Lecture # 14

Insulation Coordination

Power system insulation is influenced by over-voltages (both power frequency and surges) besides normal operating voltage. The power system include a jargon of gas, liquid and solid insulation used at variety of voltage levels and have different withstand capabilities. In general the dielectric strength of solids is higher than liquids, which in-turn is higher than gases. In contrast, following a breakdown, the dielectric strength of gases is completely recoverable, that of liquids is partially recoverable, whereas that of solid is irrecoverable. The overall insulation level is governed by insulation coordination, which sometimes refers to as forming line of defenses against transient over-voltages encountered in practice. Insulation coordination is an essential component of the growing high voltage power system. Based on insulation coordination; certain criteria are satisfied through insulation design and through overvoltage control and protection. Looks simple, but involves comparisons between maximum network overvoltages and minimum insulation breakdown voltages, the process in practice is quite complex. It is worth mentioning that most faults in power system are due to insulation failure.

Insulation Level and Coordination

Insulation level refers to the values of test voltages, which the insulation under test of particular equipment must be able to withstand. It can be established through laboratory testing and on the basis of experience gained by utilities. Insulation coordination aims at achieving the best possible and cost-effective system of technical and economical compromise between protection of personals and equipment against overvoltages; whether caused by internal or external sources. Coordination of different types of insulation in relation to application and dielectric strength, and ability to restore insulating properties to ensure long-term reliability and economical operation is essential. Therefore an important element of insulation coordination is based on computing the most severe overvoltages occurring on the system and relating these to the breakdown characteristics of the insulation through appropriate margins (factor of safety) for determining withstand voltages for the power system components together with the statistical risk of insulation failure. It helps to ensure a high degree of reliability of electrical power. Insulation coordination correlates insulation of electrical equipment with the characteristics of protective devices in such a way that the insulation is protected from excessive overvoltages caused due to disturbances for which the followings must be considered:

1. The level of the possible overvoltages occurring on the network must be known.
2. The sensitive locations of possible overvoltages in a system must be identified.
3. The use of proper protective devices; when and where necessary.
4. The correct overvoltage withstand level of insulation must be chosen for the various network components from among the insulating voltages satisfying the particular constraints.

Protection level is determined by the following conditions:

1. Type of installation.
2. Environment.
3. Equipment use.
4. Proper control of the protection levels provided by surge protective device, which requires thorough knowledge of their characteristics and behavior.

The final objective of insulation coordination is to ensure safe, optimized transmission and distribution of electrical power. This is accomplished by finding the best possible economic balance between the various parameters depending on coordination that are:

1. Cost of insulation used.
2. Cost of protective devices to be installed at sensitive locations.
3. Cost of failures including operating loss and repairs based on their probability.

Insulation coordination is accomplished in four steps as illustrated in Figure (1), with two different approaches; the deterministic approach and the statistical approach. The starting step is to remove the detrimental effects of overvoltages and to know exactly the phenomena producing them. This, however, is not always a simple task.

