Quantification of Personal Safety for Real Influence Situations

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Abstract

The subject of safety in connection with electrical facilities has been repeatedly revised and redefined over the past twenty years, as a result of new findings and more accurate measurement data. Both, the first publication of the IEC report in 1974 as well as the majority of the standards created and applied in the last fifteen years are largely based on tests performed on dogs, sheep, pigs and to a very small extent on humans. Since it is not possible to determine exactly whether a voltage is lethal for humans, due to many influencing parameters, safety margins were always used in the standards.

The question is whether, due to the unpredictability of a large part of the parameters, a newer approach using probability theory would be better. In this thesis, the origin of individual standards is discussed, why characteristic curves from different works deviate from each other and what steps need to be taken to create characteristic curves from statistical data. This knowledge is used in both conventional calculations and probability calculation and in order to create a new characteristic curve. The calculated touch voltages were compared to each other and existing standards.

Furthermore, potential ways to increase the accuracy for certain body configurations, with a new probability parameter, are identified in the probability calculation. In addition, the influence of the parameters in the shock circuit and existing options for increasing the safety measures without changing the entire safety concept is discussed and reviewed.

Kurzzusammenfassung

Das Thema Sicherheit im Zusammenhang mit elektrischen Anlagen ist in den letzten zwanzig Jahren aufgrund neuer Erkenntnisse und genauerer Messdaten immer wieder überarbeitet und neu definiert worden. Sowohl die erste Veröffentlichung des IEC-Reports im Jahr 1974 als auch die Mehrheit der in den letzten fünfzehn Jahren erstellten und angewandten Normen beruhen weitgehend auf Tests, die an Hunden, Schafen, Schweinen und zu einem geringen Teil an Menschen durchgeführt wurden. Da es aufgrund vieler Einflussgrößen nicht möglich ist, genau zu bestimmen, ob eine Spannung für den Menschen tödlich ist, wurden in den Normen immer Sicherheitsreserven verwendet.

Es stellt sich die Frage, ob aufgrund der Unvorhersehbarkeit eines großen Teils der Parameter ein neuerer Ansatz mit Hilfe der Wahrscheinlichkeitstheorie besser wäre. In dieser Thesis wird die Herkunft der einzelnen Normen diskutiert, warum Kennlinien aus verschiedenen Arbeiten voneinander abweichen und welche Schritte unternommen werden müssen, um eine Kennlinie aus statistischen Daten zu erstellen. Dieses Wissen wird sowohl bei konventionellen Berechnungen als auch bei der Wahrscheinlichkeitsberechnung verwendet und um eine neue Kennlinie zu erstellen. Die berechneten Berührungsspannungen wurden miteinander und mit bestehenden Normen verglichen.

Des weiteren werden Möglichkeiten zur Erhöhung der Genauigkeit für bestimmte Körperkonfigurationen, mit einem neuen Wahrscheinlichkeitsparameter, in der Wahrscheinlichkeitsberechnung ermittelt. Zusätzlich wird der Einfluss der Parameter im Stoßkreis und bestehende Möglichkeiten zur Erhöhung der Sicherheitsmaßnahmen ohne Änderung des gesamten Sicherheitskonzeptes diskutiert und überprüft.

Affidavit

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present master's thesis.

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Chapter 1

Introduction

The starting point for considering the safety criteria of a system is to take a closer look at the possible people involved in order to get an overview of how they interact in different accidents.[1]

The main danger for people is not necessarily asphyxiation or a immediate heart attack, but the spontaneous influence of the heart rhythm caused by contractions due to the current flowing through the body, a so called ventricular fibrillation event, which can subsequently lead to cardiac arrest. Statements about the dangerous current or voltage are made depending on,[1]:

- contact characteristics
- surface condition of the body (dry, wet)
- frequency of the current
- duration of the contact

The supply and distribution networks are increasingly expanded and designed for larger loads, which increases the magnitude of the earth fault currents. For this reason, among others, more and more attention is being paid to the various safety standards in order to limit or prevent possible hazards.
For safety recommendations, there are various national and international standards that have defined different ranges to make statements about the probability of fatality as a result of an earth fault.[2]
There are a number of papers that deal with the safety assessments made on the basis of the different studies, which include not only the calculation of the prospective contact voltages but also the permissible voltages.[2]

However, before going into the characteristics of the behaviour of the human body under voltage in this paper, it is first necessary to have a more detailed knowledge of the entire model, its prospective voltage and its behaviour when a body is introduced.

Chapter 2

Evaluation of a Given or Planned System

2.1 Overview

All electrical systems must be protected against possible touch and step voltages for the safety of the staff and the public. This means that at the beginning, possible sources of error must be systematically searched for and the influence of the individual parts of the system must be determined. In this part of the work, the most common influences are identified and examined. In other words the parts with the greatest influence on the magnitude of the shock hazard are traced and described.[3]

The following points are those that are in the foreground of this work,[3]:

- magnitude and duration of the earth fault current
- voltage distribution due to the earth fault current
- distribution of the return current
- soil resistivity
- characteristics of the body as a function of current and voltage

Local differences are found in some variables with varying degrees of influence on the output. One of the largest and most unpredictable is soil resistivity. This can vary due to geographic differences as well as weather conditions.
the calculation must either be accurately fitted to the model by multi-layer soil models with a representation of the soil medium and its inhomogeneous properties or so-called worst-case scenarios for soil resistivity are used in analytical formulas. This requires more detailed knowledge of the return current- and the earth voltage distribution of the individual worst-case scenarios.[4]

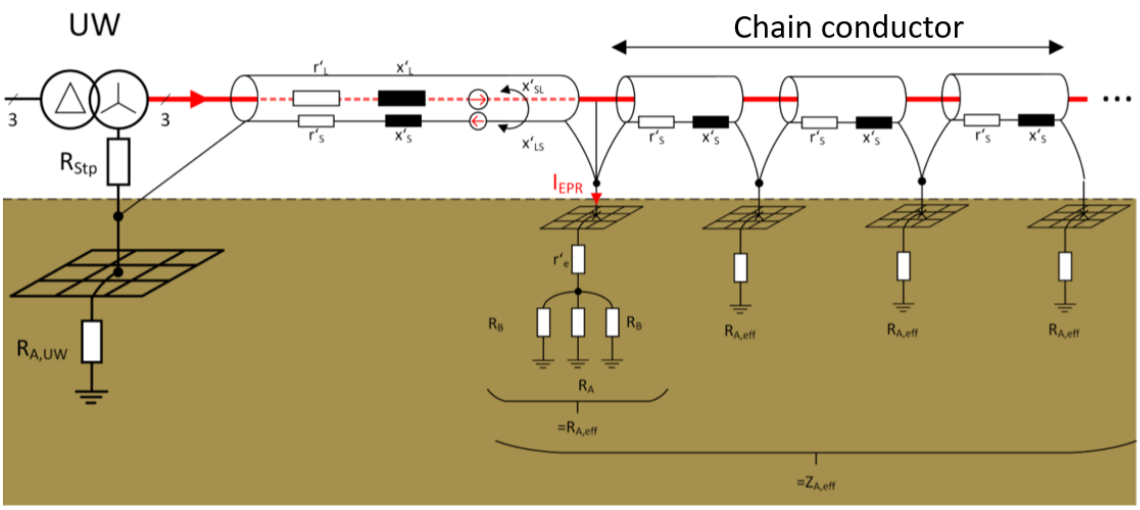


Figure 2.1: Single line scheme for earth fault current distribution [5]

2.2 Magnitude and Duration of the Earth Fault Current

It is important to realize that tolerable risks are always defined in a specific context, such as the dangerous electrical shock that occurs in or around a system built to existing standards for fault protection.
This means that for the fault protection itself, worst-case scenarios must be considered to ensure a shutdown in the specified time and thus compromise the calculation for the probability of ventricular fibrillation.[6][5]

A few of the worst case conditions for the protection of a person can be:

- low resistivity of the earth
- big contact area in saltwater-wet condition of the skin
- current flow in an unfavourable path through the body
- contact voltage corresponds to the total fault voltage
- closeness to the source and other earthing stations

The most noticeable consequence of a earth fault is the magnitude of the current compared to the current carried during normal operation. These high currents not only affect the planned system, but can also involve surrounding conductive objects, resulting in dangerously high temperatures and mechanical forces for their own and neighboring components in use.[3]
The earth potential rise (EPR) generated by the current flowing into the earth at the fault location and thus representing a hazard potential is the part to be handled in this work.

