LIGHTNING AND SURGE PROTECTION FOR ELECTRICAL SYSTEMS

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1.0 SCOPE

This data sheet describes modern procedures and practices for protecting industrial power distribution systems and associated equipment from damage caused by overvoltages due to lightning, switching, or a system abnormality.

The protection of chimneys, stacks, and related equipment against lightning is covered in Data Sheet 1-13, *Chimneys,* and of ignitable liquid storage tanks in Data Sheet 7-88, *Ignitable Liquid Storage Tanks.* Grounding details are covered in Data Sheet 5-19, *Switchgear and Circuit Breakers and Data Sheet 5-20, Electrical Testing.*

In the United States, lightning protection requirements for ordinary buildings, miscellaneous structures, and special occupancies can be found in UL 96A, *Installation Requirements for Lightning Protection Systems.* Other countries may have their own codes.

1.1 Changes

April 2012. Terminology related to ignitable liquids has been revised to provide increased clarity and consistency with regard to FM Global's loss prevention recommendations for ignitable liquid hazards.

2.0 LOSS PREVENTION RECOMMENDATIONS

2.1 Electrical

2.1.1 Direct Stroke Protection

2.1.1.1 *Overhead Ground Wires.* For severe exposure (more than 40 thunderstorm days a year), install ground wires so the protected conductors are within an angle of 20° of a plumb line through the ground wire. For moderate exposure, use a protective angle of 30° to 45°. Ensure the overhead ground wire shields the substation, including the transformer and any switchgear and the supply line for at least ½ mile. However, shielding the entire length of line is preferred. Have the overhead ground wire grounded at every pole to a low-resistance ground connection.

2.1.1.2 *Masts.* Where a single mast is employed for shielding an outdoor substation or similar apparatus, ensure the mast is high enough so the equipment being protected lies within the protected zone of a sphere 150 ft (45 m) in diameter, where the top of the mast is not over 150 ft (45 m).

2.1.1.3 *Aerial Cable.* Ground the steel messenger supporting an aerial cable and the cable sheath at every pole through a low-resistance ground.

2.1.2 Installation of Arresters

2.1.2.1 *Location.* Locate surge arresters close to the terminals of the equipment being protected. If they are installed remote from the equipment they are intended to protect and one set of arresters is used to protect two or more pieces of apparatus, evaluate the ‘‘separation effect’’.

2.1.2.2 *Grounding.* Have the surge arrester ground terminals interconnected with the grounded parts of the protected equipment; make the line and ground connections as short as possible; and ensure the path to ground from the lightning arrester and the protected equipment has sufficiently low impedance to limit the voltage to ground to a safe value. The resistance to earth of the grounding electrode alone should not exceed 1 ohm.

In areas where the water table fluctuates or soil conditions vary, have annual tests of the resistance to earth of the grounding electrode made. In areas where these conditions remain reasonably stable, a check every five years is sufficient. Have all grounding connections inspected annually to ensure they are electrically and mechanically sound.

2.1.2.3 *Underground Cables.* Where underground cables supplying important or valuable equipment are connected to exposed overhead power lines, install surge arresters at the junction point and provide them with a low ground resistance.

2.1.2.4 *Dry-Type Transformers.* When a dry-type transformer is connected directly to overhead lines or supplied through another transformer, install special low-breakdown arresters at the primary terminals of the dry-type transformer and interconnect the ground wire with the transformer case and a low ground resistance of 1 ohm or less.

2.1.2.5 *Substations.* In addition to shielding the substation, ensure each entering exposed overhead line is shielded and protected with a set of surge arresters. Additional arresters may be needed to protect the transformer depending upon the distance between the arresters and the transformer, the system voltage, and the method of grounding. See Examples 1 and 2 in Figure 16c.

2.1.2.6 *Rotating Machines.* Protect important motors or generators with station-type arresters installed in parallel with surge capacitors at the machine terminals, and interconnect them with the machine frame and a ground resistance of 1 ohm or less.

1. Provide each medium voltage (5 kV to 15 kV) motor above 500 hp with surge protection as described above.

2. Ensure each motor over 200 hp connected to open overhead lines at the same voltage level as the motor is similarly protected.

3. Protect all unit-connected generators with surge arresters and capacitors as recommended above, except that on generators which have single-turn windings, the capacitor is not required.

2.1.2.7 Switchgear

2.1.2.7.1 In areas where lightning exposure is severe, have metal clad switchgear directly connected to overhead circuits through roof entrance bushings or through noncontinuous metallic sheath cable protected with station-type arresters.

2.1.2.7.2 Where the switchgear is connected through continuous metallic-sheath cables to overhead lines, install arresters at the cable junction. They also may be needed at the switchgear depending upon the length of cable, method of neutral grounding, and the class of arrester installed at the cable junction.

2.1.2.8 Protect buildings containing or processing ignitable liquids or flammable gases that are of significant value or importance with lightning rods, especially if located in high-risk lightning areas. Refer to NFPA 780, *Standard for the Installation of Lightning Protection Systems* for details.

3.0 SUPPORT FOR RECOMMENDATIONS

3.1 Loss History

A study of lightning losses at FM client properties in the United States and Canada for the 10-year period 1973 through 1982 shows that a total of 2926 losses occurred during this period.

The number of lightning incidents varied considerably in different states and provinces depending on the frequency of thunderstorm days. (See Table 1 and Figure 1.) The actual number of lightning losses that occurred in each state or province is shown in Table 1.

Table 1. Lightning Losses by State and Province, 1973 to 1982

State	*Number*	*Ikl**	*State*	*Number*	*Ikl*	*State*	*Number*	*Ikl*
Maine	1	20	Alabama	21	60-70	North Dakota	0	30
New Hampshire	7	20	Mississippi	30	60-70	South Dakota	0	30-40
Vermont	4	20	Florida	65	70-100	Nebraska	8	50
Massachusetts	32	20	Ohio	85	40-50	Colorado	5	50-60
Rhode Island	11	20	Indiana	49	40-50	New Mexico	3	40-70
Connecticut	21	20	Kentucky	20	50	Idaho	1	20-40
New York	30	30	Tennessee	40	50-60	Nevada	1	10-30
New Jersey	53	30	Louisiana	18	50-60	Utah	1	30-40
Maryland	12	30	Michigan	41	30	Arizona	4	10-40
Delaware	1	30	Wisconsin	62	30-40	Washington	2	10-20
Pennsylvania	89	30-40	Iowa	15	40-60	Oregon	3	10-20
Virginia	16	30-40	Illinois	80	40-60	California	19	5-10
West Virginia	8	40-50	Missouri	45	50			
North Carolina	93	40-50	Arkansas	14	50-60			
South Carolina	28	50	Oklahoma	19	50			
Georgia	45	50-60	Texas	72	30-60	*Isokeraunic level		

CANADA	
Province	*Number*
Quebec	20
Ontario	35
New Brunswick	4
Brit. Columbia	0
Manitoba	4
Alberta	1

More lightning losses occurred in North Carolina, 93, than in any other state. Pennsylvania was second with 89. Six other states had more than 50 lightning losses: Ohio, 85; Illinois, 80; Texas, 72; Florida, 65; Wisconsin, 62; and New Jersey, 53.

In Canada more lightning losses occurred in Ontario, 35, than in any of the other provinces. Only a total of 65 occurred in all of the provinces.

Many transformers were damaged by lightning. There were 204 oil-insulated units, most of which were rated in excess of 600 volts; 62 were of the dry type and 89 were miscellaneous types, such as current and potential transformers.

The principal type of equipment damaged by lightning in the remaining losses included motor starters, synchronous motors, generators, circuit breakers, bus ducts, furnace transformers, distribution panels, switchgear, and wiring.

Many of these losses could have been prevented if proper shielding, surge arresters, and effective grounding had been provided.

4.0 REFERENCES

4.1 FM

Data Sheet 1-13, *Chimneys.*
Data Sheet 5-19, *Switchgear and Circuit Breakers.*
Data Sheet 5-20, *Electrical Testing.*
Data Sheet 7-88, *Ignitable Liquid Storage Tanks.*

4.2 Other

1. *American National Standard for Surge Arresters for Alternating — Current Power Circuits.* ANSI/IEEE C62.1-1981. (New York: IEEE, 1981)

2. *American National Standard Guide for the Application of Valve-Type Surge Arresters for Alternating Current Systems.* ANSI C62.2-1981. (New York: American National Standards Institute, 1981).

3. *IEEE Guide for Surge Voltages in Low Voltage AC Power Circuits.* IEEE Std. 587-1980. (New York: IEEE, 1980).

4. *American National Standard Test Specifications for Gas Tube Surge Protective Devices.* ANSI/IEEE C62.31-1981 (formerly IEEE Std. 465-1977). (New York: IEEE, 1977).

5. Johnson, I.B., et al. *Surge Protection in Power Systems.* IEEE Tutorial Course 79 EH0144-6-PWR. (Piscataway, N.J.: IEEE, 1978).

6. IEEE Working Group Progress Report. *Impulse Voltage Strength of AC Rotating Machines.* 81 WM 182-5, 1981 PES Winter Meeting.

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11. Towne, H.M. *Lightning Protection of Substations,* March 29-30, 1951 Conference of Southeastern Electric Exchange, October 1, 1954.

12. *Station Surge Arrester Seminar.* (Pittsfield, MA: General Electric Company, n.d.).

13. Boice, W.K. *Suppression of Secondary Surges Caused by Lightning Overvoltages at Transformer Primaries.* (Piscataway: IEEE, 1980).

14. *Surge Protection for Rotating Machines.* Application Data 38-423 (Bloomington, IN: Westinghouse Electric Corporation, 1970).

15. Walsh, G.W. *A New Technology Station Class Arrester for Industrial and Commercial Power Systems.* (New York: IEEE, 1977).

16. Doble Client Committee on Arresters, Capacitors, and Insulators. *Metal Oxide Surge Arresters.* Minutes of the 49th Annual Doble Client Conference, Section 9D-01. (Watertown, MA: Doble Engineering Company, 1982).

17. Doble Client Committee on Arresters, Capacitors, and Insulators. *Arrester Field Test Guide.* (Watertown, MA: Doble Engineering Company, 1976).

18. Lee, R.H. *Protection Zone for Buildings Against Lightning Strokes Using Trnasmission Line Protection Practice.* IEEE IAS 1977 Annual Transactions. (New York: IEEE, 1977).

19. *Standard for the Installation of Lightning Protection Systems. NFPA 780* (National Fire Prevention Association, 1983). Quincy, MA.

Note: The manufacturer’s literature for each surge arrester must be consulted for the characteristics of each device. This literature is far too voluminous to list here.

APPENDIX A GLOSSARY OF TERMS

The various terms used in this data sheet applying to surge arresters and their application are defined as follows:

Surge Arrester: a protective device for limiting surge voltages on equipment by discharging or bypassing surge current. It prevents continued flow of follow current to ground and is capable of repeating these functions as specified.

Valve Element: a resistor that, because of its nonlinear current-voltage characteristic, limits the voltage across the arrester terminals during the flow of discharge current and contributes to the limitation of follow current at normal power-frequency voltage.

Expulsion Element: a chamber in which an arc is confined and brought into contact with gas-evolving material.

Series Gap: an intentional gap(s) between spaced electrodes. It is in series with the valve or expulsion element of the arrester, substantially isolating the element from line or ground, or both, under normal line voltage conditions.

Valve Arrester: an arrester that includes a valve element.

Classification of Arresters: station valve arrester. Intermediate valve arrester. Distribution valve arrester. Distribution Expulsion valve arrester.

Grading or Control Ring: a metal part usually circular or oval in shape, mounted to modify electrostatically the voltage gradient or distribution.

Discharge Counter: a means for recording the number of arrester discharge operations.

Arrester Disconnector: a means for disconnecting an arrester in anticipation of, or after, a failure in order to prevent a permanent fault on the circuit and to give indication of a failed arrester.

Lightning: an electric discharge that occurs in the atmosphere between clouds or between clouds and ground.

Lightning Surge: a transient electric disturbance in an electric circuit caused by lightning.

Wave: the variation with time of current, potential, or power at any point in an electric circuit.

Surge: a transient wave of current, potential, or power in an electric circuit.

Impulse: a surge of undirectional polarity.

Oscillatory Surge: a surge that includes both positive and negative polarity values.

Crest (Peak) Value (of a wave, surge, or impulse): the maximum value that it attains.

Wave Front (of a surge or impulse): that part which occurs prior to the crest value.

Wave Tail (of an impulse): that part between the crest value and the end of the impulse.

Wave shape (of an impulse test wave): the graph of the wave as a function of time.

Wave Shape Designation (of an impulse): the wave shape of an impulse (other than rectangular) of a current or voltage is designated by a combination of two numbers. The first, an index of the wave front, is the virtual duration of the wave front in microseconds. The second, an index of the wave tail, is the time in microseconds from virtual zero to the instant at which one half of the crest value is reached on the wave tail. Examples are 1.2/50 and 8/20 waves.

The wave shape of a rectangular impulse of current or voltage is designated by two numbers. The first designates the minimum value of current or voltage that is sustained for the time in microseconds designated by the second number. An example is 75A - 1000 µsec wave.

Virtual Zero Point (of an impulse): the intersection with the zero axis of a straight line drawn through points on the front of the current wave at 10% and 90% crest value, or through points on the front of the voltage wave at 30% and 90% crest value.

Nominal Rate of Rise (of an impulse): of a wave front, the slope of the line that determines the virtual zero. It is usually expressed in volts or amperes per microsecond.

Disruptive Discharge: the sudden and large increase in current through an insulating medium, due to the complete failure of the medium under the electrostatic stress.

Flashover: a disruptive discharge around or over the surface of a solid or liquid insulator.

Sparkover: a disruptive discharge between electrodes of a measuring gap, voltage-control gap, or protective device.

Impulse Sparkover Volt-Time Characteristic: the sparkover response of the device to impulses of a designated wave shape and polarity, but of varying magnitudes. Note: For an arrester, this characteristic is shown by a graph of values of crest voltage plotted against time to sparkover.

Power Frequency Withstand Voltage: a specified root-mean-square test voltage at power frequency that will not cause a disruptive discharge.

Impulse Withstand Voltage: the crest value of an impulse that, under specified conditions, can be applied without causing a disruptive discharge.

Voltage Rating: the designated maximum permissible operating voltage between its terminals at which an arrester is designed to perform its duty cycle. It is the voltage rating specified on the nameplate.

Power-Frequency Sparkover Voltage: the root-mean-square value of the lowest power frequency sinusoidal voltage that will cause sparkover when applied across the terminals of an arrester.

Impulse Sparkover Voltage: the highest value of voltage attained by an impulse of a designated wave shape and polarity applied across the terminals of an arrester prior to the flow of discharge current.

Discharge Current: the surge current that flows through an arrester when sparkover occurs.

Discharge Voltage (IR): the voltage that appears across the terminals of an arrester during passage of discharge current.

Discharge Voltage-Current Characteristic: the variation of the crest values of discharge voltage with respect to discharge current. **Note:** This characteristic is normally shown as a graph based on three or more current-surge measurements of the same wave shape but of different crest values.

Discharge Withstand Current Rating: the specified magnitude and wave shape of a discharge current that can be applied to an arrester or specified number of times without causing damage to it.

Follow (Power) Current: the current from the connected power source that flows through an arrester during and following the passage of discharge current.

Grounded System: an electric system in which at least one conductor or point (usually the neutral conductor or neutral point of transformer or generator windings) is intentionally grounded, either solidly or through a grounding device.

Coefficient of Grounding: the ratio E_{LG}/E_{LL}, expressed as a percentage, of the highest root-mean-square line to ground power-frequency voltage E_{LG} on a sound phase, at a selected location, during a fault to ground affecting one or more phases to the line-to-line power frequency voltage E_{LL} which would be obtained, at the selected location, with the fault removed.

Notes:
1. Coefficients of grounding for three-phase systems are calculated from the phase-sequence impedance components as viewed from the selected location. For machines use the subtransient reactance.
2. The coefficient of grounding is useful in the determination of an arrester rating for a selected location.
3. A value not exceeding 80% is obtained approximately when for all system conditions the ratio of zero-sequence resistance to positive-sequence reactance is positive and less than three, and the ratio of zero-sequence resistance to positive-sequence reactance is positive and less than 1.

Withstand Voltage: highest value of applied voltage at which an arrester will not flash over.

Ungrounded System: without an intentional connection to ground. Note: Although called ungrounded, this system in reality is capacitively coupled to ground through the distributed phase-to-ground capacitance of the windings and phase conductors of the systems.

Effectively Grounded: intentionally connected to earth through a ground connection or connections of sufficiently low impedance where the coefficient of grounding does not exceed 80%, and having sufficient current-carrying capacity to prevent the buildup of voltages that may result in undue hazard to connected equipment or to persons.

Non-Effectively Grounded: the Coefficient of Grounding exceeds 80%.

Insulation Coordination: the process of correlating insulation strengths of electrical equipment with expected overvoltages and with characteristics of surge protective devices.

Withstand Voltage: the voltage that electrical equipment is capable of withstanding without failure or disruptive discharge when tested under specified conditions.

Transient Insulation Level (TIL): an insulation level expressed in terms of the crest value of the withstand voltage for a specified transient wave shape; for example, lightning or switching impulse.

Basic Lightning Impulse Insulation Level (BIL): a specific insulation level expressed in terms of the crest value of a standard lightning impulse.

Basic Switching Impulse Insulation Level (BSL): a specific insulation level expressed in terms of the crest value of a standard switching impulse.

Lightning Impulse Protection Level (LPL) (of a protective device): the maximum lightning impulse voltage expected at the terminals of a surge protective device under specified conditions of operation.

Switching Impulse Protection Level (SPL) (of a protective device): the maximum switching impulse expected at the terminals of a surge protective device under specified conditions of operation.

Switching Surge Protective Level (SSP): the greater of switching surge sparkover or switching discharge voltage.

Chopped Wave (CWW): an impulse voltage wave that is suddenly reduced substantially to zero value by the sparkover of an air gap.

Front of Wave Sparkover (FOW): the maximum spark-over on a linearly rising impulse front. The rate of rise of the front increases with arrester rating.

Let-through Sparkover (LT): a measure of the highest lightning surge an arrester is likely to withstand without sparkover in 3 µsec or less.

Temporary Overvoltage (TOV): an oscillatory overvoltage associated with switching of relatively long duration which is undamped or slightly damped.

Arrester Recovery Voltage: the crest voltage that occurs across the terminals of an arrester following a unit operation.

Research Voltage Rating of an Arrester: the maximum arrester recovery voltage permitted for a specified time following one or more unit operations with discharge currents of specified magnitude and duration.

APPENDIX B DOCUMENT REVISION HISTORY

April 2012. Terminology related to ignitable liquids has been revised to provide increased clarity and consistency with regard to FM Global's loss prevention recommendations for ignitable liquid hazards.

September 2007. Minor editorial changes were made for this revision.

January 2001. The document has been reorganized to provide a consistent format.

August 1984. Completely revised.

February 1974. First issued.

APPENDIX C SUPPLEMENTARY INFORMATION

C.1 General

Electrical breakdowns caused by overvoltages due to lightning are responsible for considerable property damage and business interruption. No section of the United States is immune, although in the Pacific Coast area lightning storms are infrequent. The Southeastern and South Central States experience the largest number of lightning storms each year.

In Canada lightning storms are fairly frequent in the provinces of Ontario and Quebec and less frequent in the other provinces. In Newfoundland they occur relatively infrequently.

Procedures outlined herein for protecting against overvoltages comply with the standard of the Institute of Electronic and Electrical Engineers and the American National Standards Institute, the requirements of the *National Electric Code,* and the recommendations of the manufacturers of electrical equipment.

Determining the surge protection requirements for a particular installation is a specialized job. The assistance of manufacturers' representatives in selecting suitable arresters and other safeguards is recommended if experienced personnel are not available.

Overvoltages on power systems are produced in a number of different ways; those of particular concern are listed below and are discussed later in more detail.

1. Lightning.

2. Contact with higher voltage systems.
3. Resonance effect in inductive and capacitive circuits.
4. Ferro-resonance.
5. Switching surges.
6. Forced current zero interruption.
7. Autotransformer connection.
8. Loss of neutral ground on a normally grounded system.
9. Sudden loss of load and/or generator overspeed.

C.2 Lightning Charge Formation

The manner in which charges are developed in thunderclouds is still somewhat controversial. There are several theories that have been advanced, some of which have been partially verified by laboratory experiments. A thorough understanding of charge formation is not necessary to apply lightning protection principles. A knowledge of the nature of the lightning discharge and its effect on the power system is important, however.

It is generally agreed that the accumulation of electricity in clouds takes place in the presence of ionized air, moisture in the atmosphere, and upward moving air currents. Also, the lower part of the cloud is predominantly negatively charged while the upper parts are predominantly positive.

C.3 Characteristics of a Lightning Stroke

The important characteristics of a lightning discharge are the current, voltage, waveshape, polarity, charge, and frequency of occurrence.

C.3.1 Current

Current measurements of more than 4000 strokes to high voltage transmission lines ranged from 2400 amps to 218,000 amps. Fifty percent of the strokes equaled or exceeded the median value of 14,000 amps. Super strokes in the order of 300,000 to 400,000 amps have been recorded in the United States and Europe, but these occur infrequently and their magnitude is an estimate because of the limitation of instrumentation.

C.3.2 Voltage

The voltage of a lightning stroke is difficult to measure, but it has been estimated that the potential difference between a charged cloud and the earth ranges from 5 to 50 MV. With voltages of this magnitude, it is obvious why it is impossible to insulate a power system sufficiently to withstand a direct lightning stroke.

C.3.3 Waveshape

The waveshape of a lightning surge is usually referred to by the wave front and the wave tail. The front is the time required to reach crest magnitude; the tail is the time to decay to half the crest value. Characteristically, a lightning discharge will crest in several microseconds and decay to half the crest value in 20 to more than 100 microseconds.

The maximum or crest value of this impulse voltage is often higher than the impulse strength of the insulation of transformers, generators, motors or other electrical equipment on the system. Insulation failures are to be expected unless proper surge protection is provided.

In the application of surge protection, the effective rate of rise is of greater importance than the elapsed time from the beginning of the surge to the crest value.

C.3.4 Polarity

Based on thousands of measurements, 90% of the strokes to earth have negative polarity, resulting from a negative charge center in the lower part of a cloud and a positive charge in the earth below.

C.3.5 Charge

The quantity of charge in a stroke may range from 2 to 200 coulombs (ampere-seconds), while the average is about 20 coulombs. A lightning stroke may have a peak current of 200,000 amps or more but being so short-lived, the surge current can easily be handled by a small conductor. The largest recorded conductor to be vaporized by a stroke is a No. 10 AWG.

C.3.6 Frequency

The frequency that lightning strokes occur to transmission lines in open country indicates the degree of exposure that occurs to a power system. Figure 1 is an isokeraunic map which shows the number of thunderstorm days per year that occur in the United States. For more currrent annual mean thunderstorm day information refer to this site www.weather.gov.

Table 2 shows the number of thunderstorm days per year that occur in each of the Canadian provinces for the period 1941 to 1970; more recent data is not yet available. The table shows the minimum and maximum number of thunderstorm days reported for each province depending on the location of the weather stations.

Table 2. Number of Thunderstorm Days Per Year, Canada

Province	*Minimum and Maximum Number*
British Columbia	0.7 to 23.9
Alberta	8.6 to 25.8
Yukon & N.W. Territories	1.1 to 12.3
Saskatchewan	7.2 to 25.3
Manitoba	5.7 to 25.9
Ontario	9.2 to 33.9
Quebec	1 to 27
New Brunswick	5.4 to 13.4
Nova Scotia	8.1 to 11.7
Prince Edward Island	7.4 to 10.8
Newfoundland	1.5 to 7.4

The number of lightning strokes to a transmission line or to open ground is assumed to vary directly with the isokeraunic level (IKL).

An analysis of several thousand strokes to transmission lines protected with a single 100-ft (30-m) high ground wire indicated that it would be struck 100 times per 100 miles per year in an area having an IKL of 30.

C.3.7 Cold and Hot Lightning

Lightning strokes may be divided into two broad categories: cold and hot. A cold lightning stroke has very high currents of relatively short duration and usually causes severe physical damage, such as splitting a tree from top to bottom. Hot lightning strokes are typified by low currents of relatively long duration which frequently set fires in forests and farm buildings.

C.3.8 Direct Strokes

Direct lightning strokes may cause damage to overhead transmission lines, to transformers, and other equipment in outdoor substations, as well as to indoor electrical apparatus supplied directly from exposed overhead lines.

Direct strokes produce about half of the significant surges that occur on power lines. However, they are attracted to power lines from only within a narrow band adjacent to it. This is illustrated by an incident where lightning struck within 200 ft (60 m) of a transmission line owned by the Public Service of New Jersey, and a lightning recording station 1600 ft (480 m) away showed no surge voltage on the phase wires.

