In order to reduce the risk of insulation failure to an economically and operationally acceptable level, the insulation withstand of substation equipment is selected with regard to expected over-voltages, taking into account the protective characteristics of the surge arresters. This technical information discusses the different aspects of insulation withstand and provides guidelines for positioning EXLIM and PEXLIM surge arresters in outdoor substations.

The insulation co-ordination of a surge arrester in the network needs to consider its own dimensioning according to protective characteristics as well as its positioning relative to other equipment and grounded objects so as not to increase the total risk for insulation failure. The insulation withstand properties of surge arresters in a substation can be divided into:

- insulation withstand of the surge arrester itself, including the insulation between flanges and grading rings, etc.
- insulation withstand between the surge arrester and grounded objects
- insulation withstand between the surge arrester and other equipment connected to the same phase, e.g. bushings.
- insulation withstand between surge arresters in adjacent phases.

The insulation withstand is the only constraint when selecting suitable clearances for EXLIM and PEXLIM surge arresters. Any effects various phase-to-ground and phase-to-phase clearances may have on the voltage distribution along the ZnO block column have been accounted for in the design of EXLIM and PEXLIM arresters, e.g. by the use of optimized grading rings.

The insulation withstand of the surge arrester itself has been thoroughly considered in the design of EXLIM and PEXLIM surge arresters. Spacings between metal flanges as well as spacings between flanges and grading rings, are sufficiently large to withstand overvoltages appearing during current discharges.

The insulation withstand of EXLIM and PEXLIM arresters has been verified by tests according to international standards, and the values obtained exceed the minimum requirements, generally by a good margin.
The phase-to-ground clearance in substations is usually based on the selected standard rated lightning and switching impulse withstand voltages. International standards, e.g., IEC 60071-1, recommend minimum clearances.

In general, the clearance between a grounded object and an EXLIM or PEXLIM surge arrester should be the same as the phase-to-ground clearance selected for other high voltage equipment in a substation. If it is not possible to use the normal phase-to-ground clearance in special applications of EXLIM or PEXLIM arresters, a smaller clearance may be chosen, considering the protective characteristics of the arrester.

The Adjusted Protective Level to be used in Figure 2, is defined as:

For lightning impulse:

\[ U_{pl} \times 1.15 \times e^{m(H/8150)} \]

For switching impulse:

\[ U_{ps} \times 1.10 \times e^{m(H/8150)} \]

Where H is the altitude in meters above sea level.

\( U_{pl} \) and \( U_{ps} \) are the lightning and switching impulse protective levels for the selected EXLIM and PEXLIM surge arresters at the respective co-ordinating currents. Table 1 suggests appropriate co-ordinating currents for different system voltage levels.

<table>
<thead>
<tr>
<th>Co-ordinating currents</th>
<th>Lightning impulse</th>
<th>Switching impulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>up to 420 kV</td>
<td>10 kA</td>
<td>below 145 kV</td>
</tr>
<tr>
<td>550 kV</td>
<td>15 kA</td>
<td>145-362 kV</td>
</tr>
<tr>
<td>800 kV</td>
<td>20 kA</td>
<td>420-800 kV</td>
</tr>
<tr>
<td>&gt; 800 kV</td>
<td>20 kA</td>
<td>&gt; 800 kV</td>
</tr>
</tbody>
</table>

Exponent “m” depends on various parameters including minimum discharge path. For insulation co-ordination purposes, with reference to IEC 60071-2, exponent m may be conservatively taken to be as per Table 2.

This is possible because there is usually a fairly large margin between the standard rated withstand voltage for a substation and the protective level of EXLIM or PEXLIM arresters. Furthermore, distance effects by fast transients do not exist in the immediate vicinity of the surge arrester.

Thus, the recommended minimum phase-to-ground clearance for EXLIM and PEXLIM surge arresters, with regard to lightning and switching overvoltages, are presented in Figure 2. These clearances are based on IEC 60071-1, Tables A.1 and A.2, and on the protective characteristics of the surge arrester. They include safety margins and altitude correction.

