soon thereafter expanded to 70 circuit at eleven companies. The approach was to gather signals arising from naturally occurring failures, during routine circuit operations, and then match recorded signals with line events known to have occurred on the circuit. Researchers eschewed simulations, because incipient failure processes were poorly understood, and largely remain so, and it is illogical to perform and rely on the results of computer simulations of phenomena for which one lacks fundamental understanding.

The R&D process evolved through multiple, progressive stages. Early field installations provided a large database of sensitively triggered waveform recordings, with high fidelity and dynamic range, which enabled new learning regarding the electrical behavior of failure processes and other line phenomena. That new learning enabled development of expertise to analyze waveform data to recognize line events, and that expertise provided the foundation for implementing specialized software techniques to automate the analysis process and deliver reports to inform circuit operators of line conditions and events. Field installations on more than 500 circuits continue to provide data to enable enhancement and refinement of event-recognition software. The database has more than 1700 circuit-years of data and continues to expand.

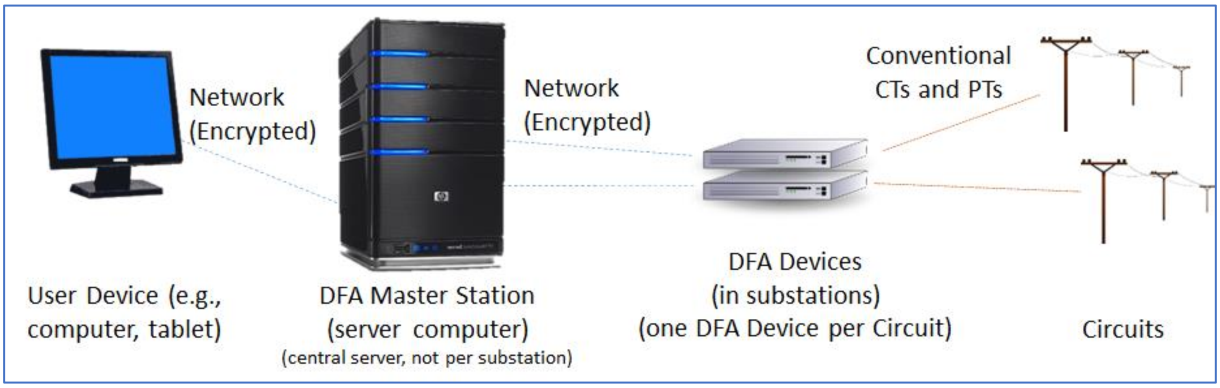

Figure 1 System architecture for the practice of DFA technology

DATA COLLECTION AND PROCESSING PLATFORM

The monitoring technology that Texas A&M developed is known as Distribution Fault Anticipation (DFA). Figure 1 illustrates the system architecture that has been implemented for its practice. In this architecture, one DFA monitoring device is applied per circuit, in the substation, connected to conventional circuit CTs and bus PTs. The monitoring device monitors performs multiple functions: it monitors continuously, triggers sensitively, records waveform snapshots of extended duration, runs the event-recognition software on the snapshots, and sends the resulting reports to a DFA master station computer. Currently, more than 500 circuits have DFA monitors, which report to a single DFA master station at Texas A&M. There is no "master" or "concentrator" on a per-substation basis; each DFA monitor sends reports directly to the single central DFA master station. Texas A&M personnel and circuit operators access DFA reports and data via browser-based interface to the DFA master station. Access is password-protected, and each company's personnel have access only to that company's circuits. Texas A&M personnel have access to all circuits, which facilitates joint review and enables continued development and enhancement of recognition and reporting software.

The architecture of Figure 1 is not the only possible architecture that could be used, but it has proven to have desirable features, such as distributed processing and storage, thereby avoiding problems inherent to architectures that requires all data to be streamed to a central location and processed there.

