Exhibit No.___(WWB-4)
Docket Nos. UE-061546/UE-060817
Witness: Walter W. Bruehl

BEFORE THE

WASHINGTON UTILITIES AND TRANSPORTATION COMMISSION

WASHINGTON UTILITIES AND TRANSPORTATION COMMISSION, Complainant, vs. PACIFICORP d/b/a PACIFIC POWER & LIGHT COMPANY Respondent.	)	**Docket No. UE-061546**
In the Matter of the Petition of PACIFIC POWER & LIGHT COMPANY For an Accounting Order Approving Deferral of Certain Costs Related to the MidAmerican Energy Holdings Company Transition.	)	**Docket No. UE-060817**

EXHIBIT NO.___(WWB-4)

LIGHTNING STUDY

February 16, 2007

Lightning Performance Analysis of Pacific Power Company – Cascade Craft Substation

Draft Report, November 2006

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1 INTRODUCTION

Pacific Power has contracted EPRI Solutions Inc. to conduct an engineering study that would analyze lightning protection to their 69 kV sub-transmission and 230 kV transmission systems interconnected to their Cascade Kraft Substation in Wallula, Washington. This study would involve lightning analysis of the transmission system serving Boise Paper in Wallula.

Due to the relatively low lightning incidence in the region, the existing 69KV and 230 kV lines have been designed as having unshielded and ungrounded configuration. With such a construction, backflash is not an issue and all flashovers are caused by direct strokes to the phase wires. The options for improving the lightning performance of such a configuration are very limited.

As a part of this analysis, EPRI Solutions will estimate the types of lightning-induced flashovers, evaluate the influence of various parameters, and investigate mitigation strategies to improve the lightning performance of the system. The desired modeling and simulation activities have been performed using EPRI's TFlash software.

2
TECHNICAL BACKGROUND

Lightning Background

Lightning is the electric breakdown of the air from high electric fields generated when electric charge separates within a cloud. Lightning may flash within a cloud, from one cloud to another, or from the cloud to the ground. Transmission lines are only affected by cloud-to-ground lightning. In the normal scenario, charge separates within a thundercloud—the upper portion becomes positively charged and the lower portion becomes negatively charged. The ground just underneath the cloud becomes positively charged (being attracted to the negatively charged lower portion of the cloud). The lightning breakdown begins in the lower portion of the cloud. The air breaks down in steps called *stepped* leaders. Each step is about 150 feet (50 meters) with pauses of about 50 μs between steps. The stepped leader may fork and form branches that each progress towards the ground. As the stepped leader progresses closer to the ground (see Figure 2-1), more charge is lowered closer to the ground. More positive charge collects on the earth in response—short upward leaders extend to meet the downward negative stepped leader.

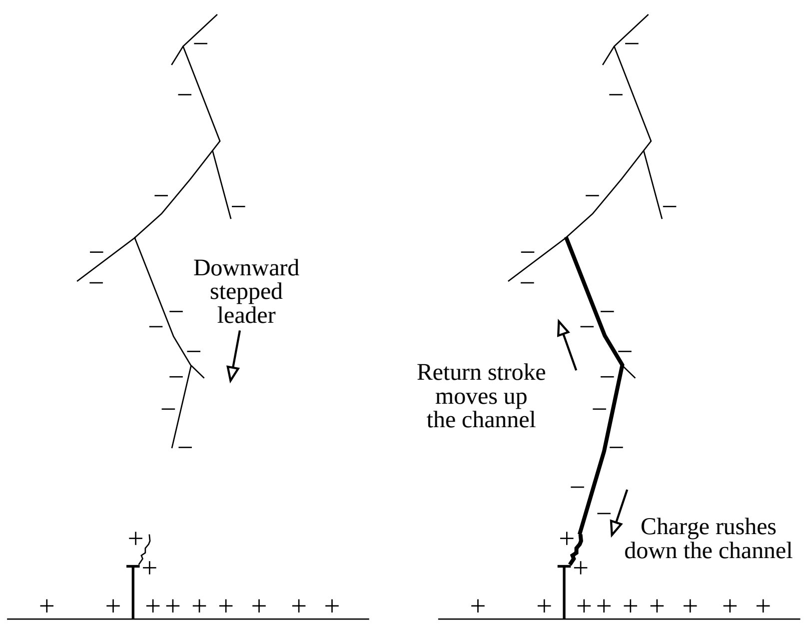


Figure 2-1
Cloud-To-Ground Lightning

When the downward leader meets the upward leader, a *return stroke* occurs—the negative charge held in the stepped leader rushes into the ground, brilliantly lighting the channel and creating a large pressure wave (thunder). The return stroke propagates up the channel at roughly 20% of the speed of light, releasing charge as it goes. The charge rushing into the ground creates a current of tens of thousands of amps peaking in a few microseconds. The current may extinguish in about 100 μs, or lower-level continuing current in the range of hundreds of amps may flow for several milliseconds (about 25% of the time, continuing currents flow following the return stroke).

Subsequent strokes may follow the first stroke. After the current extinguishes and the channel becomes dark, another pocket of charge may work its way down the same path. Fast-moving leaders called dart leaders break down the recently de-ionized path of the first stroke. Subsequent strokes typically have lower magnitudes of current and charge transferred, but subsequent stroke currents have higher rates of rise. Subsequent strokes have higher return-stroke velocities, often greater than 50% of the speed of light. The first stroke and subsequent strokes make up a lightning *flash*.

While the downward negative flash is the most common, other types of cloud-to-ground lightning occur. About five to ten percent of cloud-to-ground flashes are positive. Downward positive lightning lowers positive charge from the cloud to the ground—breakdown starts at a positive portion of the cloud usually near the top of the cloud, a positive downward stepped leader moves downward until it meets an upward negative leader close to the ground. Some positive flashes may have very large peak currents and charge. Positive flashes occur more often during winter storms, especially in certain areas. Positive flashes usually only have one stroke. Cloud-to-ground lightning may also start at the ground and rise upward, with an upward stepped leader starting at the ground. These are common on tall objects like the Empire State Building.

Normally, the lightning current injection is considered an ideal current surge (it doesn't really matter what is struck, the electrical characteristics of the current stay the same). Table 2-1 shows characteristics of a downward negative current flash. Many of the characteristics fit a log-normal distribution, which is common for data bounded at zero. The log standard deviation, $\beta = \mathrm{sd}(\ln(x_i))$, is shown for the characteristics that have a log-normal feature. The 5th and 95th percentiles are shown based on the lognormal fit. The first stroke peak current data does not fit a lognormal distribution, but Anderson and Eriksson found a good fit using two lognormal parameters, one for low currents and one for high currents. Another common approximation to Berger's data for the probability of the peak magnitude of a first stroke is [1]:

$$P(I_0 \geq i_0) = \frac{1}{1 + (i_0/31)^{2.6}}$$

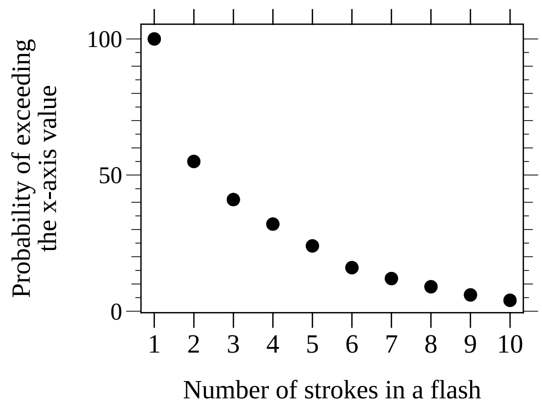
Table 2-1
Lightning Current Parameters for Downward Negative Flashes

Parameter	Percent of Cases More Than Value 95%	50% (*M*)	5%	β
First Strokes				
Peak current, kA	8	33.3	90	
Model for I≤20kA		61.1		1.33
Model for I>20kA		33.3		0.61
Time to peak, μs (virtual front time based on the time from 30% to 90% of the peak=$T_{30\text{-}90\%}$/0.6)	1.5	3.83	10	0.553
Steepness, 30-90%, kA/μs	2.6	7.2	20	0.921
Tail, time to half the peak, μs	30	77.5	200	0.577
Charge, C	1.1	4.65	20	0.882
$\int I^2 dt$, $(A)^2 s \times 10^3$	6	57	546	1.373
Subsequent Strokes				
Peak current, kA	5.2	12.3	29.2	0.530
Time to peak, μs (30-90% virtual front)	0.2	0.67	3.0	
Steepness, 30-90%, kA/μs	4.1	20.1	99	0.967
Tail, μs	6.5	30.2	140	0.933
Charge, C	0.2	0.938	4	0.882
$\int I^2 dt$, $(A)^2 s \times 10^3$	0.6	5.5	52	1.366
Flash				
Charge, C	1.3	7.5	40	1.02
Flash duration, s	0.03	0.2	1	
Number of strokes	1	2-3	9	
Interval between strokes, ms	6	35	202	1.066

Data sources: [2-4].

Although most stroke and flash characteristics are independent of each other, there are some interdependencies. CIGRE [5] examined correlations between various parameters. Larger first strokes tend to have longer rise times. For first strokes, the equivalent front rise time correlates some with the peak current; the average rate of rise does not. For subsequent strokes, the peak current is independent of the rise time, although the peak current partially correlates with the rate of rise. For both first and subsequent strokes, the peak current correlates to some degree with the maximum rate of rise. The correlations are not particularly strong in any of these cases. CIGRE used these interdependencies to find derived distributions that are useful in some stochastic simulations.

