High-Precision Location of Lightning-Caused Distribution Faults

J. G. Kappenman, *Senior Member IEEE*, M. E. Gordon*, Senior Member IEEE,* and
T. W. Guttormson*, Member IEEE*

***Abstract*—Highly accurate distribution system fault location is possible by combining lightning location data with fault monitor disturbance data and distribution feeder location (GIS) data. A 13-month monitoring and investigation program (June 1998 – July 1999) was conducted on a rural electric cooperative distribution system to test the concept.**

***Index Terms*—Lightning Stroke, GIS, GPS time stamp, disturbance, fault, lightning location, fault location.**

I. INTRODUCTION

Lightning is generally considered to be a major cause of transmission and distribution faults and outages. In particular for distribution outages, the industry has generally recognized that lightning, along with tree-contact and animal-contact are among the major causes of most outages. Because it is very difficult to forensically determine the exact cause of many faults, hard statistical evidence on percentages of each outage cause have been lacking throughout the industry. This is especially true for lightning, as the ability has not existed until now to associate lightning with locations of faults or damaged power apparatus.

Remote sensing capabilities now exist throughout North America and many other parts of the world that can detect nearly all lightning strikes in real-time with the ability to also locate the strike within 400 meters [1]. This lightning information has been successfully used in the transmission sector of the industry to quantify the impact of lightning in causing transmission system disturbances [2], [3]. A method of remote sensing can be done through time and location correlation techniques to locate lightning-caused transmission outages to the structure. This precise trouble location information has been used to target immediate, low-cost, and highly effective maintenance on the transmission system [4]-[7].

This work was supported by the Cooperative Research Network of the National Rural Electric Cooperative Association.

John G. Kappenman is with Metatech, Duluth, MN 55802 USA (e-mail: john@metatechcorp.com).

Martin E. Gordon is with the NRECA, Arlington VA 22203 USA (e-mail: meg0@nreca.org).

Thomas W. Guttormson is with Connexus Energy, Ramsey, MN 55303 (email: tomg@connexusenergy.com)

II. STUDY, CONCEPTUAL DESIGN AND RESULTS

On distribution systems, precise real-time fault locating has been extremely difficult to do using conventional approaches. Therefore, the opportunity to precisely locate lightning-caused distribution system faults using the same remote sensing techniques that have been successfully applied on transmission lines is a potentially beneficial concept. A study by the Cooperative Research Network of the National Rural Electric Cooperative Association was the industry's first such effort to extensively track a distribution system for faults and to correlate these disturbances with lightning information to precisely locate where the disturbance occurred [7], [8]. The density and geographically-widespread location of the distribution lines of a rural electric cooperative is very similar to the density of transmission networks, so similar success is expected in potential application of this technology for rural distribution systems. This capability to detect and locate lightning-caused distribution system faults has the potential to provide even greater benefits than those occurring in transmission systems. Both distribution and transmission can use this fault location information to target maintenance activities to achieve system performance improvements overtime. However for distribution, there can be very immediate operational benefits as well. Transmission system faults do not generally cause direct customer outages due to redundancy in the design of these systems. However, as faults on distribution systems occur, an outage to portions of the distribution network will cause outages of service to customers that are downstream on the feeder from this point of failure. These outages require the immediate dispatch of a repair crew to first locate the source of the outage and then to repair and restore service to customers. For rural cooperatives, the problem of locating the point of a failure over extensive service territories and difficult to access terrain can be a challenge. Just the time spent in locating the point of fault can become a significant portion of total customer outage time. This technology could be employed to precisely locate the point of an outage within a few hundred meters and in near real-time such that this location information can be used for direct and immediate dispatch of repair crews to the location, rather than driving extra miles or spending extra time in locating the source of the trouble to begin making repairs.

This paper documents an effort undertaken to actively monitor the faults and lightning incident on a rural distribution system for the purpose of providing a proof of the concepts outlined above. This study monitored faults over a 13-month period on 4 distribution feeders from a substation located in central Minnesota on the Connexus Energy system, a location with only modest annual lightning activity. The results of this study have established the basis that available lightning data combined with readily available disturbance monitoring could pinpoint the location of distribution disturbances, due to lightning, within a matter of a few spans on a distribution line.

