MODULE-4: Overvoltage Phenomenon and Insulation Coordination in Electric Power Systems

Syllabus

4.1 Natural Causes for Over voltages - Lightning Phenomenon,
4.2 Overvoltage due to Switching Surges ,System Faults and Other Abnormal conditions
4.3 Principles of Insulation Coordination on High Voltage and Extra High Voltage Power Systems

Course Objectives

To discuss overvoltage phenomenon and insulation coordination in electric power systems.

4.1 Natural Causes for Over voltages - Lightning Phenomenon

1. Lightning phenomenon is a **peak discharge** in which charge accumulated in the clouds **discharges** into a **neighbouring cloud or to the ground**.
2. The electrode separation, i.e. **cloud-to-cloud** or **cloud-to-ground** is very large, perhaps 10 km or more.

4.1.1 Charge formation in the clouds

1. The factors that contribute to the formation or accumulation of charge in the clouds are too many and uncertain. But during thunderstorms, **positive and negative charges become separated** by the heavy air currents with ice crystals in the upper part and rain in the lower parts of the cloud.
2. This charge separation depends on the height of the clouds, which range from **200 to 10,000 m**, with their charge centres probably at a distance of about **300 to 2000 m.**
3. The volume of the clouds that participate in lightning flashover are uncertain, but the charge inside the cloud may be as high as 1 to 100 C.
4. Clouds may have a potential as high as **10^7 to 10^8 V** with field gradients ranging from 100 V/cm within the cloud to as high as **10 kV/cm** at the initial discharge point The energies associated with the cloud discharges can be as high as **250 kWh**.
5. It is believed that the upper regions of the cloud are usually **positively charged,** whereas the lower region and the base are **predominantly negative** except the local region, near the base and the head, which is positive.

6. The maximum gradient reached at the ground level due to a charged cloud may be as high as **300 V/cm**, while the fair weather gradients are about 1 V/cm. A probable charge distribution model is given in Fig. 4.1 with the corresponding field gradients near the ground.

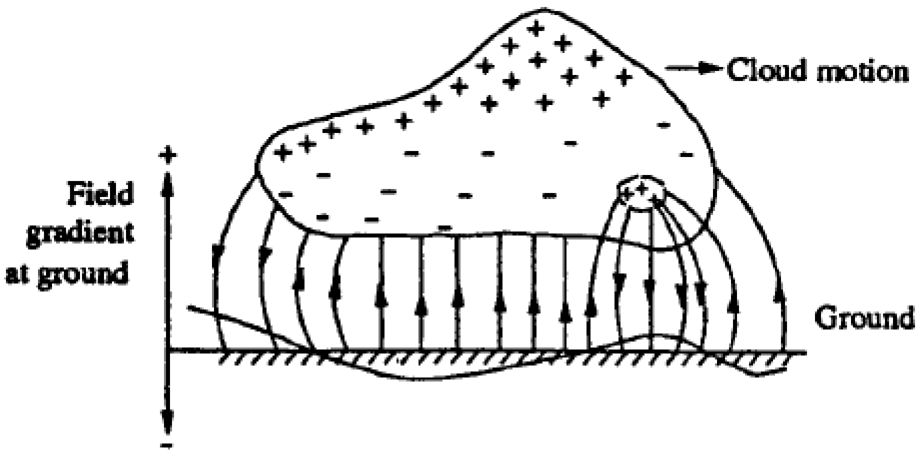


Fig. 4.1: Probable field gradient near the ground corresponding to the probable charge distribution in a cloud

Simpson's theory

1. According to the Simpson's theory (Fig. 8.2) there are three essential regions in the cloud to be considered for charge formation. Below region A, air currents travel Ground Cloud motion.Field gradient at ground above **800 cm/s**, and no raindrops fall through.
2. **In region A**, air velocity is high enough to break the falling raindrops causing a positive charge spray in the cloud and **negative charge in the air**.
3. The spray is blown upwards, but as the velocity of air decreases, the positively charged water drops recombine with the larger drops and fall again.
4. Thus **region A**, eventually becomes predominantly positively charged, while region B above it, becomes negatively charged by air currents.
5. In the upper regions in the cloud, the temperature is low (below freezing point) and only ice crystals exist
6. The impact of air on these crystals makes them negatively charged, thus the distribution of the charge within the cloud becomes as shown in Fig. 4.2.

