Insulation Coordination

What is the insulation coordination?

3.1 *insulation co-ordination* selection of the dielectric strength of equipment in relation to the operating voltages and overvoltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available preventing and protective devices

[IEC 604-03-08:1987, modified]

"strength vs. stress"
Fundamental of Insulation Coordination

Possible voltages without arresters

Withstand voltage of equipment

Voltages limited by arresters

![Graph showing the relationship between magnitude of (over-)voltage and time duration of (over-)voltage, with categories for lightning overvoltages (microseconds), switching overvoltages (milliseconds), temporary overvoltages (seconds), and highest voltage of equipment (continuously).]
# Maximum Switching Surge Levels

<table>
<thead>
<tr>
<th>Highest System Voltage (kV)</th>
<th>400</th>
<th>500</th>
<th>750</th>
<th>1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Switching Surge Level (kV)</td>
<td>2.5x400</td>
<td>2.25x500</td>
<td>2.0x750</td>
<td>1.8x1100</td>
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</tbody>
</table>
Philosophy:

It is necessary to allow a suitable margin in the insulation level above the maximum *surge overvoltage* and also permit a little risk for failure in the interest of economical adoption of insulation levels.

*Surge overvoltage*: (i) lightning overvoltage and (ii) switching surge overvoltage
Simple qualitative description (short time duration):

$V_1$ — normal peak power freq voltage
$V_2$ --- system shunt protection level
$V_3$ --- basic insulation level

$V(t)$

Prospective overvoltage

Protection margin

$V_1$, $V_2$, $V_3$
Elements Involved in Insulation Coordination

Three elements are involved in the insulation coordination discipline, namely:

• the study of the "stresses", both electrical and environmental, acting on the equipment insulation. This is usually performed by calculations or field measurements;

• the study of the "strength" (dielectric withstand characteristics) of the insulation (both new and aged) when submitted to such stresses, taking into account, when applicable, the effect of the environmental stresses (pollution, rain, snow, ice, atmospheric conditions at large altitudes), including the study of the "test and measurement techniques" which are employed to assess such strength. The strength is determined by calculations, based on suitable discharge models, and/or by laboratory/factory tests, on-site tests and in-service measurements (diagnostics);

• the assessment of the insulation performance (usually expressed in terms of risk of failure) in the considered situation of stresses and strength, including the selection and application of "protective devices and techniques", to establish the final insulation design fulfilling the specified requirements. This may be based on "deterministic" or "statistical" approach.
Insulation Coordination Principle

System

Equipment

System voltages

Overvoltage protection devices

Environment

Dielectric strength

stress versus strength
Insulation Coordination Principle

- Equipment in the system
  - Variety of amplitudes and shapes of overvoltages
  - Variety of operating conditions and age
  - Variety of environmental conditions

- Equipment in the laboratory
  - Standardized amplitudes and shapes of test voltages
  - Standardized setups and conditions
  - Standardized environmental conditions
Procedures of Insulation Coordination – 4 Steps

• Determination of the representative overvoltages
• Determination of the coordination withstand voltages
• Determination of the required withstand voltages
• Selection of the rated and of standard insulation level
Determination of the representative overvoltages $U_{rp}$

- The representative overvoltages are derived from real service conditions, but have just standardized shapes.
- They are determined in amplitude, shape and duration by system analysis, taking into account overvoltage limiting devices.

3.19

representative overvoltages $U_{rp}$

overvoltages assumed to produce the same dielectric effect on the insulation as overvoltages of a given class occurring in service due to various origins.

They consist of voltages with the standard shape of the class, and may be defined by one value or a set of values or a frequency distribution of values that characterize the service conditions.

NOTE  This definition also applies to the continuous power frequency voltage representing the effect of the service voltage on the insulation.
Determination of the coordination withstand voltages $U_{cw}$

- The coordination withstand voltages are the lowest values of withstand voltages of each overvoltage class, for which the expected low failure rate of the equipment is not exceeded over its full lifetime.
- Derived from the representative overvoltages $U_{rp}$ by the coordination factor $K_c$.