Another finding of this study demonstrated that a fault monitor used to detect and help locate distribution network faults could also observe transmission system faults at the same time, allowing for one set of instrumentation at a substation to assist in locating both transmission and distribution system faults. The extent of the new infrastructure needed to implement this fault location capability consists of a single modest fault-monitoring device located at a substation linked via simple communications. This simple infrastructure (which may already exist in some cases) can provide all the information needed when integrated with lightning and distribution asset GIS information.

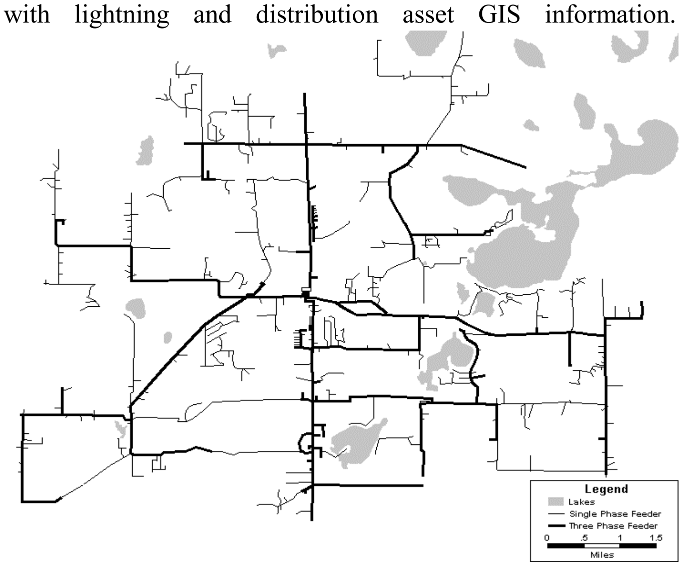

Figure 1. Map of Soderville Substation and four feeders in study region.

A. Distribution Asset Locations

Lightning data is only one of the three needed data inputs that will be required to perform distribution network fault location. It is also necessary to have highly accurate disturbance timing and asset location data to unambiguously resolve lightning-caused fault locations.

The Soderville substation is supplied from several 69kV transmission sources and has four 12kV feeders radiating from the substation, like spokes from a wheel. A location map of all four of the feeders is shown in Figure 1. Each of the four feeders starts out as a 3 Phase feeder, which is configured with C Phase as the center phase on the structure. Single-phase taps are provided off of the 3 Phase feeder for short extensions to serve loads. The distribution network serves a region of about 10 miles long by 10 miles wide (100 square miles) and has a mix of rural and suburban load density characteristics, which represents a cross-section of load types common in many rural networks.

The service area of each of the feeders will be of importance in the course of the study, as it will be desired to evaluate the ability to locate a disturbance to a specific section of a feeder. The footprint for Feeder 2 serves loads primarily north of the Soderville substation. The feeder associated with recloser position 3 at the Soderville substation serves loads that are primarily east of the substation. Feeder 4 primarily serves loads south of Soderville, while Feeder 5 provides service to loads that are west of the Soderville substation.

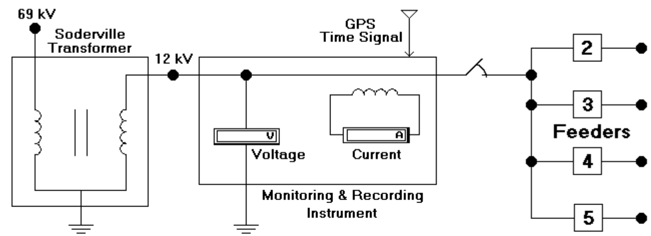

Figure 2. Disturbance monitoring schematic at the Soderville 69-12kV substation.