In most cases where a lightning stroke hits directly on phase wires or equipment terminals, a high voltage is produced that will flash over solid insulation on cables or transformers if there is no surge protection. If the flashover occurs in air or across porcelain insulation, no serious damage usually results.

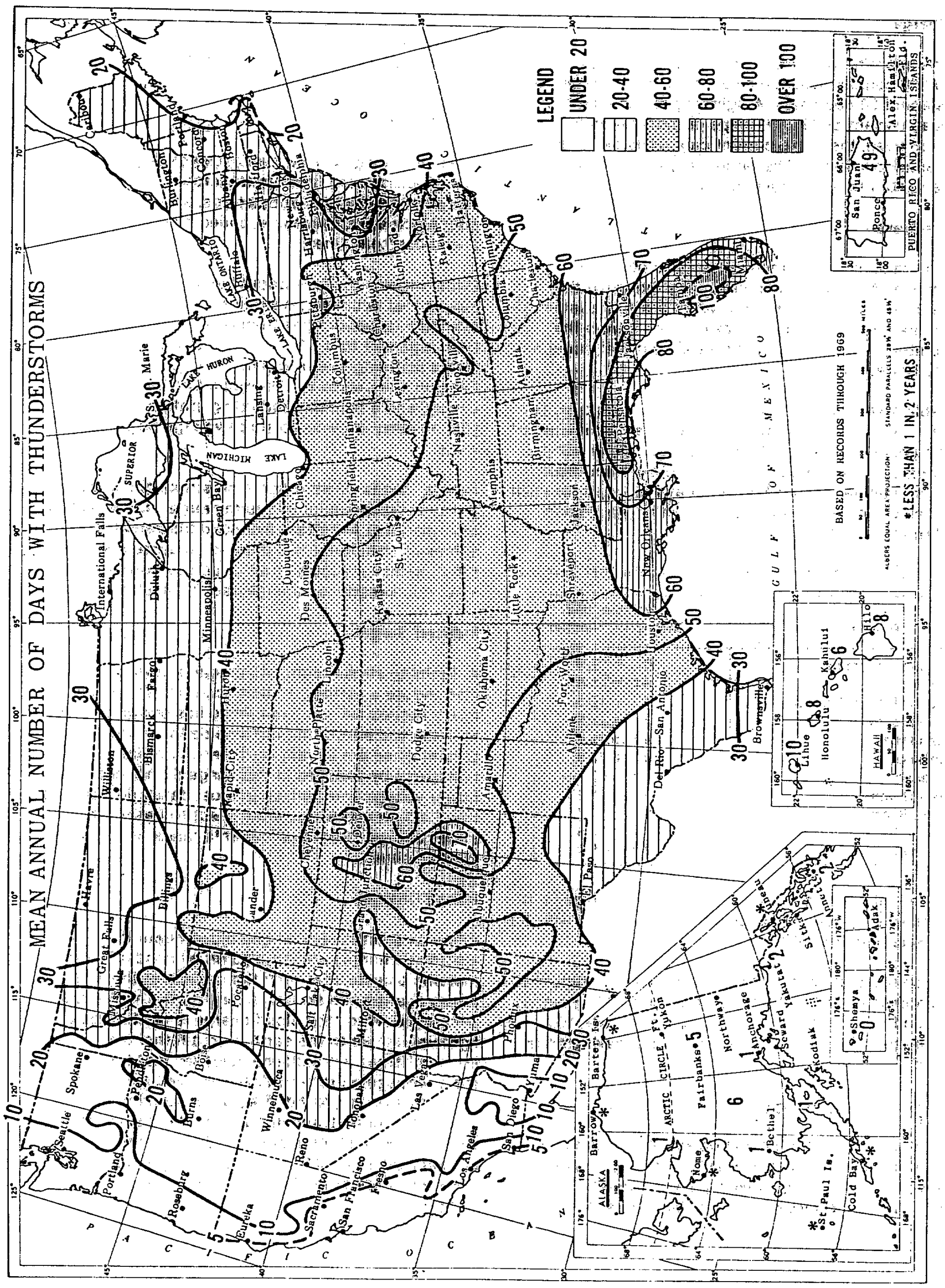


Fig. 1. Annual mean number of days with thunderstorms (U.S.A.) (U.S. Dept. of Commerce)

Fig. 1. Annual mean number of days with thunderstorms. (U.S.A.) (U.S. Dept. of Commerce)

C.3.9 Induced Surges

A lightning stroke terminating near a power line can also induce a voltage in the circuit. These voltages rarely exceed 500 kV. Experience has shown that 69 kV lines and above that are shielded with overhead ground wires are usually sufficiently insulated that flashovers by voltages in this range do not occur. Lower voltage lines, which in most cases do not have overhead ground wires, are subject to flashover by induced surges. Discharge currents range from 50 to 2000 amperes.

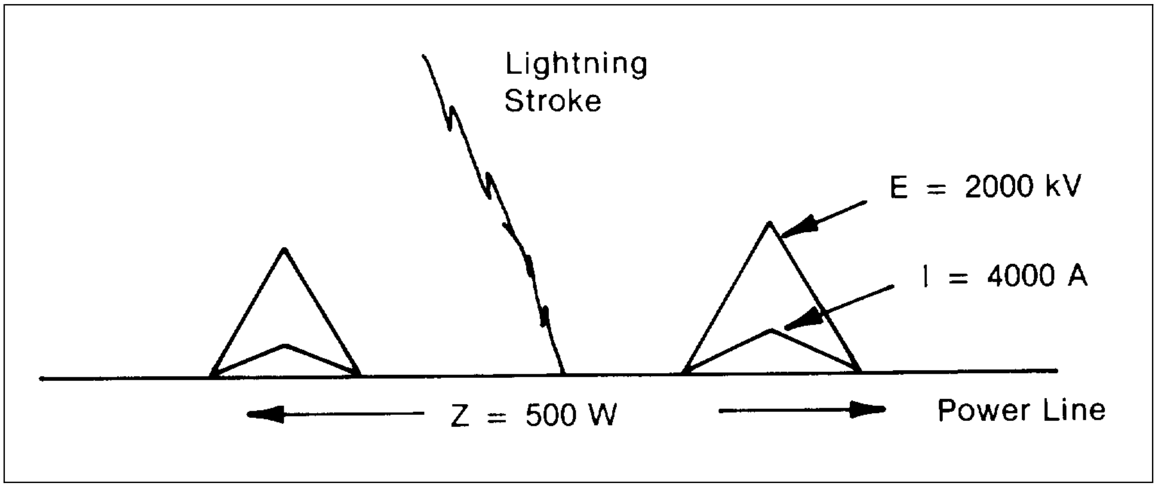


Fig. 2. Traveling waves caused by lightning stroke to power line.

C.3.10 Bound Charges

When an electrically charged cloud floats in the air, electrical charges are induced on all conductors or metallic objects at or near the surface of the earth. These charges are bound as long as the nearby cloud is charged. When the cloud charge is neutralized by a lightning stroke to the earth or to another cloud, the bound charges are suddenly released and traveling wave propagates in both directions and takes the easiest paths to ground. Frequently, combustible material is ignited, and sometimes the insulation of electrical equipment is punctured. Equipment for protection against direct strokes and surges also provides adequate protection from the release of bound charges.

C.3.11 Surge Propagation

When a lightning stroke terminates on a power system, it initiates voltage and current waves which travel in both directions from the terminating point. In a line, these travel at about 1000 ft/µsec and in a cable, about 600 ft/µsec. As shown in Figure 2, with linear impedance, the voltage and current will have the same wave shape. They are represented by the following equation:

$$E = IZ,$$

in which E is the voltage, I the current of the traveling wave, and Z the surge impedance of the conductor. A typical surge impedance of a conductor of the power lines is 500 ohms, for a cable 30 ohms, and for rotating machines 50 to 1000 ohms.

If it is assumed that the current in the lightning stroke is 8000 amps and it divides evenly where it strikes, then the conductor voltage would be equal to:

$$E = \frac{IZ}{2}, \text{ or } E = \frac{8{,}000 \times 500}{2} = 2{,}000{,}000 \text{ Volts.}$$

In other words, a traveling wave current of 8,000 amps will generate 2000 kV on the power line.

The traveling waves caused by the lightning stroke will continue along the line until they encounter a change in impedance, such as when they come to a transformer, a circuit breaker, an open circuit, another connected line, or a short circuit. At this point, the voltage and current waves are reflected back upon the line, while at the same time they travel beyond this point. Upon encountering a transformer, the reflected waves combine, resulting in double the traveling wave voltage at the transformer. The current wave at an open circuit termination is also reflected, but being of opposite polarity the result is zero current at the end of the line.

When a line ends in a short circuit, the incoming and reflected voltage waves have the same magnitude and opposite polarity, resulting in zero voltage at the terminal. However, the current waves have the same magnitude and the same polarity which doubles the traveling wave current, a well-known phenomenon. This doubling of the traveling wave current is an important factor to consider in the application of a surge arrester on the end of a line. The resistance of an arrester is very low compared to the surge impedance of the line, and the current that it will be required to discharge is nearly double the traveling wave current.

C.4 Protection Against Direct Strokes (Shielding)

One or more ground wires, often called ''static'' wires, supported parallel to and several feet or more above the conductors of overhead transmission lines, are very effective in preventing direct strokes to the transmission lines. However, in practice the possibility of a stroke to a phase conductor always exists. The static wires must be properly located and adequately grounded. This form of protection is expensive and can seldom be added at reasonable cost to an existing line of any great length.

C.4.1 Cone of Protection

Tall transmission lines are frequently protected with two overhead ground wires to shield the conductors below. If the ground wires are too high above the conductors or improperly located with respect to the conductors, lightning can still strike the conductors below. The practice in the past has been to install the ground wires so that they are at the peak of an imaginary tent within which the protected conductors are sheltered, one-half the base of the tent being equal to the height of the ground wire for important cases, and up to twice the height for less important cases.

A recent study of this so-called ''cone of protection'' has shown that the vertical boundary of the cone is not linear, as it has been assumed in the past, but is a circular arc having a radius of 150 ft (45 m) and tangent to the ground. Therefore, many high structures do not provide the expected protection against direct stroke for lower objects that are well within the cone of protection.

In the formation of a lightning stroke, a step leader that originates in a cloud charge center progresses in separate elements and is predominantly just over 150 ft (45 m) in length. As the stepped leader nears the earth it must be within about 330 ft (100 m) of an object of opposite polarity to progress toward that object. At the same instant, a short streamer is likely to extend from that object toward the approaching stepped leader and when they meet, which is somewhere in the vicinity of 330 ft (100 m), the actual stoke occurs. It follows that if the stepped leader nears the earth more than 330 ft (100 m) from a high object, *it probably will not* be attracted to that object and may strike the earth or some other object beyond the 330 ft (100 m).

A complete explanation of the development of the ''300 FT D. Rolling Sphere Principle'' is available in a paper by Ralph H. Lee published in the 1977 annual report of the Industrial Applications Society of IEEE. This concept is based in part on the above explanation of the formation of lightning strokes and the results of a research project by the Edison Electric Institute for improving the lightning protection of high voltage transmission lines. As a result of this project, Table 3 was developed showing protection angles that should be provided for different heights of the overhead ground wires to afford 99.5% protection against lightning damage. By decreasing the protection angle 10°, the protection is increased to 99.9%.

Table 3. Protection Angles for 99.5% Protection

Height Above Ground	*Protection Angle*
(25 ft)	(60°)*
(50 ft)	(47°)*
75 ft	33°
100 ft	20°
125 ft	10°
150 ft	0°
175 ft	–10°
200 ft	–20°

* Extrapolated for 25-ft and 50-ft heights.

The table shows that at 150 ft (45 m) above ground, a zero angle of protection is provided by the higher conductor. Above 150 ft (45 m), the negative angles indicate that the overhead ground wire should extend beyond the position of the conductor being protected.

The data in Table 3 was then plotted on a linear scale. When the plotted points were connected, as shown in Figure 3, they formed almost exactly the arc of a circle of 150 ft (45 m) radius tangent to the earth's surface at a point 150 ft (45 m) away from the 150 ft (45 m) high (zero protection angle) point. It should be noted that the 150-ft (45-m) radius criterion matches well with the 45 meter predominant step leader length mentioned previously.

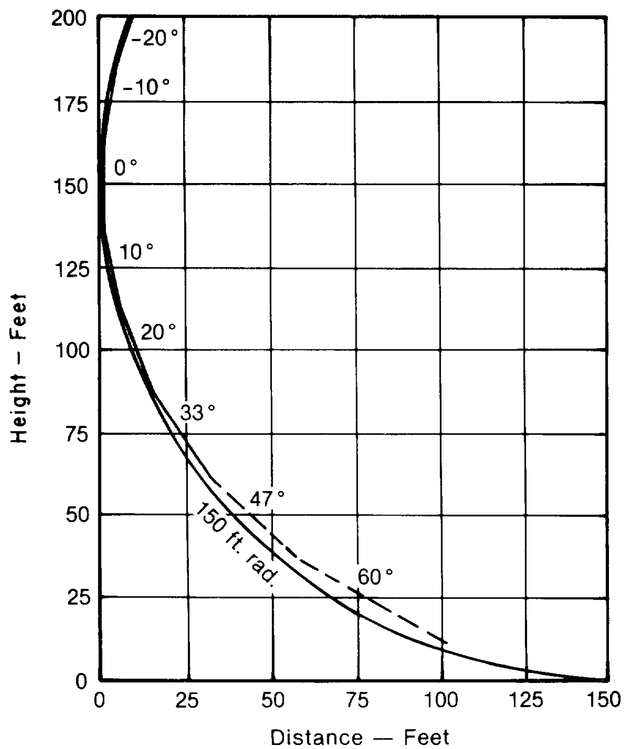


Fig. 3. Plot of data from Table 3, with 150 ft (45m) radius circle inscribed.

By applying this same concept to the protection that would be afforded by a single elevated rod or wire, an object above ground level will be protected against direct lightning strokes if it does not protrude above the surface of an inverse circular sided cone of 150-ft (45-m) radius. (See Fig. 4.)

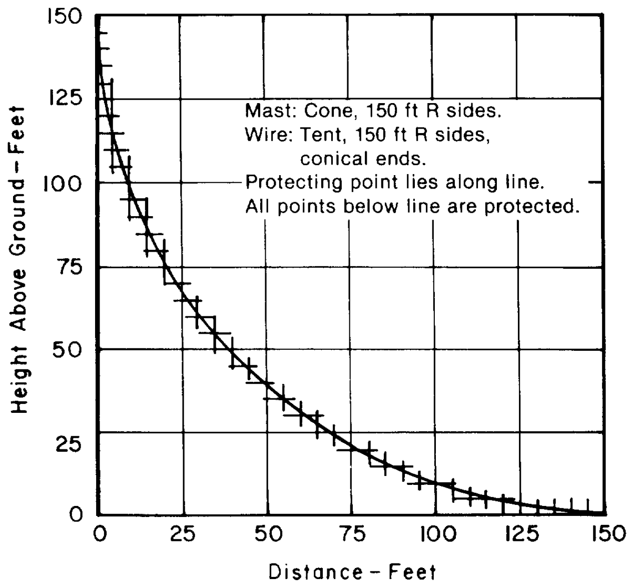


Fig. 4. Lightning protection from single mast or wire.

To better visualize this concept, imagine a sphere of 150-ft (45-m) radius [300-ft (91-m) diameter] rolling over the surface of the earth, up and over all projections above the earth surface. All objects which the sphere touches are susceptible to direct stroke, while those which the sphere does not touch because of being lifted over them by higher (protecting) objects are not susceptible to direct stroke. It is obvious that objects more than 150 ft (45 m) away from almost any high structure will receive little or no protection from that structure.

The Rolling Sphere Principle is further illustrated in Figure 5. Structure B, which lies below the 150-ft (45-m) radius curve, would be protected, but any object that projects through this radius, such as Structure A, would be exposed to direct stroke.

The new protection curve to the left of the mast is a combination of two 150-ft (45-m) radius curves intersecting on Structure A or the locus of a 150-ft (45-m) radius sphere rolling up and over Structure A, then from the roof of A until it touches the mast at Point C. The height of the mast above Point C provides no additional protection and is called ″useless height.″

Other factors in addition to tower height that influence the lightning performance of a transmission line are the number of ground wires, the number of insulators, and the resistance of the tower footings. Lines that are shielded with two ground wires usually perform better than those with only one ground wire, due to the lower surge impedance and better coupling with the phase conductors.

A ground or coupling wire sometimes installed *below* the phase conductors and shield wires of a transmission line will also help to prevent flashovers. Due to the increased coupling, the potential difference between phase conductors and grounded wires is lowered because the percentage of the ground wire potential impressed on the phase conductor is raised following the termination of a stroke on the shield wires or structure.

Transmission lines are generally considered to be ‘‘lightning-proof’’ if they are designed so that outages due to lightning are limited to one or less per 100 miles (160 km) per year. This is commonly accepted as an economical and practical design standard.

Flashovers on transmission lines due to switching surges are prevented by providing an adequate number of insulators. The number necessary is determined by the magnitude of the switching surges expected, the surge impedance of the conductors, overhead ground wires, and resistance of the tower footings.

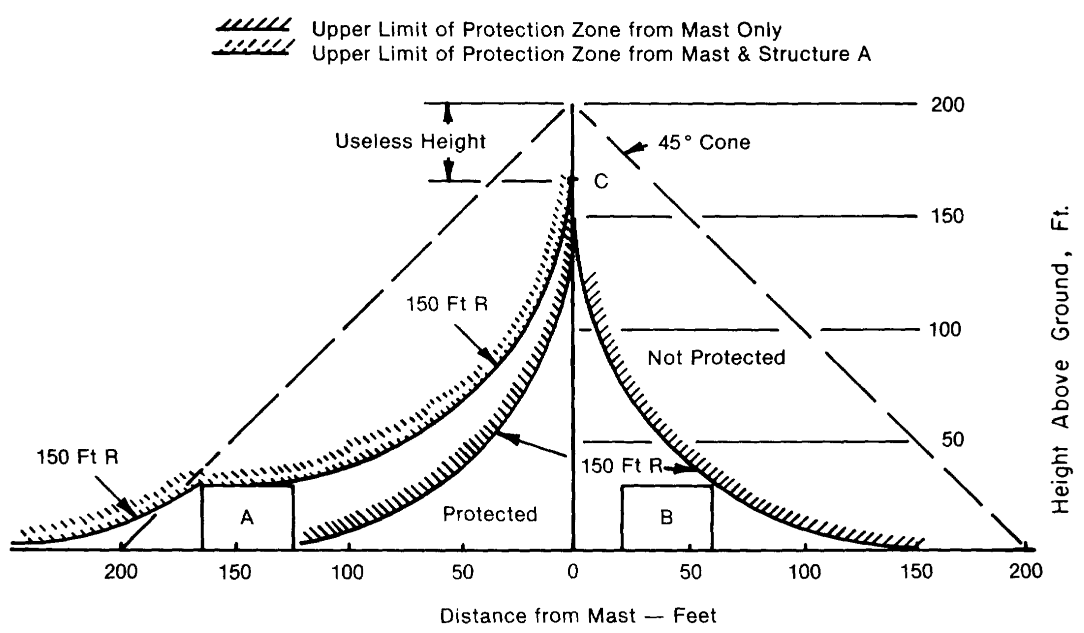


Fig. 5. 300-ft rolling sphere principle.

C.4.2 Substations

Lightning surges can enter a substation either by a direct stroke to the equipment or through transmission lines that are connected to it. The degree of shielding is vitally important in determining the protection needed. Overhead ground wires or masts are generally employed to shield against direct strokes, and surge arresters are installed to limit the magnitude of any surge voltages entering over the transmission lines. The arresters, when properly applied, will also protect against those surges that are generated within the system during switching operations.

For a small station, one or two overhead ground wires strung above the station from adjacent line towers are usually sufficient to protect all parts of the station. For larger substations, additional overhead ground wires may be used, or if this is not feasible, masts or rods may be erected at the corners or over vertical columns to protect all equipment within the substation.

The degree of shielding provided for a substation and its connected lines determines to a large extent the magnitude of the surge current that flows through a surge arrester when sparkover occurs. This is termed the *discharge current,* and will vary from 1000 to 20,000 amperes with effective shielding, depending upon the system voltage. Table 4 shows the discharge currents for various system voltages.

Table 4. Recommended Currents for Determining Discharge Voltages

Maximum System Voltage, kV	*Discharge Current, amperes*
15	. . . *
36. 5	. . . *
72. 5	5000
121	5000
145	5000
242	10000
362	10000
550	15000
800	20000

* Generally unshielded lines.

An installation is considered *effectively* shielded against direct strokes if the station and all connecting lines are shielded. To be effective, the shielding should extend for at least one-half mile from the station.

C.5 Switching Surges

Transient overvoltages occur in power systems during abnormalities or when they transfer from one operating condition to another. The overvoltage surges can take several forms, depending upon the kind of disturbance. The most common surges are those due to line switching when the line is energized or reclosed following a fault.

A switching surge differs from a lightning surge in that the switching surge voltage is lower and lasts longer because the energy source is that stored in the system capacitance. Switching surges are generated within a power system by the following methods.

1. De-energization of capacitor banks, underground cables, or lines with or without connected transformers and/or shunt reactors.

2. Energizing or de-energizing busses with airbreak switches. (Wave fronts of 10 microseconds or less are generated, which may affect the surge arresters, control circuits, and relay circuits.)

3. Energizing lines or cables with or without connected transformers and/or shunt reactors.

4. High-speed reclosing of lines with or without shunt reactors.

5. Energizing and de-energizing transformers with or without connected shunt reactors.

6. De-energizing shunt reactors.

7. Sudden loss of load on long lines with or without connected transformers.

8. Out-of-phase switching.

High transient overvoltages can be produced when inductive loads are switched, such as opening the magnetizing current of transformers.

When a line is initially energized, a surge is transmitted down the line increasing to its maximum value, the crest system voltage, as the system surge impedance is lowered. When it reaches the end of the line, the wave will be reflected. If the line is open circuited, the reflected wave will be a maximum.

The maximum surge that can occur when switching a single phase line is twice the system crest voltage. This is also the maximum value that can be generated by closing one phase of a 3-phase transmission line. If the other two phases are closed, the maximum surge will be increased as much as three times.

When a line consisting of a voltage source and a circuit breaker is de-energized, it can be represented as a generator, a switch, and a capacitor. Inasmuch as the switching device tends to interrupt the circuit at current zero and the current in a capacitive circuit leads the voltage by 90 degrees, a voltage equal to the system crest voltage remains on the line when it is disconnected from the generator. This voltage is referred to as a ‘‘trapped charge.’’ If the circuit breaker is reclosed with the trapped charge still on the line, the voltage across the breaker will be doubled and the transmitted surge is twice the surge due to energizing. When this surge reaches the open end of the line and crests at opposite polarity to the trapped charge, the resulting overvoltage will be there times the initial voltage. If the circuit breakers have no contact shunting resistances, transient network analyzer studies show that the resulting overvoltage may be in excess of five times the initial voltage.

Severe overvoltages are also produced when transmission lines or capacitor banks are de-energized. Restriking, that is, momentary re-establishment of the arc across the interrupting contacts of the circuit breaker, may occur because the recovery voltage builds up at a faster rate than the interrupting medium, and severe overvoltages are the result.

C.6 Overvoltage Due to Surges from Other Sources

Energization or de-energization of equipment with a disconnecting switch will cause a surge.

Load shedding can cause temporary overvoltages (TOV). When a large load is dropped at the end of a long transmission line, the effect is delayed at the generator because of the time lag, and a traveling wave is generated.

Temporary overvoltages (TOV) are produced by sudden loss of load or generator overspeed and voltage regulation. When a line is open circuited during heavy load conditions, it is acting like a capacitor bank and the voltage regulators are higher than necessary. The overvoltage will be sustained until the regulator is lowered. Likewise, the generator will tend to accelerate and increase both the voltage and frequency until the governor reduces the speed of the unit. In machines that have slow governor action, such as on water-wheel generators and nuclear units, this latter effect is very important.

In the majority of cases, the switching surges that occur on a system are sufficiently small that they do not cause an insulation breakdown or trip a protective device.

Power systems are commonly protected from switching surges either by controlling the magnitude of the surge when it is generated or by limiting the effects of the surge. The magnitude of the surge may be limited by incorporating surge suppression resistors in the switching device, whether it be a circuit breaker or a disconnecting switch. The magnitude may also be limited by controlling the point on the voltage wave at which the contacts close. The generated surge will be greatly reduced if the contacts close at a time that the voltage across them is at a minimum.