2.3 Appraisal of touch and step voltage

The first thing to note is that in order to establish allowable step and touch voltages, a number of bases for derivation need to be incorporated. This means that the attempt is no longer made to focus so heavily on statistical evaluations for individual cases, but rather to form a framework for the evaluation and calculation of dangerous contact voltages. It should be so general that it can be used to calculate different models and determine their safety. In this part it should be possible to determine which earth potential rise lead to which touch or step voltages, taking into account different body configurations, clothing, contact impedances, etc.. For this purpose, a circuit is considered that closes upon contact with a person and can be used for any scenario, figure 2.3.

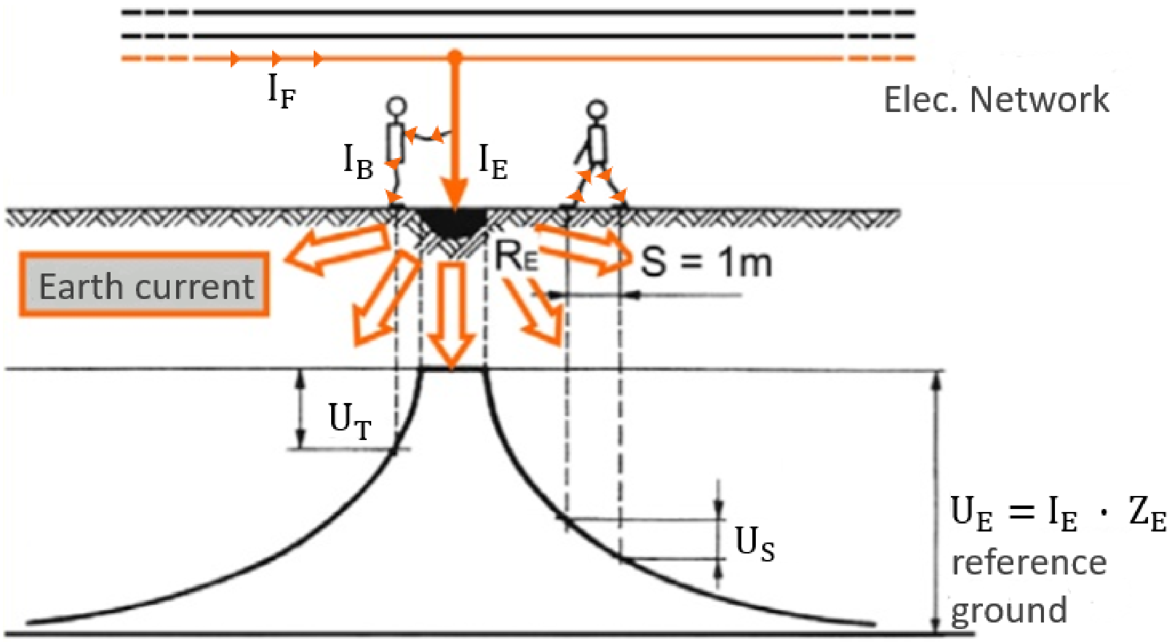


Figure 2.2: The earth potential rise U_E - touch U_T and step U_S voltage [5]

When calculating the earth potential rise for a worst-case scenario in a given Model, we get the so called prospective touch voltage, see figure 2.3 - U_{vT}. Now we need to take in account that the human body is a voltage-dependent impedance, Z_T. This means that at the moment a person comes into contact with the shock circuit, both the touch voltage and the body impedance change, making the determination of the initial touch voltage U_T visibly more difficult. In order to calculate the initial touch voltage U_T, knowledge of all relevant parameters in the shock circuit is required.[3][7]

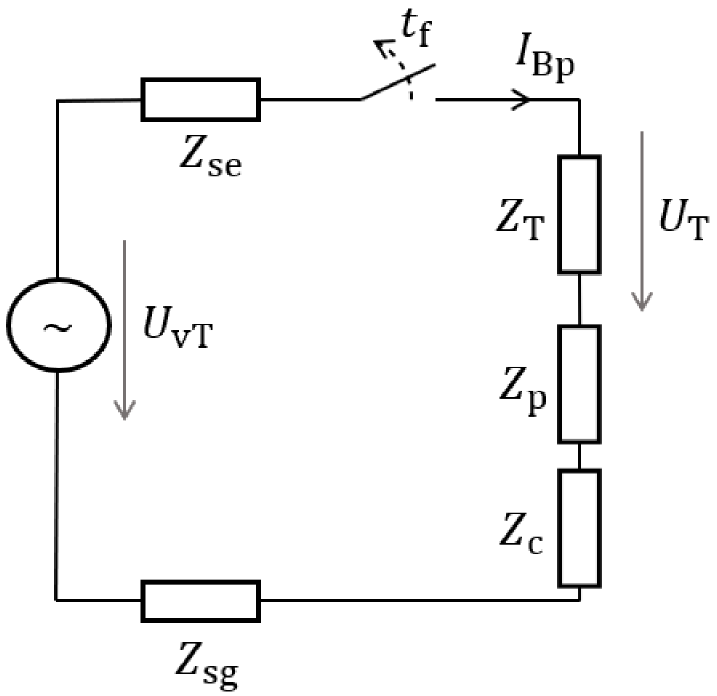


Figure 2.3: Shock circuit [8]

Parameter description,[3]:

The parameter Z_{se} describes the impedance of the electrical network, i.e. everything within the network that has an influence on the magnitude and duration of the fault at the fault location.

Z_{sg} describes the impedance of the earth return network, or rather it describes the total impedance. The fault current does not only connect to the source via a direct path. It also closes via the earth electrodes of other earthing stations, via the cable shield if present, buried metallic structures, etc..

t_f is the time the protective elements in the systems need to detect and clear the fault current.

Z_T describes the voltage-dependent impedance of the naked human body. Whereby this body can have different current flow scenarios as well as different states of the skin (dry, wet, salt water wet).

Z_p describes all serial additions that can be made directly on the body. These are protective impedances e.g. gloves, shoes, hats,... .
They may not be linear and are expected to have a break down voltage.

Z_c is the contact impedance with the ground, which means this is exactly where the person is standing at the moment they come into contact with the shock circuit.

If all these values are known, the initial touch voltage for U_{T} can be calculated with a voltage divider. The equation for this is described in the following section.[3]

$$\begin{aligned} U_{\mathrm{T}} &= \frac{Z_{\mathrm{T}}}{Z_{\mathrm{se}} + Z_{\mathrm{p}} + Z_{\mathrm{c}} + Z_{\mathrm{sg}} + Z_{\mathrm{T}}} \cdot U_{\mathrm{vT}} \\ &= \frac{Z_{\mathrm{T}}}{Z_{\mathrm{s}} + Z_{\mathrm{T}}} \cdot U_{\mathrm{vT}} \end{aligned} \tag{2.1}$$

Where $Z_{\mathrm{s}} = Z_{\mathrm{se}} + Z_{\mathrm{p}} + Z_{\mathrm{c}} + Z_{\mathrm{sg}}$

There is also the difference between touch and step voltage circuit, which means that the circuit needs to be adapted to an equivalent circuit, e.g. in a step voltage situation the legs in the circuit are in series, while in touch voltage they are in parallel. How these series and parallel circuits affect the body impedance can be seen in section 3.1.1.[7]

The touch and step voltages resulting from this calculation are probabilistic parameters in their nature due to the body impedance. This means that the values determined describe a probabilistic distribution that is not exceeded by a certain percentage of the population.

