2016 24th International Lightning Detection Conference &
6th International Lightning Meteorology Conference
18 - 21 April | San Diego, California, USA

Lightning Studies To Improve Power Quality

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***Abstract*—Lightning is a considerable source of downtime, lost productivity, and reduced revenue for electric utility consumers. In order to quantify this impact, TVA has developed an indicator to track impacts to large industrial customers. It is necessary to understand lightning trends in frequency and magnitude to prioritize mitigation efforts in a way that optimizes benefits for TVA customers. Through these efforts lightning risk is reduced and customer satisfaction is improved.**

Keywords—lightning, sag indicator, customer satisfaction

I. INTRODUCTION

Electric utility customers have continuously increasing expectations of the power system. Consequently, tracking reliability alone is no longer sufficient to assess customer pain with regard to events on the power system. Many customer-based groups have developed curves like the ITIC and CBEMA curves to evaluate compatibility between manufacturing processes and utility infrastructure (IEEE, 2012). In response, TVA's Transmission organization has developed a team of folks to assess power quality.

II. POWER QUALITY

Power Quality is defined as "any power problem manifested in voltage, current, or frequency deviations that results in failure or missed operation of utility or end user equipment" (Roger Dugan, 2003). Necessarily, there are two aspects to power quality: the power source and the end use equipment. By understanding the sensitivity of equipment within the customer facility decisions can be made about where to best remediate power problems. The figure below (EPRI, 2015) shows an example of a sensitive process and the ride through capability of that equipment.

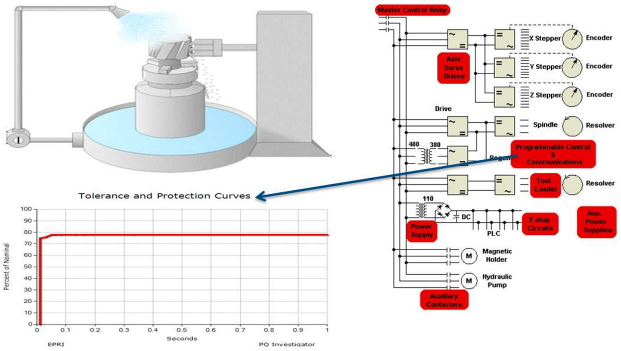


Figure 1 - Sensitive Industrial Equipment

A. *Quantifying Power Quality*

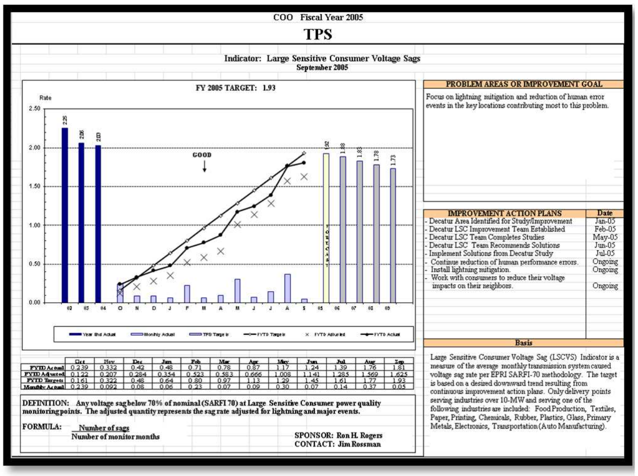
To better understand power system sourced events, TVA created the large sensitive consumer voltage sag (LSCVS) report to track power quality performance of large manufacturing facilities within the TVA footprint. This enabled TVA to begin finding trends in voltage sag issues based on location, frequency, type, and financial impact. These trends, in turn, allowed TVA to prioritize work, which maximizes the benefit to both customers and TVA.

The data for the report comes from one of the 1500 power quality monitors, digital fault recorders (DFRs), and power quality–enabled revenue meters. The data are collected from these meters on a daily basis and stored in PQView®. When a power quality meter is unavailable at a particular consumer, DFR data are used to represent performance at a given location. If necessary, the events are manually added into the site inside of PQView.

