DISTRIBUTION LIGHTNING FAULT CORRELATION & ADVANCED APPLICATIONS OF LIGHTNING DATA

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Introduction

Advances in the accurate detection of lightning location and magnitude are fostering the capability for high-quality power system impact assessments. These impact assessments can support highly cost/benefit effective decisions in diverse applications across the spectrum of transmission and distribution operations. Case study examples are provided to further illustrate the role of Impact assessment that can be considered by integrating high-quality lightning data with sophisticated power system impact data monitoring systems and/or models of power system assets and it's behavior when impacted by lightning.

A case study involving applications related to predictive design of transmission systems where performance forecasts are derived from integrating forensic stroke data are discussed.. In this case, comparisons will be discussed on the lightning performance and the cost between 69 kV transmission lines with a shielded and unshielded design, which utilizes lightning arresters.

Utilizing lightning stroke data in a forensic application to target performance problems specific to maintenance construction programs for sub-transmission and transmission systems is reviewed. This allows deterministic performance indicators of specific line sections or even structures to be derived which can be applied in a cost and time effective maintenance function (i.e., Location-Centered Maintenance^{TM}) . Further this technology can target a performance problem early on and boost asset performance goals by identification of problems before recurrent event tracking systems would normally allow for this problem identification. The successful application of lightning data at the transmission level allows for the potential application in comparable fashion to distribution levels.

Finally application of high quality lightning data holds significant potential for application on distribution systems where the potential exists to integrate observed lightning Systems to allow faster and more efficient restoration to impacted utility customers. Providing reduced crew and data with observed distribution disturbances. This application holds the potential to provide high quality damage location information to Outage Management Systems to allow faster and more efficient restoration to impacted utility customers, while also providing reduced crew and operational costs and better customer service. A Metatech/NRECA pilot program is discussed.

Exploiting Emerging Technologies from Transmission Applications

Considerable investigative work was undertaken as detailed in Reference 1, 2 to develop new application methods for lightning analysis on the performance of transmission systems. These efforts were focused on determining if lightning patterns existed and, where possible, exploiting these patterns by targeting mitigation upgrades where they would yield the greatest line performance improvements with the limited investment capital available. In short, the objective is to determine if a methodology for "Location-Centered Lightning Mitigation" can be developed to best improve transmission performance.

As a result of the recent upgrades, the National Lightning Detection Network (NLDN) currently employs hybrid sensor technology at over 106 sites located across the US that provide on average a detection efficiency upgraded from 65% to now over 90% in most areas across the continental US. Further, the location accuracy has improved on average four to six fold (from previous accuracy of 2-4 km to an accuracy of approximately 400 meters or better). Note this level of accuracy is now approximately equivalent to twice the average ruling span for a typical 115kV-transmission line. Therefore, lightning initiated transmission line faults can typically be pinpointed within one or two structures.

In addition to these improvements, the NLDN is now capable of providing information about each cloud-to-ground return stroke (i.e., "all-stroke" data), as opposed to only the first return stroke and multiplicity count provided before. The availability of all-stroke data now provides electric utilities with the level of specificity necessary to determine the casual relationship between lightning and power delivery system performance.

Combining accurate transmission line asset location with accurate lightning location and timing provides the ability to accurately pinpoint locations of asset exposure and lightning caused disturbances. The Fault Analysis and Lightning Location System (FALLS™) analysis software provides a practical, analytical tool to examine the relationship between lightning and power system performance by utilities and to make such determination on an ongoing and comprehensive basis. The above-mentioned "Location-Centered Mitigation" objectives are asset location focused. The FALLS™ analysis software is based upon the Map-Info geographical information system (GIS) and is therefore, ideally suited to map and locate lightning events relative to transmission line asset locations.

