TECHNICAL NOTE 2.0

Overvoltages – origin and magnitudes

Overvoltage protection
The TECHNICAL NOTES (TN) are intended to be used in conjunction with the
APPLICATION GUIDELINES
Overvoltage protection
Metal-oxide surge arresters in medium-voltage systems.

Each TECHNICAL NOTE gives in a concentrated form additional and more detailed information about various topics of MO surge arrester and their application under normal and special service conditions.

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Overvoltages in electrical power systems

Overvoltages in electrical supply systems result from lightning and switching actions and endanger electrical equipment. They can lead to electrical breakdown or a reduction of the lifetime of equipment.

1 Introduction

An overvoltage is per definition any voltage between phase and earth or between phases having a peak value exceeding the peak of the highest voltage of the system divided by $\sqrt{3}$ or exceeding the amplitude of the highest voltage of the system, respectively.

Overvoltage values are expressed in p.u.,

$$1 \text{ p.u.} = U_s \times \sqrt{2}/\sqrt{3}$$

(IEC 60071-1)

This means that overvoltages are in any case related to the system voltage.

Voltages and overvoltages are classified according their shape and duration. We must distinguish between continuous voltage and temporary overvoltage (TOV) with power frequency, and transient overvoltages due to lightning effects and switching operations in the time range of microseconds to milliseconds.

On-grid overvoltages (TOV) are due to short circuits or earth faults in the system, load rejections or resonances. These overvoltages with power frequency generally do not endanger the insulation of equipment and are therefore not discussed in the following.

2 Origin of overvoltages

2.1 From lightning to overvoltage

Figure 1 shows the principle of the global electric circuit. It is assumed that the earth is charged negatively and the atmosphere in a height of about 50 km is charged positively. The electrosphere as indicated in Figure 1 is conducting. Due to the electric field between the electrosphere and the earth a “fair-weather current” flows between the electrosphere and the earth. If a lightning strike occurs the thundercloud will be discharged to earth. At the same time a charge equalization will take place due to the fair-weather current. With this very simplified model of a closed current circuit the phenomenon of lightning can be illustrated. Shown schematically under the thundercloud are precipitation, lightning, and corona.

Lightning can be defined as a transient, high-current (typically tens of kiloamperes) electrical discharge in air whose length is measured in kilometers. The lightning discharge in its entirety is usually termed a “lightning flash” or a “flash”.

![Figure 1: Illustration of the global electric circuit (adapted from Rakov and Uman).](image-url)
A lightning discharge that involves an object on ground or in the atmosphere is referred to as a “lightning strike”. The terms “stroke” or “component stroke” apply only to components of cloud-to-ground discharges. Cloud-to-ground discharges constitute about 25% of global lightning activity. It is believed that downward negative lightning flashes account for about 90% or more of global cloud-to-ground lightning, and that 10% or less of cloud-to-ground discharges are downward positive lightning flashes. Upward lightning discharges are thought to occur only from tall objects (higher than 100 m or so) or from objects of moderate height located on mountain tops. The types of lightning are shown in Figure 2 (Cigré TB 549).

A lightning flash consists of one or more discharges. For downward negative lightnings 3 to 4 discharges (strokes) per flash are typically. The time duration of a stroke is in the range of some ten microseconds, the time duration between the strokes is in the range of 30 to 40 milliseconds. The lightning current parameters are taken from lightning statistics. Figure 3 shows a statistical evaluation of worldwide measured lightning currents. The curve of the mean value shows the probability of the occurred lightning current peak values.

The mostly negative cloud-to-ground lightning strikes that occur have current peak values between app. 14 kA (95% probability) and 80 kA (5% probability). With a probability of 50% the following values are reached or exceeded:

- Current peak value: 30 kA
- Rise time: 5.5 µs
- Time to half value: 75 µs

A peak value of 20 kA with a probability of 80% is often used in standardization work, and for test and co-ordination purposes of MO surge arresters. Lightning currents with peak values above 100 kA are very rare.

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Figure 2: Cloud-to-ground lightning categorization according to Berger. Top left: downward negative; top right: upward positive; bottom left: downward positive; bottom right: upward negative.

Figure 3: Statistical evaluation of lightning measurements all over the world. Described is the probability of occurrence above the lightning current’s peak values (adapted from Cigré survey).
However, in geographical regions where winter thunderstorms occur, extreme lightning strikes can reach peak values above 250 kA, with half-time values of 2,000 µs. These are typically downward positive discharges.

