

# Technical Article

## Polymeric Insulators

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### Introduction

Electrical insulator is a very important component in the electric power systems such as sub-stations and distribution & transmission lines. In-depth study and practical knowledge on this subject is necessary for the electrical professionals in the electrical power field. In the early days, insulators were made of ceramic and glass materials. But in 1963, polymeric insulators were developed and its improvements in design and manufacturing in the recent years have made them attractive to utilities. It consists of a fiberglass core rod covered by weathersheds of skirts of polymer such as silicone rubber, polytetrafluoroethylene, EPDM (ethylene propylene diene monomer) and equipped with metal end fittings. It is also called composite insulators, which means made of at least two insulating parts – a core and housing equipped with end fittings. Polymeric insulators have many advantages over the ceramic and glass insulators such as good performance in contaminated environment, light weight, easy handling, maintenance free, and considerably low cost etc. Because of these properties it is gaining popularity worldwide and replacing the conventional ceramic and glass insulators.

The scope of this technical paper is to discuss about construction, types, designing, testing, and selection of polymeric high voltage insulators.

### Historical Development

The first polymers used for electrical insulators were bisphenol and cycloaliphatic epoxy resins. Introduced commercially in the mid 1940s, bisphenol epoxy resins were the first polymers used for electrical insulators, and are still used to make electrical insulators for indoor and outdoor applications. Cycloaliphatic epoxys (CE) were introduced in 1957. They are superior to bisphenol because of their greater resistance to carbon formation. However, the first commercial CE insulators failed shortly after installation in outdoor environments. Since then, new CE formations have resulted in improved electrical performance.

In the early 1960s, distribution class (CE) insulators were first sold commercially in the U.S. under the name GEPOL. These units failed due to surface damage and puncture. CE was used later in experimental 500 kV station breaker bushings, and in 115 kV bushings in the 1970s, and for suspension insulators by Transmission Development Limited (TDL) of England. The TDL suspension insulators used slant sheds to provide natural washing of contamination. From the mid 1960s on, CE insulators were tested at up to 400 kV service voltage as suspension / strain insulators and cross-arm in the United Kingdom. For various reasons, including poor cold temperature performance and insufficient weight reduction, CE did not gain acceptance in the US for outdoor high voltage suspension insulators. But today, CE is widely used in indoor and even semi-enclosed power systems.

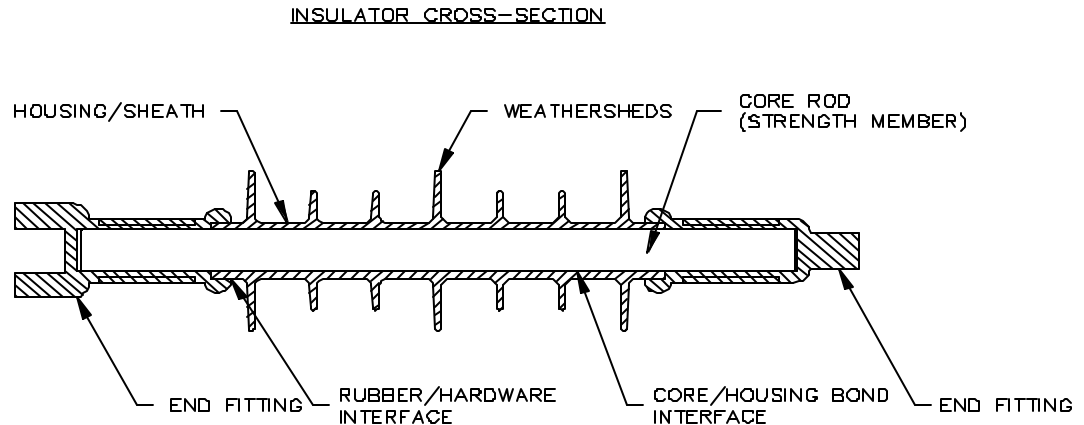
In the 1960s an insulator having porcelain sheds supported by an epoxy resin fiberglass rod was developed. It was not widely used because of further developments in lighter-weight polymeric insulating materials.

Polymeric outdoor insulators for transmission lines were developed as early as 1964 in Germany, and by other manufacturers in England, France, Italy, and the U.S. In Germany, units for field-testing were provided in 1967. In the late 1960s and early 1970s, manufacturers introduced the first generation of commercial polymeric transmission line insulators.

A large number of utilities started to experiment with the first generation composite insulators manufactured before the mid 1980s. The early experience was disappointing. Utilities initially installed these insulators in short sections of lines and at trouble spots, mostly for experimentation and data gathering. As a consequence of reported failures some manufacturers stopped producing high voltage units and others started an intensive research effort, which led to the second generation of composite transmission line insulators. These improved units have tracking free sheds, better corona resistance, and slip-free end fitting.

## Insulator Construction

### Insulator Components



**Fig. 1**

Core - The core is the internal insulating part of a composite insulator. It is intended to carry the mechanical load. It consists mainly of glass fibers positioned in a resin matrix so as to achieve maximum tensile strength.

Housing - The housing is external to the core and protects it from the weather. It may be equipped with weather sheds. Some designs of composite insulators employ a sheath made of insulating material between the weathersheds and the core. This sheath is part of the housing.

Weathersheds - Weathersheds are insulating parts, projecting from the housing or sheath, intended to increase the leakage distance and to provide an interrupted path for water drainage.

End Fitting - End fitting transmit the mechanical load to the core. They are usually made out of metal.

Coupling Zone - The coupling zone is the part of the end fitting that transmits the load to the line, to the tower, or to another insulator. It does not include the interface between the core and the fitting.

Interface - An interface is the surface between different materials. Examples of interface in composite insulators are as follows:

- |                                   |                          |
|-----------------------------------|--------------------------|
| i) Glass fiber/impregnating resin | ii) Filler/polymer       |
| iii) Core/housing                 | iv) Housing/weathersheds |
| v) Housing/end fitting            | vi) Core/end fittings    |

## Insulator Formation

Polymer insulators have a core composed of a fiberglass rod covered by polymer weather sheds. Manufacturers use various shed materials, designs, and construction methods. Basic polymer shed materials used are silicone rubber, EPM, EPDM, CE, and polytetrafluoroethylene (PTFE or Teflon). To obtain desired electrical and mechanical properties these basic material are combined with various fillers, including aluminum trihydrate.

The EP rubbers rely largely on the alumina trihydrate to avoid carbonaceous degradation. As the EP rubber surface is exposed to ultraviolet light and possible electrical arcing, the alumina trihydrate is gradually reduced to a white alumina powder on the surface. The alumina may affect the wet flashover level of the insulator. Although the silicone rubbers contain alumina trihydrate, they rely on hydrophobicity to prevent leakage currents and associated arcing.

Most manufacturers use individual sheds that were slipped over the fiberglass rod. While the CE material was cast as a single housing on the rod, the manufacturer of the silicone rubber insulator use a continuous molding process to form one continuous housing on the fiberglass rod. Some manufacturer formed a sheath on the rod, slipped the sheds onto the sheath, and then vulcanized them into place.

The metal end fittings are attached to the rod using various technologies, which include compression of the metal end fitting onto the rod (the most widely use method today), insertion of wedges into the fiberglass rod, cutting the rod end into a cone, or gluing the end fitting to the rod.

## Insulator Types

Following are the commonly used insulator types:

Dead-End/Suspension Insulator – The dead-end/suspension insulator horizontally supports the line conductor. Whereas suspension insulator vertically supports the line conductor (see Fig. 2). Both are subjected to tensile and torsional loads.

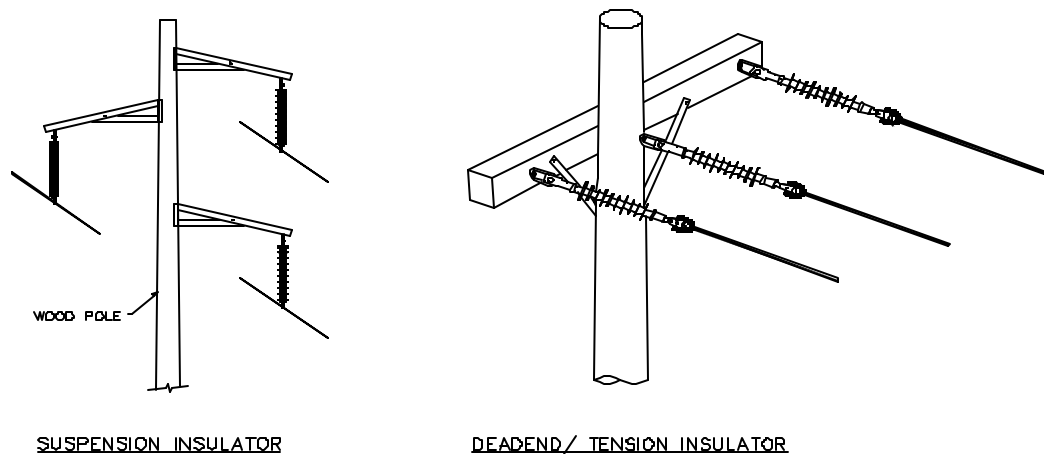
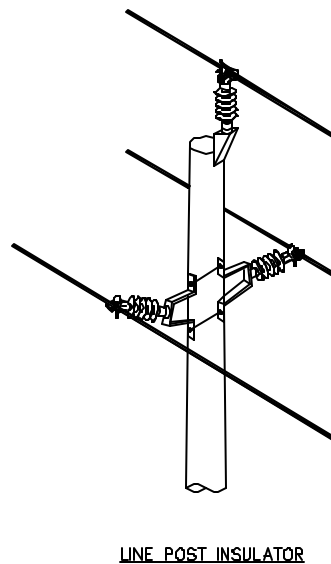


Fig. 2

Line Post/Station Post Insulator – The Line Post/Station Post Insulator horizontally or vertically supports the line conductor (see Fig. 3). It is subjected to tensile, cantilever and compressive loads.



