Improved Quantification of Lightning Impact on Transmission Lines

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Abstract

Our industry currently has good general knowledge of lightning's effect on power systems, and which system and lightning parameters are relevant to fault analysis. This information is codified in IEEE and CIGRE documents, and is embodied in commercial and public analysis tools. Unfortunately, we have had limited ability to remotely measure the relevant lightning parameters. In addition, existing lighting location systems (LLS's) do not always report the fault-causing discharge, and may provide poor geo-location of the ground attachment. Without improvements in both LLS performance and the breadth of lightning parameter measurements, we cannot validate the models that represent the lightning effects, and (more importantly) we cannot be sure if specific segments of the power delivery systems are functioning "nominally."

In this work, we provide a status report on an ongoing project that takes an in-depth look at 30+ faults on 161 kV lines in the TVA service area, including information about fault location, involved phases, structure design, ground conductivity, and local terrain. Lightning performance modeling will be done to determine the flashover threat currents associated with the faults. The measured lightning data includes standard stroke-level lightning data from the NLDN, as well as lightning electromagnetic waveform data in the LF, VLF, and ELF frequency range. The additional VLF/LF waveform data allow us to provide (previously unavailable) estimates of the lightning return-stroke impulse charge and the total flash charge transfer to ground. The LF/VLF waveform data that is available from new NLDN sensors allows us to better evaluate the wave-front characteristics of the return stroke. We will present overall performance statistics related to the faults, NLDN performance, and a summary of the new lightning parameter measurements. In addition, case studies will be used to illustrate problem cases and key findings.

Background

At present, the NLDN (National Lightning Detection Network™) data (Cummins and Murphy, 2009) is used in several ways within the utility: investigating outages, evaluating line performance and designing lines (Cummins et al., 1998). In all of these use cases, the accuracy and detection thresholds of the NLDN data are important. Missing or incorrectly classified lightning information can mislead personnel when making decisions.

During an outage, restoration personnel have been trained to look for lightning along a line within a few seconds of the event. If lightning is found, the event is classified as lightning. Typically, no additional analysis is performed. However, without performing an actual fault location and looking at precise timing and lightning parameters, one cannot be sure that lightning was the root cause!

Though it is desirable to have a known root cause for all transmission faults, the largest fault classification is "Unknown." Since 2004, the stated stroke DE of the NLDN is approximately 70%. This implies that some number of events are being missed by the NLDN. This calls into question the performance of the lightning dataset, specifically the stroke detection efficiency (DE). Naturally, improvements to the NLDN could enhance the visibility of lightning events. Additionally, data sources outside the NLDN may improve detection and characterization of the lightning events.

The ability to fully characterize lightning events is dependent on the parameters that the detection network can measure. Today, the network measures the time, location, peak current, and other waveform and quality parameters for each detected stroke. For flash data, it also provides the multiplicity (number of strokes in the flash). Though not recorded today, additional parameters like max dI/dt and front time could be estimated in order to help assess overvoltage conditions on the power system. Still other parameters like impulse charge and continuing current could be used to infer heat-related damage.

Although the NLDN does not currently provide these additional overvoltage and heat-related parameters, performance is respectable. Table 1, below, shows the historical NLDN performance based on validation studies (Biagi et al., 2007; Jerald et al., 2005) for flashes and strokes since 2004. It is important to note that outage investigation and other analysis critical to the power system rely on the stroke performance.

Table 1 - Current NLDN Performance

	Flash	**Stroke**
Detection Efficiency	90-95%	75-85% (Vaisala claims 70%)
Median Location Accuracy	350-450 meter (Vaisala claims 500m)	
Peak Current Accuracy	~20% average error (only calibrated for negative subsequent strokes)	

Though the historical performance is respectable, the NLDN is constantly improving performance. This is accomplished by improving algorithms, installing new sensors that provide waveform information and developing “propagation corrections” for each NLDN sensor thereby improving location accuracy. A new algorithm was deployed in December 2010 that improved the median location accuracy from 500 m to 250 m (Cummins et al, 2010).

Project Objectives / Approach

The project had a couple of objectives: to assess the performance of the NLDN improvements and to investigate new applications for NLDN data by using lightning data in conjunction with other data sources like Digital Fault Recorders (DFRs) and supplementary electromagnetic measurements. To accomplish the objectives, a systematic approach was used to correlate lightning and transmission line events. For every event that occurred during the study period, 161 kV lines that were equipped with Disturbance Monitoring Equipment (DME) were studied. If other sources that provide waveform data were available (like relays or power quality monitors), then they were used when DME data was not available.

