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Lightning on Overhead Transmission Lines: Dangers and Safety Measures

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Abstract

Lightning-induced disruptions on power transmission lines remain a major cause of faults in high-voltage systems, often resulting in service interruptions, equipment damage, and compromised grid stability. This study examines the primary mechanisms through which lightning impacts transmission infrastructure, including back flashover, shielding failure, and induced overvoltage. To mitigate these effects and enhance system reliability, a range of protective measures are analyzed. These include enhancing insulation levels, installing controllable discharge lightning rods, reducing tower grounding resistance, deploying coupling ground wires, and utilizing line surge arrestors. Each technique is evaluated for its effectiveness in minimizing lightning-related faults and ensuring a stable power supply. The findings emphasize the importance of integrated protection strategies tailored to specific environmental and system conditions. By implementing these safeguarding measures, utilities can significantly reduce lightning-related outages and improve the resilience of power transmission networks.

Keywords: Lightning; Power Transmission; Surge Arrestor; Flashover; Protection Measures; Grid Stability

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Introduction

Lightning is one of the main causes of electric power system fault. The entire power system consisting of power plants, substations, transmission lines, distribution feeders and consumers make up the components of the power system. The system frequency, voltage, tie-line flows, line currents and equipment loading must be controlled and kept within acceptable safety limits (Chong Tong and Mingguang Tong, 2006).

Lightning is an electrical discharge between cloud and the earth, between clouds or between the charge centers of the same cloud. Lightning is a huge spark and that take place when clouds are charged to at a high potential with respect to earth object (e.g. overhead lines) or neighboring cloud that the dielectric strength of the neighboring air is destroyed (Rahul N. Nandeshwar, 2014).

Lightning accidents are always important factors that affect power system reliability. The randomness and complexity of lightning activities has resulted in current numerous research on knowledge of transmission line lightning and many unknown elements. Lightning accidents on overhead power transmission lines stands at approximately 50% of all transmission line faults. It is therefore very necessary to effectively control/prevent lightning damages to a tolerant level (Xu Ying, XU Shi, and Heng AC 2006: Qiu Zhixian 2006).

Lightning, especially Cloud-to-Ground (CG) lightning could damage power transmission lines, distribution lines, substations and power plants. Furthermore, such hazard may lead to loss of system stability and uncontrolled separation of power networks and can even threaten the whole electric power grid. When lightning strikes a phase conductor of the transmission line, the current of the lightning stroke will encounter the surge impedance of the conductor so that overvoltage will be built up and propagate to the substation along the transmission line in wave form. This lightning incoming wave would do damage to electrical equipment and facilities in substations. For example, if the Surge Protection Device (SPD) on an incoming line is not sensitive or reliable enough, the whole station would be at risk with loss of precision devices, control systems or information network. Similarly, the lightning hazards to power system could affect the voltage profile of the power grid, load shedding, abnormal oscillation, and frequency collapse or power network separation. This can affect the dynamic balance of power system, leading to stability of power grid directly or indirectly (Chong.Tong and Mingguang.Tong, 2006).

At present, the measures of lightning protection of transmission line mainly rely on the erection of overhead ground wire of the tower top, its operation and maintenance work is mainly on the detection and reconstruction of tower grounding resistance. Due to its single lightning protection measures, it cannot meet the requirements of adequate lightning protection. The installation of coupling ground wire, the implementation of the enhanced insulation level of transmission line, lightning protection measures, subject to conditions, some of which cannot be effectively implemented, such as the addition or replacement of insulators for large climbing distance method of synthetic insulator to improve line insulation are good but not adequate (Tan Qiong, Li jingLu, Li Zhiqiang. 2011)

The harm of lightning on transmission lines

Lightning strikes cause hazards to transmission lines, including voltage overloads, insulation breakdown, flashovers, and damage to substations and transformers, leading to system instability, power outages, and safety risks. When lightning strikes a conductor, an overvoltage wave propagates along the line, potentially causing equipment failure and network disruptions. Indirect strikes near the line can also induce damaging currents and voltages through electromagnetic induction, affecting nearby components and communication systems.