**Fig. 3**

Guy Strain Insulator – The guy strain insulator insulates or isolates the guy wire for corrosion protection, higher insulation level, clearances for maintenance or normal operation, or safety to the public or others (joint-use). It is subjected to tensile and torsional loads.

## Insulator Design

### **Basic Design Concepts**

The basic designs of polymer insulators evolve around three essential components. These are, a core, a sheath or weathersheds and metal end fittings. The end fittings are attached to the core in various ways to develop the required mechanical strength for the intended application. The core consists of axially aligned glass fibers bonded together by means of an organic resin. The unprotected core with end fittings by itself is not suitable for outdoor high voltage application, as moisture, ultraviolet rays, contamination, acid, rain, ozone and voltage are conducive to the degradation of the core material and leading to electrical and mechanical failure. Hence, a protective sheath or weathersheds made from various polymer materials that have been compounded for outdoor electrical applications are applied over the core in various ways to protect the core and to provide maximum electrical insulation between the attachment ends. It is quite clear that with such a diversity of possible constructions, the performance of polymer insulators depends on the selection of materials and on the design and construction of the insulators.

### **Material Selection**

Core - The mechanical strength member of polymer insulator is a fiberglass rod. The rod, normally referred to as the core of the insulator, consists of between 70 and 75% by weight of axially aligned

glass fibers bonded by an organic resin. The resin system can be either polyester or epoxy and the rod either cast or pultruded.

Today's core is pultruded in various diameters with electrical grade E-type glass fibers and polyester resin. Two critical process parameters in the pultrusion of fiberglass rod for insulators are pulling speed and temperature of the forming die. An axial crack develops when the outside of the rod cures more quickly than the center of the rod. This occurs when either the die temperature is too high for the pulling speed or outside of the rod sets, shrinkage during curing of the bulk of the rod and produces an axial crack in the center of the rod. Bonding of glass fibers to the polyester resin is affected by process parameters as well. In pulling glass fiber, the fiber is sized or treated chemically for protection against mechanical damage during handling. Optimum bonding requires compatibility of the chemical systems; otherwise, the rod may exhibit porosity and wick moisture by capillary. The rod may still be acceptable for mechanical applications but not for polymer insulators.

Weathersheds - weathersheds for polymer insulators are manufactured from materials such as bisphenol or cycloaliphatic epoxy resins, thermoplastic rubber, and ethylene-propylene diene monomer (EPDM) and silicone elastomers. These materials are compounded with various types of inorganic fillers such as silica and hydrated alumina with concentrations ranging from a few percent to 70% by weight.

Today, the elastomeric materials of EPDM and silicone containing a minimum of 70% by weight of hydrated alumina that are in use by most of manufacturers are favored for weathersheds with silicone rubber clearly showing the best performance over all other types. Failures of some first generation polymer insulators with epoxy resin weathersheds have been attributed to depolymerization by hydrolysis. Depolymerization refers to the destruction of the molecular structure of polymer materials. Hydrolysis is the result of a chemical reaction, which takes place between the ions of water and the free ends of polymer chemical chain, which causes depolymerization to occur.

Also, insulators made from epoxy resins contain locked-in mechanical stresses that develop during curing of the resin. This occurs when mixing or curing of the resin is uneven. Circumferential cracks between sheds sometimes develop during storage of the insulator because of the locked-in stresses. However, more often the cracks develop in service as the stresses are aggravated by low temperature and line tension. The cracks extend down to the core, thereby exposing the core to moisture. Elastomers are the best weathershed material, as they do not contain locked-in mechanical stresses from the curing process. Also, elastomers are preferred at low temperatures where impact resistance is important.

Another problem that surfaced early in the experience of first generation designs were the effect of outdoor weathering on weathersheds. Weathering affects all polymer materials to some extent and being a natural phenomenon includes the effects of heat, humidity, rain, wind, contaminants in the atmosphere and ultraviolet rays of the sun. Under such conditions, the weathersheds of polymer insulators may be permanently changed, physically by roughening and cracking and chemically by the loss of soluble components and by the reactions of salts, acids and other impurities deposited on the surface. Surface become hydrophilic and moisture more easily penetrates into the volume of the weathersheds.

End Fittings - The end fittings are cast from either aluminum or malleable iron in sand castings. Some aluminum end fittings are cast in a permanent mold. The strengths of these fittings are more consistent than the sand-cast ones. Forged and extruded aluminum end fittings have strengths that are also quite consistent. However, if swaging is the method of attaching the fittings to the core, both permanent mold and forged aluminum fittings may develop cracks in service.

## **Insulator Design**

Elastomeric weathersheds in first generation insulators are individually molded and glued to the core and to each other by an epoxy adhesive. In some designs, silicone gel or silicone caulking sealant is

applied. In other designs, silicone gel or grease is used to fill the air space between the sheds and the core. Although epoxy glue provides some measure of protection against water entry, there is some uncertainty in the lifetime of such a seal. Insulators constructed from individual sheds are known to permit water reaching the core and have failed during hot line high-pressure water washing.

Most of the insulators are molded from either EPDM or silicone elastomers, in one-piece having an aerodynamic design, that is fully vulcanized to the core. The insulators are terminated with end fittings that are swaged onto the core sealing the insulator from moisture reaching the core. Some designs or end fittings of the insulators are equipped with power arc interceptors. These serve to protect against loss of seal during flashover. Aluminum end fittings of a unique design are swaged onto the core there by effectively sealing the sleeved ends from moisture.

## Pollution Consideration

**Table – 1 Pollution**

Pollution Category (Max. S.D.D.)	Environment Description	Minimum Specific	Nominal Leakage
		mm/kV	in/kV
I-light (0.06 mg/cm <sup>2</sup> )	<ul style="list-style-type: none"> <li>➤ Areas without industrial and with low density of houses equipped with heating plants.</li> <li>➤ Areas with low density of industries or houses but subjected to frequent wind and / or rainfall.</li> <li>➤ Agricultural areas.</li> <li>➤ Mountainous areas.</li> <li>➤ All areas situated 10 km to 20 km from the sea and not exposed to wind directly from the sea.</li> </ul>	16	0.63
II-Medium (0.20 mg/cm <sup>2</sup> )	<ul style="list-style-type: none"> <li>➤ Areas with industries not producing particularly polluting smoke and / or with average density of houses equipped with heating plants.</li> <li>➤ Areas with high density of houses and / or but subjected to frequent winds and / or rainfall.</li> <li>➤ Areas exposed to winds from the sea but not too close to the coast (at least several kilometers distance).</li> </ul>	20	0.79
III- Heavy (0.60 mg/cm <sup>2</sup> )	<ul style="list-style-type: none"> <li>➤ Areas with high density of industries and suburbs of large cities with high density of heating plants producing pollution.</li> <li>➤ Areas close to the sea or in any case exposed to relatively strong winds from the sea.</li> </ul>	25	0.98
IV-very Heavy (>0.60 mg/cm <sup>2</sup> )	<ul style="list-style-type: none"> <li>➤ Areas generally of moderate extent, subjected to conductive dusts and to industrial smoke producing particularly thick conductive deposits.</li> <li>➤ Areas generally of moderate extent, very close to the coast and exposed to sea-spray or to very strong and polluting winds from the sea.</li> <li>➤ Desert areas, characterized by no rain for long periods, exposed to strong winds carrying sand and salt, and subjected to regular condensation.</li> </ul>	31	1.22

S.D.D. = Salt Deposit Density

### 1. Pollution severity levels

For the purposes of standardization, four levels of pollution are qualitatively defined, from light pollution to very heavy pollution. Table-1 gives, for each level of pollution, an approximate description of some typical corresponding environments. Other extreme environmental conditions exist which merit further consideration, e.g. snow and ice in heavy pollution, heavy rain, and arid areas.

### 2. Relation between the pollution level and the specific creepage distance

For each level of pollution described in Table-1, the corresponding minimum nominal specific creepage distance, in millimeters per kilovolt (phase-to phase) of the highest voltage for insulator is also given.

### 3. Application of the "Specific Creepage Distance" concept

In order to successfully apply the "specific creepage distance" concept, certain dimensional parameters characterizing the insulator shall be taken into account.

The important parameters, that have to be taken into account, are:

#### 3.1 Parameters characterizing the profile (see Appendix-D)

The profile of an insulator is characterized by the following parameters:

- minimum distance,  $c$ , between sheds
- ratio  $s/p$  between spacing and shed overhang
- ratio  $l_d/d$  between creepage distance and clearance
- alternating sheds
- inclination of sheds
- parameters characterizing the entire insulator
  - creepage factor C.F.
  - profile factor P.F.

