Overvoltages and Insulation Coordination

- Terminology
- Overvoltages
- Insulation coordination
- Overvoltage protection devices
- Worked examples

Prof. Chengke Zhou
Email: c.zhou@gcu.ac.uk

Learning Objectives

- To understand the concepts and objectives of insulation coordination
- To understand the sources, causes and control measures, of overvoltages, including overvoltage, switching surge and lightning impulse
- To understand the protection afforded by rod gaps and surge diverters
- To understand the propagation of lightning impulses along transmission lines.
- To carry out numerical analysis and to implement designs of the techniques of insulation coordination

Insulation Coordination

This involves a set of quantitative procedure to achieve the best possible tech-economic compromise for protection of persons and equipment against overvoltages.

- The considerations include:

  - cost of insulation; cost of protective devices; cost of failures

- Insulation coordination is based on the knowledge of:
  - Quantitative description of the magnitude and frequency of the stresses to which components will be subjected.
  - Knowledge of insulation strength of components in the form of probability of failure at a particular stress
  - Information to decide whether these stresses may be usefully limited by inclusion of protective devices.

Overvoltages

- Normal voltage of a 3-ph system, the highest voltage of a 3-ph system is usually 10%

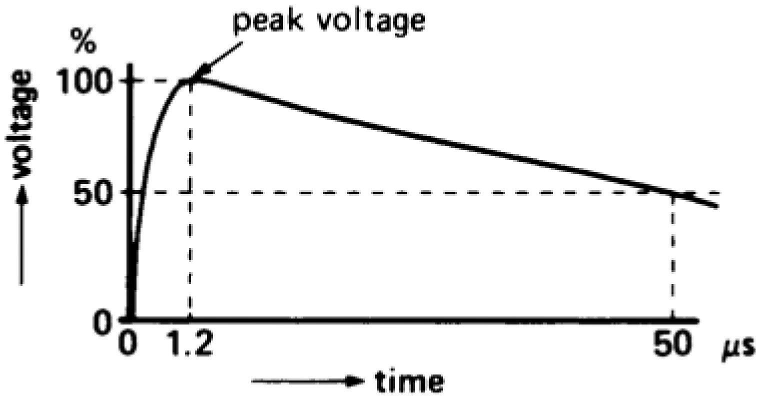
- Overvoltage
  - Temporary overvoltage
  - Switching overvoltage
  - Lightning overvoltage

overvoltage type (cause)	MV-HV over voltage coefficient	term	steepness of frequency front	damping
at power frequency (insulation fault)	$\leq \sqrt{3}$	long > 1 s	power frequency	low
switching (short-circuit disconnection)	2 to 4	short 1 ms	medium 1 to 200 kHz	medium
atmospheric (direct lightning stroke)	> 4	very short 1 to 10 µs	very high 1,000 kV/µs	high

fig. 1: characteristics of the various overvoltage types.

Basic Impulse Level (BIL)

Insulation Level (BIL): The lightning impulse voltage level the equipment insulation is required to withstand.



Standard shape of impulse voltage used to determine the BIL rating of electrical apparatus.

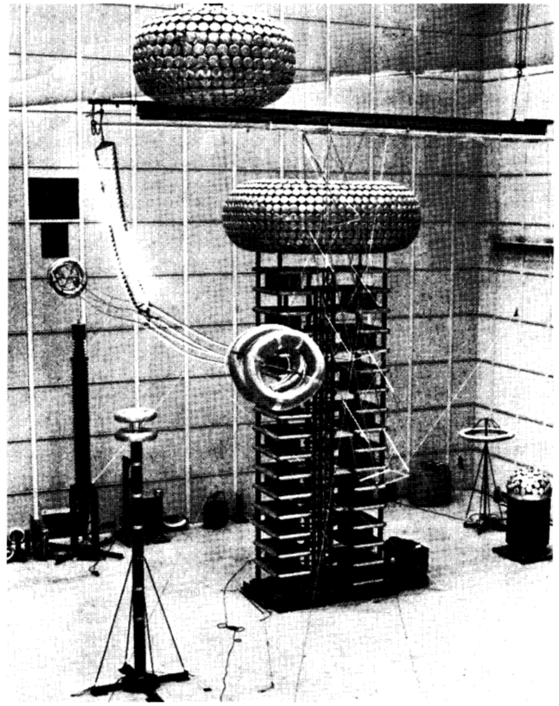


Figure 25.11
A 4 000 000 V impulse causes a flashover across an insulator string rated at 500 kV, 60 Hz. Such impulse tests increase the reliability of equipment in the field. The powerful impulse generator in the center of the photo is 24 m high and can deliver 400 kJ of energy at a potential of 6.5 MV.
(*Courtesy of IREQ*)

TYPICAL PEAK VOLTAGES FOR
1.2 × 50 µs BIL TESTS

Values are in kilovolts

1550	825	250
1425	750	200
1300	650	150
1175	550	110
1050	450	90
900	350	30

Withstand Voltage, Insulation Flashover and Puncture

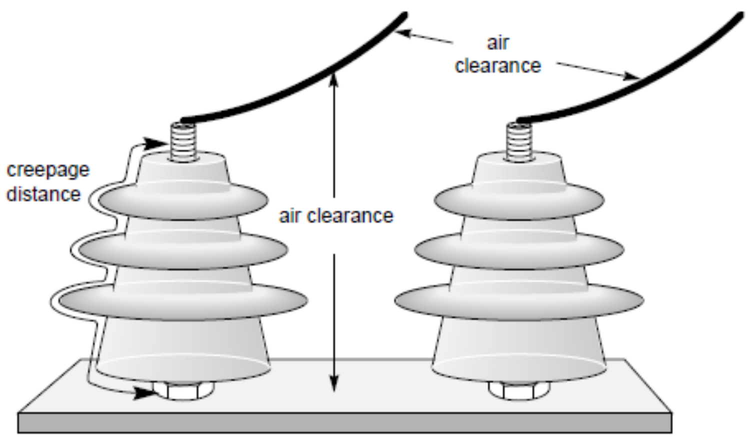
- **Withstand voltage:** is the voltage level equipment should withstand for a given length of time or number of voltage applications without failure of insulation.
- Beyond the withstand voltage, if the discharge of current is external- across insulator, it is known as flashover. If the discharge current flows through the insulation, it is known as insulation puncture.
- It is preferred in HV design that the flashover voltage is lower than that is required for the insulation to puncture.

Clearance and voltage withstand – simple coordination

Clearance --- the shortest path between two conductive parts;

Creepage distance --- the shortest path between two conductors, but following the outer surface of a solid insulator

Voltage withstand --- varies with the type of overvoltage applied (voltage level, rising front, frequency, time....). Moreover, creepage distances may be subjected to ageing phenomena, specific to the insulating material in question, causing deterioration of their characteristics.



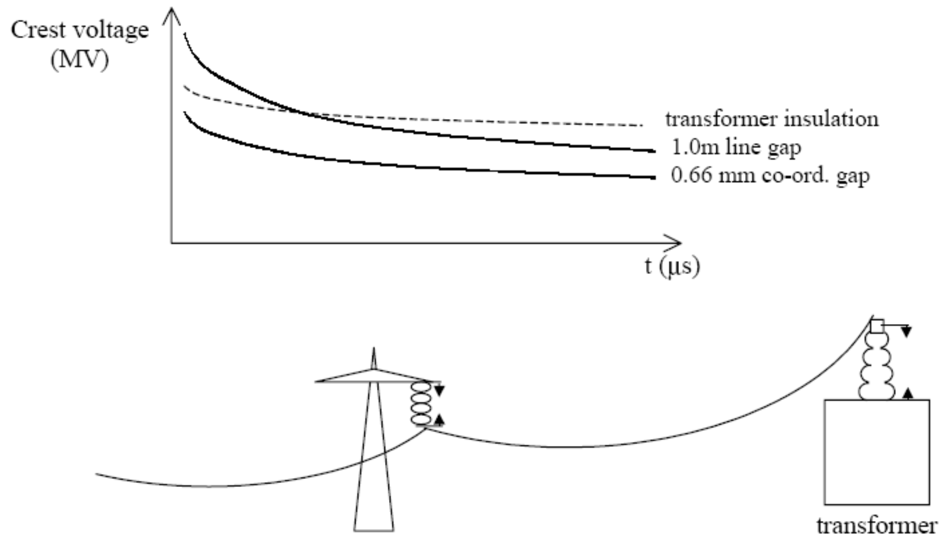


Figure 10.3 - Co-ordination using gaps

Voltage withstand

- In gases, insulation withstand voltage is a highly nonlinear function of clearance.

- For example, in air, a root mean square voltage stress of 300 kV/m is acceptable under 1 m, but can be reduced to 200 kV/m between 1 and 4 m and to 150 kV/m between 4 and 8 m. It should also be pointed out that this clearance is practically unaffected by rain.