A variety of lightning-related data were studied for each event. The base NLDN data were used to identify possible fault-causing strokes. For cases with large differences between the calculated fault location and the NLDN-computed stroke location, Vaisala’s new location algorithm was used to “reprocess” the data. In addition, the raw waveform data from the sensors were used to evaluate the underlying return-stroke wave-shape. Finally, VLF/ELF data provided through Duke University were used to confirm presence/absence of lightning and to study the lightning waveforms in detail.

After the data were collected from the different data sources, event analysis was performed. In cases where the NLDN did not locate a stroke at the proper time, The VLF/ELF waveform data and DME data was used to help decide if the event was caused by lightning. In addition, the fault location was calculated by using single ended impedance based calculations. The lightning data were then assessed to determine if a time-matched stroke (within ~ 10 ms) was in a location that corresponded to the calculated fault location. In addition to location, the intensity of the stroke was reviewed to identify if the peak current was high enough to have caused the line to flash over. Multiple reports were generated from this analysis as can be seen in Figure 1, below.

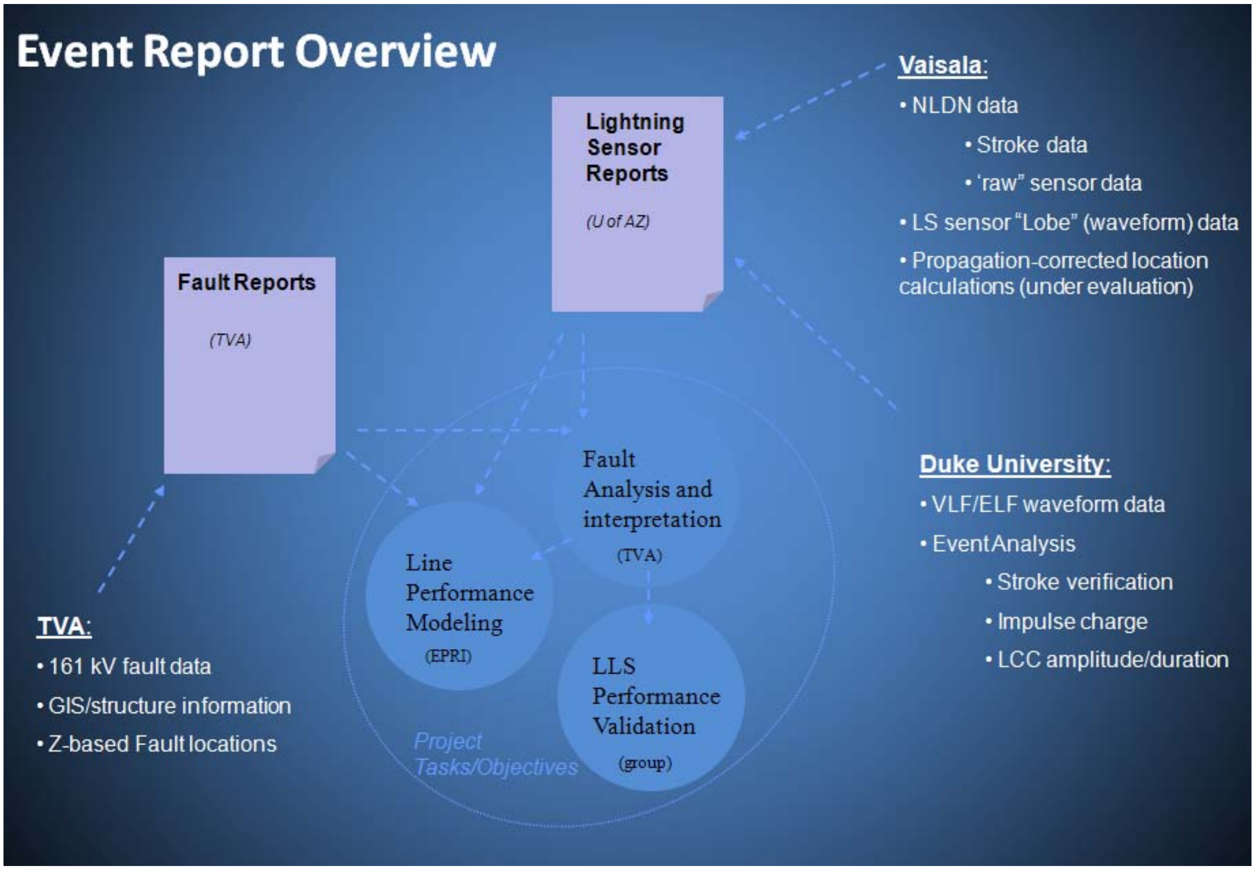

Figure 1 - Project and Event Report Overview

Results