Texas A&M personnel initially sought to identify and use an off-the-shelf platform to perform the function of the DFA monitoring device. They considered digital relays and power quality (PQ) meters. They also considered less traditional solutions, such as scientific-grade data-acquisition systems. They were unable to find a suitable off-the-shelf solution and therefore had a purpose-designed platform specified and manufactured.

- Sensitive triggering. Overcurrent relays trigger on high currents. PQ meters with conventional settings trigger on significant voltage perturbations. Some incipient failures cause small current variation and even less voltage variation and therefore do not trigger relays or PQ meters. The DFA platform was purpose-designed to enable triggering on small variations and on non-traditional parameters. This results in a frequent triggering, which necessitates the fully automated event recognition and data handling processes implemented in the system software.
- Range and resolution. Some line events, including incipient failures, cause current of significant magnitude. Others cause only low-magnitude current. This paper details one example of each type. The platform was designed to detect low-magnitude currents, on the order of a few primary amps, and high-magnitude currents, on the order of thousands of primary amps. To accomplish simultaneously the required range and the required resolution, the platform utilizes 24-bit analog-to-digital converters and has 19 ENOB (effective number of bits).
- Sample rate. The platform continuously samples three phase currents and three phase (or phase-to-phase) voltages at a rate of 256 samples/cycle. This sample rate has proven adequate to detect conditions such as those described herein. It is not known whether a higher sample rate would contain additional information useful to the purpose. It is possible, but has not been tested, that a

somewhat lower sample rate might be used with minimal degradation of capability. All waveform snapshots recorded by the DFA platform are stored at the full sample rate of 256 samples/cycle.

- Snapshot record length. Waveform recordings from relays typically have durations between a few cycles up to a second or so. Conventional PQ meters also record only a second or so at full sample rate. Researchers have found that best characterization of some events, including some incipient failures, requires continuous recordings of longer duration, at full sample rate. The DFA platform records a minimum of ten seconds, and up to 60 seconds if circuit activity continues retriggering.
- Special note. Statements above are not criticisms of relays, PQ meters, or any other platform. Those platforms were designed for certain functions and perform those functions well. Comments herein recognize that those platforms' data triggering and recording capabilities do not meet all the requirements for detecting many of the conditions detected by the purpose-built DFA platform.

CASE STUDIES

This section presents case studies of incipient failures that occurred on medium-voltage distribution circuits during routine operations. In each case, the DFA monitor at the substation provided the only independent notification of the condition. Also in each case, other tools available to the circuit operator were used to pinpoint location. Each case spanned weeks and was locatable, making final failure avoidable. In one case, action was taken, and final failure was avoided. In the other case, conventional response processes, which did not envision the newfound capabilities, did not result in timely response, and final failure occurred 18 days after the condition was detected, located, and actionable. This latter illustrates the need for updated procedures to be responsive to new capabilities.

The first case study will involve series arcing in a connection. Before delving into the details of the specific event, a brief discussion of the series-arcing phenomenon is in order.

- Series arcing differs fundamentally from shunt arcing.
  - Shunt arcing results from current flowing in an unintended path, such as between a phase conductor and ground or a ground object, or between two phase conductors. By contrast, series arcing involves unintended, generally unstable impedance to the flow of intended current (e.g., load current).
  - Shunt arcing generally arises from compromised insulation, whether that be degraded manmade insulation (e.g., failing cable insulation) or air (e.g., mechanical movement that results in contact or too-close approach of conductors at different potentials). By contrast, series arcing arises from compromised contact surfaces (unintentional impedance).
- Series arcing often is highly intermittent, as will be illustrated in case study #1.
- During active flareups, as in Figure 2, series arcing may be visible, audible, or both.