#### 3.2. Influence of the position of insulators

There is normally some change in the pollution performance of insulators designed for use in the vertical position when they are used in an inclined or horizontal position. Generally the change is for an improvement in performance, but in certain cases a reduction may result, due for example to the cascade affect of heavy rain.

#### 3.3. Influence of the diameter

Various laboratory tests appear to indicate that the pollution performance of post insulators decreased with increasing average diameter.

The following values for  $k_d$  are proposed,  $k$  being a factor to increase the creepage distance with average diameter  $D_m$  in millimeters.

- average diameter  $D_m < 300$  mm:  $k_d = 1$
- $300 \leq D_m \leq 500$  mm:  $k_d = 1.1$
- $D_m > 500$  mm:  $k_d = 1.2$

For a given profile, the average diameter  $D_m$  is given by:

$$D_m = \frac{\int_0^l D(l) dl}{l}$$

1. regular sheds  $D_m = D_1 + D_2 / 2$

2. alternating sheds  $D_m = D_1 + D_2 + 2D_1 / 2$

See Fig. 8 and 9 in Appendix–D

Where:

$l$  is the total creepage distance of the insulator.

$D(l)$  is the value of the diameter at a creepage distance  $l$ , measured from one electrode.

#### 4. Determination of the creepage distance

The minimum nominal creepage distance of an insulator situated between phase and earth is determined, according to the pollution level of the site, by the relation:

Minimum nominal creepage distance = minimum specific creepage distance (Table-1) X highest system voltage phase-to-phase for the equipment X  $k_D$

Where:

$K_D$  is the correction factor due to diameter (see sub-clause 3.3)

If insulators are to be used between phases (phase-spacers for instance), the creepage distance should be multiplied by  $\sqrt{3}$  (for a three-phase system).

### **Insulation Consideration**

There are basically three factors to consider when designing the insulators.

- The 60-Hz power voltage.
- Surge voltages caused by lightning.
- Surge voltage caused by switching.

Surge voltages provide the most stringent test and the rationale for the standard impulse voltage wave form; that is, if the insulator is properly insulated to withstand surges, it can usually accommodate the highest expected 60 Hz voltage. Insulators are more tolerant of short-duration overvoltage than sustained values. For the purpose of impulse testing, a standard waveform is defined, as shown in Fig. 4. The waveform is referred to as T1 X T2, where both values are conventionally given in microseconds. The crest value of the waveform V. The value T1 is the rise time to crest, whereas the value T2 is the fall time to 0.5 V.

A convenient analytical representation of the pulse waveform is the double-exponential expression

$$V(t) = V_1[\exp(-t / \tau_2) - \exp(-t / \tau_1)]$$

Where

$$\tau_2 = T_2 / \ln(2) = 1.443T_2$$

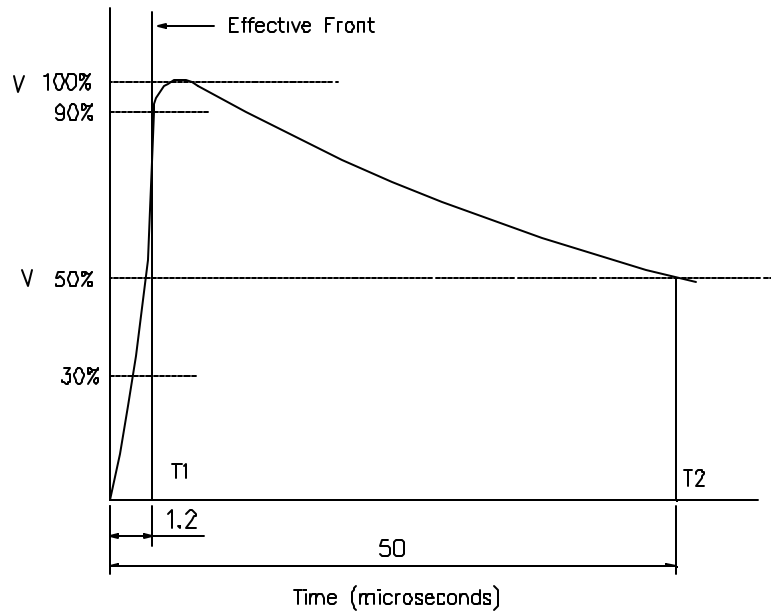
$$\tau_1 = T_1 / 5 = 0.2T_1$$

$$V_1 = V \exp(T_1 / 1.443T_2)$$

For a given well-defined voltage waveform, under specified test conditions, the following terminology is defined:

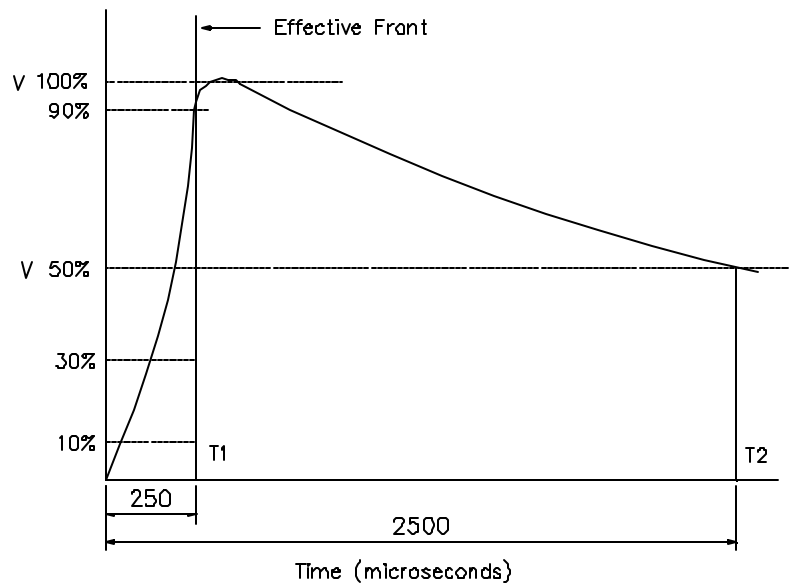
1. Critical Flashover Voltage (CFO) - The crest (maximum) voltage for which the probability of flashover is 0.50 (see Fig 4).
2. Withstand Voltage - The crest voltage  $3\sigma$  below the CFO
3. Basic (lightning) Impulse Insulation Level (BIL) - The crest voltage for which the probability of flashover is 0.10, using a 1.2/50  $\mu$ s test pulse.
4. Basic (switching) Surge Impulse Insulation Level (BSL) - The crest voltage for which the probability of flashover is 0.10, using a 250/2500  $\mu$ s test pulse (see Fig 5).





Waveform – Lightning Impulse

**Fig. 4**



Waveform – Switching Impulse

**Fig. 5**

## **Consideration of Interference and Corona**

### Generating processes

Interference with radio and television (RI and TVI) may arise when electrical discharges run on insulators and inject high-frequency currents into associated conductors, which radiate electromagnetic waves. The types of discharge which generate interference are: micro sparks between water drops or metal fittings, the latter especially in cases of corrosion; discharges across dry bands on leaky surfaces; surface corona discharges around highly stressed electrodes.

Surface corona discharges are again relatively slow phenomena, incapable of heavy generation at VHF, but principal sources at lower frequencies. Surface discharges may be prevented by hydrophobic treatment. This not only inhibits dry-band formation but also gives good voltage grading, thus removing the over voltages, which cause other types of discharge. It might appear that the installation of a corona ring would smother capacitive over voltages, while avoiding the usual power loss, which follow installation of a corona ring.

Both the above-mentioned types of discharge are, to some extent, weather dependent. Water may cause droplet discharges while suppressing contact discharges by virtue of its high conductivity and permittivity; dry bands do not a fair-weather phenomenon, the existence of which depends on the design of the insulator and the geometry of the insulators of fittings. Surface corona, if in fair weather, for which reason it has long been the practice to specify higher than normal voltages for corona inception on insulator.

### **Consideration of Capacitance Effects**

The distribution of capacitance along an insulator, and their size, govern the electric stresses, which excite generation of interference, and the coupling of the generator to the radiating antenna.

A composite insulators like a cylinder of dielectric having a relative permittivity about 6. The field intensity falls away rapidly with increasing distance from the live terminal (Fig. 6). The generating discharges occur at or near the live terminal, and the capacitance, which couples the high-frequency currents into the radiating circuit, i.e. the line and tower, is small. Composite insulators are thus significantly quieter as interfering sources than string of discs.

In a string of discs, quite large capacitance – of the order of 30 pF – are connected in cascade through the fittings. The voltage distribution is governed purely by these and by the stray capacitance to line and ground, in dry conditions. In such a voltage-dividing circuit the partition is independent of frequency: identical distributions therefore exist for the power-frequency and for the radio-frequency voltage (Fig. 6). The units at the line end are more prone to surface corona than the rest. Because of the high unit capacitance the sources are closely coupled into the line, which presents load impedance equal to one-half of the line's surge impedance. It is common practice to relieve the line end overvoltage by means of stress-grading fittings.

Some of the devices which are used to minimize surface corona, in cases like these where 'quiet' insulators are essential. Tests showed those gradients between 10 and 14 kV/cm is sufficient to break down air in contact with insulator over gaps of a few centimeters.

More about Insulators for Transmission Lines in Appendix – B.