As of the writing of this report, we have completed all the acquisition and basic analysis. Cases were categorized into one of four categories ("Good Correlation", "Poor Location", "Low Current", and "Poor Location and Low Current"). Detailed Fault and Sensor Reports were produced for three "good" cases and all cases that fall into the other three categories. We have carried out a first-order analysis of the findings, but we have not yet carried out selected field inspections/measurements or subsequent line performance modeling. There were lessons learned about both the power system fault location data and the NLDN data.

Fault Analysis:

The fault location analysis yielded some interesting findings. Some of the DME waveform data easily revealed the most likely cause of the fault to be lightning. Figure 2, below, shows a transient event that occurred near the point of lowest voltage stress. This fault was likely caused by lightning, because some external forcing function was required to generate the fault condition during this low-voltage condition. Many non-lightning-caused faults occur near the peak of the waveform, because the voltage stress is at the maximum during this time.

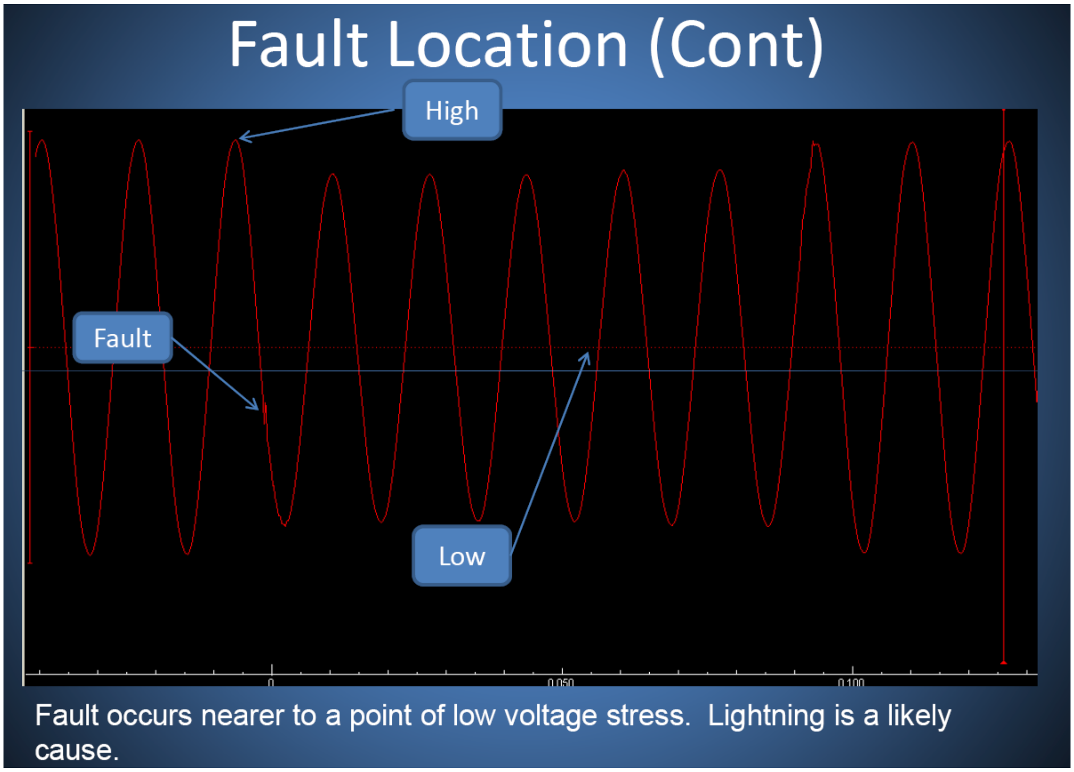

Figure 2 - Transient Event Near Zero Crossing

Fault location calculations were used to identify the expected location of the associated lightning stroke. The basic equation employed in this analysis is a derivative of Ohm's Law. The equation is shown in Figure 3, below. The voltage and current values are vector quantities while the impedance is a complex number that is a combination of the positive and zero sequence complex impedance.

