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CIGRE US National Committee
2012 Grid of the Future Symposium

Advanced Monitoring of Low-voltage Secondary Networks for the Detection and Mitigation of Arcing Faults

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SUMMARY

Low-voltage secondary networks represent a particular power-system topology deployed in load-dense urban environments requiring ultra-high reliability. These grid networks have a high degree of interconnectivity that provides multiple, redundant paths to loads and, consequently, also to faults. For nearly a century, arcing faults on grid networks have been a well-known problem, creating smoke, fires, and explosions, collectively known as manhole events, as well as disrupting normal service. Network arcing faults draw intermittent current of relatively low magnitude that seldom operates conventional protection devices. They generally remain undetected until manhole events or other operational problems cause their discovery. Discussion of arcing faults appears in secondary network literature as early as the 1920's but, as late as the early 2000's, most experts have considered them "an industry problem that presently has no available solution."

Texas A&M University has partnered with the Consolidated Edison Company of New York (Con Edison) on a project to detect, locate, and ultimately mitigate arcing faults on secondary networks. Researchers instrumented a single secondary network with thirty high-speed, high-fidelity data collection devices, as well as one functionally identical device on a primary feeder serving that secondary network. Project results show that arcing faults 1) occur more frequently than previously understood, 2) can persist for long periods, 3) can recur multiple times over a period of days or weeks, interspersed with quiescent periods of hours, days, or longer, and 4) can be detected by direct network monitoring and also by monitoring medium-voltage primary feeders serving the secondary network.

This paper presents electrical waveforms recorded during selected faults that occurred on an operational secondary network during a nominal two-year period. During this time, waveforms from thousands of distinct arcing events were recorded and analyzed, with some events having waveforms recorded simultaneously at multiple network points and at the primary-feeder point. Preliminary results suggest multi-point monitoring of secondary networks may enable identification of incipient arcing conditions before they rise to the level of a public safety hazard.

KEYWORDS

Arcing faults, low-voltage arcing, secondary networks, high-impedance faults, incipient fault detection, condition-based maintenance

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Introduction

Arcing faults have been a persistent problem on low-voltage secondary network systems for almost a century, appearing in literature dating back to the 1920's. [1] Damaged or aging cables may arc when moisture and/or other foreign matter creates a conductive path from an energized conductor to a grounded object or another conductor. An arc's intense localized heat can further degrade cable insulation, producing a variety of explosive gasses in the process. [2] These gasses propagate down conduits and accumulate in underground structures, where they mix with oxygen and can produce smoke, fires, and occasionally explosions.

Low-voltage Secondary Networks

Low-voltage secondary grid networks represent a power-system topology used primarily in load-dense urban environments having the highest reliability as a critical design requirement. These networks serve loads directly at low voltage (e.g. 120/208V) from a mesh of interconnected secondary cables, often with multiple large diameter cables (e.g. 500MCM) per phase, per line segment. Multiple medium-voltage primary feeders inject current into the secondary network via geographically dispersed network transformers, often sized at 500 or 1 000 kVA per transformer. The low impedances of the system result in high available bolted fault current levels, often quoted on the order of 30 000-50 000 amperes. [3] Also, because the system serves loads directly at 120/208V, load currents tend to be high, with a single 1 000kVA transformer serving maximum nominal load of 2 700 amperes.

Arcing faults

Although low-voltage arcing faults can produce substantial current, the intermittent nature of these faults, combined with high load currents, can render conventional overcurrent protection ineffective against arcing. Decades of field observations have noted substantial damage from network arcing faults, but the phenomenon remained poorly understood. Foundational texts expressed the conventional wisdom for 120/208V systems: "arcs are not sustained at that voltage" [4] and such faults typically clear themselves "with relatively low current," "without damage to the cable except at the fault," "in less than a tenth of a second." [5]

Although field reports consistently documented substantial damage from low-voltage network arcing, researchers had great difficulty replicating the phenomenon in the laboratory as recently as the 1990's. [6] The general lack of understanding and difficulty of detecting arcing faults led a 2001 report to conclude that the clearing of arcing faults "is an industry problem that presently has no available solution." [7]

Experimental Setup

Texas A&M University and the Consolidated Edison Company of New York (Con Edison) have been collaborating on a project for the fundamental study of arc-fault behavior on an in-service, low-voltage network. Con Edison is the largest operator of low-voltage secondary networks in the United States, operating 57 networks in New York City. Con Edison's low-voltage networks are among the most reliable power systems in the world, with a 2010 reported SAIFI of 0.023 annual interruptions per customer and SAIDI of 0.15 annual minutes per customer. For this project, researchers have monitored, for a nominal period of two years, a single secondary network serving approximately six square kilometers in Manhattan. The selected network has 26 primary feeders connected to 428 network transformers, for a total installed capacity of 373MVA.