More than half of cloud-to-ground lightning flashes are composed of more than one stroke (see Figure 2-2). A quarter of them have at least four strokes. The subsequent strokes usually have less current than first strokes, but the rate of rise of current is higher (important for the inductive voltage rise, $L\mathrm{d}i/\mathrm{d}t$). Subsequent stroke characteristics are thought to be independent of the first stroke.



Data source: [2, 3]

Figure 2-2
Number of Strokes in a Flash

A good percentage of multiple-stroke flashes have subsequent strokes to different points on the ground [6]. This implies that ground flash densities from flash counters and lightning detection networks may underestimate the number of lightning flash ground terminations.

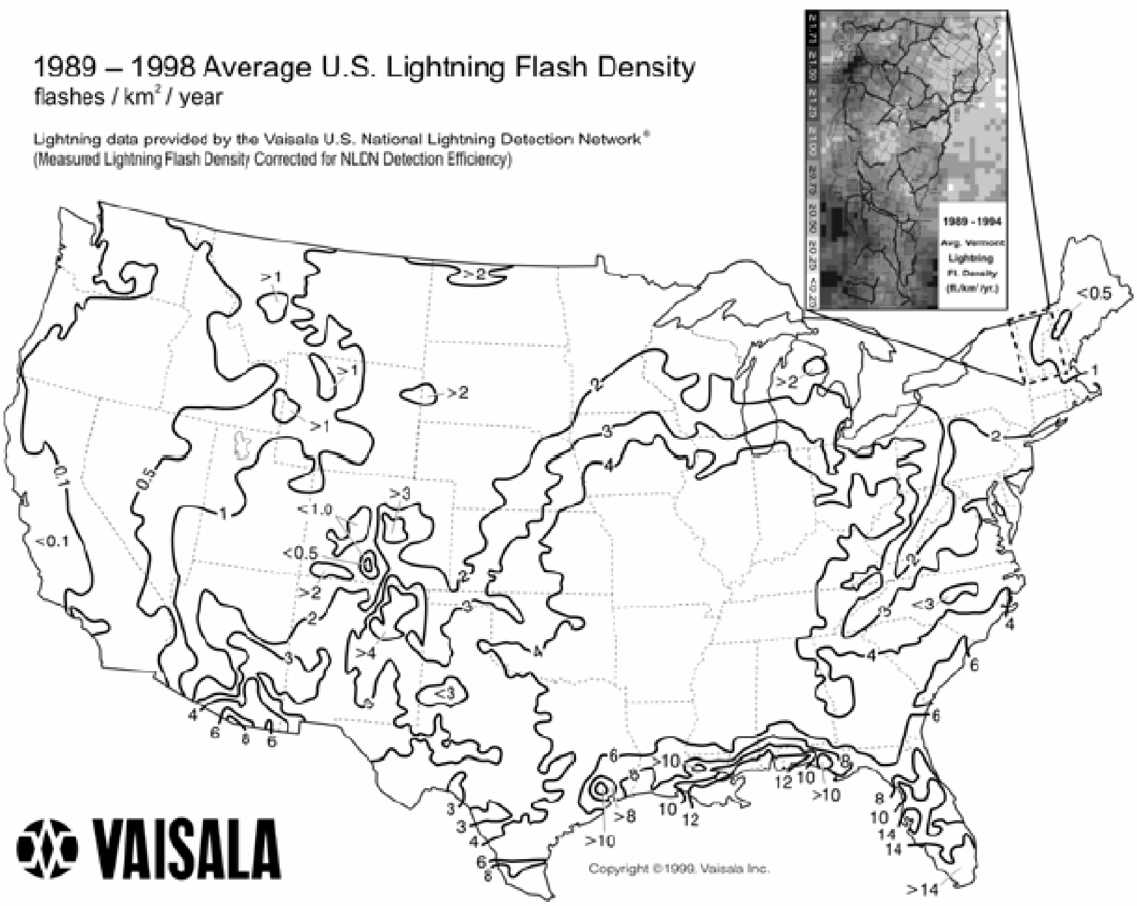
Methods for characterizing lightning incidence include:

- *Keraunic Level of Thunderstorm Days* – the annual number of days with a thunderstorm per year. This meteorology data has been kept by the weather service for at least 50 years so there is a considerable body of data collected.

- *Thunderstorm hours* – The number of hours with a thunderstorm per year. This may provide a better indication of lightning strikes to ground than keraunic level. Weather service data is also available for many years.

- *Ground Flash Density (GFD or N_g)* – The number of cloud-to-ground flashes per unit area and time (usually in flashes/km^2/year). This is the most precise description of lightning activity. It can be directly measured with flash counters or with lightning detection networks. GFD can also be crudely estimated from thunderstorm day or hour records.

Directly measured ground flash density is the best way to characterize lightning. Many areas of the world have lightning detection networks that measure the magnetic and/or electric field generated by a lightning stroke, determine if the stroke is from cloud to ground, and triangulate the stroke's position. Such systems help utilities prepare for storms: information on storm intensity, direction, and location helps determine the number of crews to call-up and where to send them. Maps generated from lightning detection networks of *ground flash density* (GFD or N_g) are the primary measure of lightning activity. Figure 2-3 shows a ten-year ground flash density contour map of the United States from the US National Lightning Detection Network (NLDN), which has been operating since before 1990.

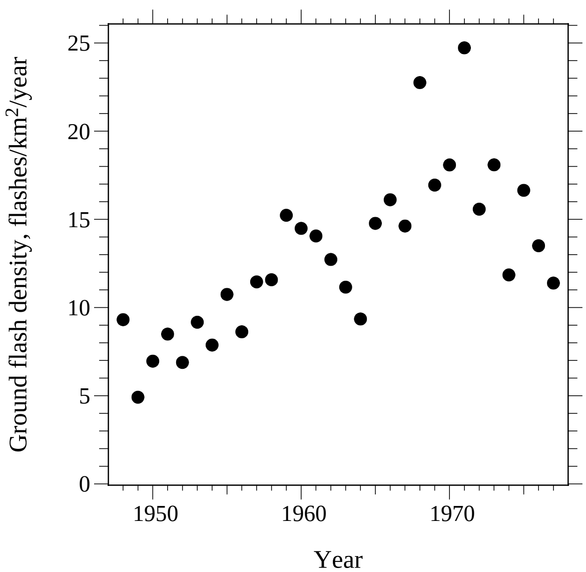


Lightning map provided by Vaisala.

Figure 2-3
Ground Flash Density from the United States National Lightning Detection Network

Lightning detection networks are also useful for correlating faults with lightning. This data helps with forensics and is even used in real time to direct crews to damage locations. From experience with correlating faults with the US NLDN and with camera monitoring studies, the system successfully captures about 90% of strokes. The most important characteristic that allows accurate correlation of faults and lightning is accurate time tagging of power system event recorders including power quality recorders, SCADA, or fault recorders (GPS works well). Position accuracy of detection networks is not good enough to determine if strokes hit a line, but it is good enough to narrow the choices of strokes considerably—almost all strokes found by the US NLDN are accurate to within one mile (1.6 km), with most accurate to 2000 feet (0.5 km).

Lightning is highly variable. It takes several hundred lightning flash counts to obtain modest accuracy for an estimate of the average flash density. A smaller geographic area requires more measurement time to arrive at a decent estimate. Similarly, a low-lightning area requires more measurement time to accurately estimate the lightning. Standard deviations for yearly measurements of lightning activity range from 20 to 50% of the mean [7]. Figure 2-4 shows the variability of ground flash density in a high-lightning area. Lightning and storms have high variability, but it's not completely random. Lightning and weather patterns may have cycles that last many years.



Data source: [8]

Figure 2-4
Estimated Annual Ground Flash Density for Tampa, Florida Based on Thunderstorm-Hour Measurements

The variability of lightning and the variability of storms is also important for utility planning regarding regulatory incentives for reliability and for performance guarantees for customers. Just a few years of data usually does not accurately depict the performance of weather-related events for a circuit or even for a whole system.

Lightning Flashover Types

The insulation for lines is composed of air and solid dielectric insulators. The geometry of the insulators and their insulation strengths are selected to ensure that if an insulation failure occurs, the failure will be a flashover in air. This flashover produces a low impedance path through which 60 Hz power current will flow. Generally, these arcs are not self-extinguishing. To interrupt the power fault will require that a protective device (circuit breaker) operate to deenergize the circuit. Four types of lightning-caused flashover can occur on transmission lines: back flashover, shielding failure, induced, or midspan.