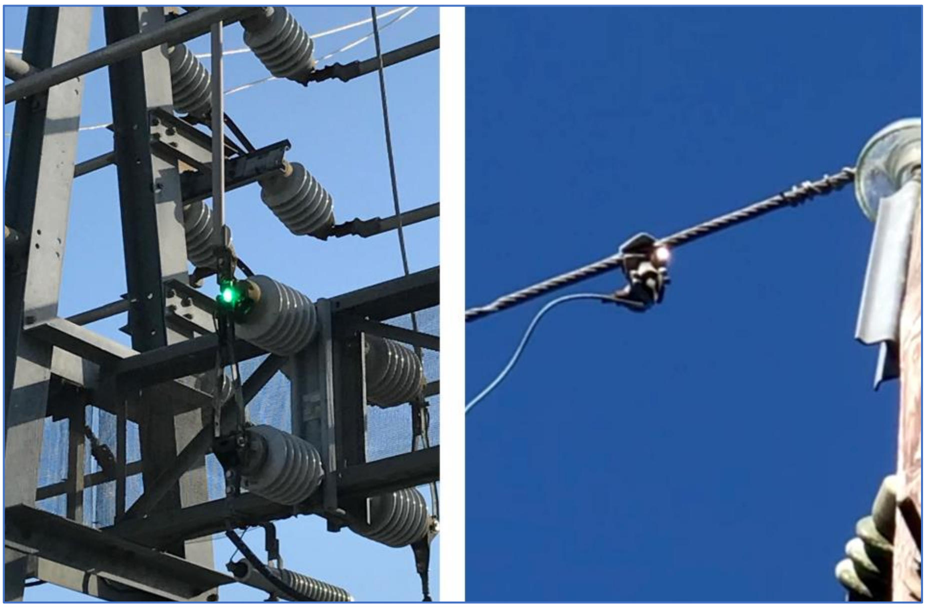

Figure 2. Examples of series arcing. Left: substation switch; Right: hotline clamp

Case Study #1: Failed Jumper with 18-Day Incipient Warning Period

The subject case involved incipient, series-arcing failure of the connection between a jumper and the primary bushing of a phase-to-phase-connected transformer on a 12 kV three-wire system. The circuit is solidly grounded, but system grounding is irrelevant to the subject case, because the condition did not involve a ground path. The incipient failure lasted 18 days, ending when the jumper separated from the bushing and caused an outage.

Figure 3 shows the incipient failure report as it appeared on the DFA system's web portal. The report shows the number of event transients detected (7950), the period over which those detections occurred (18 days), and the date and time of the last detection. The 7950 event transients are reported as a single line item, with the ability to "expand" (the + sign) the line item to show the times of each individual detection. The report also indicates that the condition affected phases B and C, consistent with a series failure of the supply to a single-phase transformer connected between those two phases. DFA software also estimated 23 kVA of connected capacity being served by the failing connection.

Figure 4 illustrates the intermittency of the series-arcing flareups. During the 18-day period, DFA detected 3403 events (containing the aforementioned 7950 event transients). Individual one-hour intervals had as few as zero and as many as 72 series-arcing events. DFA installations elsewhere have shown similar intermittency for series-arcing conditions. Perhaps counterintuitively, during the 18-day period, there was not a general increase in frequency of occurrence. Indeed, the fourth hour of the full 18-day period registered a larger number of episodes than any other one-hour period, and several subsequent days had few if any events.

The subject company has advanced metering infrastructure (AMI). Two meters were served by the secondary of the service transformer with the failing primary connection. One of those meters registered 171 voltage-below-threshold (VBT) events that correlated in time with the DFA detections, as shown as an overlay in Figure 4. For unknown reasons, the second meter, served by the same transformer secondary, registered no VBT entries.

Expand	Circuit	Event Type	Phases	Comments	Count	Last Occurred
+	[illegible]	Probable failure of switch or clamp	BC	Estimated kVA capacity beyond device: 23 kVA	7950 transients (18 days)	2022-04-12 17:35:58 [illegible]

Figure 3. Report of 18-day incipient condition (series arcing), as it appeared on the DFA system web interface