The main rack transmission lines for the grid (skeleton), its operation safety are the guarantee of the whole power grid safe operation. At present, the main performance of the transmission lines affected by lightning troubles of lightning trip-out, bolt, etc; More form of lightning tripping. So run of single power supply substation will total station blackout, directly affects the area of the whole power supply; At the same time, the higher the voltage grade, lines and lightning harm to the safe operation of the contradiction of the more prominent. Such as 500 kV line, the line running at full capacity, when the lightning tripping, due to the line with transfer to instantaneous load, will cause multiple substation of 220 kV and below power outages, the direct causes of the entire region's power outage, even can produce power grid collapse accidents due to other reasons, extend the influence of the lightning disturbance, causing a greater loss. Now, therefore, the design of the ultrahigh pressure line first line lightning protection design as a top priority Gao Jun. 2009 & Chen Huagang 1998)

Transmission lines from lightning strike is mainly due to the condition of lightning strike to make transmission line insulator is punctured, the insulation of the line moment less, cause the wire connection to earth potential hardware, discharge of cross arm, or along the insulator flashover, residual until disconnection; Generally, lightning strike tend to occur on the 10 kV line, 66 kV and above line lightning strike rarely, almost none. The lightning protection of transmission lines, therefore, the emphasis should be on preventing lightning tripping accidents.

Lightning Problem for Transmission Lines

The negative charges at the bottom of the cloud induces charges of opposite polarity on the transmission line. These are held in place in the capacitances between the cloud and the line and the line and earth, until the cloud discharges due to a lightning stroke.

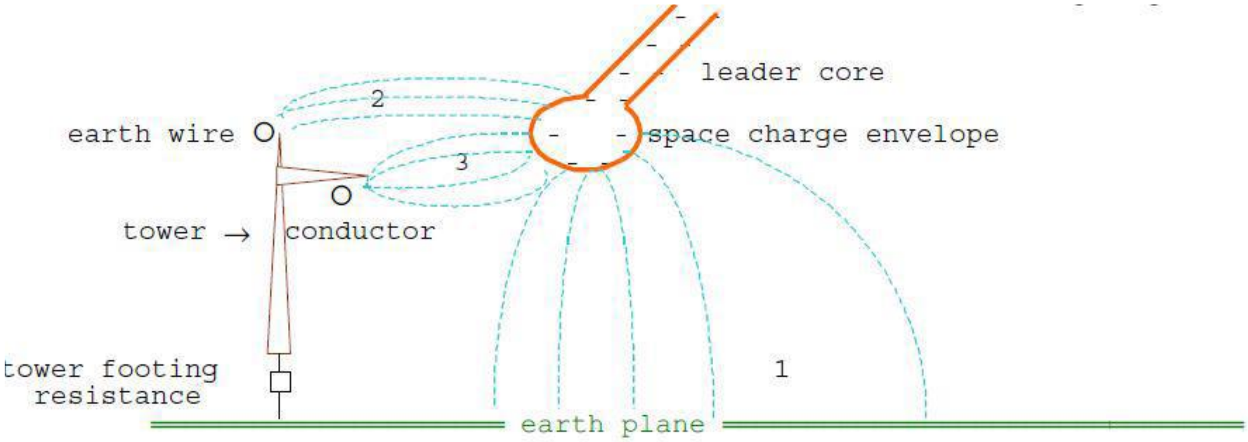

Figure 1: Lightning leader stroke and transmission line [Swati Agrawal and Manoj Kumar Nigam, 2014].

There are three possible discharge paths that can cause surges on the line.

(a) In the first discharge path

which is from the leader core of the lightning stroke to the earth, the capacitance between the leader and earth is discharged promptly, and the capacitances from the leader head to the earth wire and the phase conductor are discharged ultimately by travelling wave action, so that a voltage is developed across the insulator string. This is known as the induced voltage due to a lightning stroke to nearby ground. It is not a significant factor in the lightning performance.

(b) The second discharge path

is between the lightning head and the earth conductor. It discharges the capacitance between these two. The resulting travelling wave comes down the tower and, acting through its effective impedance, raises the potential of the tower top to a point where the difference in voltage across the insulation is sufficient to cause flashover from the tower back to the conductor. This is the so-called back-flashover mode.

(c) The third mode of discharge

is between the leader core and the phase conductor. This discharges the capacitance

between these two and injects the main discharge current into the phase conductor, so developing a surge impedance voltage across the insulator string. At relatively low current, the insulation strength is exceeded and the discharge path is completed to

earth via the tower. This is the shielding failure or direct stroke to the phase conductor. The protection of structures and equipment from the last mode of discharge by the application of lightning conductors and/or earth wires is one of the oldest aspects of lightning investigations, and continue to do so.