Back Flashover

A back flashover event can occur when lightning strikes a grounded conductor or structure. In this case, a flashover proceeds backward from tower metal to the insulated conductor. A lightning stroke, terminating on an overhead ground wire or shield wire, produces waves of current and voltage that travel along the shield wire. At the tower/pole, these waves are reflected back toward the struck point and are transmitted down the tower/pole toward the ground and outward onto the adjacent shield wires. Riding along with these surge voltages are other surge voltages coupled onto the phase conductors. These waves continue to be transmitted and reflected at all points of impedance discontinuity. The surge voltages are built up at the tower/pole, across the phase-ground insulation, across the air insulation between phase conductors, and along the span across the air insulation from the shield wire to the phase conductor. If this surge voltage exceeds the insulation strength, flashover occurs. The parameters that affect the line back flashover rate (BFR) are:

- Ground flash density
- Surge impedances of the shield wires and tower/pole
- Coupling factors between conductors
- Power frequency voltage
- Tower and line height
- Span length
- Insulation strength
- Footing resistance and soil composition

Sometimes, the design engineer can vary the shield wire surge impedance and the coupling factors, for example, using two shield wires instead of one. Normally, only insulation and footing impedance can be varied to improve back flashover performance. Reducing the footing impedance directly reduces the voltage stress across the insulator for a given surge current down the tower.

Shielding Failure Flashover

A shielding failure is defined as a lightning stroke that terminates on a phase conductor. For an unshielded line, all strokes to the line are shielding failures. For a transmission line with overhead shield wires, most of the lightning strokes that terminate on the line hit the shield wire and are not considered shielding failures.

The calculated number of shielding failures for a particular transmission line model depends on a number of factors, including the model's electrogeometric parameters; the stroke current distribution; and natural shielding from trees, terrain, or buildings. Not all shielding failures will result in insulator flashover. The critical current is defined as the lightning stroke current that, injected into the conductor, will result in flashover. The critical current for a particular transmission line conductor is calculated by:

$$I_c = \frac{2*(CFO)}{Z}$$

Where:
CFO = lightning impulse negative polarity critical flashover voltage
Z = conductor surge impedance

Induced Flashover

Severe transient overvoltage as can be induced on overhead power lines by nearby lightning strikes. On lower voltage distribution power lines, indirect lightning strikes cause the majority of lightning-related flashovers. Estimation of indirect lightning effects is crucial for proper protection and insulation coordination of overhead lines. The problem of induced flashovers from nearby lightning strikes has received a great deal of scientific attention in the past 20 years, and the result has been the development of more accurate estimation models of lightning-induced overvoltages.

Important points to remember when dealing with induced flashovers from nearby lightning strokes include:

- Insulator CFO voltages above approximately 400 kV prevent nearly all induced flashovers.

- The presence of an effectively grounded overhead shield wire or neutral on the line will reduce insulator voltages by 30–40%, depending on the line configuration.

- Line surge arresters installed every few spans can improve induced flashover performance for distribution voltage lines (spacing line arresters in this manner will seldom improve direct stroke lightning performance, only induced flashovers, and it is not recommended for transmission lines).

Midspan Flashover

Power line flashovers caused by lightning strokes near midspan are unusual for most line configurations. Midspan flashovers become more likely when midspan conductor spacing is small, such as on distribution lines, or when span lengths are very long (304.8 m or more). The voltage on a conductor follows the equation presented for a shielding failure. If the voltage rises to approximately 610 kV/m in the air gap between conductors, a long, relatively slow breakdown process might occur that might take many microseconds to complete.

Mitigation Methods

When transmission line lightning performance is unacceptable, several corrective actions are possible. The four main lightning mitigation measures are improved shielding, improved grounding, increased line insulation, and application of transmission line surge arresters.

Shielding

Adding or moving shield wires is one method of improving the lightning performance of a transmission line. A poorly placed shield wire can allow an excessive number of lightning strokes to attach directly to the phase conductors and cause flashovers. Improved shielding will reduce the number of shielding failures and their resulting flashovers on a transmission line.

Grounding

Reducing the ground impedance of a tower reduces the voltage developed on the structure when a lightning stroke hits the structure or shield wire. A lower crossarm voltage will reduce the insulation stress during a lightning event and reduce the number of back flashovers for the line. When soil resistivities are high, counterpoise is sometimes used to obtain acceptable footing impedances. Both continuous and radial counterpoises have been commonly used. The measured resistance of a continuous counterpoise can be near zero, while the actual dynamic impedance during a lightning event is much higher. Transient currents travel much slower in conductors buried in the earth. During the first few microseconds of a transient lightning event, only a small segment of a continuous counterpoise will carry lightning current. Consequently, during a lightning event, a given length of counterpoise with many radial sections attached to one tower will provide a lower dynamic impedance than the same total length of continuous counterpoise.

Insulation

The impulse flashover strength of an insulator is roughly proportional to its dry arc length. Usually on an existing transmission line design, there is not much room to significantly increase insulator length. Small increases in length will have little effect on shielding failure flashovers, but the improved insulation can have a significant effect on induced flashovers if the original insulator CFO voltage was below approximately 400 kV.

Transmission Line Surge Arresters

Spark gaps were one early form of lightning protection equipment used on power systems. The MOV lightning arrester eliminated the lightning arrester spark gap. A characteristic of the MOV material is that it essentially does not conduct at normal line voltage. At the surge overvoltage level, the MOV material goes smoothly into conduction and returns to a nonconductive state when the voltage returns to normal levels. The volt-time characteristic of the MOV arrester is only moderately affected by the rate of rise of the surge impulse.

Metal oxide surge arresters, first developed in 1968, were introduced in the United States in 1977. Because of concern for the stability and life of the metal oxide, these first station class arresters contained gaps to reduce the normal power frequency voltage placed on the blocks. Subsequently, the gaps were eliminated with improved block formulations, and the present gapless arrester evolved.

Without a gap, the normal power-frequency voltage continuously appears across the metal oxide, producing a few milliamperes of current. This low-magnitude current is not harmful. However, higher currents resulting from power-frequency voltage excursions, or temporary overvoltages (TOV) during faults or ferroresonance, will produce heating in the metal oxide. If the TOVs are sufficiently large in magnitude and long in duration, temperatures might increase enough to cause thermal run-away and an arrester failure.

The main voltage rating system for Transmission Line Surge Arresters (TLSA, see Figure 2-5) is Maximum Continuous Operating Voltage (MCOV). As the name implies, the MCOV is the maximum lineto- ground, power-frequency voltage (RMS) that can be continuously applied across the arrester. Voltages above the MCOV will cause the arrester to change impedance and absorb excessive energy from the system. Depending on the overvoltage and length of time the voltage is applied, arrester life might be shortened, or the arrester might be completely destroyed. Arrester manufacturers specify both the MCOV and the length of time voltages in excess of the MCOV can be applied without damaging the arrester. Typical TLSA can withstand 150% of the MCOVfor 5 seconds and 110% of the MCOV for 2000 hours with no loss of arrester life.

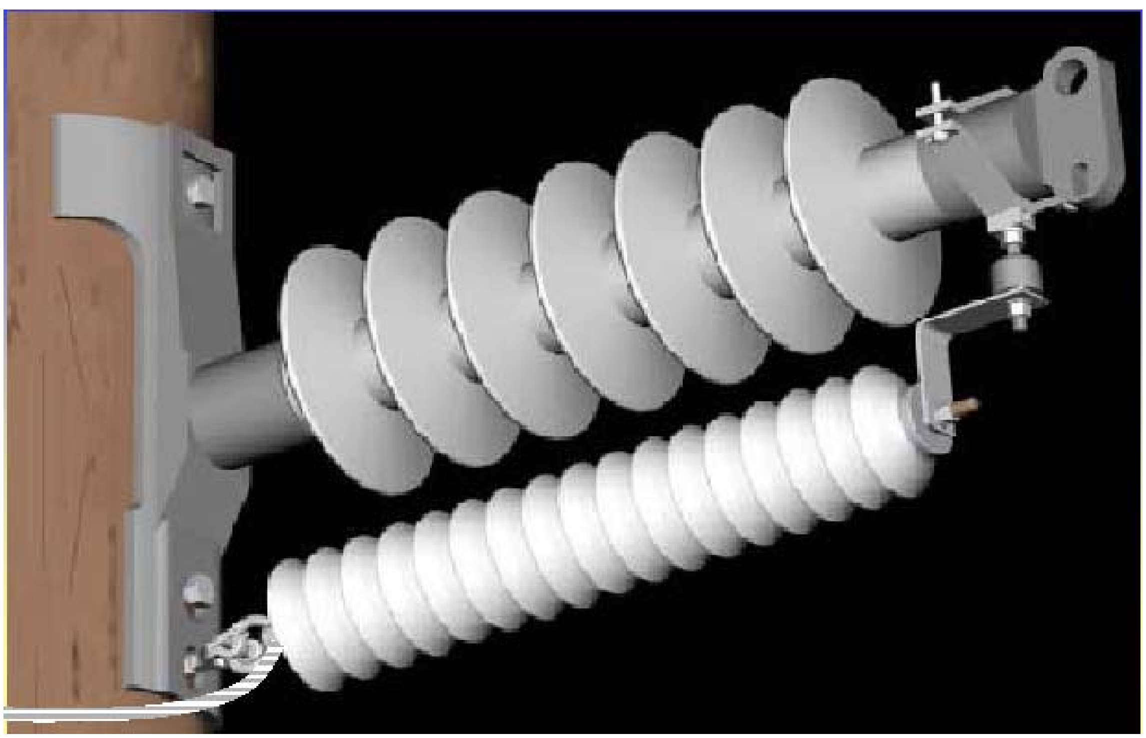


Figure 2-5
Transmission Line Surge Arrester in parallel with an Insulator

To prevent insulation flashover, Transmission Line Surge Arresters (TLSAs) are designed to limit voltages between phase conductors and the tower structure. TLSAs will prevent lightning-related flashovers in both high footing resistance areas (backflash prevention) and poorly shielded designs (shielding failure prevention), provided they are selected and located properly. Reducing the ground impedance on a transmission line that is experiencing many shielding failures will not help improve the lightning performance of the line. Shielding failure flashovers can be prevented only by improving shielding or by installing TLSAs. On transmission lines up to 230 kV, TLSAs have been applied in the United States for many years with excellent results.