In the case of a trapped charge on the line, a surge can be controlled by draining the charge from the line before it is allowed to reclose. A power transformer that is connected to the line will accomplish this when the line is opened. However, if shunt reactors are connected on the line they limit, the effective Ferranti rise on the line which can lead to reduced transient and temporary overvoltage.

Other means of suppression and control of switching surges are effective neutral grounding, excitation and speed control, potential transformers, intermediate switching stations, transformer tertiaries, circuit configuration and parameters, transfer trip, and surge arrestors.

C.6.1 Physical Contact With a Higher Voltage System

Accidental contact occasionally may occur between the primary and secondary windings of a transformer or on overhead circuits on pole lines. If the low voltage system is ungrounded, its potential will be raised to that of the high voltage system, or flashover will occur. If the neutral of the low voltage system is well grounded, the voltages appearing on the low voltage system will be much lower, but there will be high values of current flowing from the high voltage system.

C.6.2 Reasonant Effects in Inductive-Capacitive Circuits

C.6.2.1 Parallel Inductive-Capacitance Resonance

Ungrounded neutral ac systems are subject to overvoltages due to the unintentional connection of an inductive reactance between a phase conductor and ground. This can occur in several ways, such as by the operating magnetic coil in a motor starter being accidentally connected between phase and ground by a ground fault in a control wire. The ratio of the inductive reactance of the line-to-ground circuit to the total capacitive reactance of the system controls the extent of overvoltage. When these two reactances are equal, the overvoltages at this point may be 10 to 20 times normal. However, with a two-to-one range of reactance, overvoltages of three times normal or more would result.

C.6.2.2 Ferro-Resonance

A ground fault in a potential transformer or an ungrounded system, the core of which becomes saturated, can be responsible for damaging overvoltages. The effective reactance of the inductive circuit becomes much lower than the unsaturated reactance and the voltage will tend to oscillate between voltage limits. This causes the effective inductive reactance to match the capacitive reactance value. This performance is known as ferro-resonance.

C.6.3 Forced Current Zero Interruption

The term “forced current zero” or “interruption off of current zero” is used to describe the interrupting mechanism of a fuse, switch, section of a small wire conductor, or vacuum switch which can force the current zero value ahead of the normal current zero of the circuit. Any element in the circuit that can develop a high potential drop during the current flow will cause an overvoltage to appear on the connected circuit. This overvoltage will persist until the current is restored to zero.

Current limiting fuses and vacuum breakers, for example, have the property of being able to reduce the current to zero value ahead of the inherent normal current zero. During the operation of these devices, the overvoltage developed can be dangerous at some insulation levels.

C.6.4 Autotransformer Connection — Neutral Ungrounded

Autotransformers are occasionally used to interconnect two industrial electric systems of different insulation levels. Due to the common metallic interconnection between the two systems formed by the autotransformer windings, the lower voltage winding is subjected to about the same transient voltages as those that occur on the higher system voltage level. Installations of this type should be avoided unless the neutrals are solidly grounded.

C.7 Surge Protection Devices

To protect against damage due to surges generated on the system, protective gaps and arresters are commonly employed.

C.7.1 Protective Gaps

The simplest type of surge protective device is the rod gap, ring-to-rod gap, or Shephard's hook which is simply a spark gap connected between line and ground. Rod gaps or line entrance gaps on a power system are primarily used to protect open circuit breakers on an overhead line so that flashovers will occur from line to ground and not across the open contacts of the circuit breaker. In those areas where a momentary power interruption may be tolerated, rod gaps are sometimes used for the protection of transformers. The latter should have relatively high BILs when so protected. They are usually installed at the line side of the primary bushings and grounded to the tank. The adjustment of the gap is fairly critical so that when a high voltage surge occurs, the flashover will take place at some point below the impulse strength of the equipment it is protecting.

One disadvantage of the rod gap is that the gap can be too close so that it will flash over during moderate surges. Another major disadvantage is that the gaps are subjected to wide variations in sparkover due to polarity effects and atmospheric conditions such as temperature, pressure, and precipitations. When they flash over they cause a system fault that must be cleared by a circuit breaker or other interrupting device.

It is not practicable to provide sufficient insulation on electrical equipment to withstand the maximum crest voltage of lightning surges. Available equipment for protection against lightning is more economical and practical. Lightning arresters should be installed to protect all important electrical equipment exposed to lightning potentials, and the arresters should be located as near as possible to the terminals of the equipment to be protected. The purpose of the arrester is to reduce the crest voltage of the surge so that it is less than the impulse strength of the insulation (BIL), the chopped-wave withstand voltage (CWW), and the basic switching impulse insulation level (BSL) of the protected equipment.

The extent of reduction of the crest voltage depends on the impedance of the path through the arrester to ground, including the resistance between the ground electrode and the earth. Even with good grounding conditions, the voltage drop of the surge current through the arresters and the ground connection combined may be greater than the impulse strength of the insulation of the protected equipment.

The part of the surge voltage that reaches the insulation can be limited to the voltage drop through the lightning arresters alone. In properly engineered installations, this voltage drop is well under the impulse breakdown strength of the protected insulation. This is accomplished by connecting the grounding conductor from the arrester to the frame of the protected equipment, as well as to the ground connection. The ground connection should have a resistance of 1 ohm or less.

C.7.2 Valve-Type Arresters

The valve arrester is most commonly used for the protection of electrical circuits and its connected equipment. The arresters shown in Figures 6, 7 and 8 consist of one or more gaps in series with a dielectric element or so-called ''valve material.'' Under normal conditions, the gap insulates the line from ground, and the dielectric element, which is a nonlinear resistor, offers a high resistance to power frequency follow current. Where exposed to lightning potentials or other surge potentials, the air in the gap becomes ionized and it sparks over, permitting the surge current to pass to ground. The valve block offers low resistance to the surge current which results in a low discharge voltage. After the surge has passed, the voltage across the valve block drops to the system voltage and a high resistance is again offered to the power frequency follow current.

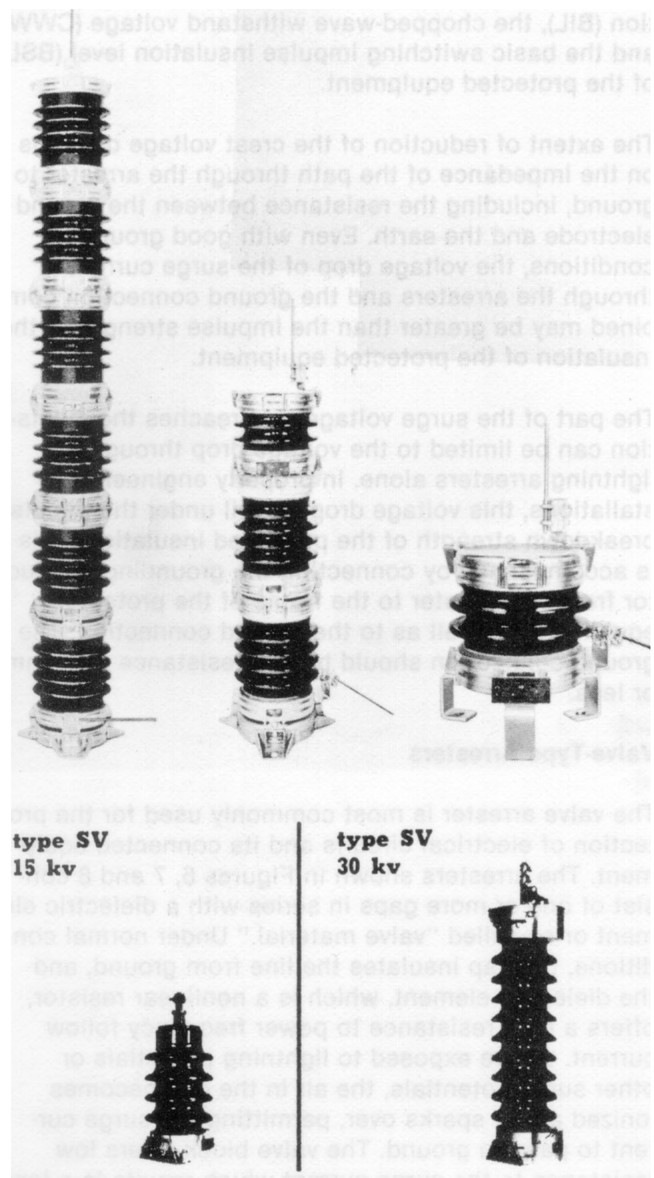


Fig. 6. Station-type arresters. (Upper) Thyrite Magne-valve station-class arresters. For important and valuable equipment in power stations and substations. Also made in line type. (General Electric) (Lower) Autovalve type S.V. arresters. Heavy construction for power stations and important substations. (Westinghouse)

Valve arresters are divided into four main classes: station (2.4 kV - 765 kV) (Figs. 6, 9, and 9a); intermediate (3 kV - 120 kV) (Fig. 7); distribution (1 kV - 30 kV) (Fig. 8); and secondary (0.175 kV - 0.65 kV). Each of these have different sparkover and discharge voltage characteristics for the same nominal voltage rating of the arrester. The root-mean-square voltage ratings in kilovolts are as shown in Table 5.

Fig. 7. Intermediate arresters, line type. Pellet arresters, 300-volts minimum to 15-kv maximum. (General Electric)

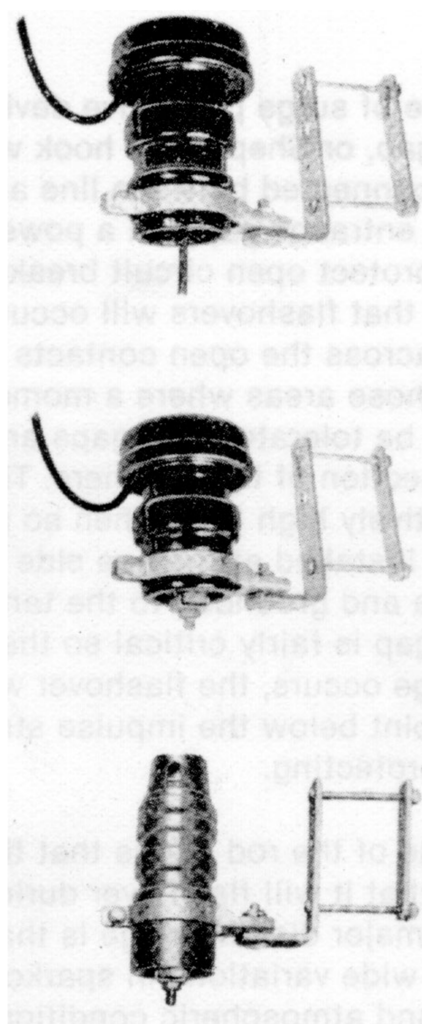


Fig. 8. Distribution arresters, valve type L.V. Rating 3 to 15 kv. (Westinghouse)

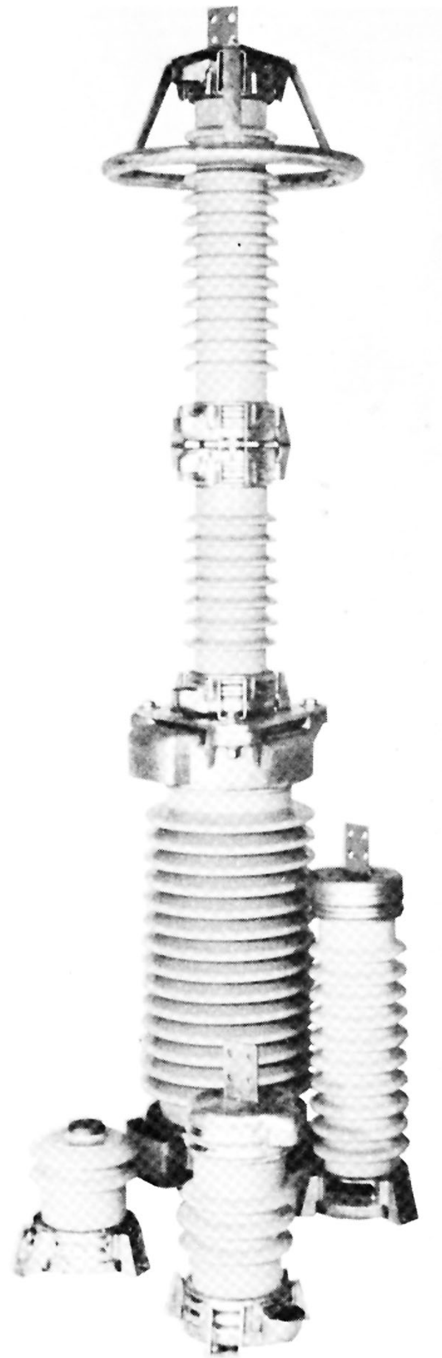


Fig. 9. Tranquell (metal oxide) station surge arrestor. (General Electric Co.)

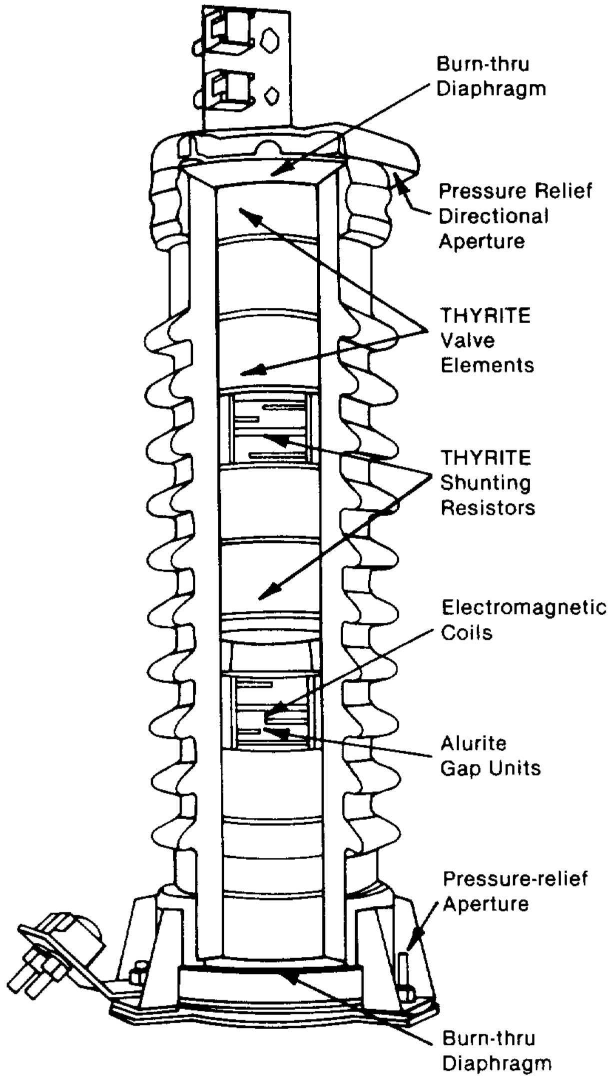


Fig. 9a. Alugard 30-kv station arrester. (General Electric Co.)

Table 5. Voltage Ratings in kV

Secondary Arresters	*Distribution Arresters*	*Intermediate Arresters*	*Station Arresters*
0.175			
0.650			
	1		
	3	3	3
	6	6	6
	9	9	9
	10		
	12	12	12
	15	15	15
	18		
	21	21	21
		24	24
	25		
	27		
	30	30	30
		36	36
		39	39
		48	48
		60	60
		72	72
		90	90
		96	96
		108	108
		120	120
			144
			168
			180
			192
			240
			258
			276
			294
			312
			372
			396
			420
			444
			468
			492
			540
			576
			612
			648
			684

Note: Because of the more stringent requirements for the protection of rotating machines, the use of arresters (all classes) rated 4.5, 7.5, 16.5, 18, 19.5, 22.5, 24, 25.5, and 27 kV is recognized for this application.

The metal oxide arrester shown in Figure 9 is a relatively new development in a station surge arrester in which the series gap has been eliminated. The valve elements are highly nonlinear resistors formulated from a zinc oxide compound. This arrester differs from the conventional arrester in that it responds to over-voltages promptly. Since there is no gap, no abrupt transient can occur such as when sparkover in the conventional arrester occurs, and there is negligible power follow current after a surge operation.

The number of parts in the metal oxide arrester is considerably reduced, resulting in improved reliability, improved performance under contaminated conditions, and smooth transition into and out of conduction as the overvoltage increases and then disappears.

The function of the valve arrester is similar to the relief valve on a steam boiler, i.e., when the pressure becomes too high, the relief valve opens and discharges the excess pressure; then it closes when conditions are safe again. During normal conditions on the system, a valve arrester is merely an insulator between the power line and ground. There is usually no flow of current through the arrester. In some types however, there is a fraction of a milliampere of current through the resistance spacers to maintain a uniform voltage distribution over the arrester gaps.

The metal oxide arrester is said to be particularly suitable for the protection of gas (SF_6) insulated substations in which surge propagation and over-voltage phenomena are quite different from those of air-insulated substations. They are available for use on nominal system voltages from 2.5 kV to 765 kV.

The nominal voltage rating of the arrester is the maximum voltage at which it is guaranteed to interrupt follow current after it has sparked over.

Station arresters are heavy-duty units designed to withstand a maximum crest current of 65,000 amperes. Distribution arresters, intermediate valve arresters, expulsion arresters, and protector tubes will also withstand 65,000 amperes; secondary arresters will withstand 10,000 amperes.

Table 6 shows other durability characteristics for station and intermediate class arresters. Distribution class arresters (Table 6a) do not have standardized pressure relief ratings. The pressure relief ratings indicate the maximum fault current that the arrester will withstand without violent disintegration.

C.7.3 Expulsion Arresters and Protector Tubes

Expulsion arresters (protector tubes) are less commonly used, but may still be found protecting power lines, and in some cases substations, where more expensive protection is not warranted. Distribution expulsion arresters are available in a number of voltage ratings from 3 kV through 18 kV. Protector tubes (Fig. 10) are available for standard voltage ratings from 13.8 kV through 138 kV.

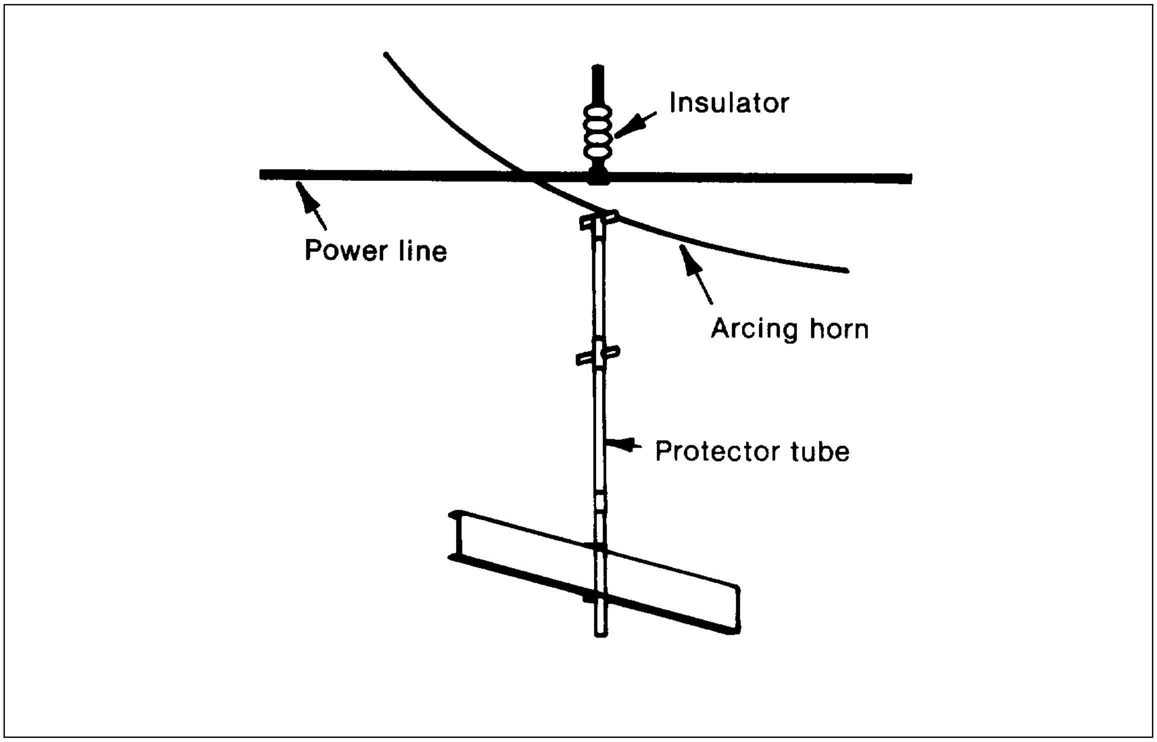


Fig. 10. De-ion protector tube. For outdoor service.

Protector tubes operate on a different principle than the valve type for interruption of the ″follow current.″ The gap is so arranged that when sparkover occurs, the arc passes through a tube that causes gas to be generated from the lining of the tube, which upon discharge out of the open end, stretches and extinguishes the arc as the alternating current wave passes through zero.

Because of the gaseous discharge, the protector tube is not suitable for indoor applications or for mounting in close proximity to other apparatus. Repeated operations also cause erosion of the tube with a gradual reduction in protection which may result in failure.

C.7.4 dc Arresters

There are several different kinds of arresters available for the protection of dc circuits and equipment depending upon the voltage and the application. dc capacitor-type arresters are employed for the protection of dc generators or motors and rotary convertors on electric railway, trolley bus, and mine haulage systems. These are available in three voltage classes: 0 to 750, 751 to 2000, and 2001 to 3900 as shown in Figures 11, 12, and 13. They are installed either indoors or outdoors and connected from line-to-ground in close shunt relation to the insulation of the apparatus being protected. Their purpose is to reduce the turn-to-turn stresses and the major insulation stress from line-to-ground. The inherent characeristics of the capacitor protects the insulation by sloping off the steep front of the lightning wave and reducing the amplitude of the wave.

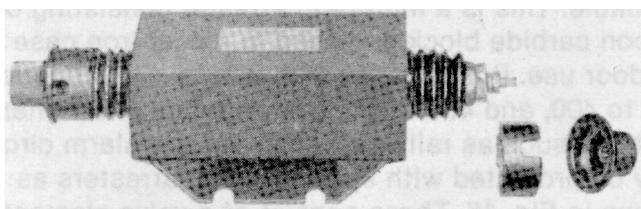


Fig. 11. dc capacitor-type arrester, 0 to 750 volts.
Molded insulation cover removed from one terminal. (General Electric)

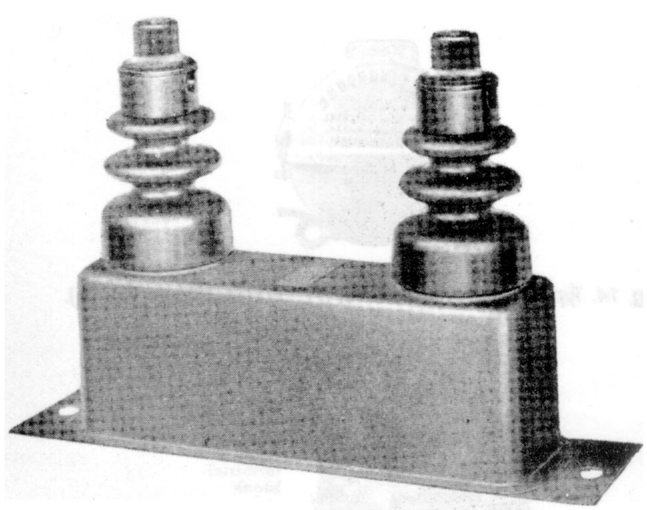


Fig. 12. Capacitor-type arrester, 751 to 2000 volts. (General Electric)

For the protection of dc rotating machinery up to 750 V, a valve-type arrester as shown in Figure 14 is also available. This is a multipath arrester consisting of a silicon carbide block enclosed in a cast iron case for outdoor use. It is made in two voltage classifications: 100 to 400, and 401 to 750 V. Low voltage low energy systems such as railway signal and fire alarm circuits may be protected with special signal arresters as shown

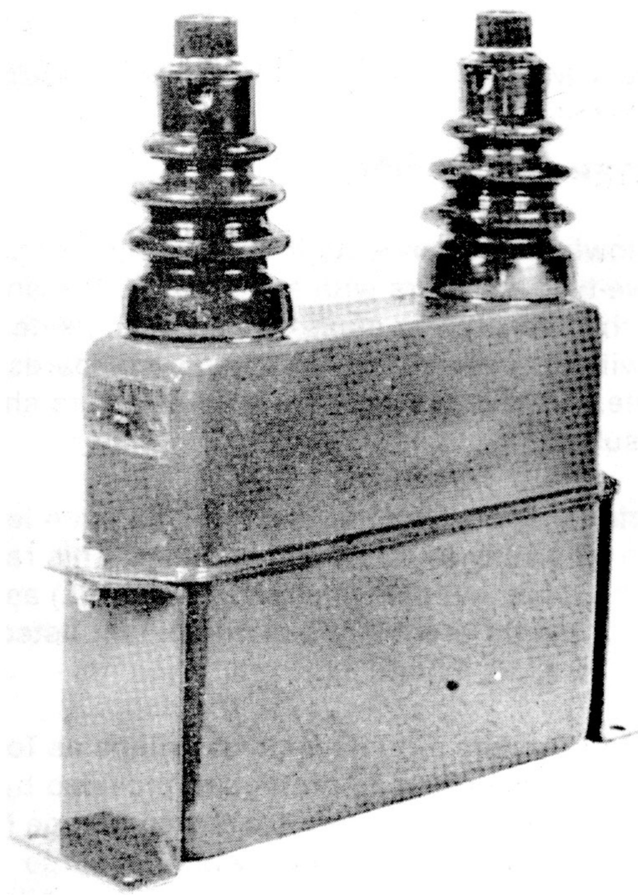


Fig. 13. Capacitor-type capacitor arrester, 2001 to 3900 volts. (General Electric)

in Figure 15. These consist of a valve element and a multispear gap enclosed in a transparent vinylite housing. They are intended for indoor use for the protection of dc circuits up to 75 volts, but may also be used on ac circuits up to 175 volts.

