Lightning Protection of Transmission Lines with Polymer-Housed Surge Arresters

M. G. Comber, M.G. Vermilye
Ohio Brass

S.F. LaCasse
Northern States Power Co.

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INTRODUCTION

The availability of polymer-house surge arresters provide utilities with new options for protecting transmission and distribution lines from lightning-induced insulator flashovers. The concept of applying surge arresters on lines is not new, but the limited practice has been because of the complexity and cost of installing heavy porcelain-housed arresters. This problem is greatly diminished with polymer-housed arresters.

Polymer-housed arresters have lower weight, typically less than 50 % of equivalent porcelain-housed arresters, therefore placing less mechanical strain on the structures and providing greater versatility in mounting arrangements. Invariably, polymer arresters can be installed on existing lines without the need for reinforcing the structures.

Over seven years of experience with polymer arresters has proven that they are less prone to moisture ingress than equivalent porcelain arresters, minimizing one of the most common causes of failure of surge arresters. While the failure rate of arresters in general is very low, the possibility of a failure and subsequent consequences must be taken into account. In the case of an internal failure of a porcelain-housed arrester, there is a significant concern of fractured porcelain being thrown with considerable force, posing a potential hazard to adjacent equipment and/or nearby people. On the other hand, polymer arresters can be designed to remain essentially intact without the need for the complex pressure relief mechanisms used in porcelain arresters. Material that might be thrown following a polymer arrester failure would typically be limited to low mass portions of polymeric housing material.

With the versatility provided by the design, polymer arresters can be readily installed, even at very high voltages, in a manner which would result in safe electrical isolation from the line in the event of an arrester failure, thus allowing line reclosure following the fault. Such isolation capability is not readily achieved with porcelain arresters.

Currently, over 100 utilities in the United States and other countries (Canada, Mexico, Colombia, Germany and Japan) are using polymer-housed line arresters.

This paper presents the basic concepts behind the application of surge arresters on transmission lines for reduction of lightning-caused outages, and describes the application of polymer-housed line arresters on 69 kV lines by two utilities.

EFFECT OF LIGHTNING ON TRANSMISSION LINES

The frequency with which lightning will strike a transmission line depends on a number of factors: the overall level of lightning activity for the area traversed by the line; the physical dimensions, primarily overall height, of the line; presence of naturally shielding objects, such as tall trees or buildings in the vicinity of the line or other lines within the same corridor.

The overall lightning activity can be characterized by lightning ground flash density, expressed in terms of number of lightning flashes to ground per square mile per year. The line itself tends to be a somewhat focussed collector of lightning and will attract flashes which would otherwise strike the ground over a swath whose width is approximately four times the average height of the uppermost conductor or shield wire. This width is commonly referred to as the shadow width of the line. From knowledge of the lightning flash density for the area and the line's shadow width, one can compute for a given section of the line the expected number of lightning strikes to the line per mile per year. This number will only be an approximation because of the statistical nature of the ground flash density, varying over time from year to year and varying over area due to variations in terrain altitude, and to other

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factors such as nearby presence of objects which would help to shield the line and intercept some of the lightning which would otherwise strike the line. The consequence of the strikes to the line depends on the design and construction of the line, the structure footing resistances, the amplitudes and waveshapes of lightning flash currents, the point along the span at which the lightning strikes, and the degree to which protection is afforded by surge arresters. All of these factors can be taken into account in a lightning performance analysis to obtain probabilistic occurrences of line outages due to lightning strikes.

The traveling wave phenomena involved are highly complex and can only be effectively evaluated through computer analysis. However, without having to resort to complex analysis, we can obtain some idea of the nature of the problems that may be encountered, and how they may be mitigated.

Lines without Overhead Shield Wires

Invariably, lightning to unshielded lines involves a strike to a phase conductor. The current available in the lightning flash splits and travels as a current surge in both directions along the conductor from the point of strike. This corresponding surge voltage is simply the product of current and surge impedance of the line. For a very modest lightning strike current of 20 kA, splitting into two equal surges of 10 kA travelling along a line having a 400 ohm surge impedance (typical for 69 - 115 kV lines), the resulting surge voltage would be 4,000 kV. This is far in excess of the critical flashover voltage of the insulators (typically 350-500 kV for 69 kV systems, 500-750 kV for 115 kV systems). Without added lightning protection means, a lightning strike to an unshielded line will invariably result in an insulator flashover and an associated line outage.

