Arcing Fault Detection for Distribution Feeders: Security Assessment in Long Term Field Trials

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***Abstract*–A downed conductor, arcing fault detection system has been designed using multiple protection algorithms. An intelligent analysis system processes the outputs from several algorithms to determine the "confidence" that a fault exists. The design includes careful attention to discriminating arcing faults from normal system activity to ensure system security.**

Key to the acceptance of this system is testing under actual field conditions. The results of long term tests on five utilities are presented. The behavior of the prototype systems to staged faults, naturally occurring faults, and normal system disturbances is described. Conclusions are drawn concerning the practical viability of this system.

I. INTRODUCTION

The detection of downed distribution conductors remains a significant problem for the electric utility industry. Public safety concerns have caused the electric utility industry to concentrate significant resources toward finding new detection methods to de-energize downed conductors. Significant sponsorship by the Electric Power Research Institute and many utilities has allowed researchers to carefully investigate the problem with specific interest during the last twenty years [1-4].

Researchers at Texas A&M demonstrated the first successful high impedance fault detection algorithm, but realized early in their investigations that no single detection mechanism could reliably identifying a majority of downed conductor faults [4]. Further research identified several detection mechanisms which could reliably detect certain classes of faults under various conditions [5-9]. Research has shown that distribution protection can be significantly improved using these fault detection algorithms in concert with classical overcurrent protection methodology.

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Investigations during the 1980s identified another significant problem. While it is relatively easy to detect an arcing fault, it can be most difficult to discriminate this situation from "normal" electrical events on the distribution feeder. This presents a specific operational problem. The dilemma – to trip or not to trip a feeder – can be resolved only if a secure decision can be made concerning the presence of a downed conductor. If an algorithm regularly identifies normal system activity as a "fault," it is virtually useless in practical relay applications. System security and service continuity are far too important to be sacrificed at the feet of a "trigger happy" algorithm. The issue of detection sensitivity versus system security has been at the heart of research investigations for the last ten years.

This paper describes a fault detection system for high impedance faults with specific descriptions of the detection algorithms and the "intelligent" fault decision element. Five prototype test installations are described along with long term field test results. Conclusions are drawn concerning the potential of this system for secure arcing fault detection when properly coordinated with existing overcurrent relays.

II. DETECTION SYSTEM DESCRIPTION

Fig. 1 illustrates the functionality of the detection system. The system's front end samples and processes the four feeder currents to determine their spectral contents. It uses two cycles of the power system fundamental frequency as its basic processing interval (i.e., 1/30th of a second on a 60 Hz system). This processing results in three quantities per interval: composite odd harmonics (180, 300, ..., 900 Hz), even harmonics (120, 240, ..., 840 Hz), and non harmonics (30, 90, ..., 930 Hz), as shown on the left of Fig. 1.

Two basic arc detection algorithms process each of these quanties: the Randomness algorithm and the Energy algorithm [4, 6]. The Randomness algorithm processes each harmonic input quantity separately. It determines its belief in the presence of arcing on the system by monitoring the input parameter, keeping an average over the last few seconds, looking for a sudden increase, and then looking for highly random behavior in the signal following this increase. The Energy algorithm monitors the same quantities and keeps an average over the most recent few seconds. It

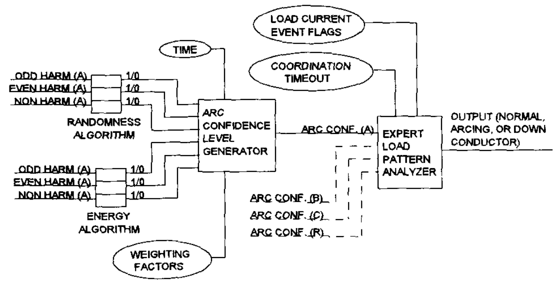

Fig. 1. The high impedance fault monitoring system applies multiple algorithms to multiple parameters in order to make a sensitive, secure decision as to the presence of an arcing fault.

determines its belief in arcing, however, based on the *persistence* of a sudden increase in the monitored parameter.