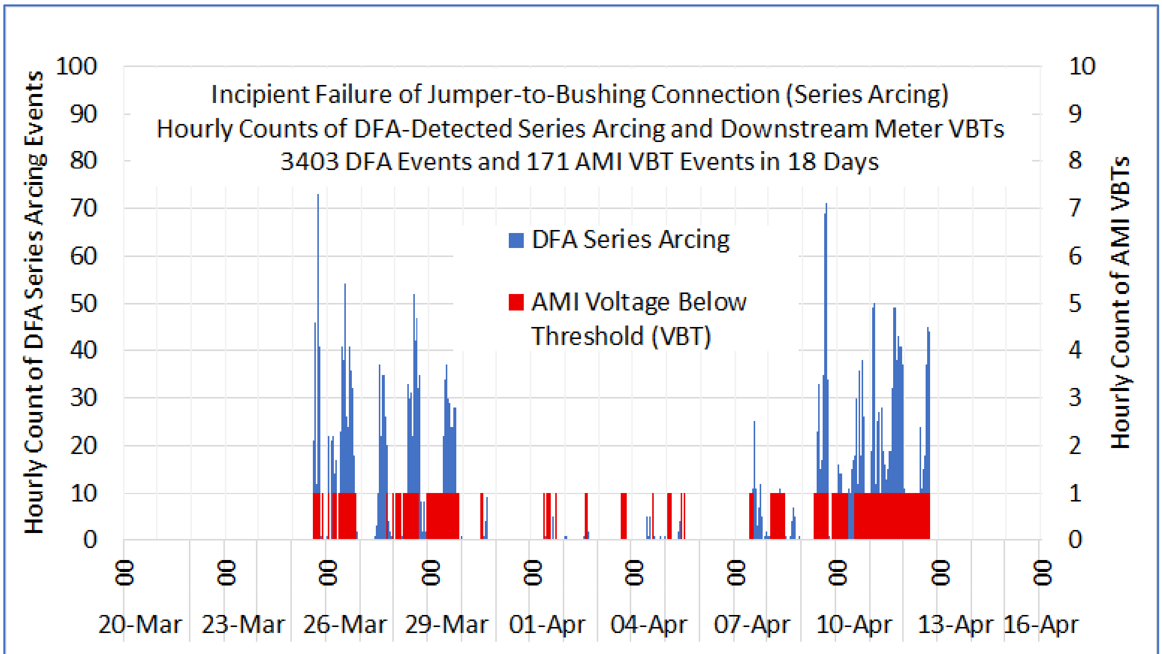

Figure 4. Hourly counts of DFA-detected series-arcing events and AMI voltage-below-threshold events

<u>Enabled Response versus Actual Response to Case Study #1</u>

The DFA monitoring system provided the sole independent alarm, the without-which-nothing for responding to the condition. Based on that alarm, company personnel queried their AMI system database and found that a single meter, on the affected circuit, began registering VBT (voltage-below-threshold) events within a few minutes of the first DFA detections of series arcing and continued registering VBT alarms at times the DFA system detected ongoing activity; see again Figure 4.

The VBT alarms provided highly specific location for the series-arcing failure, indicating a single service transformer, and they did so initially within minutes of the initial DFA detection and then repeatedly over the 18-day lifetime of the incipient failure condition. This provides adequate time and specificity of location for response and avoidance of the final separation of the jumper from the bushing. That the company did not avoid this final failure illustrates a key takeaway, namely, that procedures must be capable of taking advantage of newfound capabilities.

<u>Takeaways from Case Study #1</u>

1. New technologies can detect failures that conventional technologies cannot, in this case the incipient, series-arcing failure of a connection. This represents newfound information.
2. Some detectable incipient failures, particularly those that produce only low-magnitude current, cannot be located by conventional approaches, such as entering a fault-current level into circuit-model software. But novel approaches, in the subject case the use of AMI events, can assist in location. In the subject case, DFA-prompted examination of AMI events pointed to one specific transformer, eighteen days before the final failure.
3. For these newfound capabilities to produce value, procedures must be capable of responding to them.
4. Series arcing causes extreme localized temperatures that erode contact surfaces of current-carrying devices, such as switches and clamps, and surfaces of associated conductors. Progressive erosion eventually causes full failure of the device and/or conductor and can result in broken conductors. Early detection and response minimize risks.