Lines with Overhead Shield Wires

For properly designed lines, having well located shield wires, most lightning strikes to the line will terminate on the shield wire. The current surge will travel along the shield wire until it reaches a structure where it will be conducted down into the ground. While this appears to be an uneventful dissipation of the lightning energy, it is possible, under certain circumstances, to generate sufficient voltages across

insulators to cause them to flashover. The grounding of structures is never perfect (i.e. zero footing resistance) and the structure itself possesses a surge impedance. The current flowing through the structure and the footing resistance causes a voltage rise of the structure above ground voltage. At the same time, voltages are induced on the phase conductors through capacitive coupling. The surge voltage appearing across a phase insulator is the difference between the structure voltage and the phase conductor voltage. In many cases this can be sufficiently high to cause a "backflashover" of the insulator (so called because the structure voltage is higher than the phase conductor voltage and the insulator backflashes from structure to conductor).

Typically, the highest voltage will appear across the insulator supporting the lowermost conductor. For example, consider the line depicted in Fig. 1.
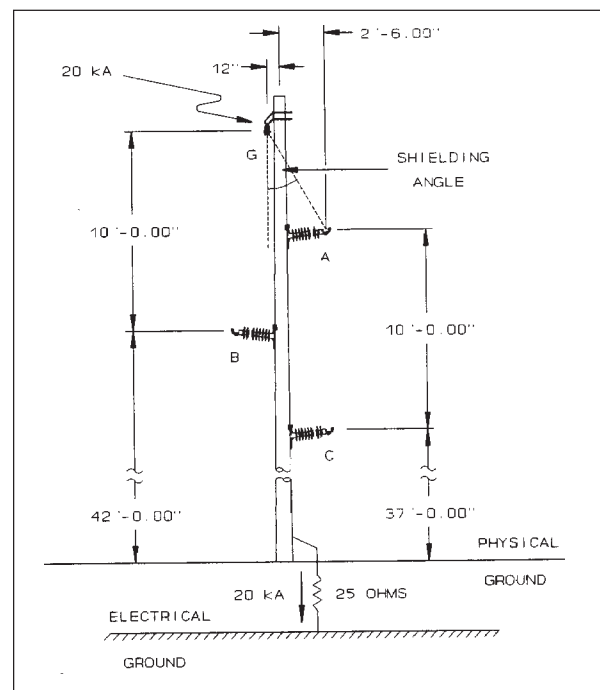

Fig. 1. Example geometry of line with overhead shield wire

Surge current flowing along the shield wire, into the structure and through the footing resistance results in (1) a voltage rise of the structure above earth potential and (2) an induced voltage on each phase conductor. The voltage (1)-(2) appears across the insulators. This is a fairly complex problem to analyze because of multiple reflections and refractions of surge voltage waves at the top and bottom of the structure, but we can obtain an appreciation of

the backflash phenomenon if we simply look at the structure voltage (1) as being the result of the surge current of 20 kA flowing through the 25 ohm footing resistance, giving a structure voltage of 500 kV. The induced voltage (2) depends on the "coupling factor" which is a function of the relative spacings of conductors to ground and conductors to shield wire. Fig. 2 shows how the coupling factor between any two conductors is determined. For the case of Fig. 1, the coupling factor between the shield wire and phase conductor C is 0.20; the voltage (2) induced on this conductor is 20% of the voltage (1) at the top of the structure, or 100 kV. The net voltage (1)-(2) appearing across the insulator supporting conductor C is then 400 kV. If the critical flashover voltage (CFO) of the insulator is 380 kV, there would be a very high probability of flashover.