After the events are in the system, each one is reviewed to identify source and root cause. The source is either TVA or the consumer. Identifying a source as TVA enables personnel to focus on issues sourced on the transmission system. Further, it helps staff work with consumers to resolve issues that are sourced on the downstream side of the meter. Next, the root cause is identified for each event. An example cause is lightning. In some cases, the root cause cannot be identified. In these cases, the event is categorized as unknown.

Many of the performance indicators within TVA have a strong weather correlation. The LSCVS indicator is no different. The indicator has a weather normalization factor to account for years when lightning is particularly low or high. The indicator is adjusted accordingly.

After all of the categorization and normalization, the indicator is produced and distributed within the company. All of the voltage sags below 70% of nominal are counted. This number is divided by the number of monitors to produce a sag rate for the month. A cumulative trend is tracked throughout the year. The indicator is shown in the figure below.


COO Fiscal Year 2005

TPS

Indicator: Large Sensitive Consumer Voltage Sags
September 2005

FY 2005 TARGET: 1.93

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
FYTD Actual	0.239	0.332	0.42	0.48	0.71	0.78	0.87	1.17	1.24	1.39	1.76	1.81
FYTD Adjusted	0.122	0.207	0.284	0.354	0.523	0.583	0.666	1.008	1.141	1.285	1.569	1.625
FYTD Targets	0.161	0.322	0.48	0.64	0.80	0.97	1.13	1.29	1.45	1.61	1.77	1.93
Monthly Actual	0.239	0.092	0.08	0.06	0.23	0.07	0.09	0.30	0.07	0.14	0.37	0.05

DEFINITION: Any voltage sag below 70% of nominal (SARFI 70) at Large Sensitive Consumer power quality monitoring points. The adjusted quantity represents the sag rate adjusted for lightning and major events.

FORMULA: $\frac{\text{Number of sags}}{\text{Number of monitor months}}$

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PROBLEM AREAS OR IMPROVEMENT GOAL

Focus on lightning mitigation and reduction of human error events in the key locations contributing most to this problem.

IMPROVEMENT ACTION PLANS	Date
- Decatur Area Identified for Study/Improvement	Jan-05
- Decatur LSC Improvement Team Established	Feb-05
- Decatur LSC Team Completes Studies	May-05
- Decatur LSC Team Recommends Solutions	Jun-05
- Implement Solutions from Decatur Study	Jul-05
- Continue reduction of human performance errors.	Ongoing
- Install lightning mitigation.	Ongoing
- Work with consumers to reduce their voltage impacts on their neighbors.	Ongoing

Basis

Large Sensitive Consumer Voltage Sag (LSCVS) Indicator is a measure of the average monthly transmission system caused voltage sag rate per EPRI SARFI-70 methodology. The target is based on a desired downward trend resulting from continuous improvement action plans. Only delivery points serving industries over 10-MW and serving one of the following industries are included: Food Production, Textiles, Paper, Printing, Chemicals, Rubber, Plastics, Glass, Primary Metals, Electronics, Transportation (Auto Manufacturing).

Figure 2 - LSC Indicator

B. *Improving Power Quality*

The indicator serves as the basis to identify improvement action plans. As part of the analysis, the root cause for each event is identified. From the graph below, it is easy to observe that lightning is the most significant downtime contributor. In 2015, over $8 million US dollars were lost due to lightning activity in the TVA region alone.

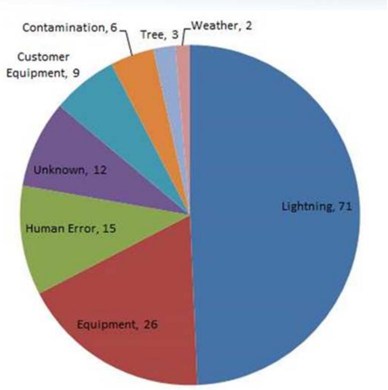


Figure 3 - Downtime Causes

Consequently, customers started to ask if lightning was getting worse. It is important to qualify what is meant by getting worse. Getting worse could be taken to mean happening more frequently. Similarly, it could mean higher peak kA. TVA attempted to answer whether lightning was getting worse using the following approach.

III. TRENDING LIGHTNING

Lightning science is statistical in nature. Very little is known about lightning from a heuristic standpoint. Most literature points to equations that mold lightning data into bins of expected values based on a few physical parameters.