## VOLTAGE DISTRIBUTION ALONG STRING AND COMPOSITE INSULATORS

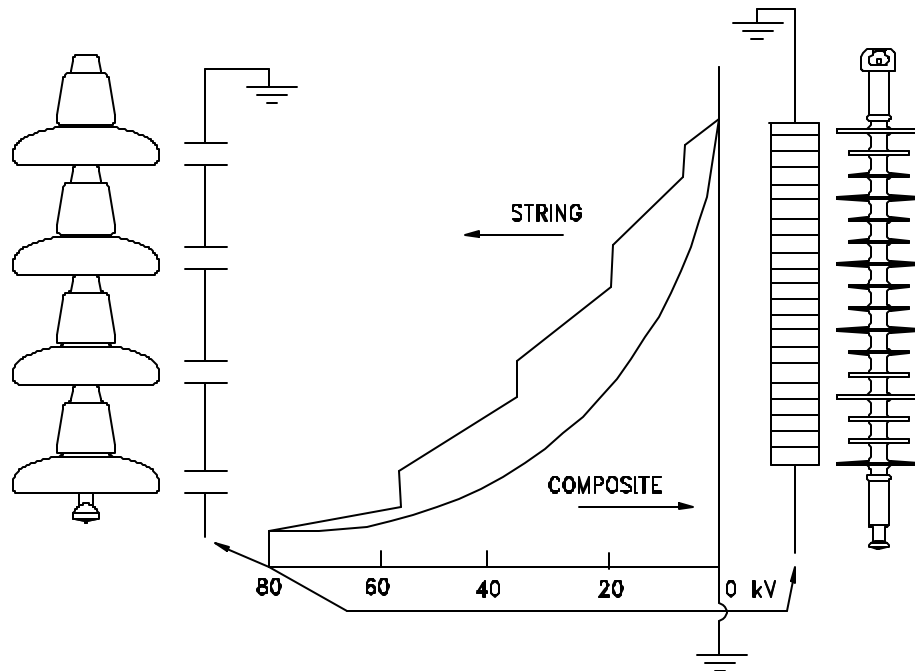


Fig. 6

## Insulator Testing

### Definitions

Tracking - Tracking is an irreversible deterioration by the formation of paths starting and developing on the surface of an insulating material. These paths are conductive even under dry condition. Tracking can occur on surface in contact with air and also on the interfaces between different insulating materials.

Treeing - Treeing is the formation of micro-channels within the material. The micro-channels can be either conducting or non-conducting and can progress through the bulk of the material until electrical failure occurs.

Erosion - Erosion is an irreversible and non-conducting deterioration of the surface of the insulator that occurs by loss of material. This can be uniform, localized or tree-shaped.

Chalking - Chalking is a surface condition where in some particles of the filler become apparent during weathering, forming a powdery surface.

Crazing - Crazing is the formation of surface micro-fractures of depths up to 0.1 mm.

Cracking - Cracking is any surface fracture of a depth greater than 0.1mm.

Hydrolysis - Hydrolysis is a chemical process involving the reaction of a material with water in liquid or vapor form. It can lead to electrical or mechanical degradation.

Puncture - Puncture can be characterized by a disruptive discharge occurring through a solid dielectric (e.g., shed, housing, or core) causing permanent loss of dielectric strength.

Specified Mechanical Load (S.M.L) - The S.M.L. is a load specified by the manufacturing, used for mechanical tests in this specification. It forms the basis of the selection of composite insulators.

Tensile Load - Tensile load is the load applied in-line with the longitudinal axis of the insulator rod and away from the end metal fitting.

Routine Test Load (R.T.L.) - The R.T.L. is the load applied to assembled composite insulators during Routine Tests. It is equal to 50% of the S.M.L.

Cantilever Load - Cantilever load is a load applied at the conductor position on the insulator, perpendicular to the conductor, and perpendicular to the rod of the insulator. This load is also called bending.

Compressive Load - Compressive Load is applied in-line with the longitudinal axis of the insulator rod and towards the base end.

#### Maximum Working Combined Loads

The maximum working combined loads are the simultaneously applied cantilever and compression loads. They produce a bending moment that should not exceed the bending moment induced by the working cantilever load rating alone.

Working Cantilever Load (W.C. L.) - Working cantilever load is a load that must not be exceeded in service.

Maximum Design Rating (MDR) - The maximum mechanical load that the insulator is designed to withstand continuously for the life of the insulator.

Proof-Test Load - The routine mechanical load that is applied to an insulator at the time of its manufacture.

Delamination - Delamination is the loss of bonding of fibers to matrix.

## **Tests**

### **Classification of Tests**

Based on the purpose of testing, the tests to be performed on polymer insulators are classified in four categories as follows:

1. Design Tests - Design tests are performed to verify the suitability of the manufacturer's design, materials, manufacturing process and technology. When an insulator is submitted to the design tests, the results shall be considered valid for all insulators of the same design that are represented by the tested one. The design tests are performed once. Design tests shall include the following tests:

#### □ Material Tests

- |   |                               |
|---|-------------------------------|
| i) Water Penetration Test                 | ii) Tracking and Erosion Test |
| iii) Aging or Accelerated Weathering Test | iv) Dry Penetration Test      |
| v) Water Diffusion Test                   | vi) Power Arc Test            |
| vii) Flammability Test                    |                               |

#### □ Mechanical Tests

- |                              |                             |
|------------------------------|-----------------------------|
| i) Tension Strength Tests    | ii) Torsion Strength Test   |
| iii) Working Cantilever Load | iv) Thermal Mechanical Test |

2. Type Tests - Type tests verify the main characteristics of the insulators, which depend mainly on its shape and size. They shall be repeated when the design, type, or size of the insulators changes. Three production line insulators of the relevant type shall meet the requirements. The following tests are recommended for this type of testing:

- |                                      |                                      |
|--------------------------------------|--------------------------------------|
| i) Low-Frequency Dry Flashover Test  | ii) Low-Frequency Wet Flashover Test |
| iii) Critical Impulse Flashover Test | iv) Radio Influence Test             |

3. Sample Tests - Sample tests verify other characteristics of the insulator, including those which depend on the quality of the manufacture and on the material used. They are performed on insulators taken at random from a lot offered for acceptance. Sample shall include the following tests:

- i) Galvanizing Test
- ii) Tension Strength Test
- iii) Dye Penetration Test
- iv) Retest Procedure
- v) Verification of Dimensions, Markings, and Metal Fittings

4. Routine Tests - Routine tests are conducted to detect and discard insulators with manufacturing defects. They are made on every insulator produced. They include tensile load (50% of S.M.L.) and visual examination tests.

### **Description and Procedure of Tests**

Tests normally performed on an insulator by the manufacturer and the user are described below:

1. Water Penetration Test - Various materials absorb varying amounts of water that may affect the polymeric materials on different ways. Electrical properties change most noticeably with moisture absorption. In particular, the dielectric strength of materials varies greatly with absorbed water and materials that absorption. In particular, the dielectric strength of materials varies greatly with absorbed water, and materials varies greatly with absorbed water, and materials that absorb almost no water are favored for electrical insulation. Mechanical properties are also deteriorated by moisture to some extent. Water penetration test is intended to determine the insulator resistance to moisture. Three samples of the insulator shall be kept immersed in boiling tap water, having 0.1% by weight of NaCl, for 100 hours. At the end of this period, the insulators shall remain in the vessel until the water cools to approximately 50°C. This temperature shall be maintained until the verification tests start. The verification tests consist of the sequence of tests described in 1.1 through 1.3 and shall be completed within 48 hours. These tests are described as followed:

1.1 Visual Examination - The housing shall be inspected visually. No cracks and no sign of dissolving or crumbling are permitted.

1.2 Steep Front Impulse Voltage Test - An impulse voltage with a front steepness of at least 1000 kV/μs shall be applied to each test section. Each test section shall be stressed with 25 impulses of positive and 25 impulses of negative polarity in accordance with ANSI standard and 10 impulses of positive and 10 impulses of negative polarity in accordance with CEA standard. Each impulse shall cause an external flashover of the test section. No puncture shall occur.

1.3. Power Frequency Voltage Test - Each test specimen shall be individually subjected to 80% of its average flashover voltage as determined by averaging five flashover voltage on each of the three test specimens. The flashover voltage shall be corrected to standard conditions. The flashover voltage shall be reached within 1 minute by increasing the voltage linearly from zero. The voltage shall be maintained for 30 minutes. No puncture shall occur and the temperature of the shank measured immediately after the test shall not be more than 20°C above ambient.

1.4. Hardness Test - The hardness of two sheds of each insulator shall be measured in accordance with ASTM D2240. The hardness must not change from the pre-boiled specimen by more than 20%.

2. Aging and Accelerated Weathering Test - Outdoor weathering is a natural phenomenon which affects all materials to some extent. Outdoor weathering includes the effects of varying temperature, humidity, rain, wind, impurities in the atmosphere, and the heat and ultraviolet rays of the sun. Under such conditions, the surface of an insulating material may be permanently changed. Physically by roughening and cracking and chemically by the loss of soluble components and by the reactions of

the salts, acids, and other impurities deposited on the surface. Surfaces become hydrophilic and water penetrates more easily into the volume of the material.

Three samples of the weathershed material shall be tested for 1000 hours by one of the following test methods, except that test without water is not permitted. Surface defects such as cracks and blisters are not permitted.

Carbon Arc Methods: ASTM D750, D1499, or G23.