A spatial and temporal location based analysis tool needs not only accurate asset location but also accurate time-stamping of disturbances occurring on those assets in order to verify that a fault was lightning induced, and/or eliminate lightning as a potential cause of the fault. The information can further provide a basis to evaluate design practices and locate areas that need upgrades. An example of the importance of fault timing can be seen. The timing accuracy of this fault (Figure 1), prior to using GPS timing, was plus or minus one minute. As can be seen, numerous flashes met both the timing and location criteria. If it was only of interest to determine fault cause, timing precision such as this is probably adequate. However, it is possible with accurate fault timing, to identify the specific stroke, which caused the fault, its characteristics and transmission structure location.

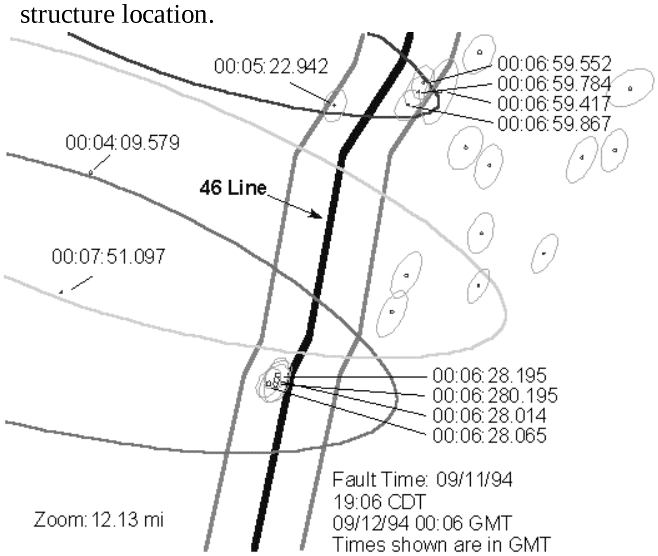

Figure 1: *Ambiguous Fault Timing inhibits Precise Lightning Correlation*

Location-Centered Maintenance

By combining NLDN data with fault timing and line location data, event by event correlation of faults with-, the lightning discharges that caused them is possible. This data is useful in determining if a line upgrade is performing as expected and to verify that lightning is the cause of a fault.

An example of the use of exposure analysis is validation of performance of one or more specific lines or line segments. This can be accomplished on existing configurations or for determining if line upgrades are performing as expected. Lightning can vary substantially from season to season and year to year. An annual or seasonal based performance assessment can not be expected to be accurate without averaging over a long period of time or using some other means to account for this variation in lightning occurrence. Therefore, it has been extremely difficult to evaluate the actual performance improvement provided by mitigation modifications in a timely manner because a number of years of experience was necessary in order to obtain meaningful results. However, new methods based upon the actual lightning stroke exposure of an asset can give a precise, nearly instantaneous measure of the exposure environment of a specific line or line segment. Once this exposure to lightning has been determined, line performance indices can be developed which relate lightning exposure to the number of faults the line has experienced before and after a mitigation modification. This can be accomplished by tracking the ratio of lightning strokes terminating within a specified buffer around the line to the number of lightning induced faults the line has experienced. This in essence defines an exposure ratio, in this case the ratio is "Strokes/Faults". Since this method uses actual cloud-to-ground lightning strokes in the immediate area of the line as detected by the NLDN, an accurate line performance index can be obtained with a season or less of data, in some cases.

An example is given below from a 115kV Line test case[2], in which performance of a recently upgraded line is compared with past performance.

Table 1 – Line Performance Verification

	Prior	Upgrade	Improvement
Faults	2	1	100%
Faults/100m/yr	33*	13.33**	148%
Exposure	31***	91***	
Strokes/Fault	15.55	91	485%

**** based on 10 Year Average***
***** based on 18 Months since Upgrade***
******18 Month Data Period before & after Upgrade***

Combining Lightning Data with electromagnetic models of a transmission line can extend the ability to analyze line performance even further. Figure 2 shows expected line lightning performance threshold curves as a function of varying stroke current magnitude and footing resistance for several lightning mitigation options. The performance threshold curves for several structural and lightning mitigation design options can be compared with expected exposure conditions to select the best trade-off between line performance and cost.

