1.1 BEWLEY LATTICE DIAGRAM

This is a convenient diagram devised by Bewley, which shows at a glance the position and direction of motion of every incident, reflected, and transmitted wave on the system at every instant of time. The diagram overcomes the difficulty of otherwise keeping track of the multiplicity of successive reflections at the various junctions.

Consider a transmission line having a resistance **r**, an inductance **l**, a conductance **g** and a capacitance **c**, all per unit length.

If _ is the propagation constant of the transmission line, and **E** is the magnitude of the voltage surge at the sending end, then the magnitude and phase of the wave as it reaches any section distance **x** from the sending end is **Ex** given by.

$$E = E .e = E .e = E e e - x - (+ j) x - x - j xx \gamma \alpha \beta \alpha \beta$$

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Where,

e **-** represents the attenuation in the length of line x

e-^{j} **-** represents the phase angle change in the length of line x

Therefore,

- Attenuation constant of the line in neper/km
- Phase angle constant of the line in rad/km.

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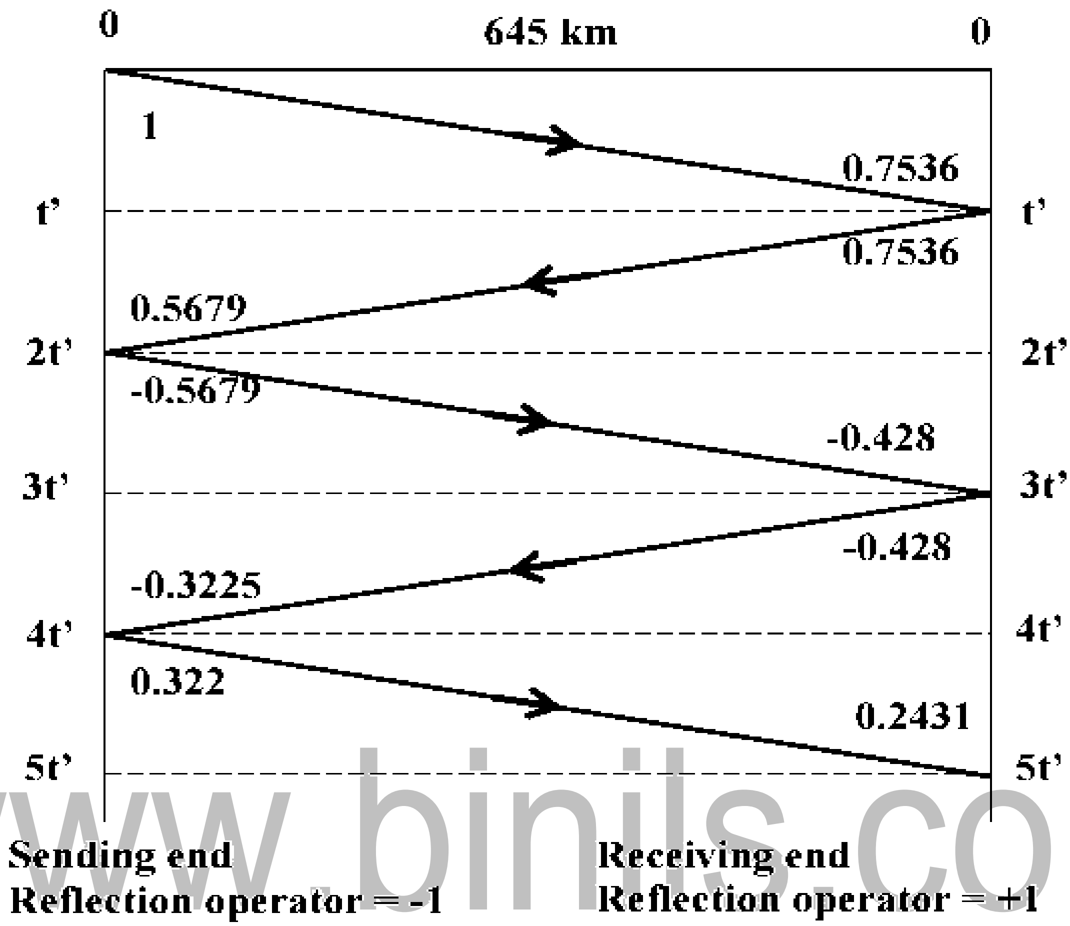

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Figure 1.1 Bewley Lattice Diagram

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 76]

It is also common for an attenuation factor k to be defined corresponding to the length of a particular line. i.e.

k = e for a line of length l.

When a voltage surge of magnitude unity reaches a junction between two sections with surge impedances Z_1 and Z_2, then a part is transmitted and a part is reflected back. In traversing the second line, if the attenuation factor is k, then on reaching the termination at the end of the second line its amplitude would be reduced. The lattice diagram may now be constructed as follows. Set the ends of the lines at intervals equal to the time of transit of each line. If a suitable time scale is chosen, then the diagonals on the diagram show the passage of the waves.

In the Bewley lattice diagram, the following properties exist.

- All waves travel downhill, because time always increases.
- The position of any wave at any time can be deduced directly from the diagram.
- The total potential at any point, at any instant of time is the superposition of all the waves which have arrived at that point up until that instant of time, displaced in position from each other by intervals equal to the difference in their time of arrival.
- The history of the wave is easily traced. It is possible to find where it came from and just what other waves went into its composition.
- Attenuation is included, so that the wave arriving at the far end of a line corresponds to the value entering multiplied by the attenuation factor of the line.

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1.2 NATURAL CAUSES OF OVER VOLTAGES

Examination of over voltages on the power system includes a study of their magnitudes, shapes, durations, and frequency of occurrence. The study should be performed at all points along the transmission network to which the surges may travel.

Types of Overvoltage

- The voltage stresses on transmission network insulation are found to have a variety of Origins.
- In normal operation AC (or DC) voltages do not stress the insulation severely.
- Over voltage stressing a power system can be classified into two main types:

External overvoltage: generated by atmospheric disturbances of these disturbances, lightning is the most common and the most severe. **Internal over voltages**: generated by changes in the operating conditions of the network.

Lightning Over voltages

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Lightning is produced in an attempt by nature to maintain dynamic balance between the positively charged ionosphere and the negatively charged earth.