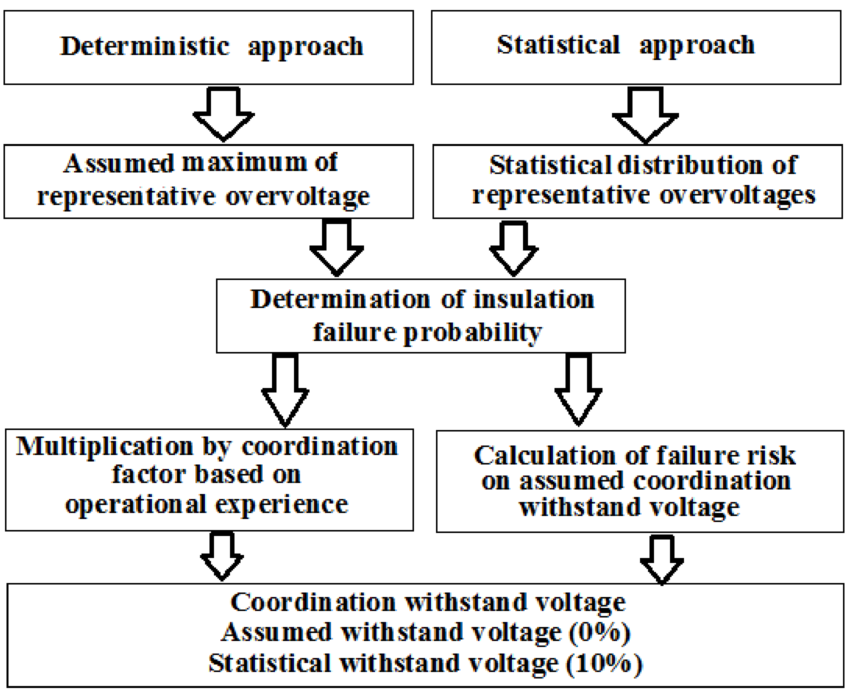

Figure 1: Insulation Coordination Process

Generally, for existing insulation coordination studies the power system has been modeled either by deterministic or by statistical methods. The shortcoming of the deterministic technique is that it assumes that the power system dynamics is linear. This makes analysis of overvoltage response of the system under transient-state less optimal for determining overvoltage withstand of system elements. The statistical method is more accurate, but the statistical evaluation of the risk cannot be assessed if the breakdown behavior of the insulation is unknown or if it is referred only to the Basic Impulse Level (BIL) of the power system component.

The performance criterion is based on the insulation selected so as to reduce to an economically and operationally acceptable level the probability that the resulting voltage stresses imposed on the equipment will cause damage to the equipment insulation or affect continuity of service, and expressed in terms of an acceptable failure rate, which includes the number of failures per year, years between failure and possible risk of failure on the insulation configuration.

The required withstand voltages are determined by converting the coordination withstand voltages to appropriate standard test-conditions, which is usually different from the coordination withstand voltages. The coordination withstand voltage is the voltage bearing capability of the insulation configuration in actual service conditions that meets the performance criterion.

Time Lags

Time lag is defined as the total time between the instant of application of voltage and the instant at which breakdown take place. It has two components, statistical time-lag T_S and formative time-lag T_f. Thus:

$$T_{Lag} = T_S + T_f \qquad 1$$

The component T_S is the total time-lapse between application of voltage and the appearance of initiatory electron to start the process leading to breakdown. Since the appearance of initiatory electron is based on probability, therefore the availability of such electrons are statistically distributed in the gap between electrodes, hence the name. Once the initiatory electrons appear, they take some time to multiply to form a critical number, which depends on the applied voltage. Thus a certain time will be taken for enough free electrons to be set free in order to form the critical number. This is referred to as statistical time lag. Once the space between electrodes becomes conducting, breakdown takes place in a short interval of time and this is referred to formative time lag. Usually the formative time-lag is very small, of the order of microseconds because the breakdown process ensues from electrons moving with velocities well-over 10^7 m/s. It has been shown that formative process is accomplished in times 10^{-7} to 10^{-6} seconds. Since the formative time-lag is generally very small as compared to statistical time-lag, the former can be neglected in most cases when time lags are to be determined, so that $T_{Lag} \approx T_S$.

Surge Protection and Coordination with Air Gap

In power systems it is necessary to coordinate the level of insulation in electrical equipment with the nature and magnitudes of the overvoltages that may be subjected on the system by external or internal sources. The choice of protective device and insulation level is a technical-economic problem. Air gaps have been and are still being used as protective devices in association with the solid insulation, which sparks over in the event of surge voltage, thus diverting the surge to the ground leaving the solid insulation unharmed. Typical spark gaps are the rod gaps, which are less costly and easy to install. Spark gaps are usually installed parallel with insulators between the live equipment terminal and ground as shown in Figure (2).

