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CIGRE US National Committee
2014 Grid of the Future Symposium

Online Assessment of Capacitor Banks Using Circuit Health Monitoring Technology

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SUMMARY
Line capacitors are used ubiquitously for voltage regulation, power factor correction, and reactive power management on distribution circuits. Utility companies spend considerable money installing and maintaining these banks. Capacitor banks are widely known for experiencing internal short circuits, fuse operations, and other failure modes.

As part of ongoing projects at Texas A&M University, researchers have documented multiple, real-world failures and other improper behavior of line capacitors. They also have documented the unique electrical current and voltage waveforms signatures these failures produce, as measurable from conventional, substation-based current and potential transformers. The resulting database contains many examples of failures detectable by conventional utility inspection and testing practices, but also many examples of failures <u>not</u> detectable by those conventional methods. Some failure modes can have consequences more deleterious to system health than simple loss of voltage support, voltage balance, or reactive power support. Based on the field experience and library of electrical signatures, researchers have developed a system known as Distribution Fault Anticipation (DFA) technology, which detects and warns utilities about a variety of line apparatus failures and pre-failures, including those involving capacitors, thereby enabling system condition awareness and condition-based maintenance for circuit apparatus, including capacitor banks.

This paper presents selected case studies from operational circuits, and describes the benefit of using DFA technology to detect capacitor problems in their pre-failure state, enabling timely repair.

KEYWORDS
Power system analytics; wildfire prevention; smart grid; advanced monitoring; vegetation management; fault anticipation; incipient faults

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Introduction

Utilities use line capacitors for voltage support, reactive power management, and power factor correction. [1, 2] Although line capacitors provide substantial benefits, they also experience a significant number of failures. [3, 4] A substantial body of literature explores optimal placement of line capacitors and their use in conservation voltage reduction (CVR), but relatively little is published on capacitor failure modes or what might be done to improve their maintenance and reliability.

Waveform-Based Detection of Failures and Pre-Failures of Line Capacitors

Researchers at Texas A&M University have spent more than a decade investigating line apparatus failures and pre-failures that can be detected by applying sophisticated signal processing and other advanced digital techniques to high-fidelity line current and voltage waveforms. Researchers have collected signatures from failing apparatus, including failing capacitor banks, and created advanced analytics, known as Distribution Fault Anticipation (DFA), to analyze waveforms and detect problems with circuit apparatus. [5] DFA's overarching goal is to provide utilities with real-time awareness of the health of their circuits.

Utility practice for maintaining capacitor banks varies, but a typical program consists of time-based maintenance. In such a program, utility personnel visit each bank on a schedule, say once per year, and perform various inspection activities, such as checking operations counters, resetting the bank's time clock, and operating the bank to make sure all three switches open and close. Some utilities also measure capacitance. Such methods identify gross failures, such as blown fuses and short-circuited capacitors, but they generally fail to identify problems such as switch bounce, switch restrike, and arcing switch contacts. Periodic inspection is inefficient, because most banks visited in any given cycle are healthy. In addition, as noted, periodic inspections cannot identify some failure modes. Finally, with annual inspection cycles, a failed capacitor can remain in service for up to a year before detection. An interesting finding of DFA research has been that repetitive high-frequency transients from certain capacitor failure modes can damage not just the involved bank but also other banks on the same circuit or even on circuits fed by the same substation bus. Periodic maintenance is unlikely to discover such problems before they cause collateral damage.

DFA technology uses automated processes to detect, record, analyze, and report failures and pre-failures of line apparatus. It reports a variety of capacitor problems, with specificity, enabling utility companies to employ condition-based maintenance for their fleet of line capacitors. DFA technology uses as its inputs conventional substation current transformers and potential transformers (CTs and PTs). DFA does not require communications with capacitor banks or other downstream line devices (e.g., hydraulic reclosers).

Case Studies

DFA technology has been developed by Texas A&M, with substantial support from the Electric Power Research Institute (EPRI) and more than a dozen utilities. Researchers worked with utilities to instrument dozens of distribution circuits, for more than a decade, using sensitive, high-fidelity, digital recording devices, and in the process created the largest extant database of electrical signatures related to failures and pre-failures of line components. The following case studies draw from this database and illustrate multiple failure modes of capacitor banks, and the potential for condition-based maintenance to improve performance.