2.3.1 Contact impedance

The contact impedance Z_c provides a possible higher impedance in the shock circuit, especially if there is a layer of high impedance material between the person and the ground surface. In the simplest scenario, knowledge of the specific ground resistivity ρ_E is needed to calculate the contact impedance, depending on the circumstances the surface resistivity ρ_1 and its thickness h_s are also needed. The equations for this differ depending on the two main cases, i.e. tapping of the voltage by touching the live part or by entering the earth potential rise, [8] page 73.

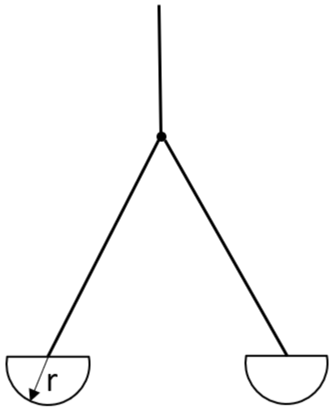


Figure 2.4: Equivalent circuit for the behaviour of the feet in relation to the ground

To set up the equations for the contact impedance, the contact points were assumed to be hemispherical earth electrodes. These hemispherical earth electrodes are assumed to have a radius of 0.05 m to calculate the impedance for the touch and step scenario:

$$\begin{aligned} Z_c &= \frac{\rho_E}{2 \cdot \pi \cdot r} \\ &\approx 3 \text{ m}^{-1} \cdot \rho_E \end{aligned} \tag{2.2}$$

<u>For the touch scenario:</u>
The current flows through the upper body then through both feet, i.e. they are connected in parallel. This means that the impedance is halved.

$$Z_c = 1.5 \text{ m}^{-1} \cdot \rho_E \tag{2.3}$$

<u>For the step scenario:</u>
The current enters one foot and exits the other , i.e. they are connected in series. This means that the impedance is doubled.

$$Z_c = 6 \text{ m}^{-1} \cdot \rho_E \tag{2.4}$$

If there is now a layer of high-resistance material on the surface of the earth, the current flow through the human body is reduced by increasing the resistance in the shock circuit. This increases the probability of survival. With this knowledge, the factor F_s is inserted into the equation 2.4 and 2.3 for the highly resistant layer. The equation requires knowledge of the resistivity of the soil ρ_E, the thickness of the layer h_s lying on the soil and its resistivity ρ_1, [8] page 73.

$$F_\mathrm{s} = 1 - \frac{0.09\ \mathrm{m} \cdot \left(1 - \frac{\rho_\mathrm{E}}{\rho_1}\right)}{2 \cdot h_\mathrm{s} + 0.09\ \mathrm{m}} \tag{2.5}$$

With the variable above, the contact impedance Z_c can now be calculated for the touch scenario:

$$Z_\mathrm{c} = 1.5\ \mathrm{m}^{-1} \cdot F_\mathrm{s} \cdot \rho_1 \tag{2.6}$$

and the step scenario:

$$Z_\mathrm{c} = 6\ \mathrm{m}^{-1} \cdot F_\mathrm{s} \cdot \rho_1 \tag{2.7}$$

2.3.2 Protective impedance

The protective impedance Z_p describes possible serial impedances that should either isolate the body from dangerous currents or limit the fault current. It is important how the contact configuration of the person in contact with the fault looks like. That is, whether the person enters an elevated ground potential or comes into direct contact with the fault. In the scenario that somebody steps in the elevated ground potential the impedance of the shoe must be doubled.
In the case of direct contact, it must also be taken into account which limbs the current flows through, hand to foot, hand to both feet, both hands to foot, etc. Depending on this, the equation must be adjusted.[8]

For the touch scenario, in the event of touching with two feet parallel or two hands parallel, the impedance Z_1 must be halved. Z_1 describes the impedance of one shoe or glove.

$$Z_\mathrm{p} = \frac{Z_1}{2} \tag{2.8}$$

For the step scenario, if both feet are wearing shoes, these are in series and must be doubled:

$$Z_\mathrm{p} = Z_1 \cdot 2 \tag{2.9}$$

Chapter 3

Body impedance and body current according to the IEC 60479-1

The current national and international standards are largely based on IEC 60479-1. This international standard is used to determine whether a body current in a given or planned system is likely to cause a lethal incident, i.e., whether it meets the requirements for protecting the public.[9]
To determine the compatibility of the body currents generated by different contact configurations, the "conventional time/current zones of effects of a.c. currents" from the international standard and the values for the voltage-dependent body impedance for different conditions are used.[9]

To identify the total body impedance for our case, we look at the factors, determined in the IEC 60479-1, that influence the impedance and are relevant in this work:

- current path
- contact voltage
- duration of the current flow
- moisture level of the skin
- contact size and configuration

3.1 Total body impedance

In the IEC 60479-1, the values of the total body impedance for an adult living human with a hand to hand current path were determined by experimentation and statistical analysis. They differ in the size of the contact area and the condition of the body (dry, wet, salt-wet).[9]

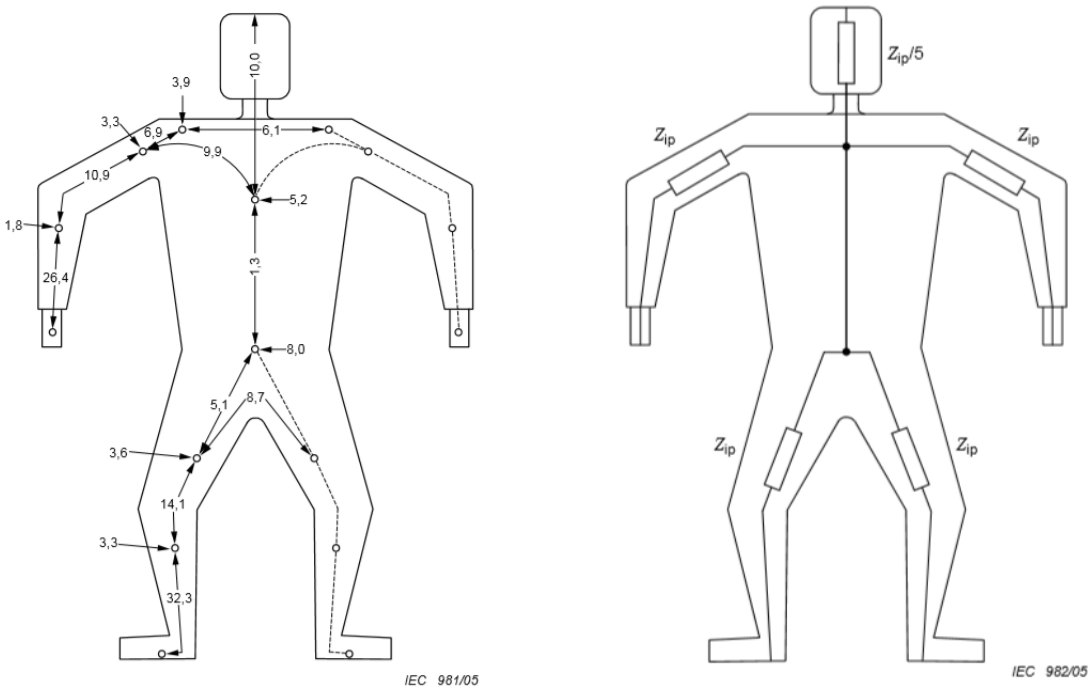
These values are presented in a probabilistic manner as in values which are not exceeded by some percentage of the population.
The statement is that one cannot fully express the impedance of humans by a single value, but must describe a probabilistic distribution with multiple values representing the human population. Individuals who are randomly selected have different impedances with a certain probability.
To show how the percentile rank of the affected living population affects the value of total body impedance, the following table, table 3.1, is included. These values show a clear difference for the risk to humans from dangerous touch voltages. Thus, with the same touch voltage but different impedance, the resulting current can be dangerous or harmless for the person affected.[9]

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	1 750	3 250	6 100
50	1 375	2 500	4 600
75	1 125	2 000	3 600
100	990	1 725	3 125
125	900	1 550	2 675
150	850	1 400	2 350
175	825	1 325	2 175
200	800	1 275	2 050
225	775	1 225	1 900
400	700	950	1 275
500	625	850	1 150
700	575	775	1 050
1 000	575	775	1 050
Asymptotic value = internal impedance	575	775	1 050

Table 3.1: Total body impedance for a current path hand to hand, [9] page 31

3.1.1 Body impedance for different contact scenarios

As mentioned earlier, the values for the impedances for the contact scenario were collected for the hand to hand configuration.
To adapt this to one's own scenario, two body models for total body impedance have been created in IEC 60479-1, the simplified model and the more accurate model for body internal impedance, figure 3.1.