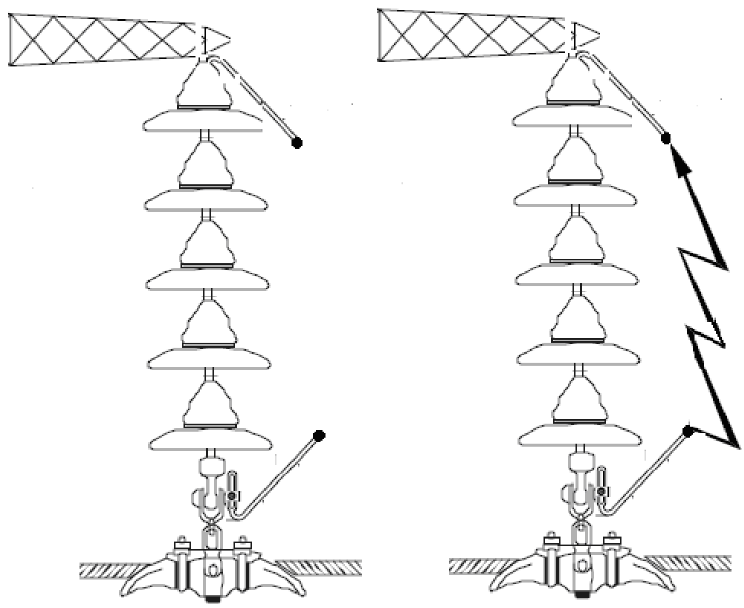

Figure 2: Arrangement of Rod Gap with Insulator String.

The air between the rods thus provides insulation in parallel with the solid insulator of the string. The gap distance setting is arranged such that the spark-over occurs at overvoltages well below the breakdown voltage of the solid insulator. Furthermore, the dielectric strength of air is less than the solid insulation string, so that the probability of breakdown of air gap is higher. Thus the spark gap acts as protective gap, but has the following disadvantages:

1. When they operate, a single-line-to-ground fault results, which will cause protective equipments in association to operate and will thus isolate the circuit. However, the alternative of insulation failure of the plant being protected is much more serious.
2. The sudden reduction in voltage during spark over of the gap places high stress on transformer inter-turn insulation, which is likely to damage if the stress exceed beyond a critical value.
3. The breakdown of plant insulation varies with the duration of the overvoltage. Usually a gap has a relatively slow response to fast rise-time overvoltage surges and performance is thus influenced by polarity and atmospheric conditions.
4. Air gaps applicable at the lower distribution voltages are vulnerable to erratic operation due to wind-borne debris, birds, fouling etc.

The rod gap is still widely used for the protection of small distribution transformers, insulator strings of overhead transmission lines and as a backup protection for the substation power transformers protected by surge arresters. World-wide, surge arresters are used as the principal or primary form of substation plant overvoltage protection, whereas rod gaps are used in addition as secondary protection, to raise the protection level of the equipment against overvoltages. Air gaps are extensively used across string of suspension insulators on overhead lines, especially up to several kilometers from substations in order to protect the substation plant from surges emanating from the overhead lines. The gap settings are usually reduced as the overhead line approaches the substation.

The gaps are arranged so that they are at a suitable distance from the solid insulation they are protecting. As shown in Figure (2), the rods are angled such that the arc is directed away from the associated insulator sheds in order to avoid possible damage during flashover. For example, on a 132 kV transmission line system the maximum value of phase-to-ground voltage possible under transient overvoltage or fault conditions is $\frac{132}{\sqrt{3}} \times \sqrt{2}$ = 108 kV. However a tolerance of ±10% is allowed which accounts for any occasional fluctuations without harming the system. The allowed maximum voltage is thus 118.8kV. The rod gaps should be adjusted to operate at 20% of the maximum fluctuating voltage that is at 118.8 kV + 0.2(118.8), which comes out to be 142.5 kV. Under impulse voltages the breakdown characteristics of the equipment to be protected are normally not known and only figures of basic insulation level will be available. In such cases the rod gaps may be adjusted to produce flashover on impulse voltage, with a 1.2/50μs wave, of 80% of the BIL of the protected equipment with a probability of 50%. Thus, for example, a 100 kV system designed for a BIL of 400 kV (withstand) may be provided with a rod gap setting of 0.8 x 400 = 320 kV.