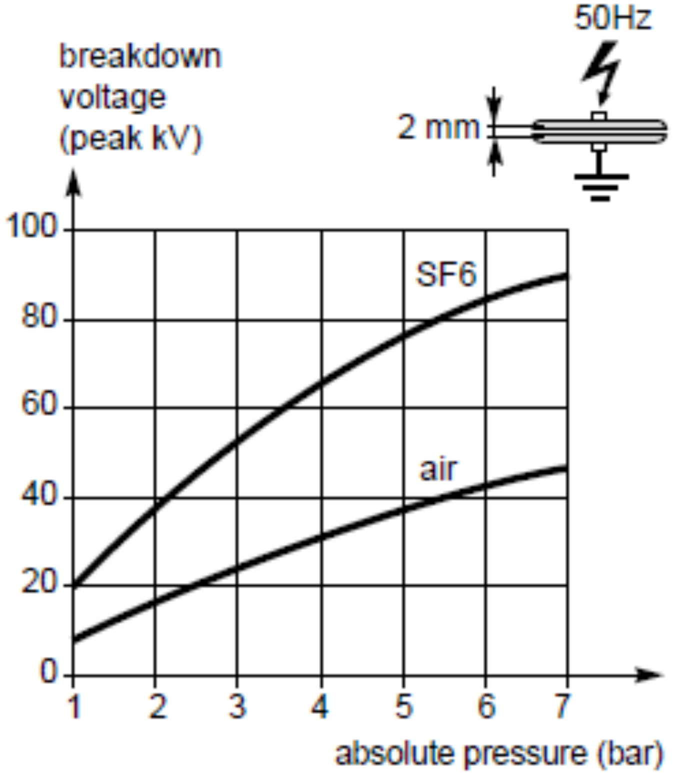


fig. 16: SF6 and air breakdown voltage as a function of absolute pressure.

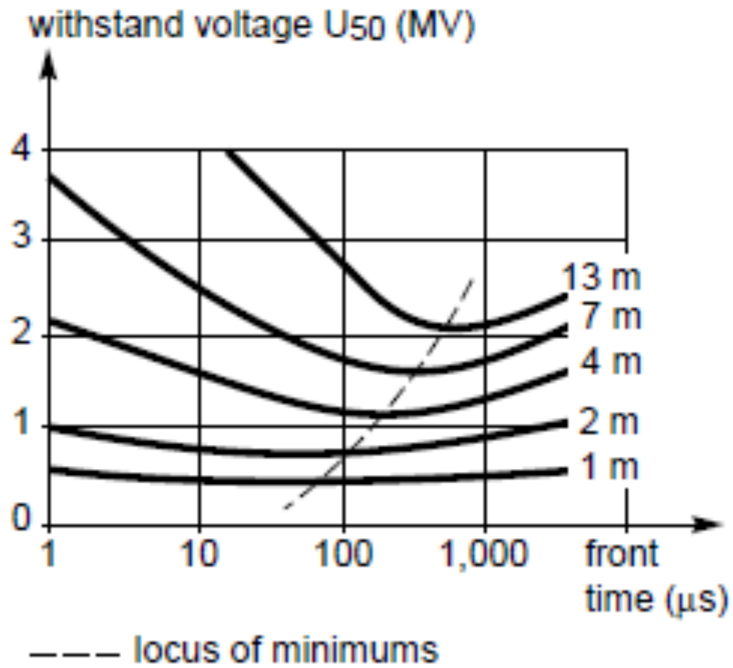


fig. 17: line showing minimum withstand values as a function of front time of impulse applied in positive polarity.

Overvoltages: Lightning Impulse

- Direct strokes: when a thundercloud directly discharges onto a transmission line tower or lines. This is the most severe condition but it rare.
- Induced strokes: When the thunderstorm generates negative charges at the base of cloud, objects such as transmission lines and towers develop induced positive charge. As a result, the line is left with huge concentration of charge which cannot leak suddenly. This is how the overvoltage surges result from indirect strokes.

- Back-flashover: if a direct strike to a tower occurs, the tower has to carry large impulse currents. If the tower footing resistance is considerable then the potential of the tower rises. This can cause insulators to back-flashover.

Lightning overvoltage

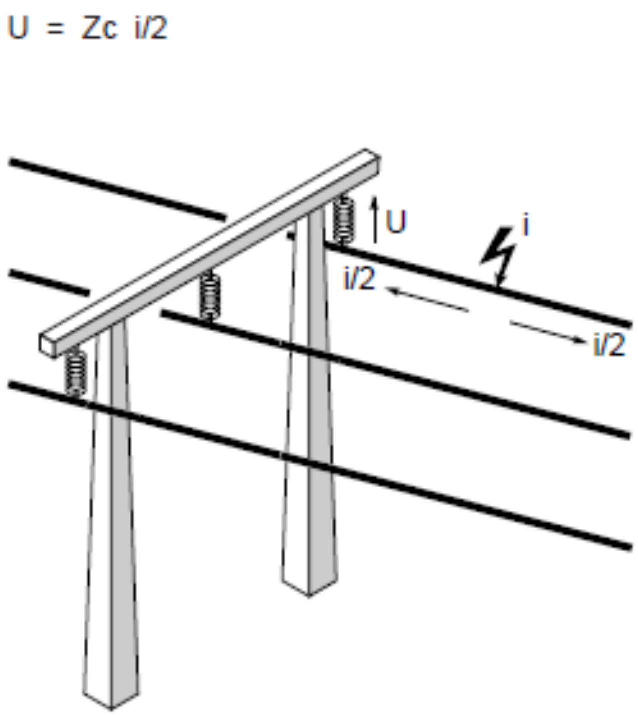


fig. 9: when lightning strikes directly, the current wave propagates on either side of the point of impact.

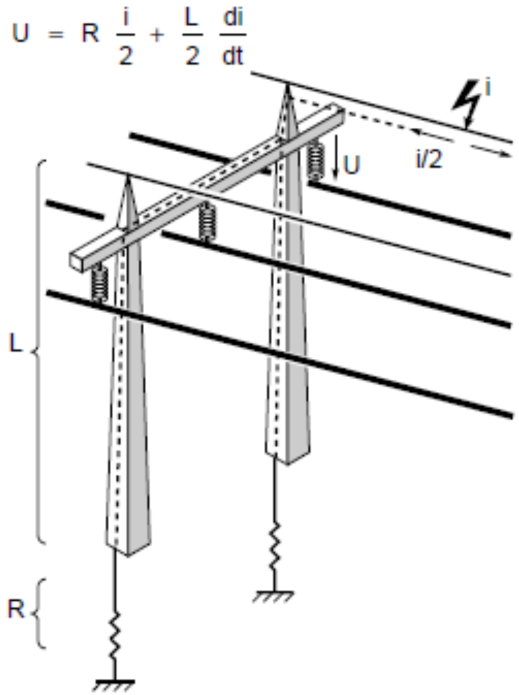


fig. 11: when lightning falls on the earth cable, current evacuation causes an increase in the potential of the pylon metal frame with respect to earth.

Direct strike and indirect strikes – latter can be controlled, see worked example 1

Lightning overvoltages

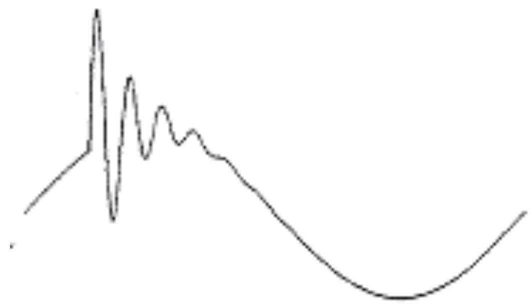
- According to IEC71, lightning surge can be simulated by a aperiodical waveform with a front duration of the order of one of μs and a tail duration of tens of μs.
  - Rise time important
- Direct strike happens when wire not well shielded.
- Striking on tower or earth wire can generate surge in conductor by back flashover or induction.
- Wavefront affacted by line termination at station.

Switching overvoltage

•When the arc between circuit breaker contacts breaks, the full system voltage suddenly appears across the open gap and hence across the circuit (consisting of R, L, and C) making up the system. The resulting voltage consists of a high frequency component superimposed onto the normal voltage. The total is known as restriking voltage and constitutes a switching surge.

•According to IEC71, switching surge can be simulated by a periodical waveform with front duration of hundreds of μs and a tail duration of thousands of μs.

•Switching surges produced by line energisation cause travelling wave on transmission line, most severe at the end remote from the switching point.