C.8 Arrester Application

The following text concerns the application of only the valve-type arresters with series gaps. The application of the new station class gapless zinc oxide arrester will be covered later when final standards are available. In the meantime the manufacturers should be consulted.

All electrical apparatus has a rated insulation level indicating its ability to resist overvoltages. This rating is called the *basic impulse insulation level* (BIL) as shown for the different kinds of equipment listed in Tables 8, 9, 10, 11, 12 and 13.

Lightning arresters also have other ratings as follows, which show the degree of protection provided by the specific arrester: 1) impulse sparkover voltage (FOW), 2) 1.2 × 50 µsec sparkover, 3) switching surge sparkover, 4) discharge voltage, and 5) durability characteristics. Table 6 shows these values for the different voltage ratings for station and intermediate class arresters, and Table 6a for valve-type distribution class arresters.

Table 7 shows the protective characteristics for station valve arresters and the discharge currents from 1500 amps through 40,000 amps. Table 7a shows the protective characteristics for intermediate valve arresters and discharge voltages for discharge currents ranging from 1500 amps through 20,000 amps.

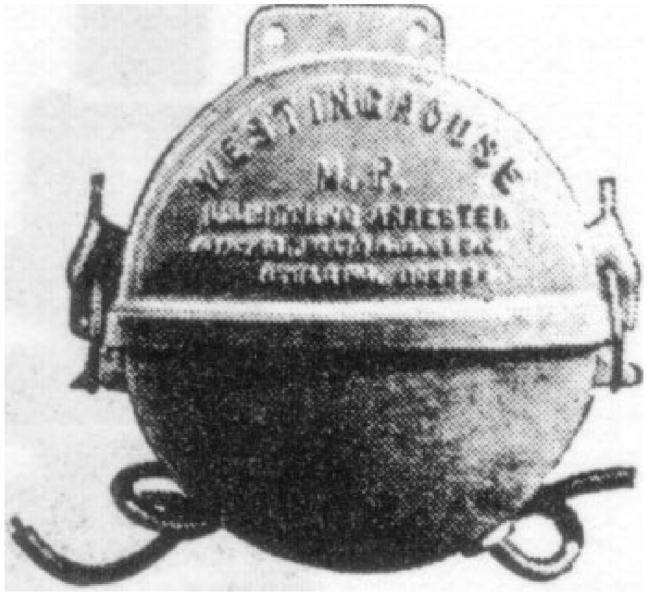


Fig. 14. Type MP valve arrester for dc circuits. (Westinghouse)

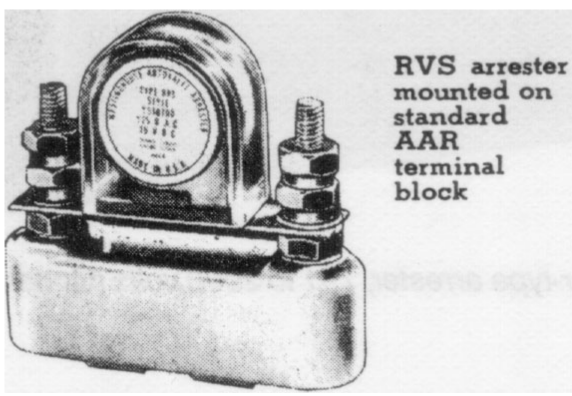


Fig. 15. Type RVS signal arrester for indoor a-c and dc circuits. (Westinghouse)

Protective characteristics for distribution arresters are shown in Tables 18 and 19 in Section C.9, Protection of Distribution System.

It is the usual practice when applying lightning arresters to provide a protective margin of 20%. That is, the arrester sparkover and discharge voltage, plus the voltage drop due to the arrester lead and the ground resistance, should be 20% less than the BIL of the apparatus being protected as expressed by the following formulas:

Protective Margin =

$$\frac{\text{Apparatus CWW}}{\text{Impulse Sparkover Voltage}} \; 100 > 20\%$$

Protective Margin =

$$\frac{\text{Apparatus BIL}}{\text{Arrester Discharge Voltage} + I_d R_G} 100 > 20\%$$

$I_d R_G$ = Voltage drop across ground resistance due to discharge current (Delete if arrester ground wire is connected to equipment frame.)
CWW = 115% BIL for all filled transformers.
CWW = 100% BIL for dry transformers.

When applying surge arresters, there are three basic items that must be carefully determined: the rating, the class, and the location.

C.8.1 Arrester Rating

The maximum sustained line-to-ground voltage that can exist at the arrester location is normally used to select an arrester rating. The lower the arrester rating, the better the protection for the apparatus on the system and the lower the cost. For systems operating at 100 kV and below, switching surge protective levels are usually not important because the insulation designed to withstand lightning overvoltages will usually withstand stresses due to switching.

Surge arresters are connected to phase-to-ground. In a 3-phase system, the phase-to-ground voltage is the system phase-to-phase voltage divided by the $\sqrt{3}$.

Table 6. Station and Intermediate Arrester Characteristics (ANSI C62.2-1981)

	Protective Levels*					Durability Characteristics†				
	Per-Unit Crest Arrester Rating					(1)	(2)	(3)	(4)	
Ratings (kV rms)	*Range of Application Nominal System Voltage (kV)*	*Front-of-Wave Sparkover*	*1.2 × 50-µs Sparkover*	*Switching Surge Sparkover*	*Discharge Voltage. 10-kA, 8 × 20-µs Wave*	*Duty Cycle Initiating Surge (crest amperes)*	*Transmission Line Discharge (miles)*	*High Current Withstand (crest amperes)*	*Pressure Relief (rms symmetrical amperes)*	
Station Class									*Class I*	*Class II*
3-9	2.2-12.47	2.24-4.24	1.89-3.30	Test	1.57-1.77	10 000	150	65 000	65 000	25 000
12-15	13.2-18	2.12-2.83	1.89-2.42	not	1.57-1.70	10 000	150	65 000	65 000	25 000
21-48	18-46	2.09-2.56	1.80-2.29	required	1.56-1.70	10 000	150	65 000	40 000	25 000
60-120	69-138	1.99-2.24	1.60-1.94	1.60-1.80	1.56-1.69	10 000	150	65 000	40 000	25 000
144-240	161-287	1.83-2.22	1.57-1.70	1.57-1.61	1.56-1.79	10 000	175	65 000	40 000‡	25 000
258-312	345	2.10-2.17	1.56-1.70	1.57-1.61	1.56-1.58	10 000	200	65 000	25 000	25 000
372 or higher	500 or higher	1.94-2.10	1.65-1.70	1.44-1.58	1.54-1.60	10 000	200	65 000	Not established	
Intermediate Class										
3-6	2.4-7.2	2.47-2.83	2.24-2.83	Test not	1.77-2.36	5 000	100	65 000	16 100	
9-48	7.2-46	2.14-2.55	1.78-2.28	required	1.77-2.07	5 000	100	65 000	16 100	
60-120	69-138	1.92-2.26	1.63-1.83	2.15-2.43	1.77-2.02	5 000	100	65 000	16 100	

* The per-unit values shown are maximum industry values from tables in Appendix A. For specific values, consult manufacturer's literature. Protective level (kV) = per-unit level × rating × 2. For example, range of FOW sparkover for a 258-kV arrester is (2.10 to 2.17) × $\sqrt{2}$ = 766 to 792 kV.

† This refers to the ability of the arrester to protect itself against the stresses resulting from:
(1) Power-follow current.
(2) The number of line miles an arrester can discharge, which is a measure of its ability to handle switching surges (see Appendix B). The general relationship (for overhead lines only) is: $D = D_L\ (Z/Z_L)(E_L/S)^2$, where D = line miles, Z = line surge impedance, S = switching overvoltage/(system maximum line-to-ground peak voltage). For D_L, Z_L, see ANSI/IEEE C62.1-1981. The use of this formula is valid only for values of D, Z, and S within about 25% of the values of D_L, Z_L, and E_L as listed in ANSI/IEEE C62.1-1981. Underground lines may require special attention because of their low surge impedance; see
Ref [20] and [21].
(3) Severe lightning discharges.
(4) Maximum permissible protective bus faults.

‡ 240-kV rating has pressure relief capability of 25000 for Classes I and II.

Table 6a. Valve-Type Distribution Arrester Characteristics (ANSI C62.2-1981)

		Protective Levels			*Durability Characteristics†*			
		*Per-Unit Crest Arrester Rating**			*(1)*	*(2)*		*(3)*
Rating (kV)	*Range of Application Maximum System Voltage (kV)*	*Front-of-Wave without External Gap (kV)*	*Sparkover with External Gap (kV)*	*Discharge with 10 kA. 8 × 20-µs Wave*	*Duty Cycle Initiating Surge (crest amperes)*	*Low-Current Long-Duration Withstand (crest amperes) (µs)*		*High-Current Withstand (crest amperes)*
3	2.6-4.5	3.30-5.89	5.66-8.01	2.71-3.25	5000	75	2000	65 000
6	4.5-7.8	3.18-4.12	5.30-6.13	2.65-3.06	5000	75	2000	65 000
9-12	7.8-14.3	2.83-3.77	4.30-5.34	2.55-3.22	5000	75	2000	65 000
15-21	18-25.8	2.32-3.54	3.87-4.56	2.49-3.09	5000	75	2000	65 000
25-30	38	2.07-3.54		2.36-2.59	5000	75	2000	65 000

* The per-unit values shown are maximum industry values from tables in Appendix A. For specific values, consult manufacturer's literature.

† This refers to the ability of the arrester to protect itself against the stresses resulting from:

(1) Cumulative power-follow current and surge discharge operations (which also determine the ability to reseal against a voltage equal to the arrester rating).

(2) Long-duration lightning.

(3) Severe lightning discharges.

NOTE: Protective level (kV) = per-unit level × rating × $\sqrt{2}$. For example, range of FOW sparkover for a 12-kV arrester is (2.83 to 3.77) × 12$\sqrt{2}$ = 48 to 64 kV.

The minimum arrester voltage rating selected should be at least 1.25 times the maximum line-to-ground operating voltage.

Actually, under normal conditions, the arrester is only exposed to 58%, ($\frac{1}{\sqrt{3}}$) of the system voltage.

For *ungrounded or noneffectively grounded systems,* the arrester voltage rating should be 100% of the system voltage rating. While the arrester is exposed to only 58% of the voltage under normal conditions, during a phase-to-ground fault it will be exposed to full phase-to-phase system voltage.

The voltage ratings for the arresters usually selected for grounded and ungrounded distribution systems are shown in Table 14.

C.8.2 Arrester Class

In selecting the arrester class the voltage ratings must be equal to or greater than the TOV and the following must be considered: (1) available voltage ratings, (2) pressure relief rating equal to or greater than the system fault, (3) protective level characteristics, and (4) durability characteristics.

In general the class of arrester is determined by the size of the equipment to be protected, as shown in the following tabulation, although the tendency is to use the higher class arrester at higher voltages.

Arrester Class	*Equipment Size*
Station	7.5 MVA and above and large or important rotating machines.
Intermediate	1-20 MVA substations.
Distribution	15 kV — Distribution class apparatus, small rotating machines, and dry-type transformers (special low sparkover types are recommmended).

Distribution class arresters are available in special low sparkover models. They are recommended for rotating machines and dry-type transformers.

For the same voltage rating, a station class arrester has a lower sparkover and discharge voltage than the intermediate class. The intermediate class arrester has lower sparkover and discharge voltages than the distribution class.

For a given discharge voltage, the station class can discharge 100% more current than the intermediate class, while the latter can discharge 50% more than the distribution class. In those systems where frequent switching occurs, particularly where capacitors are connected for power factor correction, the transients produced impose a severe time-current duty on the arrester, and station class arresters are recommended for the best protection.

C.8.3 Location of Arresters

For the best protection, the surge arresters should be installed at the terminals of the equipment to be protected. Economically and practically this is not always possible and the arresters are often installed some distance from the equipment being protected. The further away the arrester is located, the less protection it will afford. In the limiting case, the arrester is so far from the protected equipment that the voltage at the terminals, due to reflection of the traveling wave, will approach twice the arrester sparkover. When an arrester is separated from protected equipment by leads of significant length, oscillations occur which result in higher than arrester voltage at the equipment. This must be taken into account when applying surge protection.

C.8.4 Shielding

Whether an installation is effectively or noneffectively shielded against direct strokes is of major importance in providing adequate surge protection.

C.8.4.1 Effective Shielding

Effective shielding requires that all aboveground incoming lines supplying a substation be protected with an overhead ground wire extending for at least ½ mile from the substation that is grounded at each pole through as low a ground resistance that it is practicable to obtain and connected to the ground bus at the substation. Low ground resistance is particularly important at the poles nearest the substation. The outdoor substation should also be provided with a sufficient number of masts to provide a protective zone for all apparatus that requires protection.

Table 7. Protective Characteristics of Station Valve Arresters (ANSI C62.2-1981)

	Impulse Sparkover Voltage			*Switching Surge*						
	Front-of-Wave		*1.2 × 50-µs*	*Sparkover Voltage*	*Discharge Voltage for 8 × 20-µs Discharge Current Wave*					
Voltage Rating of Arrester	*Rate of Rise of Test Voltage (kV/µs)*	*kV Crest (Range of Maxima)*	*kV Crest (Range of Maxima)*	*kV Crest (Range of Maxima)*	*kV Crest for 1500 A (Range of Maxima)*	*kV Crest for 3000 A (Range of Maxima)*	*kV Crest for 5000 A (Range of Maxima)*	*kV Crest for 10 000 A (Range of Maxima)*	*kV Crest for 20 000 A (Range of Maxima)*	*kV Crest for 40 000 A (Range of Maxima)*
3	25	10-18	10-14	-	4.7-6	5.3-6.5	6-7	6.7-7.5	7.7-8.3	-
6	50	19-28	16-23	-	9.3-11	10-12	12-13	13.4-14.3	15.3-16.3	-
9	75	28.5-38	24-32	-	13.9-17	16-18	18-19	20-21.5	22.9-24.3	-
12	100	36-48	32-41	-	18.5-22	21.3-24	23.5-25.5	26.7-28.5	30.1-32.1	-
15	125	45-57	40-51	-	23.1-27.5	26.6-30	29.5-32	33.4-36	38.2-40	-
21	175	63-76	54-68	-	32.3-38.5	37.2-42	41-45	46.8-50	53.4-55.5	-
24	200	71-86	62-77	-	36.9-44	42.5-48	47-51	53.4-57	61-63.5	-
30	250	89-103	77-93	-	46.1-55	53.1-60	59-64	66.9-72	76.3-79	-
36	300	107-118	92-108	-	55.3-66	63.7-72	70.5-76	80-85	91.5-94.5	-
39	325	115-125	100-114	-	60-71.5	69-78	76.5-82.5	86.5-92	99.1-102	-
48	400	143-148	122-132	-	73.8-88	84.9-96	94-102	106-114	122-126	-
60	500	170-190	141-165	136-153	95-109	110-120	118-130	132-143	150-158	-
72	600	204-226	169-190	163-178	114-131	130-144	141-155	159-170	180-189	-
90	750	254-275	210-235	203-215	142-163	162-180	176-194	199-213	225-237	-
96	800	270-295	218-245	218-225	151-174	173-192	188-218	212-227	240-253	-
108	900	304-325	245-270	245-250	170-196	194-216	212-245	238-256	270-284	-
120	1000	338-360	272-300	272-275	188-218	216-240	235-272	265-285	300-316	-
144	1200	400-430	326-346	325-326	226-262	260-288	282-311	318-342	360-379	-
168	1400	460-525	380-404	380-381	263-305	303-336	329-362	371-399	420-442	-
180	1500	490-565	400-430	400-410	281-327	324-360	353-388	397-455	450-505	-
192	1600	520-600	427-460	426-435	300-348	346-384	376-414	424-427	480-495	-
240	2000	620-735	535-577	533-545	374-436	432-480	470-518	530-570	605-630	-
258	2000	766-790	575-620	573-585	402-438	465-474	505-515	569-575	650-666	-
276	2000	820-840	615-664	612-630	429-468	496-507	540-570	609-615	690-714	-
294	2000	875-885	653-675	653-675	458-472	528-532	576-595	653-653	735-758	-
312	2000	924-935	690-750	693-710	485-530	562-574	611-620	688-693	780-805	874-961
372	2000	1078-1100	870-890	790-830	562-610	655-680	726-738	809-826	932-955	1136-1145
396	2000	1140-1176	925-950	840-885	599-672	697-726	772-785	861-880	990-1015	1109-1226
420	2000	1200-1250	980-1005	890-940	634-713	739-770	819-830	913-930	1050-1070	1176-1294
444	2000	1265-1320	1035-1055	940-990	670-753	781-814	866-875	965-977	1110-1130	1243-1358
468	2000	1326-1390	1090-1110	992-1045	707-794	823-860	913-930	1018-1040	1170-1200	1310-1441
492	2000	1385-1425	1160-1165	1045-1090	742-830	865-925	958-1000	1070-1115	1232-1290	1500-1515
540	2000	1515-1555	1274-1280	1145-1200	814-890	949-990	1052-1070	1173-1195	1350-1390	1646-1663
576	2000	1616-1665	1359-1380	1225-1285	868-950	1012-1060	1122-1150	1251-1285	1440-1480	1755-1780
612	2000	1700-1765	1440-1480	1300-1370	924-1010	1076-1130	1193-1220	1330-1360	1531-1580	1865-1885
648	2000	1790-1865	1525-1570	1380-1445	977-1070	1138-1190	1261-1290	1407-1440	1619-1670	1974-1996
684	2000	1880-1960	1610-1680	1455-1525	1031-1130	1153-1260	1331-1360	1489-1520	1709-1765	2063-2107

Table 7a. Protective Characteristics of Intermediate Valve Arresters (ANSI C62.2-1981)

	Impulse Sparkover Voltage			*Switching Surge*					
	Front-of-Wave		*1.2 × 50-µs*	*Sparkover Voltage*	*Discharge Voltage for 8 × 20-µs Discharge Current Wave*				
Voltage Rating of Arrester	*Rate of Rise of Test Voltage (kV/µs)*	*kV Crest (Range of Maxima)*	*kV Crest (Range of Maxima)*	*kV Crest (Range of Maxima)*	*kV Crest for 1500 A (Range of Maxima)*	*kV Crest for 3000 A (Range of Maxima)*	*kV Crest for 5000 A (Range of Maxima)*	*kV Crest for 10 000 A (Range of Maxima)*	*kV Crest for 20 000 A (Range of Maxima)*
3	25	11-12	11-12	-	5.2-7.5	6-8	6.6-9	7.5-10	8.7-12
6	50	21-21	19-19	-	10.4-13.5	11.9-14	13.2-15.5	15-17.5	17.4-20
9	75	31-32.5	27.5-29	-	15.6-21	17.9-22	19.8-24	22.5-26	26.1-28.5
12	100	40-42	35.5-37	-	20.8-27	23.8-29	26.4-32	30-34	34.8-37.5
15	125	50-51	43.5-46.5	-	25.9-34	29.7-36.5	32.9-39.5	37.5-43	43.5-47.5
21	175	67-68	58-64	-	36.3-47.5	41.6-51	46.1-56	52.5-60	60.9-66
24	200	76-78	66-75	-	41.5-54	47.6-58	52.7-64	60-68	69.6-75
30	250	94-97	81-91	-	51.8-68	59.4-73	65.8-79	75-86	87-95
36	300	109-116	95-97	-	62.2-82	71.3-87	79-95	90-102	104-113
39	325	121-126	102-102	-	67.4-91	77.3-97	85.5-106	97.5-114	113-126
48	400	143-154	121-125	-	83-109	95-116	105-127	120-136	139-150
60	500	173-190	147-155	185-206	104-136	119-145	131-159	150-171	174-189
72	600	201-230	171-180	219-245	124-163	143-174	158-191	180-204	209-225
90	750	266-283	223-226	274-304	155-204	178-218	197-239	225-256	261-282
96	800	279-300	236-240	292-323	166-217	190-232	211-254	240-273	278-300
108	900	303-335	258-265	328-362	187-244	214-261	237-286	270-307	313-338
120	1000	325-370	276-295	364-400	207-272	238-290	263-319	300-338	348-380

Table 8. Relationships of Nominal System Voltage to Maximum System Voltage and Basic Lightning Impulse Insulation Levels (BILs) for Systems 1100 kV and Below (ANSI C57.12-1980)

Application	*Nominal System Voltage (kV rms)*	*Maximum System Voltage (from ANSI C84.1-1977 and ANSI C92.2-1978) (kV rms)*	*Basic Lightning Impulse Insulation Levels (BILs) in Common Use (kV crest)*				
Distribution	1.2		30				
	2.5		45				
	5.0		60				
	8.7		75				
	15.0		95				
	25.0		150	125			
	34.5		200	150	125		
	*46.0	48.3	250	200			
	69.0	72.5	350	250			
Power	1.2		45	30			
	2.5		60	45			
	5.0		75	60			
	8.7		95	75			
	15.0		110	95			
	25.0		150				
	34.5		200				
	*46.0	48.3	250	200			
	69.0	72.5	350	250			
	115.0	121.0	550	450	350		
	138.0	145.0	650	550	450		
	*161.0	169.0	750	650	550		
	230.0	242.0	1050	900	825	750	650
	345.0	362.0	1175	1050	900	825	
	500.0	550.0	1675	1550	1425	1300	
	765.0	800.0	2050	1925	1800		
	1100.0	1200.0	2425	2300	2175	2050	

* Non-preferred voltage (ANSI C84.1-1977)

Notes:

(1) BIL values in bold type-face are listed as standard in ANSI C57.12.10-1977, C57.12.20-1974, C57.12.21-1980, C57.12.22-1980, C57.12.23-1978, C57.12.24-1978, C57.12.25-1975, and C57.12.26-1975, and C57.12.30-1977.

(2) When specified, and when suitable surge protection and effective grounding are provided, lower insulation levels may be used in transformers. For high-voltage systems it is common to use insulation dependent on the degree of surge protection obtainable. For example, in 230 kV systems, BILs with corresponding low-frequency tests of 1050, 900, 825, 750, and 650 kV have been used. Application of reduced BILs is most common on grounded Y-connected systems. In applying Δ-connected transformers with reduced BILs the system should be reviewed for *effective grounding adequacy.*

(3) When reduced BILs are involved, internal and external phase-to-phase low-frequency insulation levels should not be reduced below the values listed in Table 6a.

(4) Single-phase distribution and power transformers and regulating transformers for voltage ratings between terminals of 8.7 kV and below are designed for both Y and Δ connection and are insulated for the test voltages corresponding to the Y connection, so that a single line of transformers serves for the Y and Δ applications. The test voltages for such transformers when operated Δ-connected are, therefore, higher than needed for their voltage rating.

(5) For series windings in transformers such as regulating transformers, the test values to ground shall be determined by the BIL of the series windings rather than by the rated voltage between terminals.