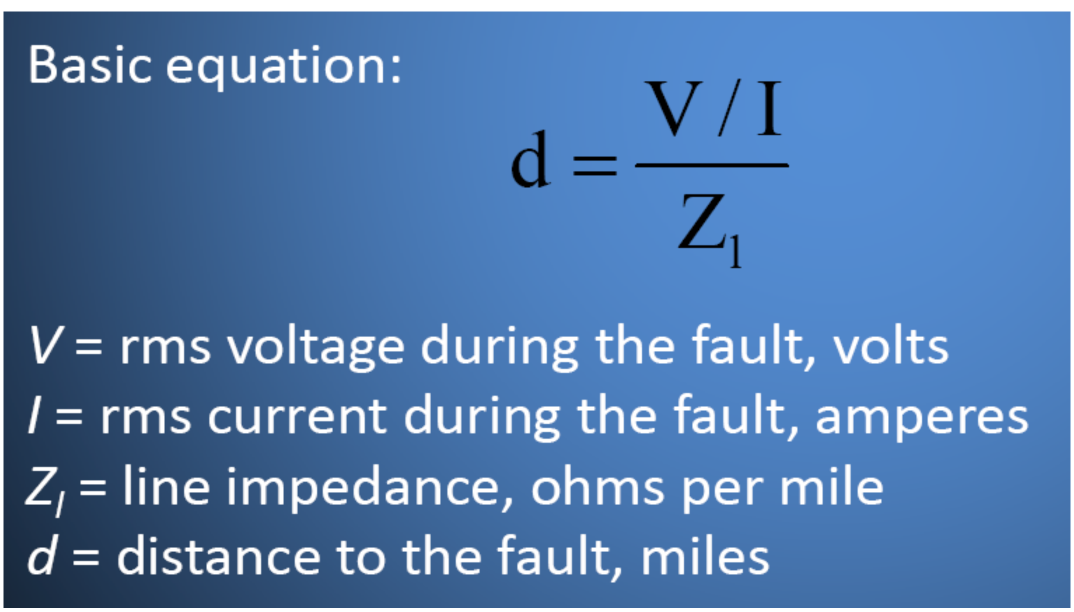

Figure 3 - Single Ended Fault Location Calculation

Selecting the point on the waveform to perform the fault location is critical. The fault must reach a steady state condition. Once the location on the waveform is selected, the voltage and current vectors can be used to calculate the fault location. This is performed from each end of the line, whenever possible. This creates a range of line structures where the fault was likely to have occurred. Figure 4, below, illustrates the fault location calculation.