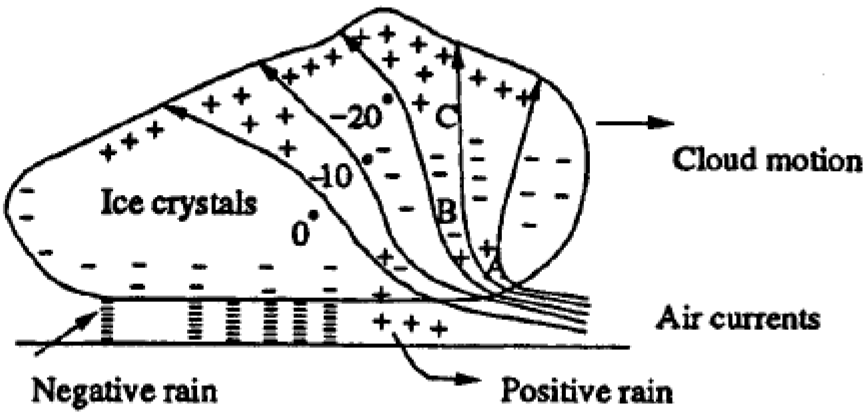


Fig. 4.2.: Cloud model according to Simpson's theory

Reynolds and Mason proposed modification, according to which the thunder clouds are developed at heights **1 to 2 km above the ground level** and may extend up **to 12 to 14 km** above the ground.

1. For thunder clouds and charge formation air currents, moisture and specific temperature range are required.
2. The air currents controlled by the temperature gradient move upwards carrying moisture and water droplets. The temperature is **O^{0}C** at about 4 km from the ground and may reach - **5O^{0}C** at about 12 km height. But water droplets do not freeze as soon as the temperature is O^{0}C. They freeze below - 4O^{0}C only as solid particles on which crystalline ice patterns develop and grow.
3. The larger the number of solid sites or nuclei present, the higher is the temperature (> -4O^{0}C) at which the ice crystals grow.
4. Thus in clouds, the effective freezing temperature range is around - 33^{0}C to - 4O^{0}C.
5. The water droplets in the thunder cloud are blown up by air currents and get super cooled over a range of heights and temperatures. When such freezing occurs, the crystals grow into large masses and due to their weight and gravitational force start moving downwards. Thus, a thunder cloud consists of super cooled water droplets moving upwards and large hail stones moving downwards.

Rate of Charging of Thunder Clouds

Mason considered thunder clouds to consist of a uniform mixture of positive and negative charges. Due to hail stones and air currents the charges separate vertically. If λ is a factor which depends on the conductivity of the medium, there will be a resistive leakage of charge from the electric field built up, and this should be taken into account for cloud charging.

Let E be the electric field intensity, v be the velocity of separation of charges, and ρ the charge density in the cloud. Then, the electric field intensity E is given by

$$\frac{dE}{dt} + \lambda E = \rho v$$

Hence
$$E = \frac{\rho v}{\lambda}[1 - \exp(-\lambda t)]$$

This equation assumes initially $E = 0$ at $t = 0$, the start of charge separation, i.e. there is no separation initially.

Let Q_s be the separated charge and Q_g be the generated charge, then

$$\rho = \frac{Q_g}{Ah}$$

and
$$E = \frac{Q_s}{A\varepsilon_0}$$

where ε_0 is the permittivity of the medium, A is the cloud area and h is the height of

$$Q_g = \frac{Q_s h}{v[1 - \exp(-\lambda t)]} = \frac{M}{v[1 - \exp(-\lambda t)]}$$

where $M = Q_s \cdot h$ = the electric moment of the thunder-storm.
The average values observed for thunder-clouds are:

time constant $= \frac{1}{\lambda} = 20$ s

electric moment $M = 110$ C-km and

time for first lightning flash to appear, $t = 20$ s

The velocity of separation of charges, $v = 10$ to 20 m/s.