(a) Accurate model ([9] page 59) (b) Simplified model ([9] page 61)

Figure 3.1: The internal impedances of the human body

Most often, the simplified model of the body internal impedance is used for the calculations, since in many scenarios only the hands and feet are involved, the result differs only minimally and is easier to calculate through quickly.
In the simplified model we see that the impedance for the path from hand to hand and from hand to foot is the same.
If you take the more accurate model, you can see that by simply adding up the values from the left hand to the left foot, you get a value of 100%. This means that the value for the contact scenario (hand to foot/hand to hand) under certain conditions (parameter of the contact areas, skin condition and the percentage of the population) can be taken directly from the table, table 3.1.[9]

In the following the calculation process for a more complicated contact configurations, in this example a push-up, is demonstrated,[9][12]:

- $U_{\mathrm{T}} = 75$ V
- $f = 50$ Hz
- condition of the skin: dry
- current path: from both hands to both feet
- contact area hands: large ; contact area feet: medium

Starting with the feet, i.e. calculating the torso to feet impedance, use table 4 with medium sized contact areas, of the IEC 60479-1 for 50 percent of the population.[9]

$$U_{\mathrm{T}} = 75\ V \Rightarrow Z_{\mathrm{TA}}(\mathrm{H-H}) = 8200\ \Omega$$

The hands have a larger contact area, which means that for the calculation of the hands to torso impedance, the value for 50 percent of the population must be taken from table 1 of IEC 60479-1.[9]

$$U_{\mathrm{T}} = 75\ V \Rightarrow Z_{\mathrm{TB}}(\mathrm{H-H}) = 2000\ \Omega$$

IEC 60479-1 contains the simplified and the more detailed body model, for this scenario the difference between the two is minimal. In this calculation, the simplified body model was chosen because its simplicity.

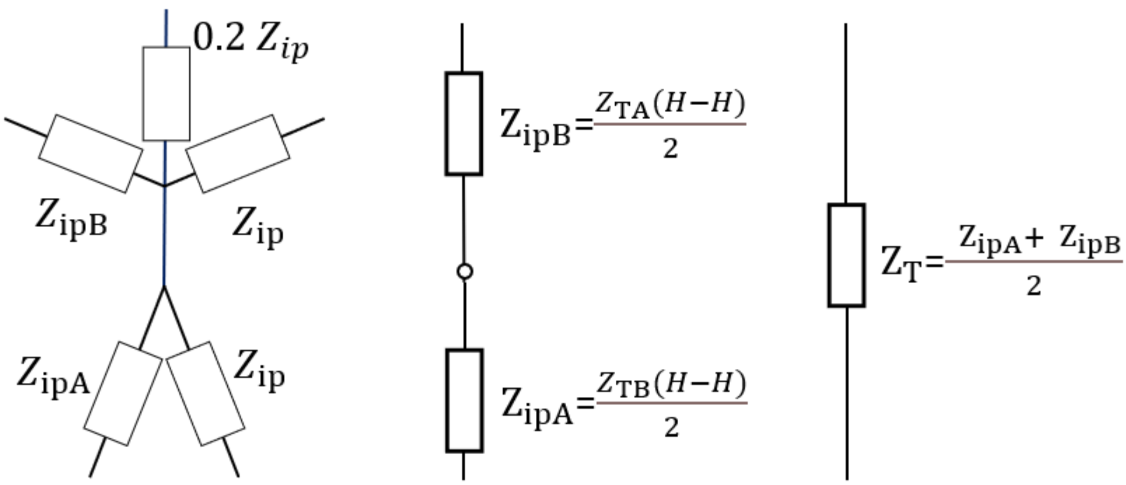


Figure 3.2: Customizing the body impedance

To calculate the path from foot-torso with medium contact area, the Impedance $Z_{\mathrm{TA}}(\mathrm{H}-\mathrm{H})$ has to be halved.

$$Z_{\mathrm{ipA}} = \frac{Z_{\mathrm{TA}}(\mathrm{H}-\mathrm{H})}{2} = 4100\ \Omega$$

Now to calculate the path from hand-torso with a large contact area, the Impedance $Z_{\mathrm{TB}}(\mathrm{H}-\mathrm{H})$ also needs to be halved.

$$Z_{\mathrm{ipB}} = \frac{Z_{\mathrm{TB}}(\mathrm{H}-\mathrm{H})}{2} = 1000\ \Omega$$

With the impedances Z_{ipA} and Z_{ipA} the body configuration of hand-foot with different sized contact areas can now be calculated.

$$Z_{\mathrm{T}}{}' = Z_{\mathrm{ipA}} + Z_{\mathrm{ipB}} = 5100\ \Omega$$

To take into account the parallel connection of the two feet and hands, the value must be divided by 2.

$$Z_{\mathrm{T}} = \frac{Z_{\mathrm{T}}{}'}{2} = 2550\ \Omega$$

3.2 The body current and the effect of the path

The current limits specified in the IEC 60479-1 have been applied in various national and international grounding standards. The magnitude of the current flowing through the body depends on the electrical network and all components connected in the moment of the fault. On the other hand, the duration of the fault is limited by the fault detection and protection, it affects both the consequence, in form of the probability of fibrillation, and the likelihood, in form of the probability of coincidence.[2][3]

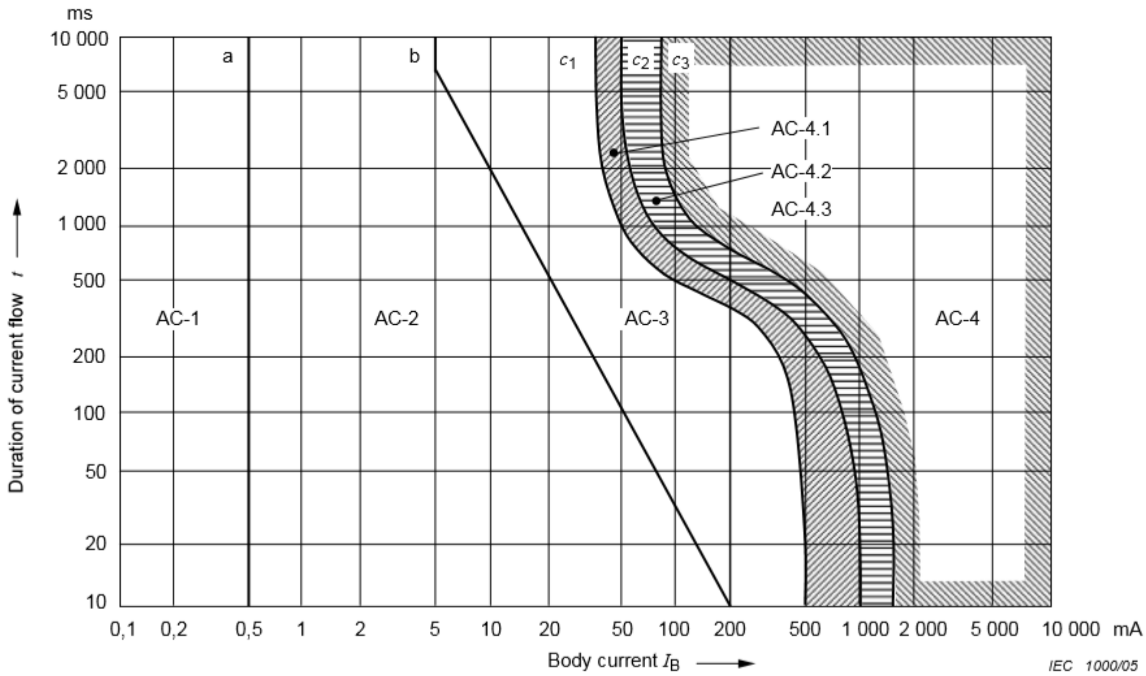


Figure 3.3: Conventional time/current zones, [9] page 91

The figure 3.3 shows how alternating currents of 15-100 Hz affect the human body. It is divided into four zones. To give an overview of the effects of the current on the human body, I will briefly explain these four zones.