B. Distribution Disturbance Monitoring

A schematic of the single-point disturbance monitor and substation one-line is shown in Figure 2. Monitoring at this single point allows for observation of all voltage or current signal disturbances on the network, whether the disturbance occurred on any one of the four 12kV feeders or even to the supply to the station from the 69kV transmission system. This monitoring instrument also had provisions to incorporate GPS timing signals to obtain the accurate time-stamps of observed events. Therefore any disturbances that were observed could be accurately time correlated with lightning or other data sources that have GPS timing accuracy. Because of the location of this monitor on the main bus section between the transformer breaker and the feeder breakers out of the substation, a disturbance that occurs on any feeder will be observed at this disturbance monitor. A more desirable, but obviously more expensive option would have been to monitor each feeder separately. This would have provided further ability to discriminate which feeder had been impacted by a disturbance. In this configuration, the monitor is only able to determine that any one of the four feeders downstream of the monitor has experienced a fault, but unable to determine on which of the four feeders that the fault occurred. This configuration for monitoring is less than optimal, but was also a conscious decision, as one of the objectives of this study was to push the technology to minimize the need for extensive monitoring appliances. This low-resolution fault monitoring data in combination with other independent data sources (such as lightning data) would be combined to test new analysis methods to harvest the details of disturbance locations.

In the case of this monitoring study at Soderville, the conducted voltage and current signals provide important details of timestamp and fault direction (high-side or low-side) details. The fault monitoring instruments can reliably determine whether a fault was high-side or low-side by the nature of the conducted voltage and current signals that are observed. For example in Figure 3a and 3b a voltage and current on C Phase at Soderville is being observed. When the fault occurs, the voltage sags (from 170 peak to 149, about 12%). Meanwhile, the current increases from 1000 amps to over 4000 amps. This combination of voltage sag with increased current indicates that the fault current is being fed from the transmission system and is flowing through the monitoring device on the low-side of the transformer and downstream to one of the four feeders.

To further add to the description of location, further aspects of the conducted signals that are being monitored may be useful. The relative amount of voltage sag and fault current increase can be an important indicator. In the case of very large voltage drops, in combination with very large current increases, a low-side fault relatively close in to the substation can be inferred. Other voltage and current signal characteristics can also be useful at times, for example if a voltage sag and fault current increase is observed on only one phase, then a low-side single-line to ground fault has occurred. This may be on either a single-phase tap or one phase of a three-phase feeder section. However, if a three-phase low-side fault has been detected, the location of probable fault locations has been substantially reduced to only the three-phase feeder sections of the network as shown in Figure 1 and thus eliminates many miles of single-phase feeder as possible location solutions. The fact that high-side faults can be reliably detected at Soderville, also means that similar forms of lightning correlation to transmission fault locations can be explored as well. In short, this monitoring capability can perform dual roles for both distribution as well as transmission operations as this project explores correlation with lightning data.

C. An Example of Fault Location

On June 4, 1999, the monitoring device at Soderville observed a C-Phase Low-side disturbance. The fault initiated at time 12:15:06.764 UT. In reviewing lightning data, lightning activity was very high in the region. Lightning activity lasted a full two hours from 11:43 to 13:43 UT and resulted in 327 strikes observed in the Soderville study region.

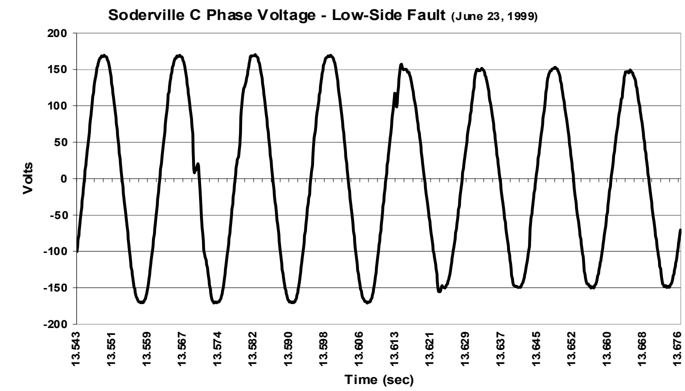

Figure 3a. Voltage waveform for C Phase observed at Soderville, indicating a 12% voltage sag,