CASE STUDY #2: INCIPIENT FAILURE OF CAPACITOR BANK VACUUM SWITCH

This second case study relates to incipient failure of a vacuum switch that is part of the control system for a switched, 1200 kvar line capacitor bank. A common failure mode of vacuum switches involves partial loss of vacuum. Vacuum switches can break currents and hold voltages, even with small physical separation of internal switch contacts, but only with near-total vacuum. When vacuum is partially lost, the switch can no longer function properly.

This case study occurred over a period of 44 days, measured from the first detected incipient-failure signature until removal from service of the offending vacuum switch. The incipient condition manifested as current pulses of high magnitude but short duration. Pulse magnitudes varied in the range of several hundred to more than 1000 instantaneous peak amperes. Figure 5 shows one such pulse. Its instantaneous peak magnitude is nearly 1000 amp, but its duration is just 1.1 milliseconds.

DFA installations at other locations have shown that compromised vacuum switches, on capacitor banks, can exhibit "leakage" of current pulses when in the open position. This presumably occurs because compromised vacuum is less competent to withstand the stress of full primary line voltage over the small physical distance between switch contacts. In the subject case, consistent with prior cases, the pulses occurred when the switch was in its open position or in the process of opening.

A total of 241 pulses occurred over a period of 44 days. Figure 6 shows the daily number of pulses for the period. As in case study #1, the trend is counterintuitive. For the first 2-3 weeks, there was a general increase, though not a uniform increase, in the number of daily pulses, a trend intuition might suggest. The pulse rate then was lower for the final several weeks, which runs counter to intuitive expectation.