Substituting these values, we get

$$Q_g = \frac{20{,}000}{v}\ \text{C}$$

$$= \frac{20{,}000}{20}\ \text{C} = 1000\ \text{C for } v = 20\ \text{m/s}$$

Calculations using Mason's theory show that a maximum charge transfer of $3 \times 10^{-3}\ T$ esu/cm^2 of contact surface for a contact period of 0.01 s, where T is the temperature difference.

4.1.2 Mechanism of Lightning Strokes

1. When the **electric Held intensity** at some point in the charge **concentrated cloud exceeds the breakdown value** of the moist ionized air (<= 10 kV/cm), an electric streamer with plasma starts towards the ground with a velocity of about **1/10 times that of the light**, but may progress only about 50 m or so before it comes to a halt emitting a bright flash of light.
2. The halt may be due to insufficient build-up of electric charge at its head and not sufficient to maintain the necessary field gradient for further progress of the streamer. But after a short interval of about 1OO µs, the streamer again starts out repeating its performance.
3. The total time required for such a **stepped leader** to reach the ground may be **20 ms**. The path may be quite lustruous, depending on the local conditions in air as well as the electric field gradients. Branches from the initial leader may also be formed. Since the progress of this leader stroke is by a series of jumps, it is referred as stepped leader. The picture of a typical leader stroke taken with a Boy's camera is shown in Fig. 4.3.

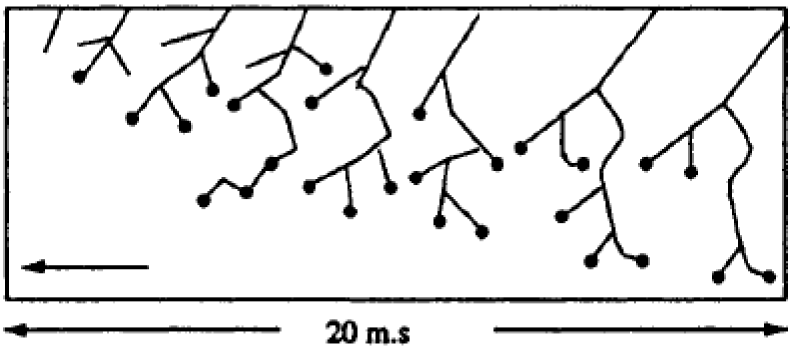


Fig. 4.3. Propagation of a stepped leader stroke from a cloud

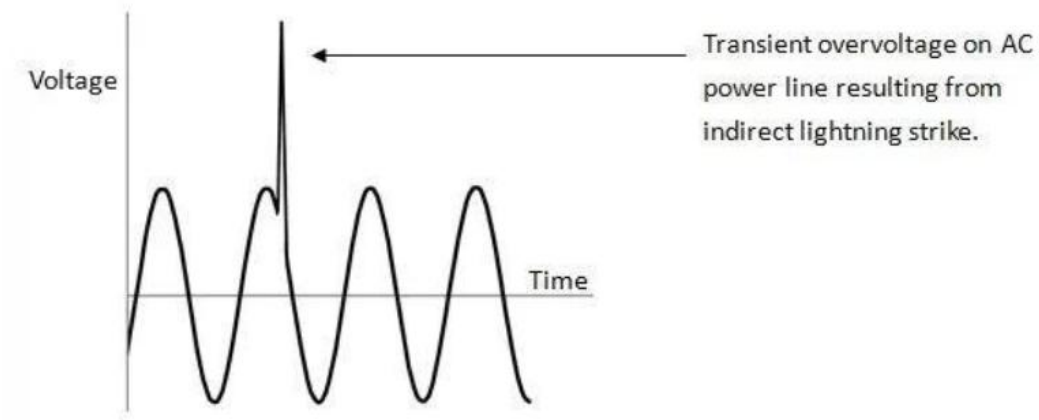
Fig. 4.4: Development of the main or return stroke

4. After the leader touches the ground, the **return stroke** follows. As the leader moves towards the ground, positive charge is directly accumulated under the head of the stroke or canal.