The protection mechanism offered by spark gaps can be understood if we consider the time-lags associated with solid insulation and the air gap provided by rod gap. It must be remembered that the basic ingredient necessary in forming ionization, which, under critical condition leading to breakdown, are the electrons. In order to initiate the cumulative process leading towards breakdown, sufficient number of free electrons must be available. Solid insulation usually fulfills this criterion due to the presence of inherited free electrons so that the statistical time-lag can be regarded as zero. On the other hand the air between rod gap may or may not contain sufficient electrons to start the process of ionization so that the statistical time-lag cannot be regarded as zero, unless pre-ionization in the form of corona exists in which case the statistical time-lag can be regarded as zero. The pre-ionization can be introduced by highly non-uniform field at sharp-tip of the spark gap that may produce slight corona in the gap, at the expense of power losses in the system. Thus on the application of voltage above a certain level, the spark gap will breakdown with 100% probability if pre-ionization exists (statistical time-lag of zero) and that the dielectric strength of the air between the rods is considerably less than the dielectric strength of the solid insulation it is protecting. In this way presence of corona in the coordinated air gap can be regarded as a "safety valve" to divert the surge energy through its flashover when surge voltage is impressed across the insulator string. The time-lags of spark gaps ranges between 2 and 10ms, depending upon the gap separation between electrodes so that the protected equipment must be capable of withstanding the flashover voltage of the gaps for this length of time. Average 50% flashover voltage values of rod-plane and rod-rod gaps for gap separation of *d* meters are given by well-known formulas, which are given in Table (1).

Table 1: 50% Flashover Voltage for Spark Gaps in Relation to Gap Length

Electrode Geometry	Average Power Frequency Flashover Voltage (kV)	Crest Value of Lightning Impulse Flashover Voltage (kV)
Rod-Plane	$V_{50} = 652(d)^{0.576}$	$500d$
Rod-Rod	$V_{50} = 850(d)^{0.576}$.	$650d$

Example 1: A 500 kV transformer bushing is protected by gap, which withstand 2pu power-frequency voltage. Determine their 50% flashover value under 50 Hz and lightning-impulse voltages, if (a) rod-plane gap is used, and (b) rod-rod gap is used.

Solution:

Given that: the withstand voltage of protecting gap is 2pu of the peak power-frequency system voltage. The calculations are based on the power-frequency voltage of 500 kV (RMS) line-voltage for which the 1pu line-to-ground peak-voltage is:

$$500 \times \frac{\sqrt{2}}{\sqrt{3}} = 408.19 \text{ kV}$$

Withstand voltage of 2pu = V_w = 408.19 x 2 = 816.38 kV. The 50% flashover value is taken to be V_{50}, as reference voltage and choosing the coordination factor of 80% or 0.8, so that according to Eq (16.1):

$$V_{50} = \frac{V_w}{0.8} = \frac{816.38}{0.8} = 1020.47 \text{ kV.}$$

(a) For a rod-plane gap: Using: $V_{50} = 652(d)^{0.576}$. Or:

$$d = \left(\frac{V_{50}}{652}\right)^{1.736} = \left(\frac{1020.47}{652}\right)^{1.736} = 2.17 \text{ m}$$

For this gap length, the lightning-impulse 50% flashover value is:

V_{50} = 500d = 500 x 2.17 = **1088.22 kV (peak)**

(b) For a rod-rod gap: $V_{50} = 850(d)^{0.576}$. Or

$$d = \left(\frac{V_{50}}{850}\right)^{1.736} = \left(\frac{1020.47}{850}\right)^{1.736} = 1.37 \text{ m}$$

For this gap length, the lightning-impulse 50% flashover value is:

V_{50} = 650d = 650 x 1.37 = **892.73 kV (peak)**

Insulation Coordination and Lightning

Reliable and economic insulation coordination is based on application of insulation for power equipment and transmission lines, which forms an interconnected system. Generally, insulation systems are designed for none or minimum possible flashovers, or if flashovers cannot be prevented such flashovers should be restricted to places where damage is not inflicted, such as air gaps or in surge arresters. When working out the insulation coordination based on lightning, the insulation levels, known as BIL (basic Impulse level or basic insulation level) must be considered. Since the transmission voltages and equipment insulation levels in a power system vary at different voltage levels, and as such therefore more than one insulation level exists for major equipment for which the designer has to work out the best possible solution. For areas of high lightning activity and switching-surge, the selection of insulation levels will be different from areas with little or virtually no lightning activity and system with short-length lines.