Referring again to Fig. 1, the system processes a total of 24 separate algorithm/parameter/phase sets (i.e., four currents times three parameters times two basic algorithms). It is conceivable, in fact likely, that all these algorithms will not always agree with one another. Therefore, the system uses the Arc Confidence Level Generator to generate an arc confidence level (on a per-phase basis). It examines the outputs of all the algorithms, and accounts for the effects of multiple indications from individual algorithms over time. It also uses a weighting factor for each algorithm/parameter set. These factors were determined by researchers' prior experience with the algorithms in hundreds of fault cases.

After the detection system determines its belief in arcing on each phase of the power system, it uses the persistence of arcing along with patterns in the 60 Hz load current to determine the status of the power system. This is the function of the Expert Load Pattern Analyzer shown in Fig. 1. It also includes a coordination timeout so that a fault which lasts only a few cycles or a few seconds can be cleared locally by a fuse or recloser. If arcing persists, however, the system signals this fact. It also determines whether it believes that the arcing is occurring while the line is still on top of a pole or that the arcing is occurring because of a down line. For example, if the arcing is preceded by a sudden, significant, single phase loss of load, this indicates that a line has indeed broken and fallen.

III. Field Test Objectives

Over the years, several utility forums have been held to identify operational problems and prioritize the needs of distribution protection engineers with respect to the practical use of a downed conductor protective relay. One fact has consistently been made very clear: An electric utility cannot regularly de-energize an entire feeder on the mere suspicion that there might be a downed conductor. The relatively low frequency of downed conductor events, coupled with the significant safety hazards associated with public power loss, makes frequent false tripping of a feeder unacceptable. In the above mentioned forums, utility engineers have made it clear that significant field testing is absolutely necessary to ensure that any proposed system will meet two objectives:

1) Offer a significant performance improvement (i.e., detection of previously undetectable faults) in an economic package.
2) Exhibit satisfactory system security (i.e., not prone to false tripping).

The following sections describe tests which are being run to validate the Texas A&M algorithms in light of the above objectives in actual field conditions.

IV. Test Methodology

In order to expose the detection algorithms to a wide range of field conditions, it was decided that long term field tests would be run on a diverse set of feeders at five different utilities. Feeders were selected on the systems of Rochester Gas and Electric, Florida Power and Light, Pacific Gas and Electric, TU Electric, and Bryan Utilities, the latter on a feeder serving the Downed Conductor Test Facility at Texas A&M University. The characteristics of the selected feeders are described in Table I.

In order to test the algorithms, a hardware platform (referred to as a high impedance fault monitor, or HIFM) was designed and implemented. The system consists of a custom analog–to–digital board for acquisition and pre-processing of feeder currents, and a commercial PC-AT motherboard for running the high impedance fault detection algorithms. The system also includes a modem port for remote polling and a front panel for displaying present system values.

TABLE I. Selected HIFM Installation Feeders

Feeder	Voltage (kV)	System, Load, and Environmental Description
A	12.5	Multi–grounded wye; 80% residential; 20% light commercial and industrial; sandy loam soil; light tree contact
B	13.2	Multi–grounded wye; 50% oil production load (large pumps, large motors, etc.), delivered via three metered points of delivery; 5% commercial; 45% rural residential, including agricultural; sandy soil; heavy tree contact
C	23	Multi–grounded wye; 95% residential; 5% commercial; light to medium tree contact
D	12.5	Multi–grounded wye; 70% residential; 20% commercial; 10% industrial; gravelly loam; heavy tree cover, but well trimmed
E	12.5	Single–grounded wye; 56% residential; 12% commercial; 15% industrial; 17% agricultural; sandy soil; irrigated desert, under development; light tree contact

One HIFM unit was installed on each feeder. The use of a modem allowed data from each unit to be retrieved for further analysis with laboratory computers. The data to be shown was collected in this way.

The philosophy of field testing consisted of long term exposure to a combination of naturally occurring faults, normal system activity, and staged faults. While it was not possible to stage faults on each feeder, most of the feeders saw naturally occurring overcurrent faults which exercised the equipment. Descriptions of selected events seen, and performance of the units are described in later sections.

V. Evaluation of Field Performance

Recall, the objectives of the field evaluation fall into two major areas. First, algorithm security is to be assessed through long term exposure to normal system activity. Second, algorithm performance in the detection of naturally occurring and/or staged faults is to be evaluated.