Researchers instrumented 30 points on the low-voltage network itself with high-speed, high-fidelity data collection devices (DCDs). The selected waveform recorders were based on equipment developed for the Distribution Fault Anticipation (DFA) project at Texas A&M University. [8] These devices record current and voltage waveforms at a rate of 256 samples per cycle on each channel, and have several gigabytes of storage available, enabling the recording of more than one hour of continuous, gap-free waveforms or numerous waveforms of shorter duration. Each device was connected to a cellular modem, which allowed data to be automatically retrieved and analyzed.

In two years of monitoring, the DCDs have recorded more than 145 000 waveform transients, representing more than 205 total hours of recorded data. Approximately 43 000 of the recorded waveform transients contained arcing signatures, some of them very brief and others sustained for longer periods. Study of these waveforms significantly advances the understanding of arcing-fault phenomena on low-voltage secondary networks. The following section presents selected illustrative case studies.

Case Studies

Arcing bursts observed over 26 hours lead to manhole fire

DCDs at two network points recorded numerous bursts of arcing on the evening of November 30, 2009. Figure 1 shows twelve seconds of RMS current from one DCD. All waveform files contain high-speed waveforms and also their RMS equivalents. Most figures presented herein illustrate RMS currents, because RMS gives a good "big picture" view.

Recorded currents contain both load current and arcing current. In Figure 1, for example, each phase has between 420 and 500 amps of load current, plus intermittent bursts of arc current of up to 300 amps. Load current can tend to mask arc current, complicating analysis. Texas A&M therefore uses algorithms to estimate pre-event steady-state current (e.g load current), including harmonics, and then digitally remove that current, leaving the current of interest for analysis. Figure 2 shows high-speed current waveforms from a short period of Figure 1, after algorithmic processing. The resultant waveforms effectively represent the arcing-fault current.

