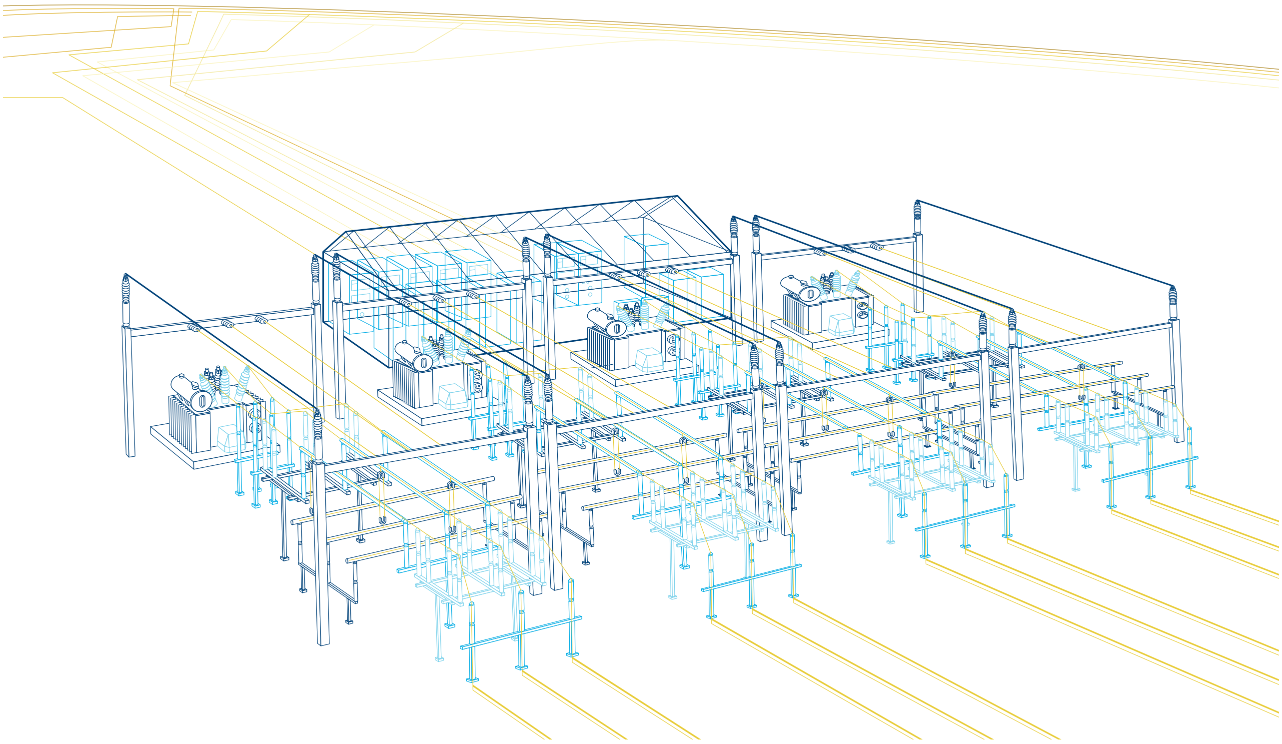
# Distribution Automation Handbook

## Section 8.1 Electrical Safety



# Contents

# 8.1 Electrical Safety

## 8.1.1 Introduction

Metallic parts of electrical equipment that can be exposed to voltage due to insulation failures are usually connected to earth potential, that is, earthed. This is done to protect the equipment against excessive overvoltages and to limit the damage to material and property and especially the hazard to the public. Mainly due to the last reason, safety regulations have been given by the authorities on how these hazard voltages must be limited. In the regulations, typically both the magnitude and duration of the hazard voltages are considered.