Modes of Lightening Flashover

The three primary modes of lightning flashover on transmission lines are Shielding Failure (SF), where a direct stroke hits a phase conductor; Backflash (BF), where a stroke hits the ground wire or tower, creating a high voltage that causes a flash to a phase conductor; and Induction(IN), where a stroke to ground near the line induces overvoltages on the phase conductors.

i). Shielding Failure (SF)

Mechanism: A lightning strike directly hits a phase conductor, bypassing the protective shield wire.

Result: The high current from the lightning stroke causes the insulator to flash over, resulting in a power outage.

ii). Backflash (BF)

Mechanism: A direct lightning strike hits the overhead ground wire or the tower structure.

Result: The tower structure and grounding system have a finite resistance. The high lightning current creates a significant voltage rise across this resistance (a phenomenon known as the "tower footing resistance" or "tower surge impedance"). If this induced voltage is high enough, it can cause a flashover from the tower or ground wire to the phase conductor.

iii). Induction (IN)

Mechanism:A lightning strike to the ground near the transmission line (but not directly on it) generates a strong electromagnetic field.

Result: This electromagnetic induction induces transient overvoltages on the phase conductors, which can cause insulation flashover. This mode is considered less hazardous and is often more manageable for line design.

Analytical Model of Generally Used Transmission Line

Shielding failure flashovers can be reduced to rare events by providing properly shielding conductors. Even poorly located shields wires failed to intercept some of the strokes to line and even poorly located shield wires intercept most of the strokes. To the line and even popularly located shield wires failed to intercept some of the strokes having prospective currents to earth above minimum amplitude the design problem then consist of steps required to locate the shield wires son to intercept strokes having prospective currents to earth above minimum amplitude. It is convenient to an analytical model which exhibits the relations between the structural and electrical parameters of the problems. The mean structural dimension of the line together with the means of striking distance of the stroke constitute the geometrical parameters. The complete analytical model consists of geometry together with an associated set of basic assumptions and mathematical relations (Kola Venkataramana Babu, Manoj Tripathy and Asheesh K Singh, 2011 & C.A. Christodoulou, G. Perantzakis, G.E. Spanakis, P. Karampelas)

Surge Arrester Protection

Lightning surge arrestors are provided at the point of termination. These arrestors absorb any surges in the line and prevent them from traveling into the substation equipment. Lightning arresters are installed on transmission lines between phase and earth is connected to the substation grounding system through short ground conductors of adequate crosssectional area in order to protect or improve the lightning performance and reduce the failure rate.

Surge arresters installed today are all metal-oxide (MO) arresters without gaps, which are the semiconductors; they function as high impedances at normal operating voltages and become low impedances during surge conditions. They are designed to break down at voltages above the highest system operating voltage (but lower than the basic insulation level of the system) thereby becoming good conductors and pass the energy of the lightning impulse to the ground. Once the voltage comes down (after the discharge of the pulse is over) the arrestors return to their original high-impedance state. An ideal lightning arrester should:

(i) Conduct electric current at a certain voltage above the rated voltage;

(ii) Hold the voltage with little change for the duration of overvoltage; and

(iii) Substantially cease conduction at very nearly the same voltage at which conduction started.

The lightning energy E (in Joules) absorbed by an arrester is computed by the relation:

$$\mathbf{E} = \int_{t0}^{t} \mathbf{u(t).i(t)dt} \qquad (1)$$

Where:

u(t) is the residual voltage of the arrester in kV and

i(t) is the value of the discharge current through the arrester in Ka.

When the absorbed energy by the arresters exceeds their maximum acceptable level of energy, then they will fail (damage). Assuming that surge arresters are the last protection measure of a transmission line, an arrester failure is considered as a line fault. The arresters failure rate is given as:

$$\mathbf{FR} = \mathbf{N_g L}\left[\left(\int_{T_t}^{\infty}\int_{I_A I_t}^{\infty} f(I_p \times h_A)\, d(I_p)\, y(t)\, d(T_A)\right) + \left(\int_{T_t}^{\infty}\int_{I_B I_t}^{\infty} f(I_p \times h_B)\, d(I_p)\, y(t)\, d(T_B)\right)\right]$$

(2)

where:

I A (T t) is the minimum stroke peak current in kA required to damage the arrester, when lightning hits on a phase conductor, depending on each time-to-half value, I B (T t) is the minimum stroke peak current in kA required to damage the arrester, when lightning hits on the overhead ground wire, depending on each time-to-half value,

f (I P) is the probability density function of the lightning current peak value,

g(Tt) is the probability density function of the time-to-half value of the lightning current,

FR is the arrester total failure rate, N g is the ground flash density in flashes per km 2 per year and L is the line length in km. [Rahul N. Nandeshwar, 2014], [Christodoulou C.A, Gonos I.F and Stalhopulos I.A, 2008)

The complete analytical model consist of geometry together with an associated set of basic assumptions and mathematical relations.