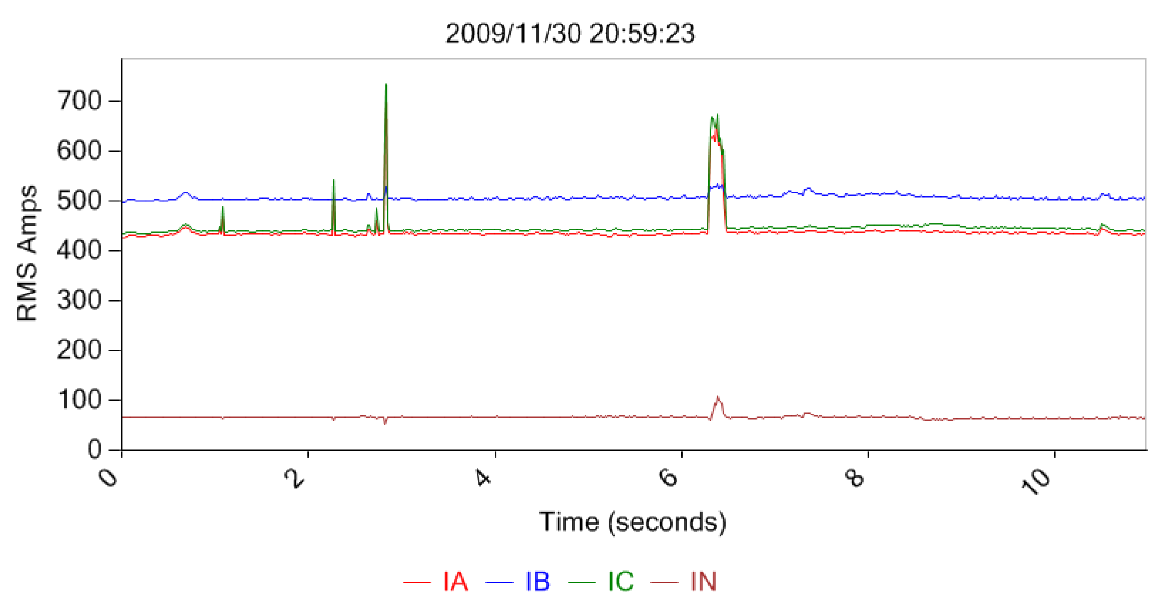

Figure 1: 12-second RMS current recording during intermittent multi-phase arcing on November 30, 2009

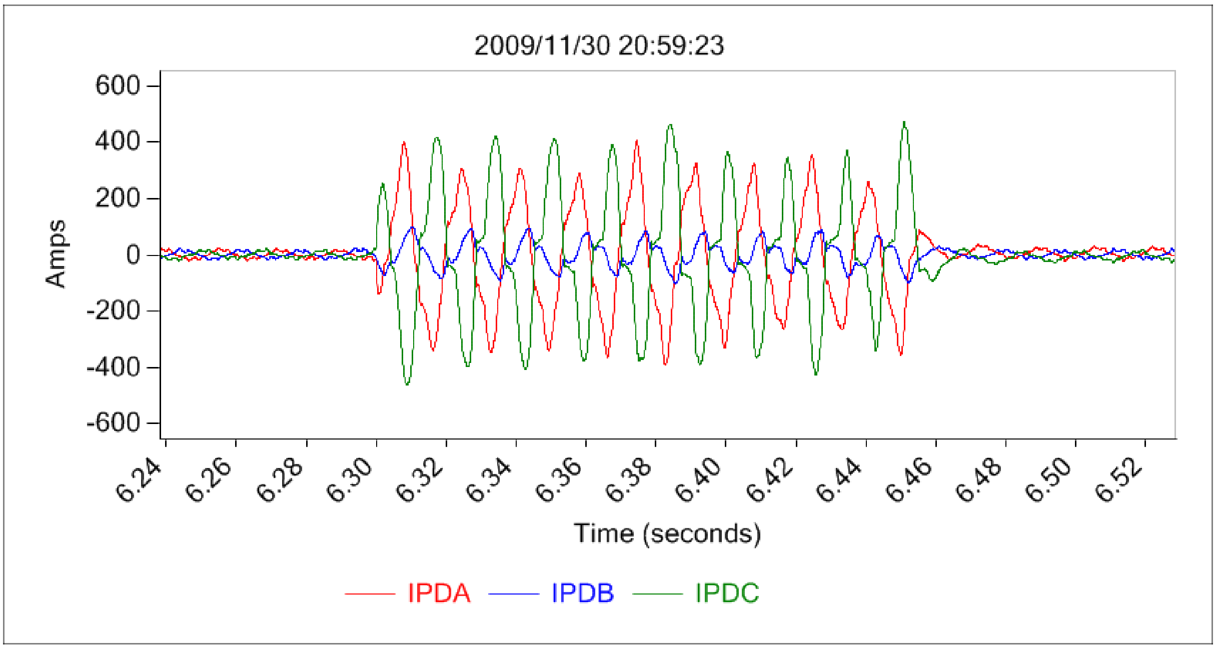

Figure 2: High-speed waveforms from a segment of Figure 1, processed to eliminate load-current effects

After the initial incident of Figures 1 and 2, both DCDs continued recording arc bursts intermittently for seven hours, and then arcing activity abruptly ceased. The next morning (December 1), researchers informed Con Edison of the previous night's activity, with the expectation that, given the severity and extended nature of the previous night's arcing, a manhole event would have been reported by conventional means. All parties were surprised to find that no such report existed. That evening, some 22 hours after the initial arcing, both DCDs recorded renewed arcing similar to the previous evening's activity. In addition, a third nearby DCD also began recording the arcing.

Whereas arcing had been intermittent for seven hours the first evening, the second evening showed semi-continuous arcing for four hours. Approximately thirty minutes into this four-hour period, Con Edison received notification of fires in two adjacent underground structures near the DCDs recording arcing. It then took crews three-and-one-half hours to extinguish the fires and isolate the fault.