Each HIFM has seen a wide range of normal system activity since installation. Collectively, the five units have experienced forty–seven unit·months of operation as of June 1993. During this time the HIFMs have been exposed to an extensive number of switching events and capacitor bank operations, under a wide range of loading conditions and variations in load levels. During this extensive test period, none of the units misoperated.

The HIFM unit on Feeder A has seen considerable staged fault activity. Tests were done to accelerate exposure of the algorithms to numerous faults in order to quantify detection performance. Even though each algorithm had been tested individually under a significant number of staged faults during previous research investigations, it was thought appropriate to test this specific HIFM equipment implementation with additional staged faults.

On seven test dates, a total of 62 downed conductor tests were staged on Feeder A. Based on prior experience, it was expected that tests on asphalt probably would result in no electrical activity and therefore could not be detected by the HIFM. However, for completeness, the faults were staged and the results noted. As expected, the fault current was too low to be measured even when the asphalt was wetted prior to the tests. These results were consistent with the general results found in the past for conductors dropped on asphalt.

The balance of the tests were run on concrete and ground/grass. To coordinate with existing utility overcurrent protection, the downed line was protected by a 30T fuse. Table II gives the results of these tests.

The HIFM is programmed to coordinate with existing overcurrent protection. In short, a coordination period is allowed in order to determine whether sectionalizing devices, fuses, or reclosing will properly clear or isolate a fault. Hence, the HIFM does not issue a "trip" command if, by coordination, the fault is otherwise eliminated.

TABLE II. Summary of Staged Fault Tests

Surface	Tests[a]	Fuse[b]	HIFM[c]
Concrete	13	6 (46%)	10 (77%)
Ground	39	33 (85%)	36 (92%)
Total	**52**	**39 (75%)**	**46 (88%)**

[a] **Tests** denotes the total number of tests for a particular surface type.
[b] **Fuse** denotes the number of tests for which a 30T fuse blew.
[c] **HIFM** denotes the number of tests which were picked up by the HIFM.

It can be seen from Table II that 75% of the faults staged on concrete and ground were cleared by a 30T fuse at the fault point. While this number is somewhat higher than previous experience, it is consistent with the percentage reported by a number of utilities. It is also higher than would be expected on a feeder using larger fuses.

A word of explanation is appropriate concerning the percentage figure listed for the HIFM. As noted above, the HIFM allows a coordination period before it identifies any event as a fault. The HIFM picked up on 46 of the 52 tests conducted on surfaces other than asphalt. However, in many of these cases, the 30T fuse blew before the end of the coordination period; in these cases, the HIFM properly aborted a pending "trip" command, since coordination with other feeder protection dictates that such a signal not be issued if a fuse clears the fault.

There was a great deal of other naturally occurring activity on the five feeders. A summary of this activity, broken down by feeder, is as follows:

Feeder A – In addition to the staged tests described in Table II, Feeder A has experienced several overcurrent faults. Finally, it has experienced one non–staged high impedance fault, which is described in the next section.

Feeder B – This installation has registered several overcurrent faults, each cleared by conventional overcurrent protection. Two are described in the next section.

Feeder C – This installation has registered over 100 overcurrent faults, each cleared by conventional overcurrent protection. One is described in the next section.

Feeder D – This installation has registered no overcurrent faults. The only activity seen was minor phase–to–phase arcing, which is described in the next section.

Feeder E – This feeder has experienced no faults or any other noteworthy activity since its installation.

VI. Performance Evaluation – Case Studies

In order to document and familiarize the reader with the activity seen by the HIFM equipment and algorithms during the forty–seven unit·months of exposure, the following cases were selected. The HIFM equipment is located at the substation level, and it collected the data from which the following figures were derived. The fault current is shown superimposed on load current. The basic unit of measurement for these figures is a two–cycle RMS value

(30 values per second). The HIFM calculates an RMS current value for each period of two fundamental frequency cycles; then, when it is triggered, it logs these readings to permanent storage for later retrieval and analysis.

Some of the figures show all three phase currents plus the residual current. For simplicity, others show only one phase current and the residual current; all four currents are shown only when they materially add to understanding the event.

Case 1 – Fig. 2, parts a – d, represents a sequence of events which occurred on Feeder A on Sunday, October 4, 1992. As shown in Fig. 2a, at 16:14, a 1.1 kA overcurrent fault occurred on ϕB. An 80 A fuse cleared this fault in 22 cycles. However, concurrent with the clearing of the ϕB fault, a 1.1 kA fault initiated on ϕC. Apparently, the original ϕB fault flashed over to ϕC. Then, after 19 cycles, the ϕC fault cleared itself.