Over fair-weather areas there is a downward transfer of positive charges through the global air-earth current. This is then counteracted by thunderstorms, during which positive charges are transferred upward in the form of lightning. During thunderstorms, positive and negative charges are separated by the movements of air currents forming ice crystals in the upper layer of a cloud and rain in the lower part.

The cloud becomes negatively charged and has a larger layer of positive charge at its top. As the separation of charge proceeds in the cloud, the potential difference between the centers of charges _increases and the vertical electric field along the cloud also increases. The total potential difference between the two main charge centers may vary from l00 to 1000 MV. Only a part of the total charge-several hundred coulombs is released to earth by lightning; the rest is consumed in inter cloud discharges. The height of the thundercloud dipole above earth may reach5 km in tropical regions. Established by a stepped discharge called a leader stroke. The leader is initiated by a breakdown between polarized water droplets at the cloud base caused by the high electric field, or a discharge between the negative charge mass in the lower cloud and the positive charge pocket below it. (Figure 1.2) As the downward leader approaches the earth, an upward leader begins to proceed from earth before the former reaches earth. The upward leader joins the downward one at a point referred to as the striking point. This is the start of the return stroke, which progresses upward like a travelling wave on a transmission line.

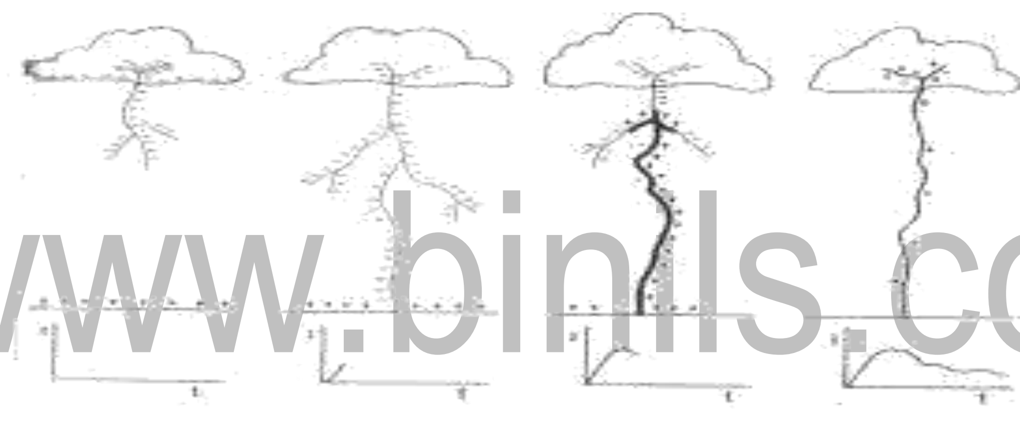

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Figure: 1.2.1 Developmental Stages Of A Lighting Flash And The Corresponding Current Surge

[Source: "High Voltage Engineering" by C.L. Wadhwa, page: 56]

LIGHTNING PHENOMENON

At the earthling point a heavy impulse current reaching the order of tens of kilo amperes occurs, which is responsible for the known damage of lightning. The velocity of progression of the return stoke is very high and may reach half the speed of light. he corresponding current.

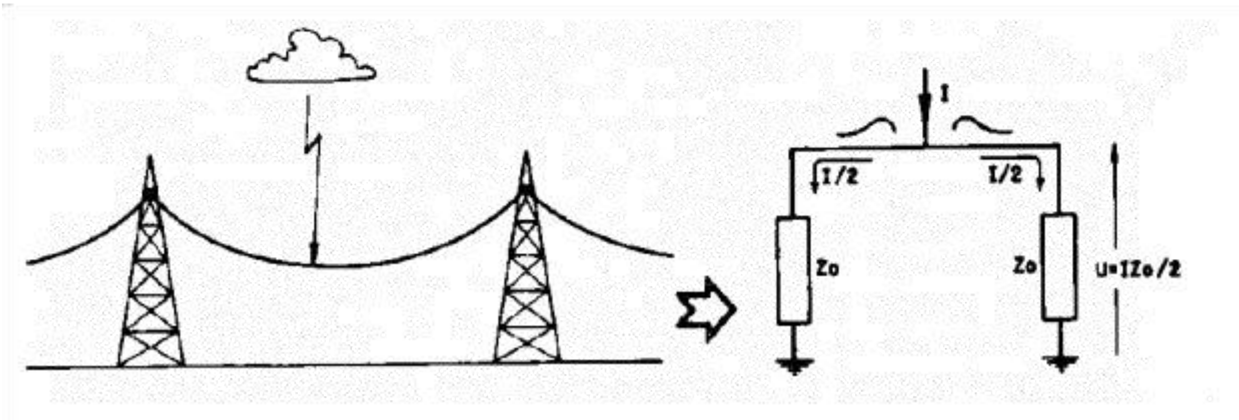

Figure 1.2.2 Developmental Lighting over voltage

[Source: "High Voltage Engineering" by C.L. Wadhwa, page: 59]

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EFFECT OF LIGHTNING

The impedance of the lightning channel itself is much larger than 1/2Zo (it is believed to range from l00to 3000 Ω).

- Lightning voltage surge will have the same shape characteristics.
- In practice the shapes and magnitudes of lightning surge waves get modified by their Reflections at points of discontinuity as they travel along transmission lines.
- Lightning strokes represent true danger to life, structures, power systems, and Communication networks.

Lightning is always a major source of damage to power systems where equipment Insulation may break down, under the resulting overvoltage and the subsequent high-Energy discharge.

Lightning has been a source of wonder to mankind for thousands of years. Scotland points out that any real scientific search for the first time was made into the phenomenon of lightning by Franklin in18th century. Before going into the various theories explaining the charge formation in a thunder cloud and the mechanism of lightning, it is desirable to review some of the accepted facts concerning the thunder.

Raindrops elongate and become unstable under an electric field, the limiting diameter being0.3 cm in a field of 100 kV/cm. A free falling raindrop attains a constant velocity with respect to the air depending upon its size. This velocity is 800 cms/sec. for drops of the size

0.25 cm dia. and is zero for spray. This means that in case the air currents are moving upwards with a velocity greater than 800 cm/sec, no rain drop can fall. Falling raindrops greater than 0.5 cm in dia become unstable and break up into smaller drops. When a drop is broken up by air currents, the water particles become positively charged and the air negatively charged. When ice crystal strikes with air currents, the ice crystal is negatively charged and the air positively charged.