When there is no overhead shield wire, installing surge arresters at every insulator location will prevent most flashovers, but the lack of a shield wire reduces the effectiveness of energy sharing between the neighboring arresters. Arrester energy duty for this application is evaluated as part of the analysis in Chapter 4.

TFlash Program Description

The TFlash program has two major components. The first section of the program, where users build a model of the line to be analyzed, is shown in the top portion of Figure 2-5. The second section of the program, shown in the bottom portion of Figure 2-5, takes data from the line model to build the electrical model for the traveling wave simulation and creates the reports.

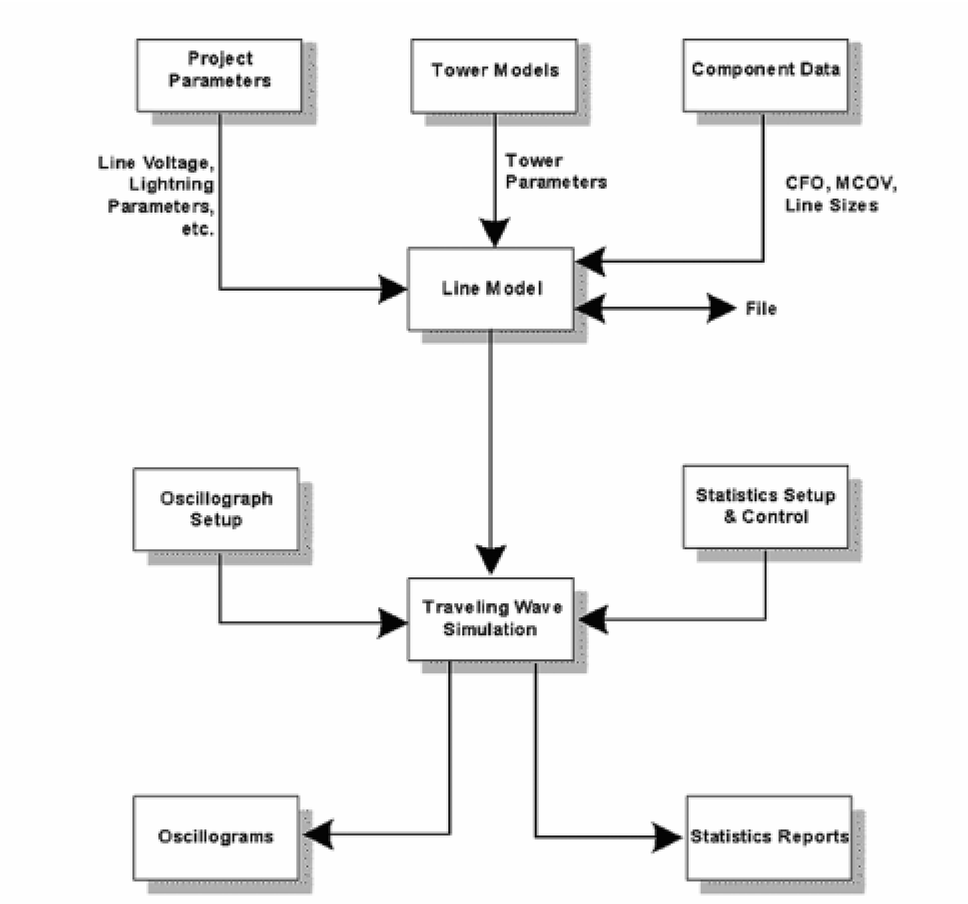


Figure 2-6
TFLASH Program Functional Block Diagram

Building a TFlash model involves the selection of towers, wires, insulators, arresters, and ground types. The user can also modify the dimensions and characteristics of the line components. The second part of the program extracts data from the model to create an electrical model of a short section of the line to be used in the simulation. It then applies the lightning current to the line and simulates the propagation of the current along the lines and towers.

Statistics Calculation Algorithm

The basic method of determining the statistical performance of a line is to divide the line into short sections by making slices across the right of way (ROW). The start and end points for making slices across the line is determined by the user options entered in the Statistics Wizard and is done according to one of these methods: Whole Line Slicing, Line Subset Slicing, or Repeating Line Segment Slicing.

The program then steps along the line one slice at a time. The length of a slice step is set to a default value that should be acceptable for most transmission lines. This value can be viewed or changed on the Advanced Calculation Options tab. This value should provide three to four slices per span. If the model has many short spans, the user might want to decrease this value. If the model has only very long spans, the user can speed up calculations by increasing this value.

At each of these slices, a cross-section of the line is made that represents all the wire locations though it. This cross section is what is used by the Stroke Incidence Table (SIT) calculation. This SIT gives the relative probability of each stroke current hitting each wire in that slice. Once a SIT is calculated, the probability of each stroke current hitting each wire can be determined from the length of the section between slices, the GFD, and the selected stroke current probability.

The next step is to apply the stroke currents to the wires and determine which insulators flash over. This is done using a Traveling Wave model of the towers and wires. To simplify and speed up calculations, the program takes the towers that the user has entered and selects a subset to use for the traveling wave simulation at each slice location. This subset can be the whole set of towers if the described line is short. The subset can also consist of multiple copies of each tower if the user selects the Repeating Line Segment calculation options. The blocks of towers are built according to one of these methods: Whole Line, Line Subset, or Repeating Line Segment.

Once a block of towers and wires has been constructed by the program, the lightning current is injected on each wire that gets hit, and the traveling waves are tracked one time step at a time until either a flashover occurs or the time limit is reached. If a flashover occurs, the location, stroke current, and probability of that stroke are saved for creating reports. If the user has selected to not stop at the first flashover, the calculation will always run until the time limit is reached, which can result in much longer calculation. If the user has selected to run a multiphase simulation, then the entire time step process is repeated six times with a different initial voltage on each phase conductor to simulate a three-phase line.

After all the strokes have been simulated at each slice, the saved flashover data are compiled into the various Statistics Report sections.

Arrester Failure Statistics Algorithm

This process is much like the statistics calculation in its use of stroke probability and the traveling wave application. It differs in the following details:

- Uses different simulation time limits for strokes to the shield wires and phase wires. The calculation times are also much longer than the flashover statistics time limit. The default flashover time limit is 6 microseconds for arrester statistics, 100 microseconds for strokes to the shield wires, and 500 microseconds for strokes to phase wires. The additional time is needed to integrate the energy through the arresters over most of the stroke duration.

- Uses different lightning waveform. This calculation uses an Equal Probability waveform. This waveform provides a more realistic stroke energy than the Fast Front waveform used in the flashover statistics calculation.

- The calculation does not stop until the full time has elapsed.

- Flashovers are disabled during this calculation.

- Only does slices at tower locations. This helps reduce calculation time by limiting the number of slices that must be calculated. Because the calculation time is so much longer than for flashovers, the difference between strokes hitting the wires between towers and the towers themselves is much shorter.

To determine the failure probability the integrated energy for each arrester is used with the failure probability curve in Figure 5-7 of EPRI report *Transmission Line Surge Arrester Impulse Energy Testing* (1000461).

3
LINE CHARACTERISTICS AND MODELING DETAILS

Line Details

The details of the 69 kV lines in the vicinity of Cascade Kraft Substation that have been included in the TFLASH model are shown in Table 3-1 . It was decided that lightning performance of nearby 230 kV lines is not going to have a significant impact for Cascade Craft sub. Consequently, 230 kV system has not been included in the model.

Table 3-1
69kV Lines around Cascade Kraft

Starting Sub	Ending Sub	Number of Poles	Line Length
Cascade Kraft	Wallula	48	5.07
Wallula	Cascade-Touchet	22	3.96
Cascade Kraft	Touchet	163	15.19
Touchet	Walla- Walla	285	12.68
Cascade Kraft	Pasco	365	18.26
Total		883	55.16

The latitude/longitude information of the substations was found from the diagrams provided and is shown in Table 3-2. The location of individual poles in the lines was obtained by interpolating the latitude and longitude of the starting and ending poles. The actual conductor types, insulator CFO values, individual span and sag information that was provided has been used for modeling the lines.

Table 3-2
Geographic Information of Stations

Substation	Latitude (degrees)	Longitude (degrees)
Cascade Kraft	45.1	-118.9
Wallula	45.073	-118.847
Cascade-Touchet	45.086	-118.794
Pasco	45.23	-119.041
Walla-Walla	45.072	-118.43
Touchet	45.042	-118.688

Tower Details

Typical tower configurations (Table 3-3, Figure 3-1, Figure 3-2, Figure 3-3 and Figure 3-4) for the lines have been used to represent the individual towers for the lines.

