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# Insulation coordination of ehv systems – an overview

Meera KS *and Kanyakumari M **

***Abstract:*** *The reliability of power supply provided by an electric power systemis judged by the frequency and duration ofsupply interruptions to its customers. Althoughthere are many causes of interruptions, breakdown of insulation is one of the most frequent.The insulation provided to the equipment has to withstand a variety of stresses(overvoltages) with varying shapes, magnitudes and duration during its service period.We cannot prevent these overvoltages in an electric network,so we need to protect against them. The main objective of Insulation coordination is to 'Design the system insulation of all power system components to minimize power interruptions and damage resulting from steady-state, dynamic and transient overvoltages in an economic fashion'.To keep interruptions to a minimum, the insulation of various equipments of the system must be so graded that flashovers occur only at intended points.*

*The magnitudes of over-voltages are usually limited to a desiredprotective level by protective devices. Thus the insulation level of the equipment has to be above the protective level by a safe margin. This paper attempts to give an overview of concepts of insulation coordination and the different methodologies of insulation co-ordination studies.*

***Keywords:*** *Insulation coordination, overvoltages, transients, Basic Impulse Insulation Level*

## 1.0 INTRODUCTION

Insulation coordination comprises of selection of the insulation strength of various power system equipment to avoid damagein case of over voltages related to lightning strikes,switching actions or phenomena related to fundamental frequency over voltages. The basic aim is not only to select the insulation strength but also to select the minimum insulation strength since minimum strength is equivalent to minimum cost. The insulation coordination aspects of a power system need to be considered in the planning phase of a project and studies performed to determine the electrical stress placed on the equipment or on the air clearance. If the insulation strength is considered to be excessive then the stresscan be reduced by use of surge arresters, protective gaps, shield wires, closing resistors in circuit breakers, controlled closing, improved grounding etc. Performing the studies at a later stage could limit the number of possibilities to mitigate over voltage problems as installation of the mitigating devices physically may not be possible due to space restrictions.

Insulation coordination of Power System networks can be classified into the following two major areas:

- Line Insulation Coordination - which includes Transmission and Distribution lines
- Station Insulation Coordination - which includes generation, transmission, and distribution substations

*Additional Director, Power System, Division, Central Power Research Systems, Banglore
**Additional Director, High Voltage Division, Central Power Research Systems, Banglore

The line Insulation coordination task involves specifying all dimensions of the transmission / distribution line towers that affects the reliability of theline such as:

- Tower clearances between the phase conductors and the ground
- Length of insulator string
- Number and type of insulators
  - Location and number of overhead ground or shield wires
  - Phase-to-ground midspan clearance
  - Rating and location of line surge arresters etc.

Similarly, the Station Insulation coordination task involves specifying of:

- Equipment insulation strength i.e.Basic Lightning Impulse Insulation Level (BIL) and Basic Switching Impulse Insulation Level (BSL) of all equipment
- Phase-ground and phase-phase clearances
- Location, rating, and number of surge arresters
- Location, type (masts or shield wires) of substation shielding
- Location, configuration, and the spacing of protective gaps etc.

The following criteria must be considered as a basis for either of the insulation coordination problems mentioned above:

- Overvoltage stresses
- Electrical strength of the equipment
- Overvoltage protection
- Desired degree of safety against overvoltages

As transmission voltages and equipment insulation levels vary at EHV levels, there exists more than one insulation level for major equipment and the designer has to work out the best solution for his system.

Both the IEC and Indian standards have recommended certain values or proposed levels for coordinating insulation. But as transmission voltages and equipment insulation levels vary at EHV levels, there exists more than one insulation level for major equipment (Table I), the designer has to work out the best solution for his system. Thus, in high lightning-prone areas or insystems with heavy switching-surge conditions, the selection of insulation levels will be differentfrom areas with little or no lightning. Generally, insulation systems aredesigned in a power system for no flashovers, or if flashovers cannot be prevented such flashoversshould be restricted to locations where no damage occurs, such as air gaps or arresters.

## 2.0 VOLTAGE STRESSES IN POWER SYSTEMS:

For proper understanding of insulation coordination the following basic terminologies are to be known.