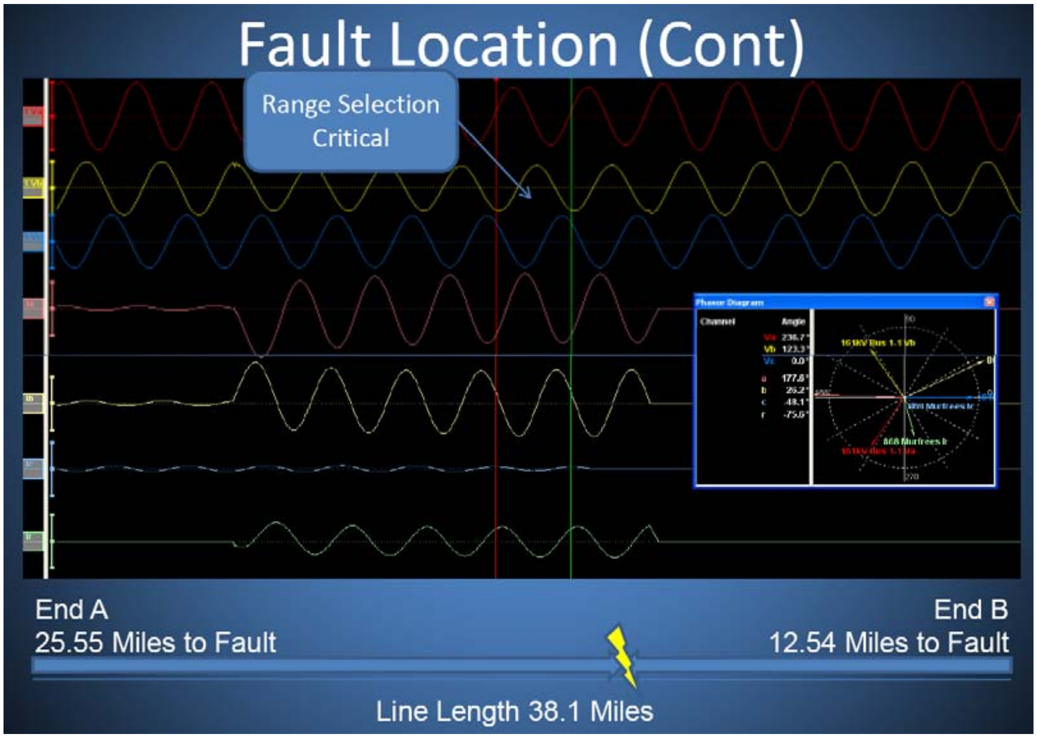

Figure 4 - Fault Location

There were multiple lessons learned from the fault location portion of the study. Good fault location is critical as not all DFR techniques work equally well. Double-ended techniques yielded better result than singled-ended techniques. Different brands of DFRs report the timestamp information differently. Since various DFR brands were used, ensuring that the timestamps are lined up with the beginning of the fault was critical to identifying possible alternative candidates for lightning. Most DMEs do not have sufficient sampling rate and bandwidth to detect the lightning waveform as opposed to detecting the fault generated by the lightning transient.

Case assessment summary:

During the study, 36 prospective cases were identified. 19 of the cases were chosen for detailed analysis. As can be seen in Table 2, below, of the 36 cases, 30 were good correlations with “normal” behavior (two cases appear twice in the table). The remaining cases revealed issues of some kind with either the data or with the line itself, falling into one of three problem categories.

Table 2 - Case Classification			
	Count	**Percent**	**Comments**
Total Cases	36	100	All 161 kV Cases
Non Correlated	0	0	No stroke reports during the flash
Wrong Stroke	1	2.8	Detected different stroke in the same flash
Low Current < 20 kA	3	8.3	Shielding Failure?
Location Error > 1 km	4	11.1	Two cases were also "low current" cases. Others could be a bad fault location or the overvoltage spread to a weak point.

Location Error Analysis:
As seen in Table 2, there were four cases where the fault location and the lighting location differed by more than 1 km. In the 19 test cases, the maximum distance from the lightning event to the line was 2066 m (Dist-to-line) while the median distance was 220 m. However, the maximum distance to the estimated fault location was 5350 m (Dist-to-fault) while the median distance was 273 m. This can be seen in Figure 5, below. The four "large-error locations" were re-calculated using Vaisala's new location algorithm. All four positions changed by less than 100 m as a result of this re-calculation, probably because of the large number of sensors (at least 5, typically more than 9) that reported these strokes. The only two strokes that were more than 1 km from the line were two of the three low-current cases (with peak currents of -9.2 kA and -16.7 kA). We do not know of cause of these location errors, but it is possible that the lightning channels were substantially non-vertical, which is common in low-current first strokes (Biagi et al., 2007, Section 3.8).

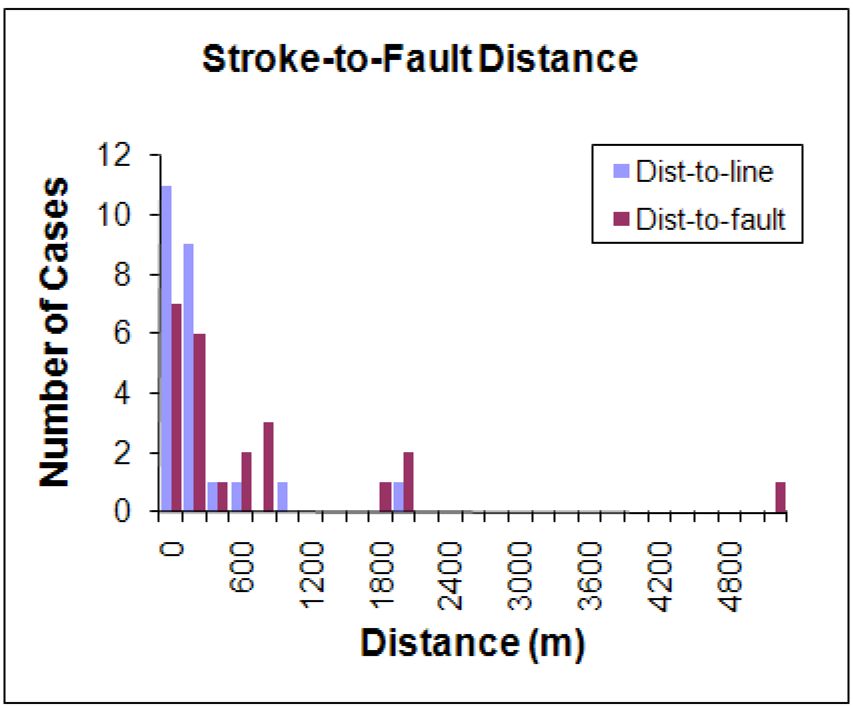

Figure 5 - Stroke to Fault Distance

With regard to the other two “large error” cases with large distance-to-fault (but small distance-to-line), the singled-ended fault locations may not be sufficient to gauge the accuracy of the lightning data. Typical relative errors using impedance based fault location are in the range of 3-6% of the line length. These results call into question the validity of the fault location calculations. Other theories remain, for example it may be possible for an over-voltage to travel several spans and flash over a weak insulators, as can be seen in Figure 6, below. This causes the flashover being spread along the line, which may negatively impact the fault location calculations.

