

Reliability of Lightning Resistant Overhead Distribution Lines

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Abstract — An assessment of the 32 year historical reliability of the 13.8 kV electrical distribution system at the Oak Ridge National Laboratory (ORNL) in Tennessee has yielded several conclusions useful in the planning of industrial power systems. The system configuration at ORNL has essentially remained unchanged in the last 32 years which allows a meaningful comparison of reliability trends for the plant's eight overhead distribution lines, two of which were built in the 1960's with lightning resistant construction techniques. Meticulous records indicating the cause, duration, and location of 135 electric outages in the plant's distribution system have allowed a reliability assessment to be performed. The assessment clearly shows how differences in voltage construction class, length, age, and maximum elevation above a reference elevation influence the reliability of overhead power distribution lines. Comparisons are also made between the ORNL historical data and predicted failure rates from ANSI and IEEE industry surveys.

I. INTRODUCTION

LIGHTNING continues to be the major cause of outages on overhead power distribution lines. Through laboratory testing and field observations and measurements, the properties of a lightning stroke and its effects on electrical distribution system components are well-understood phenomena [1]. This paper presents a compilation of 32 years of historical records for outage causes, duration, and locations for eight distribution feeders at the Oak Ridge National Laboratory (ORNL). Due to the limited growth of ORNL, the number, length and location of the 13.8 kV overhead lines have remained the same between 1960 and 1992. Except for noted differences (voltage construction class, length, age, and maximum elevation above a reference level), other factors which could influence the reliability of an overhead line have remained nearly the same. This allowed a meaningful reliability study to be performed on the entire ORNL electrical distribution system [2].

This paper discusses the main findings of the reliability assessment as it relates to lightning resistant overhead line construction techniques and offers a simple and cost effective method to reduce lightning caused outages. In addition, comparisons are made between the failure rates and causes experienced at ORNL and those in industry surveys. Where large discrepancies exist between survey data and experiences at ORNL, evidence is presented to explain the differences between ORNL's distribution system and those typical of industry.

II. DESCRIPTION OF ELECTRICAL DISTRIBUTION SYSTEM

Electrical power at the Oak Ridge National Laboratory (ORNL) in Tennessee is supplied by a single 161 kV to 13.8 kV primary substation. The average electrical load is 19 MW. Eight radial 13.8 kV overhead lines originate from the substation. The ORNL 13.8 kV distribution system is comprised of six facility 13.8 kV switchgear equipment, 37 padmounted unit substations and transformers, 46 pole mounted transformer stations, 1 mile of underground cable, and approximately 20 miles of open overhead lines. The 13.8 kV distribution system covers 10 square miles of service area. The lines range in age from 23 to 42 years.

The ORNL 13.8 kV system is a wye system which is grounded through a 4 ohm resistor at the primary substation to limit ground fault currents. Except for limited short lengths, all three phase conductors are installed on each of the overhead lines. Automatic reclosers at the primary substation are utilized on some of the overhead lines to limit downtime. No in-line reclosers or fuses are installed in the overhead lines, except for feeder 3 which has a single in-line recloser. For purposes of the assessment, a successful reclose operation is still treated as an outage because facility operations and processes are shutdown, though only momentarily.

The eight overhead lines have various lengths and follow different terrains in serving their electrical loads. Except for limited short lengths, all of the overhead lines use separate right-of-ways. Some overhead lines in the system are installed on high ridges which are predominant in the region, exposing and making them vulnerable to lightning. Due to the rural East Tennessee location, insulators are not exposed to industrial pollution or salt water. The overhead lines have been moderately maintained; equipment has been replaced as needed, and nominal 50 ft right-of-ways have been kept moderately clear.

The overhead lines use 50 to 75 ft tall wood pole construction and utilize overhead ground wires to intercept direct lightning strokes. Typically at every fourth pole, the overhead ground wire is bonded to a #4 AWG copper wire which extends down the pole to a pole butt-wrapped ground wire; no buried counterpoise ground wires are used. Distribution type lightning arresters are placed at dead-end and angle structures, at pole mounted transformer locations, and at high points on the overhead line. Station class lightning

arresters are used to protect underground cable runs, pad mounted switchgear, and unit substation transformers.