Xenon Arc Methods: ASTM G26, or D2565.

Fluorescent UV Methods: ASTM G53.

3. Dry Penetration Test - Three 10-mm long cross sections of the insulator shall be tested for porosity by performing a dye penetration test. The samples shall be placed upright on a layer of steel or glass balls in a 1% alcohol solution of fuchsin dye. The time taken for the dye to rise through the samples shall be longer than 15 minutes.

4. Water Diffusion Test - Six samples, 30 mm shall be cut from the insulator 90 degree to the axis of the core with a diamond-coated circular saw blade under cool running water. The cut surfaces shall be smoothed with a 180-grit abrasive cloth. The cut ends shall be clean and parallel. The removal of the housing is optional.

The test specimens shall be boiled in deionized water with 0.1% by weight NaCl in a glass container for 100 hours. After boiling, the samples shall be removed from the salt water and placed into tap water for at least 15 minutes. The samples shall be then placed between two plane brass electrodes and a voltage increasing at a rate of 1 kV per second shall be applied. With the applied voltage reaching a value of 12 kV and remained for 1 minute, there should be no puncture or surface flashover. The current during the whole test shall not exceed 1 mA r.m.s.

5. Power Arc Test - Three insulators having any one design of end fittings shall be tested for power are endurance while tensioned horizontally at 3000 lb. An arc shall be initiated across the insulator by means of a copper shorting fuse wire. The arc shall burn 15 to 30 cycles and its current magnitude is determined by ampere-time product ( $I \times t$ ) equal to a minimum of 150 kA cycles. Each insulator is only acceptable if there is no exposure of the core, no mechanical separation of the insulator, and no cracks in the housing.

6. Tracking and Erosion Test - The long -term performance of a polymer material used in electrical insulation design is directly related to the leakage current and the dry-band discharges that develop in service. Service experience has shown that the amplitude and frequency of dry-band discharges on electrical insulation are not dependent on design alone but also dependent on the surface properties of the polymer material used.

For many years, tracking chamber methods had been proven to be very reliable in providing enough data on expected performance for a particular model insulator under severe contaminated conditions. Tracking chambers can be classified in term of the process of wetting the sample into three groups namely salt-fog chambers, tracking wheel chambers and drizzle chambers. The tracking wheel test method imposes wet and dry cycles on a stressed surface of specimens in order to simulate the formation of dry-band arcing as it is experienced on service. It is designed to evaluate insulator shapes and/or materials for outdoor applications. Surface degradation in outdoor applications of either erosion or tracking takes place only in association with arcing over dry bands, which developed during or immediately after precipitation. The surface damage, erosion, or carbonization results from the heat of the arc, and this damage accumulates until the surface between the electrodes can no longer sustain the applied voltage. As this mechanism is the same as occurs in service, correlation with experience has been good.

Three insulators shall be tested for resistance to tracking on a tracking wheel chamber. At the end of test, there shall be no significant signs of erosion and tracking. Each individual insulator shall not suffer more than two flashover provided no damage occurs to the surface of the insulator.

7. Tensile Load Test - The element of time plays an important role in characterizing the mechanical properties on many polymer materials, particularly plastics and elastomers. Both plastics and elastomers share some of the features of a viscous fluid where stress is proportional to strain rate but independent of the strain itself, that is, they are viscoelastic. Thus, it becomes important to be concerned about how long the material must sustain load, how fast it is loaded, and how far it is compressed or elongated. It is important to recognize that these factors should be of concern and that standard material test methods often have to be modified to reflect this concern.

Three samples shall be subjected to a tensile load that shall be increased rapidly but smoothly from zero to 75% of specified mechanical load (SML) and then gradually be increased to the SML in a time between 30 and 90 seconds. If 100% of the SML is reached in less than 90 seconds. The test is passed if on failure occurs. The load shall then be increased until the insulator fails. The historical failure loads shall justify the manufacturer's choice of SML.

8. Torsional Load Test - Three insulators shall be tested to 50 Nm and release. The torsional load shall be applied to the test specimen through a torque member so constructed that the test specimen is not subjected to any cantilever stress. Failure of any one insulator after torsion to meet the dye penetration test shall constitute failure to meet the requirements of this recommendation.

9. Working Cantilever Load Test - Three insulators shall be tested. Gradually load the insulator to 1.1 times its working cantilever load rating at a temperature of  $20^{\circ}\text{C} \pm 10\text{K}$  and hold for 96 hours. The load shall be applied to the insulator as described in the definition of the cantilever load. After removal of the load; cut each insulator  $90^{\circ}$  to the axis of the core and about 50 mm from the base end fitting; cut the base end fitting longitudinally into two halves in the plane of the previously applied cantilever load. The test is regarded as passed if the threads of the base are reusable and each fiberglass rod has no delaminations, and no crack.

10. Thermal Mechanical Test - No non-ceramic material is completely resistant to heat. Time and temperature have their aging effects. Heat resistance is usually measured as change in tensile strength, elongation and hardness. Low-temperature properties indicate a stiffening range and brittle point. With some materials crystallization occurs, at which time the material is brittle and will fracture easily.

Three insulators shall be loaded at ambient temperature to at least 5% of the SML for 1-minute. During this time, the length of the insulators shall be measured. This will be the reference length. The insulators shall then be submitted to thermal variation from  $-35^{\circ}\text{C}$  to  $+50^{\circ}\text{C}$  (ANSI) and  $-50^{\circ}\text{C}$  to  $+50^{\circ}\text{C}$  (CEA) while under a permanent mechanical load of 0.5 SML for 96 hours. The time at each temperature shall be at least 8 hours per cycle. At the end of thermal cycling, the insulators shall be allowed to reach ambient temperature and the length shall again be measured using the same load as for the reference length. The increase in each insulator's length shall be no more than 2mm. It is also required that, described in section 3.

10. Flammability Test - This test is intended to check the shed housing material for ignition and self-extinguishing properties. The test shall be performed according to IEC Publication 707, method FV. The test is passed if the test specimen belongs to category FVO of IEC Publication 707.

11. Low Frequency Dry Flashover Test - Three insulators shall be tested. The initial applied voltage may be quickly raised to approximately 75% of the expected average dry flashover voltage value. The continued rate of voltage increase shall be such that the time to flashover will be not less than 5 seconds nor more than 30 seconds after 75% of the flashover value is reached. The dry flashover voltage value of a test specimen shall be the arithmetical mean of not less than five individual flashover taken consecutively.

Failure of the dry flashover value of any one of the three insulators to equal or exceed 95% of the rated dry flashover value shall constitute failure to meet the requirements.

12. Low Frequency Wet Flashover Test - Three insulators shall be tested and voltage application at not less than 1 minute after the final adjustment of the spray, the applied voltage may be raised quickly to approximately 75% of the expected average wet flashover voltage value. The continued rate of voltage increase shall be such that the time to flashover will be not less than 5 seconds nor more than 30 seconds after 75% of the wet flashover voltage value is reached. The wet flashover voltage value of a test specimen shall be the arithmetical mean of not less than five individual flashover taken consecutively. Failure of the flashover value of any one of the three insulators to equal or exceed 90% of the rated wet flashover value shall constitute failure to meet the requirements.

13. Critical Impulse Flashover Test - Three insulators shall be tested under dry conditions only and with a 1.2 X 50-microsecond wave. Failure of the positive or negative critical impulse flashover value of any one of the three insulators to equal or exceed 92% of the rated critical impulse flashover value, whichever is lower, shall constitute failure to meet the requirements.

14. Radio-Influence Voltage Test - Three insulators shall be tested. All hardware associated with the test circuit shall be relatively free of radio influence at a voltage 10% higher than the voltage at which the tests are to be performed. The wave shape of the applied voltage shall be a sine wave of acceptable commercial standards in accordance with ANSI/IEEE 4-1978. Tests shall be conducted under atmospheric conditions prevailing at the time and place of test, but it is recommended that tests be avoided when the vapor pressure exceeds 0.6 inch of mercury ( $2.02 \times 10^3$  Pascal). Since the effects of humidity and air density upon the radio-influence voltage are not definitely known, no correction factors are recommended for either at the present time. However, it is recommended for that barometric pressure and dry and wet-bulb thermometer readings are recorded so that if suitable correction factors should be determined, they could be applied to previous measurements. The specified voltage shall be applied to the test specimen, and the radio-influence voltage shall be measure in microvolts at the specified radio frequency. It is considered impractical to read radio-influence test voltage that is less than 10 microvolts. Failure of one or more insulators to meet the requirements shall constitute failure.

16. Galvanizing Test - Five pieces representative of each type of galvanized hardware used with the insulators shall be tested. Five to ten measurements shall be uniformly and randomly distributed over the entire surface and the average thickness value of each individual specimen and the average of the entire sample shall equal or exceed 78 to 86  $\mu\text{m}$ . If the average of one specimen, or if the average of the entire sample, fails to comply with the values, ten additional pieces of the same type of hardware shall be selected at random and tested. Failure of the retest sample to comply with the minimum thickness criteria shall constitute failure of the lot to meet the requirements of this recommendation.

