Reduction of Lightning Caused Interruptions on Electric Power Systems
Reduction Des Compures Dues a la Faudre Dans Les Reseaux

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Resume

L'avenement d' équipements électroniques de haute technologie dens les industries ainsi que dans les foyers, a amene les Compagnies d'Electricité á explorer de nouvelles méthodes pour ameliorer la fiabilité des lignes de puissance. Les interruptions dues á la foudre sont les plus courantes sur les systemes de puissance. Dans cet article, l'auteur focalise sur les méthodes pour reduire les interruptions causées par la foudre sur les nouvelles lignes et les lignes existantes par l'utilisation de parafoundres á enveloppe polymérique á oxyde de zinc.

Summary

The advent of high technology manufacturing equipment and home electronics devices have caused many electric utilities to explore methods of improving reliability of power lines. Lightning interruptions are among the most common type of interruptions on power systems. In this paper, the author focuses on methods to reduce lightning cause interruptions of new and of existing lines by the application of polymer-housed metal-oxide surge arresters.

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Introduction

Utilities have long sought a reliable, cost-effective method to protect transmission and distribution lines from lightning. Today's high technology equipment requires utilities to deliver quality power to residential and industrial users. This paper will briefly discuss some of the methods historically used to protect these lines and then discuss the most recent advances in this field. It will examine the following options: no protection, overhead shield wire, protector tubes and the application of metal-oxide surge arresters.

The purpose of protection methods is to minimize line insulation flashovers, since line insulation flashover will cause an interruption until the resulting line-to-ground fault is cleared.

Sample Case

A typical 115kV transmission line was modeled to determine the lightning performance of various protection options.

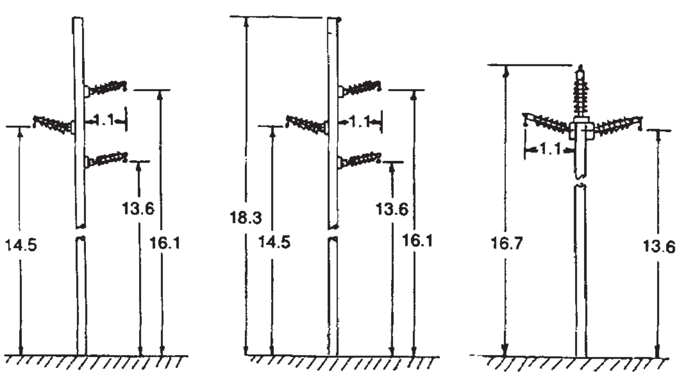
The configurations studied are shown in Figure 1.

For modeling purposes the following assumptions were made:

Span Length	-	152 meters
Grounds	-	Every Span
Shield Wire Diameter	-	9.5 mm
Phase Conductor Diameter	-	18.3 mm
Line Insulation	-	Polymer Post
	-	Positive Impulse Critical 560kV
Structure Type	-	Steel Pole
Isokeraunic Level	-	30

Figure 1

CASE I	CASE II	CASE III



No Protection OHSW "Delta" Configuration

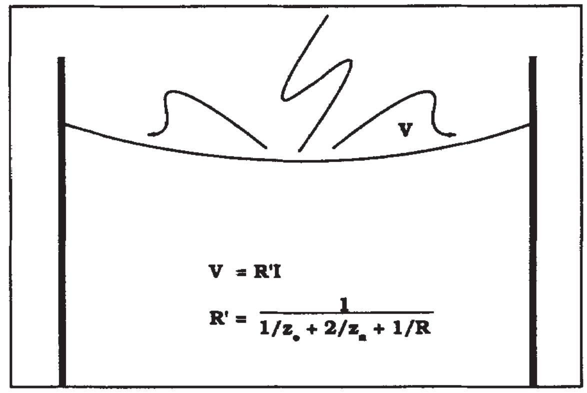
All Dimensions in Meters

No Protection Option

The simplest method of constructing a transmission or distribution line in areas of low lightning stroke density is to make no attempt to protect from lightning. This method exposes the phase conductors to direct lightning strokes.

When lightning strikes the phase conductor, a high voltage travelling wave is generated that propagates in both directions (Figure 2). The magnitude of this travelling wave is V=R'I where I = lightning stroke current and R'= (1/Zo + 2/Zn + 1/R) where Zo = stroke surge impedance (approximately 400 ohms), Zn total line surge impedance, R=ground resistance at stricken point. Flashover of the line insulation may occur when the travelling wave reaches the line insulation. (1)

Figure 2



All cases were studied using TLP* proprietary software. Based on the isokauranic level of 30 and the line geometry the line will be subjected to 20.47 strokes per 100km/yr. The results of this study are shown in Table I and show that the interruption rate without any protection is unacceptably high.