VOLTAGE IMPRESSED ON a = V_a

VOLTAGE INDUCED ON b = $V_a * CF_{ab}$
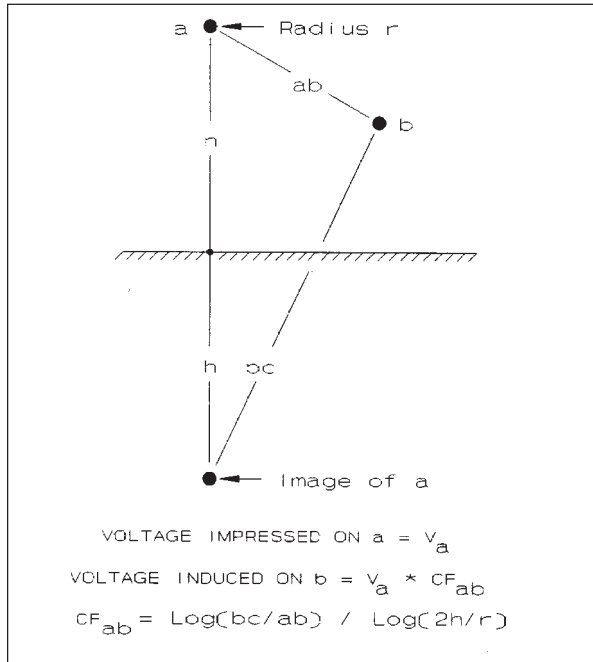
$CF_{ab} = Log(bc/ab) / Log(2h/r)$

Fig. 2.   Determination of voltage coupled from one conductor to another

Conductors closer to the shield wire have higher coupling coefficients (i.e. have higher induced voltages) and consequently have a lower net voltage appearing across their supporting insulators. In the case of Fig. 1, the coupling factor for conductor B is 0.25 and for conductor A is 0.32. The net voltages across insulators B and A for the 20 kA case would be 375 kV and 340 kV, respectively. Insulator B would then also have a fairly high probability of flashover, while insulator A would have a fairly low probability of flashover.

The intent of an overhead shield wire is to shield the phase conductors from direct lightning strikes, but this can only be accomplished to a certain level of assurance. Shielding failures can occur, and lightning can terminate directly on the phase conductors. The probability of such an occurrence depends on the shielding angle (depicted in Fig. 1) and the intensity of the lightning stroke. Shielding failures are more likely with higher shielding angles and lower stroke currents. If a phase conductor is struck directly, the consequence is essentially the same as a direct strike to an unshielded line, i.e. an almost certain insulator flashover.

APPLICATION OF SURGE ARRESTERS

Lines with Overhead Shield Wires

As indicated, backflashovers can occur on a shielded line if the level of surge current and/or structure footing resistance is sufficiently high. One approach to reducing the probability of occurrence of backflashovers is to reduce the structure footing resistances. This is not always an easy accomplishment, particularly in areas of indigenously high impedance ground, such as rock. An alternative approach is to equip the line with strategically located surge arresters. In the extreme, if appropriately rated surge arresters were located on all phases at every structure, backflashovers could be eliminated entirely. The simplified calculations given for the line geometry of Fig. 1 showed that the insulators on the lowest phase are the most vulnerable to backflashover. Thus one could consider applying surge arresters only on the lowest phase. If applied at all structures, flashover of the lowest phase insulators would be eliminated. The other phase insulators remain vulnerable for sufficiently high lightning current levels, but the overall performance of the line will be improved (i.e. probability of line outages due to insulator flashover will be reduced).

Application of arresters to the two lowest phases would yield another level of performance, intermediate between application on all phases and application on the lowest phase only. Other arrangements can be evaluated, such as application on all three phases but at every second structure. This uses the same number of arresters as the case of applying arresters on the two lowest phases at every structure. Which of these two variations would result in the

better performance depends primarily on the line design, conductor spacings and span lengths.

In the case of a shielding failure, if the struck phase has arresters installed at each structure, then a flashover will be avoided. If arresters are applied on one phase and lightning strikes a separate phase, flashover of the insulators on the struck phase is almost inevitable. However, since shielding failures are low probability occurrences in the first place, this is generally of second order concern.

Lines without Overhead Shield Wires

As previously mentioned, a lightning strike to an unshielded line with no arresters installed, will invariably result in an insulator flashover. In this case, the structure footing resistance plays no part in the mechanism. Very little improvement can be obtained by increasing the line insulation level. Without adding arrester protection, the lightning performance of the line can be significantly improved only by adding an overhead shield wire. This can be a very expensive proposition. It also now brings footing resistance back into the picture, perhaps requiring the lowering of high footing resistances to realize the anticipated benefits of the shield wire addition.