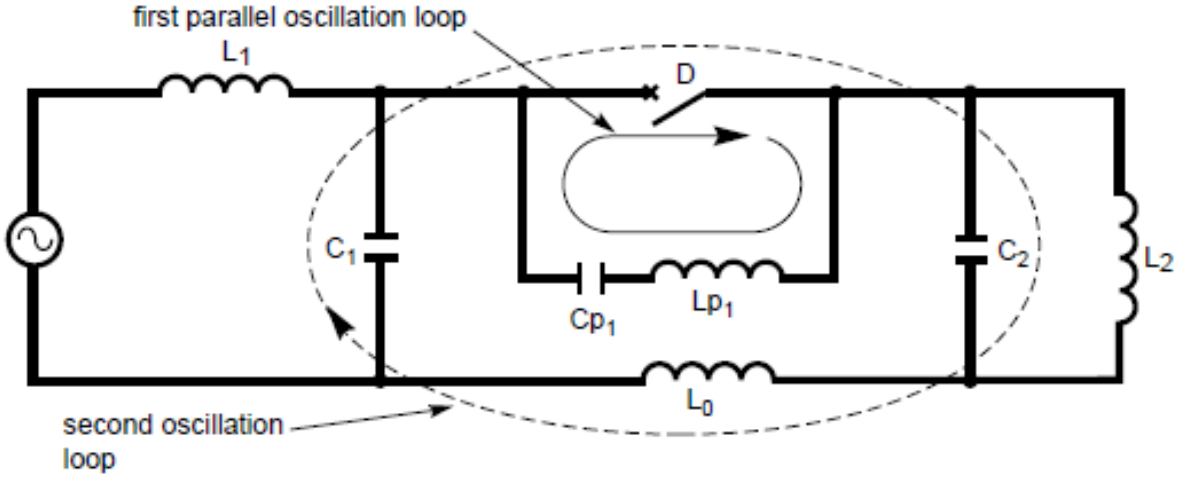


fig. 4: equivalent circuit for the study of overvoltages caused by inductive current breaking where:
Cp_1: circuit-breaker capacitance,
Lp_1: circuit-breaker inductance.

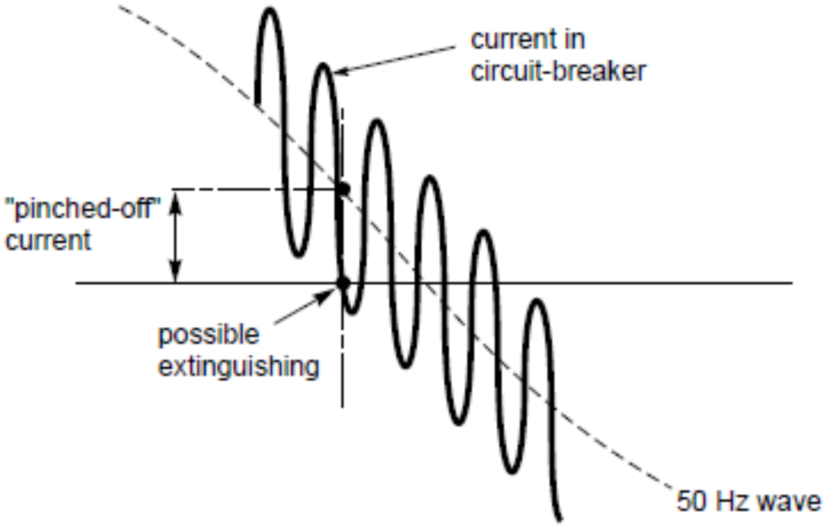


fig. 5: superimposition of a high frequency oscillating current on a power frequency current.

Surge/Impulse Propagation

- For lossless lines, where R=0, and G=∞, a surge would travel at a velocity of $1/\sqrt{LC}$, The characteristic impedance of the wave is, $Z_o=\sqrt{(L/C)}$, which is in hundreds of ohms for overhead lines, and thousands of ohms for transformer.
- At the impedance discontinuities, e.g. a surge arrives at a transformer of Z2 from an overhead line of Z1, then only part of the energy goes through and part of it gets reflected. The following equations are often used for engineering calculations:
- Transmission coefficient $\alpha = 2\times Z_2/(Z_1+Z_2)$
- Reflection coefficient $\beta = \alpha-1 =(Z_2-Z_1)/(Z_1+Z_2)$
- Worked example 2 provides an idea of reflection and transmission of surge pulses happen in power systems.

Factors affecting switching overvoltages

- Overvoltage magnitude depend on:
  - transmission line length,
  - line impedance,
  - the degree and location of compensation,
  - the circuit breaker characteristics,
  - the feeder source configuration and
  - the existence of remnant charge from prior energisation of the line.

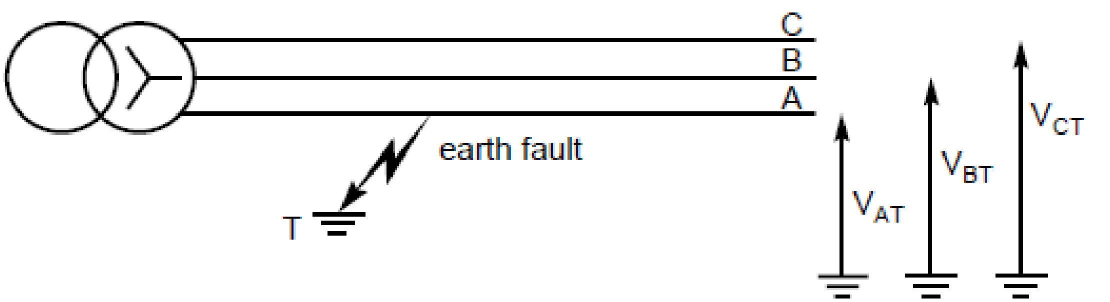
- As the above determines insulation level, reduction of the magnitude of overvoltage is important. Techniques are:
  - Resistor insertion
  - Closing of circuit breakers at close to voltage zeros.
  - The combination of the above.

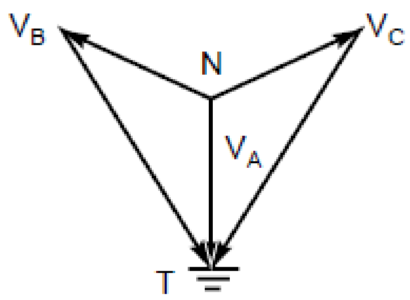
Controlling switching surges

- On systems of 400kV and above, energisation of long lines (>200km) is required.
- Voltages of 4pu can occur.
- It needs to be reduced to 2.5pu to achieve economic design of transmission line and substation.
- At 400kV, metal oxide arrestors at the send and receive end.
- At 500kV, CB pre-insertion resistors can be used, but requiring increased maintenance
- For 500kV with line length<300km, metal oxide arrestor ok with max. voltage occurring at mid-point. For >300km, additional arrestors at mid-point of line is required.

Overvoltages: Temporary overvoltage

Earth fault, Load sheding, Line energisation, ferro-resonance





the phase-earth voltage of fault-free phase is raised to the value of the phase-to-phase voltage:

$$V_{BT} = \sqrt{3}\ V_{BN}$$

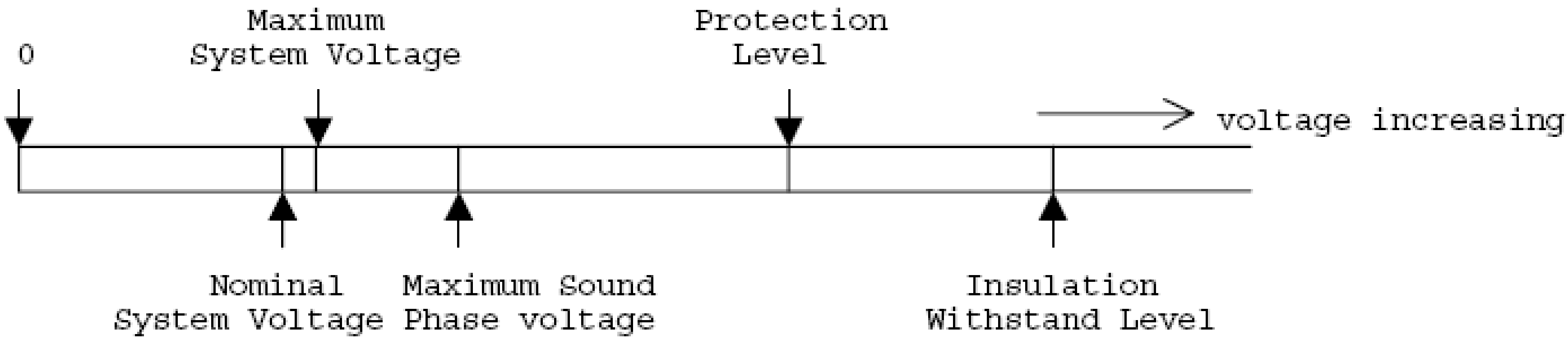
$$V_{CT} = \sqrt{3}\ V_{CN}$$

fig. 2: temporary overvoltage on an unearthed neutral network in presence of an insulation fault.