Table 3-3
Typical Tower Configurations

Starting Sub	Ending Sub	Typical Towers
Cascade Kraft	Wallula	HSL
Wallula	Cascade-Touchet	HSL
Cascade Kraft	Touchet	THP- Tower 1-94 HSL- Tower 95-163
Touchet	Walla- Walla	THP
Cascade Kraft	Pasco	A – Tower 1-192 THPA – Tower 193-365

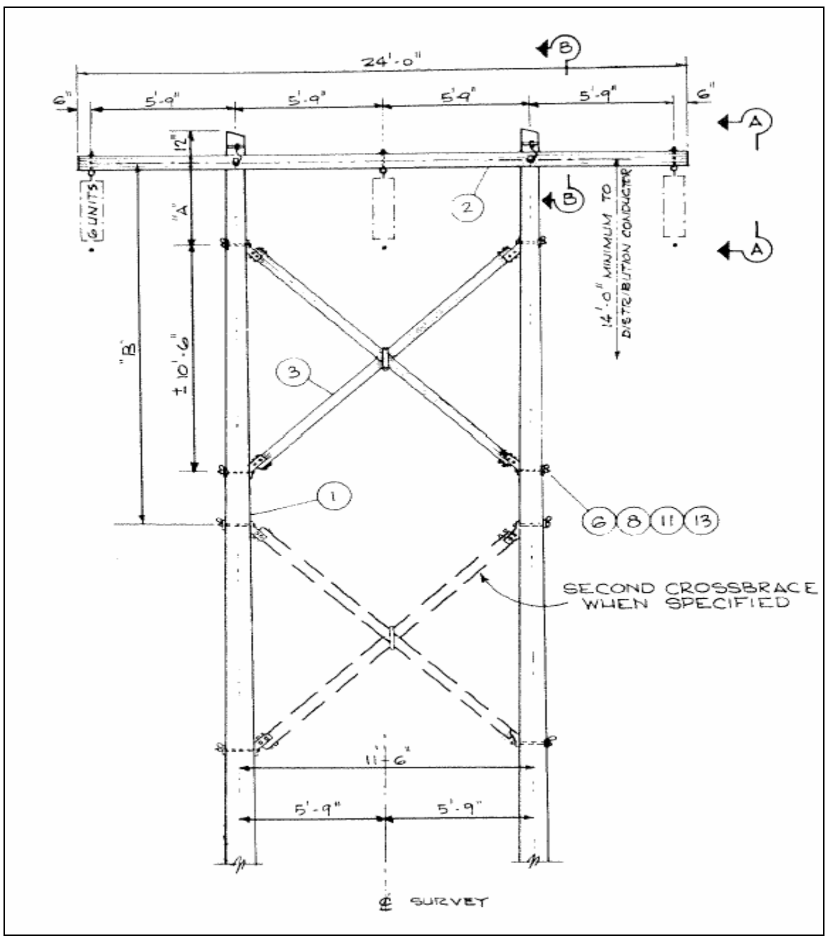


Figure 3-1: "HSL" Pole Structure

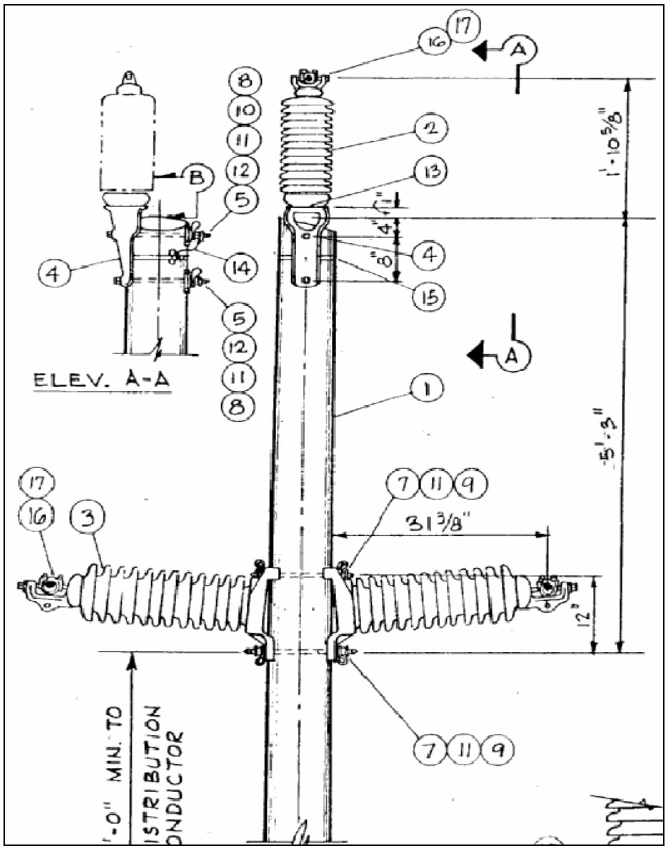


Figure 3-2: "THPA" Pole Structure

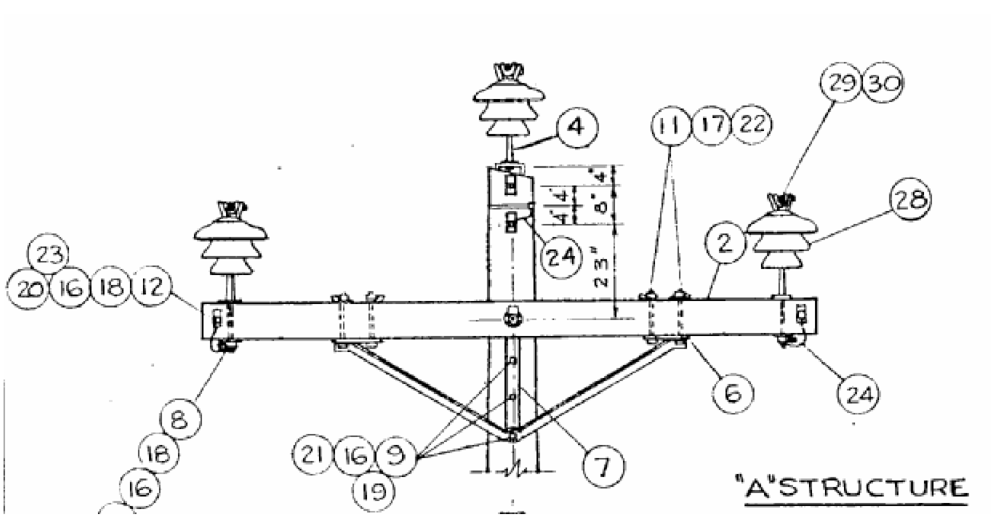


Figure 3-3: "A " Pole Structure

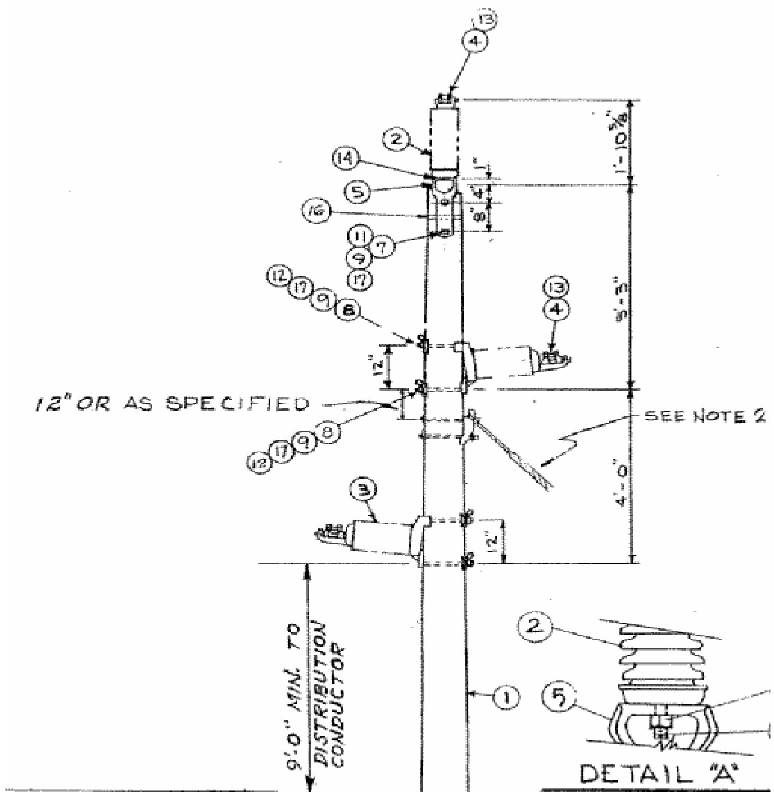


Figure 3-4: "THP" Pole Structure

4
LIGHTNING PERFORMANCE EVALUATION

TFlash is a state-of-the-art design tool that allows engineers to analyze the effect of a specified lightning challenge on a given transmission line. TFlash allows users to build detailed models of transmission lines to evaluate all aspects of lightning reliability and mitigation techniques including shielding, improved grounding, line arresters, and upgraded insulation. With this software, utility engineers can analyze the degree of protection of an existing line, define changes to the line to improve protection, or design a new line with economical lightning protection. The software also includes National Lightning Detection Network (NLDN) maps of regional ground flash densities (GFD).

TFlash is under continuous development and is available to both EPRI members and non-members. More information about TFlash can be found on the EPRI website at www.epri.com.

Lightning Performance Evaluation of Present Design

The lines, as modeled, have a total length of nearly 55 miles. The table below summarizes the basic lightning performance characteristics of the present design.