The limitation of hazard voltages in accordance with the applied safety regulations forms the basis for the design and setting value selection of the earth-fault protection of network components. This usually includes requirements or recommendations for the sensitivity of the protection and also for the limits whether the protection must be applied in tripping mode, or if alarming protection is sufficient. If the protection must be used in the tripping mode, operating speed requirements are given. This chapter outlines the close connection between the limitation of hazard voltages and the selection of setting values for the earth-fault protection. At first, basic earth-fault voltage calculation principle and the effect of hazard voltage to the human body are introduced. Secondly, the pan-European standard for earthing systems and hazard voltage regulations is briefly reviewed. Finally, guidelines in a form of an example for fulfilling the requirements set to the operation of a feeder earth-fault protection by the regulations are given.

## 8.1.2 Earth-fault voltage and earthing resistance

The earth-fault voltage $U_E$ [V] depends on the magnitudes of earth-fault current $I_E$ [A] and earthing resistance $R_E$ [Ω]:

$$U_E = R_E \cdot I_E \tag{8.1.1}$$

If the magnitude of earth-fault voltage exceeds the maximum allowed value, it can be reduced either by decreasing the earth-fault current or lowering the earthing resistance. An example of the former way is the application of Petersen coils in a network where the neutral point has been unearthed before. Another way would be the splitting of the galvanically connected network into smaller parts, which usually requires building of a new substation or at least an installation of another main transformer to the existing substation. In a solidly earthed network, the earth-fault current can be reduced by installing a current-limiting resistor or reactor to the neutral point of the network [8.1.1].

The earthing resistance depends on the soil resistivity $\rho$ [Ωm] and on the earthing electrode dimensions. The definition for the soil resistivity is the measure of resistance between the opposite sides of a cube of soil material with a side dimension of one meter.

The soil resistivity depends greatly on the soil type, structure, moist and density.
Table 8.1.1 gives some typical value ranges for different soil, water and concrete types.

**Table 8.1.1: Resistivity of soil, concrete and water [8.1.3]**

| Soil/water/concrete type | Average resistivity (Ωm) | Typical variation range (Ωm) |
|---|---|---|
| Clay | 40 | 25…70 |
| clay sand | 100 | 40…300 |
| mud, peat, mold | 150 | 50…250 |
| sand, fine sand | 2000 | 1000…3000 |
| morainic gravel | 3000 | 1000…10000 |
| esker gravel | 15000 | 3000…30000 |
| Granite | 20000 | 10000…50000 |
| wet concrete or concrete on ground | 100 | 50…500 |
| dry concrete | 10000 | 2000…100000 |
| lake and river water | 250 | 100…400 |
| groundwater, well water, spring water | 50 | 10…150 |
| seawater in the Gulf of Finland (<5‰) | 2.5 | 1…5 |

For example, in a very simple case of a vertical rod electrode the resistance to earth consists of a "serial connection" of individual resistances of successive cylindrical and hemispherical shells of soil around the rod, Figure 8.1.1. The cross-sectional area of the shells increases when the distance from the rod surface increases. This in turn decreases the individual shell resistance. Figure 8.1.1 visualizes this effect. With certain distance from the rod surface the resistance does not change significantly anymore if the distance is still increased. This means that the total resistance to earth has been reached [8.1.4].

It can be seen in Figure 8.1.1 that in this fictitious example at a distance of $X/L = 1$ approximately 90% of the total resistance or voltage between the rod and earth is incurred. Here, $X$ stands for the distance from the rod surface and $L$ the total length of the rod. In a hazardous situation, typically only a part of the total voltage to earth can be applied to a person. Typically the *touch voltage* $U_{TP}$ in Figure 8.1.1 represents the highest, and in this sense the most dangerous, hazard voltage. A special case of the touch voltage is the *step voltage*, which can appear between the feet of a person at the standing point. However, in most cases the step voltage is considerably lower than the touch voltage.