Figure 3 illustrates 60 seconds of RMS current on the second evening. Characteristics shown are generally representative of those of other recordings that evening and of other arcing faults recorded during the project. This behavior illustrates that, contrary to the industry's conventional wisdom, arcing at 120/208V can persist for extended periods of time without operating conventional protection or self-clearing. Whereas this arcing fault ultimately resulted in the conventional report of a manhole event, the project also has documented similar arcing faults that have persisted for hours, become dormant for hours, days, or longer, and then resumed at a later time. This implies that arcing may persist on a low-voltage network, for an arbitrarily long period of time, without the utility knowing of it. Furthermore, the cessation of arcing does not necessarily indicate that a fault has permanently self-cleared.

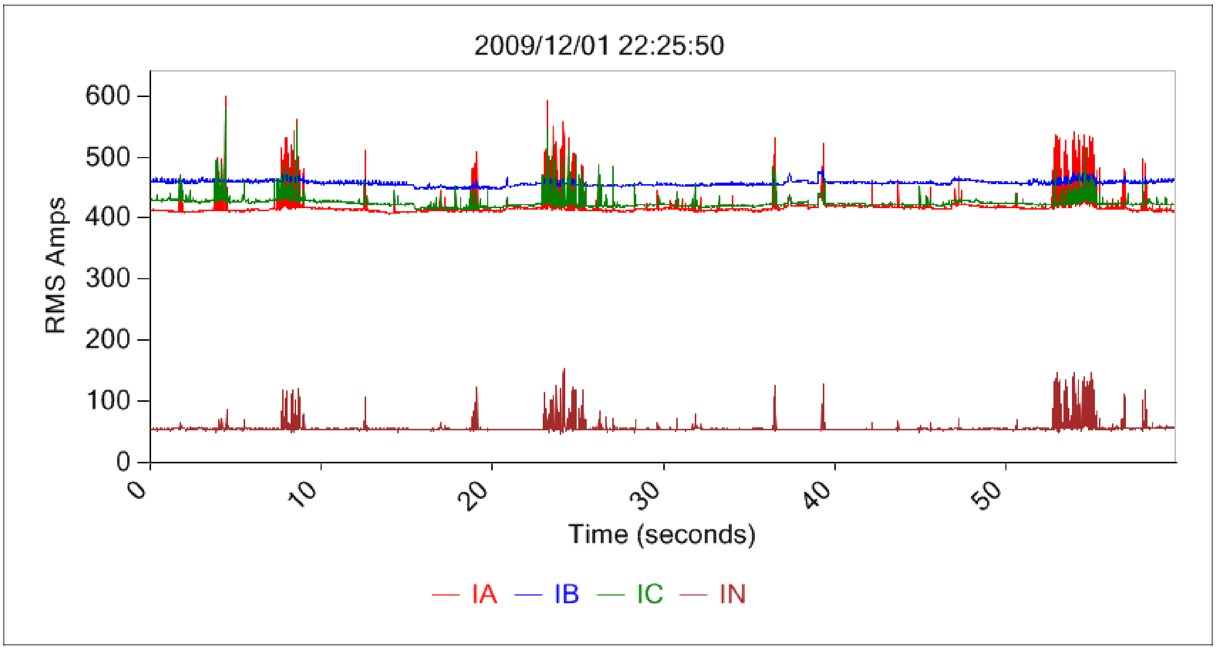

Figure 3: 60-second RMS current recorded at one network point arcing fault on December 1, 2009

Multi-point monitoring detects simultaneous arcing enabling fault location

To be of most value, arc-detection needs to be combined with means to estimate the physical location of the arcing fault. The process of fault location is complicated by multiple redundant paths from every network transformer to every potential fault point.

On January 12, 2011, five DCDs simultaneously recorded an arcing fault. Figure 4 shows RMS currents from four of the DCDs. These RMS currents represent values that have been processed with the aforementioned algorithms to remove the steady-state load current, leaving only the arc-fault current. The significant number of simultaneous measurement points for this fault offered an excellent test case for experimenting with fault-location methods.