For instance, to determine the number of lightning flashes to a line per 100 kilometers per year, one possible equation is:

$$N=0.004*T^{1.35}*(\beta+4*\eta^{1.09}) \tag{1}$$

where

N = number of lightning flashes to a line per 100 kilometers per year

T = keraunic level in the vicinity of the line (thunderstorm days/year)

η = average height of the shield wires (meters)

β = horizontal spacing between the shield wires (meters).

In this example, the constants 0.004, 1.35, and 1.09 are all used to statistically fit the flash data to known lightning occurrences. These constants can be varied based on the construction of the line, the location, the terrain, etc. It should be noted that this provides a great margin of error. Even if all constants are chosen to accurately represent the data for a year, the next year would require a different set of values.

Even the lightning data networks use a statistical approach to quantify lightning strikes. These networks use a series of detection sites and sensors working in tandem to create a best guess for any particular strike. The equations and algorithms used by these detection networks are refined over time, as the statistical models of lightning detection improves.

Since lightning determination is statistic, it is valuable to use industry documentation a guide and develop utility specific statistics. Quantifying lightning data is more complex than simply counting strikes in an area and setting a trend line. With modern lightning data networks and data tools, finding some additional insights in lightning trends can prove valuable to the bottom dollar cost of improving lightning performance of utility assets.

With millions of strikes per year in the U.S. alone, lightning determination is best summarized by three sub-data types: geographical location (latitude and longitude), time, and finally magnitude. Other factors can have some impact such as strikes per flash, incidence angle, area of certainty, and type (such as cloud to ground with positive or negative polarity, or cloud to cloud).

Location is the top tier data distinction since location on earth is the most influential part of any lightning statistic. Some locations see much greater amount of lightning than others based on their geography. For example, Florida sees a much larger number of strikes per year than California. Not only is that facet of location an important part of lightning trending, but most utilities are only interested in their own footprint.

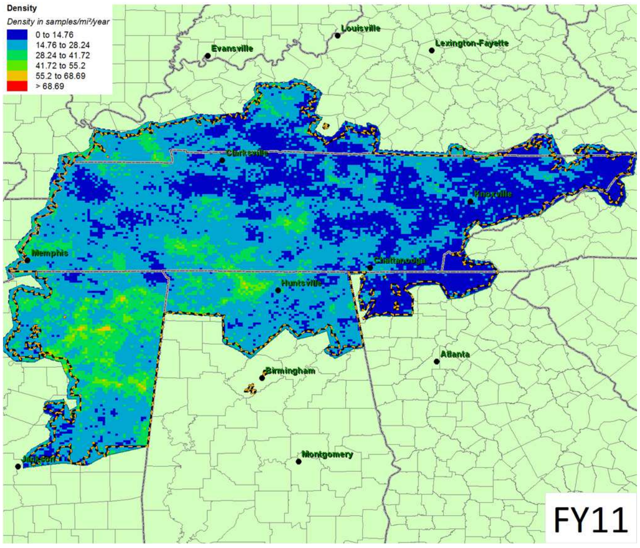
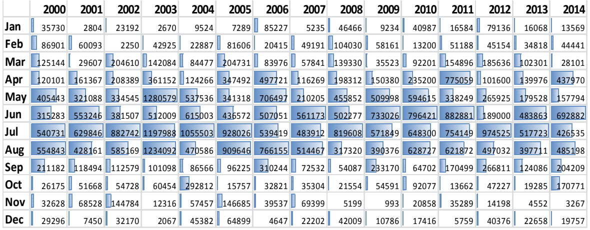