Figure 6 - Wave Travels to Weak Insulator

Even fault locations calculated using the double-ended measurements were not always accurate. Figure 7, below, shows the location analysis for our worst-case disagreement where the distance-to fault was 5.35 km but the distance-to-line was 55m. The line structures are depicted by small blue diamonds and the DFR-based fault location falls along the magenta-highlighted region of the line. The computed location of the -104 kA stroke (blue circle) is obscured by small open green squares that show the position uncertainty associated with the timing and angle information from each of the 15 reporting NLDN sensors. The figure inset provides a zoom-in on the region of the stroke location. All but one sensor report has a positional uncertainty less than 200m. We suspect that either there were multiple simultaneous lightning attachments to this line, or there was significant error in the calculated fault location.

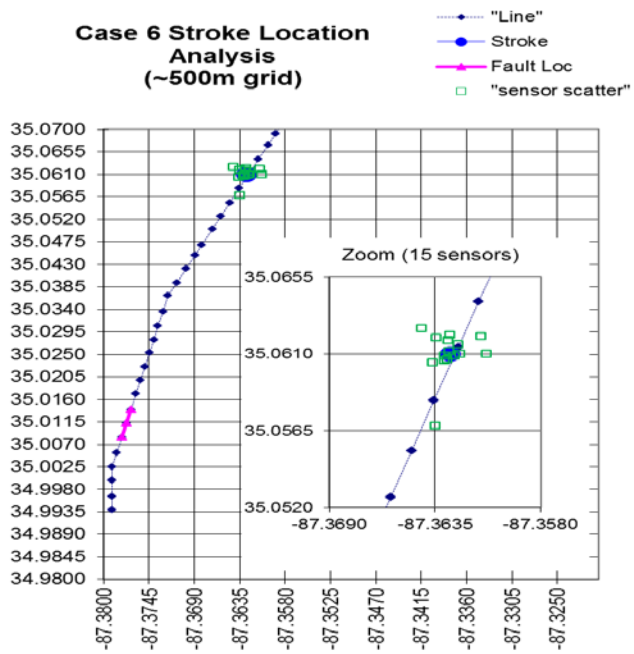

Figure 7 - Fault Location Error

Low-current cases:
The three low-current cases (peak current less than 20 kA) were clearly low-current strokes. This was validated by (1) evaluating the consistency among the NLDN sensors that reported the stroke, and (2) looking at the VLF waveforms. One of these cases (-18 kA) occurred along a 300m span leading into a substation, which could have affected shielding angles. A second low-current case (-16.7 kA) may have been associated with an upward attachment, initiated by a very high-current discharge located about 2 km away and 60 ms earlier. The third low-current case was a -10 kA stroke. Further analysis should help us determine if this was a shielding failure or a local insulation level problem.

There was also a -22 kA fault-causing stroke that is worth mentioning here. Interestingly, two faults occurred along a 1.1 km (0.68 mile) span over a river during the summer 2009 study period. One was this -22 kA stroke and one was a -56 kA stroke. Both strokes were located within 600m of the structure in the east side of the river. Clearly, there is a shielding or insulation problem at/near this structure.

Wrong stroke case:
There were no “non-detect” (not correlated at the flash level) case, but there was a missed first-stroke of a multi-stroke flash – later strokes in the flash were reported. This -122 kA stroke was reported by 44 NLDN sensors, but the online (real-time) location algorithm found too much inconsistency among the nearby reporting sensors. Qualitatively, we have experienced similar “occasional” failure of the NLDN to report high-current strokes. Interestingly, this flash caused the Optical Phase Ground to melt, associated with a phase-to-phase sag lasting 4 cycles. Analysis of the ELF/VLF data for this flash indicates a ~400 amp, 100ms long continuing current

after the first stroke. The estimated total charge transfer during this flash was approximately 70 Coulombs, which is a “1-in-1000” occurrence for negative flashes.