The first zone AC-1 with boundary "a":

Describes the possible perception zone but usually there is no startled reaction.[9]

The second zone AC-2 with the boundaries "a" and "b":

Describes the perception and involuntary muscular contraction zone.[9]

In the third zone AC-3 with the boundaries "b" and "c1":

The contraction are getting stronger, its difficult to breath and there can be reversible disturbances of the heart function.[9]

The last zone and the one with the most interest in this work AC-4:

From the "c1" boundary, the probability of ventricular fibrillation increase with current magnitude and duration.[9]

The three subdivided zones in AC-4 differ in their probability of a fibrillation event. In zone "c1 to c2" the probability of ventricular fibrillation increases up to 5%. From "c2 to c3" the probability goes up to about 50%. And with exceeding boundary "c3" its above 50%.[9]
In order to determine the tolerability of the body currents generated by different models, the safety curve "c1" was used until 2010. Since 2010 the curve "c2" is recommended in combination with IEC 61936 and the EN 50522.[2][13][14]

The figure 3.3 is valid for currents following the path from left hand to both feet. This means that if one's own scenario is different, the path of the current through the body needs to be adjusted with the heart current factor from table 3.2, to compare the current with figure 3.3.[9]
The magnitude of the current through the body depends on the magnitude of the prospective voltage and the impedances in the shock circuit. The likelihood of ventricular fibrillation occurring, however, differs from the path the current takes through the body if the current remains constant. As the table 3.2 shows, the value of the heart current factor, in this work named HF, deviates more and more from one the closer the current path is to the heart itself.

Heart factor (HF)

Current path	Heart-current factor F
Left hand to left foot, right foot or both feet	1,0
Both hands to both feet	1,0
Left hand to right hand	0,4
Right hand to left foot, right foot or to both feet	0,8
Back to right hand	0,3
Back to left hand	0,7
Chest to right hand	1,3
Chest to left hand	1,5
Seat to left hand, right hand or to both hands	0,7
Left foot to right foot	0,04

Table 3.2: Heart-current factor, [9] page 53

Now comparing the contact scenarios given in table 3.2 with figure 3.1a from the previous section. In this example, one can see which of the scenarios is closer or farther from the heart. The value of the permissible touch voltage on the body increases the smaller the value of the heart-current factor is. If one wants to calculate the permissible touch voltage at a given body current I_{B} and body impedance Z_{T}, one must include the Heart-current factor.

$$U_{\mathrm{Tp}}(t_{\mathrm{f}}) = \left(I_{\mathrm{B}}(t_{\mathrm{f}}) \cdot \frac{1}{HF} \right) \cdot Z_{\mathrm{T}}(U_{\mathrm{T}})$$

Chapter 4

Evaluation of the permissible contact voltage

There are a number of studies that have been conducted on the different safety recommendations for different safety ratings. In this section it will be shown how these differences affect the values for the tolerable contact voltages.
As mentioned in the previous chapter, the guidelines of the IEC 60479-1 have been used for years as a reference point for safety checks against dangerous touch voltages. The characteristic curves of the IEC 60479-1 fault current in magnitude and duration of current flow in comparison to other studies seem often to be the most conservative ones [10][11]. Conservative in this case means that the values taken for the safety recommendation are far more restrictive than they need to be, according to other papers.[2][9][13][16][17]

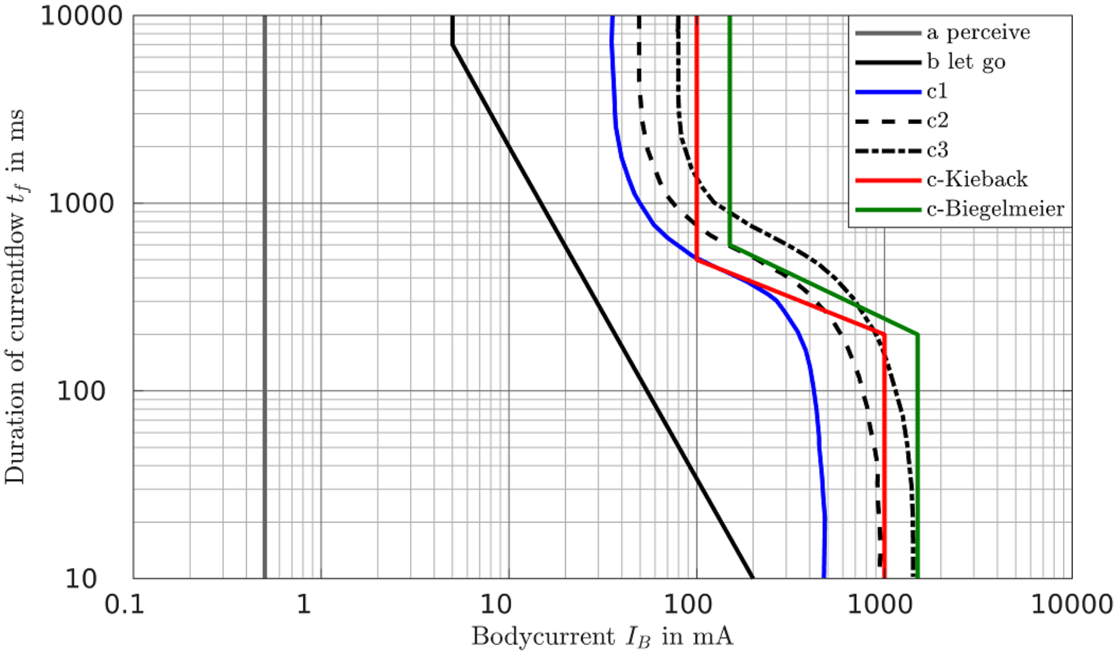


Figure 4.1: Conventional time/current zones of different papers

The base form of the figure 4.1 is from the IEC 60479-1, "c1" in blue describes a boundary. Which means the probability of ventricular fibrillation to the left of it is overall zero.[9]
In comparison to:

- and "c1-Biegelmeier" which is based on a big collection of data from experiments on hogs and a few on people. To draw the "c1-Biegelmeier" line, they compared the magnitude and heart periods of pigs and humans and found a commonality in the behavior of their fibrillation thresholds.[6]
- "c1-Kieback" which is based on recorded historical observations of electrical accidents of people. The institute EG ETEM in Cologne, has been collecting statistical data on such incidents for decades and has, among other things, used it to create the "c1-Kieback" curve as a recommendation for a new "safety curve".[15]

If we compare "c-Kieback" and "c-Biegelmeier" with a fibrillation probability of approx. 1% with "c1", it can be seen that "c1" is the conservative variant that lies far to the left of the other two. The two curves "c-Kieback" and "c-Biegelmeier" are actually designed for a risk of less than 1 %, but because of the residual risk, they are described as 1 % curves.[15]
The evaluated permissible contact voltage of the human body is considered in more detail in EN 50522.