5. By the time the **stroke reaches the ground** or comes sufficiently near the ground, the electrical field intensity on the ground side is sufficiently large to build up the path. Hence, the positive charge returns to the cloud neutralizing the negative charge, and hence a heavy current flows through the path.
6. The velocity of the return or main stroke ranges from **0.05 to 0.5** times the velocity of light, and currents will be of the order of **1000 to 250,000 A**. The return strokes vanish before they reached the cloud, suggesting that the charge involved is that conferred to the stroke itself.

There are two types of lightning strokes.

1. Direct lightning strokes
2. Indirect lightning strokeS



Over voltages are caused on power systems due to external and internal influencing factors. The voltage stress caused by over voltage can damage the lines and equipment's connected to the system.

Over voltages arising on a system can be generally classified into two main categories as below:

a) External Over voltages

This type of over voltages originates from atmospheric disturbances, mainly due to lightning. This takes the form of a surge and has no direct relationship with the operating voltage of the line. It may be due to any of the following causes:

1. Direct lightning stroke
2. Electromagnetically induced over voltages due to lightning discharge taking place near the line, called **'side stroke'.**

3. Voltages induced due to atmospheric changes along the length of the line.
4. Electrostatically induced voltages due to presence of **charged clouds nearby**.
5. Electrostatically induced over voltages due to the frictional effects of small particles like dust or dry snow in the atmosphere or due to change in the altitude of the line.

b) Internal Over voltages

These over voltages are caused by changes in the operating conditions of the power system. These can be divided into two groups as below:

1. Switching over voltages or Transient over operation voltages of high frequency:

This is caused when switching operation is carried out under normal conditions or when fault occurs in the network.

When an unloaded long line is charged, due to **Ferranti Effect** the receiving end voltage is increased considerably resulting in over voltage in the system. Similarly when the primary side of the transformers or reactors is switched on, over voltage of transient nature occurs.

2. Temporary over voltages:

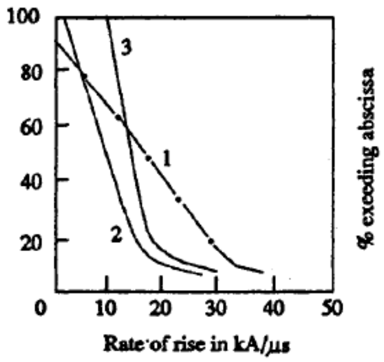
These are caused when some major load gets disconnected from the long line under normal or steady state condition

4.1.3 Parameters and Characteristics of the Lightning Strokes

The parameters and characteristics of lightning include the

1. Amplitude of the currents,
2. The rate of rise
3. The probability distribution of the above, and
4. The wave shapes lightning strokes of the lightning voltages and currents

Typical oscillograms of the lightning current and voltage waveshapes on a transmission lines are:



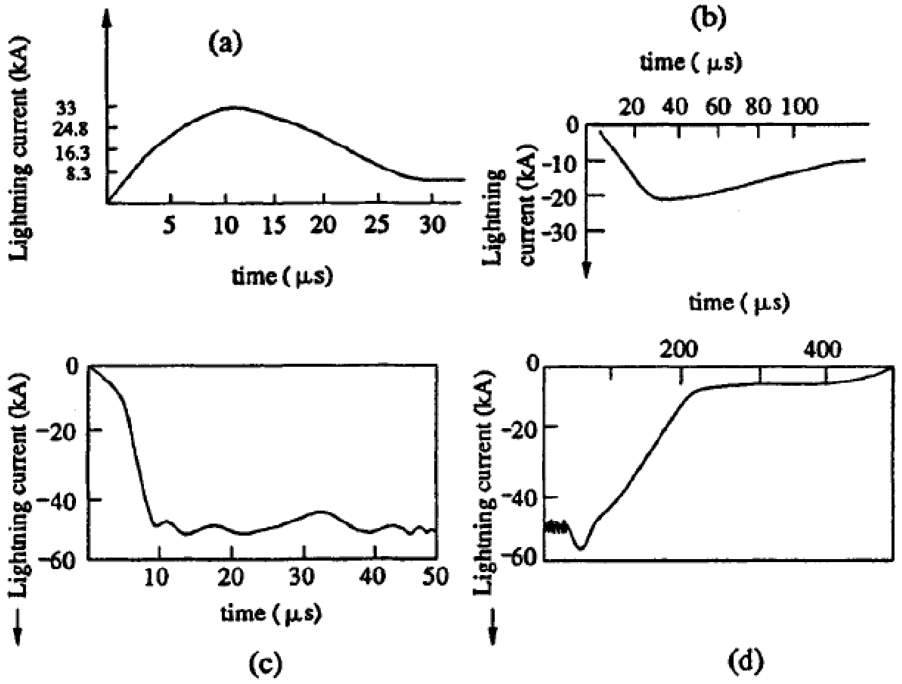


Fig. Typical lightning current oscillograms

(a) to a capacitive balloon (CIGRE)
(b) on Empire State Building (McEachron)
(c) and (d) on transmission line tower (Berger)
ref: Westinghouse T and D reference book

The high current peak may last for some tens of microseconds followed by a long duration low current portion lasting for several milliseconds. This last portion is normally responsible for damages **(thermal damage).**

Lightning currents are usually measured either directly from high towers or buildings or from the transmission tower legs.

4.1.4 Mathematical Model for Lightning

When a streamer discharge occurs to ground by first a leader stroke, followed by main strokes with considerable currents flowing, the lightning stroke may be thought to be a current source of value Q with a source impedance Z0 discharging to earth. If the stroke strikes an object of impedance Z, the voltage built across it may be taken as

$$V = IZ$$

$$= I_0 \frac{ZZ_0}{Z+Z_0}$$

$$= I_0 \frac{Z}{1+\frac{Z}{Z_0}}$$

The source impedance of the lightning channels are not known exactly, but it is estimated to be about 1000 to 3000 ft. If a lightning stroke current as low as 10,000 A strikes a line of 400 Ω surge impedance, it may cause an overvoltage of 4000 kV

4.2 Overvoltage Due To Switching Surges, System Faults And Other Abnormal Conditions

4.2.1 Origin of Switching Surges

1. The making and breaking of electric circuits with switchgear may result in abnormal overvoltages in power systems having large inductances and capacitances.
2. The **overvoltages may go as high as six times** the normal power frequency voltage. In circuit breaking operation, switching surges with a high rate of rise of voltage may cause repeated restriking of the arc between the contacts of a circuit breaker, thereby causing destruction of the circuit breaker contacts.
3. The switching surges may **include high natural frequencies** of the system, a damped normal frequency voltage component, or the restriking and recovery voltage of the system with successive reflected waves from terminations.

Characteristics of Switching Surges

(i) **De-energizing of transmission lines**, cables, shunt capacitor, banks, etc.

(ii) Disconnection of unloaded transformers, reactors, etc.

(iii) Energization or reclosing of lines and reactive loads,

(iv) Sudden switching off of loads.

(v) Short circuits and fault clearances.

(w) Resonance phenomenon like ferro-resonance, arcing grounds, etc

Switching Overvoltages In EHV and UHV Systems

Over voltages are generated in EHV systems when

1. There is a sudden release of internal energy stored either in the electrostatic form (in the capacitance) or
2. In the electromagnetic form

The different situations under which this happens are:

i) Interruption of low inductive currents (current chopping) by high speed circuit breakers. This occurs when the transformers or reactors are switched off

ii) Interruption of small capacitive currents, such as switching off of unloaded lines etc.