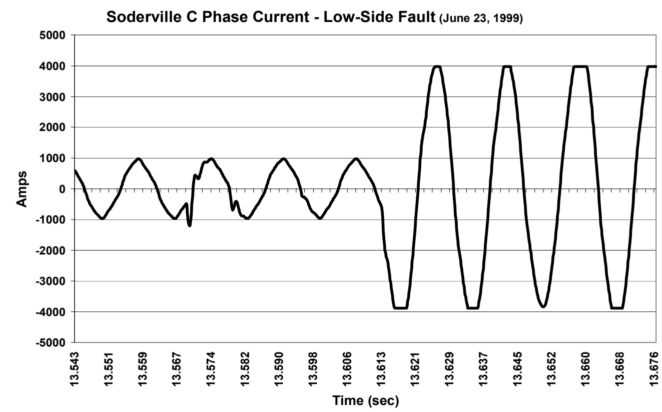

Figure 3b. C Phase current indicating large fault current being supplied from the Soderville transformer to one of the four feeders

The disturbance produced a clear C Phase indication in the disturbance monitor. Voltage drop was 38% and fault current increased to over 3700 Amps. Using a simple time filter of +/- 1 Minute from 12:15 UT and a spatial filter of 10 by 10 miles centered on the Soderville substation, the total number of candidate lightning strokes drops to a total of 19 strokes at the locations shown in Figure 4. As shown here, a large number of lightning strikes occurred in rapid succession in a well-defined region of Feeder 5 on the Soderville distribution system. This initial correlation already begins to precisely delineate the probable location of the distribution disturbance to a small section of Feeder 5 about 1.5 miles downstream from the Soderville substation. Figure 5 provides a more refined time filter of +/- 1 Second which narrows the total number of candidate strokes to a cluster of 8 strokes in a more geographically confined section of Feeder 5. Many of these strokes are occurring in portions of the Feeder 5 in which single-phase distribution taps are present. These distribution taps all involve C or B Phase extensions; hence the fault being detected primarily on C Phase fits well with the lightning and asset location correlation so far.

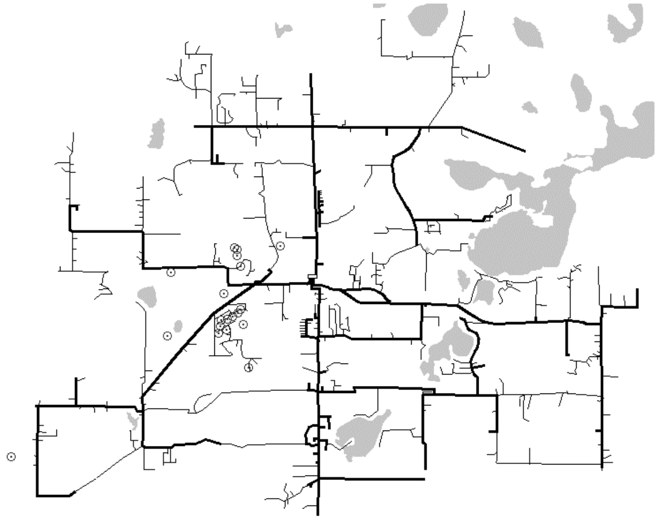

Figure 4. Location of all lightning strikes correlating with time of C Phase disturbance on June 4, 1999 12:15:06.764UT and using coarse time filter of + or – 1 minute and location filter of 100 square miles of Soderville study region. A total of 19 lightning strokes are candidates using these simple filters.

Using a time filter of +/- 0.83 msec, the candidate strokes that fit this time window now drops to only two strokes. These lightning strikes vary only slightly in location, however the first strike has a lightning current magnitude of –37 kA while the second strike was only a –18 kA magnitude. The location of the two strikes are shown in Figure 6, which indicates that the later of the two strokes is positioned directly over an area of single phase feeders, while the first strike is located a few hundred feet away from the main 3 phase feeder section.