Insulation coordination and design

- Check operating voltage under normal conditions
- Characteristics of the system
- Calculation of temporary overvoltage
- Calculation of switching overvoltage/ (design gaps and arrestors)
- Calculation of lightning overvoltage/Lightning overvoltage characteristics
- Insulation design as regards operating voltage and temporary overvoltage
- Selection of rated impulse withstand voltage of apparatus / introduction of means for reducing lightning voltage
- Selection of lightning withstand impulse voltage of apparatus.
- Line insulation level, earth wire, gaps,

Conventional approach to insulation coordination



Insulation level (1kV<Um<245kV)(IEC)

Max.volt. for equip. Um (kV, rms)	Power fre. short-dur. withstand volt. (rms, kV)	Lightning impulse withstand (peak, kV)	Max. volt. for equip. Um (kV.rms)	Power fre. short-dur. withstand volt. (rms, kV)	Lightning impulse withstand (peak, kV)
3.6	10	20,40	52	95	250
7.2	20	40,60	72.5	140	325
12	28	60,75,95	123	185,230	450,550
17.5	38	75,95	145	185,230,275	450,550,650
24	50	95,125,145	170	230,257,325	550,650,750
36	70	145,170	245	325,360,395, 460	650,750,850, 950,1050

Insulation level for Um>245kV (IEC)

Max. Volt Um for equip. (rms, kV)	Longitudinal insulation (kV, peak), switching	Ph-earth switch impulse wstd. (kV, peak)	Ph-ph ratio to ph-earth, (kV, peak)	Ph-earth lightning impulse wstd. (kV, peak)
300	750, 750	750, 850	1.5 1.5	850,950 950,1050
362	850, 850	850, 950	1.5 1.5	950,1050 1050,1175
420	850 950 950	850 950 1050	1.6 1.5 1.5	1050,1175 1175,1300 1300,1425
525	950 950 950	950 1050 1175	1.7 1.6 1.5	1175,1300 1300,1425 1425,1550
765	1175 1175 1175	1300 1425 1550	1.7 1.7 1.6	1675,1800 1800,1950 1950,2100

Statistical Approach to Insulation Coordination

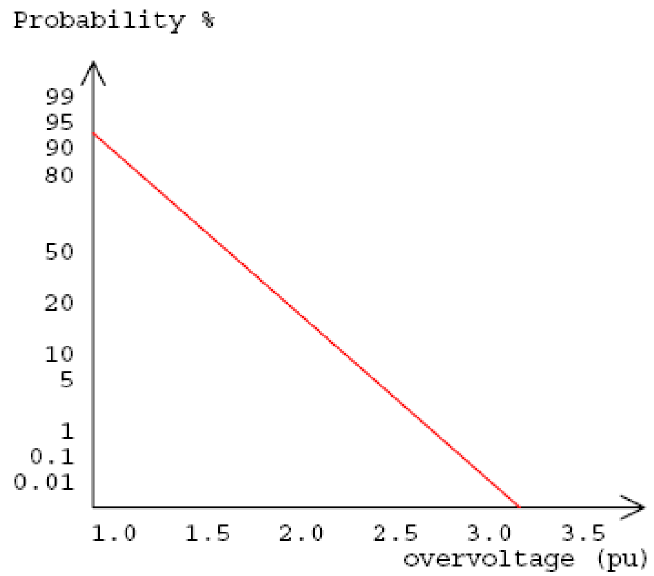
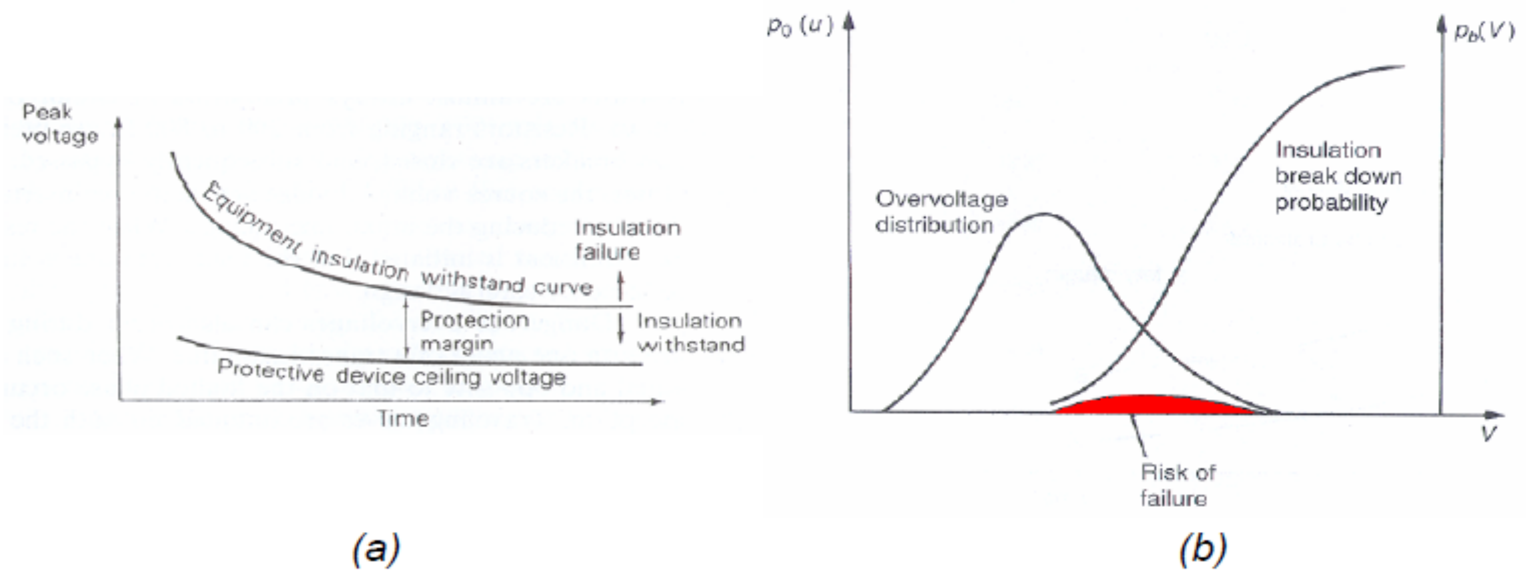
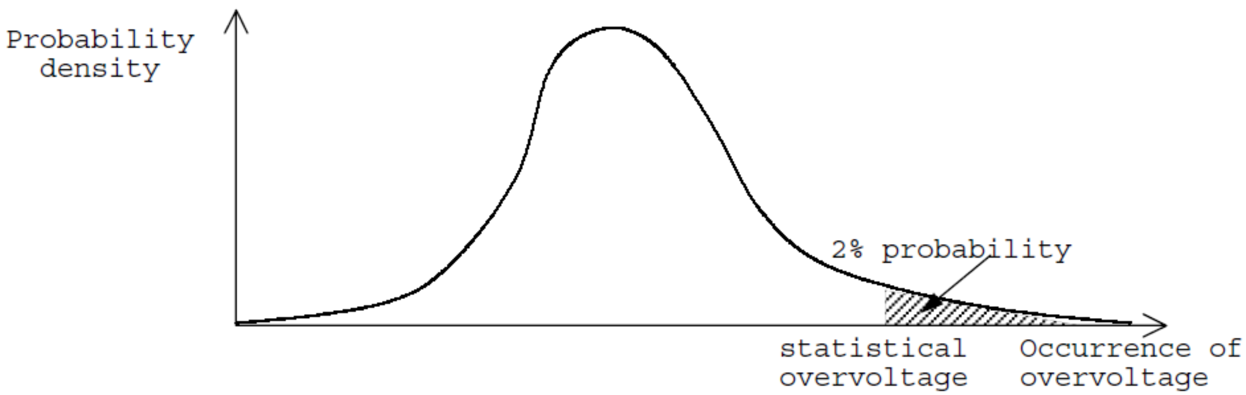


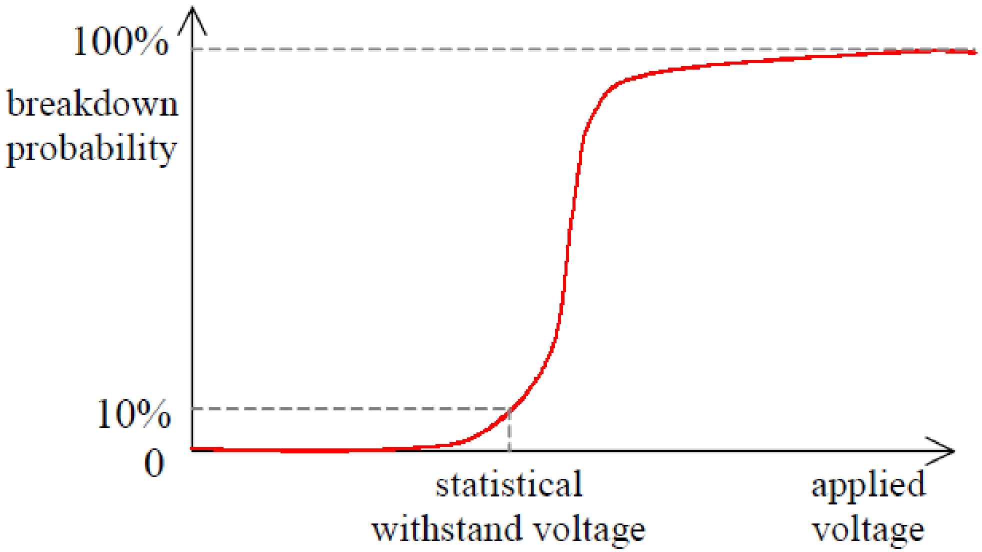
Figure 10.5 Probability of overvoltage exceeding abscissae



(a): The concept of a deterministic protection margin and (b): The concept of a statistical risk of failure.