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Wilson’s Theory of Charge Separation Wilson‘s theory is based on the assumption that a large number of ions are present in the atmosphere. Many of these ions attach themselves to small dust particles and water particles. It also assumes that an electric field exists in the earth‘s atmosphere during fair weather which is directed downwards towards the earth (Figure.1.4 (a)). The intensity of the field is approximately 1 volt/cm at the surface of the earth and decreases gradually with height so that at 9,500 m it is only about

0.02 V/cm. A relatively large raindrop (0.1 cm radius) falling in this field becomes polarized, the upper side acquires a negative.

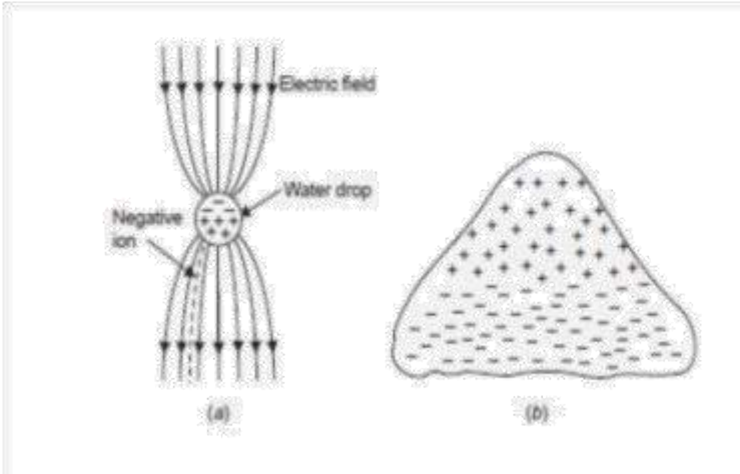

Figure:1.2.3 (a) Capture of negative ions by large falling drop (b) Charge separation in a thunder cloud according to Wilson's theory.

[Source: "High Voltage Engineering" by C.L. Wadhwa, page: 61]

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Wilson's Theory of Charge Separation

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polarized, the upper side acquires a negative charge and the lower side a positive charge. Subsequently, the lower part of the drop attracts –ve charges from the atmosphere which are available in abundance in the atmosphere leaving a preponderance of positive charges in the air.

The upwards motion of air currents tends to carry up the top of the cloud, the +ve air and smaller drops that the wind can blow against gravity. Meanwhile the falling heavier raindrops which are negatively charged settle on the base of the cloud. It is to be noted that the selective action of capturing –ve charges from the atmosphere by the lower surface of the drop is possible. No such selective action occurs at the upper surface. Thus in the original system, both the positive and negative charges which were mixed up, producing essentially a neutral space charge, are now separated.

Thus according to Wilson‘s theory since larger negatively charged drops settle on the base of the cloud and smaller positively charged drops settle on the upper positions of the cloud, the lower base of the cloud is negatively charged and the upper region is positively charged (Figure.1.4 (b)). **Simpson's and Scarse Theory** Simpson‘s theory is based on the temperature variations in the various regions of the cloud. When water droplets are broken due to air currents, water droplets acquire positive charges whereas the air is negatively charged. Also when ice crystals strike with air, the air is positively charged and the crystals negatively charged. The theory is explained with the help of Figure.

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cloud according to Simpson‘s theory Let the cloud move in the direction from left to right as shown by the arrow. The air currents are also shown in the diagram. If the velocity of the air currents is about 10 m/sec in the base of the cloud, these air currents when collide with the water particles in the base of the cloud, the water drops are broken and carried upwards unless they combine together and fall down in a pocket as shown by a pocket of positive charges (right bottom region in Fig. 7.23). With the collision of water particles we know the air is negatively charged and the water particles positively charged. These negative charges in the air are immediately absorbed by the cloud particles which are carried away upwards with the air currents. The air currents go still higher in the cloud where the moisture freezes into ice crystals.

The air currents when collide with ice crystals the air is positively charged and it goes in the upper region of cloud whereas the negatively charged ice crystals drift gently down in the lower region of the cloud. This is how the charge is separated in a thundercloud. Once the charge separation is complete, the conditions are now set for a lightning stroke.

Mechanism of Lightning Stroke Lightning phenomenon is the discharge of the cloud to the ground. The cloud and the ground form two plates of a gigantic capacitor and the dielectric medium is air. Since the lower part of the cloud is negatively charged, the earth is positively charged by induction. Lightning discharge will require the puncture of the air between the cloud and the earth. For breakdown of air at STP condition the electric field required is 30 kV/cm peak. But in a cloud where the moisture content in the air is large and also because of the high altitude (lower pressure) it is seen that for breakdown of air the electric field required is only 10 kV/cm. The mechanism of lightning discharge is best explained with the help of Fig. 1.6. After a gradient of approximately 10 kV/cm is set up in the cloud, the air surrounding gets ionized. At this a streamer (Fig. 1.6(a)) starts from the cloud towards the earth which cannot be detected with the naked eye; only a spot travelling is detected.

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The current in the streamer is of the order of 100 amperes and the speed of the streamer is0.16 m/μ sec. This streamer is known as pilot streamer because this leads to the lightning phenomenon. Depending upon the state of ionization of the air surrounding the streamer, it is branched to several paths and this is known as stepped leader (Fig.1.6(b)). The leader steps are of the order of 50 m in length and are accomplished in about a microsecond. The charge is brought from the cloud through the already ionized path to these pauses. The air surrounding these pauses is again ionized and the leader in this way reaches the earth (Fig.1.6(c)).Once the stepped leader has made contact with the earth it is believed that a power return stroke(Fig. 1.6(c)) moves very fast up towards the cloud through the already ionized path by the leader. This streamer is very intense where the current varies between 1000 amps and 200,000 amps and the speed is about 10% that of light. It is here where the

–ve charge of the cloud is being neutralized by the positive induced charge on the earth (Fig. 1.6 (d)).