Later, at 22:24, a ϕC arcing fault occurred on this feeder (Fig. 2, parts b – d). The substation breaker operated once, staying open for 30 seconds before reclosing. After this, the breaker did not operate again. The fault persisted for approximately 5–1/2 minutes before an 80 A fuse cleared it.

Post–mortem analysis of the fault site revealed that approximately 50 feet of #4 Cu conductor was on the ground. Also, at the point where the conductor broke, the repair crew found the remains of a small bird. It seems likely that the fault at 16:14 may have damaged the ϕC conductor sufficiently to weaken it, leading to its breakage later at 22:24.

During the event, the HIFM recognized the presence of arcing on the system, and "alarmed" the presence of the arcing fault.

Case 2 – Fig. 3 illustrates the RMS current measured during a staged high impedance fault on Feeder A, in which approximately six feet of 1/0 ACSR was in contact with undisturbed grassy ground. As shown, the fault blew a 30T fuse in approximately 2–1/2 seconds. The HIFM recognized the event, but did not issue an alarm because of the brevity of the fault.

Case 3 – Fig. 4, parts a and b, illustrate the RMS current measured during another test staged under the same conditions as those for Fig. 3. Again, six feet of 1/0 ACSR were in contact with undisturbed grassy ground at the same physical location. Also, the tests occurred within minutes of one another, and no conditions of the test setup changed. However, as often happens, the results were dramatically different. This test continued for over ten minutes. At the beginning of the test, the arcing was very active. After 1 – 2 minutes, the level of arcing decreased greatly. Also, the arcing became much more sporadic. Toward the end of the test, the conductor would arc fairly heavily for a few seconds, and then not arc visibly at all for several seconds to several tens of seconds, at which time another burst started. Finally, the fault quit arcing at all, and the test ended. The HIFM detected this fault and alarmed it as an arcing fault.

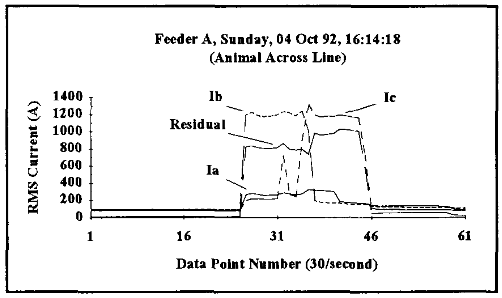

Fig. 2a. ϕB fault caused by animal on line; flashed over to ϕC fault as ϕB faul cleared (fuse); ϕC fault was self–clearing.

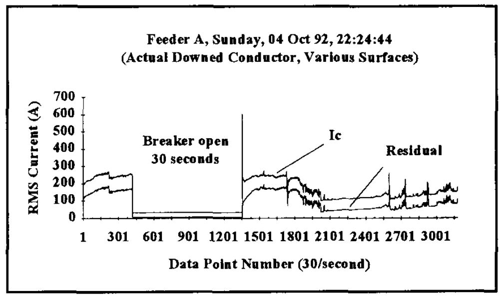

Fig. 2b. ϕC down conductor fault.

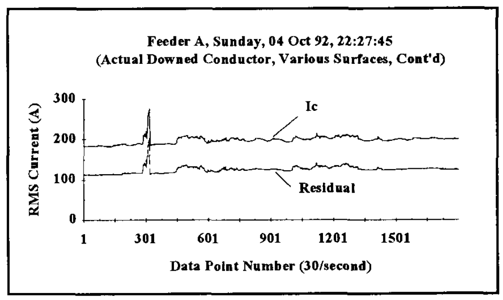

Fig. 2c. ϕC down conductor fault, continued.

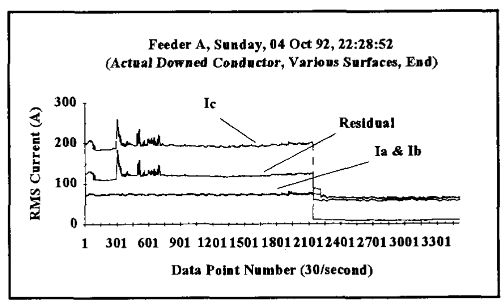

Fig. 2d. ϕC down conductor fault, continued.