The mean conductor height can Hg can be computed from the fig 3

$$H_g = H_{gt} - \left(\frac{2}{3}\right)(Sc) \quad \textbf{(3)}$$

Hgt= height of conductor at the tower,

Sc= sag of the conductor;

$$H_g = H_p + \triangle \quad (4)$$

Hg = Height of ground wire from earth

Hp = Height of phase conductor from earth

Dvp= Phase to phase vertical distance

Dhp= Phase to phase horizontal distance

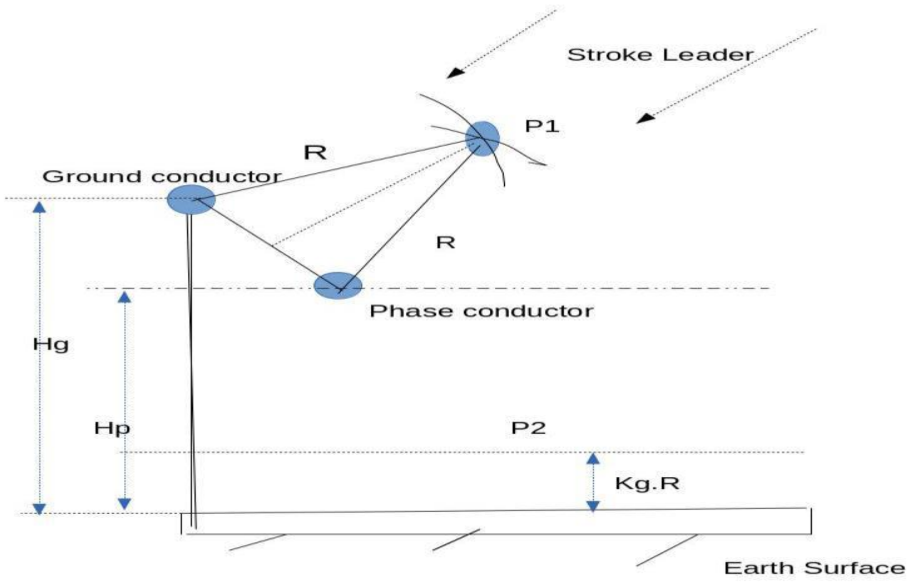

Figure 2: Analytical model of transmission line. [Rahul N. Nandeshwar, 2014].

Hgt = height of the shield wire at the tower

Ss = sag of the shield wire

The striking distances are given by

$$R = aI_p^b + C \quad (5)$$

(According to the standard IEEE model of Transmission line were a = 10),

b = 0.65 and c = 0)

$$R = 10i_P^{0.65} \quad (6)$$

And for Height dependent model (Rizk Model)

$$a = 4027Hg^{0.41} \quad (7)$$

As leader immerges to transmission line protective theory says that the Both Ground wire and Phase conductor produces protective arc around them. This protective arcs cuts each other in space at a point terminating point. The termination point of a lightning stroke to a transmission line can be a ground wire, a phase conductor, a metal tower or even the ground. According to the electro-geometrical model theory, it is able to determine the termination point, when the striking distance is known.

The striking distance, r is give as:

$$r = A.\, i^{b} \qquad (8)$$

Where A and b are constants. The striking distance is depending on the peak current amplitude of the leader stroke, if a lightning strike on transmission line from point P1 and P2 position from fig 5, the following points should be considered;

(i) If lightening strokes disappear before point P, will goes to ground wire i.e. the transmission line has been saved.

(ii) If lightening strokes goes between points P1 and P2 then it will strike directly to the phase conductor i.e. it will cause damage to the transmission line and can harm to useful equipments.

(iii) If lightening stroke strike after point P2 then it will goes to ground and transmission line will be saved.