Table 4-1
Summary of Lightning Model Simulation Results (Present Design)

Category	Number per Year
Direct Strikes	2.123
Back Flashovers	0.000
Phase Strike/Shielding Failure Flashovers	2.123
Total Flashovers	2.123

The configuration of the system is such that almost all of the flashovers are the shielding failure kind arising out of the direct strikes on the phase wires. The number of resultant lightning faults (3.85 per 100 mile) in the 69kV system that are likely to result in a year is still low compared to typical 69 kV line fault rates as documented in a 1992 transmission survey that was carried out by EPRI in 1992 (Figure 4-1). 16 utilities in U.S. responded in this survey that covers nearly 55,000 transmission line miles. The median fault rate for 46-69 kV lines was about 18 faults/100 miles/year.

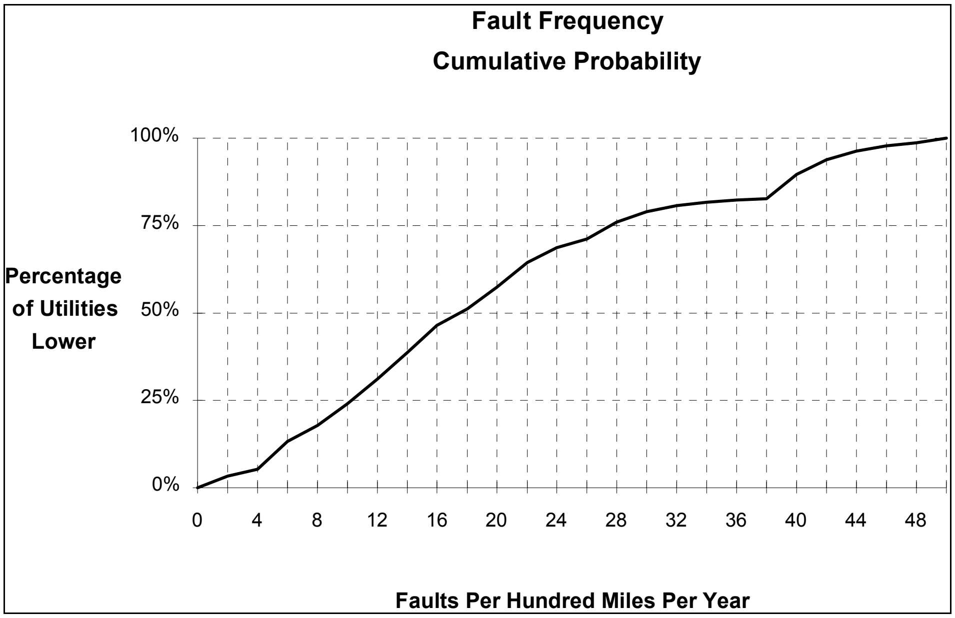


Figure 4-1
46-69kV Fault Performance Survey Results

The following are some general guidelines for voltage sag performance that have been developed based on the surveys and experience from around the world [12].

Table 4-2
General Guidelines for Voltage Sag Performance Expectations

Voltage Sag Performance (number of events/year below ITIC curve)	Voltage Sag Performance (number of events/year below SEMI F-47 curve)	Description of systems where this level of performance could be expected
0-5 events per year	**0-2 events per year**	♦ Transmission supply to a facility with low fault exposure ♦ Some underground systems that have low fault exposure ♦ Sites with power conditioning that includes ride through support for voltage sags and/or interruptions
5-10 events per year	**2-5 events per year**	♦ Typical transmission system supply ♦ Underground systems ♦ Distribution systems with low fault exposure
10-30 events per year	**5-15 events per year**	• Typical medium voltage (distribution system) supply to a facility
>30 events per year	**>15 events per year**	• Medium voltage (distribution system) that has higher fault exposure ▪ long, overhead distribution systems with significant exposure to faults ▪ areas of high lightning flash density

It is also helpful to understand typical voltage sag performance levels for critical customers typically supplied from transmission and subtransmission systems. Figure 4-2 provides results of a survey that was performed of utilities that have supplies to critical customers like semiconductor industry facilities.. It is evident that SARFI-ITIC levels in the range of 2-7 events per year can be achieved at these customer supply points.

It is apparent from the worldwide survey results about the fault performance and voltage sag performance of the critical customer supply systems that the fault performance associated with lightning events for lines directly supplying Cascade Kraft should not result in an excessive number of events at the plant. This needs to be considered in combination with all other possible causes of faults on these lines.

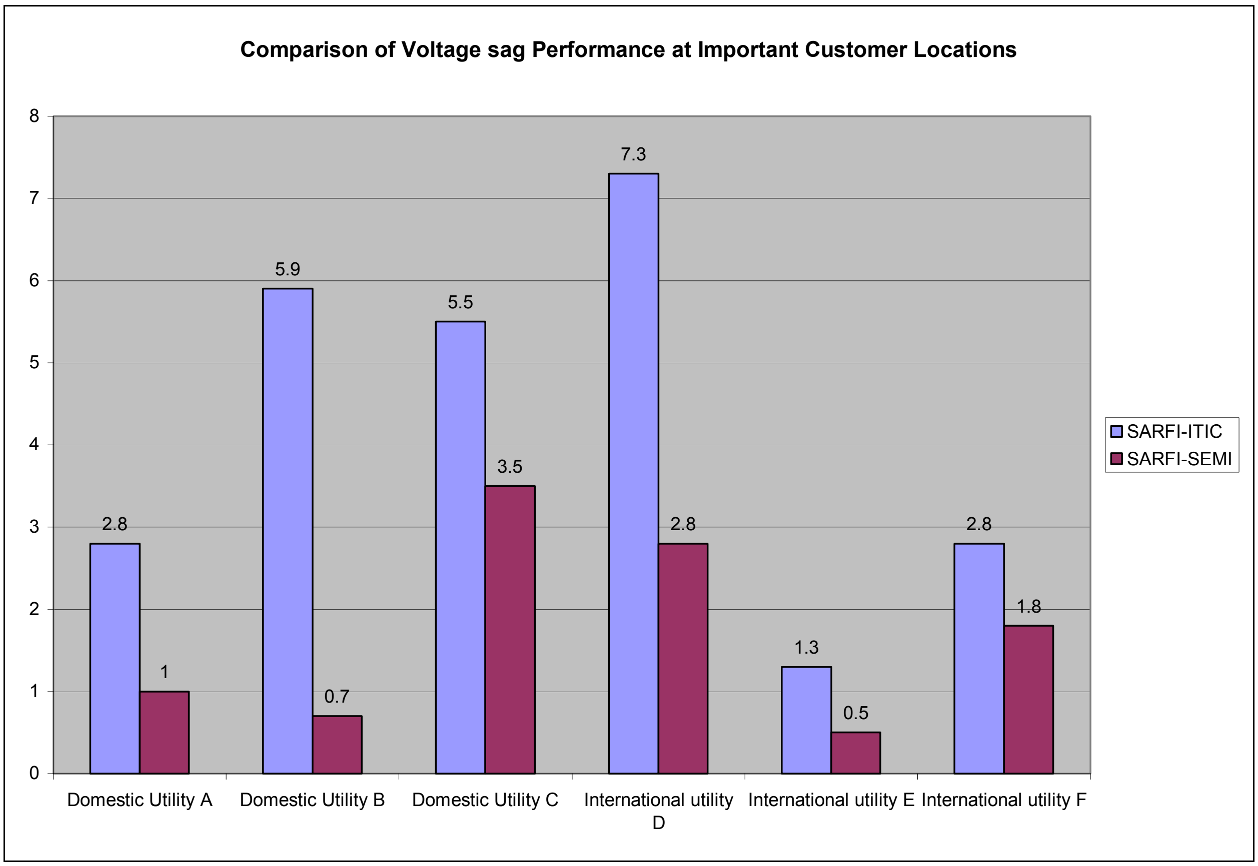


Figure 4-2
Comparison of SARFI Performance for Critical Customer Supply Systems around the World

Improving the Lightning Performance

Some steps can be taken, if it is desired to improve the lightning performance of the supply system. But, the solutions to improve the performance of an unshielded and ungrounded configuration that are economically feasible are very limited

One potential approach would be a substantial increase in insulator string lengths (and possibly phase spacing). Small increases in insulator withstand will not help much as it will require just a slightly larger stroke current to cause a flashover (virtually all strokes are causing flashovers with present design). Therefore, significant modifications would be required to have any appreciable improvement in lightning performance and it would be less expensive to put arresters in parallel with insulators than replace all insulators. Therefore, the option of significantly increasing insulation strength has not been covered and is not being recommended.

Basically, the choices available for improving performance are to change the line design to include shield wires or protect the insulators in the existing design with line arresters.

Addition of a Shield Wire

This option is likely to involve replacement of the existing structures and grounding at each pole. Addition of shield wire would serve to reduce the direct hits to the line resulting in reduction of the shielding failure flashovers. But, a portion of the lightning strokes that are intercepted by the shield wire are likely to result in back flashover depending on the magnitude of lightning current and the footing resistance of the poles.