It is this instant which gives rise to lightning flash which we observe with our naked eye. There may be another cell of charges in the cloud near the neutralized charged cell. This charged cell will try to neutralize through this ionized path. This streamers known as dart leader (Fig.1.6 (e)). The velocity of the dart leader is about 3% of the velocity of light. The effect of the dart leader is much more severe than that of the return stroke. The discharge current in the return streamer is relatively very large but as it lasts only for a few microseconds the energy contained in the streamer is small and hence this streamer is known as cold lightning stroke whereas the dart leader is known as hot lightning stroke because even though the current in this leader is relatively smaller but it lasts for some milliseconds and therefore the energy contained in this leader is relatively larger.

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It is found that each thunder cloud may contain as many as 40 charged cells and a heavy lightning stroke may occur. This is known as multiple stroke. 1.2.3 Line Design Based On Lightning The severity of switching surges for voltage 400 kV and above is much more than that due to lightning voltages. All the same it is desired to protect the transmission lines against direct lightning strokes. The object of good line design is to reduce the number of outages caused by lightning. To achieve this following actions are required. (I) The incidence of stroke on to power conductor should be minimized. (ii) The effect of those strokes which are incident on the system should be minimized.

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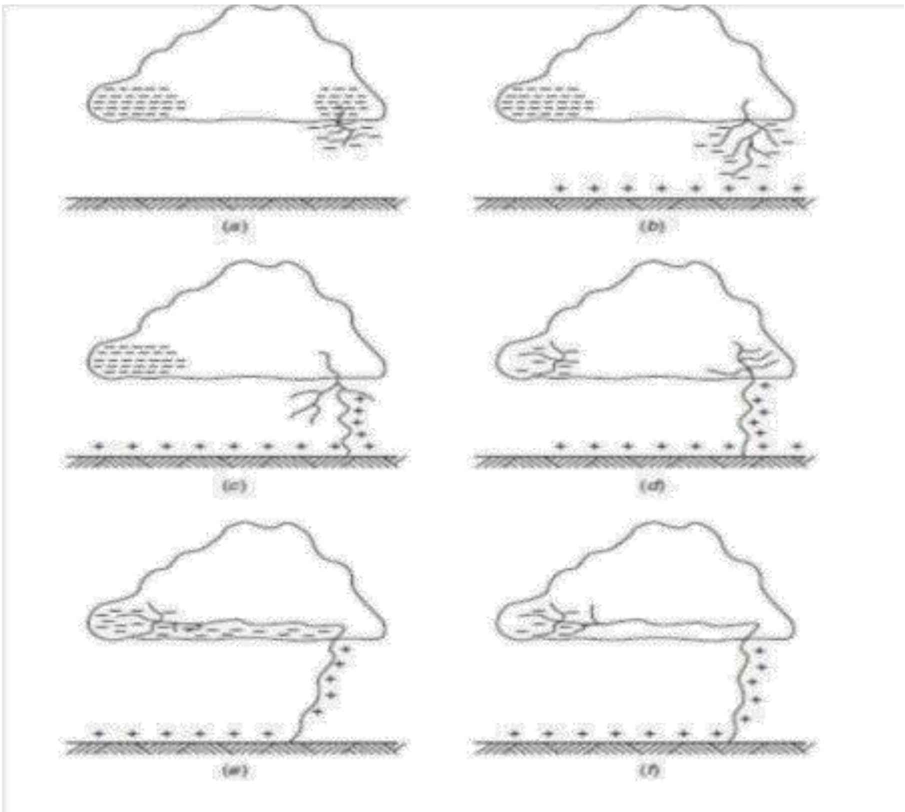

Figure 1.2.4 Lightning mechanism

[Source: "High Voltage Engineering" by C.L. Wadhwa, page: 66]

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1.3 CORONA AND ITS EFFECT

Corona is a phenomenon that has the capability for degrading insulators, and causing systems to fail. In this discussion, formulas are provided to calculate the voltage at which corona occurs, and a mention is made of a useful application for corona.Corona, also known as partial discharge, is a type of localized emission resulting from transient gaseous ionization in an insulation system when the voltage stress, i.e., voltage gradient, exceeds a critical value.

The ionization is usually localized over only a portion of the distance between the electrodes of the system. Corona can occur within voids in insulators as well as at the conductor/insulator interface.

Corona Inception

Corona inception voltage is the lowest voltage at which continuous corona of specified pulse amplitude occurs as the applied voltage is gradually increased. Corona inception voltage decreases as the frequency of the applied voltage increases.Corona can occur in applications as low as 300V.

Corona Extinction

Corona extinction voltage is the highest voltage at which continuous corona of specified pulse amplitude no longer occurs as the applied voltage is gradually decreased from above the corona inception value. Thus, once corona starts, the voltage must be decreased to get it to stop.

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Corona Detection

Corona can be visible in the form of light, typically a purple glow, as corona generally consists of micro arcs. Darkening the environment can help to visualize the corona. We once attached a camera (set to a long exposure time) to a viewing window in a vacuum chamber to confirm that corona was indeed occurring, and thereby confirming our suspicions. You can often hear corona hissing or cracking. Thus, stethoscopes or ultrasonic detectors (assuming you can place them in a safe location) can be used to find corona. In addition, you can sometimes smell the presence of ozone that was produced by the corona. (Who said you don’t use all your senses when troubleshooting?). It is important that the voltage source and the coupling capacitor exhibit low noise so as not to obscure the corona. In its simplest form the pulse detection network is a resistor monitored by an oscilloscope. Don't dismiss this simple technique as crude, as we once used this method to observe the presence of corona in an improperly terminated high voltage connector, even after a dedicated corona tester failed to find any.

Corona Effects

The presence of corona can reduce the reliability of a system by degrading insulation. While corona is a low energy process, over long periods of time, it can substantially degrade insulators, causing a system to fail due to dielectric breakdown. The effects of corona are cumulative and permanent, and failure can occur without warning.

Corona causes:

- Light
- Ultraviolet radiation
- Sound (hissing, or cracking as caused by explosive gas expansions)
- Ozone
- Nitric and various other acids
- Salts, sometimes seen as white powder deposits
- Other chemicals, depending on the insulator material
- Mechanical erosion of surfaces by ion bombardment
- Heat (although generally very little, and primarily in the insulator)
- Carbon deposits, thereby creating a path for severe arcing.