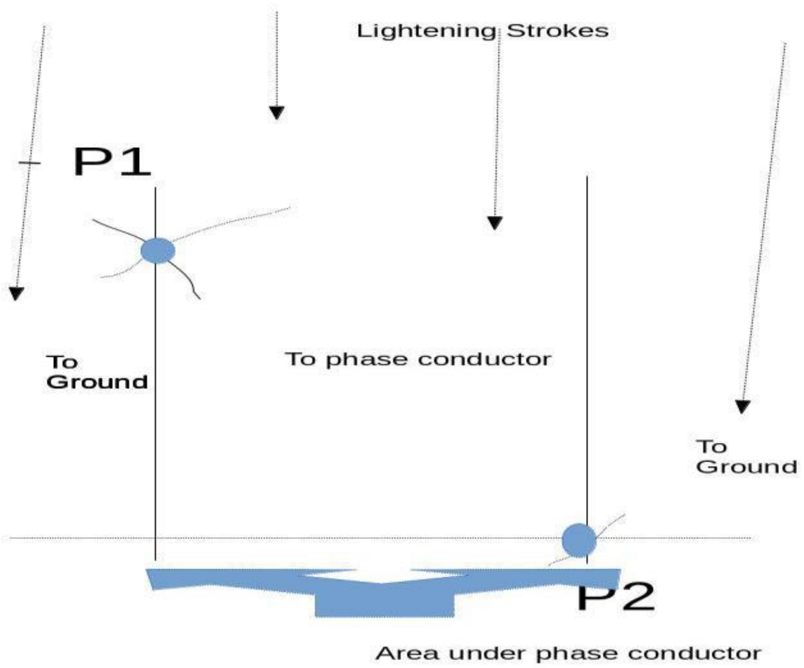

Figure 3: Area of region showing immerging lightening stroke. [Rahul N. Nandeshwar, 2014].

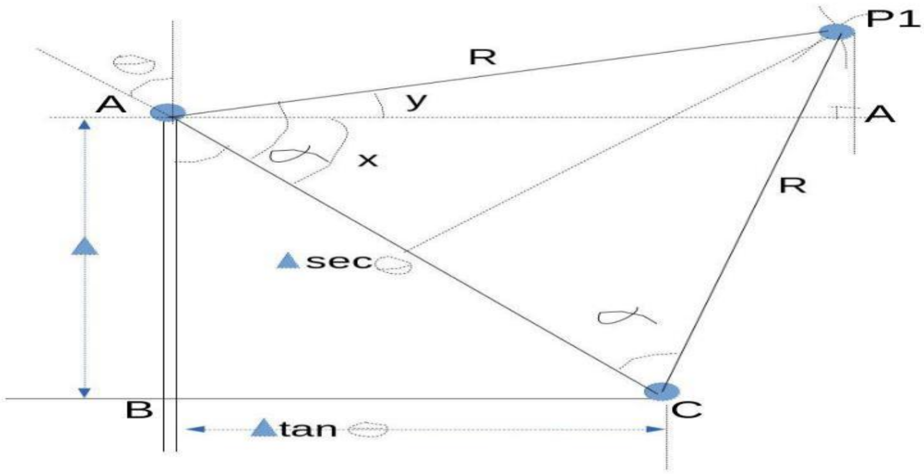

Figure 4: Calculating the co-ordinate of P1. [Rahul N. Nandeshwar, 2014].

The analytical model structures of 330kV transmission tower as shown in fig 4 in this paper, with various physical

parameters are as follows:

Hg = Height of ground wire from earth

Hp = Height of phase conductor from earth

△= Hg − Hp

R = radius of protective arc produced by both conductor during lightening θ Shielding angle between Ground wire and

phase conductor now considering fig 4

.Applying geometrical method for calculating co-ordinates in triangle ABC

AB = Hg – Hp and θ

Shielding angle is BC = △tan(θ)

Applying Pythagoras theorem from fig 6;

$$AC = \sqrt{\triangle^2 + \left(\triangle^2 \tan^2(\theta)\right)} = \triangle \sec(\theta) \quad (9)$$

$$A(0, H_g) \text{ and } C\left(\triangle \tan(\theta, Hg)\right)$$

For triangle ACP1 α=∠y+∡X

$$\cos(\alpha) = \frac{\left(\triangle/_2 \text{ x } \sec(\theta)\right)}{R}, \quad \text{i.e; } \alpha = \cos^{-1}\left[\frac{\left(\triangle/_2 \text{ x } \sec(\theta)\right)}{R}\right] \tag{10}$$