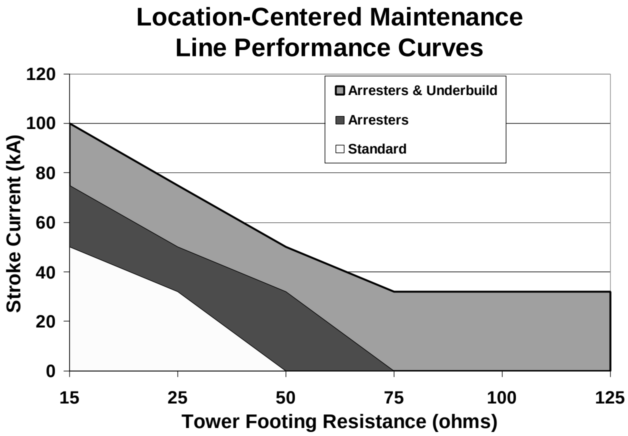

Figure 2: *115kV Transmission Line Case*

These curves can also be used to identify specific lines or sections of a line that may require maintenance attention. For example, if faults are occurring on a shielded high voltage line from low current lightning events, this may indicate that a design parameter, such as deteriorating structure grounds, has varied from the desired tolerance in the area where the faults are occurring. Take the case of the assessment of the impact related to a 70 kA lightning stroke at a structure where the tower footing resistance was 97 ohms. The above chart clearly indicates that a backflash failure should have occurred because the line design was not sufficient to withstand this challenge. In fact for this design with arresters only, a structure with a footing resistance above 20 ohms likely would have experienced a backflash. On the other hand, if the lightning challenge had been 40kA at a structure with a 34-ohm footing resistance, the event should not have resulted in a backflash. However, if it had, this gives immediate and highly useful data that a deficiency has now developed at this particular structure.

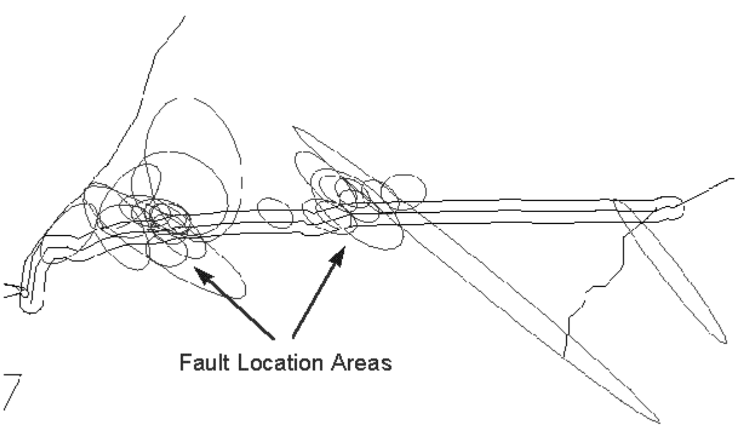

Figure 3: *Observed Clustering of Faults & Ability To Target Upgrade Areas*

In another situation, this technology was used to show that only 2 eight-mile sections of line were the major source of numerous lightning disturbances, which occurred on a 62-mile long 115kV line (Figure 3). This Location-Centered Maintenance ability allows immediate and selective targeting of upgrades to address vulnerable sections of line, rather than unnecessary upgrading portions of the system that are less impacted. The performance of the delivery systems can be closely monitored and when upgrades are needed this targeted approach has the potential to save in future construction and maintenance expenditures, as well as quickly targeting problems and reducing the likelihood for further failures to reoccur.