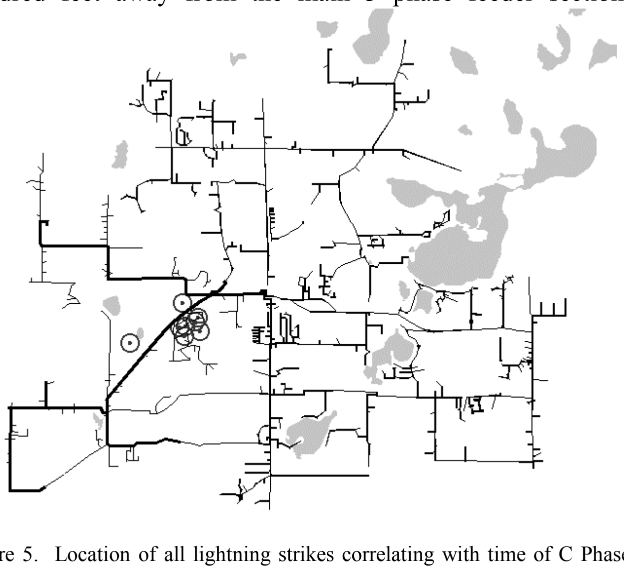

Figure 5. Location of all lightning strikes correlating with time of C Phase disturbance on June 4, 1999 12:15:06.764UT and using coarse time filter of + or – 1 second and location filter of 100 square miles of Soderville study region. A total of 8 lightning strokes are candidates using a more refined time filter with the coarse spatial filter.

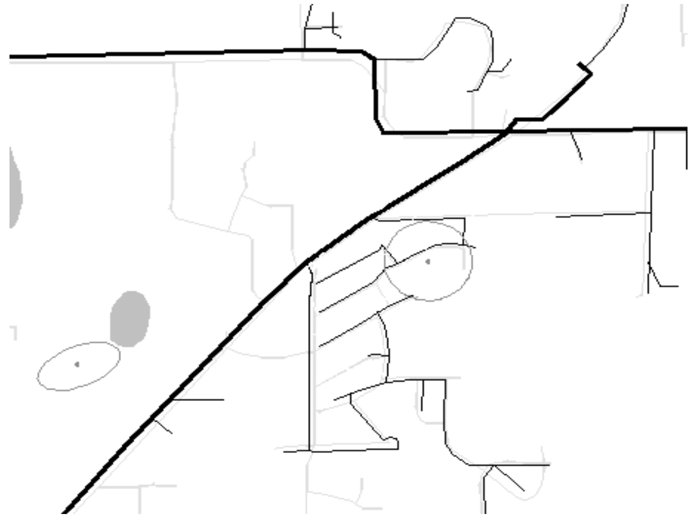

Figure 6. Location of all lightning strikes correlating with time of June 4, 1999 12:15:06.764UT and using refined time filter of + or – 0.83 msec and refined location filter of Soderville study region. The feasible lightning strikes are reduced to two candidates, however only one of the strokes is located near a section of C-Phase single-phase feeder and is the most feasible location result.

D. Validation

Other fault events were used to further validate this methodology, for example shown in Figure 7 is the location of candidate lightning strikes that correlate within +/- 1 Second to a A & C Phase fault on June 23, 1999. This correlation provides a very small section of 3 Phase feeder also on Feeder 5. Since this fault involved two phases, the correlation with a three phase section of this feeder provides good agreement.

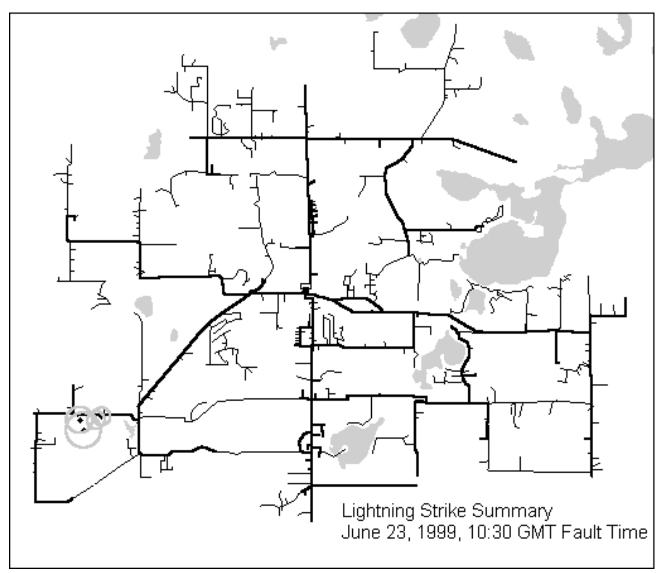

Figure 7. Location of all lightning strikes correlating with time of A & C Phase fault on June 23, 1999 10:30:13UT and using refined time filter of + or – 1 Second and coarse location filter of Soderville study region. A geographically tight cluster of 5 strokes on a small 3 Phase section of Feeder 5 correlates with the disturbance.