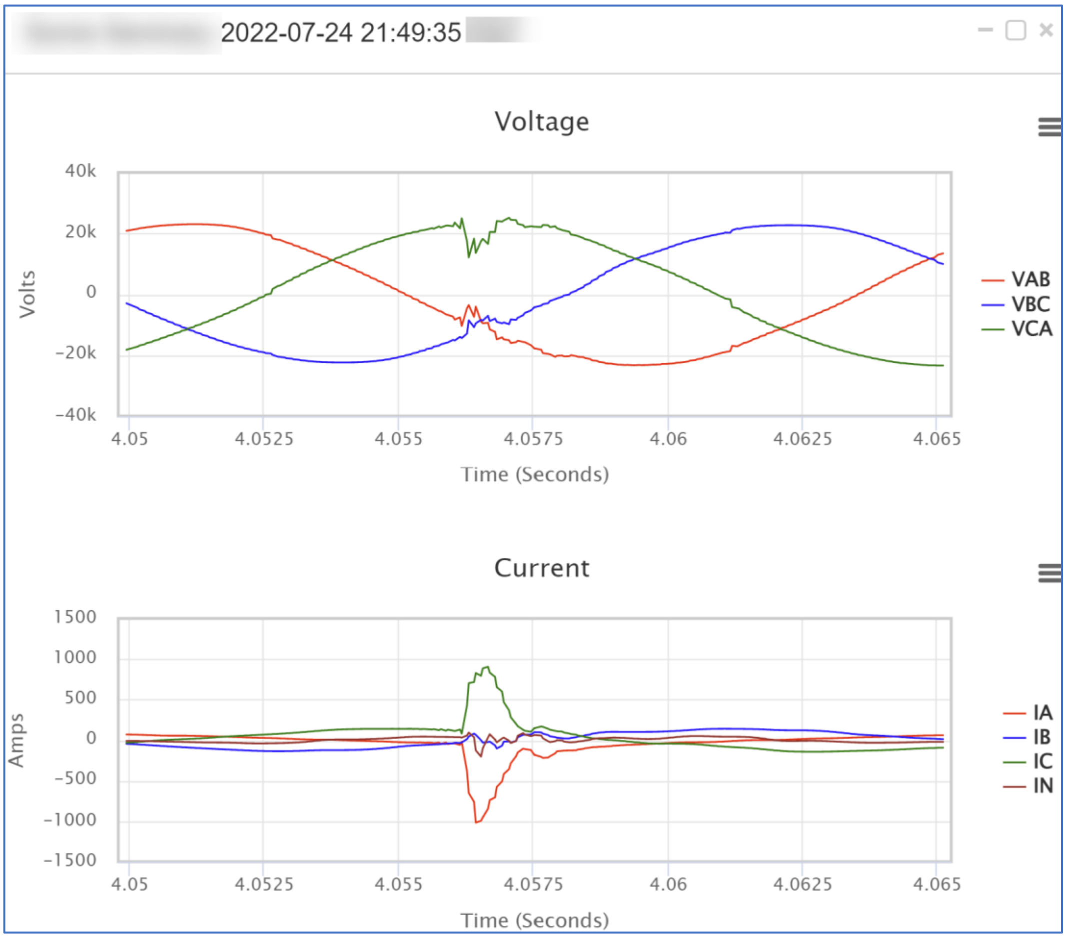

Figure 5. One of hundreds of pulses related to incipient failure of a capacitor bank vacuum switch

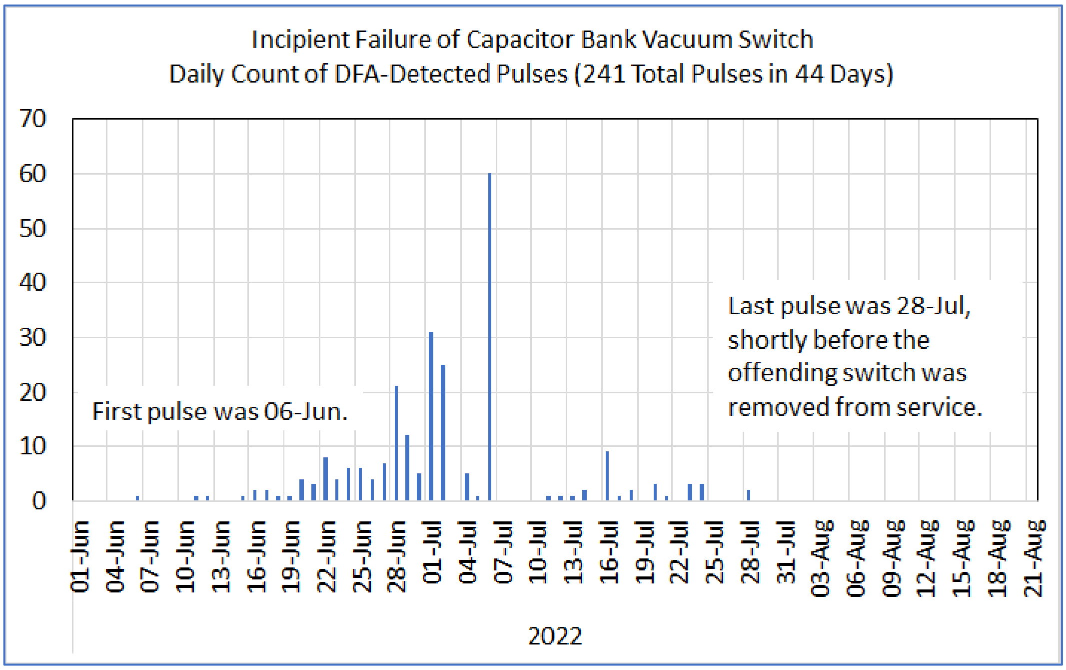

Figure 6 Daily counts of DFA-detected pulses associated with incipient-failure switch