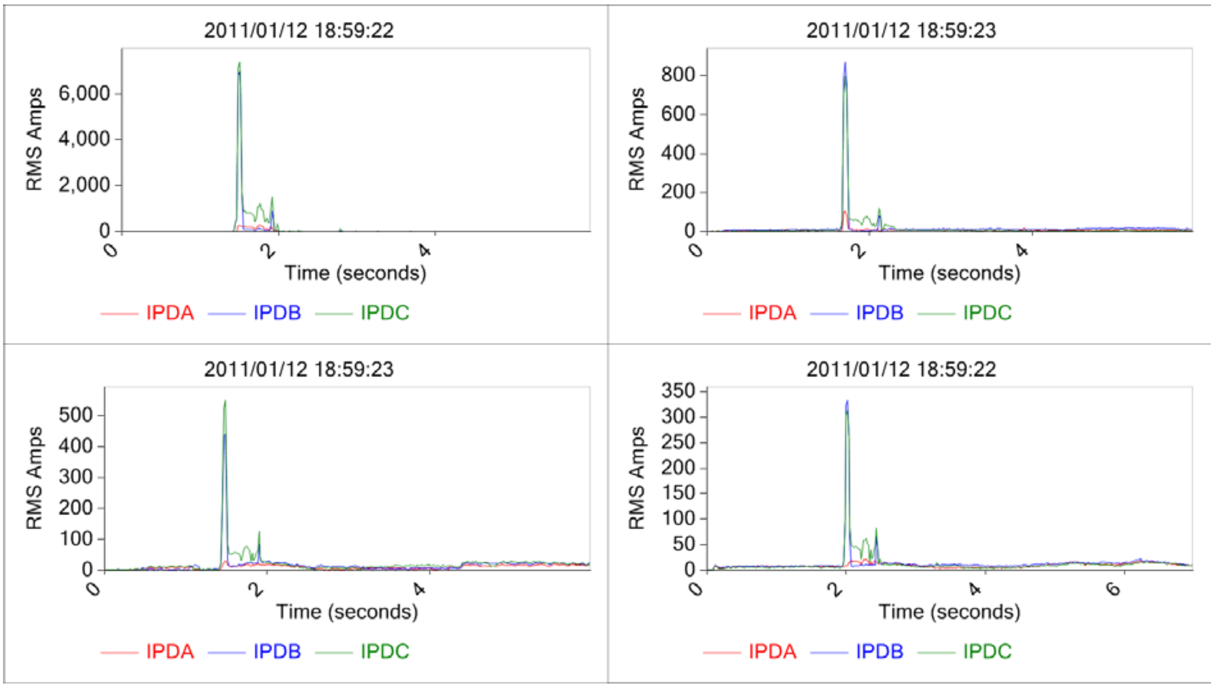

Figure 4: Simultaneous observations of an arcing fault at four locations (note different Y-axis scales)

This incident occurred before fault-location estimation techniques had been developed. Later, using simultaneous DCD measurements from the five network points, in concert with utility models, researchers were able to estimate the likelihood of the arcing being from any arbitrary structure on the network. Once the fault-location routine identified a likely structure, Con Edison sent a crew to investigate. In the identified structure, the crew found significant damage to cables, almost certainly caused by the recorded fault. Repairs were made and no further arcing has occurred. Of note, because of the status of development of the location technique, the investigation did not occur until four months after the fault. This implies that the identified cables had existed, in their severely compromised condition, for four months without notice.

Since that time, DCD recordings of multiple other arcing faults have been used to detect incipient arcing and then to locate damaged cables. Although it cannot be proven that all conditions so identified eventually would have caused manhole events, it is probable that at least some would have done so.

Conclusion

Low-voltage grid networks provide high reliability, but they also create certain challenges, including persistent arcing. Research findings suggest that arcing faults can persist on these networks for extended periods of time (e.g. hours), and can recur over extended periods of time (e.g. weeks) without notice by the utility or by the public. Even on the most advanced operational networks, utilities seldom become aware of arcing cables until they receive from the public a report of smoke, fire, or explosion.

Results presented in this paper suggest that in the future, advanced monitoring devices on secondary networks could be used to detect, locate, and mitigate arcing faults, resulting in the prevention of some manhole events.

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