Table 9. Interrelationships of Dielectric Insulation Levels for Liquid-Filled Transformers Used on Systems with BILs 2425 kV and Below (ANSI C57.12-1980)

		Low Frequency Voltage Insulation Level (kV rms)	**Impulse Levels*			*†Front-of-Wave Impulse Levels*		**Switching Surge Level (line-to-ground) (kV Crest)*
				Chopped Wave				
Application	*BIL kV*		*Full Wave (kV Crest)*	*(kV Crest)*	*Minimum Time to Flashover (μs)*	*Minimum Crest Voltage (kV)*	*Specific Time to Sparkover (μs)*	
Distribution	30	10	30	36	1.0	—	—	—
	45	15	45	54	1.5	—	—	—
	60	19	60	69	1.5	—	—	—
	75	26	75	88	1.6	—	—	—
	95	34	95	110	1.8	—	—	—
	125	40	125	145	2.25	—	—	—
	150	50	150	175	3.0	—	—	—
	200	70	200	230	3.0	—	—	—
	250	95	250	290	3.0	—	—	—
	350	140	350	400	3.0	—	—	—
Power	45	10	45	54	1.5	—	—	‡20
	60	15	60	69	1.5	—	—	‡35
	75	19	75	88	1.6	—	—	‡38
	95	26	95	110	1.8	165	0.5	‡55
	110	34	110	130	2.0	195	0.5	‡75
	150	50	150	175	3.0	260	0.5	‡100
	200	70	200	230	3.0	345	0.5	‡140
	250	95	250	290	3.0	435	0.5	‡190
	350	140	350	400	3.0	580	0.58	‡280
	450	185	450	520	3.0	710	0.71	375
	550	230	550	630	3.0	825	0.825	460
	650	275	650	750	3.0	960	0.96	540
	750	325	750	865	3.0	1070	1.07	620
	825	360	825	950	3.0	1150	1.15	685
	900	395	900	1035	3.0	1240	1.24	745
	975	430	975	1120	3.0	—	—	810
	1050	460	1050	1210	3.0	1400	1.40	870
	1175	520	1175	1350	3.0	1530	1.53	975
	1300	575	1300	1500	3.0	—	—	1080
	1425	630	1425	1640	3.0	—	—	1180
	1550	690	1550	1780	3.0	—	—	1290
	1675	750	1675	1925	3.0	—	—	1390
	1800	800	1800	2070	3.0	—	—	1500
	1925	860	1925	2220	3.0	—	—	1600
	2050	920	2050	2360	3.0	—	—	1700
	2175	980	2175	2500	3.0	—	—	1800
	2300	1040	2300	2650	3.0	—	—	1900
	2425	1090	2425	2800	3.0	—	—	2010

* Test made only *when specified.*

† Must be specified prior to transformer design.

‡ When specified, switching surge tests are normally specified only on one winding of 450 kV BIL and higher.

These voltage values shall be used to establish the limiting induced switching surge voltage in low-voltage windings when a high-voltage winding is tested.

Table 10. Insulation Levels for Dry-Type Transformers (ANSI C57.12.01-1979)

Nominal Equipment Voltage (1)	*BIL (kV) (2)*	*Low Frequency Voltage Levels (kV rms), Winding to Winding, and Winding-to-Ground*		*Impulse Levels (Positive Polarity)*	
		Grounded Y† (3)	*Ungrounded Y D ‡ (4)*	*Full Wave 1.2 × 50 µs (kV Crest)*	*Chopped Wave Minimum Time to Flashover (µs)*
*120-1200**			*4*		
1200GrdY/693	10	4		10	1.0
2520	20		10	20	1.0
4360GrdY/2520		10			
4160			12		
7200	30			30	1.0
8720GrdY/5040		10			
8320	45	—	19	45	1.25
12 000*			31		
13 800					
13 800GrdY/7970	60	10		60	1.5
18 000			34		
22 860GrdY/13 200	95	10		95	1.6
23 000	110		37	110	1.8
24 940GrdY/14 400		10			
27 600*			40		
34 500GrdY/19 920	125	10		125	2.0
34 500	150	—	50	150	2.25

* Nonpreferred voltage (ANSI C84.1-1977).

† Applicable to solidly grounded wye windings (see 5.10.2 and 5.10.3). Such windings shall also be capable of withstanding two times rated voltage (with neutral grounded) from line terminals to ground and between line terminals.

‡ The BIL associated with a grounded Y line-to-line voltage rating is also applicable to the same delta line-to-line voltage rating, provided the system is effectively grounded at the location of the surge arrester in accordance with the system criteria described in ANSI C62.2-1969, Guide for Application of Valve-Type Lightning Arresters for Alternating-Current Systems.

Notes:

(1) The BIL values of Table 4 are based on ANSI C62.2-1969, using low-sparkover surge arresters and a 5 kA discharge current. If there is any possibility that the transformer terminals will be subjected to transient overvoltages exceeding their BILs, they should be protected with appropriate surge arresters.

(2) Insulation levels for voltages between listed values of Table 4 may be determined as follows:
   (a) Coordinate with available surge arresters per ANSI C62.2-1969, or
   (b) Use insulation level for the next higher voltage rating.

(3) When specified, other BILs may be furnished.

In addition to providing effective shielding, substation equipment should be protected against voltage surges by the proper application of surge arresters. In some cases, these arresters may not afford adequate protection due to the circuit distance between the arresters and the transformer, the method of grounding, and the system voltage. In such cases, a separate set of arresters are necessary to protect the transformer.

Although each case should be considered separately, for station equipment rated 23 kV and above having full BIL insulation, separation distances of 75 to 200 ft can usually be tolerated. For equipment rated 15 kV and below, the best practice is to avoid any separation distance.

In effectively shielded stations, discharge currents rarely exceed 5000 amperes.

C.8.4.2 Noneffectively Shielded Substations

In noneffectively shielded substations, which are usually small and not over 34.5 kV, the arresters should be installed close to the transformer terminals. A low resistance ground connection is also required along with short interconnection of the transformer case. Discharge currents of 20,000 amperes are recommended for use in checking the insulation protection.

Table 11. Rated Voltages and Insulation Levels for AC Switchgear Assemblies

Rated Voltage (rms)		*Insulation Levels (kV)*		
Rated Nominal Voltage	*Rated Maximum Voltage*	*Power Frequency Withstand (rms)*	*DC Withstand**	*Impulse Withstand*
Metal-Enclosed Low-Voltage Power Circuit Breaker Switchgear				
Volts	Volts			
240	250	2.2	3.1	—
480	500	2.2	3.1	—
600	630	2.2	3.1	—
Metal-Clad Switchgear				
kV	kV			
4.16	4.76	19	27	60
7.2	8.25	36	50	95
13.8	15.0	36	50	95
34.5	38.0	80	†	150
Metal-Enclosed Interrupter Switchgear				
kV	kV			
4.16	4.76	19	27	60
7.2	8.25	26	37	75
13.8	15.0	36	50	95
14.4	15.5	50	70	110
23.0	25.8	60	†	125
34.5	38.0	80	†	150
Station-Type Cubicle Switchgear				
kV	kV			
14.4	15.5	50	†	110
34.5	38.0	80	†	150
69.0	72.5	160	†	350

From IEEE Std 27-1974.

* The column headed ''DC Withstand'' is given as a reference only for those using direct-current tests and represents values believed to be appropriate and approximately equivalent to the corresponding power frequency withstand test values specified for each voltage class of switchgear. The presence of this column in no way implies any requirement for a direct-current withstand test on alternating-current equipment. When making direct-current tests, the voltage should be raised to the test value in discrete steps and held for a period of 1 min.

† Because of the variable voltage distribution encountered when making direct-current withstand tests, the manufacturer should be contacted for recommendations before applying direct-current withstand tests to the switchgear. Potential transformers above 34.5 kV should be disconnected when testing with direct current. Refer to 6.8 of ANSI C57.13-1968, and in particular to 6.8.2 which reads ''Periodic kenotron tests should not be applied to transformers of higher than 34.5 kV voltage ratings.''

C.8.4.3 Metal-Clad Switchgear

The insulation levels of switchgear are comparable to those of liquid-filled transformers of 500 kVA and smaller and the problems of protection are much the same.

Table 12. Voltage Ratings for Metal-Enclosed Bus

		Insulation Level (kV)			
Rated AC Voltage (kV rms)		*Power Frequency Withstand (rms)*			
Nominal	*Rated Maximum*	*(Dry 1 Minute)*	*(Dew 10 Seconds)**	*DC Withstand (Dry)†*	*Impulse Withstand*
0.6	0.63	2.2	—	3.1	—
4.16	4.76	19.0	15	27.0	60
13.8	15.00	36.0	24 (36)	50.0	95
14.4	15.50	50.0	30 (50)	70.0	110
23.0	25.80	60.0	40 (60)	85.0	150
34.5	38.00	80.0	70 (80)	‡	200
69.0	72.50	160.0	140 (160)	‡	350

For applications of isolated phase bus to generators, the following voltage ratings apply:§

	Power Frequency Withstand (rms)			
Rated kV of Generator (rms)	*(Dry 1 Minute)*	*(Dew 10 Seconds)*	*DC Withstand (Dry)*	*Impulse Withstand*
14.4 to 24	50	50	70	110

From IEEE Std 27-1974.

* Applied to porcelain insulation only. Values in parentheses apply to ‘‘high creepage’’ designs.

† The column headed ‘‘DC Withstand’’ is given as a reference only for those using direct-current tests and represents equivalent to the corresponding power frequency withstand test values specified for each voltage class of bus. The presence of this column in no way implies any requirement for a direct-current withstand test on alternating-current equipment. When making direct-current tests the voltage should be raised to the test value in discrete steps and held for a period of 1 min.

‡ Because of the variable voltage and distribution encountered when making direct-current withstand tests, the manufacturer should be contacted for recommendations before applying direct-current withstand tests to these voltage ratings. Potential transformers above 34.5 kV should be disconnected when testing with direct current. Refer to 6.8 of ANSI C57.13-1968, and in particular to 6.8.2 which reads, ″Periodic kenotron tests should not be applied to transformers of higher than 34.5 kV voltage rating.″

§ These ratings are applicable to generators rated 14.4 to 24 k V which are directly connected to transformers without intermediate circuit breakers and where adequate surge protection is provided. These bus withstand ratings are compatible with or in excess of required withstand values of the generators.

Where metal-clad switchgear is supplied directly by means of an overhead metallic sheathed cable, arresters should be installed at the junction point between the transmission lines and the cable. Whether a set of arresters is also needed at the switchgear depends upon 1) the length and type of cable, 2) junction arrester protective level voltages, and 3) method of system neutral grounding.

If the cables are nonmetallic-sheathed types, arresters are required at the switchgear because they have higher surge impedance than the metallic-sheathed cables which can also be interconnected with the arrester ground and switchgear ground bus. In this case, station class arresters will afford adequate protection, although distribution arresters may also be used but will afford less protection. The installation of a neutral or a ground wire in the same duct with each 3-phase nonmetallic-sheathed cable provides practically the same surge impedance as continuous metallic-sheathed cable, and surge protection can be applied accordingly.

As a precautionary measure, the momentary capability of the sheath of 3-phase cables should be investigated before grounding both ends, and special consideration may be necessary for single-phase cable with shields that cannot be grounded at both ends.

C.8.4.4 Dry-Type Transformers

Lightning protection for dry-type transformers must be carefully engineered where the connecting circuits are exposed. Compared to liquid-filled transformers, they have considerably less resistance to lightning. For example, a 15 kV dry-type transformer has a BIL of 60 kV, while a 15 kV oil-filled distribution transformer has a BIL of 95 kV.

Protection of dry-type transformers against switching surges is of little concern. They are used mostly for applications involving low voltages and involve high ratios of insulation strength to operating voltage. Consequently, the magnitude of most switching surges is not high enough to cause damage to dry-type transformers.

Table 13. Electrical Characteristics of Transformer Bushings
(applies only to bushings 34.5 kV and below not listed in ANSI/IEEE Std 24-1977.) (ANSI C57.12-1980)

	Outdoor Bushings								
	Power Transformers†				Distribution Transformers†				
		60 Hz Withstand		Impulse Full Wave	60 Hz Withstand		Impulse Full Wave	Indoor Bushings‡	
System Voltage (kV)*	Minimum Creepage Distance in. mm	1 min Dry (kV)	10 s Wet (kV)	Dry Withstand (kV) (1.2 × 50 µs)	1 min Dry (kV)	10 s Wet (kV)	Dry Withstand (kV) (1.2 × 50 µs)	60 Hz Withstand (kV) 1 min Dry (kV)	Impulse Full Wave Dry Withstand (kV) (1.2 × 50 µs)
1.2	—	—	—	—	10	6	30	—	—
2.5	—	21	20	60	15	13	45	20	45
5.0	—	27	24	75	21	20	60	24	60
8.7	—	—	—	—	27	24	75	30	75
8.7	7178	35	30	95	—	—	—	—	—
15.0	—	—	—	—	35	30	95	50§	110§
18.0	—	—	—	—	42	36	125	—	—
25.0	—	—	—	—	—	—	—	60	150
34.5	—	—	—	—	—	—	—	80	200

* The nominal system voltage values given above are used merely as reference numbers and do not necessarily imply a relation to specific operating voltages.

† Power transformers indicate transformers rated above 500 kVA and distribution transformers indicate transformers rated 500 kVA and below.

‡ Indoor bushings are those intended for use on indoor transformers. Indoor bushing test values do not apply to bushings used primarily for mechanical protection of insulated cable leads. Wet test values are not assigned to indoor bushings.

§ Small indoor transformers may be supplied with bushings for a dry test of 38 kV and impulse test of 95 kV.

Table 14. Commonly Applied Voltage Ratings of Arresters on Distribution Systems (ANSI C57.12-1980)

System Voltage (kilovolts rms)		*Usually Applied Arrester Ratings (kilovolts rms)*			
Nominal Voltage	*Maximum Voltage Range B**	*Four-Wire Multigrounded Neutral Wye*	*Three-Wire Unigrounded Neutral Wye*	*Delta and Ungrounded Wye*	*Spacer-Cable Circuits†*
2400	2540			3	
4160Y/2400	4400Y/2540	3	6		3
4160	4400			6	
4800	5080			6	
6900	7260			9 or 9/10	
8320Y/4800	8800Y/5080	6	9 or 9/10		6
12 000Y/6930	12 700Y/7330	9 or 9/10	9/10 or 10		9/10 or 10
12 470Y/7200	13 200Y/7620	9 or 9/10	12		9/10 or 10
13 200Y/7620	13 970Y/8070	9/10 or 10	12		9/10 or 10
13 800Y/7970	14 520Y/8380	9/10, 10, or 12	12		12
13 800	14 520			15	
20 780Y/12 000	22 000Y/12 700	15	18		18
22 860Y/13 200	24 200Y/13 970	18	21		21
23 000	24 340			25	
24 940Y/14 400	26 400Y/15 240	18	21		21
34 500Y/19 920	36 510Y/2180	25 or 27	30		30
34 500	36 510			36 ‡ or 37 ‡	

* See ANSI C84.1-1977 and ANSI C84.1a-1980.

† The use of spacer cables at most system voltages has had limited application, reducing the experience factor in establishing arrester ratings usually applied. Where experience is a factor, arrester ratings lower than 1.5 × nominal system line-to-ground voltage have been used. This is taken into account for the voltage ratings listed.

‡ Nonstandard distribution arrester voltage ratings.

C.8.4.5 Transformers Connected Directly to Overhead Lines

When transformers are directly connected to overhead lines, special low sparkover distribution class arresters should be installed in direct shunt with the dry-type transformer. The resistance of the ground connection should not exceed 1 ohm. The arrester ground should also be directly connected to the transformer case. If the resistance of the ground connection is high, the resulting voltage drop across the ground connection must be added to the arrester discharge voltage, the sum of which could easily exceed the BIL rating.

C.8.4.6 Transformer Connected by Cable to Overhead Lines

Where a dry-type transformer is supplied through cable, an arrester at the line-cable junction will not always protect the transformer from a lightning produced surge depending upon the cable length and the transformer BIL. In such cases, a special low sparkover distribution class arrester installed at the transformer terminals should be provided.

C.8.4.7 Transformer Connected to Overhead Line through Liquid-filled Transformer

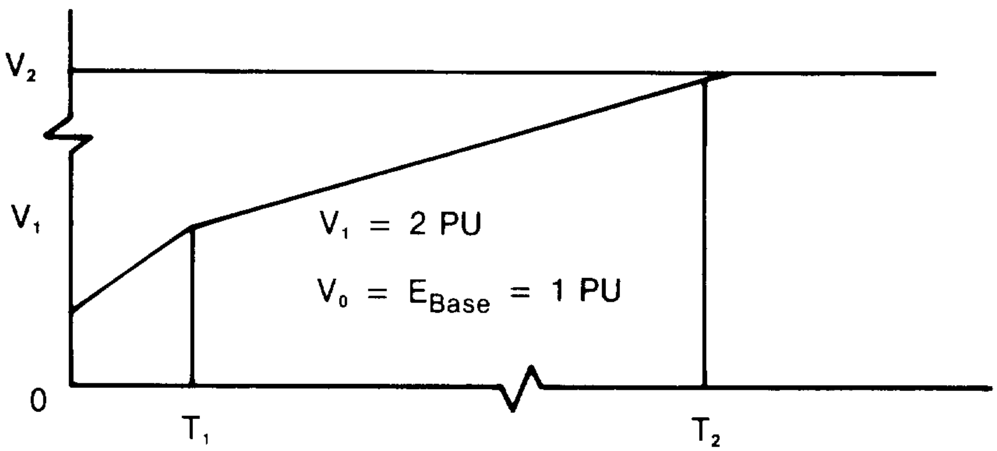
Where a dry-type transformer is supplied through a shielded cable from the secondary side of an oil-filled transformer, any surge on the overhead line will be transmitted through the transformer and appear on its secondary. Where the cable is long (over 75 feet), reflected voltages will increase the voltage at the dry-type transformer terminals to the point where it may exceed 80% of its BIL, and special distribution arresters may be necessary at the terminals to protect it properly.

C.8.4.8 Rotating Machines

The insulation strength of rotating machines is low compared with oil-insulated equipment because space is limited and the insulation is dry.

The windings of modern machines have two general types of insulation: turn-to-turn and conductor-to-iron insulation or ground wall insulation. There are no established ANSI/IEEE impulse standards for the insulation structure of rotating machines. Since 1960 however, it has been accepted practice when applying surge protection to use a value of 1.25 times the crest of the one minute ac proof test of twice rated voltage plus 100 [$1.25 \sqrt{2}\, 2E_{LL} + 1000$)] for the impulse strength of rotating machine insulation. At that time it was agreed by the machine manufacturers that the impulse strength of the ground wall insulation was well above this value before being placed in service.

Recently however, a Working Group of the Institute of Electrical and Electronic Engineers has arrived at the current consensus on the volt-time impulse withstand strength of machine insulation as shown in Figure 16a and reasonable agreement is likely. Under consideration is the time T_2 to reach maximum applied surge; whether it should be 10 µsec., 5 µsec, or some shorter time, to accurately reflect the insulation capability on multi-turn machines. It also appears that a single recommendation will apply to both motors and generators.



$$E_{BASE} = \sqrt{2}\, E_{L\text{-}N} = \frac{\sqrt{2}}{\sqrt{3}} E_L$$

E_L = Rated Volts, L-LinkV

T_1 = 2000 NS

T_2 = 10 µsecs. Accepted practice may be reduced.

$$V_2 = 1.25\sqrt{2}\,(2\,E_L + 1) = \left(4.33 + \frac{2.17}{E_L}\right) P\mu$$

Rated kV-E_L	V_0, kV	V_1, kV	V_2, kV	V_2, PU
0.46	0.375	0.75	3.4	9.0
0.575	0.47	0.94	3.8	8.1
2.3	1.9	3.8	9.9	5.27
4.0	3.3	6.5	15.9	4.87
4.6	3.8	7.5	18.0	4.80
6.6	5.4	10.8	25.1	4.66
13.2	10.8	21.6	48.4	4.49
18.0	14.7	29.4	65.4	4.45
20.0	16.3	32.7	72.5	4.44
25.0	20.4	40.8	90.2	4.42

Fig. 16a. Probable impulse withstand, volt-time, for a-c rotating machinery.

The envelope of withstand strength shown in Figure 16a is essentially in accord with long-established manufacturers' recommendations. It is a composite based on both the impulse strength of ground wall insulation and impulse strength of turn insulation.

For adequate protection of rotating machines, the following is essential:

1. Effective shielding.
2. Arresters at the machine terminals.
3. Surge capacitors at the machine terminals.
4. Low resistance ground connections, interconnected with the machine frame and the arrester and capacitor.

The complete basic protective circuit for rotating machines is shown in Figure 16b. The arrester A_L limits the incoming voltage and the inductance L and capacitance C lengthen the time to crest and limit the rate of rise of the voltage at the machine terminal. The second arrester A_M limits the magnitude of the voltage from the machine terminal to its frame.

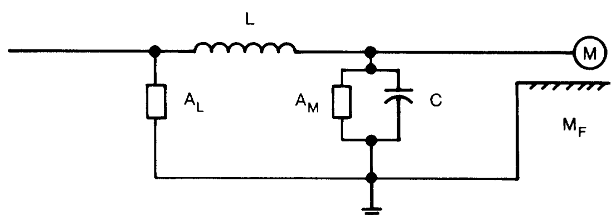


Fig. 16b. Fundamental protection scheme.

As illustrated in Figure 16c, there are four different practical methods in use for obtaining the series inductance and control of the voltage impressed on the LC circuit. Example 1 of this figure shows the use of a choke coil or reactor as a bumped inductance. Example 2 uses a length of line from 500 feet (152 m) for 650V machines and 1500 feet (457 m) for all higher voltage machines out to the line arrester A_L. Example 3 in Figure 16c shows a length of cable with a grounded metallic sheath connected between the machine and the overhead line. The cable must be long to be effective and afford protection with the line arrester A_L at the cable junction. If the cable is not long enough, additional inductance in the form of a choke coil or more line with another arrester will be required as shown by the dashed lines in Example 3. Example 4 shows a transformer installed between the machine protection and the line which provides high inductance and a high degree of protection. With this arrangement all the grounds are readily connected together.

Regarding Example 2, which shows an unshielded time, a stroke hitting the line between the line arrester and the machine would impair the protection because the full required inductance would not be in series with the capacitor and the line arrester cannot limit the voltage on the system as effectively as it would for a stroke hitting ahead of the arrester.

Another disadvantage of this arrangement is that the resistance of the ground connection of the line arrester should not exceed 2 or 3 ohms. Otherwise the voltage drop due to high currents flowing through the ground connection when added to the discharge voltage of the arrester could permit voltages which may damage the turn-to-turn insulation.

If the average number of lightning strokes to a transmission line of 100 times per 100 miles per year is used in an isokeraunic level (IKL) of 30, the average probability of a stroke on 1500 feet (457.5 m) of line is about one in 3-½ years. With the protection illustrated in Example 2, many of the strokes will not be severe enough to damage the machine.

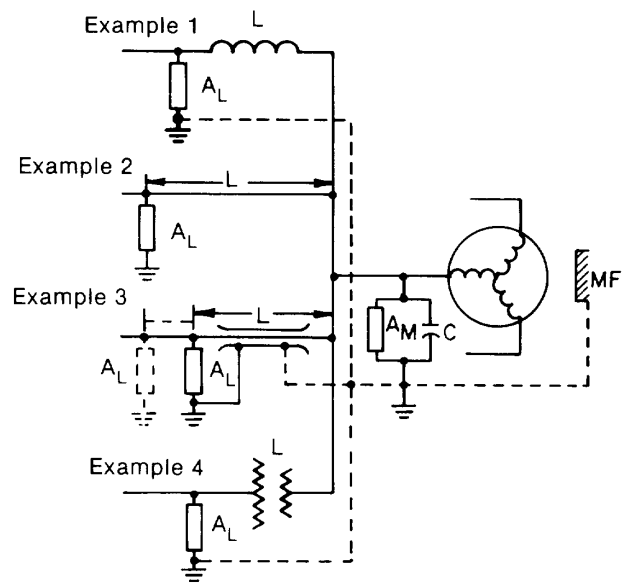


Fig. 16c. Practical means of obtaining series inductance.

With the above arrangement the maximum permissible pole and arrester ground resistance R_G may be higher as shown in the following tabulation.

Spacing of Pile Grounds	*250 ft (76 m)*	*125 ft (38 m)*
Valve Type Line Arrester Ground Resistance	2-5 ohms	4-10 ohms

If the above values of ground resistance cannot be obtained, a buried counterpoise connecting all the grounds together should be installed.

If the shield wire is not used, another method of improving the protection (illustrated in Example 2) is installing additional line arresters as shown in Figure 17.