- Nominal System Voltage: is the phase-to-phase RMS voltage for which the system is designed such as 11 kV, 33 kV, 132 kV, 220 kV, 400 kV etc.
- Maximum System Voltage:is the maximum allowable power frequency phase to phase RMS voltage that occurs during low load or no load condition in a power system. The insulation levels are dependent on the highest system operating voltage and not on the nominal voltages.

Nominal System Voltage (kV RMS)

| | | | | | | |
|---|---|---|---|---|---|---|
| 11 | 33 | 66 | 132 | 220 | 400 | 765 |

Maximum System Voltage (kV RMS)

| | | | | | | |
|---|---|---|---|---|---|---|
| 12 | 36 | 72.5 | 145 | 245 | 420 | 800 |

- Factor or Coefficient of Earthing: is theratio between the highest rms phase-to-earth power frequency voltage on the healthy phases during an earth fault and the rms phase to earth power frequency voltage prior to the fault. With an effectively earthed neutral (solid or resistance grounding) this is less than 80 %, where as it is more in case of noneffectively earthed systems. This condition is satisfied when the ratio of zero sequence reactance to positive sequence reactance is less than three and the ratio of zero sequence resistance to positive sequence resistance is less than one.

## (A) Voltage Stresses

Equipment overvoltage withstand capability is related to the magnitude andduration of the overvoltages. They are the decisive factors for the choice of Insulation levels of various equipment. The magnitude and time duration of these overvoltages must be carefully studied and compared with equipment capabilities for achieving a perfect insulation co-ordination

An overvoltage is defined as the voltage between phase to ground (or between phases) with peak value exceeding the peak value derived from the highest system voltage. Their time period generally is for about a few microseconds to milliseconds (insignificant compared to steady state period). They are important for "quantifying" power system transients and thus the insulationstresses. The magnitude and effective duration of different types of overvoltage are shown in figure 1.

**(i)** Temporary overvoltages (TOV): TOV are undamped or weakly damped oscillatory overvoltages, characterized by frequencies from few HZ to a few hundred HZ and of duration of few seconds. They have a dual significance for insulation coordination:

- Choice of the rated voltage or operating voltage at which the Surge Arrester is required to limit and subsequently reseal
- Determination of the required insulator string length, shape of the insulator and the creepage distance in presence of pollution

These overvoltages are generally caused by:

- Load Rejection:

**(a)** Generator transformer terminals – causing a voltage rise of 1.15 pu and of duration approximately one second

**(b)** In the network: causing a voltage rise of 1.1 pu and of duration approximately ten seconds

However the TOV depends upon the quantum of load disconnected, line length and the short circuit power of the feeding station.

- Single –Phase faults: (voltage rise in the healthy phases)

**(a)** With solid earthing: 1.2 to 1.4 pu

**(b)** With insulated star point or compensation at the neutrals : 1.73 pu

  - Ferranti Effect
  - Ferroresonance
  - Other Resonance phenomenon
  - Harmonic overvoltages

**(ii)** *Switching overvoltages (SOV):* A phase to ground overvoltage at a given location in a system due to various switching events with a time frame in milliseconds range (short duration). Switching overvoltages are of concern only on systems 220 kV and above. The magnitudes of switching surges for systems below 220 kV generally do not exceed 1.5pu of the system phase to ground voltage. A typical switching impulse standard wave shape is 250/2500 μsecs (time to crest / time to half value of crest).

The possible causes of SOV are:

- Line Energization
- Reclosing onto trapped charge
- Opening breakers (Transient Recovery Voltages - TRV)
- Capacitor Switching
- Breaker Restrike
- Inductor Switching (current chopping) etc.

A statistical overvoltage value (used in insulation coordination studies) is an overvoltage generated by a specific event on the system such as line energization, reclosing, etc. with a crest value that has a 2% probability of being exceeded. Its value exceeds 2.0 pu without any mitigating devices and lies in the range of 1 to 2 per unit of the crest phase to ground voltage, when preinsertion resistors, lightning arresters etc. are used.

A switching overvoltage study (as part of insulation coordination studies) is generally carried out to quantify the overvoltages and surge arrester energy duties associated with switching events and fault occurring /clearing operations. The primary intent is to verify that transient overvoltage mitigating devices (e.g., surge arresters, pre-insertion resistors, synchronous close control) are adequate to protect electrical equipment.