Exponent m

<table>
<thead>
<tr>
<th>System voltage</th>
<th>Lightning impulse</th>
<th>Switching impulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 800 kV</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>&gt; 800 kV</td>
<td>1.0</td>
<td>As per Fig. 1</td>
</tr>
</tbody>
</table>

Table 2

Figure 1: Dependence of exponent m on the co-ordination switching impulse withstand voltage.

Where \( U_{cw} = 1.1 \times U_{ps} \) for phase to ground. For phase-to-phase, \( U_{cp} \) is equivalent to the rated switching impulse withstand voltage phase-to-phase.

The minimum clearance is determined either by lightning or switching impulse withstand, whichever renders a larger value. In case the clearance requirements for arresters on systems greater than 800 kV calculated from the above are higher than selected for the protected equipment, the same clearance requirements as for the equipment should also apply for the arresters.
The clearance between an EXLIM or PEXLIM surge arrester and other high-voltage equipment connected to the same phase, e.g. bushings or post insulators, is usually not of importance during normal operating conditions. In polluted conditions, however, the transient voltage distribution on the insulator surfaces may become extremely uneven. This creates high voltage stresses between the surge arrester housing and any high-voltage insulator positioned nearby.

It is recommended therefore to choose half the phase-to-ground clearance determined in the previous section for the spacing between the upper (energized) end of the EXLIM or PEXLIM surge arrester, and the top (energized) end of other high-voltage equipment.

Furthermore, for the case of an inclined high-voltage equipment e.g. a bushing, it is recommended to use the phase-to-ground clearance selected for the surge arrester also for the spacing between the lower (grounded) end of the surge arrester, and the bottom (grounded) end of other high-voltage equipment.

Figure 3 shows these recommendations, where D is the selected phase-to-ground clearance for the selected EXLIM or PEXLIM surge arrester. For the case with a vertically mounted bushing and if a PEXLIM arrester is used with a better pollution performance than a porcelain type EXLIM arrester the suggested required distance D at the lower end may be omitted.
The phase-to-phase clearance for high-voltage equipment in a substation is normally based on the selected standard rated lightning and switching impulse phase-to-phase withstand voltages. International standards, e.g. IEC 60071-1 recommend minimum phase-to-phase clearances. Note that the normal selection of surge arrester protective levels does not directly protect the phase-to-phase insulation since two arresters in series must be considered.

In general, the clearance between EXLIM and PEXLIM surge arresters in adjacent phases should be the same as the phase-to-phase clearance selected for other high-voltage equipment in the substation. If it is not possible to use the normal phase-to-phase clearance in a special application of EXLIM or PEXLIM surge arresters, the minimum clearance with regards to lightning overvoltages can be derived from Figure 4. The electrode configuration established by the grading rings on two adjacent EXLIM or PEXLIM surge arresters which are equipped with grading rings is more favourable compared to arresters without grading rings. Therefore separate curves are given in Figure 4 for EXLIM or PEXLIM arresters with or without grading rings.

The clearances shown in Figure 4 are based on the assumption that one phase is subjected to a lightning overvoltage, while the voltage on the adjacent phase is at the peak of the maximum power frequency operating voltage (opposite polarity). Obviously, these clearances will also cover the case of lightning overvoltages of the same polarity appearing simultaneously on two or three phases.

$$U_{pl} \times 1.15 \times e^{H/8150} + U_m \times \sqrt{2/\sqrt{3}}$$

where
- $U_m$ is according to IEC 60071-1 the highest voltage for equipment, which is usually equal to the highest system voltage.

- $U_{pl}$ is the lightning impulse protective level for the selected EXLIM or PEXLIM arrester at the recommended co-ordination current (see Table 1).

- $H$ is the altitude in meters above sea level.