Table I

CASE I: No Protection

Structure Footing Resistance (Ohms)	Percent Flashovers	Average Flashovers Per 100 km/yr
5	99.4	20.35
200	99.7	20.42

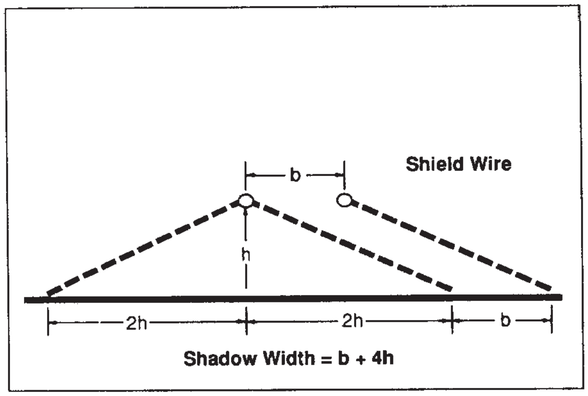
Shield Wires

One of the most common methods of protecting transmission lines from lightning strikes is by use of an overhead shield wire. The theory behind this method is for the shield wire to intercept strokes so they cannot directly strike the phase conductors.

A properly shielded transmission line will intercept all strokes that would have terminated on the earth in the protected "shadow width". The shadow width is shown in Figure 3.

*TLP – A proprietary software jointly developed and owned by Ohio Brass and Power Technologies, Inc.

Figure 3



Lines that are protected by shield wires are still prone to lightning caused interruptions by one of two causes. These are shielding failures and backflashes.

Shielding failures occur when the lightning stroke does not terminate on the tower or shield wire, but on the phase conductor instead. A high voltage develops at the stricken point and a travelling wave is generated and propagates in both directions. If this travelling wave is of sufficient magnitude, it will cause an insulator flashover. This flashover will result in a service interruption, which is similar to the no protection option analyzed earlier.

The shielding failure rate calculation depends on the conductor geometry. Whitehead and others (2) have developed a model with allows for calculation of the shielding failure rate.

Typically the line is considered to be effectively shielded when the angle between the line from the overhead shield wire to the protected conductor and the vertical is less than 30°. With effective shielding, it is possible to minimize direct strokes to the phase conductors. But, this does not necessarily mean that the line will have satisfactory lightning performance.

Direct strokes to the overhead shield wire can cause flashover from the structure to the phase conductor by a process known as backflash.

The stroke current induces voltages in the phase conductor. The voltages induced in the phase conductors are determined by the coupling factor Kn times the structure top voltage. This voltage is a function of time, footing resistance and structure geometry.

The voltage stress on the line insulation is equal to the difference between the structure voltage at the insulator attachment point and the induced voltage in the phase conductor.

If the voltage stress across the line insulation exceeds the flashover voltage of the insulator, a flashover will occur.

Case II was studied using various ground footing resistances and protection methods. The results of this study are summarized in Table II below.

Table II

CASE II: OHSW Alone

Structure Footing Resistance (Ohms)	Critical Current (kA*)	Percent Flashovers	Average Flashovers Per 100 km/yr
5	>200.0	6.4	1.55
10	182.0	7.7	1.85
25	86.7	12.3	2.97
50	49.2	27.1	6.55
100	27.3	57.6	13.92
200	16.4	85.7	20.73

*Stroke to shield wire.

The critical current is the current that will be just enough to cause flashover of the line insulator.

The increased height of the line due to the addition of the shield wire increases the number of strokes to the line by 18 percent to 24.18 per 100 km/yr.

At high footing resistances the percentage of flashovers to the line are nearly as high as for an unshielded line. These are due to backflashes.

The resulting backflash has a very fast rate of rise. There is evidence that these rapidly rising waves may be responsible for substation transformer failures, even where metal-oxide arresters are used in the substation. (3)

Protector Tubes

In the 1930s much was learned about the lightning performance of transmission lines. Many lines had been constructed without overhead shield wires and the performance of these lines was less than desired. The retrofit of a shield wire was expensive so a more effective method of improving the lightning performance was required.

The method developed was the expulsion protector tube (4). The expulsion protector tube was an early predecessor of the modern metal-oxide arrester line arrester.

The expulsion protector tube was designed to provide a low impedance path to ground for the lightning surge current. It discharged to ground at a voltage below the flashover voltage of the line insulation.

The expulsion protection tube was constructed in a fiber tube with an internal gap. The tube was not directly connected to the line but had an external gap between the protector and the phase conductor.