Predictive Performance & Line Design Applications at Sub-Transmission Levels

A study was undertaken for United Power Association to review 69kV design options for a recent transmission construction addition. The project presented a number of difficulties and complexities; rocky/high resistance soil conditions, the need to accommodate a 25kV distribution underbuild, the reluctance to use ground-wire stand-offs because of winter icing conditions, and the desire to provide a highly reliable service from the proposed line to a large radial served customer system. The construction standards for UPA limited them between a choice of shielded or unshielded designs, with structure options a shown in Figure 4.

The high soil resistivity in the area proved to be another important factor in the decision to build an unshielded transmission line verses a shielded design. The overhead shield wire design can allow a backflash to the lower phases during a lightning event due to the high resistivity soils. With the unshielded design, the lightning discharge. is controlled through the arrester by clipping the voltage below the insulator flashover rating and diverting the energy to ground.

The lightning study consisted of detailed EMTP stroke current withstand simulations combined with historic lightning exposure data. Four alternative designs were evaluated which consisted of Case A; a shielded 4-wire design using the TV-PI structure and three unshielded designs using the TS-PI structure (see Figure 4). The unshielded design alternatives included Case B; a design with arresters protecting only the top 69 kV conductor, Case C; a design using no shielding or arresters, and Case D; a design using arresters to protect all the 69 kV conductors.

TS-P1 TV-P1

Figure 4*:* *Unshielded & Shielded Structure Design Options*

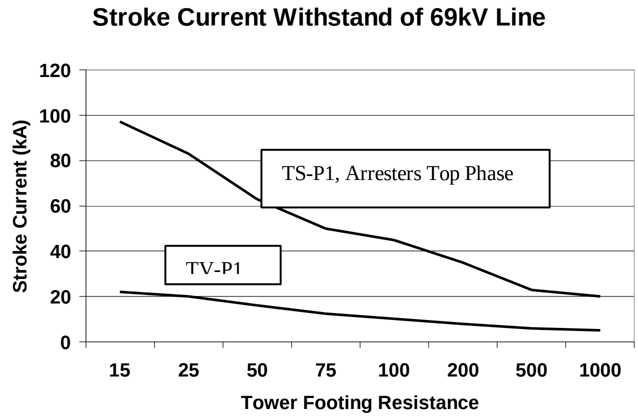

Figure 5: *69kV Circuit Performance with 100 Ohms Footing Resistance*

EMTP was used to determine the stroke current withstand of each of the four design alternatives. Figure 5 shows the expected stroke current withstand of the 69 kV circuit for the two primary designs, Case A and Case B, as derived from the EMTP simulations. The results indicate that in all cases and at all simulated footing resistance's, the stroke current withstand of the 69 kV circuit of Case B, the unshielded design with an arrester protecting the top 69 kV phase, was significantly better than that of the Case A, the shielded 4-wire design. Although the improvement in stroke current withstand varied depending on footing resistance, on average the 69 kV circuit of Case B could withstand a lightning stroke current approximately 300% higher than that of Case A. This performance improvement can be directly linked to the greater CFO of the 69 kV phases of the unshielded design as compared to that of the shielded 4-wire design.

However, even though stroke current withstand is an important design attribute, knowing it alone is not enough to rank the lightning performance of the various alternatives. For example, if Case A had a stroke current withstand of 100 kA and Case B had a stroke current withstand of 50 kA, intuitively one would think that the performance of Case A would be significantly better than that of Case B. However, if the line is only rarely exposed to lightning strokes in excess of 50kA, the expected performance of the two alternatives may actually be nearly identical. Therefore, the expected exposure of the line to lightning also needs to be evaluated in order to determine what effect, if any, differences in the stroke current withstand will have on the line's expected lightning induced outage rate.

This estimate is provided by use of the historic lightning data, combined with the FALLS software, to determine the lightning exposure and current distributions expected along the specific route proposed for the line. This method insured that any microclimate effects, are accounted for in the performance results. In this case, an indicated historic stroke density of 1.2 strokes per square kilometer per year was observed, further the historic data indicated a magnitude distribution. Table 2 shows the stroke current profile of all the cloud-to-ground strokes that occurred within 2 km of the proposed route (based on 1995 & 1996 data). The stroke currents ranged from a low of 12kA to a high of 159kA with an average stroke current of 25kA.