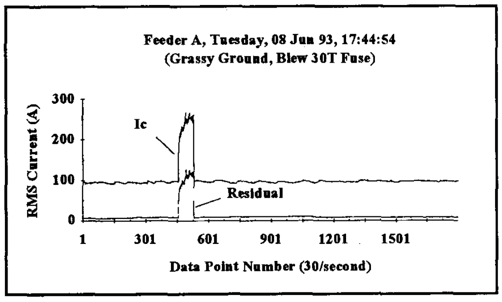

Fig. 3. Staged high impedance fault on grass, which blew 30T fuse.

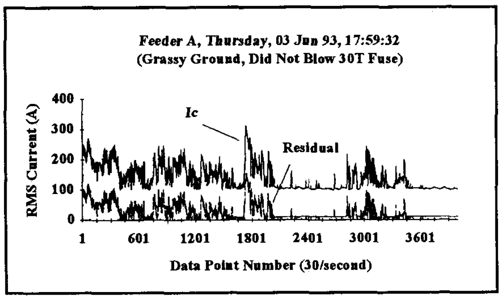

Fig 4a. Staged high impedance fault on grassy ground which did not blo 30T fuse.

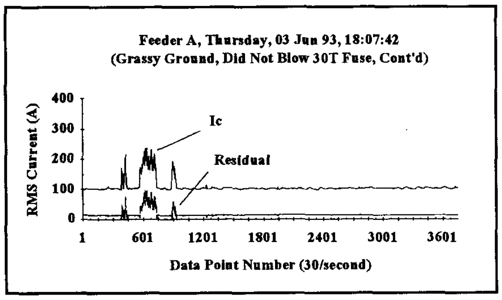

Fig. 4b. Staged high impedance fault on grassy ground which did not blo 30T fuse, continued.

Case 4 – Figs. 5 and 6 illustrate the RMS current during two high impedance faults staged on concrete. Test conditions for the two tests were very similar (e.g., conductor type and length of conductor in contact with surface were the same), although they were staged on different days. However, the one shown in Fig. 5 blew a 30T fuse in approximately ten seconds, while the one shown in Fig. 6 persisted for several minutes without blowing a 30T fuse. The latter finally stopped arcing of its own accord after approximately five minutes. The HIFM picked up on each of these events, but did not alarm the one in Fig. 5 because of its brevity.

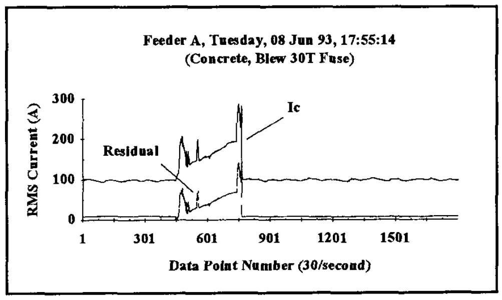

Fig. 5. Staged high impedance fault on concrete which did blow 30T fuse.

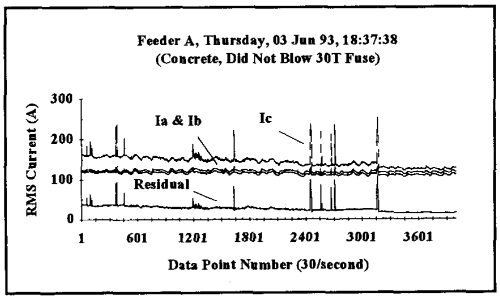

Fig. 6. Staged fault on concrete which did not blow 30T fuse.

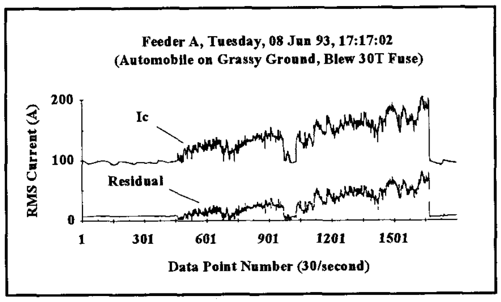

Fig. 7. Staged high impedance fault on car parked on grass.