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Beneficial Corona

The sound generation effects of corona can be utilized to build high accuracy audio speakers! The major advantage is that there is zero mass that needs to be moved to create the sound, so that transient response is improved.

Corona Prevention

Corona can be avoided by minimizing the voltage stress and electric field gradient. This is accomplished by using utilizing good high voltage design practices, i.e., maximizing the distance between conductors that have large voltage differentials, using conductors.

1.4 OVER VOLTAGES DUE TO SWITCHING SURGES

The increase in transmission voltages needed to fulfill the required increase in transmitted powers, switching surges have become the governing factor in the design of insulation for EHV and UHV systems. In the meantime, lightning over voltages come as a secondary factor in these networks. There are two fundamental reasons for this shift in relative importance from lightning to switching surges as higher transmission voltages are called for:

- Overvoltages produced on transmission lines by lightning strokes are only slightly dependent on the power system voltages. As a result, their magnitudes relative to the system peak voltage decrease as the latter is increased.
- External insulation has its lowest breakdown strength under surges whose fronts fall in the range 50-500 micro sec., which is typical for switching surges.
- According to the International Electro-technical Commission(IEC) recommendations, all equipment designed for operating voltages above 300 kV should be tested under switching impulses (i.e., laboratory-simulated switching surges).

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Temporary over voltages

The purpose of this Guide is to provide information on transient and temporary over voltages and currents in end-user AC power systems. With this information in hand, equipment designers and users can more accurately evaluate their operating environment to determine the need for surge protective devices (SPDs) or other mitigation schemes. The Guide characterizes electrical transmission and distribution systems in which surges occur, based upon certain theoretical considerations as well as on the data that have been recorded in interior locations with particular emphasis on industrial environments. There are no specific mathematical models that simulate all surge environments; the complexities of the real world need to be simplified to produce a manageable set of standard surge tests. To this end, a scheme to classify the surge environment is presented.

operational upset. Surge protective devices acting primarily on the voltage are often applied to divert damaging surges, but the upset can require other remedies.

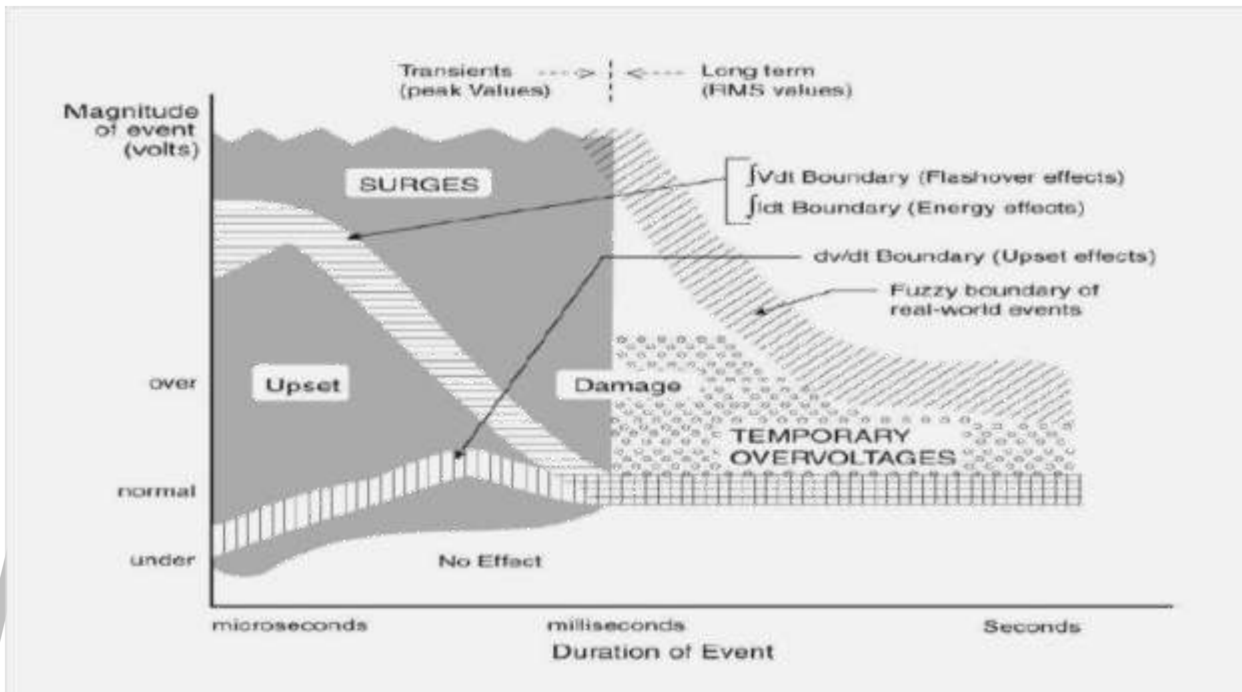

Figure 1.4.1 Simplified relationship among voltage, duration, rate of change, and effect on equipment.

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 110]

Temporary over voltages represent a threat to equipment as well as to any surge protective devices that may have been provided for the mitigation of surges. The scope of this Guide includes temporary over voltages only as a threat to the survival of SPDs, and therefore includes considerations on the selection of suitable SPDs. No equipment performance requirements are specified in this Guide. What is recommended is a rational, deliberate approach to recognizing the variables that need to be considered simultaneously, using the information presented here to define a set of representative situations.

Answers may not exist that address all of the questions raised by the considerations listed above. In particular, those related to specific equipment sensitivities, both in terms of component failure and especially in terms of processing errors, might not be available to the designer. The goal of the reader may be simply selecting the most appropriate device from among the various surge protective devices available and meet the requirements of the equipment that they must protect. Subsets of the considerations in this section might then apply, and the goal of the reader may then be the testing of various surge protective devices under identical test conditions. The following can guide the reader in identifying parameters, seeking further facts, or quantifying a test plan.

Desired Level of Protection

The desired level of protection can vary greatly depending upon the application. For example, in applications not involving online performance, protection may only be needed to reduce hardware failures by a certain percentage. In other cases, such as data processing or critical medical or manufacturing processes, any interruption or upset of a process might be unacceptable. Hence, the designer should quantify the desired goal with regard to the separate questions of hardware failure and process interruption or upset.