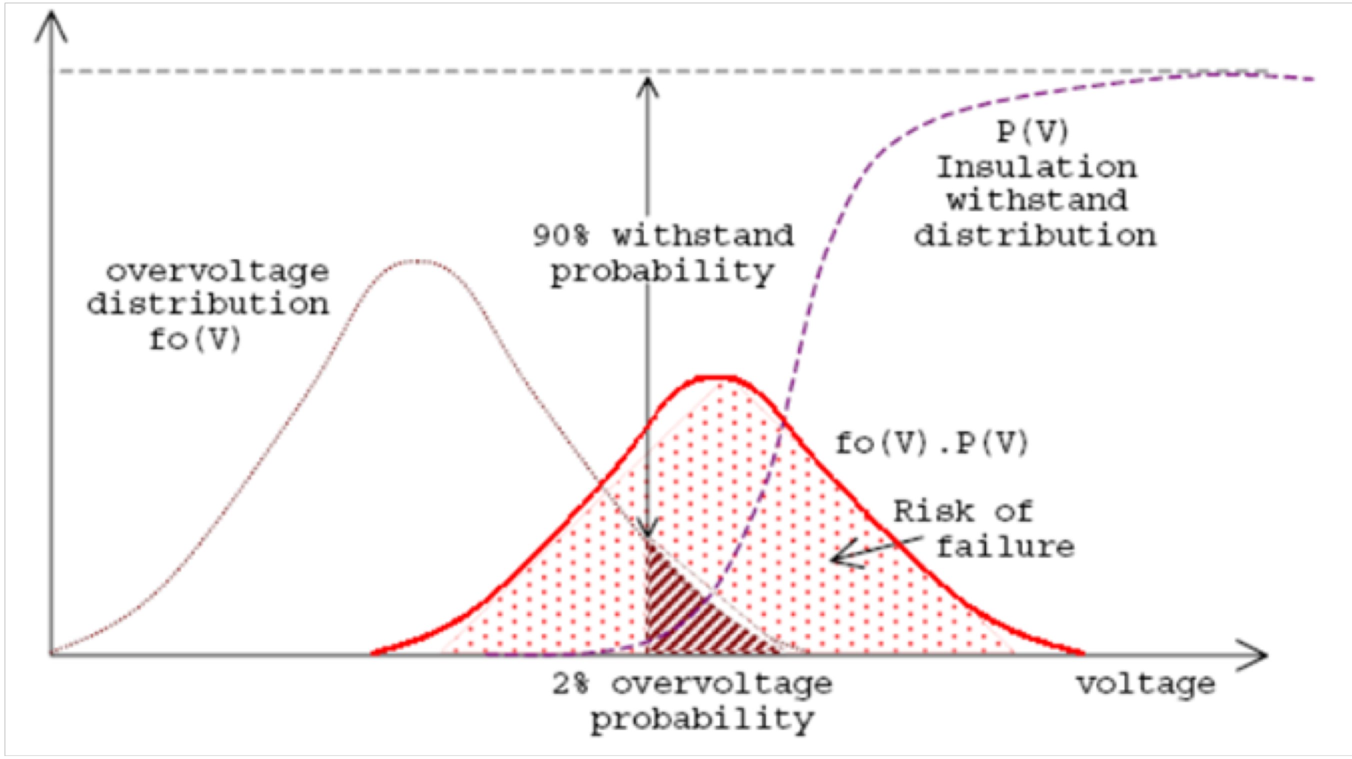
Statistical Impulse Voltage



Statistical Impulse Withstand Voltage

Evaluation of risk factor

- Risk of failure = $\int f_0(V)\times P(V)\, dV$
- Here, f(V) –overvoltage distribution, P(V)—Prob. Of insulation failure

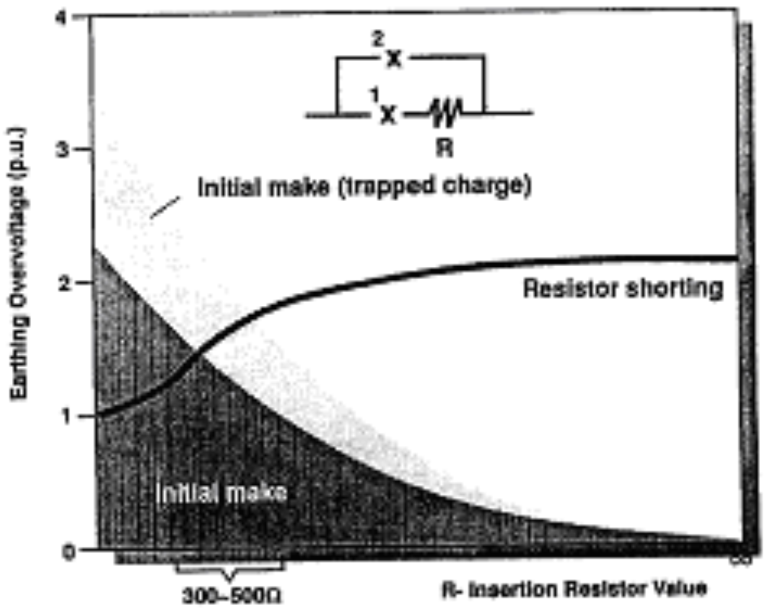


Insulation protection devices

- CB pre-inserted resistor
- Surge arrestors
- Overhead shielding wires

CB pre-insertion resistors

- Resistor reduces magnitude of overvoltage surges.
- Resistor needs to be removed at some point in time.
- Removal of resistor creates another surge.
- Optimum value ranges between 300-500Ω.



Overvoltage reduction with closing resistors

Spark-gaps or rod-gaps

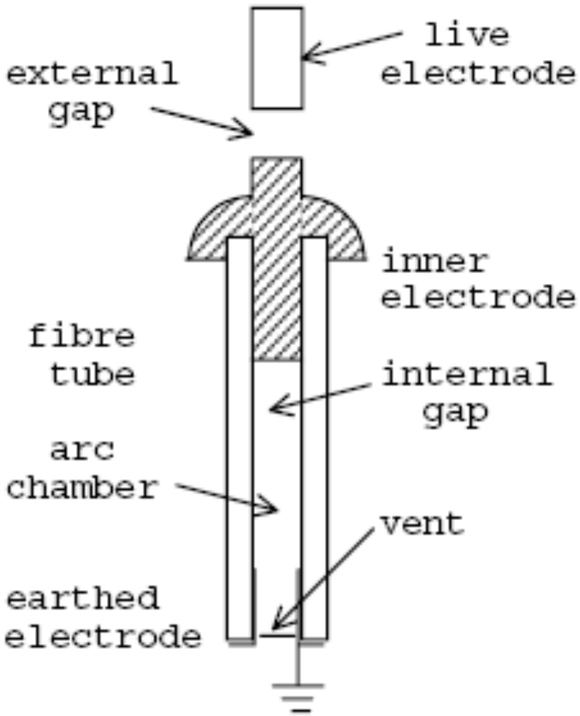


Figure 10.9 - Expulsion Tube

These take the form of rod or horn gaps across insulators or transformer bushings.

These gaps provide poor protection for short, high impulses. In addition, operation of such a gap results in a earth fault on the power system and has to be cleared by the protection relays.

Surge arresters

- A surge arrester is a device to protect electrical equipment from over-voltage transients caused by
  - external (lightning) or
  - internal (switching) events.
- To protect a unit of equipment from transients occurring on an attached conductor, a surge arrester is connected to the conductor just before it enters the equipment.

Surge Arrestor

- Surge diverter (or lightning arrestors) consists of one or more spark gaps in series, together with one or more non-linear resistors in series.
- Silicon Carbide (SiC) and Zinc Oxide (ZnO) are the material often used.
- ZnO arrestor can be gapless as its normal follow current is negligible. It is becoming increasingly more popular due to reliability, thermal and electrical stability.