Application of surge arresters will often be a more attractive alternative. As for a shielded line, maximum protection is achieved with application of arresters on all phases at every structure. For such an application, flashovers can be eliminated entirely. One can consider other alternatives between this extreme and the other extreme of using no arresters at all, each giving some intermediate level of lightning performance between perfect and none. For typical types of unshielded construction, there will be one uppermost phase conductor (or two such conductors for a double circuit configuration) which will be the most likely to be struck by lightning. Thus a common intermediate-level application is installation of arresters on the uppermost phase at every structure. Then, when the uppermost conductor is struck by lightning, one or more arresters conduct the surge current to the structure and to ground, and an insulator flashover is avoided. In essence, the unshielded line has been converted to a shielded line, without the expense and complexity of adding an extension to the structures to allow the installation of an overhead shield wire.

Estimation of Benefit of Arrester Installations

For a line with or without an overhead shield wire, one can perform analyses to estimate the lightning performance for a variety of arrester installation schemes. The analyses can be very complex, and certainly involve much more detailed representation of parameters than dealt with in the simplified views presented above. Line design parameters which play an important role are: conductor configurations, spacings and heights above ground, span lengths, structure types, and footing resistances. These are all deterministic parameters, but all may vary significantly over the length of the line. Other parameters affecting the performance are of a statistical, rather than deterministic, nature. These include lightning ground flash density, lightning flash current levels, rates-of-rise of current wavefronts and duration of tails, location of strike to the line (at structure, along the span, to a shield wire or to a phase conductor), and insulation withstand levels.

Special purpose computer programs greatly facilitate the analysis. One such program is TLP, custom developed for Ohio Brass by Power Technologies Inc., Schenectady, New York. This program has been used to aid utilities in this country and abroad in selecting arrester installation schemes to meet a desired level of lightning performance. Such analyses typically involve a Monte Carlo probabilistic analysis and compare the calculated "before" and "after" performance of the line for the same statistical distributions of the lightning parameters, to determine the relative improvement to be expected from the arrester application. In theory, the "before" results should match the utility's actual prior experience. However, this can be, at best, only an approximation for a number of reasons. For example: the utility may not be able to accurately determine the cause of every outage and may incorrectly attribute some outages to lightning strikes; calculations are based on lightning data averaged over many years while experience may be documented for non-average lightning seasons; actual footing resistances may not be accurately known and may vary significantly from the values used in the analysis. For reasons such as these, it is best to look at relative performance between the various cases.

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PRACTICAL APPLICATIONS ON 69 kV SYSTEMS

Northern State; Power

NSP has a mix of shielded and unshielded lines on their 69 kV system. In 1992, approximately 30% of all 69 kV feeder outages were caused by lightning strikes, predominantly to unshielded lines. Each strike to the unshielded lines caused several feeders to trip. NSP reviewed the performance data of 440 miles of unshielded and 2000 miles of shielded 69 kV lines over the previous 10 years. The review indicated that the average annual lightning-caused outage rates were 20.1 and 4.25 per 100 miles of unshielded and shielded lines, respectively. Based on this information, NSP decided to take action to improve the lightning performance of several unshielded lines.

Some of the lines in question were more than 50 years old and used wood pole construction with pintype insulators and arcing horns (Fig. 3) having a CFO as low as 270 kV. Others used porcelain post insulators. Three alternatives considered: (1) add a shield wire to the existing structures; (2) install arrester/insulator assemblies on the existing lines; (3) rebuild with shielded, horizontal post structures. After cost comparison of three options, option (3) was eliminated since it would cost $125-150k per mile versus $33k per mile for option (1). The question then was which of the two remaining alternatives, (1) or (2), was the most attractive. Lightning performance for the two alternatives was evaluated with the TLP software package. For alternative (2), two different schemes were considered: (a) arresters on the top phase only, but at every structure; (b) arresters on all three phases, but only at every third structure. The two schemes use the same number of arresters, but (b) involves climbing one-third as many structures as (a) for the installation.

Line parameters for the cases evaluated are as shown in Fig. 4 (this geometry - less the bayonet and shield wire - is representative of NSP unshielded lines).