Table 2 – Line ROW Observed Stroke Data Profile 1995 & 1996

Cumulative %	Stroke Current (kA)
10	15.97
20	17.26
30	18.76
40	19.61
50	21.29
60	23.49
70	25.99
80	29.56
90	37.31
95	51.58
100	159.16

The expected performance of each line design can be calculated by taking into account the stroke density of all the strokes which exceed the line's stroke current withstand at any specified footing resistance. Table 3 lists the expected performance for the proposed line assuming a 100 ohm footing resistance, the lightning performance chart as shown in Figure 5 and the lightning exposure (Stroke Current profile) as shown in Table 2. As mentioned, the two primary designs consisted of Case A. a shielded design and Case B, an unshielded design using arresters to protect only the top 69 kV conductor. Case C consisted of a completely unprotected line, and Case D used arresters to protect all the 69 kV conductors.

Table 3 – Expected Performance Comparison @ 100 Ohms Footing Resistance

Case	Lightning Protection Method	Expected Lightning Performance
A	Shielded	2.36 faults /yr
B	Arresters-Top Phase	0.12 faults/yr
C	None -Unshielded	1.81 faults/yr
D	Arresters-All Phases	~0 faults/yr

Lightning Data Applications for Distribution Systems

Potentials for application of this technology to rural electric sub-transmission and distribution systems may be equally successful and is the basis for a demonstration project that is underway with the National Rural Electric Cooperative Association, Connexus Energy, and Metatech Corp. The potential for direct customer impacts and power quality improvement is even more pronounced on rural electric systems because of the momentary and sustained outages that result to the end-users on the impacted delivery assets. Further, because of the remote locations of rural utility infrastructures, restoration times can be lengthy due to the difficulties in precisely locating where a failure occurred compounded by the long rural feeder lengths. This technology of precise lightning location combined with asset based spatial and temporal correlation's can enable the ability to perform economic real-time/system wide precise fault location assessments that are caused by lightning. In rural electric system applications, this technology base would allow efficient and precise trouble location on extensive and remote feeder assets. This integration of lightning data into an Outage Management System has the potential to facilitate faster repair and restoration for impacted customers and lower cooperative operation costs.

Distribution systems can be impacted by both direct strikes by lightning as well as through induced over-voltages as a result of induction from nearby lightning strikes. Most data that is available on lightning performance of distribution systems is statistical in nature only, since no means has been available until present to continuously allow precise location of lightning and its associated current magnitude. This combination of data with refined modeling capabilities allows performance of in-depth discrete forensic analysis of lightning-initiated fault events.

This analysis will provide basic answers to conditions and design factors in which lightning will result in either momentary and sustained faults as well as those conditions in which lightning arc quenching occurs without producing a power frequency fault. Momentary faults on distribution systems are a growing source of power quality concern for sensitive load customers. This monitoring program will provide a means of determining to what extent lightning is a root-cause source of these disturbances, which are otherwise difficult to quantify or eliminate. Further, this work will provide an assessment of the potential for real-time lightning-caused fault location to facilitate rapid location and restoration for impacted customers.

Figure 6 provides a conceptual layout of the type of spatial correlation output that is conceivable for a near-real-time location of a distribution disturbance that is associated with lightning.