## **Insulator Selection**

### **Mechanical Parameters**

The process for selecting the strength rating of composite or ceramic insulators is identical. Based on strength alone, a composite insulator can directly replace insulators made of porcelain or glass. Composite insulator's strength rating is as defined in the Table-2. Historically, when selecting an insulator's strength rating a two to one safety factor has been applied because all materials have a time-load characteristic that reduces their residual strength over time. Most manufacturer rate composite insulators at a maximum working load equal to 50% of the Ultimate Load rating.



**Table-2 Insulator Strength Rating Definition**

Loading	Non - ceramic		Ceramic
	Suspension	Post	
Maximum Short Term Load (one minute)	SML (Specified Mechanical Load)	UCL (Ultimate Cantilever Load)	M&E (Mechanical and Electrical Strength)
Maximum Temporary Load (one week)	50% to 60% of the SML	Not Defined	Not Defined
Maximum Working Load (continuous)	RTL (Routine Test Load) 50% of the SML	WCL (Working Cantilever Load) 50% or UCL	TPL (Tension Proof) 50% of the M&E and WCL 40% of the UCL

**Loading Considerations – Ice and Wind**

Establishing the everyday working load of an insulator requires that ice and wind conditions for the area of application be considered. Ice and wind can add considerable load to the conductor and insulators, resulting in greater loads. Table-3 lists parameters to use for calculating ice and wind loads for each region.

The following example determines the total loading of ice, wind and conductor weight. This calculation does not include the weight of the insulators and other items that increase the load on the insulators. Normally, such items should be added to the final load. A composite insulator's weight is a small percentage of the total weight; therefore, omitting it from the calculation will have minimal effect on the outcome.

**Table-3 Loading Parameters**

Loading	Radial Ice thickness (in)	Horizontal Wind Pressure (lbs./sq. ft.)	Temperature (degree F)	Constant (lbs./ft.)
Heavy	0.50	4 (40 mph)	0	0.30
Medium	0.25	4 (40 mph)	+15	0.20
Light	0	9 (60 mph)	+30	0.05

**Table-4 Steps Used in Calculating the Total Load on a Conductor**

1. Select ice and wind parameters	Determine maximum radial ice thickness and wind pressure from the local standard.
2. Calculate vertical load	Conductor and ice weight between insulator span, including spacers and other equipment the conductor supports.
3. Calculate horizontal load	Horizontal wind pressure on the conductor, radial ice thickness, spacers and other equipment the conductor supports.
4. Calculate combined load	Vector sum of the horizontal and vertical loads.
5. Calculate total conductor load	Combine load plus the loading constant from Table 3.

## Electrical Parameters

An insulator's electrical parameters should be selected to maintain an economic balance between system performance and the cost of over insulation. Increasing an insulator's electrical parameters will provide greater system protection at a higher price and, for long power lines the cost can be substantial. Therefore, insulation requirements for power systems should be considered on an individual basis because of the uniqueness of power system configurations, grounding techniques, and protection scheme.

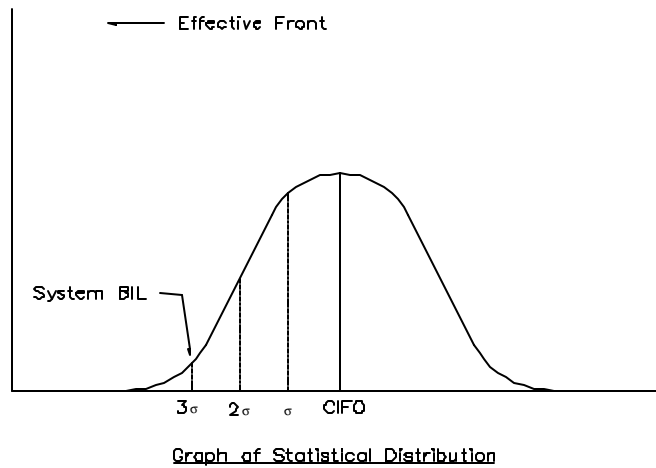
### CIFO Selection

Generally, an acceptable flashover probability is incorporated into the design of a transmission line because it's not economically feasible to protect against all occurrences of lightning overvoltages. These overvoltages result from shielding failures caused by direct strokes to the conductor, from back-flashover caused by strokes to the tower and shield wire, and from induced voltages caused by strokes to nearby grounded objects. When a flashover occurs, an insulator is not normally affected and will recover, unlike transformer insulation that will be damaged. This ability allows an insulator's flashover level to be selected by a statistical process that gives it an expected flashover probability. The capability of an insulator to resist flashover caused by lightning strokes relies on the air gap distance (Dry Arc) between its live and ground end. Therefore, as the system insulation level increases, so must the insulator's length.

**Table-5 Recommended BIL at various operating voltages**

<b>Voltage Class (kV)</b>	<b>BIL (kV)</b>	<b>Reduced BIL (kV)</b>
15	110	
23	150	
34.5	200	125
46	250	
69	350	
92	450	
115	550	450/350
138	650	550/50
161	750	650/550
196	900	
230	1050	900/825/750
287	1300	1175/1050/900
345	1550	1425/1300/1050
500	1800	1675/1550/1300

The equipment used in a power system comprises items having different breakdown or withstand voltages and different voltage time characteristics. In order that all items of the system are adequately protected there is a need to consider the situation as a whole and not items of plant in isolation; i.e. the insulation protection must be coordinated. To assist this process, standard insulation levels are recommended and these are summarized in Table-5. Reduced basic insulation impulse levels are used when considering switching surges and are also summarized in Table-5.



**Fig. 7**

Statistical data has shown that the CIFO should be applied at three standard deviations ( $\sigma$ ) above the system BIL; this will provide an acceptable flashover probability. Since the standard deviation is equal to 3% the required CIFO can be computed directly from the system BIL.

1. The BIL is usually expressed as a per unit of the peak (crest) value of the normal operating voltage to earth; e.g. for a maximum operating voltage of 362 kV.

$$1 \text{ p.u.} = \sqrt{2} \times (362 / \sqrt{3}) = 300 \text{ kV}$$

$$\text{so that a BIL of } 2.7 \text{ p.u.} = 810$$

kV Calculation of using formula (Fig. 7):

Using Typical System BIL

$$\text{CIFO} = \text{BIL} / 0.91$$

#### Low Frequency Ling Duration (60Hz) Selection

Insulators must perform under two types of electrical stresses, i.e., those caused by temporary overvoltages and those caused by the steady state nominal system voltage. Typically the occurrence of an overvoltage is an uncommon event and limited to a relatively short time. This type of stress can be determined by a system analysis and then be accounted for when selecting the insulator requirements. For system voltages through 230 kV, the dry flashover value is typically five times the maximum line to ground power frequency voltage. This margin results in a wet flashover value of three to five times the line to ground power frequency voltage. Normally, experience with the area and design or a system study is required to determine the minimum insulation strength.

#### Switching Surge Selection

A switching overvoltage is caused by a switching operation or a fault on the system that occurs during line reclosing, fault clearing, and switching of capacitive or inductive circuits. Surge developed by these operations is generally of short duration, highly damped, and has unpredictable amplitudes.

Switching surge requirements depend on the transmission-line design and location, i.e.; clearances between live parts and ground, altitude, and system grounding. For system voltages below 300 kV the probability of a switching surge flashover is negligible and lightning surges are of more concern. Above 300 kV, grounding and shield design determine whether a switching surge or lightning surge has the greater influence. Often, because of improved grounding techniques, tower designs, and line shielding methods, switching surge levels are more representative of the system requirements. Table-6 lists typical switching surge overvoltage from the Transmission Line.

**Table-6 Typical Switching Surge Levels**

Cause of Switching Surge	Maximum per Unit* Overvoltage
Energize 200 mile line, no closing resistors	3.5
Fault initiation on unfaulted phase	2.1
Fault clearing	1.7 to 1.9
Energize line and transformer	1.2 to 1.8
First restrike on capacitor bank	3.0

\*Per unit voltage, expressed in maximum phase to ground system voltage.

Contamination Performance

The long term electrical performance of a polymer insulator is contingent upon the weatherability of the polymer material and the level of electrical stress subjected to the material. If the material weathers poorly or the electrical stress is too high, the polymer could prematurely degrade and lead to a shortened service life.

The weathering of the material is a natural event caused by many factors, some of which are; wind, rain, heat, cold, humidity, pollutants from factories and automobiles, and ultraviolet rays from the sun. A polymer material's ability to endure these conditions for an extended period is dependent upon its chemical composition.

Hydrophobicity is the characteristic of silicone rubber that sets it apart from other commonly used insulator materials. Since silicone rubber does not readily wet-out, leakage current remains low and flashover are prevented. Even when the insulators are heavily contaminated, silicone has the unique ability to impart hydrophobicity to the contaminated layer due to the migration of low molecular weight silicone polymer molecules into the contaminate. Contamination flashover performance of silicone is far superior to other insulation materials, and because the contamination layer is hydrophobic, power washing of silicone insulators is not required. To determine pollution category, use Table-1.

Calculation of insulator leakage distance example:

Pollution category II-Medium

Required Leakage = (system kV line) X (5% voltage regulation) X (leakage/kV line)

Grading Ring Selection

Corona discharges can form on the metallic ends of an insulator when the electric-field intensity exceeds the dielectric strength of the surrounding air. Several factors that affect the onset of corona are air pressure, humidity, end fitting material, and voltage level. If the end fitting has sharp edges or is irregular in shape, corona can result from a concentration of the electric field. Grading rings reshape the electric field, thus, reducing corona discharge on the insulator, high RIV levels, and power losses. If corona persists, it may damage the polymer material and lead to insulator failure.