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Equipment Sensitivities

Specific equipment sensitivities should be defined in concert with the above mentioned goals. The sensitivities (immunity) will be different for hardware failure or process upset. Such definitions might include: maximum amplitude and duration of the surge remnant that can be tolerated, wave-form or energy sensitivity, et cetera.

Power Environment

The applicable test waveforms recommended in this Guide should be quantified on the basis of the location categories and exposure levels as explained in the corresponding clauses of the Guide. The magnitude of the rams voltage, including any anticipated variation, should be quantified. Successful application of surge protective devices requires taking into consideration occasional abnormal occurrences. It is essential that an appropriate selection of the SPD limiting voltage is based on actual characteristics of the mains voltage.

Performance of Surge Protective Devices

Evaluation of a surge protective device should verify a long life in the presence of both the surge and electrical system environments described above. At the same time, its remnant and voltage levels should provide a margin below the immunity levels of the equipment in order to achieve the desired protection. It is essential to consider all of these parameters simultaneously. For example, the use of a protective device rated very close to the nominal system voltage might provide attractive remnant figures, but can be unacceptable when a broad range of occasional abnormal deviations in the amplitude of the mains waveform are considered. Lifetime or overall performance of the SPDs should not be sacrificed for the sake of a low remnant.

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Test Environment

The surge test environment should be carefully engineered with regard to the preceding considerations and any other parameters that are important to the user. A typical description of the test-environment includes definitions of simultaneous voltages and currents, along with proper demonstrations of short-circuit.

It is important to recognize that the specification of an open-circuit voltage without simultaneous short-circuit current capability is meaningless. Cost Effectiveness The cost of surge protection can be small, compared to overall system cost and benefits in performance. Therefore, added quality and performance in surge protection may be chosen as a conservative engineering approach to compensate for unknown variables in the other parameters. This approach can provide excellent performance in the best interests of the user, while not significantly affecting overall system cost.

Definitions

The definitions given here have been developed by several standards-writing organizations and have been harmonized

Back Flashover (Lightning):

A flashover of insulation resulting from a lightning strike to part of a network or electrical installation that is normally at ground potential. Blind Spot: A limited range within the total domain of application of a device, generally at values less than the maximum rating. Operation of the equipment or the protective device itself might fail in that limited range despite the device's demonstration of satisfactory performance at maximum ratings.

Clamping Voltage:

Deprecated term. See measured limiting voltage.

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Combination Surge (Wave): A surge delivered by an instrument which has the inherent capability of applying a 1.2/50 us voltage wave across an open circuit, and delivering an 8/20 us current wave into a short circuit. The exact wave that is delivered is determined by the instantaneous impedance to which the combination surge is applied.

Combined Multi-Port Spd: A surge protective device integrated in a single package as the means of providing surge protection at two or more ports of a piece of equipment connected to different systems (such as a power system and a communications system).

Coordination Of Spds (Cascade): The selection of characteristics for two or more SPDs to be connected across the same conductors of a system but separated by some decoupling impedance such that, given the parameters of the impedance and of the impinging surge, this selection will ensure that the energy deposited in each of the SPDs is commensurate with its rating.

Direct Strike: A strike impacting the structure of interest or the soil (or objects) within a few meters from the structure of interest. Energy Deposition: The time integral of the

power dissipated in a clamping-type surge protective device during a current surge of a specified waveform. Failure Mode: The process and consequences of device failure.
Leakage Current: Any current, including capacitive coupled currents, that can be conveyed from accessible parts of a product to ground or to other accessible parts of the product.

Lightning Protection System (LPS): The complete system used to protect a space against the effects of lightning. It consists of both external and internal lightning protection systems.
Lightning Flash To Earth: An electrical discharge of atmospheric origin between cloud and earth consisting of one or more strikes.
Lightning Strike: A single electrical discharge in a lightning flash to earth.

Mains: The AC power source available at the point of use in a facility. It consists of the set of electrical conductors (referred to by terms including service entrance, feeder, or branch circuit) for delivering power to connected loads at the utilization voltage level.
Maximum continuous operating voltage (MCOV): The maximum designated root-mean-square (rms) value of power-frequency voltage that may be applied continuously between the terminals of the arrester.

Measured limiting voltage: The maximum magnitude of voltage that appears across the terminals of the SPD during the application of an impulse of specified wave shape and amplitude.
Nearby strike: A strike occurring in the vicinity of the structure of interest.

Nominal System Voltage: A nominal value assigned to designate a system of a given voltage class.

Nominal Arrestor voltage: The voltage across the arrestor measured at a specified pulsed DC current, IN(dc), of specific duration. IN(dc) is specified by the arrestor manufacturer.
One-Port SPD: An SPD having provisions (terminals, leads, plug) for connection to the

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AC power circuit but no provisions (terminals, leads, receptacles) for supplying current to the AC power loads.

Open-circuit voltage (OCV) : The voltage available from the test set up (surge generator, coupling circuit, back filter, connecting leads) at the terminals where the SPD under test will be connected.

Point of strike: The point where a lightning strike contacts the earth, a structure, or an LPS.

Pulse life: The number of surges of specified voltage, current amplitudes, and wave shapes that may be applied to a device without causing degradation beyond specified limits. The pulse life applies to a device connected to an AC line of specified characteristics and for pulses sufficiently spaced in time to preclude the effects of cumulative heating.

Response time (arrestor): The time between the point at which the wave exceeds the limiting voltage level and the peak of the voltage overshoot. For the purpose of this definition, limiting voltage is defined with a 8/20 Its current waveform of the same peak Current amplitude as the waveform used for this response time.

Short-Circuit Current (Scc): The current which the test set up (surge generator, coupling circuit, back filter, connecting leads) can deliver at the terminals where the SPD under test will be connected, with the SPD replaced by bonding the two lead terminals. (Also sometimes abbreviated as SCI).

SPD disconnect or: A device for disconnecting an SPD from the system in the event of SPD failure. It is to prevent a persistent fault on the system and to give a visible indication of the SPD failure.

Surge Response Voltage: The voltage profile appearing at the output terminals of a protective device and applied to downstream loads, during and after a specified impinging surge, until normal stable conditions are reached.