For a given lightning stroke current to the shield wire or tower, a lower footing impedance will lower the crossarm voltage and will result in fewer back flashovers of the phase insulators. Conversely, a higher footing impedance will increase the crossarm voltage and result in more back flashovers. As the footing impedance is reduced, fewer and fewer back flashovers will occur until the footing impedance is approximately zero. Even with near zero footing impedance, some back flashovers will still occur because of the crossarm voltage developed by the lightning stroke current flowing down through the tower surge impedance. In summary, reducing tower footing impedance will reduce the transmission line back flashovers, but there is a practical limit to the reduction possible. Some portion of the lightning strokes will continue to cause faults due to backflashovers.

The costs associated with this approach are likely to be prohibitive due to the expenses associated with replacing the existing structures and significant grounding efforts at each structure. The cost of building new transmission lines (1995 Dollars/mile) is shown in Table 4-3. If the cost of building the line in 1995 dollars is picked as $130K/mile, the cost of rebuilding 55 miles after adjusting for inflation comes to nearly $9M. It may be difficult to justify the cost for any improvement in lightning performance that is likely. Therefore, the approach is not recommended for the situation at hand.

Table 4-3
Typical Costs and Capacity of New Transmission Lines (1995 Dollars)

Voltage	Type of Supporting Tower and Number of Circuits	Size of Power Line	Normal Rating MW	Cost per Circuit per Milea
60 kV	wood pole, single	4/0 AWG	32	$120,000
60 kV	wood pole, single	397.5 kcmil	56	$125,000
60 kV	wood pole, single	715.5 kcmil	79	$130,000
115 kV	wood pole, single	4/0 AWG	64	$130,000
115 kV	wood pole, single	397.5 kcmil	108	$135,000
115 kV	wood pole, single	715.5 kcmil	151	$140,000

aThese costs do not include right-of-way costs.

Source: CSA Energy Consultants, "Existing Electric Transmission and Distribution Upgrade Possibilities, "(Arlington, VA, July 18, 1995), p. 9.

Use of Transmission Line Surge Arresters

As already mentioned, the use of transmission line arresters would help to improve the lightning performance of the unshielded line configuration provided they are selected and located properly. The expected lightning performance of a series of arrester placement options was calculated using the developed TFLASH model. The option has been evaluated for the four most common tower configurations and the results are analyzed.

For these options, a tower down lead and ground would need to be installed on each arrester protected pole. If the arresters are not chosen for all the phases, the pole ground value is going to be important as higher value means that back flashover on unprotected phase(s) may become significantly high enough to be a concern. Therefore, two values of pole ground (25 and 100 ohms) have been evaluated for the variations in which arresters are not selected for all the three phases.

"HSL" Structure

The total line length corresponding to poles of this configuration is about 16 miles and comprises of 139 poles (See Table 3-3). In this configuration, the three phase conductors are at same level with vertical insulator strings suspended from a cross-arm (See Figure 3-1). For this section, the simulations included the effect of placing an arrester on the every phase of every pole; the effect of placing arresters on all three phases of alternate poles and the effect of placing an arrester on the outer phases of every pole. The simulation results are summarized in Table 4-4 .

Table 4-4
Arrester Placement and Lightning Performance Results (HSL Structures)

Option	Phase Shielding Flashovers /year	Back Flashovers /year	Total Flashovers /year	Arrester Failures/year
No Arresters	0.600	0.00	0.600	N/A
Every pole, All phases	0.000	0.00	0.000	0.448
Alternate Pole, All Phases	0.581	0.000	0.581	0.512
Every Pole, Outer phases (25 ohms pole ground)	0.016	0.00	0.016	0.752
Every Pole, Outer phases (100 ohms pole ground)	0.016	0.056	0.072	0.752

Some of the observations from the simulation results are as follows:

- Use of surge arresters on all the phases of every tower is preventing all the phase strike flashovers.
- Use of surge arresters on every phase of alternate towers is causing only a marginal reduction in phase strike flashovers. This option is definitely not going to provide any significant benefit.
- Use of surge arresters on outer phases of every tower is preventing most of the phase strike flashovers. It was expected as majority of the lightning strokes are likely to be intercepted by the outer conductors. The arrester failure rate is higher for this option though in comparison to arresters on all the three phases.
- As expected, higher value of pole ground (100 ohms) is resulting in some back flashovers.

"THPA" Structures

The total line length corresponding to poles of this configuration is about 8 miles and comprises of 173 poles (See Table 3-3). In this configuration, the outer conductors are at same height but the middle conductor is at the top of the pole at a greater height (See Figure 3-2). The outer conductors are suspended through horizontal Lapp insulators while the middle phase is suspended through a vertical Lapp insulator. For this configuration, the simulations included the effect of placing an arrester on the every phase of every pole and the effect of placing an arrester on the top phase alone of every pole. The simulation results are summarized in Table 4-5

Table 4-5
Arrester Placement and Lightning Performance Results (THPA Structures)

Option	Phase Shielding Flashovers /year	Back Flashovers /year	Total Flashovers /year	Arrester Failures /year
No Arresters	0.317	0.00	0.317	N/A
Every pole, All phases	0.000	0.00	0.000	0.232
Every Pole, Top phase (25 ohms pole ground)	0.002	0.02	0.022	0.246
Every Pole, Top phase (100 ohms pole ground)	0.002	0.132	0.134	0.246

Some of the observations from the simulation results are as follows:

- Use of surge arresters on all the phases of every tower is preventing all the phase strike flashovers.
- Use of surge arresters on the top phase of every tower is almost eliminating the phase strike flashovers. It is expected as a higher proportion of the lightning strokes are likely to be intercepted by the top conductor. Also, there is a slight incidence of back flashovers due to the unprotected phase insulators. The arrester failure rate is a bit higher for this option though in comparison to arresters on all the three phases.
- Higher value of pole ground (100 ohms) is resulting in significant increase in the incidence of back flashovers.

"A" Structures

The total line length corresponding to poles of this configuration is about 10 miles and comprises of 192 poles (See Table 3-3). In this configuration, the outer conductors are at same height but the middle conductor is at the top of the pole at greater height (See Figure 3-3). All the conductors are suspended at the top of vertical pin insulators. For this configuration, the simulations included the effect of placing an arrester on the every phase of every pole and the effect of placing an arrester on the top phase alone of every pole. The simulation results are summarized in Table 4-6 .

Table 4-6
Arrester Placement and Lightning Performance Results (A Structure)

Option	Phase Shielding Flashovers /year	Back Flashovers /year	Total Flashovers /year	Arrester Failures /year
No Arresters	0.387	0.00	0.387	N/A
Every pole, All phases	0.000	0.00	0.001	0.285
Every Pole, Top phase (25 ohms pole ground)	0.117	0.01	0.127	0.299
Every Pole, Top phase (100 ohms pole ground)	0.117	0.07	0.177	0.299

Some of the observations from the simulation results are as follows:

- Use of surge arresters on all the phases of every tower is preventing all the phase strike flashovers.
- Use of surge arresters on the top phase of every tower is reducing phase strike flashovers by 70%. It was expected as a higher proportion of the lightning strokes are likely to be intercepted by top conductor. There is a slight incidence of back flashovers from the unprotected phase insulators. The arrester failure rate is a bit higher for this option though in comparison to arresters on all the three phases.
- Higher value of pole ground (100 ohms) is resulting in significant back flashovers.

"THP" Structure

The total line length corresponding to the poles of this configuration is about 20 miles and comprises of 379 poles (See Table 3-3). In this configuration, the three conductors are at different heights (See Figure 3-4). The top conductor is at the top of the pole suspended through a vertical lapp insulator while the remaining two conductors are at lower heights suspended through horizontal lapp insulators. For this configuration, the simulations included the effect of placing an arrester on the every phase of every pole and the effect of placing only an arrester on the top phase of every pole. The simulation results are summarized in Table 4-7.

Table 4-7
Arrester Placement and Lightning Performance Results (20 mile length)

Option	Phase Shielding Flashovers /year	Back Flashovers/ year	Total Flashovers /year	Arrester Failures/yea r
No Arresters	0.819	0.00	0.819	N/A
Every pole, All phases	0.000	0.00	0.000	0.657
Every Pole, Top phase (25 ohms pole ground)	0.001	0.068	0.069	0.825
Every Pole, Top phase (100 ohms pole ground)	0.001	0.419	0.420	0.825

Some of the observations from the simulation results are as follows:

- Use of surge arresters on all the phases of every tower is preventing all the phase strike flashovers.
- Use of surge arresters on the top phase of every tower is preventing most of the phase strike flashovers. It was expected as majority of the lightning strokes are likely to be intercepted by top conductor. There is a slight incidence of back flashovers from the unprotected phase insulators. The overall arrester failure rate is a bit higher for this option though in comparison to arresters on all the three phases.
- Higher value of pole ground (100 ohms) is resulting in significant back flashovers.

Combined Analysis

The results of the analysis of individual structures are combined and presented here in Table 4-8. Option 1 in the table corresponds to the case where arresters are used for each phases in all the poles for all the four types of structures. Option 2a corresponds to the case in which line arresters are used for outer two conductors in HSL configuration and for the top conductor in THP, A and THPA structures. In this option, 20 ohms is used as the value of individual pole grounds. Option 2b is similar to Option 2a other than the value of individual pole grounds being 100 ohms.