Figure 4 - Lightning Flash Density Map

Time is the second most important way to separate the data out. As climate follows a yearly pattern with Earth's orbit, so do lightning trends. The time deviations can be by year, month, hour, season, etc. However, yearly trends provide the best insight to lightning patterns in a given area. Below is a chart that shows lightning per year per month in the TVA service region from 2000 to 2014.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Jan	35730	2804	23192	2670	9524	7289	85227	5235	46466	9234	40987	16584	79136	16068	13569
Feb	86901	60093	2250	42925	22887	81606	20415	49191	104030	58161	13200	51188	45154	34818	44441
Mar	125144	29607	204610	142084	84477	204731	83976	57841	139330	35523	92201	154896	185636	102301	28101
Apr	120101	161367	208389	361152	124266	347492	497721	116269	198312	150380	235200	775059	101600	139976	437970
May	405443	321088	334545	1280579	537536	341318	706497	210205	455852	509998	594615	338249	265925	179528	157794
Jun	315283	553246	381507	512009	615003	436572	507051	561173	502277	733026	796421	882881	189000	483863	692882
Jul	540731	629846	882742	1197988	1055503	928026	539419	483912	819608	571849	648300	754149	974525	517723	426535
Aug	554843	428161	585169	1234092	470586	909646	766155	514467	317320	390376	628727	621872	497032	397711	485198
Sep	211182	118494	112579	101098	86566	96225	310244	72532	54087	233170	64702	170499	266811	124086	204209
Oct	26175	51668	54728	60454	292812	15757	32821	35304	21554	54591	92077	13662	47227	19285	170771
Nov	32628	68528	144784	12316	57457	146685	39537	69399	5199	993	20858	35289	14198	4552	3267
Dec	29296	7450	32170	2067	45382	64899	4647	22202	42009	10786	17416	5759	40376	22658	19757

Figure 5 - Flash Density

Finally, lightning magnitude is a way to further identify lightning trends in a given area during a certain timeframe. It is valuable to know besides just the number of strikes, the number of high magnitude versus the number of low magnitude strikes.

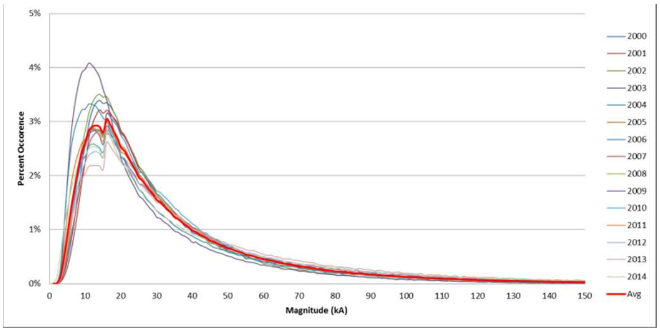


Figure 6 - Lightning Magnitude Probability

All this information together paints a picture when looking at lightning performance of TVA assets. Some immediate conclusions can be drawn from this data:

- Lightning density is higher in the west side of the service territory than the east. This is because the east side of the territory offers natural shielding from the ridges and trees as well as less weather than the lower, wetter west.
- Summertime produces more lightning than winter. This is due to storms developing more often in the summer due to the higher humidity and daytime heating.
- Average strike magnitude is about 20 kA and on average is not moving much. This information helps determine equipment ratings and lightning performance specifications.

IV. Quantifying Lightning Performace

Lightning trending is best evaluated over multi-year studies, usually at least 5 years but preferably 10 to 15 years. Answering the question "is lightning getting worse?" is a difficult problem to assess, while the customer asking is expecting a simple yes or no answer. The bottom line question being asked, however, reads more like "is my equipment more exposed to damage-causing lightning than before?". To answer that we looked to the lightning statistics in the TVA service territory.

Looking at the flash count for individual months over 15, 10, and 5 year studies show some trend in the future expected lightning frequency. Looking at a 15 year window, 6 months trended upwards while 6 months trended downwards in number of flashes. With a 10 year window that changes to 4 trending up and 8 trending down. Looking at 5 years also shows 4 up and 8 down. However, overall the trend for all three durations shows an overall downward trend in number of flashes.

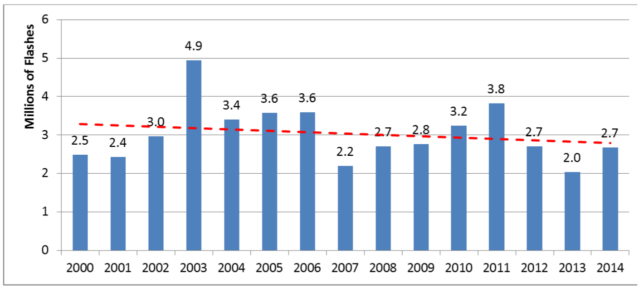


Figure 7 - Flash Quantity Trend

This can be taken to mean that there actually is less lightning being produced every year. Maybe due to pollution or global climate shift or climate patterns in the Atlantic. Or it can be taken to mean that algorithms for detecting lightning flashes have evolved to determine fewer false flashes. Conversely, it is important to remember - lightning science is a statistical game - and just like a roll of the dice, the previous outcome does not affect the future. All that to say, even though there is a downward trend now, that might not always be the case. For TVA values, the average is around 3.04 million flashes per year - an important number to note.