Assuming that in medium-voltage systems a lightning current of 30 kA diverts in the case of a far-distance direct lightning strike, and that flash-overs between phases and at insulators occur, one can get a nominal discharge current of $I_n = 5$ kA. A wave shape of approximately $8/20$ µs results for the lightning current if a flashover occurred at one or more insulators.

A worst case to be considered is a direct lightning strike in a phase wire in front of a substation without an insulator between the point of strike and the substation. In this case it can be assumed that a lightning current of e.g. 20 kA diverts in both directions of the line and half of the lightning current (10 kA) travels undamped into the substation.

2.1.1 Possible points of lightning strike
Overvoltages in distribution systems occur due to direct lightning strikes to a phase wire, lightning strikes to a pole, or lightning strikes to earth or earthed objects near an overhead line. Figure 4 gives an overview about the possible points of lightning strikes. It is worth to mention that the earthing of the poles and substations is of high importance and must be in all cases as low as possible. The lower the footing resistance of the poles and the earth mat of substations is, the better will be the protection. An earth resistance of less than 10 Ω is generally recommended. In some special cases earth resistance values of 1 Ω or 2 Ω are requested.

![Figure 4: Points of lightning strikes to an overhead line.](image-url)

**Figure 4:** Points of lightning strikes to an overhead line.

Far-distance lightning to the phase wire  
Lightning to the top of a pole  
Lightning to the phase wire close to the substation  
Direct lightning to a substation or the phase

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LPS Lightning protection system  
$R_{p}$ Earth resistance of the pole  
$R_{s}$ Earth resistance of the substation
2.1.1.1 Direct lightning to a substation or to the phase wire in front of a substation
A substation must be protected by a lightning protection structure (LPS) to avoid any direct lightning to equipment in the substation. This can be done by Franklin Rods or earth shielding wires above the substation. The total lightning current \( i_b \) must be diverted directly to earth, see the right part of Figure 5. The earth resistance \( R_{E,S} \) of the substation has to be as low as possible. MO surge arresters can protect only against surges travelling along the line into the substation.

The worst case of a lightning strike is the direct strike to the phase wire in front of the substation without any insulator between the point of strike and the equipment to be protected. In Figure 5 the principle is shown. Assuming the lightning strike has a lightning current \( i_b = 20 \text{kA} \). The lightning current will be divided, so that a current impulse with a peak value of 10 kA appears on both sides of the point of strike, travelling along the line in both directions.

The current is coupled with the surge impedance \( Z \) and this results in a lightning overvoltage \( u \) travelling with the speed of light along the line. Assuming a surge impedance of \( Z = 450 \Omega \) a voltage with a peak value of \( u = 4,500 \text{kV} \) will occur. This is too high and will destroy the transformer.

Therefore, MO surge arresters at the entrance of the substation are a must.

2.1.1.2 Lightning to the phase wire close to the substation and far-distance lightning strike
Figure 6a shows the case that a lightning strikes the phase wire and only one pole is between the point of strike and the transformer. The same values as in the case shown in Figure 5 are assumed. The voltage \( u \) travels along the line in direction of the substation. In the moment when the voltage arrives at the insulator of the pole and becomes higher than the flashover voltage of the insulator the insulator will flash over and a part of the lightning current will be diverted via the pole to the earth, which results to a break-down of the voltage. As long as the earth resistance \( R_{E,P} \) is not zero the voltage will rise again and travel with a wave shape as indicated in Figure 6a in direction of the transformer.

Figure 6b shows again a lightning strike in the phase wire, in this case some spans away from the substation. The same will happen as explained in the example above: in the moment the voltage wave reaches the flashover voltage of the insulator, a flashover occurs and the voltage will break down and rise again, depending on the earth resistor \( R_{E,P} \). This happens at each insulator, as indicated in Figure 6b.

Finally, a voltage wave shape limited to the flashover value of the insulators, will arrive at the substation. Depending on the distance between the point of strike and the substation a considerable damping of the voltage wave will occur, which results in a reduction of the steepness of the overvoltage.
Figure 5: Principle of lightning strike to a substation

Figure 6a: Lightning strike to the phase wire close to the substation

Figure 6b: Far-distance lightning to the phase wire
Figure 7: Direct lightning to the top of a pole

Figure 8: Principle of near-by lightning

Figure 9: Principle of switching overvoltages
2.1.1.3 Lightning strike to the top of the pole

Figure 7 shows the case of a direct lightning to the top of a pole (or an earthed shielding wire). If the earth resistance $R_{E,P}$ of the pole is assumed to be zero the whole lightning current $i_b$ would go directly into the earth. Because the earth resistance of a pole is never zero, a potential rise $U_{pole}$ will occur due to the lightning current, as indicated in Figure 7.