Resistance to earth of each pole ground is typically 15 ohms or less. At higher elevations in the system, resistance to earth is substantially greater than 15 ohms, especially during the dry summer months. At these high points, ground rods were driven and bonded to the pole grounding systems in the 1960's in an attempt to decrease lightning outages. These attempts were only partially successful in lowering the outage rate.

From a surge protection standpoint, the variety of pole structures used (in-line, corner, angle, dead-end, etc.) and the variety of insulators and hardware used does not allow each 13.8 kV overhead line to be categorized with a uniform impulse flashover rating (170 kV; etc.) or a numerical BIL voltage class (95 kV BIL; etc.). For simplicity purposes in the analysis, each overhead line was categorized with a nominal voltage construction class (15 kV, 34 kV, or 69 kV).

Six of the eight overhead lines (feeders 1 through 6) were built with typical REA Standard horizontal wood crossarm construction utilizing single ANSI Class 55-5 porcelain pin insulators (nominal 15 kV insulation). The shield angle of the overhead ground wire to the phase conductors is typically 45 degrees.

One overhead line (feeder 7) was built with transmission type wood pole construction because the line extended to a research facility which was to have generated electrical power to feed back into the grid. Pole structures of this line are of durable wood crossarm construction which utilize double ANSI 52-3 porcelain suspension insulators to support the conductors (nominal 34 kV insulation). The shield angle of the overhead ground wire to the phase conductors for feeder 7 is typically 30 degrees.

In 1969, an overhead line (feeder 8) was intentionally built with "lightning resistant" construction in an attempt to reduce lightning caused outages. Pole structures of the line have

phase over phase 24-inch long fiberglass suspension brackets with double ANSI 52-3 porcelain suspension insulators to support the conductors (nominal 69 kV insulation). The shield angle of the overhead ground wire to the phase conductors for feeder 8 is typically 30 degrees.

III. FAILURE ANALYSIS

A. System Operating History

For the purposes of this paper, an electrical outage is defined as the unplanned loss of power to a load. This condition is also commonly referred to as a "forced outage" or a "failure" of the power system component under study, (in this case, the overhead distribution lines) [3]. Instances of transient power disturbances resulting in a momentary degradation of power quality (e.g., voltage sags and surges) were not recorded and, as a result, were not considered in the assessment.

A review of the historical data showed each outage could be categorized as being due to one of five distinct failure-initiating events: weather-related phenomena (lightning, wind, etc.), animal contact, equipment failure (insulation breakdown, loose connections, etc.), human error (usually switching errors), or unknown factors. The failure data was compiled for each of the eight 13.8 kV feeders and is presented in Table I, along with pertinent information regarding feeder construction, elevation, length, and age.

A key finding of the failure analysis is that weather-related events account for over half (56%) of the feeder outages recorded. Fifty-seven of the 76 weather-related outages were attributed to lightning. Insulation breakdown damage due to lightning is also suspected in at least a dozen of the equipment failures observed. The data indicates overhead lines which pass over high terrain are less reliable because of the greater exposure to lightning. For example, feeder 3 had the most

TABLE I
FEEDER CHARACTERISTICS AND OUTAGE CAUSES

	Feeder Number								Total	
	1	2	3	4	5	6	7	8		
Construction Voltage Class (kV)	15	15	15	15	15	15/34	34	69	-	
Elevation above Substation (ft)	150	150	450	100	180	220	220	150	-	
Length (miles)	0.3	0.7	5.9	0.8	1.7	2	6.3	1.7	-	
Age (years)	42	42	39	32	32	32	32	23	-	
Number of Outages	13	7	48	19	30	12	3	3	135	
Cause:	Weather	4 (31%)	6 (86%)	32 (67%)	11 (58%)	16 (53%)	5 (42%)	1 (33%)	1 (33%)	76 (56%)
	Animal	0 (0%)	0 (0%)	1 (2%)	0 (0%)	4 (13%)	1 (8%)	0 (0%)	0	6 (4%)
	Equipment	3 (23%)	0 (0%)	10 (21%)	5 (26%)	5 (17%)	3 (25%)	1 (33%)	1 (33%)	28 (21%)
	Human Error	6 (46%)	0 (0%)	4 (8%)	3 (16%)	1 (3%)	3 (25%)	0 (0%)	1 (33%)	18 (13%)
	Unknown	0 (0%)	1 (14%)	1 (2%)	0 (0%)	4 (13%)	0 (0%)	1 (33%)	0	7 (5%)
Frequency (Outages per year)	0.41	0.22	1.71	0.59	1.07	0.38	0.09	0.13	4.60	

recorded outages (48), of which two-thirds were due to weather-related events; this feeder is also the highest line on the plant site, rising to an elevation of 450 ft above the reference valley elevation. Overhead lines that are longer and to which more substations and equipment are attached were also observed to be less reliable (more exposure to lightning and more equipment to fail). The age of the line does not appear to significantly lessen its reliability as long as adequate maintenance is performed; none of the lines have had a notable increase in the frequency of outages as the lines have aged.