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Surge Protective device (SPD): A device that is intended to limit transient overvoltages and divert surge currents. It contains at least one nonlinear component—a surge reference equalizer. A surge protective device used for connecting equipment to external systems whereby all conductors connected to the protected load are routed—physically and electrically—through a single enclosure with a shared reference point between the input and output ports of each system.

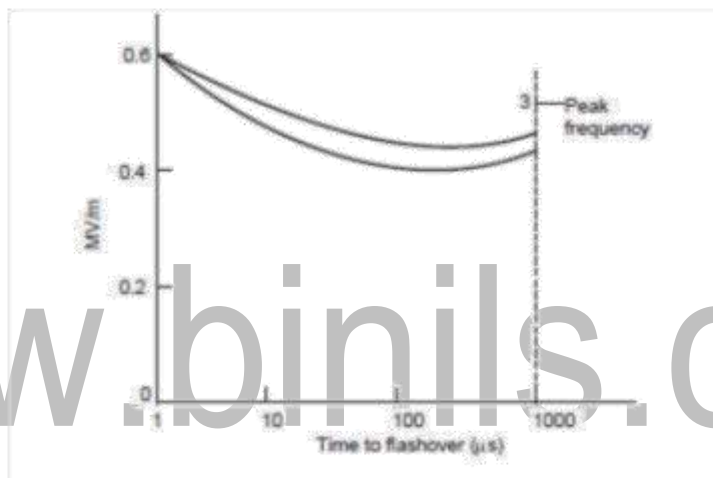

Figure.1.4.2 Variation of F.O. V/m as a function of time to flashover

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 121]

It can be seen that the standard impulse voltage (1/50 μ sec) gives highest flashover voltage and switching surge voltage with front time varying between 100 to 500 μ sec has lower flashover voltages compared to power frequency voltage. The flashover voltage not only depends upon the crest time but upon the gap spacing and humidity for the same crest time surges.

It has been observed that the switching surge voltage per meter gap length decreases drastically with increase in gap length and, therefore, for ultra high voltage system, costly design clearances are required. impulse is lower than the negative polarity switching impulse.

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It breakdown voltage of positive and gaps increases approximately 1.7% for 1 gm/m3 increase in absolute humidity. For testing purposes the switching surge has been standardized with wave front time 250 μ deceit is known that the shape of the electrode has a decided effect on the flashover voltage of the insulation.

Lot of experimental work has been carried on the switching surge flash over voltage furlong gaps using rod-plane gap and it has been attempted to correlate these voltages with switching surge flash over voltage of other configuration electrodes.

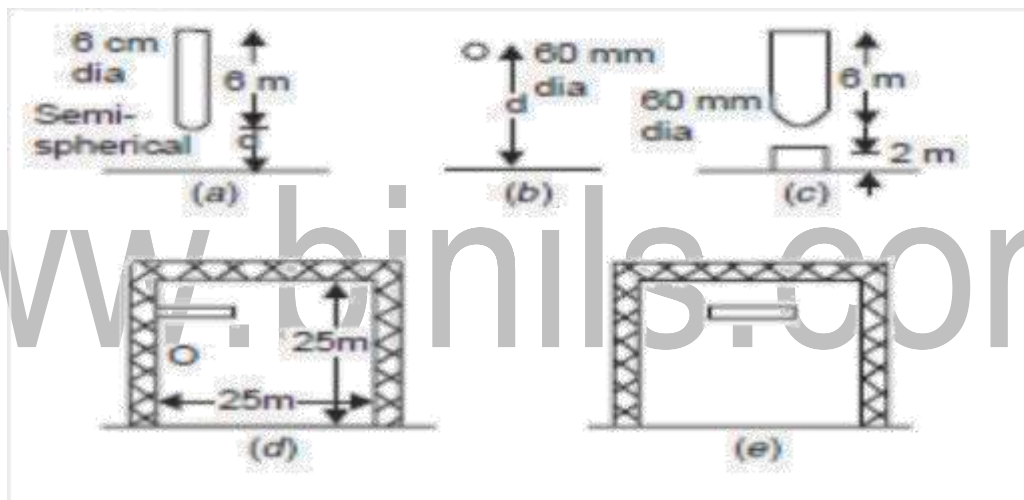

Figure.1.4.3 Different gap geometries

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 126]

1.5 PROTECTION AGAINST OVER VOLTAGES

Transients or surges on the power system may originate from switching and from other causes but the most important and dangerous surges are those caused by lightning. The lightning surges may cause serious damage to the expensive equipment in the power system (*e.g*. generators, transformers etc.) either by direct strokes on the equipment or by strokes on the transmission lines that reach the equip-ment as travelling waves. It is necessary to provide protection against both kinds of surges. The most commonly used devices for protection against lightning surges are :

(i) Earthing screen

(ii) Overhead ground wires

(iii) Lightning arresters or surge diverters

Earthing screen provides protection to power stations and sub-stations against direct strokes whereas overhead ground wires protect the transmission lines against direct lightning strokes. How- ever, lightning arresters or surge diverters protect the station apparatus against both direct strokes and the strokes that come into the apparatus as travelling waves. We shall briefly discuss these methods of protection.

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(i) The Earthing Screen

The power stations and sub-stations generally house expensive equipment. These stations can be protected against direct lightning strokes by providing earthing screen. It consists of a network of copper conductors (generally called shield or screen) mounted all over the electrical equipment in the sub-station or power station. The shield is properly connected to earth on atleast two points through a low impedance. On the occurrence of direct stroke on the station, screen provides a low resistance path by which lightning surges are conducted to ground. In this way, station equipment is protected against damage. The limitation of this method is that it does not provide protection against the travelling waves which may reach the equipment in the station.

Overhead Ground Wires

The most effective method of providing protection to transmission lines against direct lightning strokes is by the use of overhead ground wires For simplicity, one ground wire and one line conductor are shown. The ground wires are placed *above* the line conductors at such positions that practically all lightning strokes are intercepted by them (*i.e*. ground wires). The ground wires are grounded at each tower or pole through as low resistance as possible. Due to their proper location, the *ground wires will take up all the lightning strokes instead of allowing them to line conductors.