3.24
co-ordination withstand voltage $U_{cw}$
for each class of voltage, the value of the withstand voltage of the insulation configuration in actual service conditions, that meets the performance criterion

3.22
performance criterion
basis on which the insulation is selected so as to reduce to an economically and operationally acceptable level the probability that the resulting voltage stresses imposed on the equipment will cause damage to equipment insulation or affect continuity of service. This criterion is usually expressed in terms of an acceptable failure rate (number of failures per year, years between failures, risk of failure, etc.) of the insulation configuration

Typical for Germany: 0.1% per year $\Rightarrow$ 1 failure in 1000 years

3.25
co-ordination factor $K_c$
factor by which the value of the representative overvoltage must be multiplied in order to obtain the value of the co-ordination withstand voltage

[IEC 60071-1]
Deterministic approach

 Assumed maximum of representative overvoltage

 Multiplication by coordination factor based on operating experience

 Statistical approach

 Statistical distribution of representative overvoltages

 Determination of failure probability of insulation

 Calculation of failure risk depending on assumed coordination withstand voltage

 Coordination withstand voltage
 Assumed conventional $U_{cw}$ (0% value) Statistical $U_{cw}$ (10% value)
Determination of the required withstand voltages $U_{rw}$

- The required withstand voltages are determined by converting the coordination withstand voltages to appropriate standard test conditions.
- Usually different from the coordination withstand voltages.
- Derived from the coordination withstand voltages $U_{cw}$ by the safety factor $K_s$ and the atmospheric correction factor $K_t$ or the altitude correction factor $K_a$.

3.27
required withstand voltage
$U_{rw}$
est test voltage that the insulation must withstand in a standard withstand voltage test to ensure that the insulation will meet the performance criterion when subjected to a given class of overvoltages in actual service conditions and for the whole service duration. The required withstand voltage has the shape of the co-ordination withstand voltage, and is specified with reference to all the conditions of the standard withstand voltage test selected to verify it.

3.30
safety factor
$K_s$
overall factor to be applied to the co-ordination withstand voltage, after the application of the atmospheric correction factor (if required), to obtain the required withstand voltage, accounting for all other differences in dielectric strength between the conditions in service during lifetime and those in the standard withstand voltage test.

Influences covered by the safety factor $K_s$

- Differences in equipment assembly
- Dispersion in product quality
- Quality of installation
- Aging of the installation during expected lifetime
- Other unknown influences
Determination of the required withstand voltages $U_{rw}$

- The required withstand voltages are determined by converting the coordination withstand voltages to appropriate standard test conditions.
- Usually different from the coordination withstand voltages.
- Derived from the coordination withstand voltages $U_{cw}$ by the safety factor $K_s$ and/or the altitude correction factor $K_a$.

3.28 atmospheric correction factor

$K_t$

factor to be applied to the co-ordination withstand voltage to account for the difference in dielectric strength between the average atmospheric conditions in service and the standard reference atmospheric conditions

It applies to external insulation only, for all altitudes

NOTE 1 The factor $K_t$ allows the correction of test voltages taking into account the difference between the actual atmospheric conditions during test and the standard reference atmospheric conditions. For the factor $K_t$, the atmospheric conditions taken into account are air pressure, temperature and humidity.

NOTE 2 For insulation co-ordination purposes usually only the air pressure correction needs to be taken into account.

3.29 altitude correction factor

$K_a$

factor to be applied to the co-ordination withstand voltage to account for the difference in dielectric strength between the average pressure corresponding to the altitude in service and the standard reference pressure

NOTE The altitude correction factor $K_a$ is part of the atmospheric correction factor $K_t$. [IEC 60071-1]
Selection of the rated and of the standard insulation level
(set of standard rated withstand voltages \( U_w \))

- Most economical set of standard withstand voltages \( U_w \) of the insulation to prove that all the required withstand voltages are met.
- For each range (I or II) a combination of only two withstand voltages defined:
  - Range I: standard lightning impulse withstand voltage
    standard short-duration power-frequency withstand voltage
  - Range II: standard switching impulse withstand voltage
    standard lightning impulse withstand voltage
- For range I, only phase-to-earth standard withstand voltages are defined, which have to cover phase-to-earth, phase-to-phase and longitudinal insulation.