(i) *Lightning Overvoltages (LOV):* These overvoltages are due toatmospheric origin and it is fundamentally not possible to prevent them. They are detrimental to equipment insulation and coordination is to be effective mainly against such overvoltages. The lightning overvoltage is determined at the point where lightning strikes, from the product of the impressed lightning current and the surge impedance. The travelling waves emanating from the point where the lightning strikes are subjected to damping by the frequency-dependant resistance of the conductor, ground and by the corona resulting in an increase in the front time of the wave (0.6 to 1.0 μs/km) dependant on the travel time.

LOV as part of insulation coordination studies are carried out to quantify the overvoltages throughout the substation with the primary intent of determining location and number of surge arresters within the substation.

**(i)** *Very Fast Front Overvoltages (VFTO):*These types of overvoltages occur in gas insulated substations (GIS) due to restrikes in the operation of disconnector switch and circuit breaker. These restrikes could generate a large number of VFTO with a rise-time of the order of a few nanoseconds followed by high frequency oscillations. VFTO in UHV GIS are likely to exceed the lightning overvoltage if no measures are taken to control them.

## (B) Over Voltage Mitigation

Power stations, substations and receiving stations generally have equipments like transformers, reactors and other valuable equipment with non-restoring type of insulation which have to be guarded most carefully against internal breakdown created due to the voltage stresses generated in the system due to reasons explained in the previous sections. Therefore protective devices have to be used which shunt the overvoltages to ground thereby preventing the insulation from getting damaged.

Pre-Insertion Resistors: need to be sized according to equipment being switched to prevent excessive switching overvoltages. However, repeated failures of the PIR's in the breaker have led to the consideration of the use of line-entrance /line end arresters for control of SOV. Few utilities have successfully adopted the arresters thus replacing PIR's. However, PIR's provide a superior means of reducing the SOVs along the entire line, whereas arresters only decrease the SOVs within a relatively short distance from the arrester.

- *Synchronous-Close/Open Control:* Requires the use of independent pole operated breakers and associated controller based on equipment being switched to prevent excessive switching over voltages from being initiated
- *Surge Arresters:* They are the devices used to clip and limit high amplitude transient overvoltages. They are normally designed so that they can deal with lightning and switching overvoltages. In general surge arresters cannot and are not intended to limit temporary overvoltages, instead they should withstand the TOV without sustaining damage. Fig. 1 shows the various overvoltages occurring in a power system vs their magnitudes, the withstand voltage of equipment and the level of protection provided by arresters.