As would be expected, the empirical data presented in Table I confirms the two overhead lines which have been insulated to a higher level (34 or 69 kV) have significantly better reliability records than those utilizing 15 kV class construction. Feeder 7 (insulated to 34 kV) and feeder 8 (insulated to 69 kV) have had only 3 outages each over their 32 and 23 year life spans, respectively. These lines follow similar terrain and are comparable in length and age to the 15 kV class lines, yet they have a combined failure rate of 0.22 failures per year versus 4.32 failures per year for the remaining feeders.

B. Comparison to Survey Data

Although the extensive historical data points to lightning and lightning-induced equipment failures as major contributors to the ORNL feeder outages, it is also useful to establish whether the frequency and nature of these outages are typical of industry. To accomplish this, the failure causes of all ORNL feeders were re-tabulated to match the categories of "failure-initiating causes" for open wire installations as published in ANSI/IEEE Standard 493-1990 [3]. The standard presents the results of an IEEE sponsored reliability survey of industrial

plants completed in 1972. Table II compares the data obtained from this survey to that compiled from the ORNL records.

The comparison between the ORNL historical data and the IEEE survey data indicates that, as a percentage of total outages, transient overvoltage disturbances at ORNL are twice the industrial average. Based upon the empirical data presented, this discrepancy is due to a heightened vulnerability of the plant's overhead distribution system to lightning. This theory is also supported by the fact that the region's relatively high isokeraunic level subjects the surrounding area to approximately 60 thunderstorm days per year. At an isokeraunic level of 60 thunderstorm days per year, one can estimate two lightning strokes per mile of line per year [4]. Insulation breakdown is also double the industrial average. Again, lightning damage to conductor insulators and lightning arresters is suspected for this anomaly.

Explanations for the differences in the other categories are also postulated. Overheating failures are less than the industrial average because ORNL does not overload transformers or conductors to the extent that general industry does. Failures resulting from vehicular accident, vandalism, digging, and shorting by objects are less likely because of the restricted access to the ORNL site. Other failure causes (e.g., mechanical part failure, animal contact, and human error) were found to be similar to the industrial averages.

Standard 493-1990 also presents failure rates for two subclasses of open wire installations (0-15 kV and above 15 kV) [3]. As can be seen from Fig. 1, failure rates for the 15 kV class ORNL feeders are over four times the industry average, which is indicative of the substantially higher percentage of lightning-induced failures noted in Table II.

TABLE II
COMPARISON OF FAILURE CAUSES - INDUSTRIAL AVERAGE VS. ORNL ACTUAL

Failure-Initiating Cause		IEEE Survey [3] Industrial Average	All Feeders at ORNL
1	Transient overvoltage disturbances (lightning, switching surges, arcing ground fault in ungrounded system)	26%	47%
2	Overheating	21%	0%
3	Other insulation breakdown	8%	16%
4	Mechanical breaking, cracking, loosening, abrading, or deforming of static or structural parts	7%	7%
5	Mechanically caused damage from foreign source (digging, vehicular accident, trees, etc.)	10%	6%
6	Shorting by tools or metal objects	14%	7%
7	Shorting by birds, snakes, rodents, etc.	3%	4%
8	Other (human error, unknown cause, etc.)	11%	13%

However, the feeders employing lightning-resistant construction exhibit outage rates reasonably close to the industry average for the above 15 kV subclass. This comparison provides additional evidence supporting the effectiveness of these techniques in areas susceptible to frequent lightning.