(iii) Ferro-resonance condition

The other situations of switching that give rise to switching over voltages of shorter duration **(0.5 to 5 ms) and lower magnitudes (2.0 to 2.5 p.u**.) are:

(a) Single pole closing **SF_6 circuit breaker**

(b) Intimation of fault current when the L-G or L-L fault is cleared

(c) Resistance switching used in circuit breakers

(d) Switching lines terminated by transformers

(e) Series capacitor compensated lines

(f) Sparking of the surge diverter located

4.2.2 **Causes of Over voltage in Power System**

1. Increase in voltage for the very short time in power system is called as the **over voltage**. It is also known as the **voltage surge or voltage transients**.
2. The voltage stress caused by over voltage can damage the lines and equipment's connected to the system.

There are two types of causes of over voltage in power system.

1. Over voltage due to external causes
2. Over voltage due to internal causes

Transient over voltages can be generated at high frequency (load switching and lightning), medium frequency (capacitor energizing), or low frequency. Over voltage due to external causes: This cause of over voltage in power system is the lightning strokes in the cloud.

Now, how lightning strokes are produced. So when electric charges get accumulated in clouds due to thunder Strom caused due to some bad atmosphere process.

This type of over voltages originates from atmospheric disturbances, mainly due to lightning. This takes the form of a surge and has no direct relationship with the operating voltage of the line. It may be due to any of the following causes:

A) Direct lightning stroke

B) Electromagnetically induced over voltages due to lightning discharge taking place near the line, called 'side stroke'.

C) Voltages induced due to atmospheric changes along the length of the line.

D) Electrostatically induced voltages due to presence of charged clouds nearby.

E) Electrostatically induced over voltages due to the frictional effects of small particles like dust or dry snow in the atmosphere or due to change in the altitude of the line.

The potential between the clouds and earth breaks down and lightning flash takes place between the cloud and ground when this voltage becomes 5 to 20 million volts or when the potential gradient becomes 5000V to 10000V per cm.

4.2 System Faults

Over voltage tends to stress the insulation of the electrical equipment's and likely to cause damage to them when it frequently occurs. Over voltage caused by surges can result in spark over and flash over between phase and ground at the weakest point in the network, breakdown of gaseous/solid/ liquid insulation, failure of transformers and rotating machines.

4.2.1 Overvoltage Protection

There are always a chance of suffering an electrical power system from abnormal over voltages. These abnormal over voltages may be caused due to various reason such as, sudden interruption of heavy load, lightening impulses, switching impulses etc. These over voltage stresses may damage insulation of various equipments and insulators of the power system. Although, all the over voltage stresses are not strong enough to damage insulation of system, but still these over voltages also to be avoided to ensure the smooth operation of electrical power system.

These all types of destructive and non destructive abnormal over voltages are eliminated from the system by means of overvoltage protection.

4.2.3 **Voltage Surge**

The over voltage stresses applied upon the power system, are generally transient in nature. Transient voltage or voltage surge is defined as sudden sizing of voltage to a high peak in very short duration.The voltage surges are transient in nature, that means they exist for very short duration. The main cause of these voltage surges in power system are due to lightning impulses and switching impulses of the system. But over voltage in the power system may also be caused by, insulation failure, arcing ground and resonance etc.

The voltage surges appear in the electrical power system due to switching surge, insulation failure, arcing ground and resonance are not very large in magnitude. These over voltages hardly cross the twice of the normal voltage level. Generally, proper insulation to the different equipment of power system is sufficient to prevent any damage due to these over voltages. But over voltages occur in the power system due to lightning is very high. If over voltage protection is not provided to the power system, there may be high chance of severe damage. Hence all over voltage protection devices used in power system mainly due to lightning surges.

4.2.3 Switching Impulse

Switching Impulse or Switching Surge

When a no load transmission line is suddenly switched on, the voltage on the line becomes twice of normal system voltage. This voltage is transient in nature. When a loaded line is suddenly switched off or interrupted, voltage across the line also becomes high enough current chopping in the system mainly during opening operation of air blast circuit breaker, causes over voltage in the system. During insulation failure, a live conductor is suddenly earthed. This may also caused sudden over voltage in the system. If emf wave produced by alternator is distorted, the trouble of resonance may occur due to 5th or higher harmonics. Actually for frequencies of 5th or higher harmonics, a critical situation in the system so appears, that inductive reactance of the system becomes just equal to capacitive reactance of the system. As these both reactance cancel each other the system becomes purely resistive. This phenomenon is called resonance and at resonance the system voltage may be increased enough.