4.1 Calculating the permissible contact voltages

Assuming that the value of the earth fault current for a known system has already been calculated and the magnitude and progress of the earth potential rise across the ground impedance has been determined, assumptions must now be made for the safety framework for the individuals who may come in contact. First of all, the condition of the person must be determined, whether protective clothing is worn (gloves, safety shoes, etc.), the condition of the skin (dry, wet, salt water wet), is it standing on the soil or on something else (tiles, asphalt, etc.). It is also important to know the contact configuration, i.e. the current path through the body and the size of contact surface.[9][16]

The permissible boundaries agreed for high-voltage installation, the values of the body current of "c2" from the IEC 60479-1 for a five percent probability of ventricular fibrillation are used for the maximum allowable current through the body. For the impedance of the body, the values for 50 percent of the population is selected. The duration of the body current equals to the fault duration. Therefore, the tripping time of the upstream active safety device must be included in the calculation.[9][16]

The equation to calculate the permissible touch voltage, Annex A of the EN 50522:2010 is used in this part of the work.[13]

$$U_{\mathrm{Tp}} = I_{\mathrm{B}}(t_{\mathrm{f}}) \cdot \frac{1}{HF} \cdot Z_{\mathrm{T}}(U_{\mathrm{T}}) \cdot BF \tag{4.1}$$

For I_{B} and Z_{T} in the equation 4.1 the values for I_{B} can be taken directly from "c2" of figure 4.1, for Z_{T} the tables from IEC60479-1 are used e.g. table 3.1 (for dry skin and large contact area). The heart current factor (HF) is used to adjust according to table 3.2. However, the body factor (BF) must be calculated using one of the models in figure 3.1 to fit the contact configuration.

Since the impedance Z_{T} is a voltage dependent impedance, a single value cannot be simply inserted in this equation to obtain the permissible touch voltage. To start the calculation, it needs an initial voltage for which the first value of the impedance is chosen, with this value and the ones mentioned above, the linear interpolation can now be performed.[9]

SHORT EXAMPLE:

The following assumptions apply to the calculation of permissible values of the prospective touch voltage in high-voltage installations:

- the contact configuration: one hand to both feet, H-BF
- there are no extra serial impedances, $Z_{\mathrm{s}} = 0$
- the value body impedance Z_{T} is not exceeded by 50 % of the population
- the probability of ventricular fibrillation is less than 5 %, "c2"

The values which are needed to calculate the permissible touch voltage:

- fault duration: $t_{\mathrm{f}} = 200$ ms
- initial touch voltage: $U_{\mathrm{T}} = 175$ V
- Body factor for the Body configuration: BF = 0.75
- Heart factor for the Body configuration: HF = 1

For $t_{\mathrm{f}} = 200$ ms $\rightarrow$ $I_{\mathrm{B}}(t_{\mathrm{f}}) \approx 600$ mA

For $U_{\mathrm{T}} = 175$ V $\rightarrow$ $Z_{\mathrm{T}}(U_{\mathrm{T}}) = 1325\ \Omega$

$$
\begin{aligned}
U_{\mathrm{Tp1}} &= I_{\mathrm{B}}(t_{\mathrm{f}}) \cdot \frac{1}{HF} \cdot Z_{\mathrm{T}}(U_{\mathrm{T}}) \cdot BF \\
U_{\mathrm{T1}} &\rightarrow Z_{\mathrm{T1}} \\
U_{\mathrm{Tp2}} &= I_{\mathrm{B}}(t_{\mathrm{f}}) \cdot \frac{1}{HF} \cdot Z_{\mathrm{T1}}(U_{\mathrm{T1}}) \cdot BF \\
U_{\mathrm{T2}} &\rightarrow Z_{\mathrm{T2}} \\
U_{\mathrm{Tp3}} &= I_{\mathrm{B}}(t_{\mathrm{f}}) \cdot \frac{1}{HF} \cdot Z_{\mathrm{T2}}(U_{\mathrm{T2}}) \cdot BF \\
&= \ldots \\
U_{\mathrm{Tpn}} &= 600\ \mathrm{mA} \cdot \frac{1}{1} \cdot 847\ \ \Omega \cdot 0.75\ \ = \underline{\underline{419\mathrm{V}}}
\end{aligned}
\tag{4.2}
$$

The voltage is recalculated in each iteration step. With the newly calculated voltage and the table 3.1, the total body impedance can be found for the next iteration step. This is repeated until the difference between the last two results are minimal. In this example a value of below 1 V.[9]

4.1.1 Permissible touch voltage for variable fault duration's

In figure 4.2 the touch voltage is evaluated for the fault duration of 10 ms to 10 s, a Matlab® script is written using the equation 4.1.
If special consideration is given to additional impedances, the y-axis of the figure 4.2 would be called the permissible prospective touch voltage. However, as there is only one person in the shock circuit, the whole potential is on this person and the parameter is referred to as the permissible touch voltage.[13]
Loops were created to calculate and record both the body current I_{B} with the variable fault duration t_{f} and the total body impedance Z_{T} with the voltage U_{T} by means of interpolation. However, this process was not only carried out for one contact configuration, but for four different cases. The criteria for these four cases are: large contact area, dry skin, total body impedance values for 50 % of the population and a probability of 5 % that ventricular fibrillation will occur.[13]

Contact configuration	Heart-current factor (HF)	Body factor (BF)
left hand - right hand (LH-RH)	0.4	1
right hand - both feet (RH-BF)	0.8	0.75
left hand - both feet (LH-BF)	1	0.75
both hand - both feet (BH-BF)	1	0.5

Table 4.1: Contact configurations

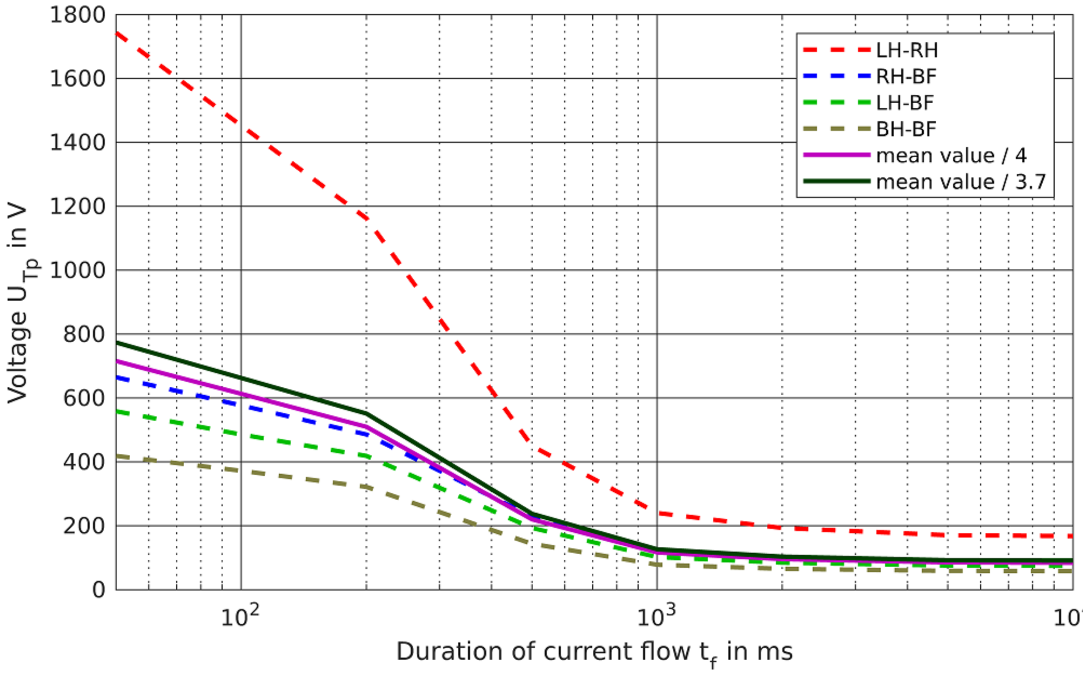


Figure 4.2: Permissible prospective touch voltage for 50 % of the population

Figure 4.2 shows change of how the permissible touch voltages with the contact configuration. The greatest difference occurs in the "left hand - right hand" case compared to the others. This is because of the high body factor (BF) and low heart current factor (HF) in this configuration. However, all these contact voltages have the same probability of ventricular fibrillation.
In order to protect both the public and workers from dangerous touch voltages, the curves, in particular the mean value of the 4 scenarios - the purple curve in figure 4.2 according to EN 50522:2010, are used. These have a direct influence on the development of the grounding system, as can be seen in the following section.[13]