Four cases were run: (0) shielded, base case; (1) shielded; (2a) unshielded, arresters top phase every structure; (2b) unshielded, arresters all phases every third structure. The estimated ground flash density was 12.4 strokes/square mile/year. For the shielded
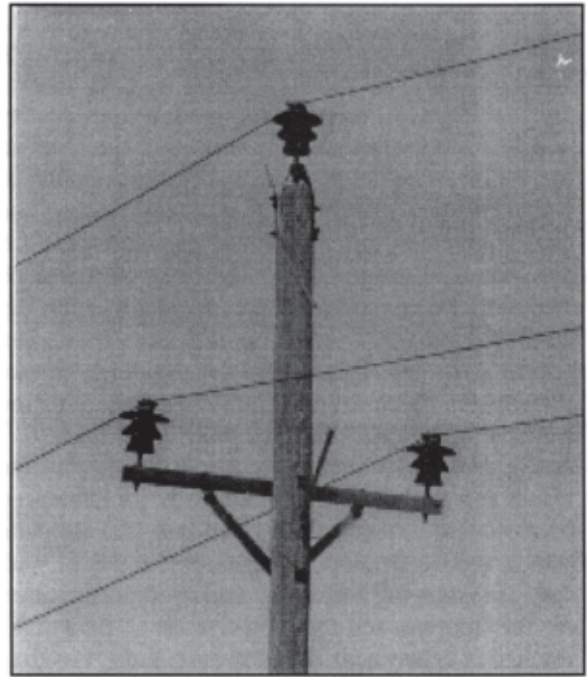

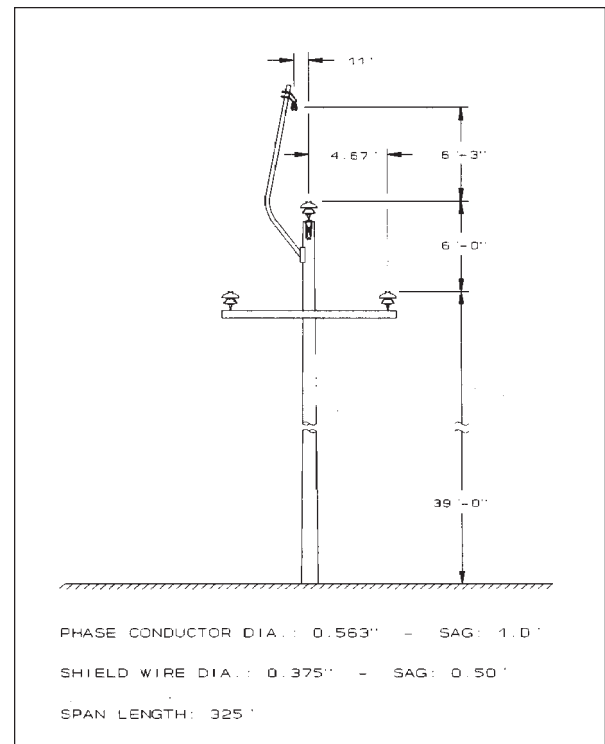Fig. 3. Typical NSP unshielded 69 kV line

PHASE CONDUCTOR DIA.: 0.563" – SAG: 1.0'

SHIELD WIRE DIA.: 0.375" – SAG: 0.50'

SPAN LENGTH: 325'

Fig. 4. Line parameters used in performance studies

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case, this resulted in an estimated average number of strikes to the line of 16.6 per year. For the unshielded cases, the corresponding number was 14.6 per year. Results of the lightning performance analyses are given in Table I, along with the calculated cost of implementing each alternative. The critical currents listed are the lightning stroke currents for which the probability of a line insulation flashover is 50%. For the base case (case 0 - unshielded line) essentially every strike to the line results in a flashover. Performance is not influenced by footing resistance. Case 1 and case 2(a) are quite comparable in terms of lightning performance, with case 2(a) showing somewhat improved performance as the footing resistance increases. Case 2(b) resulted in between 30 and 60 % more flashovers than case 2(a).