But all these above mentioned reasons create over voltages in the system which are not very high in magnitude.

But over voltage surges appear in the system due to lightning impulses are very high in amplitude and highly destructive. The affect of lightning impulse hence must be avoided for over voltage protection of power system.

Methods of Protection Against Lightning

These are mainly three main methods generally used for protection against lightning. They are

- Earthing screen.
- Overhead earth wire.
- Lighning arrester or surge dividers.

Earthing Screen

Earthing screen is generally used over electrical substation. In this arrangement a net of GI wire is mounted over the sub-station. The GI wires, used for earthing screen are properly grounded through different sub-station structures. This network of grounded GI wire over electrical sub-station, provides very low resistance path to the ground for lightning strokes.

This method of high voltage protection is very simple and economic but the main drawback is, it can not protect the system from travelling wave which may reach to the sub-station via different feeders.

Overhead Earth Wire

This method of over voltage protection is similar as earthing screen. The only difference is, an earthing screen is placed over an electrical sub-station, whereas, overhead earth wire is placed over electrical transmission network. One or two stranded GI wires of suitable cross-section are placed over the transmission conductors. These GI wires are properly grounded at each transmission tower. These overhead ground wires or earth wire divert all the lightning strokes to the ground instead of allowing them to strike directly on the transmission conductors.

Lightning Arrester

The previously discussed two methods, i.e. earthing screen and over-head earth wire are very suitable for protecting an electrical power system from directed lightning strokes but system from directed lightning strokes but these methods can not provide any protection against high voltage travelling wave which may propagate through the line to the equipment of the sub-station.The lightning arrester is a devices which provides very low impedance path to the ground for high voltage travelling waves.

The concept of a lightning arrester is very simple. This device behaves like a nonlinear electrical resistance. The resistance decreases as voltage increases and vice-versa, after a certain level of voltage.The functions of a lightning arrester or surge dividers can be listed as below.

Under normal voltage level, these devices withstand easily the system voltage as electrical insulator and provide no conducting path to the system current.

On occurrence of voltage surge in the system, these devices provide very low impedance path for the excess charge of the surge to the ground.

After conducting the charges of surge, to the ground, the voltage becomes to its normal level. Then lightning arrester regains its insulation properly and prevents regains its insulation property and prevents further conduction of current, to the ground.

There are different types of lightning arresters used in power system, such as rod gap arrester, horn gap arrester, multi-gap arrester, expulsion type LA, value type LA. In addition to these the most commonly used lightning arrester for over voltage protection now-a-days gapless ZnO lightning arrester is also used.

4.3 Insulation Co-ordination

Insulation Coordination in Power System was introduced to arrange the electrical insulation levels of different components in the electrical power system including transmission network, in such a manner, that the failure of insulator, if occurs, confindes to the place where it would result in the least danmage of the system, easy to repair and replace, and results least disturbance to the power supply.

When any over voltage appears in the electrical power system, then there may be a chance of failure of its insulation system. Probability of failure of insulation, is high at the weakest insulation point nearest to the source of over voltage. In power system and transmission networks, insulation is provided to the all equipment and components.

Insulators in some points are easily replaceable and repairable compared to other. Insulation in some points are not so easily replaceable and repairable and the replacement and repairing may be highly expensive and require long interruption of power. Moreover failure of insulator at these points may causes bigger part of electrical network to be out of service. So, it is desirable that in situation of insulator failure, only the easily replaceable and repairable insulator fails. The overall aim of insulation coordination is to reduce to an economically and operationally acceptable level the cost and disturbance caused by insulation failure. In insulation coordination method, the insulation of the various parts of the system must be so graded that flash over if occurs it must be at intended points.

For proper understanding the insulation coordination we have to understand first, some basic terminologies of the electrical power system. Let us have a discussion.