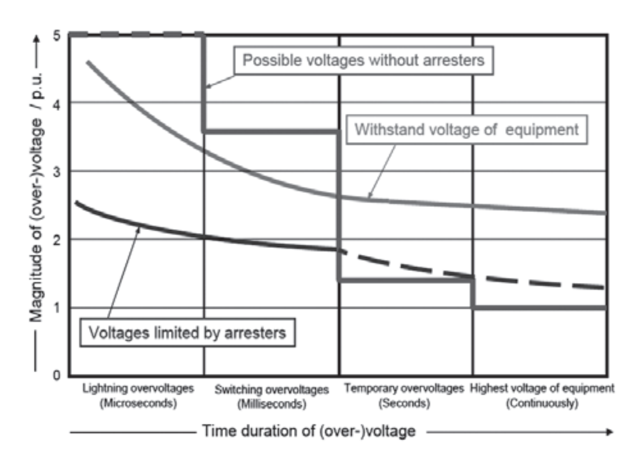


FIG 1: TYPES OF OVERVOLTAGES – MAGNITUDE AND DURATION

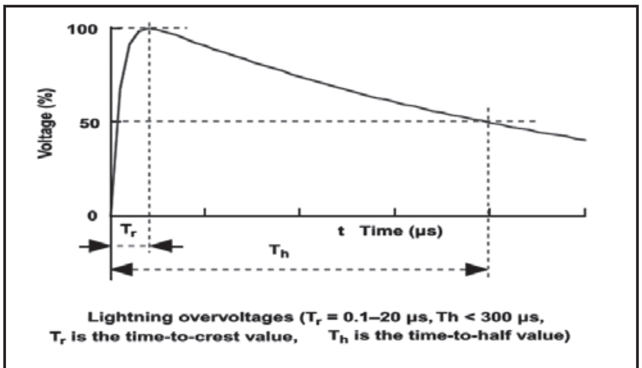


FIG 2(A): LIGHTNING OVERVOLTAGE WAVE SHAPE

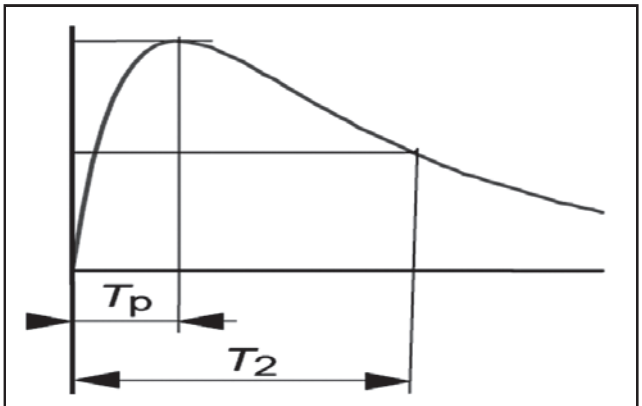


FIG 2(B): SWITCHING OVERVOLTAGE WAVE SHAPE

## 3.0 INSULATION AND INSULATION LEVELS:

Besides the voltage stresses (discussed above) occurring during operation, the electric strength of the insulation provides an additional basis for dimensioning of the insulation. The insulation can be:

- *Internal*(solid, liquid, or gaseous), which is protected from the effects of atmospheric conditions (eg. transformers, cables, gas insulated substations, oil circuitbreakers, etc.) *–non-self restoring insulation*
- *External* (in air), which is exposed to atmospheric conditions (e.g., bushings, bus support insulators, disconnect switches, line insulators, air itself (tower windows, phase spacing), etc.– *self restoring insulation*

Insulation has the following two types of basic withstand characteristics:

- BIL (Basic Impulse Insulation Level):

The BIL (IEEE standards [1]) or basic lightning impulses withstand voltage [2] is the electrical strength of insulation expressed in terms of the crest value of the standard lightning impulse.

- BSL (Basic Switching Impulse Insulation Level):

The BSL (IEEE standards) or switching impulses withstand voltage [2] is the electrical strength of insulation expressed in terms of the crest value of a standard switching impulse.

Both the BIL and BSL are specified by standard lightning impulse and the standard switching impulse wave shapesshown in Figures 2(a) and 2(b) and are described by their time to crestand their time to half value of the tail. The standard BIL and BSL values as defined in standards are given in Table I.

**TABLE 1**
**STANDARD INSULATION LEVELS - VOLTAGE > 220 KV**

| Highest voltage for equip-ment Um kV rms | Standard rated switching impulse withstand voltage | | | Standard rated lightning impulse withstand bvoltage kV peak |
|---|---|---|---|---|
| | Longitudi-nal insulationa kV (peak value) | Phase-to-earth kV (peak value) | Phase-to-phase (ratio to thephase-to-earth-peak value) | |
| 300a | 750 | 750 | 1.5 | 850 |
| | | | | 950 |
| | 750 | 850 | 1.5 | 950 |
| | | | | 1050 |

| | | | | |
|---|---|---|---|---|
| 362 | 850 | 850 | 1.5 | 950<br>1050 |
| | 850 | 950 | 1.5 | 1050<br>1175 |
| 420 | 850 | 850 | 1.6 | 1050<br>1175 |
| | 950 | 950 | 1.5 | 1175<br>1300 |
| | 950 | 1050 | 1.5 | 1300<br>1425 |
| 550 | 950 | 950 | 1.7 | 1175<br>1300 |
| | 950 | 1050 | 1.6 | 1300<br>1425 |
| | 950<br>1050 | 1175 | 1.5 | 1425<br>1550 |
| 800 | 1175 | 1300 | 1.7 | 1675<br>1800 |
| | 1175 | 1425 | 1.7 | 1800<br>1950 |
| | 1175<br>1300 | 1550 | 1.6 | 1950<br>2100 |
| 1100 | - | 1425d | - | 1950<br>2100 |
| | 1425 | 1550 | 1.7 | 2100<br>2250 |
| | 1550 | 1675 | 1.65 | 2250<br>2400 |
| | 1675 | 1800 | 1.6 | 2400<br>2550 |
| 1200 | 1550 | 1675 | 1.70 | 2100<br>2250 |
| | 1675 | 1800 | 1.65 | 2250<br>2400 |
| | 1800 | 1950 | 1.60 | 2550<br>2700 |

a Value of the impulse voltage component of the relevant combined test while the peak value of the power-frequency component of opposite polarity is Um ×√2 / √3.