Since the lightning protection problem is based on statistical approach, the knowledge of lightning and thunderstorm activity in the transmission line region, in terms of keraunic number is essential. It has been observed that the number of incident lightning strokes on a tower or ground wire along the span of a transmission line is represented by an expression:

$$N_s = FK_L[0.0133(h + 2h_g) + 0.1D_g] \qquad 2$$

Where h is the height of the tower, h_g is the height of ground wires at mid-span and D_g is the distance between ground wires if in case they are more than one. F is between 0.15 and 0.2 and will depend upon the keraunic level, which needs field observations along the specific line-route and the tower height h, ground wire height h_g at mid-span and the separation between ground wires D_g. Since a lightning can strike at any point on a transmission line, the fraction that might hit a tower-top has to be ascertained.

The lightning striking a tower, will encounter an impedance to ground, which is governed by the tower-footing resistance R_F, the surge impedance of the ground wire Z_g, the coupling to line conductors K_f, and the surge impedance Z_{SL} of the lightning stroke channel. The surge impedance of the lightning stroke channel is approximately 400Ω. Neglecting reflections up and down the tower and the coupling to the phase conductor, the tower-top potential V_t is approximately given as:

$$V_t \approx \frac{I_S}{\left(\frac{1}{R_F} + \frac{2n_g}{Z_g} + \frac{1}{Z_{SL}}\right)} \qquad 3$$

Where n_g is the number of ground wires and I_S is the surge current. Knowledge of tower-footing resistance is therefore essential and methods for calculation of this quantity for various types of footing arrangements such as driven rods, horizontally buried wires (counterpoises) is also required. When the tower-top experiences the above voltage, the insulator strings supporting the conductors will experience a maximum voltage V_{ST} of:

$$V_{ST} = V_t(1 - K_f) + V_{pm} \qquad 4$$

Where V_{pm} is the peak value of line-to-ground power-frequency voltage, and K_f is the coupling factor between ground wire(s) and the phase conductor, which is between 0.2 and 0.3.

Example 2: A 132 kV overhead transmission line with a single ground wire has tower height 24 m with ground line height at mid-span 15 m passes from a region which has an average of 40 thunderstorm days in a year. Calculate the probable number of strokes contacting 100 km of line per year anywhere on the line. Assume F = 0.15.

Solution:

Given that: h = 24m, h_g = 15m and K_L = 40 thunderstorm days / year. D_g = 0 for a single ground wire. Therefore using:

$$N_s = FK_L[0.0133(h + 2h_g) + 0.1D_g]$$

Or

$$N_s = 0.15 \times 40[0.0133(24 + 2\times 15) + 0.1(0)] =$$ **4.31 strokes / year / 100km of line.**

It can therefore be estimated that there may be **4 to 5** strokes/year /100 km length of line.

Example 3: A tower of a 220 kV transmission line has a 20 Ω footing resistance and two ground wires each with Zg = 500 Ω. The lightning stroke surge impedance is Z_{SL} = 400 Ω. For surge current of 40 kA (peak), calculate the tower-top potential for (a) two ground wires and (b) single ground wire.