Case 5 – Fig. 7 illustrates a high impedance fault in which a coil of 1/0 ACSR was in contact with the roof of a sub–compact automobile which had intact steel belted radial tires. For this test, the car was on grassy ground, and some of the grass was tall enough to contact the wheel rims and parts of the metal underbody of the car. During this test, and during several other tests under identical conditions, the fault current began at very low levels, as shown. Then, the fault current built slowly, finally blowing the 30T fuse.

Similar tests (not shown) were conducted only several feet from the place in which the first test was conducted, but on vegetation that was not tall enough to contact any metal parts of the car. In these cases, no measurable fault current flowed. Each of these tests was allowed to persist for several minutes before it was deenergized. Apparently, in the former cases, even the small conduction allowed through the vegetation was enough to initiate arcing, and once initiated, the smoke–filled air was able to sustain arcing.

Case 6 – Fig. 8 illustrates a capacitor bank closing event on Feeder A. To capture this, the HIFM sensitivity setting was very high. Due to the transient nature of this event, the HIFM issued no alarms even though it retained the data. This figure is interesting because it illustrates the non–synchronous closing of the three phases of the capacitor bank, causing a brief increase in the level of the residual current; further it demonstrates the HIFM algorithms' security against such events.

Case 7 – Figs. 9 and 10 illustrate two overcurrent faults on Feeder B. The fault in Fig. 9 was caused when a car hit a pole, causing the phase conductors to fall. As shown, a downstream recloser operated four times and locked out.

The cause of the fault in Fig. 10 is unknown. However, the figure shows that downstream protection tripped and reclosed twice, successfully clearing the fault on the second attempt.

In each case, the HIFM recognized the event. However, because of the relative brevity of each fault, and because of proper operation of overcurrent protection devices, the HIFM properly recognized the proper operation of the conventional protection and took no action.

Case 8 – Fig. 11 illustrates a temporary overcurrent fault on Feeder C which cleared with one reclose. However, because of the large amount of inrush caused by the reclose operation, and because the feeder was operating at a large percentage of its relay pickup level, a second trip operation occurred. The HIFM recognized the event; however, it did not alarm since it recognized the operation of the overcurrent protection.

Case 9 – Fig. 12 shows minor ϕ–ϕ arcing on Feeder D. The cause of this arcing is unknown. However, the fact that none of the arcing involves ground suggests that there was some foreign object across the primary, most likely a tree limb. This HIFM alarmed this condition as arcing five times over a period of 14 hours.

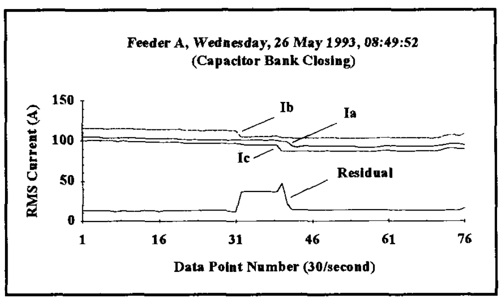

Fig. 8. Capacitor bank operation, showing unsynchronized phase closings.

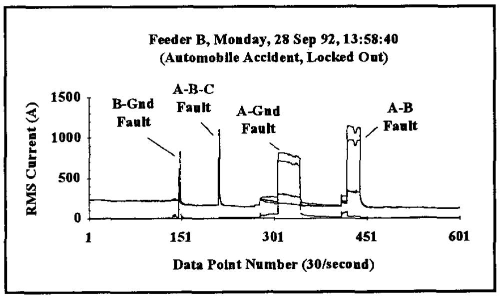

Fig 9. Overcurrent fault, tripped to lockout, caused by car hitting pole.

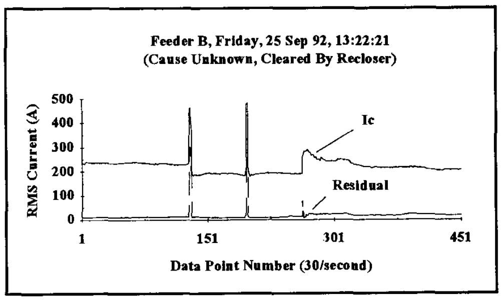

Fig. 10. Temporary overcurrent fault, cleared with two operations of recloser Cause of fault is unknown.