The equation to calculate the mean values, according to the calculation in appendix B of the EN 50522:2010[13]:

$$U_{\mathrm{Tp}} = \frac{U_{\mathrm{Tp}}(\text{LH-RH}) \cdot 0.7 + U_{\mathrm{Tp}}(\text{RH-BF}) + U_{\mathrm{Tp}}(\text{LH-BF}) + U_{\mathrm{Tp}}(\text{BH-BF})}{4} \tag{4.3}$$

The equation to calculate the mean values for U_{Tp}, if the weighting is taken into account[13]:

$$U_{\mathrm{Tp}} = \frac{U_{\mathrm{Tp}}(\text{LH-RH}) \cdot 0.7 + U_{\mathrm{Tp}}(\text{RH-BF}) + U_{\mathrm{Tp}}(\text{LH-BF}) + U_{\mathrm{Tp}}(\text{BH-BF})}{3.7} \tag{4.4}$$

4.2 Verification of compliance of the earthing system according to EN 50522:2010

4.2.1 Basic design of an earthing system

Figure 4.3 serves to check whether the boundaries were met when designing the earthing system, with regard to the resulting touch voltage and body current. The design for the layout of figure is based on [13], page 26.

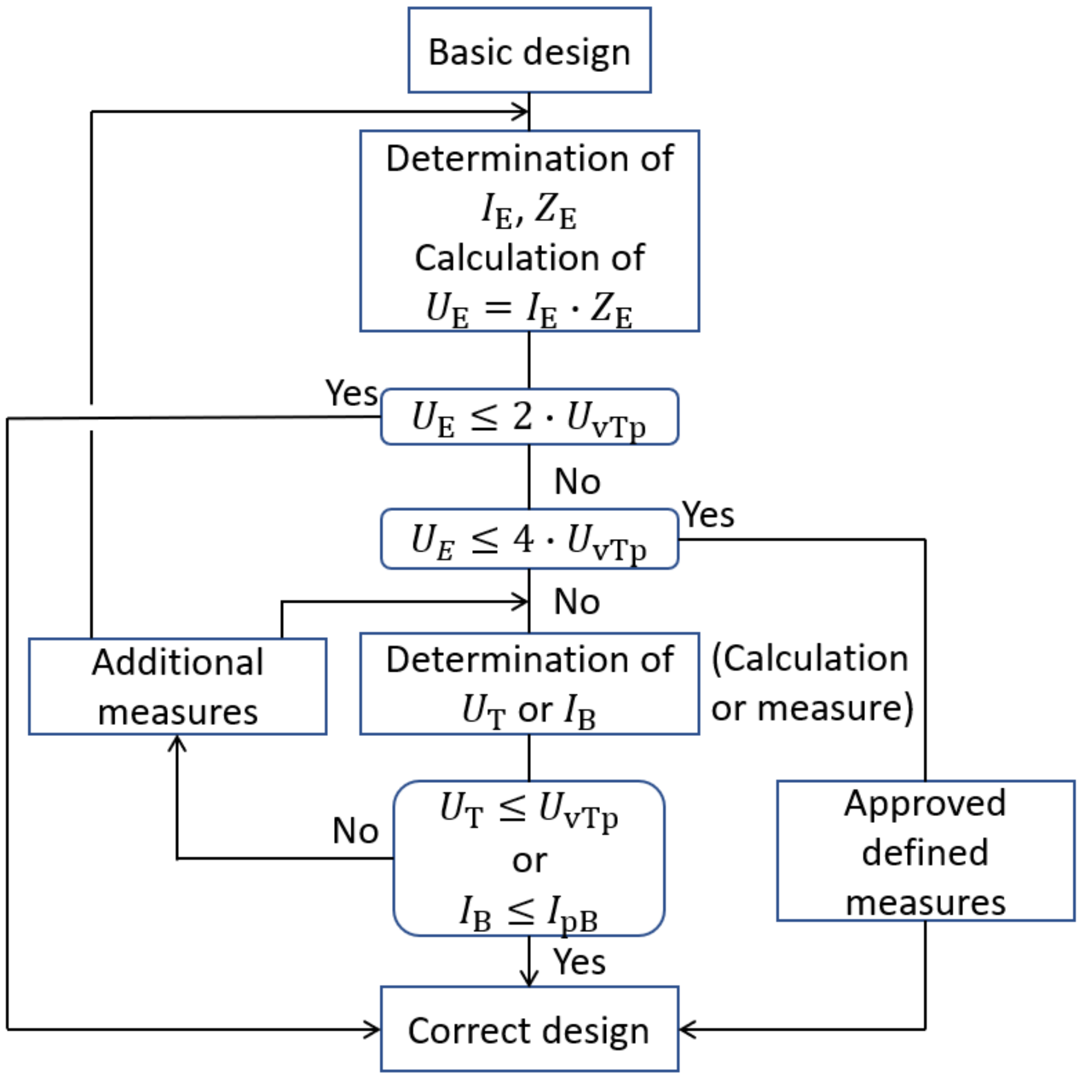


Figure 4.3: Compliance of the earthing system according to EN 50522

4.2.2 Calculation of the earth potential rise $U_\mathbf{E}$

First Step: Determination of the earth current $I_\mathbf{E}$

The earth current for installations with an earth fault compensation coil is calculated according to EN 50522:2010 page 22 with the equation:

$$I_\mathrm{E} = r \cdot \sqrt{I_\mathrm{RES}^2 + I_\mathrm{L}^2} \tag{4.5}$$

- I_RES ... residual earth current.
  If this is not known, 10 % of the calculated capacitive earth fault current can be used.
- I_L ... sum of the rated currents of parallel earth fault coils of the systems under consideration
- r ... reduction factor

Second Step: Determination of the earth impedance $Z_\mathbf{E}$

According to EN 50522:2010 page 58, the value of the earth impedance is calculated as follows:

$$Z_\mathrm{E} = \frac{U_\mathrm{EM}}{I_\mathrm{M} \cdot r} \tag{4.6}$$

- U_EM ... measured voltage between the earthing system and a probe in the area of the reference earth
- I_M ... measured test current
- r ... reduction factor for measurement case

Final Step: Determination of the earth potential rise $U_\mathbf{E}$

Now the earth potential rise can be calculated with the calculated earthing current I_E and earth impedance Z_E:

$$U_\mathrm{E} = Z_\mathrm{E} \cdot I_\mathrm{E} \tag{4.7}$$

Chapter 5

Permissible body current derived from data of pigs and people

Experiments on animals similar to humans in terms of their organism and response most closely to humans especially cardiological were carried out, whereby the pig is in the focus here. For this reason, a very large number of investigations and calculations have been carried out to establish correlations between human and animal bodies. This has led to the realisation that although the fibrillation thresholds of humans and animals are different, they are dependent on their cardiac period. Analysis of aggregate statistical data on pigs and humans showed that under similar conditions, the human fibrillation threshold is higher than that of pigs, but the gradient is very similar, overall humans survive a relatively higher magnitude of current than pigs, as one can see in figure 5.1.[15]

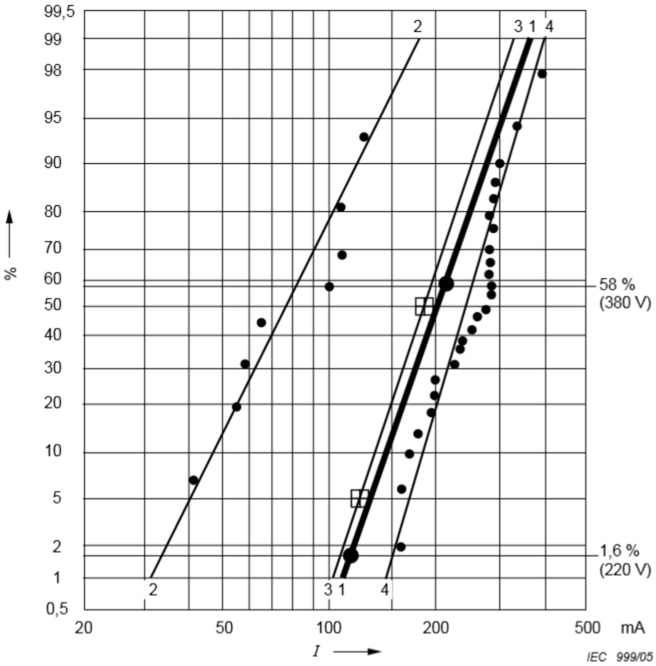


Figure 5.1: Fibrillation data for dogs, pigs and sheep and persons for $Z_{\mathrm{T}}(5\%)$ [9]

In figure 5.1, "1" describes humans, "2" dogs, "3" pigs and "4" sheep's. in this work, the relationship between "1" and "3" is most closely examined.