Another facet to consider is the average strength or magnitude of the lightning. Stronger lightning can be more devastating and has a higher chance to break down insulation due to the energy involved. On the contrary, weaker lightning has a chance to bypass shielding by coming in at low angles.

Similar to the analysis of flash quantity, flash magnitude can be trended and depending on the window the correlation can be shown to be upward or downward. Again, this data is subject to statistical anomalies and evolving algorithms. Lightning is not directly measured by an instrument - it is only determined with best guess calculations developed over time. The TVA data shows a slight increase in magnitude over time, but the important point to take away is the average magnitude is about 20 kA.

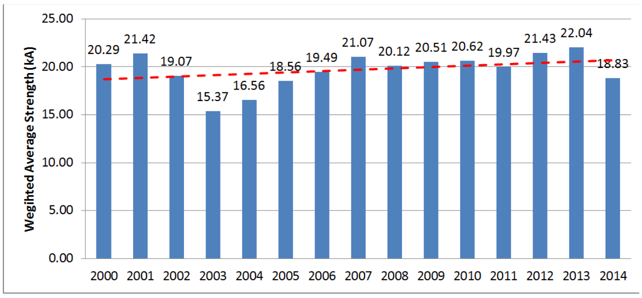


Figure 8 - Weighted Average Trend

The question should not be "is lightning getting worse?" Showing these trends without an associated analysis of exposure or lightning caused outage rates the trend is not meaningful. The takeaway is that on average TVA receives 3 million flashes a year with a normal magnitude of 20 kA. The question should be "what are you doing to make lightning performance better?"

V. IMPROVING LIGHTNING PERFORMANCE

Lightning impacts the reliability of the transmission system by exposing protective equipment to fault conditions. If properly mitigated, transmission lines should be able to route lightning energy around sensitive transmission components to earth ground without interrupting anything. Mitigation techniques include increasing insulation (insulator bells and fiberglass cross arms), installing shield wire or improving the shield wire angle, improving ground resistance (counterpoise), or installing lightning arrestors.

Mitigation is applied on a targeted basis - that is, assets with high exposure to lightning are identified and improved. Data across several 'trouble lines' is analyzed and rank is given in an order of severity. TVA maintains a rolling 5 year count of the following categories as a result of lightning:

- CPI - Connection Point Interruptions - the number of connection points (customers and local power companies) on a transmission line interrupted
- LNS - Load Not Served - the number of system minutes an asset is out and unable to serve load
- Interruptions - the number of bulk interruptions to a line

Each category is interdependent and changes with the system configuration, but is an impact to the reliability of the grid. Each categorical list ranks the 30 worst transmission lines for that particular metric. Each list is concatenated into an overall list, keeping rank data intact. The average rank across all three categories is taken and an overall performance list is created.

This list is used as a jumping point to start mitigation projects. Lines that have recently been mitigated are excluded since it often takes 5 to 15 years to realize the efforts of a mitigation project.

After determining where lightning mitigation projects will be, the line is analyzed to show trends in it's lightning performance over time. A 15 year study is done to show a few key statistics that justify a project. For each year the following data is gathered:

- The count of flashes within a 1 mile buffer
- The number of interruptions caused by lightning
- The length of the line

Valuable trends can be found with a little math using this data, including:

- Exposure - a graph showing the number of interruptions as bars and number of flashes within one mile as a line