Solution:

Given that:

$R_F = 20\ \Omega$

$Z_g = 500\ \Omega$

$Z_{SL} = 400\ \Omega$

$I_S = 40$ kA

(a) Tower top potential for two ground wires n_g = 2, therefore using:

$$V_t = \frac{I_S}{\left(\frac{1}{R_F} + \frac{2n_g}{Z_g} + \frac{1}{Z_{SL}}\right)}$$

Or

$$V_t = \frac{40000}{\left(\frac{1}{20} + \frac{2(2)}{500} + \frac{1}{400}\right)}$$ = **661.15 kV**

(b) Tower top potential for a single ground wire n_g = 1, therefore using:

$$V_t = \frac{I_S}{\left(\frac{1}{R_F} + \frac{2n_g}{Z_g} + \frac{1}{Z_{SL}}\right)}$$

Or

$$V_t = \frac{40000}{\left(\frac{1}{20} + \frac{2}{500} + \frac{1}{400}\right)} = \mathbf{708\ kV}$$

It can be seen that increasing the number of ground wires reduces the tower-top potential. In this example there is a reduction of 46.85 kV, or about 6.62%.

Example 4: In Example (3) if the line has a coupling factor between line and ground conductors K_f = 0.2, find the voltage experienced by the insulator string for (a) two ground wires and (b) single ground wire.

Solution:

Given that: K_f = 0.2. The maximum value of line-to-ground potential for 220 kV line is: $V_{pm} = 220 \times \frac{\sqrt{2}}{\sqrt{3}}$ = 179.6 kV

(a) For two ground wires, using: $V_{ST} = V_t(1 - K_f) + V_{pm}$ or:

$$V_{ST} = 661.15(1 - 0.2) + 179.6 = \mathbf{708.52\ kV}$$

(b) For a single ground wire in which case the tower top potential is 708kV

$$V_{ST} = 708(1 - 0.2) + 179.6 = \mathbf{746\ kV}$$

Example 5: A 500 kV transmission line with horizontal arrangement of conductors has 25 discs per insulator string in V-shaped arrangement and two ground wires spaced 16m apart at 21m height at mid-span and 27m at the tower. The tower-footing resistance is 40 Ω and each insulator disc in a string has a BIL for flashover of 100kV. The surge impedances are: Ground wire; 500 Ω, stroke; 400 Ω. Assume 50% of strokes to contact within 25% line span from the tower and at the tower-top. The coupling factor between ground and phase conductor is 0.2. The keraunic number is 40 thunderstorm days per year. Calculate the possible surge current for fair and wet weather.

Solution:

Given that: Number of disc in a string = 25

h = 27 m
h_g = 21 m
D_g = 16 m
R_F = 40 Ω
Z_g = 500 Ω
Z_{SL} = 400 Ω
K_f = 0.2 and K_L = 40 thunderstorm days / year

Using:

$$N_s = FK_L[0.0133(h + 2h_g) + 0.1D_g]$$

Or $N_s = 0.2 \times 40 \times [0.0133(27 + 2 \times 21) + 0.1 \times 16]$ = 20.14 strokes/100 km-year.

Using: $$V_t = \frac{I_S}{\left(\frac{1}{R_F} + \frac{2n_g}{Z_g} + \frac{1}{Z_{SL}}\right)}$$

Or $$V_t = \frac{I_S}{\left(\frac{1}{40} + \frac{2(2)}{500} + \frac{1}{400}\right)} = 28.16 I_S$$

Thus: $$V_t = 28.16 I_S$$

$$V_{pm} = 500 \times \frac{\sqrt{2}}{\sqrt{3}} = 408.16 \text{ kV}$$

Using: $$V_{ST} = V_t(1 - K_f) + V_{pm}$$

Or

$$V_{ST} = 28.16 I_S (1 - 0.2) + 408.19 = 22.52 I_S + 408.19$$

Assuming BIL of 100 kV for a single disc, the flashover voltage of 25 discs = 25 × 100 = 2500 kV in fair weather. In rain, flashover voltage = 75 x 25 = 1875 kV. Therefore:

$$2500 = 22.52 I_S + 408.19$$

Thus: $I_S = \frac{2500 - 408.19}{22.52}$ = **92.88 kA in fair weather**

And $I_S = \frac{1875 - 408.19}{22.52}$ = **65.13 kA in rainy or wet weather**