Case Study 1: A Capacitor Controller Goes Haywire

Line capacitors often have controllers that routinely switch the banks ON and OFF. Many banks use a combination of time-of-day, temperature, and voltage as a proxy for determining when they should switch ON. Banks typically cycle ON and OFF one or perhaps two times per day.

This case study involves a capacitor controller that malfunctioned by cycling ON and OFF far too frequently. In less than two months, the capacitor logged more than 3,000 switching operations, the equivalent of many years of cycling once or twice per day. After several weeks of excess switching, presumably in response to stresses created by the frequent switching, one phase of the bank failed in a short circuit, resulting in an overcurrent fault that caused a fuse operation. The excess switching frequency continued, and even accelerated. On the most active day, the capacitor switched 185 times in a single day!

After approximately two months, the problem escalated. By this time, contacts of the capacitor switches had experienced thousands of operations, well in excess of their design. The degraded, internal contacts of one of the two functional phases failed to make a good connection, resulting in inter-contact arcing. Recall that, each time a capacitor switches ON, it creates a significant voltage transient, which in turn creates a significant current transient. Electrically, contact arcing is similar to a switch opening and closing many times per second. When a capacitor's switch contacts arc, therefore, numerous high-frequency transients occur in a short period of time. These transients create substantial high-frequency voltage distortion, directly and immediately affecting customers, particularly those with sensitive loads. The transients also may damage customer- and utility-owned equipment on the circuit.

The inter-contact arcing continued for several days, after which the switch finally failed in an open-circuit condition. The utility company then investigated and documented failures found in the field. The result of the thousands of capacitor operations is surprising. Not only did the capacitor with the faulty controller fail, but the nearly continuous series of voltage transients resulted in the failure of two other capacitor banks, one of which was located on an adjacent circuit. Texas A&M researchers have seen similar sympathetic failure elsewhere, in which arcing in one capacitor causes failure of another capacitor. This occurs because voltage transients couple directly to the circuit and thereby to the bus and other circuits.

In a contrasting event, a few months later, a capacitor controller at another utility company malfunctioned in a similar manner. That utility performed annual capacitor maintenance on its line capacitors, a process that included changing out controllers. After a crew replaced the controller on a particular bank, which previously was functioning normally, the DFA system detected that bank switching 22 times in a single day. The next morning, the utility responded by adjusting controller settings, thereby avoiding the consequences seen at the first utility.

Case Study 2: Failure of Capacitor Switch

The following series of events occurred over a 2 ½ month period in late 2013 on a DFA-monitored circuit. The utility in this example uses a one-way paging system to switch its line capacitors. After each switching operation, that system monitors the VARs at the substation to verify 1) that the switching occurred, 2) that the level of VAR change was as expected, and 3) that all three phases operated (i.e., balanced operation).

In late November, a DFA device began detecting unusual transients, one of which is shown in Figure 1. The utility searched its distribution management system and trouble tickets, but found no notice of anything likely to be related to the transients. The utility and researchers continued to use the DFA to monitor the phenomenon and thus documented more than 500 episodes of the transient over a 2 ½ month period. After 2 ½ months, the frequency of the episodes seemed to increase, suggesting possible acceleration toward a full failure, and the utility took corrective action.

When a capacitor bank switches ON, it causes two distinct electrical phenomena: a high-frequency transient and a sustained step change in voltage. Contrary to a commonly voiced assumption, both phenomena are readily measurable in bus-level voltage. In the subject case, each waveform record had a transient, consistent with a capacitor switching operation, but it did not exhibit the expected step change in voltage. The lack of step change indicates that, if the transient resulted from a capacitor-related event, the capacitor was not switching normally.