There are other important independent comparisons that can be made which further validate this location accuracy approach. As shown in Figure 7, the fault on June 23, 1999 was determined to be located approximately four miles downstream of the Soderville substation, while the June 4 fault, as located in Figure 6, is approximately 1.5 miles from the substation. Both faults happened to be located on the same feeder, so conductor impedances are the same for at least the first 1.5 miles in determining voltage and current conditions. The fault further downstream would be expected to have lower fault current and less voltage sag due to the added impedance of an additional 2.5 miles of feeder in the circuit. The levels of voltage sag and fault current that were detected in these two events support these differences in locations. In the case of the close-in fault on June 4, the voltage sagged to 62% of the nominal voltage, while the fault on June 23 located further away from the Soderville sub only caused a sag to 78% voltage. The fault current observed for the close-in fault of June 4 reached a level of over 3700 Amps, while the further away June 23 fault had a peak fault current of 3300 Amps. Therefore, both the voltage and current conditions observed on June 4 and June 23 are able to independently support the more-precise locations that were determined through these lightning correlation approaches.

III. Conclusions

Power system faults, whether temporary or permanent, are difficult to locate. These methods for lightning-caused fault location have shown to be highly accurate in locating the source of the fault and can therefore be the basis to develop or enhance outage management systems in a utility operation. These capabilities can also be readily provided to any size organization (large or small) with a highly automated and in-expensive service that will provide a trouble crew with precise location information. This will provide the crew, before they leave the service building, information on where the outage is on the system. Knowing this, time spent in locating the fault can be minimized, which will expedite the total restoration time for customer outages. In addition to the benefits of faster restoration, knowing the location and cause of all disturbances (even those that are temporary), will provide detailed and specific information on problem areas in any organization's network. This information can highlight and therefore help to narrowly target problems that can result in faster and less-expensive fixes than have been possible to date.

IV. References

[1] Cummins, K.L. Burnett R.O., Hiscox W.L., Pifer A.E.: "Line Reliability and Fault Analysis Using the National Lightning Detection Network", Precise Measurements Conference, Arlington, 1993.

[2] Chisholm W.A., Chow Y.L., Srivastava K.D., "Travel Time of Transmission Towers," IEEE Transaction on Power Apparatus and Systems, Volume PAS- 104 Number 10, October 1985

[3] Anderson J.G., Chapter 12 of Transmission Line Reference Book 345 kV and Above 2nd Edition Revised, Palo Alto, California: Electric Power Research Institute, 1987.

[4] Kappenman John G.. Van House David L., "Location-Centered Mitigation of Lightning-Caused Disturbances" IEEE Computer Applications in Power, Volume 9 Number 3, July 1996

[5] Van House David L.. Tuel Jeffrey, "National Lightning Detection Network and Fault Analysis and Lightning Location System" presented at the Minnesota Power Systems Conference, St. Paul Minnesota, October 1995

[6] Kappenman John G.. Van House David L., "Utility Fault Diagnostics: Use of the NLDN at Minnesota Power" presented at the 1995 International Lightning Detection Conference, Tucson, Arizona, February 1995

[7] Kappenman John G. "Distribution Lightning Fault Correlation and Advanced Applications of Lightning Data," presented at the 1999 IEEE T&D Conference, New Orleans, April 1999.

[8] Kappenman, John G., Radasky, William A., "Advanced Applications of Lightning Data for Fault Location & Distribution Outage Management," presented at the 2000 International Lightning Detection Conference, Tucson Arizona, November 2000.