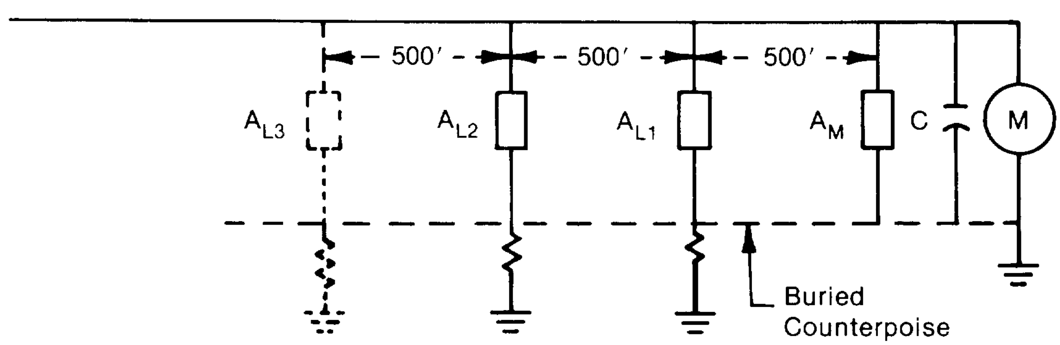


Fig. 17. Additional arresters provided for line used to provide inductance and not shielded.

The maximum permissible line arrester ground resistance with arresters spaced 500 ft (152 m) apart is shown in the following tabulation:

	Two Sets of Arresters	*Three Sets of Arresters*
Valve-Type Line Arrester	AL1 and AL2	AL1, AL2 and AL3
	5-10 ohms	10-20 ohms

If these values of ground resistance cannot be obtained, a buried counterpoise connecting all grounds together should be installed.

Where the lightning exposure is severe and grounding conditions are unfavorable and continued operation of the machine is important, the reliability of protection for Example 2 can be greatly improved by installing a shield wire grounded at every pole in addition to the line arrester and the machine grounds as shown in Figure 18.

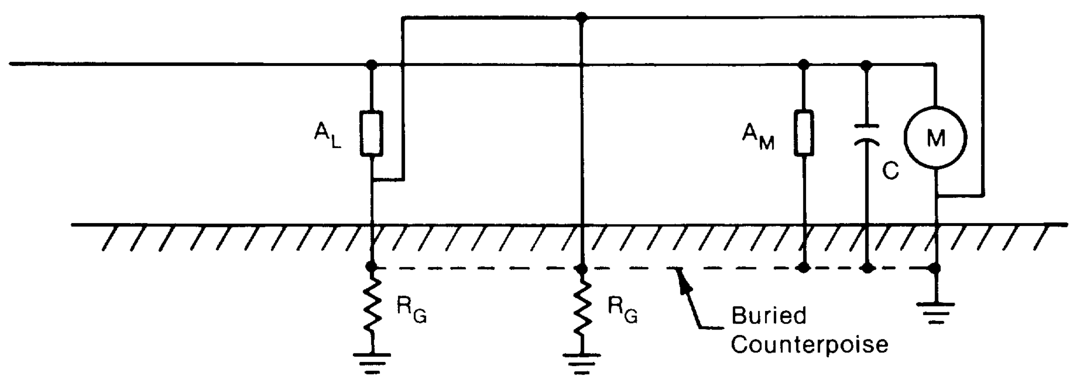


Fig. 18. Length of line used as inductance with overhead shielded wire.

The length of conductor between the line arrester A_L and the machine in Figure 18 should not be less than 500 feet (152.4 m) but it need not be more, and the overhead shield wire should be installed in accordance with the recommended practice. In general the shielding angle should not exceed 30 degrees. The insulation between the shield wire and down leads and the line conductors should be able to withstand 250,000 volts of 1-½ × 40 microsecond wave shape without flashover.

The basic lightning protective scheme for directly connected machines is shown in Figure 19. This scheme shows capacitors and arresters at the machine terminal, and in some cases at the neutral of the machine, and one or more arresters on the line. The phase conductors are also shielded by an overhead ground wire. The arresters AM and AN limit the magnitude of the surge voltage to a value less than the machine's conductor-to-ground insulation strength. The rate of rise of the surge voltage at the machine terminals is also decreased by the arrester A_L, which discharges the majority of the surge current and limits the voltage applied to the inductance of the transmission line at the capacitor C. Since the value of C and the rating and characteristics of A_L are fixed, it is only necessary to determine the minumum separation D in order to obtain sufficient inductance.

The protection required for surge-grounded neutral machines and for ungrounded neutral machines up to and including 6900 volts that are directly connected to exposed overhead lines is shown in Figure 20. Terminal protection is required on each phase.

For machines rated at 11.5 kV and above metallically connected to exposed overhead lines and not effectively grounded, the recommended protection is shown in Figure 21. Terminal protection is required on each phase.

Table 15 shows protection levels of station-type arresters of one manufacturer for the protection of rotating ac machines. These are recommended for large important machines. For smaller machines the distribution type may be used if the higher cost of the station type is not warranted.

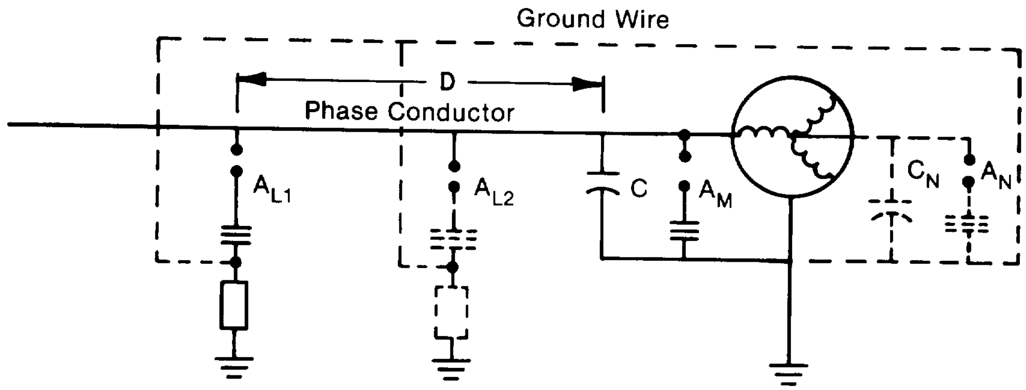
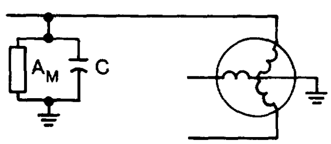


Fig. 19. Basic scheme for providing lightning protection for machines directly connected to overhead lines.



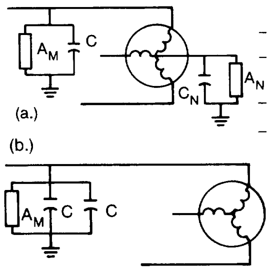
*The neutral is considered grounded as far as effects on the reflected voltage are concerned if the impedance between neutral and ground does not exceed 50 ohms of resistance of 0.2 ohm of 60-cycle reactance per 100 ohms of winding surge impedance. Minimum surge impedance may be considered 100 ohms unless actual value is known. This grounding is from standpoint of surge reflection only and does not necessarily determine whether the system is or is not effectively grounded for the purpose of selecting a voltage rating for the arrester.

Machine Voltage Class	*Capacitor C Rating*		*Machine Arrester A_M Rating Kv Rms*	
			System Neutral Grounded	
	Microfarad	*Kv Rms*	*Effectively*	*Not Effectively*
For Grounded and Ungrounded Machines				
650	1.0	0.65	0.65	0.65
2400	0.5	2.4	3.0	3.0
4160	0.5	4.16	3.0	4.5
4800	0.5	4.8	4.5	6.0
6900	0.5	6.9	6.0	7.5
For Grounded* Machines (for Ungrounded* 11.5 and 13.8 Kv Machines, see Figure 20).				
11500	0.25	11.5	9.0	12.0
13800	0.25	13.8	12.0	15.0

Fig. 20. Protection for surge-grounded neutral machines and ungrounded neutral machines to 6900 volts.

If the machine is not surge grounded at the neutral, then arresters and surge capacitors should be installed at the neutral or double surge capacitors at the line terminals. (See Fig. 21, Sketch b)

The information in Table 15 is primarily for motors and generators with multiturn windings. In the past, large generators with single-turn coils in the stator windings and unit connected to delta-wye step-up transformers properly protected with arresters and effectively shielded from direct lightning strokes were considered as adequately protected. Experience has shown that the generator can be damaged by positive and negative surges arriving simultaneously on two phases, ineffective shielding, failure of the high side protective equipment, and accidental interconnection between the high-side and low-side transformer windings due to internal failure. Accordingly, the present practice is to recommend the installation of surge arresters at the terminals of the machine. Capacitors are not required where the generator has single turn coils.



Machine Voltage Class	*Terminal Equipment*			*Neutral Equipment*		
	Capacitor C Rating		*Arrester A_M Rating*	*Capacitor C_N Rating*		*Arrester A_N Rating*
	Microfarad	*Kv Rms*	*Kv Rms*	*Microfarad*	*Kv Rms*	*Kv Rms*
If System is Not Effectively Grounded from Arrester Standpoint — Figure (a)						
11500	0.25	11.5	12	0.5*	6.9	7.5
13800	0.25	13.8	15	0.25	11.5	9.0
Or as in Figure (b)						
11500	2×0.25	11.5	12	. . .	. . .	. . .
13800	2×0.25	13.8	15	. . .	. . .	. . .
If System is Effectively Grounded from Arrester Standpoint — Figure (a)						
11500	0.25	11.5	9	0.5*	6.9	7.5
13800	0.25	13.8	12	0.25	11.5	9.0
Or as in Figure (b)						
11500	2×0.25	11.59	9	. . .	. . .	. . .
13800	2×0.25	13.8	12	. . .	. . .	. . .

*0.25 microfarad would be sufficient, but standard 6.9 kv capacitor is 0.5 microfarad.

Fig. 21. Protection for machines rated at 11.5 kV and above, metallically connected to overhead lines, not effectively grounded.

Table 15. Protection Levels of Station-Type Arresters Designed for Machine Protection

Lightning Arrester				*Rotating Ac Machine*					
Rating kv Rms	*Maximum Impulse Sparkover kv Crest†*	*Maximum Discharge Voltage kv Crest‡*		*Machine Circuit Neutral Grounding Effectively Grounded*			*Not Effectively Grounded*		
		1500 Amperes	*5000 Amperes*	*Voltage Class*	*Standard 60 Hertz Sparkover*	*Impulse Withstand Strength kv Crest*	*Voltage Class*	*Standard 60 Hertz Sparkover*	*Impulse Withstand Strength kv Crest*
650 Volts*	3	3	3.5	650	3.3	4	650	3.3	4
3	9.5	8	9.5	2400	8.2	10	2400	8.2	10
3	9.5	8	9.5	4160	13.2	16	—	—	—
4.5	14.5	12	14	4800	15.0	19	4160	13.2	16
6	19	16	19	6900	20.9	21	4800	15.0	19
7.5	24	20	23	—	—	—	6900	20.9	21
9	28	24	28	11500	33.9	42	—	—	—
12	37	32	37	13800	40.5	50	11500	33.9	42
15	46	40	47	—	—	—	13800	40.5	50
16.5	51	44	51	Machine voltages in these ratings are not standardized. Large generators usually have impedance grounded neutral.			14400	42.1	53
18	55	48	56				16500	48.0	60
19.5	60	52	61				18000	52.3	65
21	64	56	65				20000	57.9	72
24	76	67	78				24000	69.2	86

* Standard 3-phase secondary-type valve arrester.

† Sparkover on test wave rising to sparkover voltage in 10 microseconds.

‡ Crest voltage across arrester during discharge of a 1500-ampere or a 5000-ampere 8 × 20 micro-second current.

C.8.4.9 Insulation Coordination

Insulation coordination is the process of correlating the insulation withstand level with expected overvoltages and with the protective characteristics of surge protective devices.

The ‘‘three point method’’ of insulation coordination as described in the following text is in accordance with ANSI-C62.2-1981 and the tutorial course on Surge Protection in Power Systems, Course Text 79EH0144-6-PWR developed by the IEEE - Surge Protection Committee of the IEE Power Engineering Society. This method makes use of the ratios of insulation withstand to arrester protective levels for 1) front-of-wave, 2) full wave, and 3) switching surge ranges. In addition, the effect of the length of the leads (‘‘separation effect’’ [SE]), if significant, separating the arrester from the protected equipment is evaluated.

Significant separation occurs where the crest of the voltage of the protected insulation exceeds the arrester protective level sufficiently to reduce protective margins or ratios to unacceptable levels and must be taken into consideration.

In this method the basic assumption is made that the insulation will be protected over the entire range of lightning and switching impulses that can occur in service, provided the margin is adequate at the three points.

There are five standard protective ratios (PR) and protective margins (PM) which are identified as follows:

1. Where separation is not significant.

a) PR(1)=CWW/FOW PM(1)=[PR(1)-1]100
b) PR(2)=BIL/LPL PM(2)=[PR(2)-1]100
c) PR(3)=BSL/SSP PM(3)=[PR(3)-1]100

2. Where there is significant separation.* (See Note below)

d) PR(1S)=CWW/E_1 PM(1S)=[PR(1S)-1]100
e) PR(2S)=BIL/E_1 PM(2S)=[PR(2S)-1]100
f) PR(3)=BSL/SSP PM(3S)=[PR(3)-1]100

*Separation effects are significant when they result in a PR that is less than 1.15. Table 16 gives the maximum separation that may be used without violating the 1.15 minimum limit for PR(1S) as shown in the following tabulation:

PR Limits For Coordination.

PR(1)≥1.2 PR(1S)≥1.15
PR(2)≥1.2 PR(2S)≥1.15
PR(3)≥1.15 PR(3)≥1.15

Table 16. Maximum Allowable Separation

	*Number of Lines**							
	1		*2*		*3*		*4*	
	Allowable Separation, D†							
PR(1)‡	*(feet)*	*(meters)*	*(feet)*	*(meters)*	*(feet)*	*(meters)*	*(feet)*	*(meters)*
1.2	*10*	*3*	*14*	*4. 3*	*18*	*5. 5*	*22*	*6. 7*
1.4	*14*	*4.3*	*20*	*6. 1*	*26*	*7. 9*	*32*	*9. 8*
1.6	*20*	*6.1*	*29*	*8. 8*	*39*	*12*	*50*	*15*
1.8	*30*	*9.1*	*46*	*14*	*64*	*20*	*84*	*26*
1.9	*37*	*11. 3*	*61*	*19*	*88*	*27*	*118*	*40*
2.0	*49*	*14. 9*	*84*	*26*	*130*	*40*	*187*	*60*
2.1	*68*	*20. 7*	*132*	*40*	*234*	*71*	*397*	*121*

* After Rules 2 and 3 have been applied.

† D = arrester lead length L + transformer lead length S (where L and S are measured from their junction with the path of the incoming surge).

‡ This table is based on the use of CWW = 1.15 BIL. If surge front is reduced by the multiple-line effect (see Rule 5, C3.2) such that sparkover occurs after 2 µs, the table should not be used.

Note: Table separations are calculated using an incoming surge with a rate of rise of 8.33 crest kV/µs/kV (rms) of arrester rating.

PM Limits For Coordination.

PM(1)≥20	PM(1S)≥15
PM(2)≥20	PM(2S)≥15
PM(3)≥15	PM(3)≥15

C.8.4.10 Satisfactory Coordination

Insulation coordination is considered to be satisfactory when all the criteria for PR limits and PM limits for coordination (which are applicable) as shown above are fulfilled.

C.8.4.10.1 Curve Method of Evaluation Insulation Coordination

Insulation coordination may also be evaluated by the ‘‘curve method’’ which compares insulation withstands with arrester protective levels graphically as described in Part VI of the Examples.

The separation effect (SE) is a function of the rate of rise and magnitude of the incoming surge voltage and the distance between the arrester and the equipment.

In some multiline, two-transformer bank stations, adequate protection can be provided by one arrester set. A reduction process is used to describe an equivalent base case which can then be evaluated as follows.

The base case, as illustrated in Figure 22, consists of a single supply line to a junction point C from which a lead L extends to the arrester and a lead S goes to the transformer.

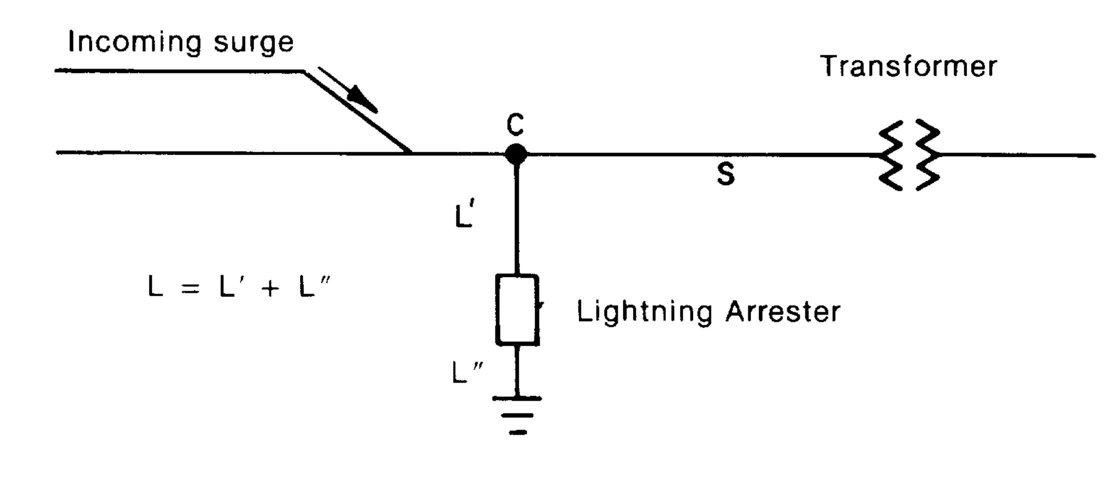


Fig. 22. Base case for separate calculations.

The multi-line two-transformer stations shown in Figure 23 may be reduced to an equivalent base case by application of the following rules;

Rule 1. Remove the transformer that is not being considered.

Rule 2.

a) Identify junction c, the common point between transformer lead (S), arrester lead (L), and the line assumed to have an incoming surge.

b) Identify S as the bus connection between junction C and the transformer.

c) Identify L as the connection between junction C and the surge arrester.

Rule 3. Identify junction t, the common point between the surged line, bus connection to transformer 1, and bus connection to transformer 2. Note that t and C may be the same point. Also that t does not exist in a single-transformer station.

A Class A connection has junction t either coincindent with C or on the line side of C.

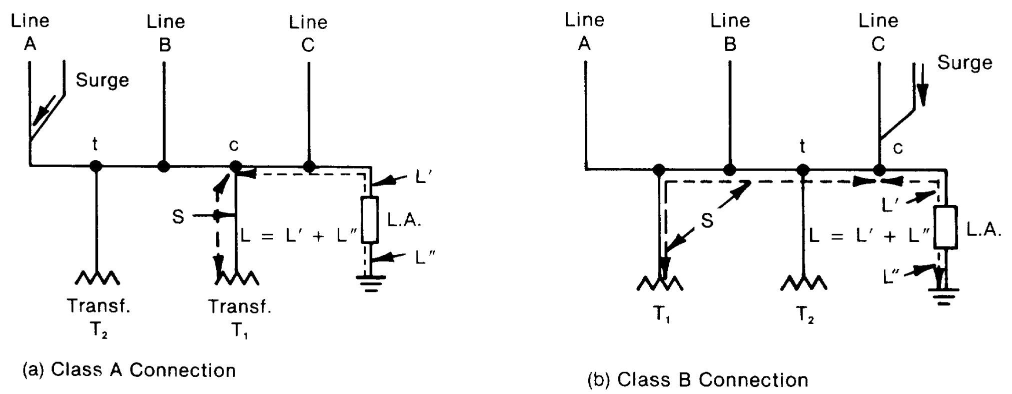


Fig. 23. Multi-line, two-transformer station.

A Class B connection has a junction C on the line side of t.

Rule 4. Increase the calculated value of separation effect α by 5% where α Class B connection is used.

Rule 5. Remove all lines connected between junction C and the arrester terminal.

Referring to Figure 23a, note that one line is connected to L between C and the arrester. The effect of such lines is to adversely affect the voltage at the transformer having the longest lead from point C, which results in increasing the separation effect.

Rule 6. Multiply the rate of rise of the incoming surge by 3/(n + 2) where n is the number of lines including the surged line which remain after applying Rule 5.

The rate of rise $R_f = \dfrac{3R_f}{n + 2,}$

Where R_f is the rate of rise of the incoming surge in kV/microsecond. (Use the standard FOW sparkover test rate of rise.) R_f is the equivalent rate of rise of incoming surge in kV/microsecond at protected equipment depending upon the number of lines.

To determine the electrical surge separation distance, the distance D from the arrester ground to the protected equipment is defined as follows:

D = S + L (Fig. 22)

Where S = the combined length of bus and jumper connections between junction C and the protected equipment terminals.

L = The combined length of bus and jumper connections between junction C and the arrester ground.

The physical distance D and the rate of rise of the surge R_f and the velocity V and the protective level of the arrester E_f is used to determine the electrical surge distance from the protected equipment as follows:

$D = D(R_f/E_f/V)$

where D = S + L in feet.
R_f = Rate-of-rise of incoming front, kV/µsec.
E_f = Arrester front of wave sparkover in kV.
V = Traveling wave velocity (1000 ft/µsec for conductors in air, 600 ft/µsec in cable).

The separation effect constant α is defined as follows:

where $\alpha = E_i/E_f$
α = Separation effect constant.
E_i = Voltage at protected equipment.

The separation effect constant α can also be shown to be equal to the equation of the following curve (Fig. 24.):

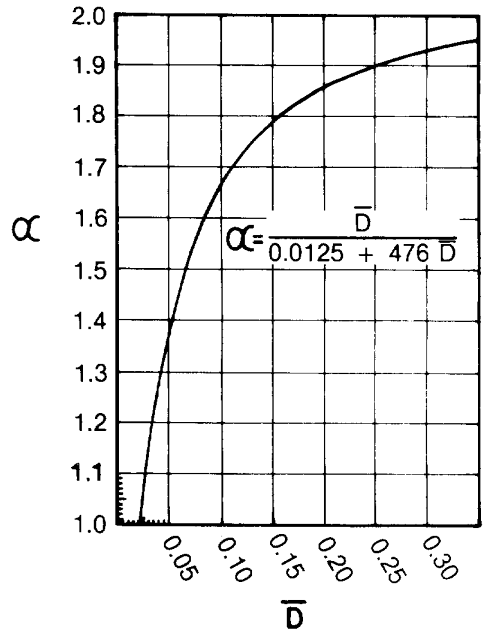


Fig. 24. Curve for determining a = $\frac{\text{Voltage at Transformer}}{\text{Voltage at Arrester.}}$

$$\alpha = \frac{\overline{D}}{0.0125 + 476D}$$

If the separation distance D does not exceed the values in Table 16, then separation effects need not be considered when PR(1) and PR(2) are met.

The rates of rise in switching surges are quite low compared to lightning surges, and separation effects are correspondingly low. Therefore separation effects can be ignored when checking BSL, SPL coordination.

In applying the 3-point method of insulation coordination as described above, for specific values of front of wave sparkover (FOW), chopped wave withstand (CWW) and arrester protective levels needed to calculate the several protective ratios, it is best to procure this information from the arrester manufacturer's literature as shown in Table 9. This information is from one specific manufacturer and may vary for other manufacturers.

For proper insulation coordination, the protective ratios (a), (b), (c) or (d), and (e), as applicable must be satisfied. For example:

1. Lightning front of wave coordination Point PR(1) calculated from $\frac{CWW}{FOW}$ must be equal to or exceed 1.2.

2. Lightning full wave coordination Point PR(2) calculated from $\frac{BIL}{LPL}$ must be equal to or greater than 1.2 and

3. The switching surge coordination Point PR(3) calculated from $\frac{\text{BSL}}{\text{SSP}}$ must be equal to or greater than 1.15.

In achieving coordination it is possible that the first arrester selected has protective levels that will not coordinate with the desired insulation withstand levels. When this occurs other alternatives must be considered such as: 1) an arrester with a lower lightning or switching surge protective level involving a different class, design or voltage rating; 2) changing the arrester location to reduce the separation distance S, or arrester lead length L or both; 3) increasing the insulation level of the equipment to be protected; 4) improving the shielding; 5) installing additional arresters at a different point in the station.

In lieu of the availability of specific information, the following approximate factors can be used to estimate the withstand voltages of mineral-oil-immersed equipment. For insulation coordination the front-of-wave factor should be checked with the equipment manufacturer.

Table 17. Factors for Estimating Withstand Voltages of Mineral-Oil-Immersed Equipment

Impulse Duration	*Withstand Voltage*	*Equipment*
Front of wave*	1.3 to 1.5 × BIL	Transformers.
(0.5 µs)*		Reactors.
Chopped wave	1.29 × BIL	Breakers,
(2 µs)*		15.5 kV and above.
Chopped wave*	1.1 to 1.15 × BIL	Transformers.
(3 µs)*		Reactors.
	1.15 × BIL	Breakers,
		1.15 kV and above.
Switching surge	0.83 × BIL	Transforme
(100 × (†) µs)		rs. Reactors.
Switching surge	0.63 to 0.69 × BIL	Breakers,
(250 × 250 µs)		362-800 kV‡.