b These values apply as for phase-to-earth and phase-to-phase insulation as well; for longitudinal insulation they apply as the standard rated lightning impulse component of the combined standardrated withstand voltage, while the peak value of the power-frequency component of opposite polarity is 0,7 × Um × √2 / √3.

c This Um is a non-preferred value in IEC 60038.

d This value is only applicable to the phase-to-earth insulation of single phase equipment notexposed to air

## 4.0 INSULATION COORDINATION METHODOLOGIES

The most commonly used methods of insulation coordination presently in use are the conventional or deterministic method and the probabilistic method[2].

- **Conventional Method** – In this method the minimum strength of insulation is set equal to the maximum stress.

The various power system components in service may face different values of transient voltage stresses – switching voltage impulse and lightning impulse voltage. The maximum magnitude of the voltage reaching the power system component can be reduced by protective devices such as lightning arresters in the system. If the insulation level of the power system components is maintained above the protection level of the protective device by a certain margin (protection margin – 15 to 20 % -fig 3), then ideally there will be no breakdown of insulation of the power system equipment. This procedure is generally adopted for power transformers (nonself restoring insulation).

- **Probabilistic Method** -In this methodthe insulation strength or clearances is selected based on a specific reliability criterion (eg. for a transmission line it may be selected based on alightning flashover rate or for a station based on mean time between failures (MTBF)).

The choice of the method for insulation coordination is generally based on the characteristics of the insulation. For example -

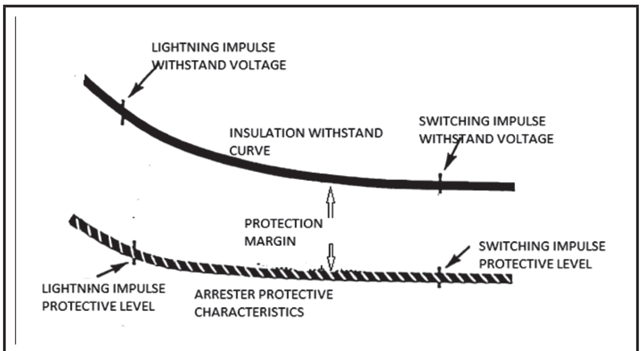


FIG 3: PROTECTION MARGIN –INSULATION COORDINATION

the insulation strength of air is generally described statistically by a Gaussian cumulative distribution, and thereforethis strength distribution may be convolved with the stress distribution to determinethe probability of flashover. However in case of transformer insulation only the conventional method can be used as the insulation strength is specified by BIL for lightning surge and BSL for switching surge.

The following paragraphs describe in brief the procedures for substation and transmission line insulation coordination.

- **Substation Insulation Coordination**

The insulation coordination for substations is to be carried out considering both lightning surges and switching surges. However, switching overvoltages become important only for systems with nominal system voltage greater than 220 kV i.e. EHV systems.

(α) Insulation coordination for *lightning surges*:

All air insulated substations are connected to the rest of the power system via incoming and outgoing overhead transmission lines. Thus, iflighting strikes anyof these lines connected to the station within one or two spans, a surge is likely to enter the stations via these lines. The probability of surges entering the station is more with increased number of lines connected to the station.

The back flashover occurring across the transmission line insulation during lightning striking a ground wire also allows the lightning surges to enter into the substation. However, back flashover phenomenon is rare in EHV systems owing to the high insulation withstand strength.

Lightning surges (whose amplitude will be approximately equal to the flashover level of the insulator across which back flashover has occurred)entering the substation have a high probability of causing flashovers if there are no arresters provided at the transformer terminals. However, a properly coordinated arrester placed close to the transformer, with sufficient protection margin will protect the transformer.

With relevance to insulation coordination, Arresters used in substations are characterized by (i) the arrester operating voltage (maximum continuous operating voltage -MCOV) (ii) Lightning impulse protective level (LIPL) and (iii) Switching impulse protective level (SIPL).

After the insulation levels (basic lightning impulse withstand voltage and switching impulse withstand voltage) and arrester characteristics are determined, they are then coordinated to ensure that there is required safety margin between them (fig 3).Another important factor to be considered in the insulation coordination study of substations for lightning surges is the location and distance between critical insulation points in the station. This is because, farther the distance of the arrester from the protected insulation, results in reduced protection due to the effect of travelling waves.