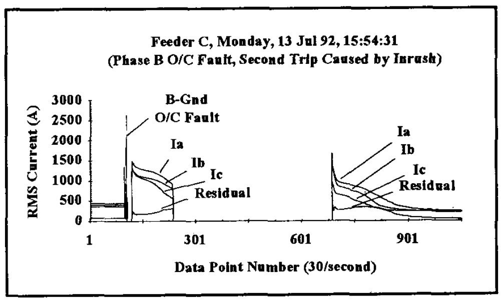

Fig. 11. ϕB temporary fault, cleared by reclosing, in which inrush caused a second operation.

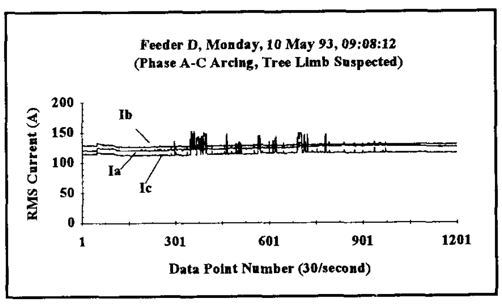

Fig. 12. Minor ϕ–ϕ arcing on Feeder D.

VII. Summary and Conclusions

After forty-seven unit·months of exposure, the high impedance fault detection algorithms have shown good fault detection sensitivity with excellent security against false tripping. Exposure to large numbers of "normal" system events has shown that the system algorithms and logic can adequately discriminate between fault conditions and other disturbance events.

Exposure to staged faults indicates a high probability that a downed conductor will be detected if it is not cleared by overcurrent devices. Approximately 25% of the faults were not cleared by fuses or other overcurrent protection; most of these were detected by the HIFM equipment. Most of the fuse–cleared faults were also detected by the HIFM, and would have "tripped" had a fuse not blown. Coordination logic with overcurrent devices allows for sectionalizing and fault isolation before a feeder is tripped.

The five HIFM installations continue to operate, gathering data and field experience. Based on results to date, we are most pleased with their performance. While the demonstration hardware has had some minor operational problems, the viability of implementing the Texas A&M University high impedance fault detection algorithms and coordination logic have been effectively demonstrated. The case studies given show the wide range of events which have been seen by the HIFM units. The proper response of the HIFM devices has been most gratifying. Field tests continue and additional results will be reported at a later date.

It is expected that once implemented in commercial grade hardware, the algorithms will be a valuable and effective addition to the protection of any distribution feeder.

VIII. Biographies

B. Don Russell (F '92) received the B.S. and M.E. degrees in Electrical Engineering at Texas A&M University. He holds a Ph.D. from the University of Oklahoma in power system engineering. Dr. Russell is Professor of Electrical Engineering and Director of the Power System Automation Laboratory of the Electric Power Institute at Texas A&M University. His research centers on the use of advanced technologies to solve problems in power system control, protection, and monitoring. He holds several awards and patents for advanced digital technology applications. Dr. Russell is a member of the PES Executive Board and Chair of the Awards and Recognition Department. He is a member of the Substation Committee, and chairs several working groups. He chairs the annual TAMU Conference for Protective Relay Engineers and the Fault and Disturbance Analysis Conference. He is a Registered Professional Engineer and a member of the Texas Society of Professional Engineers.

Carl L. Benner (M '86) received the B.S. and M.S. degrees from Texas A&M University in 1986 and 1988. He is a member of the IEEE Power Engineering Society. He is a Registered Professional Engineer and a member of the Texas Society of Professional Engineers. Since 1988, he has managed the Power System Automation Laboratory. His research interests include microprocessor-based monitoring, control, and protection of power systems. Much of his work has centered on the detection of high impedance faults.

IX. Acknowledgments

This research would not have been possible without the financial support of the Electrical Power Research Institute. We also wish to acknowledge the excellent support and cooperation of Bryan Utilities, Rochester Gas and Electric, Florida Power and Light, TU Electric, and Pacific Gas and Electric, who provided demonstration sites.

X. References

[1] *Detection of Downed Conductors on Utility Distribution Systems,* IEEE Tutorial Course # 990EH0310-3-PWR, 1989, 48 pp.

[2] S. J. Balser, K. A. Clements, and E. Kallaur, *Detection of High Impedance Faults*, EPRI Final Report # EL–2413, June 1982, 158 pp.

[3] I. Lee, *High Impedance Fault Detection Using Third Harmonic Current*, EPRI Final Report # EL–2430, June 1982, 94 pp.