Next Steps

While the current phase of this research is not quite complete, many lessons have been learned. However, it is already apparent that there is a need for additional research. For example, based on the gaps we have already identified it is clear that outfitting some lines with additional instrumentation is desirable. The exact nature of the instrumentation, be it additional lightning measurement equipment or more sensitive DME equipment, is unspecified. However, the following may be considered:

- Instrumented structures to measure transients
- Instrumented structures to collect lightning information
- Instrumented substations to collect lightning information
- Camera systems to collect lightning information

Discussion and Conclusions

The NLDN lightning network provided reliable and useful data for identifying root cause of problems on the power system, reporting more than 95% (35 of 36) fault-causing strokes with reliable peak current and location estimates. Vaisala’s improved location algorithm had little impact on the calculated locations in this study, presumably because of the large number of NLDN sensors that detect fault-causing strokes. Single-ended DFR fault locations appear to be less accurate than the lightning locations. There were three faults on 161 KV lines (~10% of the cases studies) that were unquestionably caused by strokes with peak currents below 20 kA, warranting careful line inspection and modeling. Finally, using the NLDN data in conjunction with other data sources like DFRs and VLF/ELF electromagnetic sensors produced the best results for root cause analysis of power system events.

References

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Cummins K and Murphy M. (2009), An Overview of Lightning Locating Systems: History, Techniques, and Data Uses, With an In-Depth Look at the U.S. NLDN (2009 - invited paper), IEEE Transactions on Electromagnetic Compatibility, Vol. 51 (3), pp. 499-518, August 2009.

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Jerauld J., V. A. Rakov, M. A. Uman, K. J. Rambo, D. M. Jordan, K. L. Cummins, J. A. Cramer (2005), An evaluation of the performance characteristics of the U.S. National Lightning Detection Network in Florida using rocket-triggered lightning, J. Geophys. Res., 110, D19106, doi:10.1029/2005JD005924.

Appendix

Sensor Summary Report

TVA/EPRI Project 2009-10

Ken Cummins
May 2010

Fault Information

Date/time (CDT): September 17, 2009 05:36:17.584 CDT
September 17, 2009 10:36:17.584 GMT

Brief Summary:

"Normal" Phase C-to-ground fault

Fault Reference Number:

Case 2: L5610 "Line Name"

Basic NLDN Sensor Reports:

Total # of sensors seeing ground-wave: 16

Total # of sensors seeing ionospheric-propagated waves: 41

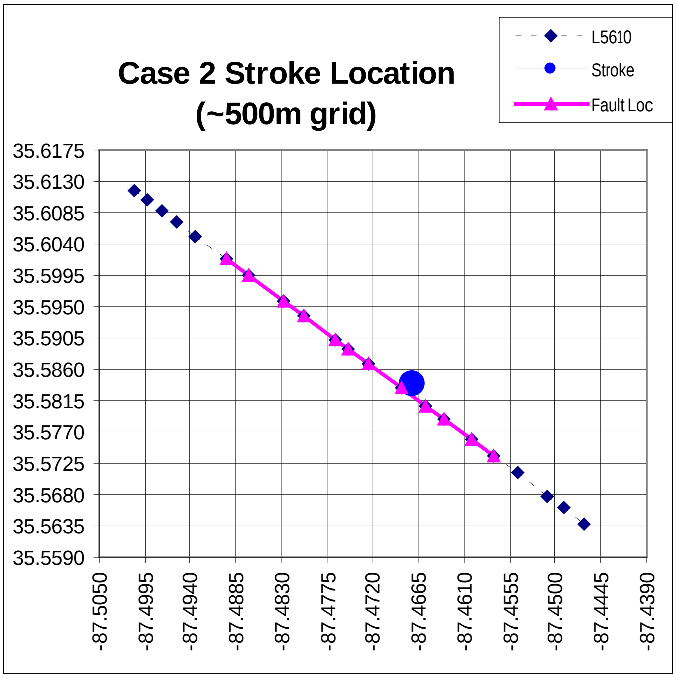
Waveform Parameters:

Sensor	SignalStr	Dist(km)	RT(µS)	PTZ(µS)
006	-307.0	126.7	10.2	30.2 (max)
024	-247.1	143.0	10.0	30.2 (max)

NLDN Location Report:

Location Information:

Date	time(GMT)	lat	lon	Ip(kA)	SMA(km)	Chi	NSR
09/17/09	10:36:17.578	35.5838	-87.4672	-71.9	0.4	0.7	16