The following recommendations for corona extinction and RIV are given by proposed ANSI standard C29.12:

- Minimum Corona Extinction Level  
115% of the nominal line to ground voltage.
- Maximum RIV  
100 μV at 115% of nominal line to ground voltage.

The elevation at which insulator is applied is an important consideration when specifying grading rings. Tests have shown that corona extinction and inception levels decrease with increasing altitude; approximately a 1% change for every 1000 feet above sea level. However, the effect is not as significant below 3000 feet since the bulk of corona tests occur near this level. Therefore, corona extinction levels must be adjusted for applications above 3000 feet. Grading rings are selected according to the corona extinction level. A variety of ring shapes and sizes are necessary to meet the requirements of the different voltage levels and insulator configurations. Generally, by increasing a corona rings diameter or thickness the inception level increases.

### **Insulator Characteristics**

Following are the typical characteristics of an insulator:

#### Service Conditions

- i) Weather Degree
- ii) Pollution Category
- iii) Altitude
- iv) Insulator Configuration

#### Physical Characteristics

- i) Section Length
- ii) Dry Arc Distance
- iii) Leakage Distance

#### Electrical Characteristics

- i) Max. System Voltage
- ii) System BIL
- iii) Insulator CIFO
- iv) Min. Dry 60 Hz Flashover
- v) Min. Wet 60 Hz Flashover
- vi) RIV

#### Mechanical Characteristics

Specified Mechanical Load (S.M.L.) - for Suspension Insulator

Ultimate Cantilever Load - for Line Post or Station Post Insulators

### **Conclusion**

The use of polymeric insulators in the electric power sub-stations and distribution & transmission lines is beneficial because of its many advantages such as contamination performance, reduced construction costs, light weight, easy handling, low or no maintenance, vandalism resistance and compact design.

Historically, North America has been the leader in the use of composite insulators and this continues to be the case for high voltage application. Most users have a number of composite insulators on trial on their system's highest voltage transmission lines. For some time they have been used in limited numbers where porcelain and glass unit have been unable to fulfill their requirements and better performance can be obtained by using composite insulators. Recently composite insulators have been used on a large scale for several major high voltage transmission line projects. In general, some user appears to be waiting for more in-service data before committing to composite insulators on a large scale. All users appear to agree that the key advantages of composite insulators over ceramic or glass insulators are superior.

## Appendix - A

### **Parameters Characterizing the Insulator Profile**

1. Minimum distance  $c$  between sheds -  $c$  is the minimum distance between adjacent sheds of the same diameter (Fig.8). This distance is important in rainfall conditions to avoid bridging between two successive sheds. According to present knowledge, a value of  $c$  in order of 30 mm or more fulfils this requirement.

For insulators having an overall length less than or equal to 550 mm, or for insulators with small shed overhang  $p$  (see clause 2) ( $p \leq 40$  mm) a value of  $c$  in the order of 20 mm is acceptable.

2. Ratio  $s/p$  between spacing and shed overhang - The ratio  $s/p$  describe the limitation on providing arbitrarily too high a leakage distance by either over dimensioning the shed overhang  $p$  or by unjustifiably increasing the number of sheds. The ratio is important for self-cleaning properties of insulators.

$s/p$  should be equal to or greater than 0.8. Field experience shows that this value can be reduced to 0.65 in the case of plain sheds (without ribs).

$s$  is the vertical distance between two similar points of successive sheds (spacing).

$p$  is the maximum shed overhang (Fig.8 and Fig.9).

3. Ratio  $l_d/d$  between creepage distance and clearance - The ratio  $l_d/d$  describe the use of the creepage in order to avoid local short-circuiting and should be lower than 5.

$d$  is the straight air distance measured between two points situated on the insulating part or between any point located on the insulating part and the other on a metal part.

$l_d$  is the part of the creepage path measured between the above two points.

4. Alternating sheds (see Fig.9) - The difference ( $p_1 - p_2$ ) between two consecutive shed overhangs is important in rain conditions to avoid bridging between them.

$p_1$  is the shed overhang of the larger shed

$p_2$  is the shed overhang of the smaller shed

This difference ( $p_1 - p_2$ ) should be in general greater than or equal to 15 mm.

5. Inclination of sheds - The inclination of sheds is important for the self-cleaning properties

6. Parameters characterizing the entire insulator - The insulators, as far as their performance under pollution is concerned, can be designed in different manners. When the pollution severity increases, a solution to satisfy the specific creepage concept is obviously to increase the length of the insulator while keeping the same shed profile. The different parameters given above characterize local parts of a profile, but it still necessary to characterize the entire insulator by the creepage factor (C.F.) and by the profile factor (P.F.). These two factors depend on the pollution severity.

C.F. has a theoretical and scientific meaning, while P.F. is an empirical quantity derived from experience.

#### 6.1. Creepage factors C. F.

The creepage factor, C.F., is equal to  $l_1 / S_2$

Where

$l_1$  is the total creepage distance of an insulator, and

$S_2$  is the arcing distance, which is the shortest distance in air, outside the insulator, not considering arcing horns, between the metallic parts to which the voltage is normally applied.

$l$  being the creepage distance of the insulated leakage path measured between the two points which defines  $s$ .

It is advisable to keep:

P.F. above 0.8 for pollution level I and II,

P.F. above 0.7 for pollution level III and IV

It is advisable to keep:

C.F.  $\leq 3.50$  for pollution levels I and II

C.F.  $\leq 4$  for pollution levels III and IV

## 6.2. Profile factor P.F.

The P.F. is defined as the ratio of the simplified leakage distance to the actual insulating creepage distance measured between the two points, which define the spacing  $s$ .

The simplified leakage distance is the sum of:

$2p + s$  for insulators in Fig.8

$2p + 2p + s$  for insulators in Fig.9

Thus, P.F. is equal to:

$(2p + s) / l$  for insulators in Fig.8

$(2p_1 + 2P_2 + s) / l$  for insulators in Fig.9

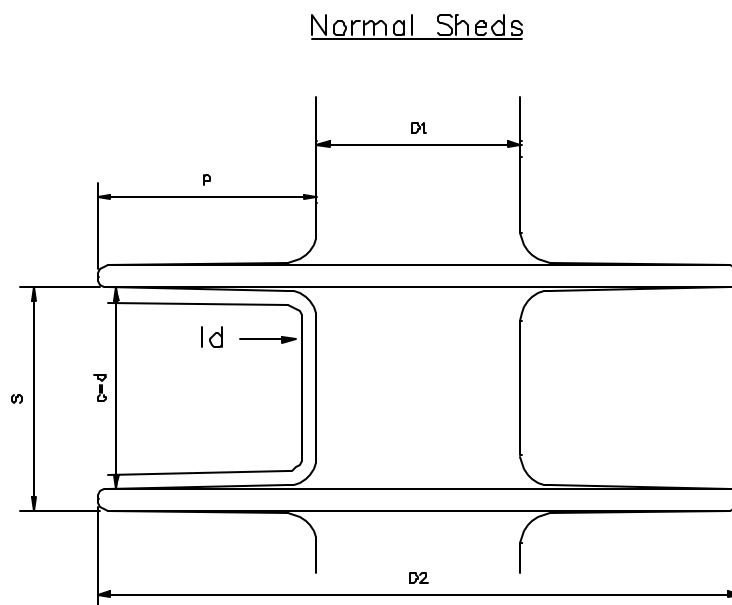


Fig. 8

## Alternating Sheds

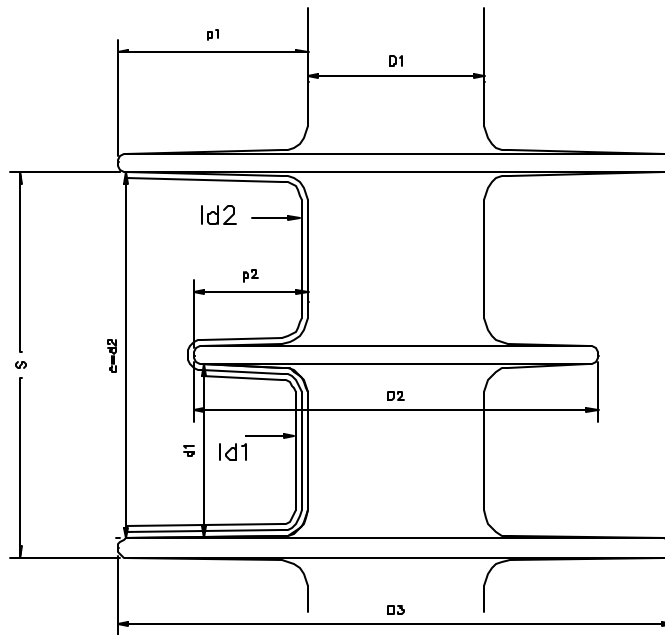


Fig. 9

## Appendix – B

### Guide for Sizing Insulator for High Voltage Transmission Lines

#### Basic impulse insulation level or basic insulation level (BIL)

It is the reference levels expressed in impulse crest (peak) voltage with a standard wave not longer than a  $1.2 \times 50 \mu s$  wave. System insulation as calculated by suitable methods shall be equal or greater than the BIL. The withstand voltage is the level that the insulator will withstand for a given length of time or number of applications without disruptive discharge occurring, i.e. a failure of insulation resulting in a collapse of voltage and passage of current (sometimes termed 'sparkover' or 'flashover' when the discharge is on the external surface). The BIL is usually expressed as a per unit of the peak (crest) value of the normal operating voltage to earth.