[4] B. Don Russell, *Detection of Arcing Faults on Distribution Feeders*, EPRI Final Report # EL–2757, December 1982, 146 pp.

[5] M. Aucoin, "Status of High Impedance Fault Detection," *IEEE Transactions on Power Apparatus and Systems*, Vol. 104, No. 3, March 1985, pp. 638-644.

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

[7] B. Don Russell, Ram P. Chinchali, and C. J. Kim, "Behaviour of Low Frequency Spectra During Arcing Fault and Switching Events," *IEEE Transactions on Power Delivery*, Vol. 3, No. 4, October 1988, pp. 1485-1492.

[8] D. I. Jeerings and J. R. Linders, "A Practical Protective Relay for Down–Conductor Faults," *IEEE Transactions on Power Delivery*, Vol. 6, No. 2, April 1991, 565–571.

[9] Adly A. Girgis, Wenbin Chang, and Elham B. Makram, "Analysis of High–Impedance Fault Generated Signals Using a Kalman Filtering Approach," *IEEE Transactions on Power Delivery*, Vol. 5, No. 4, October 1990, pp. 1714–1724.

Discussion

JOHN T. TENGDIN, Consultant - San Clemente CA   The presenter of this paper emphasized the point that the algorithm, as it existed in the field tests, required that there must be a loss of 60 Hz load FOLLOWED by an output from the "Arc Confidence Level Generator" in order that a downed conductor be declared. This emphasis is missing from the written paper. As implemented during the described tests, what loss of load (in % or amps) was necessary before the system would declare a downed conductor? The "Arc Confidence Level Generator" looks at odd harmonics, even harmonics, and non harmonics. Are they equally weighted? What would be the effect of looking only at odd harmonics? At only 3rd harmonics? The authors mention future commercial grade hardware. Has the paper's algorithm been incorporated in a commercial product? If so, how do its field tests compare with those in this paper? In the commercial product, is the level of load loss prior arcing noise a settable parameter?

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Carl L. Benner and B. Don Russell (Dept. of Electrical Engineering, Texas A&M University, College Station, TX) We thank Mr. Tengdin for his detailed comments and questions. We will attempt to satisfy each question in order.

First, Mr. Tengdin is correct that the high impedance fault monitor (HIFM) requires a significant loss of load prior to the detection of arcing for the HIFM to classify the event as a downed conductor. The final sentence of Section II of the paper mentions this, but Mr. Tengdin correctly points out that the paper may not stress it enough.

The percentage loss of load that the HIFM required during field tests was 15%. However, during none of the staged tests did we drop load, since we conducted these tests on a working feeder. Other customers on the feeder would not be happy if we interrupted their service whenever we conducted tests! Since we dropped no load, the HIFM indicated arcing rather than a downed line. However, this is a limitation of our tests, not of the HIFM.

To answer Mr. Tengdin's question about the weights in the Arc Confidence Level Generator, the weight factors are different for each parameter and for each algorithm. These weights represent our past experience and represent the relative effectiveness of the different algorithms as applied to the different parameters.

Mr. Tengdin raises the possibility of using only odd harmonics, or in particular only the third harmonic. Our experience has shown that the odd harmonics, including the third, are sometimes capable of identifying arcing faults. However, the odd harmonics also are the most prone to falsely indicating a fault when a fault does not exist. This is due in large part to the prevalence of normal loads that generate odd harmonics. Also, capacitor banks heavily influence the level of odd harmonics, in particular the third. In fact, it has been our experience that the odd harmonics, whether the third taken singularly or all odd harmonics combined, are the least useful of the three groups that we use. The even harmonics and non harmonics show more sensitivity than the odd harmonics, while also maintaining higher security against false indications.

Mr. Tengdin's final questions address commercialization of the techniques that the HIFM embodies. At the time of writing of the original paper, these techniques had not been released as a commercial product. Since that time, General Electric has released their Digital Feeder Monitor (DFM), which does incorporate the HIFM's techniques. Initial testing of the DFM here at Texas A&M has given results similar to those demonstrated with the HIFM. Several utilities are planning tests of their own, but none have completed them to date. The level of load loss prior to arcing noise is a settable parameter in the commercial device.

We hope that this closure adequately addresses each of Mr. Tengdin's concerns.

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