NSP selected five lines to equip with arresters, three using the scheme of case 2(a) and two using the scheme of case 2(b). Fig. 5 shows an example of an installation. An analysis of outage rates before and after the line modifications was performed. The National Lightning Detection Network was used to determine the number of lightning strikes within ~ 21/2 miles of the lines, allowing a calculation of the average ground flash density. To permit a valid comparison between line performances, the outage rates were normalized to the same ground flash density. The ground flash density chosen for normalization was that used in the performance study described above, namely 12.4 strokes/square mile/ year. On this basis, Table II compares the results obtained for the period April-August l993 (after the line modifications) with the historical data for the four year period 1989-1992 (prior to modification of the lines).

As evidenced by the ground flash density (GFD) figures, 1993 was a year of exceptionally high lightning activity compared to the prior 4-year average. Even so, fewer outages than normal were experienced. When adjusted to be on the same GFD base, the reduction in outage rates with arrester protection is seen to be very significant, with the protection scheme (a) using a top-phase arrester every structure resulting in the better performance. This experienced performance is quite consistent with the calculated performance, as indicated in Table III.

On the basis of the 1993 experience, NSP installed arresters on an additional nine 69 kV lines in the Fall of 1993 and the Spring of 1994. As of May, 1994, NSP had installed over 5,000 arresters, of which only two failures have been experienced. Installation costs were as expected ($10k to $13k per mile), making the arrester protection of the lines a cost effective means of improving lightning performance.
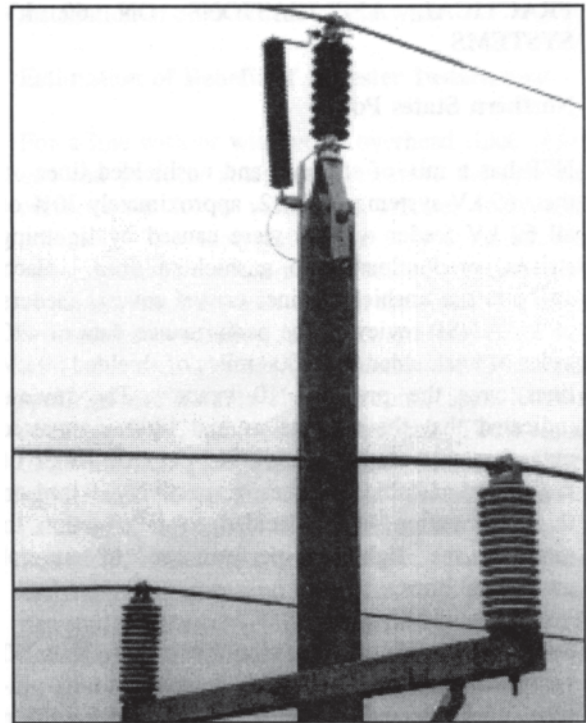

Fig. 5. NSP 69 kV line equipped with line arrester on top phase

LAKELAND ELECTRIC AND WATER UTILITIES

Several years ago, the Lakeland, Florida, Department of Electric and Water Utilities adopted a new standard of 69 kV line construction which did not use the common overhead shield wire. When considered against the isokeraunic map, the decision process and perspective of Lakeland should be of interest to other utilities.

TABLE I. CALCULATED LIGHTNING PERFORMANCE FOR DIFFERENT FOOTING RESISTANCES

Case	Cost per mile	10 OHM		25 OHM		50 OHM	
		Critical current (kA)	Average F/O (#/100 mi/yr)	Critical current (kA)	Average F/O (#/100 mi/yr)	Critical current (kA)	Average F/O (#/100 mi/yr)
0	----	1.6	41.7	1.6	41.7	1.6	41.7
1	$33k	108.6	6.9	46.9	19.1	26.6	34.3
2 (a)	$13k	135.2	10.3	57.0	17.4	32.8	27.4
2 (b)	$10k	51.6	13.1	21.9	30.3	13.3	35.7

Case 0:   Base case - unshielded line before modification
Case 1:   Shielded line
Case 2(a):   Unshielded line, arresters on top phase every structure
Case 2(b):   Unshielded line, arresters on all phases every third structure