The impulse critical sparkover of the assembly was below the flashover voltage of the line insulation. For example, for a 115kV protector tube, the positive impulse critical sparkover of the gap was 575kV while the line insulation positive impulse critical flashover voltage was 695kV assuming 7 - 5-3/4 x 10" porcelain bells were used.

Once the gap sparked over, the flow of system current through the protector tube had to be interrupted. The follow current arc vaporized material from the walls of the tube. The gases from the well deionized the arc enough to allow for interruption of the follow current at the next system current zero.

While protector tubes could withstand high current lightning strokes of up to 100kA, they had limited ability to interrupt system current. The protector tube used at 115kV could interrupt system currents in the range of 850 to 5,000 amps. The increasing system available fault currents reached levels where protector tubes could no longer interrupt. This could lead to catastrophic failure.

Due to their size and operating characteristics, protector tubes were sometimes difficult to mount. For example, at 115kV a tube capable of interrupting 5,000 amps would have a visible flame path of 14 feet during operation.

During interruption of system follow current, some of the fiber lining was consumed. This led to a change in the interrupting current range and eventually the protector tube became ineffective. Also, there was burning of the external gap electrode leading to changes in gap spacing. Even with their shortcomings, the utility experience with protector tubes was favorable from a protection standpoint (5). The use of direct connected metal-oxide varistor surge arresters overcomes these shortcomings.

Metal-Oxide Surge Arrester Protection

Two recent developments have led to means of significantly improving line lightning performance.

These are high voltage polymer insulator and metal-oxide varistor technologies. The combination of these two technologies have allowed the development of lightweight, reliable and complete line protection systems.

This paper models polymer line post insulators and polymer-housed metal-oxide arresters. This type of assembly gives many advantages over porcelain type assemblies including weight savings. For example, the polymer assembly for a single phase has a weight of 43 kg while the porcelain counterpart weighs 193 kg.

Directly connected polymer-housed arresters provide consistent protective levels as compared to gaps which require careful installation and adjustment.

The polymer-housed arresters used in this study are gapless and as a result have minimal internal airspace. For porcelain arresters of this type, the internal free airspace leads to moisture ingress due to seal pumping and eventual failure. Up to 86 percent of porcelain arrester failures are due to moisture ingress.(6) The polymer-housed arresters eliminate this moisture ingress problem to make a very reliable assembly, thereby ensuring the arresters do not leak and negatively impact the line performance.

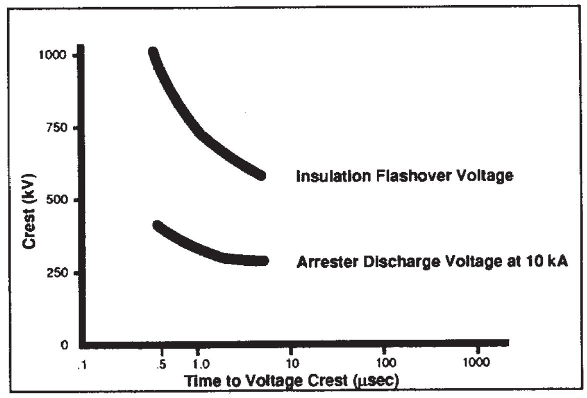
The polymer insulators in these assemblies have been in use since 1975 and the polymer arresters since 1986. These technologies have been successfully combined since 1988.

The metal-oxide surge arresters use nonlinear metal-oxide varistors having a high impedance at 60Hz system voltage. When a high voltage surge (such as from lightning) is impressed on the surge arrester, the impedance of the metal-oxide varistors drops dramatically.

The metal-oxide surge arrester used in this grounded 115kV system example has a Maximum Continuous Operating Voltage (MCOV) of 70kV. The MCOV of a surge arrester is the continuous 60Hz line-to-ground voltage that can be supported for the life of the arrester.

The metal-oxide surge arrester is connected electrically in parallel with the line insulation. The metal-oxide surge arrester limits the surge voltage across the line insulation by going into conduction at a voltage below the flashover voltage of the line insulation. The relationship between the discharge voltage of the 70kV MCOV arrester and the flashover voltage of the line insulation is shown in Figure 4.

Figure 4



After the surge arrester has successfully discharged the lightning surge, the voltage across the arrester returns to the line-to-ground value.

Since the metal-oxide arresters used in this application are gapless, the arrester is only in conduction for the duration of the lightning stroke. This event is of too short duration to be detected by relaying methods. Therefore, the operation of the surge arrester will not result in an interruption.

The unprotected line has an excessively high interruption rate. In some cases it is impossible to retrofit with a shield wire. Case I was studied by modeling with arresters on the top two phases of alternate structures. The results of this are shown below in Table III.