* Time to chop.

† Time above 90% of crest ≥ 200 µs. Time to first voltage zero ≥ 1000 µs.

‡ Includes air blast and SF_6 breakers.

C.9 Protection of Distribution Systems

Distribution lines are generally not shielded and consequently are particularly susceptible to direct lightning strokes. Transient overvoltages resulting from lightning are also of greater concern than those due to switching of distribution systems. Accordingly, insulation coordination in distribution systems is of major importance, based on lightning surge voltages and current discharge voltages.

The basic principles of arrester selection and application as previously discussed also apply to distribution arresters, but there are specific differences in the application of valve-type surge arresters for the protection of distribution lines and equipment which must be considered and are described in the following text. Protective levels and durability characteristics of distribution arresters that comply with ANSI/IEEE specifications are shown in Table 18. Tables 19 and 20 show other data on protective characteristics of available distribution and secondary arresters compiled from domestic manufacturers' catalogs which can be used in general insulation coordination studies if specific data on surge arrester is not available. For accurate insulation coordination specific information from the manufacturer of the particular arrester being employed should be obtained.

Table 18. Valve-Type Distribution Arrester Characteristics

		*Protective Levels Per-Unit Crest Arrester Rating**			*Durability Characteristics†*		
					(1)	*(2)*	*(3)*
Rating (kV)	*Range of Application Maximum System Voltage (kV)*	*Front-of-Wave without External Gap (kV)*	*Sparkover with External Gap (kV)*	*Discharge with 10 kA. 8 × 20-µs Wave*	*Duty Cycle Initiating Surge (crest amperes)*	*Low-Current Long-Duration Withstand (crest amperes) (µs)*	*High-Current Withstand (crest amperes)*
3	2.6-4.5	3.30-5.89	5.66-8.01	2.71-3.25	5000	75 2000	65 000
6	4.5-7.8	3.18-4.12	5.30-6.13	2.65-3.06	5000	75 2000	65 000
9-12	7.8-14.3	2.83-3.77	4.30-5.34	2.55-3.22	5000	75 2000	65 000
15-21	18-25.8	2.32-3.54	3.87-4.56	2.49-3.09	5000	75 2000	65 000
25-30	38	2.07-3.54		2.36-2.59	5000	75 2000	65 000

* The per-unit values shown are maximum industry values. For specific values, consult manufacturers' literature.

† This refers to the ability of the arrester to protect itself against the stresses resulting from:
(1) Cumulative power-follow current and surge discharge operations (which also determine the ability to reseal against a voltage equal to the arrester rating).
(2) Long-duration lightning.
(3) Severe lightning discharges.

NOTE: Protective level (kV) = per-unit level × rating × $\sqrt{2}$. For example, range of FOW sparkover for a 12-kV arrester is (2.83 to 3.77) × 12 $\sqrt{2}$ = 48 to 64 kV.

Table 19. Protective Characteristics of Distribution Valve Arresters

Voltage Rating of Arrester	*Impulse Sparkover Voltage*					*Discharge Voltage for 8 × 20-µs Discharge Current Wave*				
	Front-of-Wave			*1.2 × 50-µs*						
	Rate of Rise of Test Voltage (kV/µs)	*Without External Gap*	*With External Gap*	*Without External Gap*	*With External Gap*					
		kV Crest (Range of Maxima)	*kV Crest (Range of Maxima)*	*kV Crest (Range of Maxima)*	*kV Crest (Range of Maxima)*	*kV Crest for 1500 A (Range of Maxima)*	*kV Crest for 3000 A (Range of Maxima)*	*kV Crest for 5000 A (Range of Maxima)*	*kV Crest for 10 000 A (Range of Maxima)*	*kV Crest for 20 000 A (Range of Maxima)*
3	25	14-25	24-34	12-22	24-30.5	8-10	8.4-11.5	10-12.4	11.5-13.8	12.5-15.7
6	50	27-35	45-52	23-30	35-47	16-20	17-23	20-24	22.5-26	25-30
9	75	39-48	60-68	34-45	48-65	24-30	25-34	29-36.5	32.5-41	36-46
10	83.3	40-48	62-68	35-49	48-67	25-30	27.5-34	29.5-37	32.5-44	36-52
12	100	49-60	73-82	44-54	59-79	32-40	34-46	29.5-48	43-53	49-61.5
15	125	53-75	84-95	49-63	69-92	40-50	42-55	39-60	54-65.5	60-76
18	150	61-90	99-116	58-75	79-110	48-60	52-66	46-72	65-78	71-91
21	175	69-90	115-125	66-75	—	56-70	59-75	68-80.5	74-90	82-103
27	225	83-98	—	75-98	—	70-80	76-86	82-89	90-96	99-107
30	250	88-95	—	81-88	—	76-89	84-97	91-101	100-110	111-124

Table 20. Protective Characteristics of Secondary Valve Arresters

	Impulse Sparkover Voltage			*Discharge Voltage for 8 × 20-µs Discharge Current Wave*	
	Front-of-wave	*1.2 × 50-µs*			
Voltage Rating of Arrester	*Rate of Rise of Test Voltage (kV/µs)*	*kV Crest (Range of Maxima)*	*kV Crest (Range of Maxima)*	*kV Crest for 1500 A (Range of Maxima)*	*kV Crest for 5000 A (Range of Maxima)*
0.175	10	2.3-3.0	2.1-2.5	1.0-1.5	1.4-1.8
0.650	10	2.9-3.8	2.5-3.5	2.2-3.8	2.9-5.0

On 15-kV systems insulation coordination for equipment connected to overhead lines has been more or less neglected because the protective margin (PM) between the standard equipment basic lightning impulse insulation level (BIL) and the protective characteristics of modern distribution arresters is usually substantially more than 20%. However, on distribution systems rated at 25 kV and higher, insulation coordination is quite important especially where reduced BIL values are used for line protection and for protection of underground distribution systems.

The following arrester applications require special consideration with respect to duty requirements to which the arrester is subjected or in regard to protection requirements: 1) protection of shunt capacitor banks, 2) protection of switches, reclosers, etc., 3) protection of voltage regulators, 4) protection of underground circuits; and 5) exposure to contaminated atmospheres.

C.9.1 Selection of Arrester Rating

Voltage ratings of the arresters that are commonly applied to the different types of distribution systems, 1) delta connected, 2) three-wire wye unigrounded at the source and 3) four-wire multigrounded wye, are shown in Table 21. The type of construction of these systems include open wire, spacer cable, and underground.

For delta systems the arrester rating should be equal to or greater than the maximum phase-to-phase voltage.

For three-wire unigrounded wye systems (grounded at the source only), instead of calculating the phase-to-ground voltages during single line-to-ground faults, it is usually acceptable to employ an arrester rating at least equal to 80% of the maximum phase-to-phase voltage with no fault on the system. When the unigrounded system is grounded through an impedance, the 80% rule is usually not applicable and the voltage on the unfaulted phases must be calculated to determine the arrester rating.

If it is possible on a system where a phase has been interrupted to back feed through part of the circuit through devices such as transformers or capacitors, the arrester should be at least equal to the phase-to-phase voltage.

For four-wire multigrounded-wye systems (including spacer-cable circuits) which have been commonly employed for many years, the arrester ratings used have been established by long experience. The higher voltage distribution systems being installed on the spacer-cable circuits do not have the benefit of this long experience. For these systems the following method for establishing the arrester ratings was developed:

Table 21. Commonly Applied Voltage Ratings of Arresters on Distribution Systems

System Voltage (kilovolts rms)		*Usually Applied Arrester Ratings (kilovolts rms)*			
Nominal Voltage	*Maximum Voltage Range B**	*Four-Wire Multigrounded Neutral Wye*	*Three-Wire Unigrounded Neutral Wye*	*Delta and Ungrounded Wye*	*Spacer-Cable Circuits†*
2400	2540			3	
4160Y/2400	4400Y/2540	3	6		3
4160	4400			6	
4800	5080			6	
6900	7260			9 or 9/10	
8320Y/4800	8800Y/5080	6	9 or 9/10		6
12 000Y6930	12 700Y/7330	9 or 9/10	9/10 or 10		9/10 or 10
12 470Y/7200	13 200Y/7620	9 or 9/10	12		9/10 or 10
13 200Y/7620	13 970Y/8070	9/10 or 10	12		9/10 or 10
13 800Y/7970	14 520Y/8380	9/10, 10, or 12	12		12
13 800	14 520			15	
20 780Y/12 000	22 000Y/12 700	15	18		18
22 860Y/13 200	24 200Y/13 970	18	21		21
23 000	24 340			25	
24 940Y/14 400	26 400Y/15 240	18	21		21
34 500Y/19 920	36 510Y/2180	25 or 27	30		30
34 500	36 510			36‡ or 37‡	

* See ANSI C84.1-1977 and ANSI C84.1a-1980.

† The use of spacer cables at most system voltages has had limited application, reducing the experience factor in establishing arrester ratings usually applied. Where experience is a factor, arrester ratings lower than 1.5 × nominal system line-to-ground voltage [31] have been used. This is taken into account for the voltage ratings listed.

‡ Nonstandard distribution arrester voltage ratings.

1. For four-wire multi-grounded-wye open wire circuits the nominal phase-to-ground voltage of the system is multiplied by 1.25.

2. For spacer-cable circuits the nominal phase-to-ground voltage of the system is multiplied by 1.50. For open-wire systems having operating voltages not listed in Table 21, the 1.25 factor should be used to determine the arrester rating and the 1.5 factor for spacer-cable circuits.

C.9.2 Insulation Coordination

Insulation coordination for distribution system is based on the following protection margins:

PM(1) = (CWW/FOW – 1)100

PM(2) = (BIL/IR – 1)100

CWW = 1.15 × BIL for oil-filled, air, and inorganic insulation.

CWW = BIL for dry-type (organic) insulation.

In general PM(1) and PM(2) should both be at least 20%, but PM(1) can usually be neglected when distribution arresters are connected directly across overhead equipment insulation and separation effects (SE) are minimized. However, when arresters are used for line protection, underground systems protection, or drytype insulation protection, PM(1) must be considered. A PM(1) of at least 20% should be provided for drytype insulation. To calculate PM(2), it is recommended practice to select a value of discharge current that will be exceeded infrequently so that the discharge voltage at this reference level for a specific arrester will result in a smaller PM(2). There is no surge current level that is generally accepted on which to base insulation coordination, but currents in the 10kA to 20kA range are frequently used. Table 20 shows the discharge voltages at currents up to 20kA. The arrester discharge voltage values for higher currents may be obtained from the manufacturer.

C.9.3 Arrester Lead Wires

When protecting underground systems, it is especially important to keep the lead wires connecting the arrester as short as possible. PM(2) does not include an allowance for the voltage developed across these wires. For insulation coordination it is necessary that the arrester discharge voltage characteristic include the arrester discharge voltage plus the connecting lead wire voltage. When lightning currents are discharged through the inductance of the lead wires, a voltage is produced that must be added to the arrester discharge voltage.

It is common practice to have the voltage produced in the lead wire of 1.6 kV per foot of lead wire. The length of the lead wire is measured from the point at which the arrester line connection is made to the line to the point at which interconnection is made to the protected equipment ground, less the length of the arrester.

C.9.4 Arrester Clearances

Distribution arresters should be installed with at least the clearances to energized conductors and equipment and to grounds as shown in Table 22. These clearances are also suitable for arresters in metal enclosures.

Table 22. Recommended Minimum Clearances

Arrester Voltage Rating kV rms	*Surge Arrester BIL, kV Crest**	*Recommended Minimum Clearances Inches (Millimeters)†*	
		To Ground(s)	*Between Phases*
3	45	1-¾(45)	2 (51)
6	60	2-¾ (70)	3-¼ (83)
9	75	4 (102)	4-¾ (121)
10	75	4 (102)	4-¾ (121)
12	85	4-¾ (121)	5-½ (140)
15	95	5-½ (140)	6-¾ (171)
18	125	8 (203)	9 (229)
21	125	8 (203)	9 (229)
25	(150)*	9-½ (241)	11 (279)
27	150	9-½ (241)	11 (279)
30	150	9-½ (241)	11 (279)

* 1.2 × 50-µs full-wave BIL per Table 4 in ANSI/IEEE C62.1-1981; the value shown for 25-kV rating has not been standardized.

† Clearances measured from metal parts of arrester line terminal and dictated by minimum flashover to maintain BIL in accordance with ANSI/IEEE C62.1-1981 and to allow for the bias effect of 60-Hz voltage between adjacent phases. Air insulation between arrester and wall(s) or between arresters is assumed. Minimum clearance required between bottom stud on arrester and enclosure floor need be only that required to install ground connection and to provide sufficient space for free operation of the disconnector if used.

C.9.5 Protection of Capacitor Banks

Pole-mounted shunt capacitor banks are usually protected by arresters connected line to ground at the bank or close to it, and the ratings are the same as used elsewhere on the system. On systems where the capacitors are connected grounded-wye, they can be charged to high voltages by lightning currents and should be able to handle a high-energy discharge. Where the capacitor banks are undergrounded, only minor surge discharge duty is required by the operating arresters.

C.9.6 Protection of Switches, Reclosers, etc.

Switches operated at the open position should be protected by arresters on both sides of the switch. Reclosers should be protected by installing arresters on both the source and load sides. For the type of recloser that is constructed with a built-in bypass protector across the series coil, a fair degree of protection is obtained with only one arrester installed from line to ground on the source side. This assumes in normal operation the recloser is in the closed position, but if it is open for any reason there is a possiblity of lightning damage.

C.9.7 Protection of Series Windings

Voltage Regulators connected to exposed circuits are best protected by installing distribution arresters at or near the source and load side terminals, and the arrester ground interconnected to the regulator tanks.

Series Current-Limiting Reactors. An arrester connected from terminal to terminal will prevent over-voltages due to incoming surges unless there is a built-in shunt resistor. An arrester should also be installed on the line side of the reactor and connected between line and ground. The manufacturer should be consulted in all cases.

Autotransformers. Where the voltage across the series windings is less than 25% of the voltage across the common winding, serious overvoltages due to lightning surges are usually controlled by a gap or arrester supplied by the manufacturer. For other applications adequate protection will be afforded by arresters installed at the high-voltage and low-voltage terminals and interconnected to the transformer tank.

C.9.8 Protection of Equipment on Underground Systems

The difficulties associated with providing adequate protection for underground systems arise mostly from being unable, from a physical standpoint, to install the arresters close to terminating points or points where there is a substantial change in surge impedance. Otherwise, the application of arresters is similar to the procedures followed for protecting overhead equipment.

When arresters cannot be installed at individual equipment locations in the underground system, they are located at the junction of the overhead line conductors and the underground cable. Recently, consideration has been given to installing arresters on underground transformers on systems rated at 15 kV and above in order to provide larger protective margins for the transformers. The voltages that propagate into the underground cable after sparkover of the arrester at the riser pole is the sum of the arrester sparkover voltage plus the inductive voltage drop in the arrester connecting leads. These voltages as they propagate in the cable may double their value due to reflections at open switches, terminating transformers, and similar points where there is a change in impedance.

For the determination of protective margins, the following rules should be used to calculate the voltages at terminating points.

1. Assume no attenuation. This is a conservative assumption for cables that exceed 300 feet (91.5 m) in length.

2. Assume incident voltages will double at open points and terminating transformers.

3. Use manufacturers' published values for front-of-wave sparkover and discharge voltage at 10 kA.

4. Calculate inductive voltage drop in arrester connecting leads based on 1.6 kV per foot.

5. Compare double front-of-wave sparkover voltage with chopped wave withstand for liquid-filled transformers and with BIL for dry-type transformers. Compare the doubled sum of discharge voltage, at assumed current, and connecting lead voltage with transformer BIL.

Then, using the recommended protective margin of 20%:

Oil: $CWW \geq 1.2 \times 2 \times FOW$

Dry: $BIL \geq 1.2 \times 2 \times FOW$

Both: $BIL \geq 1.2 \times 2 \times (IR + V_{lead\ wire})$

C.9.9 Contaminated Atmospheres

Failures of lightning arresters in contaminated atmospheres are rare but they may occur due to the combined effect of accumulations of contaminants on the arrester along with foggy conditions or light rain, frost, or wet snow. Preventive measures are periodic cleaning, and in some cases the application of nonconducting, non-tracking, water-repellant greases to the insulating surfaces of the arrester.

C.9.10 Example Calculations for Determining Adequacy of Surge Protection

The one-line diagram in Figure 25 shows the main supplies of a typical distribution system including a 10,000-kVA oil-insulated main substation transformer which supplies a 1500-kVA dry-type transformer.

Examples 1 and 2 illustrate the calculations needed as previously described in the text to determine the adequacy of the surge protection for these two units where the separation effect is not a factor.

Example 3 illustrates an installation where the separation effect must be considered in the calculations to determine if the surge protection is satisfactory.

Example No. 1 (Ref. ANSI Standard C62.2-1981, Section 3.7)

Determine adequacy of surge protection for main substation transformer (1.) in Figure 25.

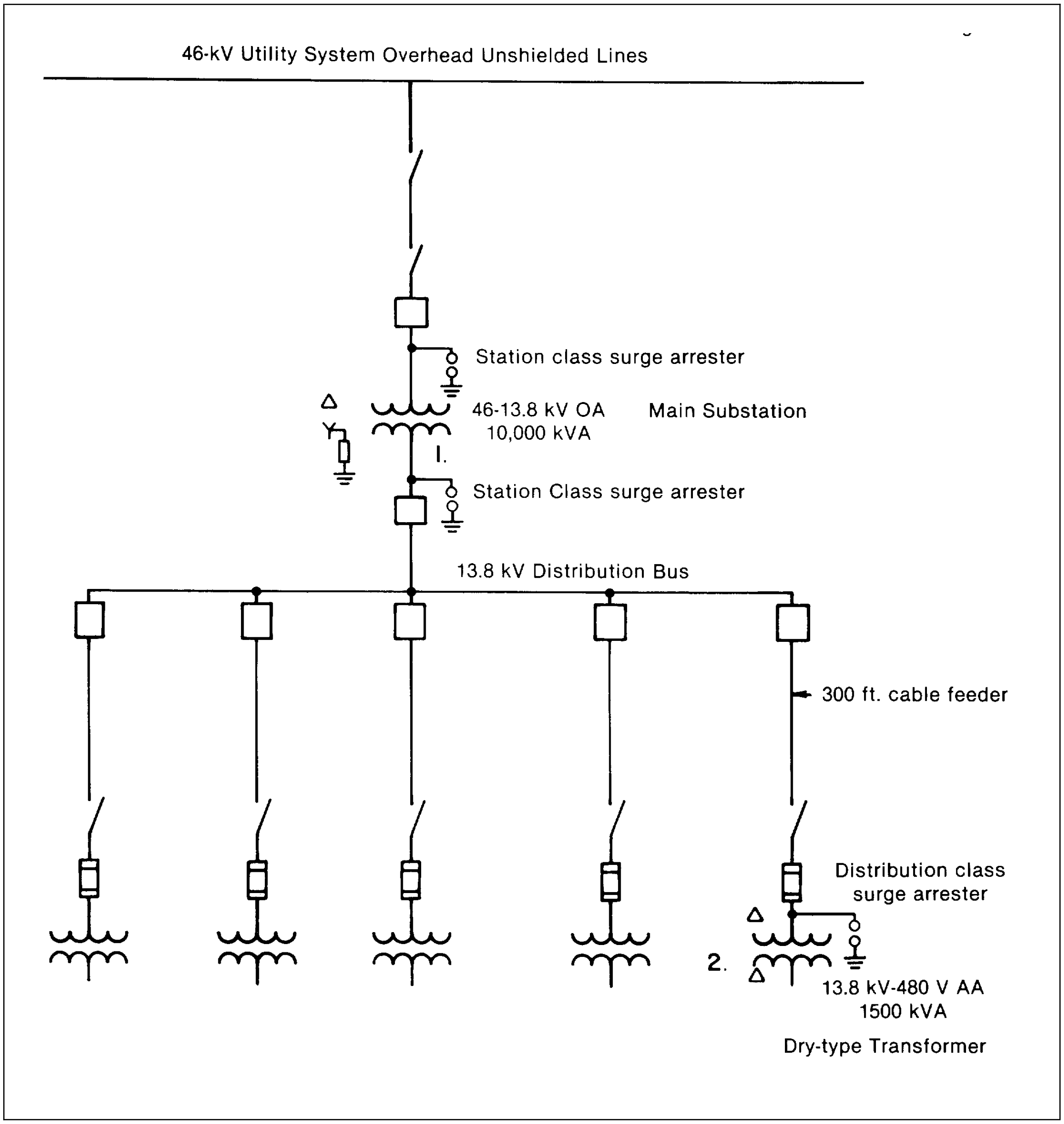


Fig. 25. Sample one-line diagram (partial) for examples 1 and 2. (for evaluation of adequacy of transformer surge protection using methods of ANSI/IEEE standard C62.2-1981).

Assumptions:

1. Transformer BIL is 250 kV (fully insulated), chopped wave withstand insulation level (CWW) is 290 kV. (See Table 9.)

2. Station class surge arresters are provided with 3 circuit feet of transformer primary bushings. Separation effect (α factor) is negligible.

3. Surge arresters are of the series-gapped, valve-type of modern manufacture.

4. The surge arrester ground terminal leads are connected directly to the transformer ground connection, minimizing effects of ground (earth) resistance on surge behavior of the arrester-transformer system.

5. The 46-kV utility system is effectively grounded at the substation.

$\left(\frac{R_o}{X_1} \leq 1 \text{ and } \frac{X_0}{X_1} \leq 3 \right)$, allowing use of 80% rated surge arresters.

Note: The values used for surge arrester characteristics in these calculations are chosen from a single manufacturer's tables. Characteristic values for surge arresters of other manufacturers or series may vary slightly from those used here.

Calculations:

$$PR(1) = \frac{CWW}{FOW} + \frac{290}{120} = 2.42$$

Limit from
ANSI C62.2-1981
1.2 (min)

Values used:
CWW = 290 kV
FOW = 120 kV
(39 kV Station Class surge arresters used)

$$PR(2) = \frac{BIL}{LPL} + \frac{250}{104} = 2.40$$

Limit from
ANSI C62.2-1981
1.2 (min)

LPL = The greater of 1.2 × 50 µs sparkover voltage - 104 kV BIL = 250 kV or lightning discharge voltage at selected current - 102 kV LPL = 104 kV, (assuming 20 kA discharge current)

Note: Switching surge protective margins PR(3) are not considered here, because experience has shown that switching surges are not troublesome at this voltage level.

Conclusions:

Since both PR(1) and PR(2) are larger than the limits specified in the referenced standard, surge protection is adequate.

Example No. 2 (Ref. ANSI Standard C62.2-1981, Section 3.9)

Determine adequacy of surge protection for 1500-kVA dry-type transformer (2) in Figure 25.

Assumptions:

1. Transformer BIL is 60 kV (standard BIL; see ANSI/IEEE Standard C57.12.01-1979 or Table 10).

2. Distribution class surge arresters of the low sparkover type are installed in the transformer enclosure, as close as is practical to the transformer primary connections.

3. The surge arresters are of the series-gapped, valve type of modern manufacture.

4. The surge arrester ground terminal leads are connected directly to the transformer ground connection, minimizing effects of ground (earth) resistance on surge behavior of the arrester-transformer system.

5. The 13.8-kV distribution system is not effectively grounded (low-resistance grounded scheme), requiring the use of fully-rated (15-kV) arresters.

Note: The values used for surge arrester characteristics in the following calculations are chosen from a single manufacturer's tables. Characteristic values for surge arresters of other manufacturers or series may vary slightly from those used here.

Calculations:

	Values used
Minimum BIL = 1.2 (FOW)	FOW = 56 kV (from
55.2 = 1.2 (46)	manufacturer's literature)

Conclusions:

The specified minimum BIL is 55 kV; the transformer's as-supplied BIL is 60 kV. Therefore, insulation coordination is satisfactory.

Note: This example uses the most favorable conditions to prove satisfactory insulation coordination. If the dry-type transformer was built with a lower BIL value, was connected to an exposed overhead line, or if different surge arresters were used, insulation coordination may not be achieved.