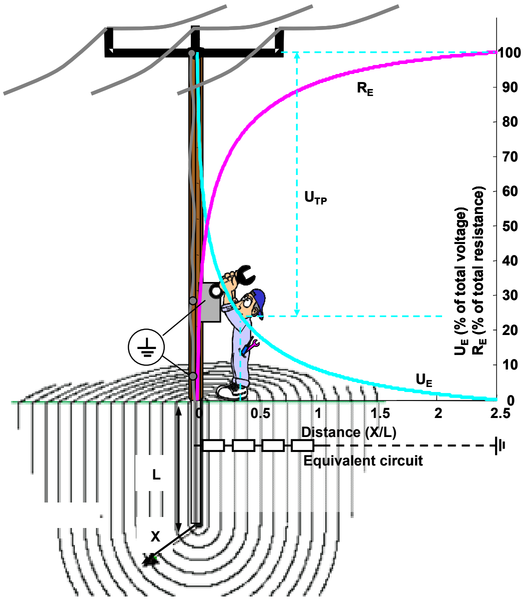


**Figure 8.1.1:** **Schematics of resistance to earth for a simple rod electrode and formation of the touch voltage $U_{TP}$.**

For other typical earthing electrode arrangements, the resistance to earth can be estimated as follows:

**Table 8.1.2: Estimation of earthing resistance for typical electrode geometries [8.1.3].**

| Electrode type | Equation | Notes |
|---|---|---|
| **Ball on the earth's surface** | $R_E = \frac{\rho_E}{\pi D}$ | |
| **Plate on the earth's surface** | $R_E = \frac{\rho_E}{2D}$ | s << D |
| **Vertical rod or pipe on the earth's surface** | $R_E = \frac{\rho_E}{2\pi L} \ln \frac{4L}{1{,}36 \times d}$ | d << L |
| **Vertical rod or pipe buried in the soil** | $R_E = \frac{\rho_E}{2\pi L} \ln \frac{4L}{1{,}36 \times d} \times \frac{2h + L}{4h + L}$ | d << L |
| **Horizontal conductor on the earth's surface** | $R_E = \frac{\rho_E}{\pi L} \ln \frac{2L}{1.36 \times d}$ | d << L |
| **Horizontal conductor buried in the soil** | $R_E = \frac{\rho_E}{2\pi L} \ln \frac{L^2}{1{,}85 \times h \times d}$ | d << 4h |
| **Grid** | $R_E = \frac{\rho_E}{2D} + \frac{\rho_E}{L}$ | |

Where

| | |
|---|---|
| $L$ | is the electrode length [m], |
| $D$ | is the diameter of a ball, plate or grid electrode [m], |
| $d$ | is the diameter of a rope-strand conductor electrode or half of the width of a strip electrode [m], |
| $s$ | is the thickness of a plate electrode [m] |

$\rho_E$ is the soil resistivity [Ωm] and

$h$ is the electrode burying depth [m]

The ball electrode can be considered as a good approximation for a tower foundation. The equation for the plate electrode is given for round shape geometry, but it can be used for a square plate as a good approximation. Generally, the resistance of an electrode buried deep in the soil is about 50% of that located on the earth's surface. Resistance values of a few other earthing electrodes having more complex geometry and dimensions are given in Table 8.1.3 [8.1.1], [8.1.3].

**Table 8.1.3: Earthing resistances of various types of electrodes [%] compared to the corresponding values of a straight conductor buried 0.7 m deep in the soil. L denotes the total length of the electrode [m].**

| Electrode length L (m) | 20 | 60 | 200 | 600 |
|---|---|---|---|---|
| Electrode shape | $R_E$ in relation to $R_E$ of a straight conductor | | | |
| — | 100 | 100 | 100 | 100 |
| 0,2 m<br>2 m<br>20 m ↕ ⌶ | 133<br>109<br>92 | 144<br>123<br>98 | 155<br>135<br>109 | 159<br>143<br>119 |
| ∟ | 103 | 103 | 102 | 102 |
| ⅄ | 107 | 106 | 106 | 105 |
| + | 116 | 115 | 114 | 112 |
| ✻ | 136 | 135 | 132 | 129 |
| ✳ | 159 | 158 | 154 | 148 |
| ○ | 109 | 108 | 107 | 106 |