### Definitions

<table>
<thead>
<tr>
<th>3.34</th>
<th>standard rated withstand voltage ( U_w )</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>standard value of the rated withstand voltage as specified in this standard (see 5.6 and 5.7)</td>
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<th>3.35</th>
<th>rated insulation level</th>
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<td></td>
<td>set of rated withstand voltages which characterize the dielectric strength of the insulation</td>
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<th>3.36</th>
<th>standard insulation level</th>
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<tbody>
<tr>
<td></td>
<td>set of standard rated withstand voltages which are associated to ( U_m ) as specified in this standard (see Table 2 and Table 3)</td>
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</tbody>
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<tr>
<th>3.23</th>
<th>withstand voltage</th>
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<tbody>
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<td></td>
<td>value of the test voltage to be applied under specified conditions in a withstand voltage test, during which a specified number of disruptive discharges is tolerated. The withstand voltage is designated as:</td>
</tr>
</tbody>
</table>

|      | a) conventional assumed withstand voltage, when the number of disruptive discharges tolerated is zero. It is deemed to correspond to a withstand probability \( P_w = 100 \% \); |
|      | b) statistical withstand voltage, when the number of disruptive discharges tolerated is related to a specified withstand probability. In this standard, the specified probability is \( P_w = 90 \% \). |

**NOTE**: In this standard, for non-self-restoring insulation are specified conventional assumed withstand voltages, and for self-restoring insulation are specified statistical withstand voltages.
Procedure of Insulation Coordination

Flowchart for insulation coordination in IEC 60071-1

- Origin and classification of stressing voltages (see 3.16 & 3.17)
- Protective level of overvoltage limiting devices (see 3.21)
- Insulation characteristics

- Performance criterion (see 3.22)
- Statistical distribution (+)
- Inaccuracy of input data (+)
- Effects combined in a coordination factor $K_s$ (see 3.25)
- Altitude correction factors $K_a$ (or Atmospheric correction factor $K_{at}$) (see 3.28 & 3.29)
- Equipment test assembly (*)
- Dispersion in production (*)
- Quality of installation (*)
- Ageing in service (*)
- Other unknown factors (*)
- Effects combined in a safety factor $K_s$ (see 3.30)

- Test conditions (see 6)
- Test conversion factor, $K_{con}$ (see 3.32)
- Standard withstand voltages (see 5.6 and 5.7)
- Ranges of $U_m$ (see 5.8)

- System analysis (see 5.2)
- Representative voltages and overvoltages, $U_p$ (see 3.19)

- Selection of the insulation meeting the performance criterion (see 5.3)

- Co-ordination withstand voltages, $U_{sw}$ (see 3.24)

- Application of factors to account for the differences between type test conditions and actual service conditions (see 5.4)

- Required withstand voltages, $U_{rw}$ (see 3.27)

- Selection of rated withstand voltages (see 3.33) from the list of the standard rated withstand voltages $U_a$ (see 3.32) (see 5.5 and 5.10)

- Rated or standard insulation level: set of $U_a$ (see 3.35 and 3.36)
Step 2: Statistical Approach

Occurrence of overvoltage, in particular switching overvoltage is statistical in nature.

This method is based on a given risk of flashover which is calculated by combining the flashover voltage function of the insulation structures with the overvoltage probability density function.
Let \( P_0(V_i)dV \) be the probability of a surge voltage occurring as an overvoltage between \( V_i \) and \((V_i+dV)\).

Let \( P_d(V_i) \) be the probability for flashover of insulation.

The probability that both the above events occurring simultaneously at an overvoltage \( V_i \) is

\[
P_0(V_i)P_d(V_i)dV
\]
The risk of failure for entire voltage range is

\[ R = \int_{0}^{\infty} P_0(V)P_d(V)dV \]
A simplified procedure to evaluate the risk of failure is given by the IEC which defines the **safety factor,** $\tau$, as a ratio of the statistical withstand voltage to that of statistical overvoltage. The former is the voltage level that causes sparkover 10% of the time, while the latter is the voltage likely to exceed 2% of all the overvoltage.

\[
\tau = \frac{V_d s}{V_s}
\]

![Diagram](image)

(a) Statistical (max) overvoltage

(b) Statistical withstand voltage
In practice, the insulation level and protective margin are arrived at by

(i) selecting the risk of failure $R$,
(ii) the statistical safety factor, $\tau$, and
(iii) then fixing the withstand voltage and designing the insulation level of any equipment or apparatus corresponding to 90% or 95% of the withstand voltage thus fixed
Statistics of Shunt Protection

Solid = Risk of failure of system hardware
Crosshatched = Risk of shunt protection device activating
Statistical safety factor ($\tau$) and its relation to the risk of failure ($R$)