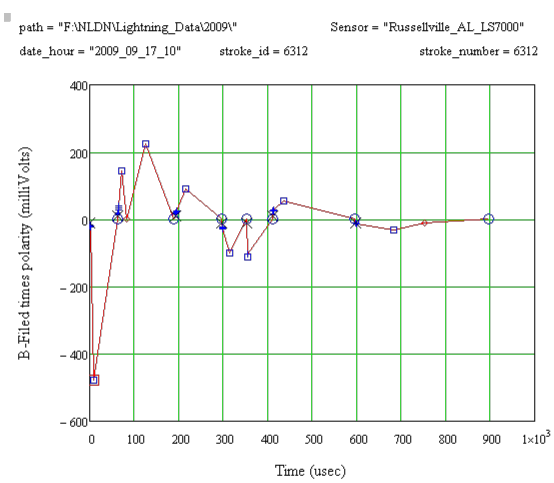


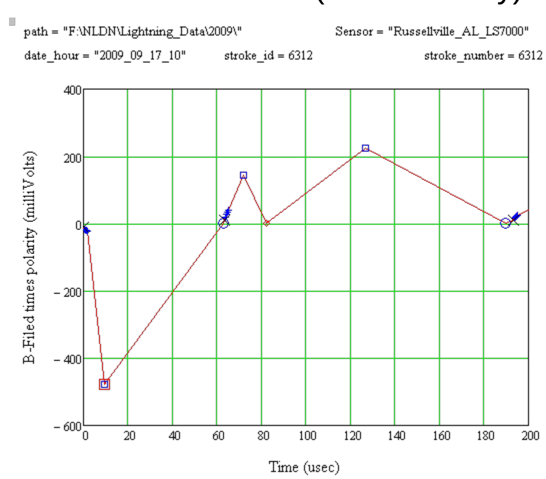
The stroke location is within 129m of structure 192. This structure is within the fault location uncertainty region specified by TVA.

Sensor Peak Current Variation: +/- 4.5 kA (RMS)

New Sensor Parameters:

Waveform reconstructions: Russellville sensor site (130 km away)





Parameters:

Risetime: 9.6 µs
PTZ time: 53.3 µs

Rise Shape: single peak
Impulse Duration: 62.9 µs

VLF/ELF Waveform Analysis:

We compute an impulse charge transfer to ground of –14.6 C for the first stroke, not unusual for a high peak current stroke. Strokes 2 and 3 contained impulse charge transfers of -2.3 and -3.7 C.

Following stroke 1 the flash contained a weak signature of long continuing current, with an estimated maximum of 300A. This continuing current lasted approximately 250 ms and transferred no more than 75C to ground.

Flash Summary:

The fault-causing stroke was the first of 3 strokes reported by the NLDN. The NLDN report all discernable strokes. The subsequent strokes were low-current. Relevant stroke and flash parameters are shown below. Unusual values are highlighted in yellow.

Stroke Time	**Interstroke Time (ms)**	**Peak Current (kA)**	**Rise-time (μs)**	**Impulse Charge (coulombs)**	**Continuing Current Charge (coulombs)**
10:36:17.578	--	-72	9.6	-14.6	<75
10:36:17.578	36	-13		-2.3	--
10:36:17.578	138	-16		-3.7	--

Interpretation:

The NLDN provided accurate measurements for this flash. This was a moderately high-power flash. The large first stroke peak current (~72 kA) produced the fault. The first-stroke risetime was somewhat long. The total charge transfer during the flash was moderate.

Fault Summary Report

Draft by Theo Laughner
September 21, 2009
Modified KLC in 2010

Line Name 161 kV

Fault Information

Fault Reference Number: 92087 (Case # 2)
Date/Time (CDT/CST based on DST Rules): 9/17/2009 5:36:18 (Fault Time) 5:36:17.578 (Stroke Time)

Location Information

Points of Interest (i.e. Structures)

Point Description	Latitude	Longitude
Str.191	35.586	-87.472
Str. 192*	35.583	-87.468
Str. 193	35.580	-87.465

Quality of location and fault time information

Terrain Description

Rolling Hills

Natural Shielding/Easement Description

Trees

Electrical Information

Phases Involved

Phase C to Ground Fault

Structure Build Description

Tower: E20, Double Circuit, Configuration: Vertical, Shield Wire(s): 2, Insulator: 11 bells

Arrester Configuration

None

Ground Quality

Counterpoise on Strs. 182-192, 194, 199 and 200

Comments:

*TVA selected structure