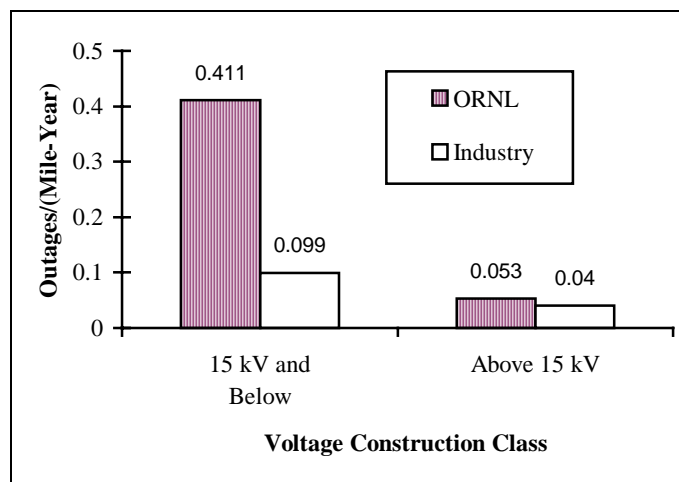


Fig. 1. Outages per Mile-Year Based on Insulation Level

IV. LIGHTNING RESISTANT CONSTRUCTION

The term "lightning resistant" has been arbitrarily defined as the use of high insulation (34 kV or 69 kV) hardware when applied on a lower voltage (13.8 kV, 4.16 kV; etc.) overhead line as a means of appreciably decreasing the lightning outage and recloser action rate. The increased insulation is applied in conjunction with overhead ground wires, lightning arresters and pole structure grounding. In effect, the construction method brings overhead distribution lines up to subtransmission lightning protection standards. Through judicious application, the construction can be applied to sections of distribution lines which have greater lightning exposure in order to reduce weather related outages.

On typical 15 kV insulated line construction, lightning flashovers often cause 60 cycle power follow and feeder trip. With the higher insulation construction, outage rates are reduced by limiting the number of flashovers and the resultant power follow which causes an overcurrent device to trip. This allows lightning arresters to perform their duty of dissipating lightning energy to earth. The number of recloser actions and their resultant momentary outages are also reduced. This is beneficial for critical facilities and processes which cannot tolerate even momentary outages. An additional benefit is that outages due to animal contact are also reduced because of the greater distance from phase conductor to ground on pole structures.

Distribution line equipment to increase line insulation values are "off the shelf" items and proven technology. New lightning resistant construction typically utilizes horizontal line

posts, fiberglass standoff brackets or any other method which would increase the insulation value. The replacement of standard pin insulators with line post insulators of greater flashover value is an effective means to retrofit existing wood crossarm construction. The doubling and tripling of dead-end and suspension insulators is also a means of increasing flashover values on existing angle and dead-end structures. Current fiberglass, polymer, and epoxy technologies provide an affordable means to increase line insulation.

V. CONCLUSION

While the use of increased insulation levels to reduce lightning flashovers and the resultant outages on overhead distribution lines has been thoroughly tested and demonstrated in laboratory and experimental tests [5], long term historical field data has positively demonstrated that the use of "lightning resistant" construction can greatly reduce outages. Field use at ORNL has shown that in areas which are vulnerable to lightning, the use of increased insulation and a smaller shielding angle is an impressive and cost effective means to appreciably increase the reliability of overhead distribution lines.

This reliability study clearly illustrates that the insulation requirements for high-reliability distribution feeders should be determined not by the 60 Hz operating voltage but rather by withstand requirements for the lightning transients or other high voltage transients that are impressed upon the line. Electrical equipment (switchgear, insulators, transformers, cables, etc.) have a reserve (BIL level or flashover value) to handle momentary overvoltages, and by increasing that reserve, the service reliability is appreciably increased.

As the electrical industry gradually moves away from standard wood crossarm construction and moves toward more fiberglass, polymer and epoxy construction, increased insulation methods can be applied as part of new construction or as part of an upgrade or replacement effort. In considering new or upgraded overhead line construction, the incremental increased cost of the higher insulation equipment is small in proportion to the total costs of construction (labor, capital equipment, cables, electric poles, right-of-way acquisition). Its cost effectiveness varies with the application and the conditions to which it is applied. Economic benefits include increased electrical service reliability and its inherent ability to keep manufacturing processes and critical loads in service. Other more direct benefits include less repair of overhead distribution lines, which can have a significant reduction in maintenance cost due to less replacement materials and a large reduction in overtime hours for maintenance crews.

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