Nominal System Voltage

Nominal System Voltage is the phase to phase voltage of the system for which the system is normally designed. Such as 11 KV, 33 KV, 132 KV, 220 KV, 400 KV systems.

Maximum System Voltage

Maximum System Voltage is the maximum allowable power frequency voltage which can occurs may be for long time during no load or low load condition of the power system. It is also measured in phase to phase manner.

List of different nominal system voltage and their corresponding maximum system voltage is given below for reference,

Nominal System Voltage in KV 11 33 66 132 220 400

Maximum System Voltage in KV 12 36 72.5 145 245 420

NB - It is observed from above table that generally maximum system voltage is 110 % of corresponding nominal system voltage up to voltage level of 220 KV, and for 400 KV and above it is 105 %.

Factor of Earthing

This is the ratio of the highest rms phase to earth power frequency voltage on a sound phase during an earth fault to the rms phase to phase power frequency voltage which would be obtained at the selected location without the fault.

This ratio characterizes, in general terms, the earthing conditions of a system as viewed from the selected fault location.

Effectively Earthed System

A system is said to be effectively earthed if the factor of earthing does not exceed 80 % and non-effectively earthed if it does.Factor of earthing is 100 % for an isolated neutral system, while it is 57.7 % ($1/\sqrt{3} = 0.577$) for solidly earthed system.

Insulation Level

Every electrical equipment has to undergo different abnormal transient over voltage situation in different times during its total service life period. The equipment may have to withstand lightning impulses, switching impulses and/or short duration power frequency over voltages. Depending upon the maximum level of impulse voltages and short duration power frequency over voltages that one power system component can withstand, the insulation level of high voltage power system is determined.

During determining the insulation level of the system rated less than 300 KV, the lightning impulse withstand voltage and short duration power frequency withstand voltage are considered. For equipment rated more or equal 300 KV, switching impulse withstand voltage and short duration power frequency withstand voltage are considered.

Lightning Impulse Voltage

The system disturbances occur due to natural lightning, can be represented by three different basic wave shapes. If a lightning impulse voltage travels some distance along the transmission line before it reaches to a insulator its wave shaped approaches to full wave, and this wave is referred as 1.2/50 wave. If during travelling, the lightning disturbance wave causes flash over across an insulator the shape of the wave becomes chopped wave. If a lightning stroke hits directly on the insulator then the lightning impulse voltage may rise steep until it is relieved by flash over, causing sudden, very steep collapse in voltage. These three waves are quite different in duration and in shapes.

Switching Impulse

During switching operation there may be uni-polar voltage appears in the system. The wave form of which may be periodically damped or oscillating one. Switching impulse wave form has steep front and long damped oscillating tale.

Short Duration Power Frequency Withstand Voltage

Short duration power frequency withstand voltage is the prescribed rms value of sinusoidal power frequency voltage that the electrical equipment shall withstand for a specific period of time normally 60 seconds.

Protection Level Voltage of Protective Device

Over voltage protective device like surge arrestors or lightning arrestors are designed to withstand a certain level of transient over voltage beyond which the devices drain the surge energy to the ground and therefore maintain the level of transient over voltage up to a specific level. Thus transient over voltage can not exceed that level. The protection level of over voltage protective device is the highest peak voltage value which should not be exceeded at the terminals of over voltage protective device when switching impulses and lightening impulses are applied.

As we discussed above that a component of electrical power system may suffer from different level of transient voltage stresses, switching impulse voltage and lightning impulse voltage. The maximum amplitude of transient over voltages reach the components, can be limited by using protecting device like lightning arrestors in the system. If we maintain the insulation level of all the power system component above the protection level of protective device, then ideally there will be no chance of breakdown of insulation of any component. Since the transient over voltage reaches at the insulation after crossing the surge protective devices will have amplitude equals to protection level voltage and protection level voltage impulse insulation level of the components.

Generally, the impulse insulation level is established at 15 to 25 % above the protective level voltage of protective devices.

Course Outcome

At the end of the course, student will be able to:

CO-4: Interpret overvoltage phenomenon and insulation coordination in electric power systems.