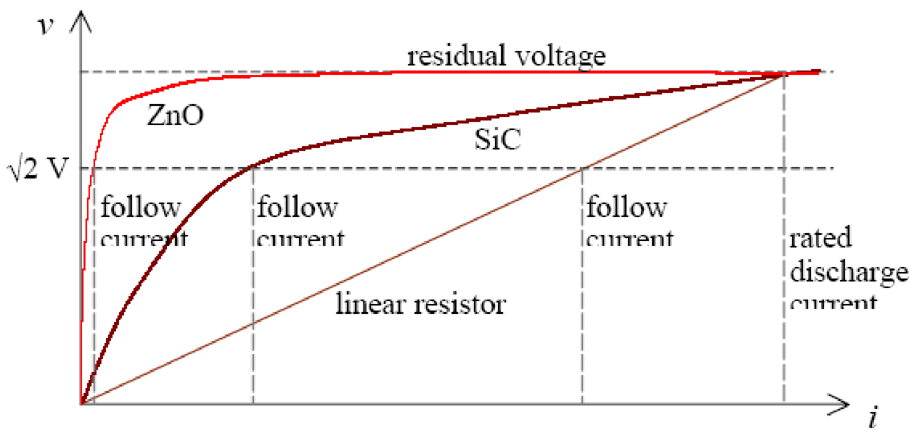


Figure 10.10 - Volt-Ampere characteristics of non-linear elements

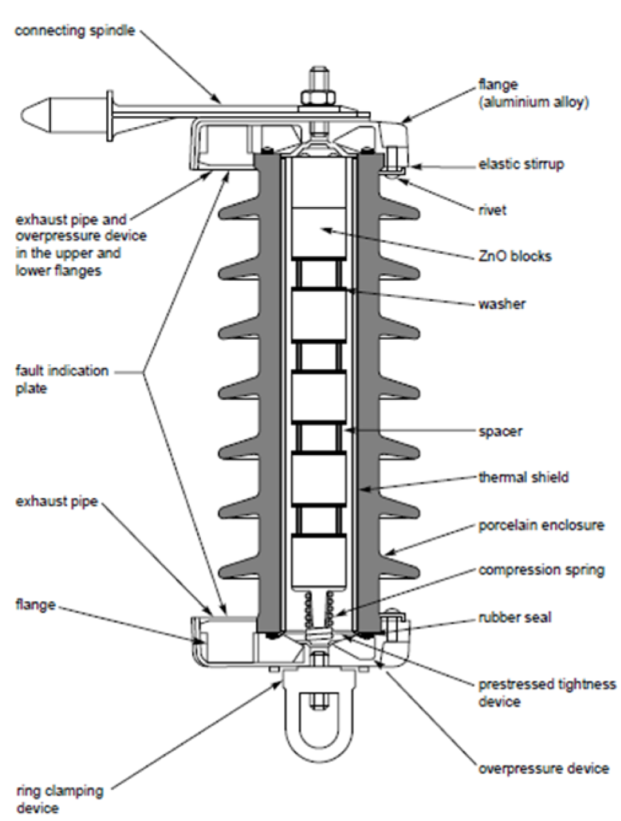


fig. 23: example of the structure of a ZnO arrester in a porcelain enclosure for the EDF 20 kV network.

Worked example 1: To limit a indirect lightning overvoltage

- A 3-phase 69kV line having BIL of 300kV is supported on steel towers and protected by a circuit breaker. The ground resistance at each tower is 20Ω whereas the neutral of the lines is solidly grounded at the transformer just ahead of CB. During an electric storm, one of the towers is hit by lightning stroke of 20kA.

- Calculate the voltage across each insulator string under normal conditions.

- Describe the sequence of events during and after the lightning stroke.

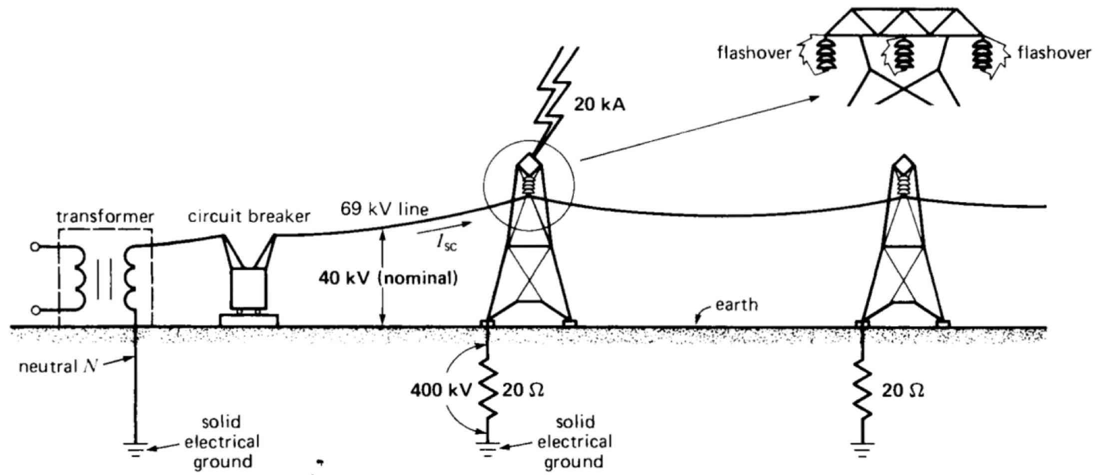


Figure 25.12
Flash-over produced by lightning as it flows to ground.

Example on lightning analysis

- A 3-phase 69kV line having BIL of 300kV is supported on steel towers and protected by a circuit breaker. The ground resistance at each tower is 20Ω whereas the neutral of the lines is solidly grounded at the transformer just ahead of CB. During an electric storm, one of the towers is hit by lightning stroke of 20kA.

- Calculate the voltage across each insulator string under normal conditions.

Solution

a. Under normal conditions, the line-to-neutral voltage is $69\ \text{kV}/\sqrt{3} = 40\ \text{kV}$ and the current flowing in the tower ground resistance is zero. The steel tower is therefore at the same potential as the ground. It follows that the peak voltage across each insulator string (line to tower) is $40\sqrt{2} = 57\ \text{kV}$.

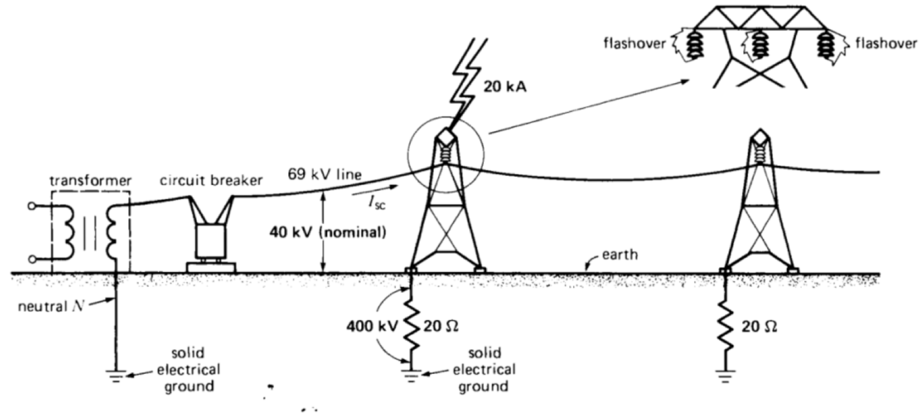


Figure 25.12
Flash-over produced by lightning as it flows to ground.

Example on lightning analysis

- A 3-phase 69kV line having BIL of 300kV is supported on steel towers and protected by a circuit breaker. The ground resistance at each tower is 20Ω whereas the neutral of the lines is solidly grounded at the transformer just ahead of CB. During an electric storm, one of the towers is hit by lightning stroke of 20kA.

•Describe the sequence of events during and after the lightning

b. When lightning strikes the tower, the voltage across the ground resistance suddenly leaps to 20 kA × 20 Ω = 400 kV. The voltage between the tower and *solid* ground is therefore 400 kV, and so the potential difference across all three insulator strings jumps to the same value. Because this impulse exceeds the insulator BIL of 300 kV, a flashover immediately occurs across the insulators, short-circuiting all three lines to the steel cross-arm. The resulting

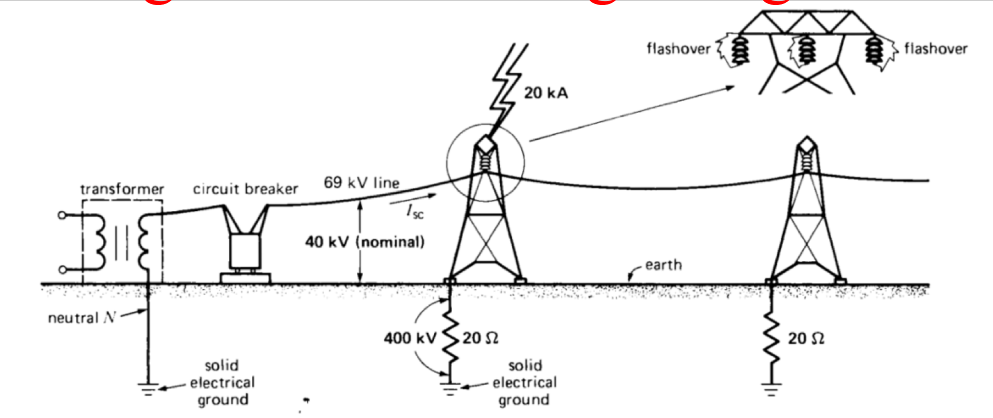


Figure 25.12
Flash-over produced by lightning as it flows to ground.

3-phase short-circuit initiated by the lightning stroke will continue to be fed and sustained by a heavy follow-through current from the 3-phase source. This short-circuit current I_{sc} will trip the circuit breaker, producing a line outage.

Example on lightning analysis

- A 3-phase 69kV line having BIL of 300kV is supported on steel towers and protected by a circuit breaker. The ground resistance at each tower is 20Ω whereas the neutral of the lines is solidly grounded at the transformer just ahead of CB. During an electric storm, one of the towers is hit by lightning stroke of 20kA.

•Describe the sequence of events during and after the lightning stroke.