## 8.1.3 Effects of hazard voltage to the human body

At higher voltage levels, electricity causes damage by burns and chemical changes in the blood, whereas at lower voltage levels the effect of a current flowing through the heart causes death by ventricular fibrillation. For this a current of 40 to 100 mA is usually sufficient when it coincides with certain phase of the heart's pumping period. An example relation between the duration and magnitude of this current can be seen in Figure 8.1.2 [8.1.1], [8.1.3], [8.1.4], [8.1.6].

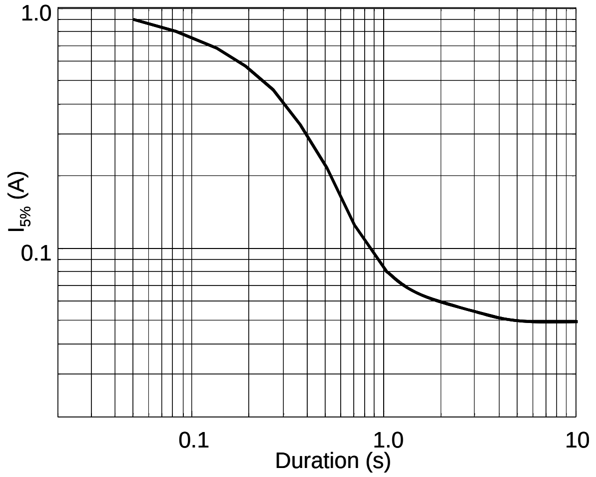


**Figure 8.1.2:** **Currents corresponding to 5% probability of ventricular fibrillation when the current coincides with the dangerous period of the heart cycle (current path: left hand – both legs) [8.1.1], [8.1.3], [8.1.4], [8.1.6].**

In addition to the information about the effects of current, the expected total impedance must be known in order to estimate the dangerous levels of hazard voltages. This impedance depends on the magnitude of the touch voltage and the current path. Estimations of the total impedance of the human body are shown in Figure 8.1.3, which is valid for a current path from hand to hand or hand to legs [8.1.1], [8.1.3], [8.1.4], [8.1.6].

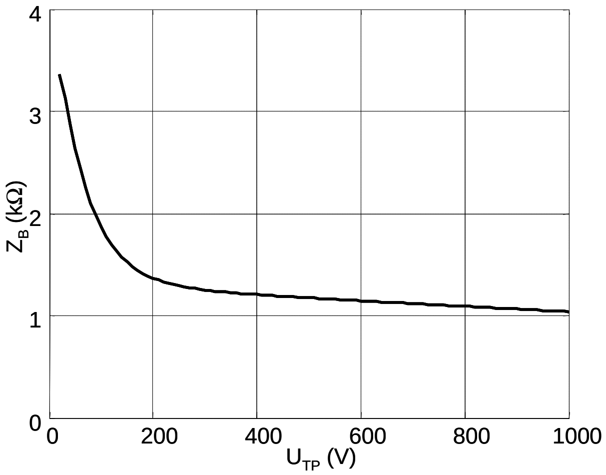


**Figure 8.1.3:** **Typical impedance of the human body as a function of touch voltage, 50% probability [8.1.1], [8.1.3], [8.1.4], [8.1.6].**

Combining the information of Figure 8.1.2 and Figure 8.1.3, the dependence of hazard voltage levels on the electric shock durations can be evaluated and this has been done, for example, in references [8.1.2] and [8.1.3]. The fundamental result is shown in Figure 8.1.4, which is based on a 5% probability of ventricular fibrillation. The results are somewhat conservative, because the additional resistance of shoes and gloves in addition to the soil resistance of the standing point was not taken into account.