Table 4-8
Lightning Performance and economic analysis (55 mile length)

Option	Phase Shielding Flashovers /year	Back Flashovers/ year	Total Flashovers /year	Arrester Failures /year
Existing	2.123	0	2.123	N/A
Option 1	0.000	0	0	1.622
Option 2a	0.136	0.098	0.234	2.122
Option 2b	0.136	0.677	0.803	2.122

Some of the observations from the combined results are as follows:

- Use of Option 1 is preventing all the phase strike flashovers.
- Use of option 2a is reducing overall flashovers by about 90%. The arrester failure rate is a higher (about 25%) for this option but it is likely that the failure rate will be much lower with higher energy arresters. Initial cost for this option is significantly lower (60% reduction) than the option 1.
- Use of option 2b is reducing overall flashovers by about 60%. This may be attributed to the increased incidence of back flashovers due to the higher value of pole ground resistance assumed. Depending on the effectiveness of pole grounding resistance that can be achieved, arresters could be required on all three phases (Option 1).
- The options that have been evaluated are resulting in improvement in lightning performance in terms of reduction/elimination of flashovers. The results show that a significant arrester failure rate is possible, which would reduce the effectiveness of the entire approach to improving performance. These results correspond to arresters having energy rating of 2.2 kJ/kV MCOV. Higher energy arresters will have much lower failure rates – this is analyzed below.

Arrester Failure Analysis

Arrester failure results if the lightning current surge results in excessive energy in the arrester (one or more arresters will have to dissipate the energy of the lightning surge when they are operating for direct strikes to the line, compared to backflashes that have much lower energy associated with them). Arresters fail as a short circuit, resulting in a fault condition that will have to be cleared by line breakers. TLSA is typically equipped with an isolating device that would disconnect it during this event that would permit successful reclosing of the line. Thus, the system would return to normal after the surge event is over but a momentary outage would have occurred due to arrester failure (and a voltage sag affecting customers like Boise Cascade).

Arrester manufacturers specify the energy withstand capability of their arresters. It has been found from the field experience and laboratory studies such as one conducted by EPRI that published numbers are quite conservative. .EPRI has conducted impulse energy testing of commercially available arresters having published energy withstand capability of 2.2 kJ/KV MCOV to enable an accurate prediction of arrester failures. This statistical arrester energy withstand characteristic is used by TFLASH to predict arrester failure rates.

In order to understand the failure rate of the arresters for the solutions discussed in preceding section, the impact of one stroke on a tower having HSL configuration is illustrated here. It is assumed that lightning stroke hits the phase conductor at Tower 10. The lightning stroke waveform that has been used for the analysis is shown in Figure 4-3 and the parameter values are given in Table 4-9. The failure probabilities of the arresters associated with this lightning stroke are given in Table 4-10.

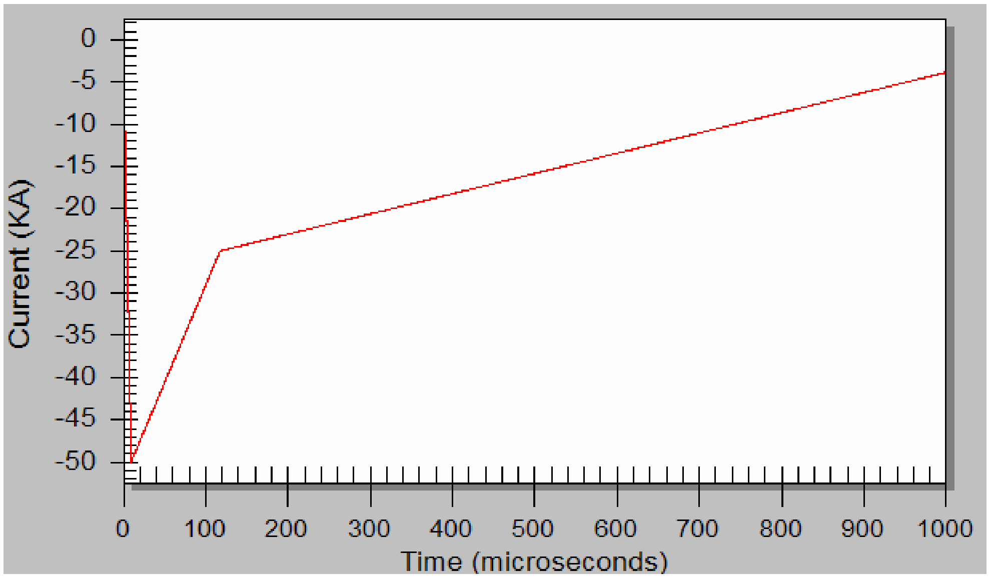


Figure 4-3
Stroke Current Waveform

Table 4-9
Stroke Current Parameters

Parameter	Value
Peak Current (kA)	50
Rise time (uS)	9
Half time (uS)	117
Total time(uS)	1160

Table 4-10
Arrester Failure Probability

Tower	Arrester Energy	kJ/kV	Failure Probability
7	115.8	2.8	0.0152
8	168.4	4.0	0.0402
9	232.5	5.5	0.0707
10	320.2	7.6	0.1623
11	236.1	5.6	0.0724
12	169.1	4.0	0.0405
13	114.1	2.7	0.0143
Total			0.4156

It is seen that the energy sharing happens with the arresters on the neighboring poles and the overall failure probability of a line arrester for this particular stroke is found to be nearly 40%. It may be noted that this probability corresponds to the arrester having an energy capability of about 2.2 kJ/KV MCOV. The failure probability of the high energy capability arresters can be expected to be much less. Therefore, it is recommended that arresters having energy capability of at least 7-8 kJ/kV MCOV be considered for the solutions to achieve a low arrester failure rate.

Economic Analysis

The cost of the line arrester solutions that have been evaluated will be influenced primarily by the cost of the hardware and its installation. The equipment price of line arresters is influenced by its energy handling capability as shown in Table 4-11. The installation cost would include the labor cost of mounting the units, costs associated with running the down lead to the bottom of the pole and its grounding. The rough estimate of the installation cost is $1K/unit.

Table 4-11
Arrester Cost and Failure rates (HSL Structures)

Arrester Manufacture/Make	Total Energy Capability (kJ/kV)	Approx Purchase Cost/unit ($)
ABB PEXLIM Q	7.8	900.00
Cooper Power	2.8	300.00

The economic comparison of the solutions is presented in Table 4-12 . For the purpose of economic analysis, it is assumed that $2k is the total cost of purchasing and installing one high energy capability unit. The cost of significant grounding that may be needed for Option2a and Option 2b has not been included as it will depend on the existing grounding conditions.

Table 4-12
Economic Analysis of Line Arrester Solutions (55 mile length)

Option	Arrester Units required	Total cost ($ in Millions)
Option 1	2649	5.3
Option 2a/Option 2b	1022	2.04

5
CONCLUSIONS

EPRI's TFLASH software was used to evaluate the lightning performance of the 69 kV system around Cascade Kraft substation of PacifiCorp. It was found that for the existing line configuration (unshielded and ungrounded structures), lightning should result in approximately 2 flashovers per year. These flashovers would be *shielding failure* type due to the lightning directly hitting the phase conductors due to the absence of any shield wire. This low number may be attributed to the relatively low lightning incidence in the region.

These lightning-caused faults must be considered in combination with other causes of transmission line faults (trees, birds, etc.) to determine the overall fault performance of the line that results in voltage sags that can affect important customers. Voltage sags that can affect Boise Cascade may also result from faults on other transmission lines that are electrically close to the plant. Examples of voltage sag performance and transmission line fault rates from other systems around the world are presented in this report to illustrate typical characteristics. Voltage sag rates in the range of 2-5 events per year where the voltage at the plant is below 70% (SARFI-70) can be considered normal in most parts of the world.

It should be noted that the analysis in this report only addresses the lightning caused faults on the particular transmission lines supplying the plant. Other causes of transmission line faults and faults on other lines in the transmission system are not addressed by the solutions evaluated.

Improving the lightning-caused fault performance can be achieved by redesigning the line construction to include shield wires that would prevent most direct strikes to the phase conductors. However, this solution would not prevent all lightning faults because backflashes can still occur due to the buildup of voltage across the pole grounding conductor and the grounding resistance. The performance improvement will depend on the effectiveness of grounding at each pole. Due to the cost and the fact that the solution would not prevent lightning-caused faults, this solution is not recommended.

Use of transmission line surge arresters is generally the preferred approach under the given circumstances. Manufacturers have designed arresters that can be installed in parallel with existing insulators specifically for this purpose. They are more commonly used in high lightning areas but the solution could improve performance on this line as well. The analysis shows that arresters on the outside phases or the highest phase can prevent most of the faults due to direct strikes to the line. However, backflashes on the unprotected phase are possible (more likely if low ground resistance values cannot be obtained). Arresters on all three phases at each tower would be required to prevent almost all faults due to direct strikes.

Even with arresters on all three phases, faults can still result if the arrester fails due to high lightning stroke energy. Significant arrester failure probabilities were found in the simulations and high energy arresters (line discharge class 3 or higher as per IEC-60099-4 standard) are recommended to reduce this probability to much lower values.

Following options may be considered if some cost-saving is desired at the expense of slightly worse lightning performance and slightly higher arrester failure rate. The success of these options would depend on the grounding conditions as a higher value of pole ground impedance is likely to introduce significant back flashovers on the unprotected insulators.

- TLSA only on the outer phases of the towers with HSL configuration
- TLSA only on the top phase of the towers with A, THP and THPA configuration

A
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