TABLE II. COMPARISON OF OUTAGE RATES BEFORE AND AFTER LINE MODIFICATION

	No. of lines	Total miles	Total no. of strokes (±2.5 mi)	Avg GFD (strokes/mi²)	No. of outages	Outage rate (per 100 mi)	Normalized outage rate (per 100 mi per year)
Unprotected (before mod)	5	161	5235 (avg/yr)	6.5	38	23.6	45.0
Protection scheme (a)	3	104	7681	14.8	13	12.5	10.5
Protection scheme (b)	2	57	8483	29.8	21	36.8	15.3

TABLE III. COMPARISON OF EXPERIENCED OUTAGE RATES WITH CALCULATED PERFORMANCE (GFD = 12.4 strokes/mi²/yr)

	Normalized actual	Calc. for different footing resistances	
		10 ohm	25 ohm
Unprotected	45.0	41.7	41.7
Protection scheme (a)	10.5	10.3	17.4
Protection scheme (b)	15.3	13.1	30.3

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On the latest lightning flash density map of the United States, the 225 square mile Lakeland service territory coincides almost exactly with the area of highest density (20-23 flashes/mi2 per year). In the middle of this zone, Lakeland operates 100 miles of shielded 69 kV subtransmission and 16 miles of 230 kV transmission lines. A high number of lightning-caused outages occur on the 69 kV system, but very few on the 230 kV lines, even when the difference in circuit miles is taken into consideration.

While computer studies of the problem were performed, some other level of comfort was sought that omitting shield wires from new construction was a sound move. A simple "table napkin" analysis served this purpose. With average line heights of 58 ft. (resulting in a shadow width of 232 ft.) and 100 miles of total line length, the "vulnerable" area is 4.4 square miles, giving an expected number of lightning strikes to the 69 kV system of 101 per year for a ground flash density of 23 flashes/mi2/yr. This is without the effect of considerable natural shielding which is estimated to reduce the number of strikes to the lines by about 25 %, to an estimated 75 per year. Over the last two years, the lightning-caused outages on the 69 kV system averaged 39 per year, or about one outage for every two lightning strikes.

This simple analysis supported the observation that shield wires were doing a poor job in protecting the lines from lightning. Other observations were that: (1) the extra height needed to run the shield wire widens the zone of vulnerability, increasing the number of strikes to the line; (2) shield wire adds about $27k per mile to the construction cost of a new 69 kV line; (3) shield wires are not without maintenance problems, with 5 cases of mechanical failure having occurred over the last two years.

Lakeland reached the conclusion that using shield wires for 69 kV construction should stop . Though this decision was originally sought through a sophisticated and complex analysis, the "table napkin" analysis became a reassuring and refreshing after-the-fact defense of the often-questioned decision.

Actually, the first application of line arresters was on an existing 1.33 mile shielded 69 kV line. In this case, no outages have been recorded over a two year period.

Subsequently, new unshielded construction has included a 5 mile line with arresters on every phase at every pole, and a 7.4 mile line with arresters on all phases at every third pole. After six months of service history, the 5 mile section has recorded no lightning-caused outages while the 7.4 mile section has experienced one outage resulting from flashover on the top phase at a pole without arresters. A typical installation is shown in Fig. 6.
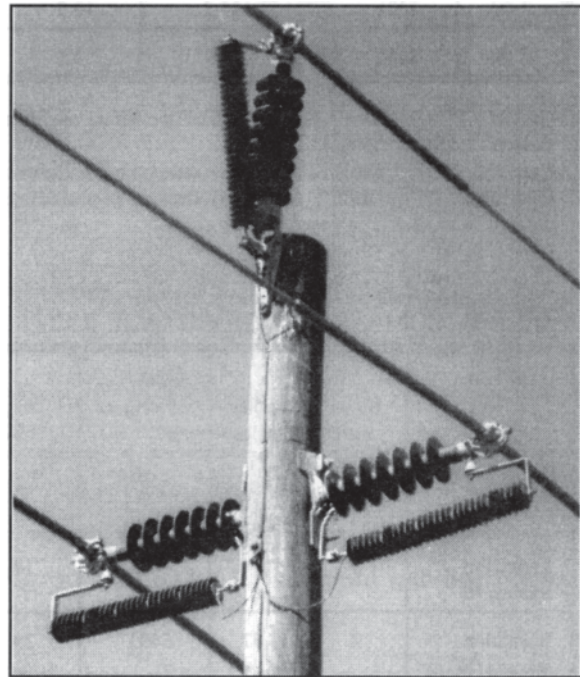

Fig. 6. Lakeland 69 kV line equipped with line arresters on all three phases

For one other case of new construction, in an area well-shielded by trees and for a line which does not serve a critical function, the line was built without shield wires and without arresters. No performance data are yet available from this line.