In view of the many customers affected by such a load interruption, we try to limit the number of outages by ensuring a low resistance between the towers and ground. In this example, if the tower resistance had been 10 Ω instead of 20 Ω, the impulse voltage across the insulators would have risen to 200 kV and no flashover would have occurred.

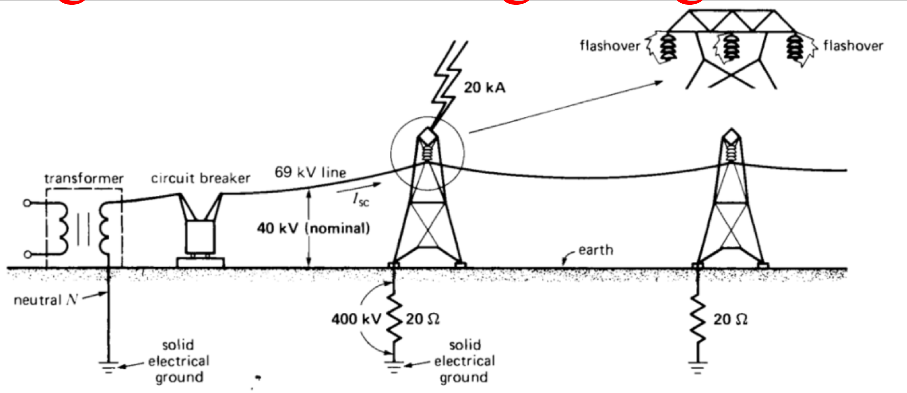


Figure 25.12
Flash-over produced by lightning as it flows to ground.

Note that lightning currents of 20 kA are quite frequent, and they last only a few microseconds.

Another way of avoiding a line outage is to use a circuit breaker that recloses automatically, a few cycles after it trips. By that time the disturbance due to lightning will have disappeared and normal operation of the system can resume.

Worked Example 2

An underground cable of inductance 0.189mH/km and of capacitance 0.3μF/km is connected to an overhead line having an inductance of 1.26mH/km and capacitance 0.009μF/km. Calculate the transmitted and reflected voltage and current waves at the junction if a surge of 200kV travels to the junction,

(a) along the cable, and (b) along the overhead line

Solutions:

Solutions

Surge impedance of cable $Z_1 = \sqrt{\frac{L_1}{C_1}} = \sqrt{\frac{0.189\times10^{-3}}{0.3\times10^{-6}}}$ =25.1Ω, similarly Z_2=374.2Ω.

(a) when the surge travels along the cable, the reflected wave:

$\beta = \frac{Z_2 - Z_1}{Z_1 + Z_2} = \frac{374.2-25.1}{374.2+25.1} = 0.874$

The reflected voltage wave: Vr= β V = 0.874x200kV =175kV

The transmitted wave Vt=(1+ β)V = 1.874x200kV = 375 kV

The reflected current wave ir = 175kV/25.1 = 7 kA

The transmitted current wave it = 275/374.2 = 1 kA.

(b) when the surge travels along the cable, the reflected wave:

$\beta = \frac{Z_1 - Z_2}{Z_1 + Z_2} = \frac{25.1-374.2}{374.2+25.1} = -0.874$

The reflected voltage wave: Vr= β V = -0.874x200kV = -175kV

The transmitted wave Vt=(1+ β)V = (1-0.874)x200kV = 25 kV

The reflected current wave it = 175/374.2 = -467 A.

The transmitted current wave ir = 25kV/25.1 = 1 kA

Worked example 2: Separation limit for lightning arrestors

- Determination of distance of arrestor to equipment *l*. assuming β as reflection coefficient, Et: equipment voltage, Ea: arrrestor voltage, de/dt: rate of rise of lightning impulse.
- The maximum of volt. At equipment as a result of reflection is:

$$E_t = E_a + \beta \frac{de}{dt} x \frac{2l}{300}$$

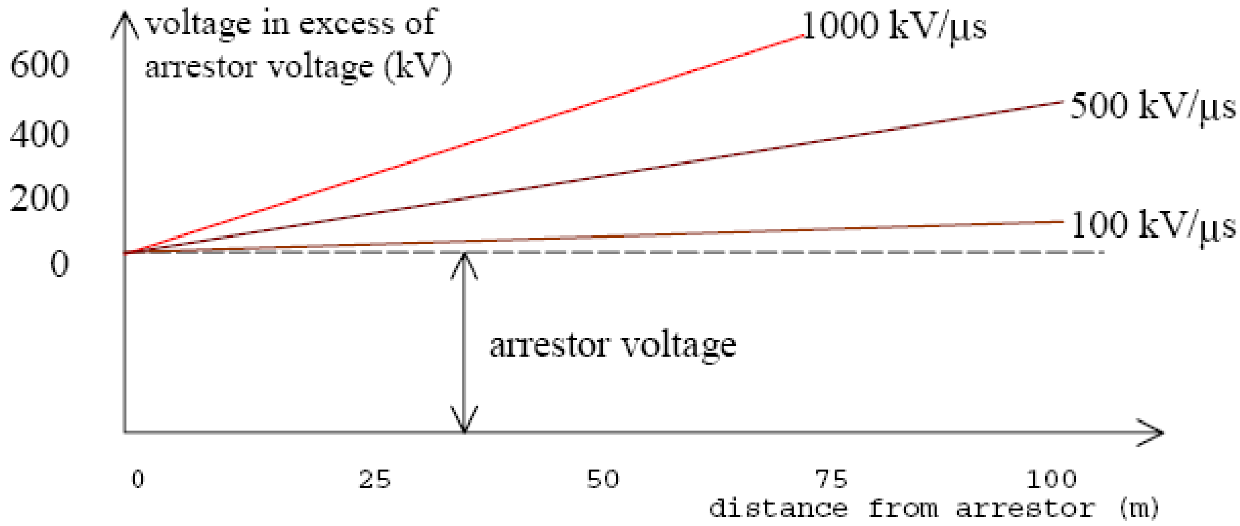


Figure 10.12 - Lightning arrestor separation

Worked Example 2

A lightning arrestor having a flashover voltage of 650 kV is located on a main 132-kV busbar providing protection to a 132/33kV transformer having a surge impedance of 1600Ω. The arrestor is subject to a surge of 500kV rising at 1000kV/μs originating on a 132-kV line, of surge impedance 400Ω, connected to the transformer via a busbar. The transformer is effectively earthed.

(i)Assuming the arrestor is 90 meters away from the transformer, determine the time required to travel between the two plant items, transmission and reflection coefficient for the lightning impulse.

(ii) Sketch the voltage waveform at the location of arrestor and the location of transformer.

(iii) The lightning impulse insulation level of the transformer on the 132kV side is 900kV. Determine, stating any assumptions made, the maximum possible voltage at the transformer terminal.

(iv) What would have been the maximum separation permissible between the transformer and the lightning arrestor, if the BIL of the transformer was 900 kV and a protective margin of 25 % is required, for the above case?

[Note: $E_t = E_a + \beta(de/dt) \times 2l/300$]

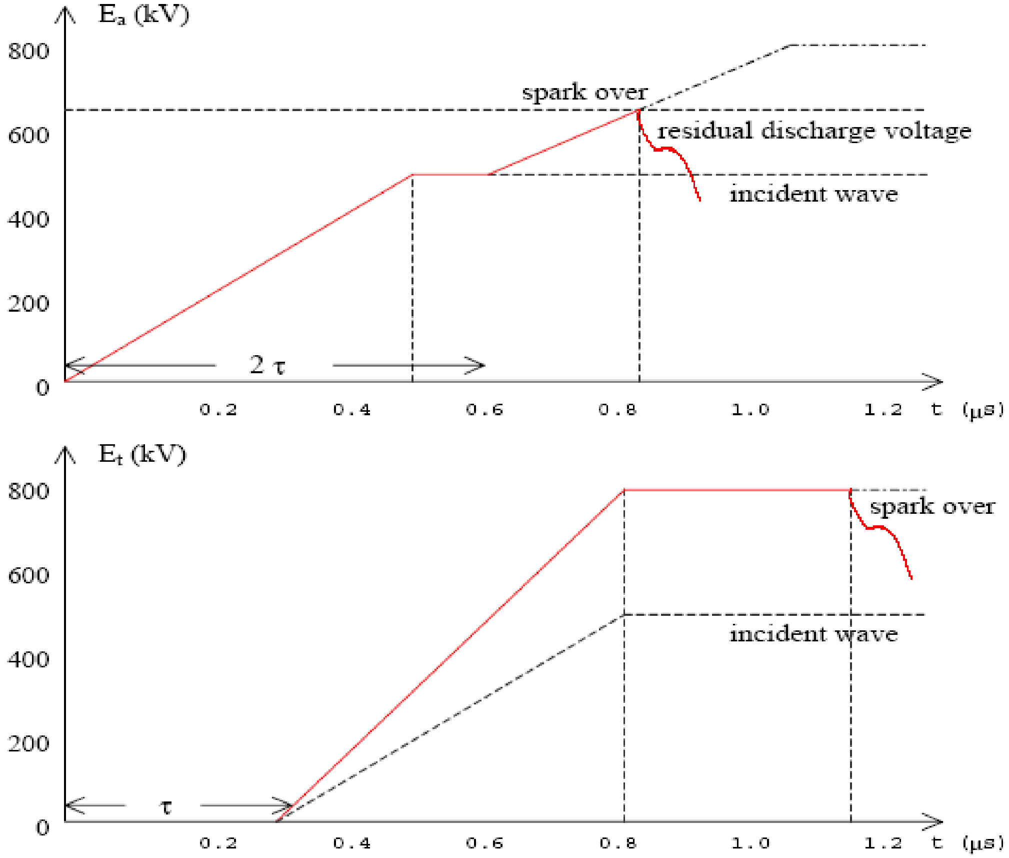
Solution

(i) If the separation is 90 m, travel time of line J = 90/300 = 0.3 μs (1)