Example No. 3

I. Evaluation of Surge Protection (See Figs. 26 and 27.)

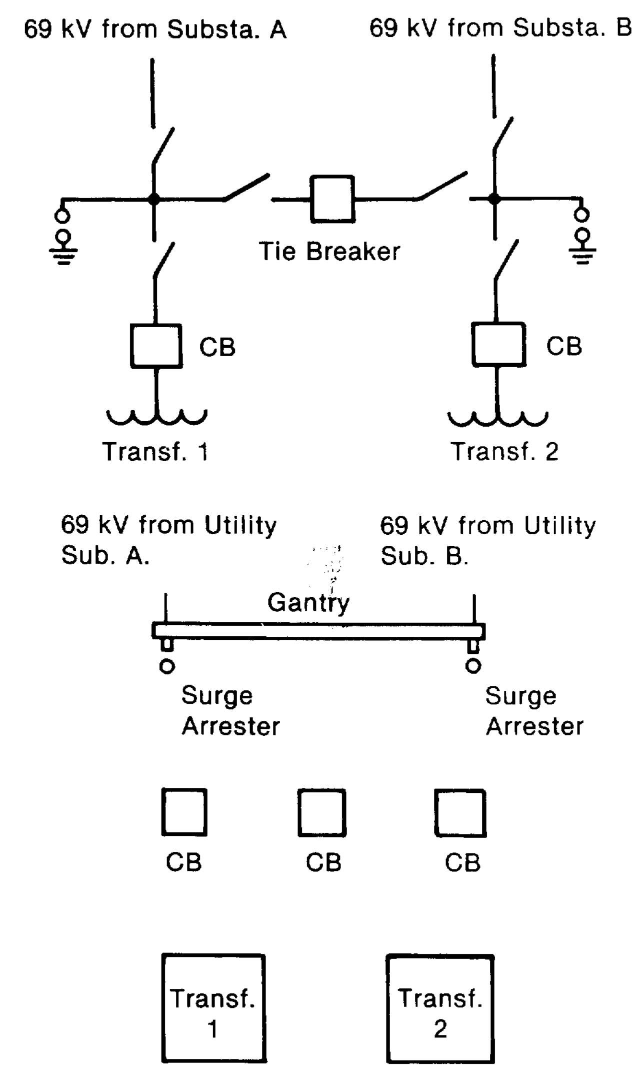
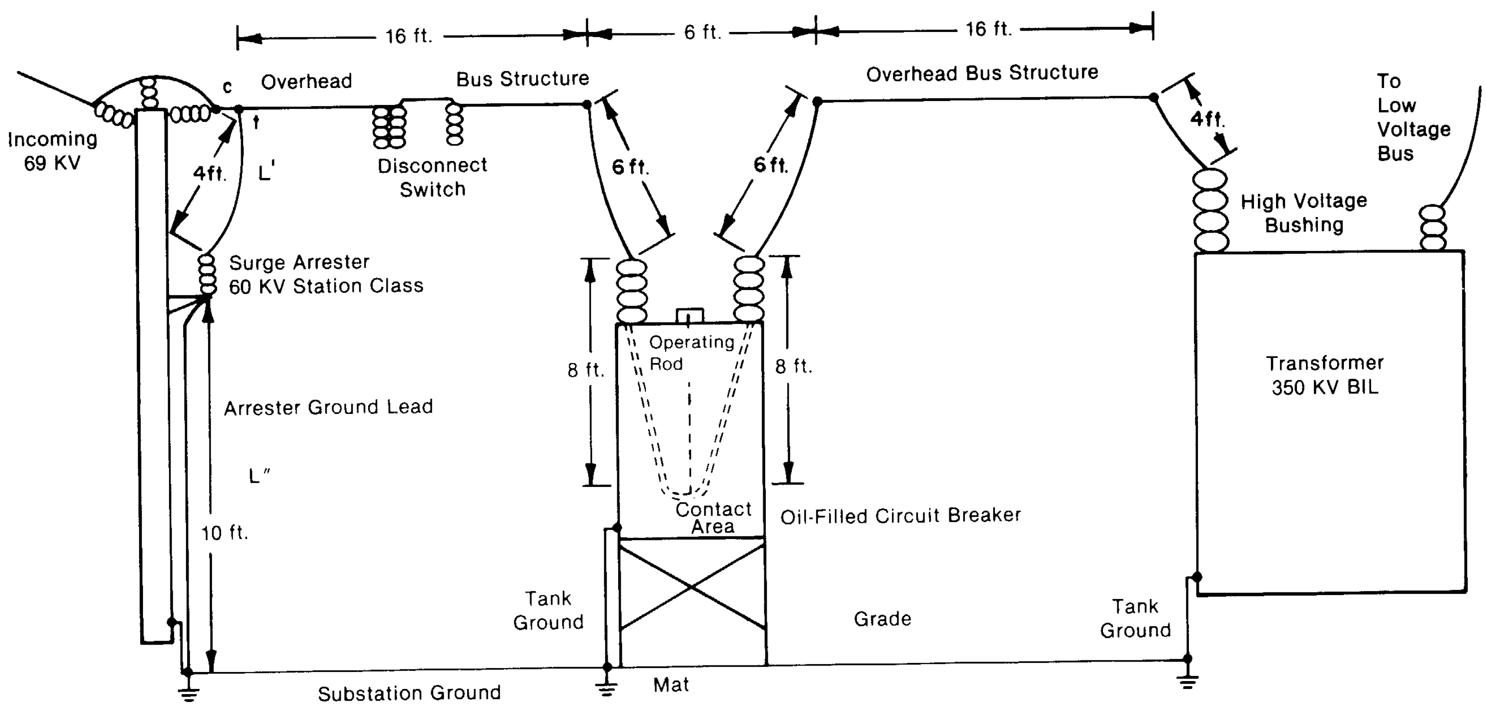


Fig. 26. Plan view and schematic of substation shown in Figure 27.



Note: Dimensions shown are for illustrative purposes only. Actual dimensions for evaluation of a specific case should be obtained from the as-built construction drawings.

Dimensions for Evaluation of Separation Effect:

L =

Circuit feet between arrester connection to surged line (L') and station ground mat (L″),excluding arrester length. L' equals 4 feet, L″ equals 10 ft. L = L' + L″ = 14 feet.

S =

Circuit feet between junction "c" and the protected equipment (transformer) terminals. S includes jumper lengths, the path length through the circuit breaker, and bus lengths. S equals 16 + 6 + 8 + 8 + 6 + 16 + 4 feet, or 64 feet.

D = L + S or 78 feet.

Fig. 27. Sectional view of substation shown in Figure 26.

Notes:

1. The characteristic values chosen for transformer transient insulation levels in this example are those which a transformer built to ANSI/IEEE Standard C57.12.00-1980, *IEEE Standard General Requirements For Liquid-Immersed Distribution, Power, And Regulating Transformers,* would possess. Proper evaluation of a specific case requires that these values be obtained from the transformer manufacturer.
2. The characteristic values chosen for surge arrester performance in this example are taken from the manufacturer's literature for a specific model of 60 kV, station class, gapped, valve-element-type surge arrester. Proper evaluation of a specific case requires that these values be obtained from the surge arrester manufacturer.
3. The methods presented in this example will provide good results when properly applied. For critical and/or complex cases, the use of a computer model may provide more accurate results and different conclusions.
4. These methods are *not* applicable to use of the gapless, metal-oxide surge arresters. For application of those devices, consult the arrester manufacturer.

A. Information Required

1. System characteristics:

Nominal voltage. The voltage at which the surge protection is to be applied. For this example, 69 kV is used.

Degree of Grounding. Also called the grounding coefficient. This value is dependent on the zero and positive sequence characteristics (X_o, X_1, and R_o) of the electrical system at the point where the arrester is connected. For this example, the system is considered effectively grounded. That is, the following conditions are met:

$$\left(\frac{X_o}{X_1} \leq 3 \text{ and } \frac{R_o}{X_1} \leq 1\right)$$

Available Short Circuit Current. At the point of surge arrester application. This value should be determined by calculation (may be obtained from the supplying electric utility), and should not exceed the pressure relief characteristics for the arrester chosen. For this example, it is assumed that the proper arrester class is used.

Temporary Overvoltage History. At the arrester location. This aspect should be discussed with the supplying electric utility, and may influence arrester voltage rating. For this example, it is assumed that the proper arrester voltage rating has been chosen.

Physical Arrangement of Equipment. From construction drawings. For this example, see Figure 27.

2. Characteristics of equipment to be protected:

BIL, Front of Wave, Withstand, CWW, BSL.

Obtained from nameplate, manufacturer's specifications, or construction standards. For this example, the transformer is assumed to conform to the ANSI/IEEE construction standard, and the following values are chosen:

BIL — 350 kV

Front of Wave Withstand.

580 kV
CWW — 400 kV
BSL — 280 kV

3. Surge protective device characteristics:

Front-of Wave Sparkover, 1.2 × 50 µs Sparkover, Discharge Voltage, Switching surge protective level.

Obtained from arrester manufacturer's specifications. For this example, the following values were selected (see Note 2., above):

FOW Sparkover: 170 kV
1.2 × 50 µs sparkover: 141 kV
Discharge voltages: 122 kV @ 5 kA
137 kV @ 10 kA
147 kV @ 15 kA
156 kV @ 20 kA

Switching Surge Protective Level: 136 kV

B. Selection of Arrester Rating

1. *Voltage rating.* The arrester chosen must have a voltage rating compatible with the maximum expected line-to-ground voltage on the protected system. The degree of grounding for a given system will be used to determine whether an arrester voltage rating of less than system line-to-line votlage may be used. For all systems operating at less than 242 kV, it is customary to select an arrester voltage rating of 1.25 times the maximum expected line-to-ground voltage. For this example, the 69 kV system is assumed to be effectively grounded mum expected line-to-ground voltage. For this example, the 69 kV system is assumed to be effectively grounded $\frac{X_0}{X_1} \leq 3$, and $\frac{R_0}{X_1} \leq 1$, allowing use of 60-kV arresters. The maximum system line-to-line voltage is 72.5 kV, the maximum line-to-ground voltage under normal operating conditions is $72.5/\sqrt{3}$ kV, or 41.9 kV; 1.25 times the maximum line-to-ground voltage is 52.3 kV. The station class surge arrester voltage rating which is closest to *and* equals or exceeds 52.3 kV is 60 kV, making this voltage rating correct for this application. Depending on the degree of grounding for a specific case, higher rated arresters may be required.

2. *Arrester Class.* Each surge arrester class has a specific short-circuit (called ''pressure relief'') rating which must be observed in case of arrester failure. These ratings must be compared with the system's available short circuit current to ensure that a failed arrester will not explode violently.

The station class arresters have the highest pressure relief ratings, the intermediate class somewhat lower, and the distribution class the lowest.

For this example, a station class arrester was chosen which has adequate pressure relief capability.

II. Evaluation of Protection Where Separation Between the Surge Arresters and the Protected Equipment is Not Considered.

Note: This method may be used where surge arresters are connected in close proximity to the terminals of the protected equipment. If there is a significant separation between devices, then the methods described later must be used.

Step A.

Compare equipment chopped wave withstand (CWW) to surge arrester front-of-wave (FOW) characteristics. The ratio between CWW and FOW should equal or exceed 1.2.

Example of Figure 26

$$\frac{CWW}{FOW} = \frac{400 \text{ kV}}{170 \text{ kV}} = 2.4$$

This meets the criterion established above.

Step B.

Compare equipment BIL to surge arrester lightning protective level (LPL). LPL or let-through-level is defined as being the higher of the 1.2 × 50 µsec sparkover value or the arrester discharge voltage (IR). To determine the arrester discharge current for an effectively shielded location (that is, where the incoming lines are protected by an overhead shield wire for at least 2500 ft from the station, and the station itself is properly shielded from a direct lightning stroke), the following values may be used.:

Maximum System Voltage, kV	*Discharge Current, kA*
15	*
36.5	*
72.5	5
121	5
145	5
242	10
362	10
550	15
800	20

* Generally, utility distribution systems at this voltage are not effectively shielded. However, if shielding is adequate, the use of 5 kA discharge currents will produce conservative results. For noneffectively shielded locations, 20 kA should be used for arrester discharge current.

The ratio of BIL to LPL should equal or exceed 1.2.

Example of Figure 26.

$$\frac{BIL}{LPL} = \frac{350\ kV}{141\ kV} = 2.5$$

This meets the criterion established above.

141 kV is chosen as the LPL because the arrester discharge voltage at 5 kA (effectively shielded location) is 122 kV, and the 1.2 × 50 µsec sparkover value (141 kV) is the higher value.

Step C. (69 kV and higher voltage systems)

Compare the transformer's basic switching impulse insulation level (BSL) to the arrester's switching surge protective level (SSP) characteristic. The ratio of BSL to SSP should equal or exceed 1.15.

Example of Figure 25.

$$\frac{BSL}{SSP} = \frac{280\ kV}{136\ kV} = 2.1$$

This meets the criterion established above.

III. <u>When to Evaluate Separation Effects.</u>

If the surge arresters are not connected in close proximity to the terminals of the protected equipment, if the connecting leads from the line to the surge arrester top terminal and/or from the surge arrester bottom terminal to the ground mat are long, if the protective ratios calculated above are marginal, or if a critical piece of electrical equipment is involved, the following steps should be taken:

1. Estimate the distance, D, in circuit feet (Fig. 27).

2. Multiply dimension D by 1.6 kV/foot and add this figure to the surge arrester's FOW and LPL characteristics and re-evaluate the ratios calculated in Steps A and B above. Both ratios should be equal to or greater than 1.2.

3. If either or both ratios are less than 1.2, then the station should be evaluated by the reduction process described in the following section.

4. If both ratios remain equal to or greater than 1.2, then one can be reasonably certain that separation effects are not significant.

From the example of Figures 26 and 27.

D = 78 feet
78 feet (1.6 kV/ft) = 125 kV

Arrester FOW = 170 kV
170 kV + 125 kV = 295 kV

Transformer CWW = 400 kV

$$\frac{400}{295} = 1.36$$

Arrester LPL = 141 kV
141 kV + 125 kV = 266 kV

Transformer BIL = 350 kV

$$\frac{350}{266} = 1.32$$

Both ratios exceed 1.2, so separation effects probably are not significant.

If either ratio calculated above was less than 1.2, then the reduction and evaluation process in the next section would be necessary.

IV. Reduction of Station to the Base Case for Evaluation of Separation Effects.

In order to evaluate a surge protection installation with multiple incoming lines, several steps must be taken to reduce the station to the simplest form for analysis. Refer to Figures 28 and 29.

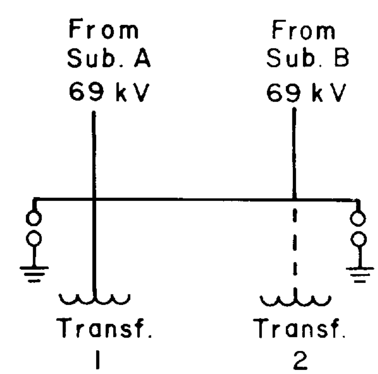


Fig. 28. Illustration of Step 1.

Step 1

Remove transformers that are not under consideration.

In this simple, symmetrical station, either transformer may be studied. It is assumed that the results will hold true for either transformer. In this example, Transformer 1 is being evaluated; Transformer 2 is removed. The equivalent circuit now looks like Figure 28. (Disconnect switches and circuit breakers are not shown.)

Step 2

Refer to Figure 29. Identify junction ‘‘c’’, the common point between the line having the incoming surge, the arrester connection, and the transformer connection. Identify the distance, ‘‘S’’, between junction ‘‘c’’ and the transformer bushings. Identify the distance, ‘‘L’’, between junction ‘‘c’’ and the arrester’s connection to the ground mat, exclusive of arrester length.

In this example, it is assumed that the 69-kV line from the utility substation ‘‘A’’ is the surged line.

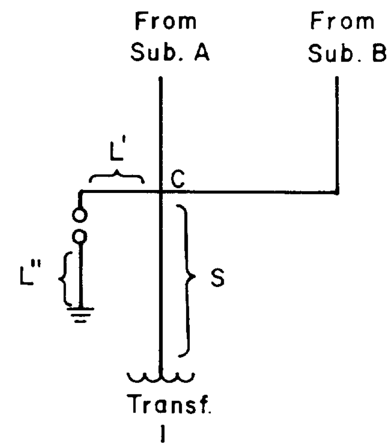


Fig. 29. Illustration of Step 2.

Step 3

Identify junction ''t'', which is the common point between the surged line, the bus connection to Transformer 1, and the bus connection to Transformer 2. Junctions ''t'' and ''c'' may be the same point, or may be different points. If junction ''t'' is *not* on the surged line side or coincident with junction ''c'', the value of α calculated below must be increased by 5%.

In this example, junctions ''c'' and ''t'' are coincident.

Step 4

Remove any lines connected between the arrester terminal and junction ''c''. In this example, there are no lines connected between these points.

Step 5

Multiply R_f (defined below) by 3/(n + 2) where n is equal to the number of lines remaining after Step 4 is completed.

In this example, two lines (one from substation A and one from substation B) remain connected, so R_f will be multiplied by 3/(2 + 2), or 0.75.

V. Separation Effect Calculations

A. Reduce station to the base case equivalent per IV above.

B. The following parameters will be used:

S = The distance in circuit feet between junction ''c'' and the protected equipment terminals. See Figure 29.

L = The distance in circuit feet between junction ''c'' and the surge arrester's connection to the ground mat, less the length of the arrester body.

D = S + L

R_f = The rate of rise of the incoming surge in kV/µsec. For most calculations, the following may be used:

Arrester ratings 3-240 kV

$$R_f = \frac{\text{Arrester voltage rating}}{12} \times 100 \text{ kV/µsec, with a maximum of 1200 kV/µsec}$$

Arrester rating 258-612 kV
2000 kV/µsec

R_f should be multiplied by the value calculated in Step 5 of the reduction process described in IV above.

E_{f1} = The arrester's front-of-wave sparkover characteristic in kV.
E_{f2} = The arrester's LPL in kV.
E_{i1} = Transient voltage at the protected insulation for sparkovers in less than 8 µsec.
E_{i2} = Transient voltage at the protected insulation for sparkovers in the 8 to 50 µsec range.
α = Separation effect (should be increased by 5% if conditions specified in Step 3 of IV above are met).
v = Velocity of surge wave. For open-wire lines, 1000 ft/µsec is used. For cables, velocity is ½ to ⅔ that of open-wire lines.

In this example (Fig. 26 and 27), the following values are chosen:

S = 64 ft
L = 14 ft
D = 78 ft
$R_f = \frac{60}{12} \times 100 = 500$ kV/µsec × 0.75 kV/µsec
(See IV, Step 5 above.)
E_{f1} = 170 kV
E_{f2} = 141 kV
E_i = To be calculated below.
α = To be calculated below.
v = 1000 ft/µsec

C. Fomulas for calculations of E_i and α

	Example
1. $\bar{D} = \frac{D\,(R_f/E_f)}{v}$	$D = \frac{78\,(375/170)}{1000}$ D = 0.17
2. $\alpha = \frac{\bar{D}}{0.0125 + 0.476(D)}$	$\alpha = \frac{0.17}{0.0125 + (0.476)(0.17)}$ α = 1.82
3. $E_{i1} = (\alpha)E_{f1}$	E_{i1} = (1.82)(170) E_{i1} = 309 kV
4. $E_{i2} = (\alpha)E_{f2}$	E_{i2} = (1.82)(141) E_{i2} = 257 kV

D Insulation coordination considering separation effects.

1. Compare CWW to E_{i1}. The ratio should be equal to or greater than 1.15.

In this example, CWW/E_{i1} = 400/309 = 1.29, which is satisfactory.

2. Compare BIL to E_{i2}. The ratio should be equal to or greater than 1.15.

In this example, BIL/E_{i2} = 350/257 = 1.36, which is satisfactory.

3. Compare BSL to SSP. The ratio should be equal to or greater than 1.15.

In this example, BSL/SSP = 280/136 = 2.1, which is satisfactory.

VI. Insulation Coordination by the Curve Method.

Note: This method may be used as an alternative to the method described in II above. It is not suitable to evaluation of insulation protection where separation effects are a potential problem.

The values plotted on the curves in Figure 30 are taken from the example of Figures 26, 27, and 29.

How to Plot Curve

Transformer Curve. Plot four points for the following withstand voltages as obtained from the manufacturer or from standards: 1) front-of-wave (if available), 2) chopped-wave, 3) full-wave (BIL) at about 8 µs, and 4) switching surge at about 300 µs. Connect the points with a dotted or dashed line showing disjointed curves at the chopped-wave point, extending the full-wave voltage as a straight line from about 8 to 50 µs and the switching surge withstand voltage as a straight line extending from approximately 50 to 200 µs and passing through the plotted 300 µs point. It is not possible to interpolate exactly between points on the curve. Good

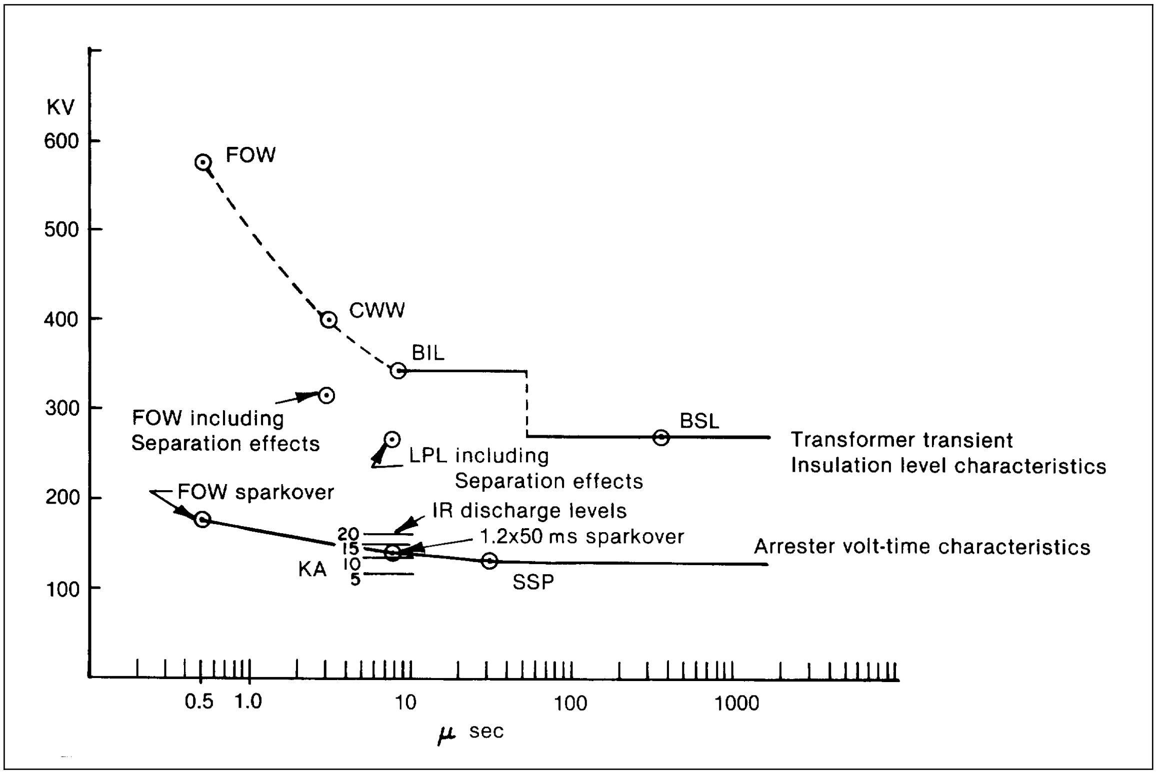


Fig. 30. Insulation coordination by the curve method.

experience has been obtained with the assumptions implicit in the preceding rules: a) The full BIL strength will apply for front times between 8 and 50 µs. b) Minimum switching surge withstand occurs between 50 and 2000 µs.

Arrester Curve. Approximate sparkover curve as follows:

A. Plot three points for the following published sparkover voltages for the specific arresters to be installed: 1) front-of-wave, 2) 1.2 × 50 sparkover (at 8 µs), and 3) switching surge protective level as a straight line from about 30 to 2000 µs. Connect the points with a curve of approximately the shape shown. If a manufacturer's voltage-time sparkover curve is available, it may be used instead of the approximation.

B. Draw a ladder of lines each extending from 5 µs to 10 µs at levels corresponding to 5 kA, 10 kA, and 20 kA discharge voltage. Add a similar line passing through the 1.2 × 50 µs sparkover.

Two additional points, corresponding to FOW and LPL when separation effects are considered, are shown in Figure 30 for illustrative purposes. If separation between the arresters and the protected equipment is significant, the method described elsewhere in this data sheet will provide a satisfactory means of evaluating separation effects.

How to Use the Curve

The criteria of both 1. and 2. must be met for satisfactory coordination:

1. Locate the point between 0.5 and 50 µs where the separation between withstand and arrester curve(s) is minimum. (Treat 1.2 × 50 sparkover and selected discharge kA lines as separate curves.) Calculate

PR = Withstand voltage/Arrester voltage

PR must be equal to or greater than 1.20 at this point.

2. Make a similar check between 50 and 2000 µs. PR must be equal to or greater than 1.15.