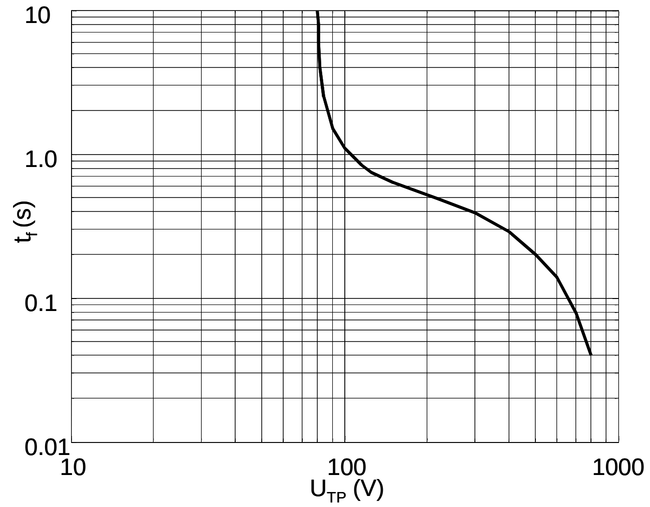


**Figure 8.1.4: Permissible touch voltages for limited fault duration.**

### 8.1.4 Permissible touch and earth-fault voltages vs. relay settings

When considering the limitation of an earth-fault voltage, usually only a part of this voltage appears as a dangerous hazard voltage that can be subjected to a person. In this respect, the touch voltage is typically the highest when the person is in direct contact with the source of the hazard voltage, for example, the surface connected to the rod electrode in Figure 8.1.1. Depending on the design and type of the earthing electrode, the maximum touch voltage as a percentage of the total earthing voltage can be estimated [8.1.1], [8.1.2], [8.1.3].

The maximum permissible touch voltages as presented in the pan-European standard [8.1.2] are principally shown in Figure 8.1.4. According to this standard, a correct design is generally achieved by the following measures:

- Installation becomes a part of a global earthing system, where the resistances are generally considered low enough to prevent dangerous touch voltages. This kind of an earthing system is created by the interconnection of local earthing systems that ensure by the proximity of the earthing system that there are no dangerous voltages. Urban areas where the equipment earthing of medium-voltage networks is connected to the system earthing of the low-voltage system belong to this category.
- If the earth-fault voltage is not higher than twice the maximum permissible touch voltage $U_{TP}$ in Figure 8.1.4, the design is accepted. This is based on the assumption that the maximum touch voltage is 50% at highest of the total earth-fault voltage.
- If the earth-fault voltage is higher than twice the permissible touch voltage $U_{TP}$ in Figure 8.1.4 but less than four times the value in question, a sound design is achieved by corrective measures, for example by using potential grading. Using this type of electrode the maximum touch voltages are typically 25% at highest of the total earth-fault voltage, which must be verified by calculations or measurements.

This is valid if the duration of the earthing voltage is limited to maximum 10 seconds. Longer times can usually be accepted if the touch voltage is not higher than 75 V.

The above information can be converted to operating speed and sensitivity requirements set to the earth-fault protection. To illustrate this an example of a 20 kV feeder earth-fault protection scheme is presented in Figure 8.1.5. The neutral point of the network is compensated. The IED2 at the substation includes three protection stages, and the IED1, a pole-mounted circuit recloser, is located downstream the feeder and includes two protection stages. The protection stages of both IEDs use the same directional residual overcurrent principle. The following requirements are set on the operation of the protection:

- Operating speed requirement as per HD 637 S1 with $U_E \leq 2 \cdot U_{TP}$, where $U_E = R_E \cdot I_E$ [8.1.2]
- Alarming protection if $U_{TP}$ is lower than 65 V or if the fault resistance is higher than 3 kΩ
- Sensitivity requirement in terms of fault resistance so that faults with as high a fault resistance value as possible can be detected
- Selective operation in terms of time and sensitivity so that the IED closest to the fault trips first

Based on the above requirements, the design is performed in the best way with the help of a coordination diagram, which is an earth-fault current or residual voltage vs. time characteristic, showing:

- All limiting factors that affect the design, such as
  - Operating speed requirement ( $\nabla$ 1 in Figure 8.1.5 ).
  - Earth-fault current/residual voltage limit for tripping/alarming protection ( $\Delta$ 2 in Figure 8.1.5 ) and the corresponding fault resistance value
  - Earth-fault current/residual voltage limit for the sensitivity requirement ( $\Delta$ 3 in Figure 8.1.5 ) and the corresponding fault resistance value
- Based on the above factors, a suitable multistage operating characteristic for the protection is applied in the IEDs with settings that coordinate by time and sensitivity, Figure 8.1.5.

In modern numerical IEDs multiple protection stages are available, and a high flexibility in the stage parameterization and setting selection is a standard feature. Therefore, the implementation of protection schemes that optimally fulfill the given requirements is feasible and economical.

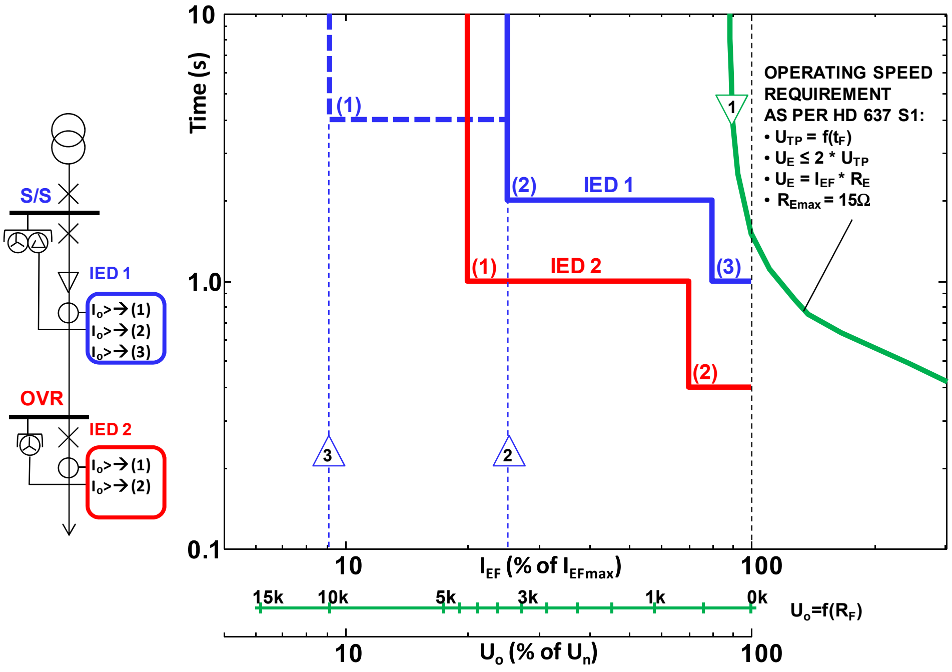


**Figure 8.1.5:** **Example operating speed and sensitivity requirements for earth-fault protection and their relationship to the operating characteristic of a multistage earth-fault protection.**

## References

**[8.1.1]** Lehtonen M. & Hakola T.: "Neutral Earthing and Power System Protection," ABB Transmit Oy, 1996.

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**[8.1.3]** "SFS 6001 Suurjännitesähköasennukset," SESKO SK 99, 2001 National Standard.

**[8.1.4]** "Effects of current on human beings and livestock," IEC Publication 60479-1 Part 1: General aspects, 1994.

**[8.1.5]** "IEEE Guide for Safety in AC Substation Grounding," ANSI/IEEE Publication Std 80-1986.

**[8.1.6]** Biegelmeier, G.: "Wirkungen des elektrischen Stroms auf Menschen und Nutztiere. Lehrbuch der Elektropathologie," VDE-Verlag, Berlin,1986.

# Document revision history

| Document revision/date | History |
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