When the direct lightning stroke occurs on the transmission line, it will be taken up by the ground wires. The heavy lightning current (10 kA to 50 kA) from the ground wire flows to the ground, thus protecting the line from the harmful effects of lightning. It may be mentioned here that the degree of protection provided by the ground wires depends upon the footing resistance of the tower. Suppose, for example, tower-footing resistance is R_1 ohms and that the lightning current from tower to ground

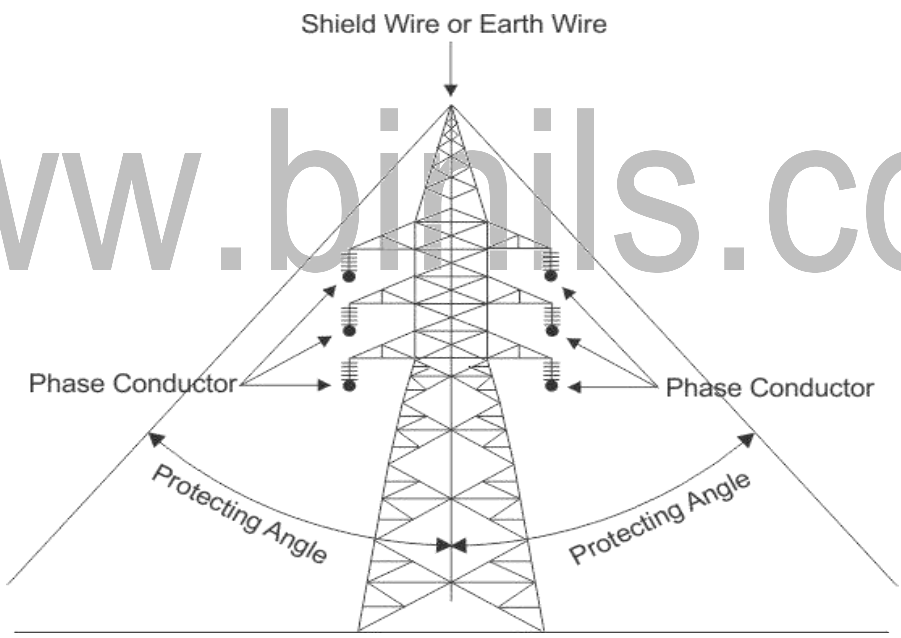

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Figure.1.5.1 Over Head Ground Wire

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 113]

Since V_t (= I_1R_1) is the approximate voltage between tower and line conductor, this is also the voltage that will appear across the string of insulators. If the value of V_t is less than that required to cause insulator flashover, no trouble results. On the other hand, if V_t is excessive, the insulator flashover may occur. Since the value of V_t depends upon tower-footing resistance R_1, the value of this resistance must be kept as low as possible to avoid insulator flashover.

Advantages:

- It provides considerable against direct lightning srokes on transmission lines.
- A grounding wire provides damping effect on any disturbance travelling along the line as it acts as a short-circuited secondary.
- It provides a certain amount of electrostatic shielding against external fields. Thus
- it reduces the voltages induced in the line conductors due to the discharge of a neighbouring cloud.

Disadvantages

- It requires additional cost.
- There is a possibility of its breaking and falling across the line conductors, thereby causing a short-circuit fault.

(ii) Lightning Arresters

The earthing screen and ground wires can well protect the electrical system against direct lightning strokes but they fail to provide protection against travelling waves which may reach the terminal apparatus. The lightning arresters or surge diverters provide protection against such surges. A lightning arrester or a surge diverter is a protective device which conducts the high voltage surges on the power system to the ground.

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Figure shows the basic form of a surge diverter. It consists of a spark gap in series with a non-linear resistor. One end of the diverter is connected to the terminal of the equipment to be protected and the other end is effectively grounded. The length of the gap is so set that normal line voltage is not enough to cause an arc across the gap but a dangerously high voltage will break down the air insulation and form an arc. The property of the non-linear resistance is that its resistance decreases as the voltage (or current) increases and vice-versa.

Action. The action of the lightning arrester or surge diverter is as under :

- Under normal operation, the lightning arrester is off the line *i.e.* it conducts **no current to earth or the gap is non-conducting.

➢ On the occurrence of overvoltage, the air insulation across the gap breaks down and an arc is formed, providing a low resistance path for the surge to the ground. In this way, the excess charge on the line due to the surge is harmlessly conducted through the arrester to the ground instead of being sent back over the line.

- ➢ It is worthwhile to mention the function of non-linear resistor in the operation of arrester. As the gap sparks over due to overvoltage, the arc would be a short-circuit on the power system and may cause power-follow current in the arrester. Since the characteristic of the resistor is to offer high resistance to high voltage (or current), it prevents the effect of a short-circuit. After the surge is over, the resistor offers high resistance to make the gap non-conducting. Two things must be taken care of in the design of a lightning arrester. Firstly, when the surge is over, the arc in gap should cease. If the arc does not go out, the current would continue to flow through the resistor and both resistor and gap may be destroyed. Secondly, *I R* drop (where *I* is the surge current) across the arrester when carrying surge current should not exceed the breakdown strength of the insulation of the equipment to be protected.

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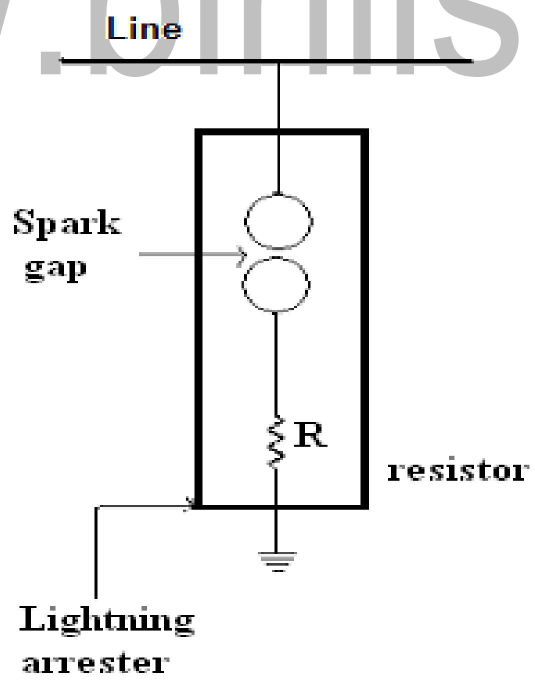

Figure.1.5.2 Lightning arrestor

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 115]