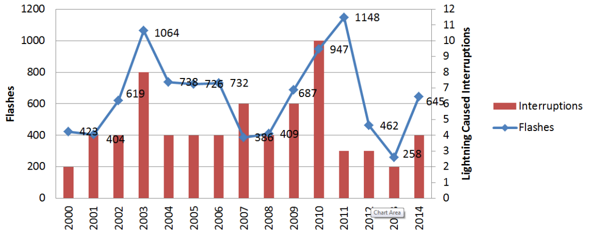


Figure 9 - Exposure

- Outage Rate - Interruptions * Length / Number of Flashes
  - This is a percentage that shows the performance of the line over time while taking into account the length of the line.
  - Shows the future number of interruptions based on historical performance

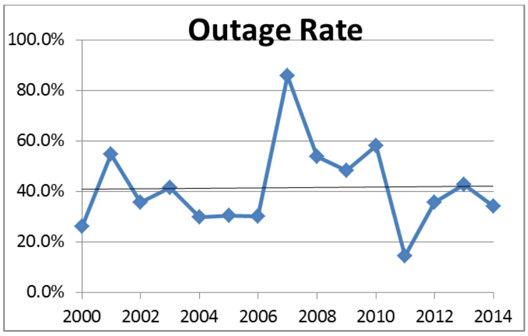


Figure 10 - Outage Rate

- Tripout Rate - Interruptions * (100 km / Length)
  - This rate shows the performance of the line over time with respect to other transmission lines.
  - Makes it easier to compare a 10 km line and a 100 km line

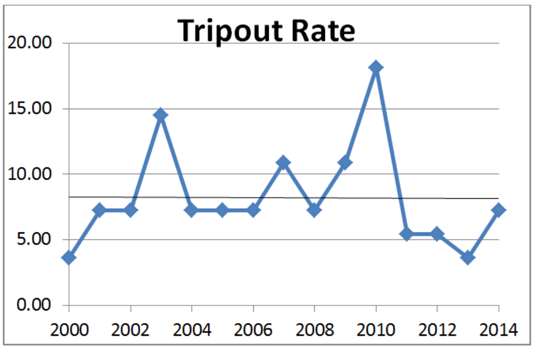


Figure 11 - Tripout Rate

There is a great incentive to reduce transmission line interruptions. The less interruptions there are to the line, the less there are to the customers fed from those lines. Targeted mitigation and statistical analysis of historical lightning performance at TVA provides an efficient way to determine projects and reduce customer exposure to lightning.

VI. CUSTOMER SATISFACTION

A strong relationship exists between how TVA addresses recurring customer issues and customer satisfaction on service delivery. The LSCVS indicator is one tool to allow TVA to focus on one area important to the viability of industry—keeping equipment going. The chart below [Figure below] shows how weather conditions or other operational issues drag this rating down during years with high weather activity or other unusual operational events (such as 2008). The PQ group uses the LSCVS to kick off improvement teams and works toward once again meeting operational needs. TVA has averaged a 93% satisfied customer ranking (with power quality) over the past 10 years.

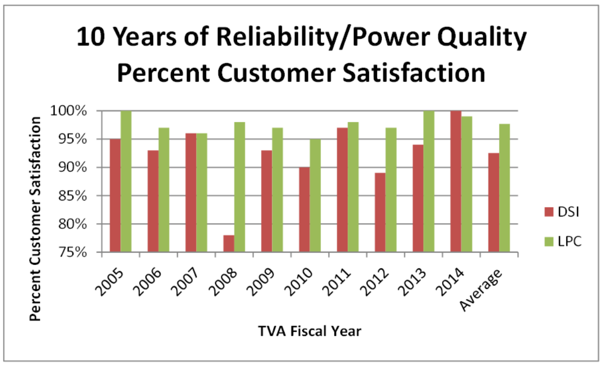


Figure 11 - Customer Satisfaction

VII. CONCLUSION

Educating transmission staff on how their system operations involving lightning impact industry is an important activity. Industries expect their suppliers to continually improve performance and work on reducing recurring events. In 2003, TVA realized it did not have an indicator to track voltage sag performance at delivery points and it established the LSCVS transmission performance indicator. Since that time, TVA transmission has worked to reduce the number of events impacting this indicator. One focused effort toward indicator improvement is to identify where lightning produces significant impacts and work to mitigate that exposure to customers. The LSCVS indicator, along with focus on individual customer concerns, has helped TVA average over a 93% customer satisfaction rating for the large industries over the past 10 years.

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