$$\alpha = y + x \quad \alpha = 90 - (\theta - y)$$

$$\alpha = \cos^{-1}\left[\frac{\left(\triangle/_2 \text{ x } \sec(\theta)\right)}{R}\right] = [90 - (\theta - y)]$$

$$\left[\frac{\left(\triangle/_2 \text{ x } \sec(\theta)\right)}{R}\right] = \cos^{-1}[90 - (\theta - y)] \tag{11}$$

$$\left[\frac{\left(\triangle/_2 \text{ x } \sec(\theta)\right)}{R}\right] = \sin(\theta - y) \quad \sin^{-1}\left[\frac{\left(\triangle/_2 \text{ x } \sec(\theta)\right)}{R}\right] = (\theta - y)$$

$$y = \left[\theta - \sin^{-1}\left(\frac{\left(\triangle/_2 \text{ x } \sec(\theta)\right)}{R}\right)\right]$$

Therefore, the co-ordinates of the point P1 will be

$$P1\left(R\cos(\theta), Hp + R\sin(\theta)\right) \tag{12}$$

And for finding co-ordinates of point P2 we can use generalized circle equation

$$(x - x1)^2 + (y - y1)^2 = R^2 \tag{13}$$

$$y = K_g R \quad y1 = Hp \quad x1 = \left(\triangle \tan(\theta)\right)$$

Applying the co-ordinate of P2 equation we have;

$$P2\left(\sqrt{R^2 - (K_g R - Hp)}\right) + \left(\triangle \tan(\theta), K_g R\right) \tag{14}$$

Transmission line with area of 100km can be simply calculating use following formula [Rahul N. Nandeshwar, 2014].

$$a = \frac{(P2 - P1)x100}{100} \tag{15}$$

Preventive Measures On High Voltage Transmission Lines

Protecting overhead transmission lines against lightning strokes is one of the most important tasks to safeguard electric power system and to prevent the disturbing energy from reaching sensitive equipment, since lightning is a usual cause of faults in overhead lines. The protection of the lines is achieved with the following;

i). Strengthen the insulation level of transmission line

Insulation level and lightning withstand level is proportional to the power transmission line, to strengthen the detection of faulty insulators, ensure the transmission line with sufficient insulation strength is an important factor to improve the lightning withstand level of transmission line. As the commonly used to increase insulators or replacement for large climbing distance method of synthetic insulator to improve line insulation, to prevent the lightning strikes the tower lightning voltage effect is good, but to prevent the shielding effect is poor, and the increase of insulators by the tower head insulation gap and the guide line of safety distance constraints, so the line insulation of the enhancement is limited.

ii). The proper use of transmission line lightning arrester

Because lightning arrester installation tower and conductor is potential difference over the action of lightning arrester voltage, lightning arrester join shunt, ensure insulator flashover is not. According to actual operation experience, the lightning trip-out more frequently on the high voltage transmission lines of selective installed lightning arrester can achieve very good lightning protection effect. Across the country have already been used a certain number of transmission line lightning arrester, reflect the good operation. Figure 7 shows the transmission line lightning arrester. [Wang Qinghao, Ge Changxin, Xue Zhicheng, Sun Fengwei, Wu Shaoyong, Li Zhixuan, 2011].

iii). Reduce the tower grounding resistance:

Transmission lines of grounding resistance is inversely proportional to the lightning resisting level, according to each of the soil resistivity tower, as far as possible to reduce the grounding resistance of tower, which is to improve the lightning resisting level of high voltage transmission lines, is the most economic and effective method.

iv). Add ground coupling:

Due to the coupling between the ground can make the wire and cable coupling coefficient increases, and through the thunder and lightning tower flow on both sides of the shunt, thus improve the lightning resisting level of the transmission lines. And coupling ground installation is generally applicable to the hills or mountains across, can lead to play an effective shielding protection, use and strike from the principle is also reduced exposure segment of the wire. But the strength of the tower, the safe distance, cross and lines at the bottom of the transportation, the influence of such factors as so erect coupling ground for the old line is not easy to implement.

Conclusion

Lightning is a primary cause of faults in electric power systems, potentially leading to instability, grid separation, and widespread outages. Effective lightning protection for overhead transmission lines involves measures such as improving insulation, installing controllable discharge lightning rods, reducing tower grounding resistance, adding coupling ground wires, and utilizing transmission line arresters. These strategies are implemented based on regional lightning activity, topography, and soil resistivity to minimize accidents and losses.

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