Transmission coefficient $\alpha = 2 \times \frac{1600}{1600+400} = 1.6$

Reflection coefficient $\beta = 1.6 - 1 = 0.6$

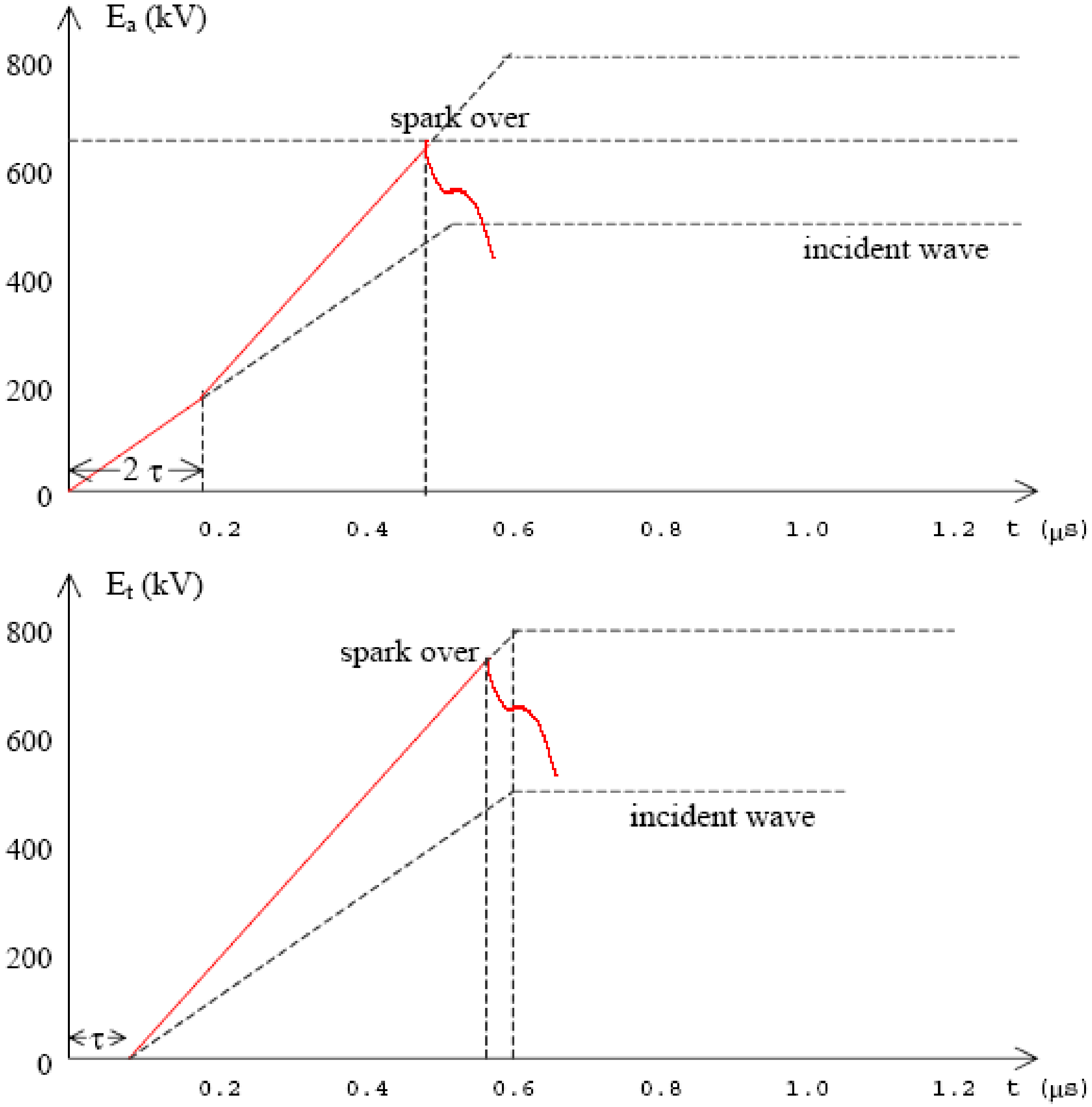
(ii) The impulse arrives at arrestor 0.3μs earlier than at transformer. The sketch below shows how the voltages at arrestor and transformer terminals change.



Sketch - if distance is 30 meters

If the separation is 30 m, travel time of line J = 30/300 = 0.1 :s

In this case the voltage waveforms at the arrestor and the transformer location are as follows.



(iii)

The maximum value of the voltage E_t at the terminal for each case can be determined from $E_t = E_a + 0.6\frac{de}{dt} \times \frac{2l}{300}$ up to a maximum of 0.6 E_a.

For 90 m, maximum E_t -> 650 + 0.6 x 1000 x 90 x 2 / 300 = 1010 kV (the peak impulse could be higher than 500kV, which can result in higher transformer terminal voltage)

Therefore maximum E_t = 800 kV (800kV obtained from the drawing)

(iv)

For a protective margin of 25 %, maximum permissible surge at transformer = 900/1.25 = 720 kV

Therefore 720 = 650 + 0.6 x 1000 x 2 L / 300

This gives the maximum permissible length L = 17.5 m.

Worked example 3: Overhead Shielding Wire

- Shielding wire can be used to protect against direct strikes only on a short length of line prior to substation.
- When a surge ***e*** approaching terminal equipment exceeding critical value of $\boldsymbol{e_0}$, corona occur.
- If an earth wire is connected, all voltage above max. surge (may cause insulation failure) will be distorted by corona.
- Corona extracts energy from surge and lose to atmosphere.
- Corona power increases with square of excess voltage, distortion is not uniform.
- Corona increase effective conductor size, thus capacitance. Inductance remain unchanged, surge will have lower velocity.

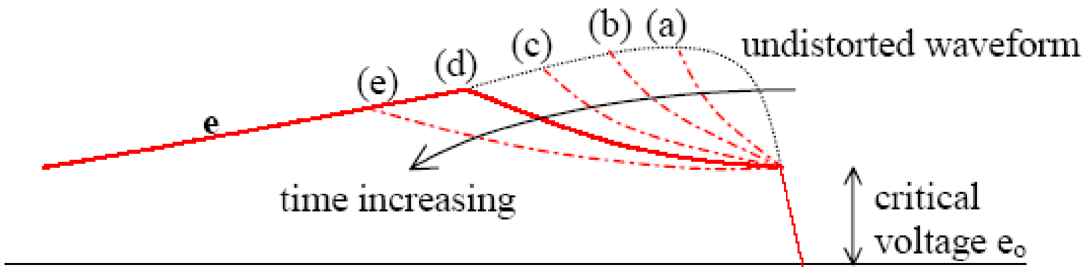


Figure 10.7 - Modification of waveshape due to corona

Worked Example 3

A transformer has an impulse insulation level of 850kV and is to be operated with a margin of 15% under lightning impulse conditions. The transformer has a surge impedance of 1600Ω and is connected to a transmission line having a surge impedance of 360Ω. A short length of overhead earth wire is to be used for shielding the line near transformer from direct strikes. Beyond the shielded length, direct strokes on the phase conductor can give rise to voltage waves of the form $820e^{-0.05t}$ kV (where t is expressed in μs).

$$\frac{\Delta t}{x} = \frac{1}{B}\left[1 - \frac{e_o}{e}\right] \quad \mu s$$

If the corona distortion in the line is represented by the expression , where B=120m/μs and e_o=180kV, determine the minimum length of shielding wire necessary in order that the transformer insulation will not fail due to lightning surges.

Solution:

The maximum permissible voltage is

850kV x (100-15)%=850 x 0.85 =722.5kV

The transmission coefficient is 2x1600/(1600+360) = 1.63

Thus the maximum surge voltage allowed is 722.5/1.63= 443.25kV.

This means that the distortion along the lines must reduce the voltage to 443.25kV.

Therefore, $820e^{-0.05t}$ = 443.25 kV. This gives the delay time as t = 12.3 µs

Substituting into equation, $$\frac{\Delta t}{x} = \frac{1}{B}[1 - \frac{e_o}{e}] \quad \mu s$$

we have, B=120m/µs, e_0=180kV, e = 443.25kV, Δt=12.3µs,

solving the equation gives x =2485m. So the minimum length of shielding wire should be 2485m. Any lightning impulse within the distance, if not arrested, will cause danger of flashover or breakdown.