Table III

CASE I: No OHSW Plus Top Two Phase Arresters Alternate Structures

Structure Footing Resistance (Ohms)	Critical Current (kA*)	Percent Flashovers	Average Flashovers Per 100 km/yr
5	84.4	6.6	1.35
10	76.6	9.1	1.86
25	50.0	19.9	4.06
50	32.0	45.1	9.23
100	19.5	71.1	14.68
200	11.7	89.1	18.24

At 100 Ohms the addition of arresters reduces the interruption rate by 28% over no protection. As will be shown later, applying arresters more frequently further reduces the interruption rate.

The use of surge arresters on existing shielded construction with higher footing resistances can reduce lightning caused interruptions.

Case II was studied by modeling with arresters on the lower phase of every other structure.

The results are summarized in Table IV below.

Table IV
CASE II: OHSW Plus Alternate Structure Lower Phase Arresters

Structure Footing Resistance (Ohms)	Critical Current (kA*)	Percent Flashovers	Average Flashovers Per 100 km/yr
5	189.1	5.5	1.32
10	165.6	7.6	1.83
25	123.4	9.3	2.25
50	69.5	16.2	3.91
100	39.8	38.1	9.21
200	25.0	63.2	15.27

*Stroke to shield wire.

For footing resistances of 100 ohms, the addition of the surge arresters reduces the interruption rate by 34 percent over shield wire alone.

While the application of arresters for retrofit will reduce interruptions, it is possible to further improve lightning performance by a different line configuration.

The configuration shown in Case III was modeled using four different protection methods using arresters on all three phases of every third structure, then on all three phases alternate structures, next by applying arresters to the top phase of every structure and finally with arresters on all three phases of every structure.

The results of the lightning performance study are summarized in the tables below.

Table V
CASE III: Arresters All Phases Every Third Structure

Structure Footing Resistance (Ohms)	Critical Current (kA*)	Percentage Flashovers	Average Flashovers Per 100 km/yr
5	93.8	4.7	1.01
10	85.2	7.2	1.54
25	49.2	19.2	4.10
50	28.1	53.6	11.43
100	16.4	85.2	18.16
200	10.9	92.1	19.62

*Stroke to top phase.

Table VI
CASE III: Arresters All Phases Alternate Structures

Structure Footing Resistance (Ohms)	Critical Current (kA*)	Percentage Flashovers	Average Flashovers Per 100 km/yr
5	90.6	5.4	1.16
10	84.4	6.1	1.29
25	47.7	21.8	4.65
50	30.5	48.4	10.31
100	19.5	71.6	15.26
200	12.5	88.6	18.89

*Stroke to top phase.

Table VII
CASE III: Arresters Top Phase Every Structure

Structure Footing Resistance (Ohms)	Critical Current (kA*)	Percent Flashovers	Average Flashovers Per 100 km/yr
5	>200.0	7.1	1.50
10	158.6	9.2	1.96
25	103.1	11.0	2.34
50	59.4	20.0	4.26
100	32.8	48.6	10.35
200	20.3	74.2	15.82

*Stroke to shield wire.

Table VIII
CASE III: Arresters All Phases Structure

Structure Footing Resistance (Ohms)	Critical Current (kA*)	Percent Flashovers	Average Flashovers Per 100 km/yr
5	>200.0	0.0	0.00
200	>200.0	0.0	0.00

The lower profile of this line reduces the total number of strokes to the line by 12 percent to 21.3 per 100km per year when compared to the overhead shield wire option.

The single-phase and three-phase insulator assemblies are shown in Figures 5 and 6.