The other possibility of flashover is across the circuit breaker insulator in case of open breaker due to voltage doubling effect. Sometimes arresters are used at the line entrance of station to eliminate the voltage doubling at the open breaker terminals.

(α) Insulation coordination for *switching surges*:

The switching surges at the end of the transmission lines are those that impinge on the station insulation. There are various reasons due to which switching surges are generated in a system as already discussed above. The general practice followed in the insulation coordination for switching surges for stations is that the station insulation strength must be equal to or greater than the line insulation strength required for switching surges if no arresters are used on the line side of the circuit breaker. However, if line arresters are used the station insulation strength may be chosen solely based on the arrester characteristics without considering the line insulation strength as necessary isolation is provided by the arresters between the lines and station.

- **Transmission Line Insulation coordination**

The procedures mentioned in substation insulation coordination are also applicable to transmission line insulation coordination. The transmission line insulation is self-recovering and hence statistical methods are used for insulation coordination of transmission lines.

Insulation coordination for *Lightning surges:*

Direct lightning strikes to transmission line are prevented by providing shield wire / earth wire at a suitable height from the top most conductor of the transmission line. If the conducting shield wire is properly connected to transmission tower body and the tower is properly earthed (low tower footing resistance) then direct lightning strokes can be avoided from all the conductors coming under the protective angle (30° for lines upto 220 kV and 20° for lines 400 kV).

Back flash overs caused due to lightning strikes on shield wires are the most significant cause of outage on transmission lines. Cases where Back Flashover Rates (BFR) are high (not able to reduce within the acceptable values), surge arresters are placed across the line insulation to prevent flashovers [2]. In such cases, the primary application problem is the arrester energy and the current discharged through the arrester which is to be thoroughly evaluated. In general utilities consider the use of line arresters as a last resort when all other methods (use of counter poises etc.) to reduce the BFR have failed.

Insulation coordination for Switching surges:

Switching surges are one of the factors for determining the air clearances and are important for transmission lines with voltages exceeding 220 kV. Switching surges (slow font over voltages) of interest for transmission lines are the line energisation and re-energisation over voltages. Re-energisation over voltages require more attention for transmission lines where fast three-phasereclosing is employed, because of presence of trapped charges.

The Switching Surge Flashover Rate (SSFOR) is determined by numerical integration of the stress-strength relationship. The stress in this case is the switching over voltage (SOV) quantified by a probability distribution (fig 4) and strength is the switching impulse withstand voltage (CFO) [5].

The random nature of the statistical over voltages is generally described by Guassian or Normal distribution function. For SOV the distribution is defined by two related parameters E2 and σ0/E2 where E2 is the statistical switching over voltage σ0–standard

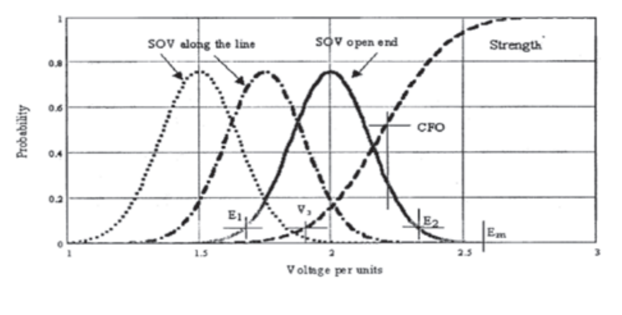


FIG 4: SOV STRENGTH CHARACTERISTICS

deviation. The probability that the SOV equals or exceeds E2 is 0.02, or in other words, 2% of the SOV's equals or exceeds E2 is considered for studies. IEC 60071-2 [4]and IEEE 1313.2 [2] discusses this process in detail.

## 5.0 CONCLUSIONS

A brief explanation of insulation coordination methodologies for EHV substation and transmission lines has been presented in this paper. The task of insulation coordination is complex and computer simulations using digital computer packages like EMTP or PSCAD aids the process. As explained, Insulation coordination studies will investigate surge arresterratings and insulation levels for substation equipment. For substations with voltages up to 220 kVlightning will have the major impact on surge arrester selection. For substation equipment with voltage levels 345 kV and higher, transient overvoltages from switching surges has greater impact on surgearrester selection and substation equipment insulation levels.

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