Capacitor restrike (severe)	2022-07-24 21:49:35
Capacitor restrike (severe)	2022-07-23 00:19:27
Capacitor restrike (severe)	2022-07-18 18:49:54
Capacitor restrike (severe)	2022-07-17 00:19:59
Capacitor restrike (severe)	2022-07-14 23:49:30
Capacitor restrike	2022-07-13 07:49:31
Capacitor restrike	2022-07-04 00:49:36
Capacitor restrike (severe)	2022-07-01 19:19:42
Capacitor restrike (severe)	2022-07-01 04:49:37
Capacitor restrike	2022-06-30 13:19:32
Capacitor restrike	2022-06-29 19:49:48
Capacitor restrike	2022-06-29 05:49:43
Capacitor restrike (severe)	2022-06-28 14:49:43

Figure 7. Partial listing of DFA-detected restrike and severe restrike events related to the incipient-failure switch

DFA software classified many of the pulses simply as high-current pulses of very-short duration, and others more precisely as restrike or even severe restrike. Figure 7 provides a partial listing of the pulses that DFA specifically classified in the restrike categories.

As a bit of an aside, analysis of the pulse episodes showed that many occurred coincident with switching of the subject bank, a finding that is not surprising, but that many others occurred coincident with switching of other capacitor banks, including capacitor banks on other circuits served by the same substation bus. Upon reflection, this is not particularly surprising, because energizing a capacitor bank causes a high-frequency transient that can have significant magnitude and that affects bus voltage and therefore everything connected to all circuits served by that bus. If one considers an open vacuum switch, whose compromised vacuum results in its being on the verge of internal, contact-to-contact flashover, even during steady-state operation, then it is reasonable to believe it possible for the added transient voltage from the switching of a distant capacitor to precipitate actual flashover. Indeed, that is what appears to have caused a majority of the 241 pulses associated with this case study #2.

As Figure 5 shows, the current pulses were phase-to-phase. The subject company operates its capacitors ungrounded and uses only two switches, leaving one terminal of the bank permanently connected to a primary phase. The ungrounded nature of the bank means that, under normal conditions, having two switches open and the third phase permanently connected is electrically equivalent to having all three phases open. The phase-to-phase pulses are consistent with one phase permanently connected and two switches open but one switch intermittently "leaking" pulses.

As in case study #1, the DFA system raised the sole independent alarm related to the incipient failure. Data from the DFA system also indicated that the offending bank was a 1200 kvar bank and logged times at which it switched on and off. The company's asset database indicated that the subject circuit had four capacitor banks, one of them an 1800 kvar bank and the other three 1200 kvar banks. The company uses a centralized system to dispatch capacitor switching operations, and that system logs each switching time for each bank. Comparison of the DFA timestamps and the central capacitor control system timestamps definitively identified a specific 1200 kvar bank.

In response, company personnel removed from service the switches of the offending bank. Personnel then used the DFA system to confirm that the removed switch indeed has been the offender, by confirming that no pulses occurred after its removal from service.

At this writing, the company is planning laboratory analysis to confirm the exact failure mode.

Company Response to Case Study #2

The DFA monitoring system provided the sole independent alarm, the without-which-nothing for responding to the condition. Based on that alarm, personnel compared timestamps in the control system log with timestamps reported by the DFA system. This process provided highly specific location, enabling preemptive removal of the offending switch and avoidance of further consequences.

Takeaways from Case Study #2

1. New technologies can detect failures that conventional technologies cannot, in this case the incipient failure of a vacuum switch on a capacitor bank. This represents newfound information.
2. In the subject case, DFA-prompted examination of capacitor switching times pointed to one specific capacitor bank.
3. This newfound information enabled preemptive action and avoidance of further consequences of the compromised vacuum switch.

CONCLUSIONS

Failures of line apparatus may be preceded by periods of incipient failure that manifest detectable electrical activity. Practical use of that fact requires effective detection, location, and response. New, sensitive monitoring, coupled with sophisticated software for recognizing incipient conditions, can detect low- and high-magnitude incipient failure signatures, thus providing newfound information that can enable improved performance and safety of electric circuits. Some detectable incipient failures, particularly those with low-magnitude current, can be challenging to locate, but other information available to circuit operators sometimes can assist with location or at least targeting of patrols. The final requirement is effective, timely response, which may require rethinking of long-established procedures.