Figure 5

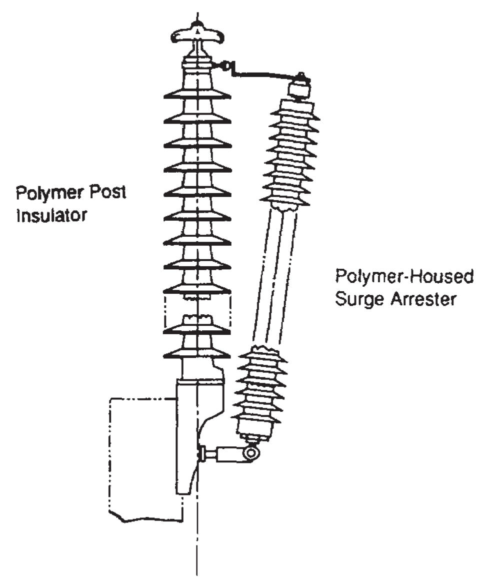
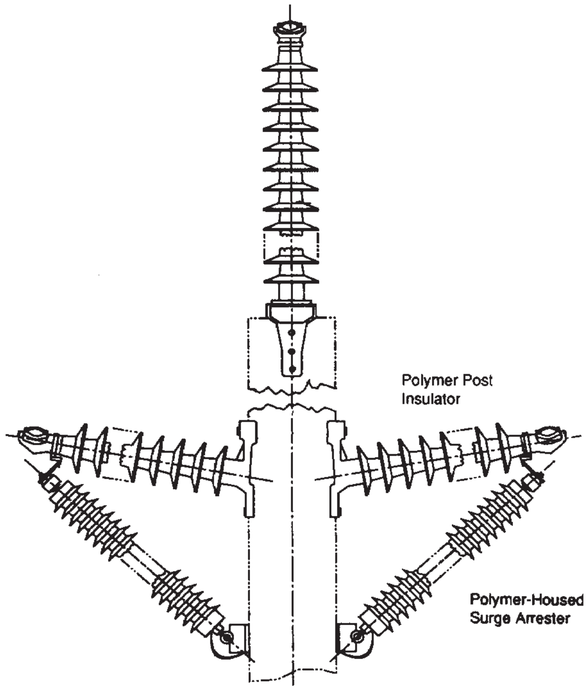


Figure 6



Summary

The results of the studies at 100 Ohms footing resistance are summarized in Table IX below.

Table IX

Case	Configuration	Total Flashovers Per 100 km/yr
I	No Protection	20.41
II	OHSW Alone	13.92
I	Arresters Top 2 Phase Alternate Structures No OHSW	14.68
II	Arresters Lower Phase Alternate Structures – Plus OHSW	9.21
III	Arresters All Phases Every Third Structure	18.16
III	Arresters All Phases Alternate Structures	15.26
III	Arresters Top Phases Every Structure	10.35
III	Arresters All Phases Every Structure	0.00

Arresters on the top phase of every structure results in a 26% improvement over shield wire alone. Therefore, for new construction the elimination of the shield wire and use of top phase arresters results in a better performing line.

Field Experience

Several U.S. utilities have line surge arresters in service at voltages up to 230kV.

Duke Power and Georgia Power have the most comprehensive data on outage rates due to lightning before and after installation of surge arresters.

Duke Power had a 27.8km 100kV line experiencing 8.3 interruptions per year. By installing surge arresters to supplement a shield wire, the interruption rate has been reduced by 55 percent to 3.7 per year. (7)

Georgia Power had a 27.0km 115kV line experiencing 11 interruptions per year. By installation of surge arresters, the outage rate has been reduced by 72 percent to three per year. (8)

Conclusion

Lightning interruptions are becoming a major problem for electric utilities. The application of surge arresters provides better performance than overhead shield wires.

The use of surge arresters gives up significant improvement in lightning performance over use of overhead shield wire alone.

In addition to improved lightning performance, the use of polymer-housed surge arresters and polymer post insulators have other benefits including:

- Reduced pole top weight
- Reduced line structure heights (15 percent in the case studied)
- Reduced line losses due to elimination of shield wire
- Reduced magnetic fields due to closer phase spacing.

Those utilities currently using direct connected surge arresters are pleased with the performance of these devices.

(1) "Protection of Transmission Lines Against Lightning: Theory and Calculations," L.V. Bewley, "General Electric Review," Vol. 40, April 1937, pp. 180-188; May 1937, pp. 236-241.

(2) G.W. Brown, E.R. Whitehead. "IEEE Transactions on Power Apparatus and Systems," Vol. PAS-88, 1969, pp. 617-626.

(3) R.E. Clayton, I.S. Grant, et al. "Surge Arrester Protection and Very Fast Surges," IEEE Transaction Power Apparatus and Systems, August 1983, Vol. 102, pp. 2400-2412.

(4) "Electrical Transmission and Distribution" Reference book, "Central Station Engineers Westinghouse Electric Corporation," 1964, pp. 559-607.

(5) "Protector Tubes for Power Systems," H.A. Peterson, et al, AIEE Transactions, Vol. 59, May 1940, pp. 282-288.

(6) CEA 077D 184A, Canadian Electrical Association, "Application Guide for Surge Arresters on Distribution Systems," Sept. 1988, p. 29.

(7) Bill Bonny, Duke Power, Hi-Tension News, Ohio Brass, Winter 1987, Vol. 56, No. 1, pp. 3-6.

(8) Nick Bledsoe, Georgia Power, Hi-Tension News, Ohio Brass, March/April 1991, Vol. 62, No. 2, pp. 8-9.