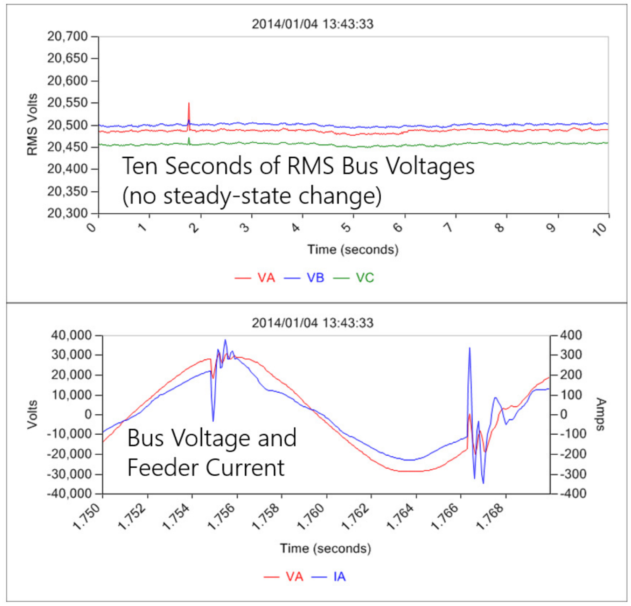

Figure 1 : Voltage transients during switch failure.

The polarity of the current and voltage waveforms indicated that this event was "behind" the DFA device – either on the bus, or on an adjacent circuit. In the subject case, the bus serving the DFA-monitored circuit had no bus capacitors, and only one other circuit. This suggested a likely problem with a capacitor on the non-DFA circuit. To confirm that the problem was indeed capacitor-related, the utility created a plan to pull fuses from all five capacitor banks on the non-DFA circuit. They then would continue monitor the DFA system to make sure the transient episodes had ceased. When they began executing this plan, however, they found an anomaly at the first bank they visited. The bank was in the OFF position, according to the control system, but the crew measured 0.7 amperes of current in one of the bank's phases. Had the bank been ON, the expected current flow would have been approximately 30 amperes. The crew pulled the fuses from this capacitor bank, removing it from service, but based on the 0.7-ampere anomaly, they abandoned the rest of the plan and left the other four banks in service. The transients reported by the DFA system ceased, confirming the suspicion that the capacitor switch was the root cause of the problem.

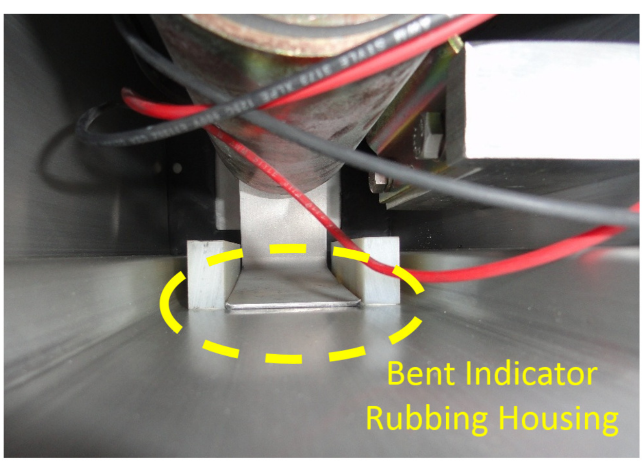

Figure 2 : Inside of switch, showing damaged indicator

The utility subsequently removed the switch from the bank and engaged a vacuum switch expert to perform a post-mortem analysis. The switch has a sight window with a mechanical red/green indicator, which moves with the switch's operating rod, for the purpose of giving visual validation of the switch's open/closed status.

The indicator of the subject switch was bent, causing it to bind on the switch housing. The vacuum expert surmised that the binding indicator caused torsion on the operating rod, which in turn damaged the vacuum switch's bellows, thereby allowing seepage of air into the vacuum chamber. Loss of vacuum is a well-known cause of failure of vacuum switches.

Even though the utility had a fairly sophisticated capacitor switching scheme, and had a state-of-the-art advanced metering infrastructure (AMI) system, their only notice of the capacitor switch's pre-failure condition came from the DFA system. Early detection enabled the utility to make repairs proactively and thereby avoid escalation of the condition into a full failure, with possible consequences of improper capacitor operation and potentially catastrophic failure of the vacuum bottle, with the possibility of explosion and potential fire ignition.

Case Study 3: Failure of Capacitor Switch, Part 2

Another capacitor failure example at the same utility illustrates the variety of ways in which capacitor switches can cause bank failures. As in the previous example, the subject bank is controlled by a one-way paging and VAR-change validation system. On 11 May, the DFA system detected the bank switching OFF and reported severe restrike during the operation. Capacitor restrike is a condition that occurs as a bank switches OFF. The switch's dielectric integrity breaks down, enabling current flow to resume, typically just momentarily, through the gap between the switch's just-opened contacts.