Assuming again a lightning current of $i_b = 20 \text{ kA}$ and an unfavorable high earth resistance of $R_{E,P} = 100 \Omega$, an overvoltage of $U_{pole} = 2,000 \text{ kV}$ will arise on the pole. This voltage exceeds by far the voltage withstand value of the insulators, and a “back-flash” from the pole to the phase wire will occur. Consequently, an overvoltage travels along the line in direction of the substation, as shown.

2.1.1.4 Near-by lightning into the earth

The principle of overvoltages induced in an overhead line is shown in Figure 8. If a lightning current $i_b$ hits the earth, or an earthed object close to the line, a voltage $U_i$ will be induced into the phase wire because of the magnetic field $H$ around the lightning current. The magnitude of the induced voltage can be approximated with the equation from Rusck:

$$U_{\text{max},i} = Z_0 \frac{h}{x} \cdot i_b$$

Where:
- $U_{\text{max},i}$: Peak value of induced voltage
- $Z_0$: Mutual impedance between point of strike and overhead line
- $h$: Height of overhead phase wire
- $x$: Shortest distance between point of strike and line
- $i_b$: Lightning current

Assuming a lightning current of $i_b = 20 \text{ kA}$, a mutual impedance of $Z_0 = 30 \Omega$, a height of $h = 5 \text{ m}$ and a distance of $x = 100 \text{ m}$, an induced overvoltage of $U_{\text{max},i} = 30 \text{ kV}$ will appear on the phase wire.

2.2 Switching overvoltages

Switching overvoltages occur due to circuit breaker operations, disconnector operations, re-strikes of circuit breakers and operation of fuses, to mention the main reasons. Switching actions may be intended or unintended. They depend strongly on the circuit breaker characteristics and the line configuration and can be estimated by system simulations.

In medium-voltage systems switching overvoltages are not so critical. They can reach values up to 3.5 p.u. in a worst case. For a 24 kV-system it would result to app. 68 kV. This value is normally not critical for the insulation. However, vacuum breakers can produce very steep overvoltages. In this case, and due to reflections critical overvoltages may occur.
3 Standardized voltage wave shapes

The voltages and the overvoltages that stress the insulation are determined in amplitude, shape and time duration. For each class of voltages and overvoltages standard voltage shapes are determined that represent the effects of the original voltages with respect to test purposes and insulation coordination, see Table 1.

It must be understood that the wave shapes and magnitudes of the overvoltages occurring in the system due to lightning incidents and switching operations are never known. The standardized voltage wave shapes represent the critical parameters and are used for test purposes. Standardized voltages and overvoltages with power frequency (TOV) are used in labs for insulation withstand tests of the arrester housings, and for evaluation of the TOV performance of MO surge arresters.

Lightning overvoltages with the wave shape 1.2/50 µs are used for voltage withstand tests of insulators, and therefore also for tests of the arrester housing. It is worth to mention that a very critical test for transformers is a voltage withstand test with a chopped lightning voltage impulse.

This is because of the voltage breakdown (high dU/dt) that stresses the windings of the transformer and may lead to unacceptable high voltage resonances in the transformer. Switching overvoltages with the wave shape of 250/2500 µs are not used for testing medium-voltage equipment.

4 Summary

Overvoltages in electrical systems result from lightning flashes and switching operations. They can be power frequency overvoltages (TOV) or transient overvoltages. Power frequency overvoltages (TOV) generally do not endanger the insulation of electrical equipment. Most critical in medium-voltage systems are transient overvoltages due to lightning flashes. Their magnitude depends only on the lightning current and can be extremely high. Depending on the point of strike of the lightning different wave shapes and magnitudes may occur.

Switching overvoltages and induced overvoltages can occur quite frequently in medium-voltage systems, but their magnitude is generally not so high to lead to a flashover or to endanger the insulation of equipment. However, due to the high occurrence rate they may weaken liquid and solid insulation (aging), which results finally in a reduction of the lifetime of the insulation.

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Table 1: Classes and shapes of overvoltages, Standard voltage shapes and Standard withstand voltage tests (IEC 60071-1).

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<td>T2 ≤ 20 ms</td>
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* To be specified by the relevant apparatus committees.
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