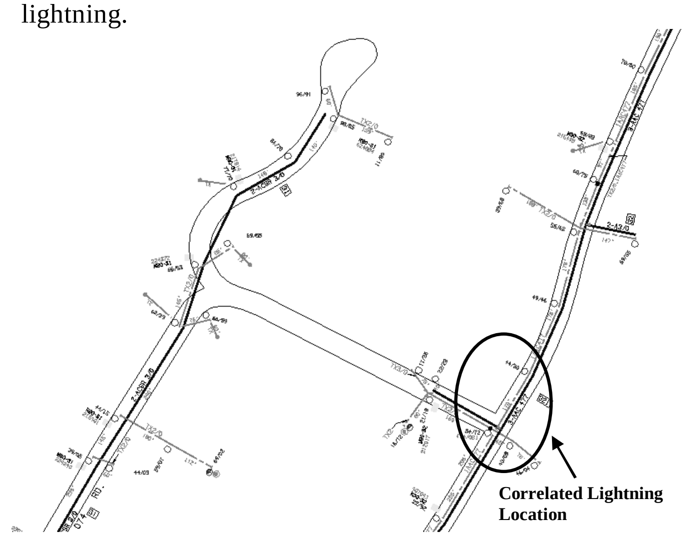

Figure 6: *Distribution Fault Location Correlated With Lightning Location Data*

This correlation capability provides a useful geographic referencing that can be employed for immediate crew dispatch and faster trouble location and system restoration. In distribution systems that have asset densities similar to transmission networks, application of this technology can be expected to provide positive and unambiguous location accuracy of the disturbance source.

Late in the 1998 lightning season a joint NRECA project was initiated with Metatech and Connexus Energy of Anoka Minnesota. A BMI sensor with GPS time clock was installed at the Connexus Soderville 69/12kV distribution substation. Through a set of simple voltage and current measurements on the 12kV bus, the recorder is able to provide disturbance notification and time stamping that can be utilized for lightning location correlation with disturbance events that are due to lightning activity. On August 7, 1998, a disturbance was observed at Soderville at 01:17:05.56GMT, which correlated to a set of two lightning events observed at 01:17:05.359. These were both positive polarity 33kA and 36kA events at locations approximately 30 miles away from the Soderville substation. The disturbance was the result of a 69kV momentary associated with the lightning event.

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Author Biographical Information

John G. Kappenman is a 1976 graduate in Electrical Engineering from South Dakota State University, after graduation he joined Minnesota Power (1977-1998) holding a number of positions. In 1998 he joined Metatech Corporation and is the Manager of their Applied Power Solutions Division. He directs the development of products, services, and consulting that are provided to clientele worldwide, and primarily focusing on Lightning and Space Weather impacts on electric utilities. He has been an active researcher in power delivery technologies and his primary engineering contribution has been his research work on lightning and magnetic storms and their disruptive effects on electric power systems. He led a utility industry effort to deploy a monitoring satellite that would provide advanced warnings of geomagnetic storms which was launched by NASA in August 1997. He has also been a collaborator with EPRI and Global Atmospherics on the development and application of the Fault Analysis and Lightning Location System. He is also one of the principle researchers in several EPRI research projects on Thyristor Controlled Phase Shifting Transformers and holds a US Patent for his design of this device.

He is a Senior Member of the Institute of Electrical and Electronics Engineers and the Power Engineering Society, and is the Past Chairman of the Transmission and Distribution Committee(1994-1996). He is also a member of a number of working groups and standards committees, T&D Awards Committee, and the Herman Halperin Award Committee. He has served (1993-1998)as an Instructor at the University of Minnesota-Duluth Department of Electrical and Computer Engineering. He has published over 30 papers in a variety of subject areas. He is a recipient of the IEEE Walter Fee Outstanding Young Engineer Award, the IEEE Prize Paper Award, the Westinghouse Nikola Tesla Award and two EPRI Innovator Awards. In February 1997, Mr. Kappenman provided presentations to the US Presidents' Commission on Critical Infrastructure Protection on the Potential Impact of Geomagnetic Storms on Electric Power System Reliability and also served as an Invited Lecturer at the International Space University on Space Weather and Impacts on Electric Power Systems. In 1999, Mr. Kappenman has been selected to Co-Chair a NATO Advanced Science Institute Conference on Space Weather Hazards.