The next day, the DFA recorded the capacitor switching OFF again, but with no indication of restrike. The day after that, the DFA detected the bank switching OFF again. This time it exhibited severe restrike, and the restrike escalated into an overcurrent event, as illustrated electrically by Figure 3. After being informed of the problem, the utility performed a root cause analysis on the affected bank. The utility crew found that the affected phase had a blown fuse and a blown lightning arrestor. Surprisingly, however, when the utility performed conventional high-potential testing of the switch, the switch passed that test.

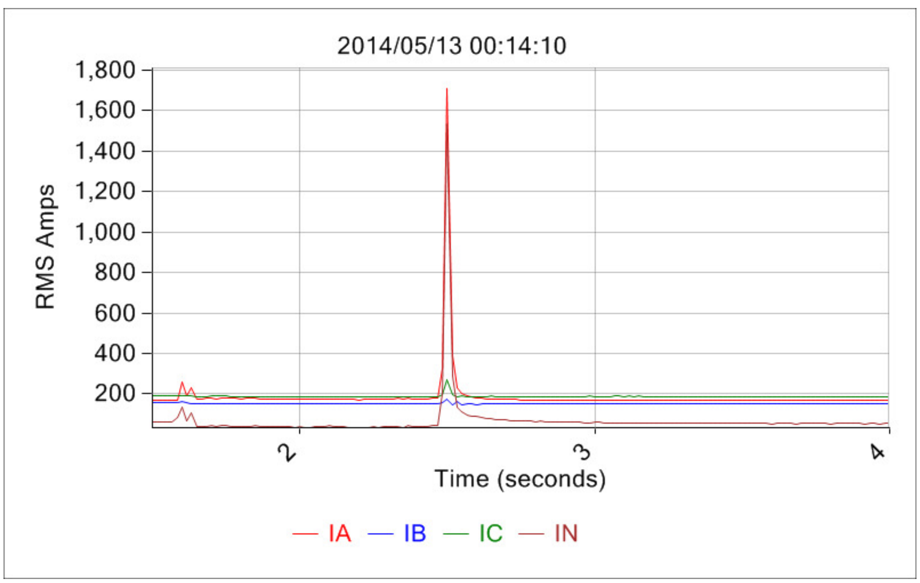

Figure 3 : Waveform showing restrike and overcurrent caused by switch failure

In this particular case, the failure began with the vacuum switch, which failed to open cleanly and resulted in a significant restrike event. The restrike caused repetitive, high-voltage transients, which apparently caused the lightning arrestor to go into conduction, resulting in the overcurrent fault, which in turn blew the fuse. The utility inspected the three switches on the capacitor, which all passed a high-pot test. Further analysis from an outside expert is scheduled to determine the cause of the restrike.

In this example, the utility's paging system would have, and did detect the first unbalanced switching operation, which occurred later that afternoon. Absent information provided by the DFA system, however, the utility likely would not have correctly diagnosed the condition. Indeed, even with DFA-provided information, the utility initially believed that the damage was caused by lightning, given the failed arrestor, even though the last indication of lightning in the area was several months before. In such a case, where the switch passes standard testing, the utility company may return it to service, only to have additional problems in the future. Proper diagnosis was provided by the DFA system. In addition, if DFA were used in a fully operational mode, a utility company could act upon the first notice of restrike and thereby avoid the blown fuse and arrester.

Conclusion

Many utilities use line capacitors to improve voltage regulation and power factor. Capacitors experience significant failure rates, but there is little industry understanding of the root causes and progressive nature of some failure modes.

A decade of sensitive monitoring of dozens of distribution circuits has produced new insight into a wide variety of failure and pre-failure modes of line apparatus, including capacitor banks. This paper has presented three capacitor-specific case studies, involving failing capacitor controllers and switches. Capacitor problems, if not repaired, can create abnormal voltage transients, affecting sensitive customers and potentially damaging other line apparatus.

Prompt detection and diagnosis of line apparatus failures and pre-failures creates the potential for condition-based maintenance and can increase reliability, operational efficiency, and safety.

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