The five different design configurations now existing on the Lakeland system will form the basis of an empirical assessment of lightning performance. The assessment will combine data from a lightning location service with breaker operation data from the Lakeland SCADA system. When lightning strikes near a line segment and this event coincides with a breaker operation on that segment, then it will be assumed that a lightning flashover occurred. The data will be archived and averaged over four years to achieve statistical validity. Magnitude and polarity of the offending lightning strikes will also be collected.

As long as the performance of a new design is shown to be no worse than the original shielded line performance, Lakeland will not return to shield wire designs for 69 kV. With the assumption that the new designs will perform better than the old, the information gathered should provide support for setting new standards for arrester use and spacing.

BIOGRAPHIES

Michael G. Comber
Mike Comber graduated with BSc. and MSc. degrees in Electrical Engineering from the University of Aston in England. After a brief period with the Central Electricity Generating Board as a System Planner, working on expansion of the 275 kV and 400 kV national grid system, he moved to the United States in 1968 for a position with General Electric Company as a design engineer in the Distribution Transformer Department. During this time he obtained an ME degree in Power Systems Engineering from Rensselaer Polytechnic Institute (RPl).

In 1972, he joined the staff of what was then GE's Project UHV (now EPRI/HVTRC - High Voltage Transmission Research Center) as a Research Engineer working on corona and field effects of high voltage AC and DC transmission lines. He is a co-author of several chapters of the EPRI "Red Book" (Transmission Line Reference Book -345 kV and Above).

In 1982 he was appointed Manager of Surge Arrester Development. In this position he was responsible for design and development of several of GE's metal oxide surge arrester products. He later was appointed to the position of Manager of Engineering which included responsibilities for managing the high voltage bushing design efforts and the GE high voltage laboratory in Pittsfield, MA.

In 1989, he left GE to join Ohio Brass as Vice-President of Engineering, the position he now holds. In this position he is responsible for all aspects of design, development and test of the company's surge arrester and insulator products.

He is a Senior Member of IEEE, and is active in IEEE, CIGRE and IEC activities related to surge arresters and insulators.

Michael G. Vermilye
Mike Vermilye is a 1987 Graduate of the Cuyahoga Community College with an Associate of Applied Science Degree in Electrical and Electronic Engineering Technologies.

In 1986, he joined the Controllix Corporation (a manufacturer of metal-enclosed capacitor banks and relaying/control panels) as a Quality Assurance Technician. In 1987, he transferred to Design Engineering, becoming Engineering Manager in 1989. In 1990, he joined ASC Industries, Inc. (a manufacturer of medium voltage switchgear and metal-enclosed capacitor banks) as a Sales Engineer. In 1991, he joined Ohio Brass as a Sales Engineer responsible for distribution and transmission line surge arresters. In 1994, he was appointed to the position of Product Manager for transmission line surge arresters and fiber-optic insulators.

He has been an Associate Member of IEEE since 1992.

Steve F. LaCasse
Steve LaCasse obtained his BS degree m Electrical Engineering in 1972. He has been employed at Northern States Power since that time, with 5 years as an engineer in the System Operating department and 17 years in Transmission Engineering. He has held his present position of Superintendent, Transmission Engineering since 1990.

He has served as a member of EPRI's Underground Transmission Task Force for 9 years. He is a Registered Professional Engineer in Minnesota, North Dakota and South Dakota, and is a Member of IEEE.

Robert M. Reedy
Bob Reedy has been with the Lakeland (Florida) Department of Electric and Water Utilities for 19 years. He has served in technical and managerial roles in most functional areas of the utility, but has a special interest in system protection and control.

He earned his BEE and MSEE degrees at Auburn University, and his MBA degree at Florida Southern College. His graduate thesis (Auburn University, 1975) was entitled "A Study of the Effect of Earthwire Materials on Lightning Induced Voltages and Currents in Transmission Lines".

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