Example: for a maximum operating voltage of 362 kV.

$$1 \text{ p.u.} = \sqrt{2} \times (362 / \sqrt{3}) = 300 \text{ kV}$$

$$\text{so that a BIL of } 2.7 \text{ p.u.} = 810 \text{ kV}$$

Recommended BIL at various operating voltages, see Table-1

Up to an operating voltage of 345 kV the insulation level is determined by lightning, and the standard impulse consideration is suffice. Above this value, however, the overvoltage resulting from switching are higher in magnitude and therefore they decide the insulation.

The design withstand level is selected by specifying the risk of flashover, e.g. for 550 kV towers a 0.13 percent probability has been used. At 345 kV, design is carried out by accepting a switching impulse level of 2.7 p.u. which corresponds to the lightning level. At 500 kV, however, a 2.7 p.u. Switching impulse would require 40 per cent more tower insulation than that governed by lightning. The tendency is therefore for the design switching impulse level to be forced lower



with increasing system operating voltage and for control of the surges to be made by the more widespread use of resistance switching in the circuit breakers or use of surge diverters. For example, for the 500 kV networks the level is 2 p.u. and at 765 kV it is reduced to 1.7 p.u. if further increases in system voltage occur, it is hoped to decrease the level to 1.5 p.u.

### Capacitance Model

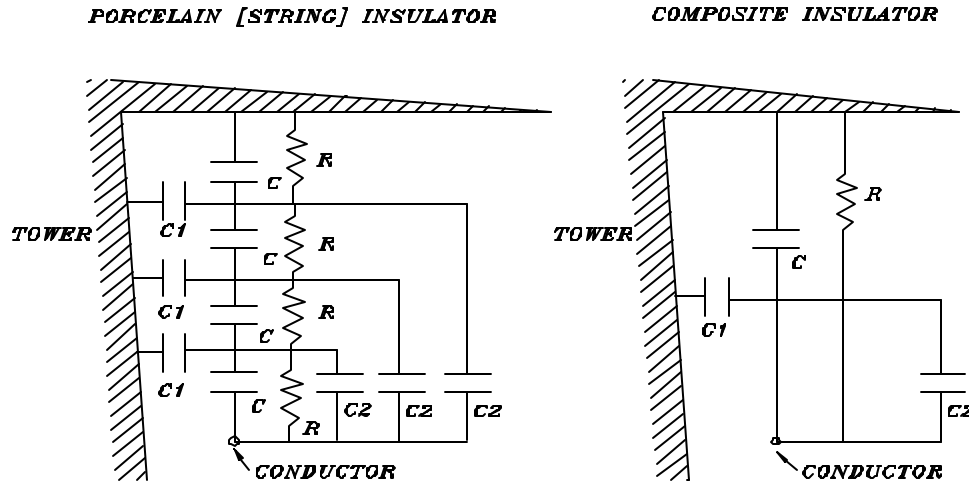


Fig. 10

Equivalent Capacitance:

$$\text{Porcelain (String) Insulator} = C_{eq} + C_{1eq} + C_{2eq}$$

$$\text{Composite Insulator} = C + C_1 + C_2$$

Where

C = self-capacitance of disc or composite insulator

C<sub>1</sub> = capacitance insulator to earth

C<sub>2</sub> = capacitance insulator to line

R = leakage resistance

Owing to the capacitance existing between the insulator, conductor, and tower, the distribution of voltage along the insulator is not uniform, the insulator part nearer the conductor being the more highly stressed. Methods of calculating this voltage distribution are available, but extra care may be given of the value owing to the shunting effect of the leakage resistance. Two models, one porcelain (string) insulator and second for composite insulator, illustrate the capacitance distribution (see Fig.10). This resistance depends on the presence of pollution of the insulator surfaces and is considerably modified by rain and fog.

### Line Capacitance and Inductance

The parameters of interest for circuit analysis are inductance, capacitance, resistance, and leakage resistance.

The inductance of a single-wire line

$$= \mu_0 / 4\pi [1 + 4 \ln \{(d - r) / r\}] \text{ H / m}$$

Where d is the distance between the centers, and r is the radius, of the conductors.

When performing load flow and balanced-fault analysis on three-phase system it is usual to consider one phase only with the appropriate angular adjustments made for the other two phases. Therefore, phase voltages are used and the inductances and capacitances are the equivalent phase or lone-to-neutral values. For a three-phase line with equilateral spacing the inductance and capacitance with respect to the hypothetical neutral conductor are used, and this inductance can be shown to be half the loop inductance of the single-phase line, i.e. the inductance of one conductor.

The line-neutral inductance for equilateral spacing  

$$= \mu_0 / 8\pi [1 + 4 \ln \{(d - r) / r\}] \text{ H / m}$$

The capacitance of a single-phase line

$$C = \pi \epsilon_0 / [\ln(d - r) / r] \text{ F / m}$$

With three-phase conductors spaced equilaterally, the capacitance of each line to be hypothetical neutral is double that for the two-wire circuit, i.e.

$$C = 2\pi \epsilon_0 / [\ln(d - r) / r] \text{ F / m}$$

In practice, the conductors are rarely spaced in the equilateral formation, and it can be shown that the average value of inductance or capacitance for any formation of conductors can be obtained by the representation of the system by one of equivalent equilateral spacing. The equivalent spacing  $d_{eq}$  between conductors is given by

$$d_{eq} = \sqrt[3]{d_{12} \cdot d_{23} \cdot d_{31}}$$

Often, two three-phase circuits are electrically in parallel; if physically remote from each other, the reactances of the lines are identical. When the two circuits are situated on the same towers, however, the magnetic interaction between them should be taken into account. The use of bundle conductors, i.e. more than one conductor per insulator, reduces the reactance; it also reduces conductor-surface voltage gradients and hence corona loss and radio interference. Unsymmetrical conductor spacing results in different inductances for each phase which causes an unbalanced voltage drop, even when the load currents are balanced. The residual or resultant voltage or current induces unwanted voltage into neighboring communication lines. This can be overcome by the interchange of conductor positions at regular intervals along the route, a practice known as transposition. In practice, lines are rarely transposed at regular intervals and transposition is carried out where physically convenient, e.g. at substations. In short lines the degree of unbalance existing without transposition is small and may be neglected in calculations.

## Corona

The high voltages at which transmission lines operate produce electric field strengths of sufficient intensity to ionize the air near the phase conductors. This effect, called corona, is detectable as a buzzing, hissing sound and visually as a faint bluish aura surrounding the conductors. The critical field intensity  $E_c$  at which this ionization begins for dry air is

$$E_c = 30 \sqrt{dm} [1 + (0.3 / \sqrt{dm} r)] \text{ kV/cm}$$

Where

$d$  = relative air density =  $3.92 b/T$ .

$b$  = atmospheric pressure in cm Hg.

$T$  = absolute temperature in K.

$m$  = stranding factor ( $0 < m < 1$ ).

$m = 1$ , smooth cylinder.

$m = 0.9$ , weathered ACSR.

$r$  = conductor radius in cm.

Corona ring on the insulator reduces electric field intensity levels in the conductor vicinity. Corona has three undesirable features: audible noise, power loss, and radio interference. Audible noise due to corona may be divided into two components: 120 Hz hum and random noise (sizzling sound). Both are measured in decibels:

$$\text{dB} = 20 \log P/P_0$$

Where

$P$  = sound pressure in bar.

$P_0$  = reference pressure in bar

= 0.2 nbar

= threshold of human hearing at 1000 Hz.

The average human ear does not respond equally to all frequencies, being most sensitive to sounds between 2 and 3 kHz. Thus, sound measurements are typically made through a weighting network, which attempts to match the ear's frequency variable response. One such network is network A, and measurements so weighted are measured in dB (A). Even though audible noise may be readily measured, deciding in maximum design levels is an extremely complex problem. Measuring human noise tolerance is complicated; relative noise levels are provided in Table-3. A rough but typical maximum level might be 52 dB (A) at 30 m from the line under high humidity atmospheric conditions (which maximize corona).

An expression for fair weather single-phase corona loss is:

$$P = (3.37 \times 10^{-5} fV^2F) / [\log_{10}(2s/d)]^2 \quad \text{kW/phase mile}$$

Where

$V$  = rms line to neutral voltage in kV.

$f$  = frequency in Hz.

$F$  = corona factor determined by test.

$s$  = phase spacing.

$d$  = conductor diameter.

The power loss is small computing to about 1 to 2 kW/km for 500 kV, 3 conductors per phase bundle. However, corona losses increase dramatically when the line encounters precipitation in any form, with frost creating the worst situation. Losses can run as high as 30 kW/km, with an average of about 2.4 kW/km expected for line design similar to our 500 kV example located in the Southeastern United States.

Radio frequency (RF) interference is also a problem, occurring essential over a frequency range from 0.2 to 4 MHz, centered around  $f_0 = 0.8$  MHz. Precipitation increases RF interference, as does high humidity. As conductor age, RF interference levels tend to decrease.

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