The minimum phase-to-phase clearance for EXLIM or PEXLIM arresters with respect to switching overvoltages should always be based on the selected standard rated switching impulse phase-to-phase withstand voltage for the substation. Consequently the clearances specified in IEC 60071-1, Table A.3, are valid for most applications of EXLIM and PEXLIM arresters. If a special application requires a minimized phase spacing, the favourable electrode configuration established by the grading rings on EXLIM and PEXLIM surge arresters may permit a further reduction of the phase-to-phase clearance.

Figure 5 shows recommended phase- to-phase clearances for EXLIM and PEXLIM surge arresters equipped with grading rings with regard to switching overvoltages. These clearances are derived from the Transmission Line Reference Book, 345 kV and above, Second Edition, Figure 11.8.10, with an adequate safety margin applied. The necessary altitude correction should, by definition, be included in the standard rated switching impulse phase-to-phase withstand voltage selected for the substation.

The minimum phase-to-phase clearance is determined either by the lightning or by the switching impulse withstand, whichever renders the larger value.
Recommended minimum phase-to-phase clearance for lightning overvoltages

![Graph of Recommended minimum phase-to-phase clearance for lightning overvoltages](image1)

Recommended minimum phase-to-phase clearance for switching overvoltages

![Graph of Recommended minimum phase-to-phase clearance for switching overvoltages](image2)

Note! Rated switching impulse withstand voltage shall include altitude correction if applicable.
The following example shows the application of the presented guidelines for selecting minimum clearances for EXLIM and PEXLIM surge arresters in a 420 kV substation.

The substation is situated at an altitude of 200 m above sea level and equipped with arresters type EXLIM P360-GM420. The basic insulation withstand data for the substation is:

- Rated lighting impulse withstand voltage: 1425 kV phase-to-ground
- Rated switching impulse withstand voltage: 1050 kV phase-to-ground, 1575 kV phase-to-phase

According to IEC 60071-1, Tables A.1 and A.2, the minimum recommended phase-to-ground clearance is 2.6 m. The recommended minimum phase-to-phase clearance is 3.6 m, according to IEC 60071-1, Table A.3. We assume that these clearances are not possible to achieve for the surge arresters in this example. The minimum permissable values can be determined as follows:

According to Table 1 the appropriate co-ordinating discharge currents for a system voltage level of 420 kV are 10 kA for lightning impulse and 2.0 kA for switching impulse. The corresponding protective levels of the EXLIM P360-GM420 surge arrester used in this substation are 819 kV and 728 kV respectively (see ABB Buyer’s Guide).

The Adjusted Protective Level to be used in Figure 2 for determination of the phase-to-ground clearance, is:

- For lightning impulse: 
  \[ 819 \times 1.15 \times e^{200/8150} = 965 \text{ kV} \]
- For switching impulse: 
  \[ 728 \times 1.10 \times e^{200/8150} = 821 \text{ kV} \]

As seen in Figure 2, phase-to-ground clearances of 2.0 m and 1.9 m are required. The minimum phase-to-ground clearance is therefore the higher value of these two i.e. 2.0 m.

The Adjusted Protective Level to be used in Figure 3 for determination of the phase-to-phase clearance is:

- For lightning impulse: 
  \[ 819 \times 1.15 \times e^{200/8150} + 420 \times \sqrt{2}/\sqrt{3} = 1308 \text{ kV} \]

The EXLIM P360-GM420 is fitted with grading rings. According to figure 4 a minimum clearance of 2.0 m is required based on the lightning impulse strength.

- For switching impulse, the minimum phase-to-phase clearance for the surge arrester is based on the rated switching impulse withstand voltage of the substation, since the phase-to-phase clearance in a substation is normally not protected by the arresters. In this case, the selected rated switching impulse withstand voltage phase-to-phase is 1575 kV. As seen in Figure 5, the required minimum phase-to-phase clearance, taking into account the favourable electrode configuration created by the grading rings, is 3.0 m.

Hence, the minimum permissable clearances for the EXLIM P360-GM420 surge arresters in our example substation are 2.0 m phase-to-ground and 3.0 m phase-to-phase.