In the paper: "A new approach to protection against harmful electric shock based on tolerable risks and fault protection by automatic disconnection of supply for a.c. 50/60 Hz and for d.c."[6], the so-called conventional factors f_v are used for the conversion of the magnitude of the fibrillation thresholds between animals and humans. For pigs, a value of $f_\mathrm{v} = 2.8$ was calculated.[6]

In another paper, of "Kieback 2009" [15], this factor of 2.8 is examined in more detail. It was recognised that $f_\mathrm{v} = 2.8$ is only applicable in certain cases and that with the evaluation of the human and pig data, the factor should be between 2.54 and 2.92. This was only possible through the collection of decades of data for human electrical incidents. In appendix A, the comparison of the animal experiments and the statistical evaluation of accidents is shown in figure A.1. This diagram was used to create the figure 5.2 and figure 5.3. The table 5.1 is a statistic for the same contact configurations as already calculated in section 4.1.1. This clearly shows, as already displayed in figure 4.2, that of the four cases, the scenario "both hands - both feet" is the most dangerous one. The lethality describes the ratio of persons who died when a defined current coursed through the body to all persons who were affected by this current. So the lethality of electrical accidents is dependent on the magnitude of the body current I_B. [15]

Stromweg	Niederspannung, 50 Hz (> 130 V – 400 V) Stromunfälle mit Strommarken infolge Durchströmung Dauer der Durchströmung > 300 ms				
	Anzahl der Unfälle		Relat. Verteilung [%]		Letalität
	Insgesamt	davon tödlich	Insgesamt	tödlich	L [%]
Hand-Hand	2.891	82	77,3	48,5	2,84
Hand-Fuß	349	19	9,2	11,2	5,44
Hand-Füße/Hände-Fuß	294	18	7,7	10,7	6,12
Hände-Füße	106	20	2,8	11,8	18,67
Verkürzte Stromwege					
• bei Längsdurchströmung (Hand-Rumpf (Brust/Rücken/Gesäß))	86	20	2,4	11,8	23,26
• bei Querdurchströmung (Hände-Rumpf(Brust/Rücken))	22	10	0,6	6,0	45,45
• Verkürzte Stromwege insgesamt	108	30	3,0	17,8	27,78
Insgesamt	3.748	169	100	100	4,51

Table 5.1: Statistic for electrical accidents [15]

With the new data for f_{v}, the current threshold for ventricular fibrillation is established in a zone, the gray area in appendix A.1.[15]
This means that it should be possible to produce a figure for the probability of ventricular fibrillation as a function of the short-term and long-term range of dangerous current flows through the body.
With this knowledge, the probability surface distributions will now be created as part of this work.

IEC 60479-1[9]:
In order to draw the probability surface distribution, the current values with their associated fibrillation probabilities must first be determined. For this purpose, the figure 3.3 is used and the following values were set for the curves: "c2" - 5% and "c3" - 50%. Using the inverse cumulative distribution function of the standard normal distribution (probit function), the probit transformation of "c2" and "c3" is performed. The distribution function F(y) on the vertical-axis replaces y by $y = k \cdot x + d$ (for probit = y + 5, $k = 1/\sigma$ and $d = -k \cdot \mu$) to establish the equation of the straight lines. With the probit values "c2", "c3" and the corresponding currents I_{c2}, I_{c3} as a function of the fault duration t_{f}, one can now calculate the gradient k and the y-intercept d for all times t_{f}. With the parameters k and d now known for different t_{f}, one can calculate the corresponding body current I_{B} for a given cumulative probability of fibrillation using the inverse of the cumulative distribution function, exp(($F^{-1}(p/100)$ + 5 - d) / k). The cumulative distribution function for long and short duration can be seen in figures 5.2 and 5.3. [15]

Derived data:
First, we consider the "long duration" for the accidents, i.e. for a time of
$t_{\mathrm{f}} \geq 500$ ms. The values for the impedance of 5% and 50% of the population are used. The values for 95% of the population are neglected because many safety factors are present at these values and thus dangerous touch voltages hardly occur. With these values, the data from human electrical incidents and the experimental data from animals, a range was created, a so-called scatter band for the possible lethal body currents. The outer edge of the gray rectangle calculated in figure A.1, on the side of the lower body current was chosen for the "long duration", for safety reasons.[15]
For the "short duration" the data of Buntenkötter's animal experiments with a transmission factor of 2.8 for a time of $t_{\mathrm{f}} = 200$ ms was used.[15]
With the values for the gradient k and the y-intercept d read from figure A.1 we can now calculate the corresponding body currents I_{B} using the probit straight equation with the values for the probit probabilities. To draw the figure 5.2 and figure 5.3, the cumulative distribution function (cdf) must be used for the vertical axis in order to calculate the probabilities in percentage for the various currents I_{B}, which are logarithmically displayed on the horizontal axis.

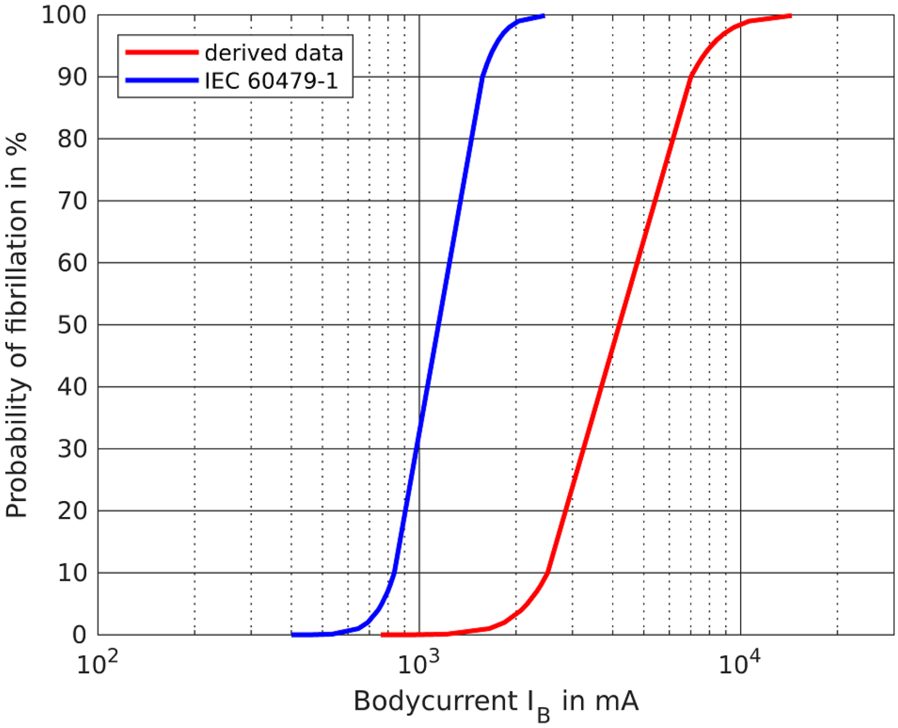


Figure 5.2: Probability surface distribution - derived data for $t_f \leq 300$ ms, IEC 60479-1 for $t_f = 100$ ms

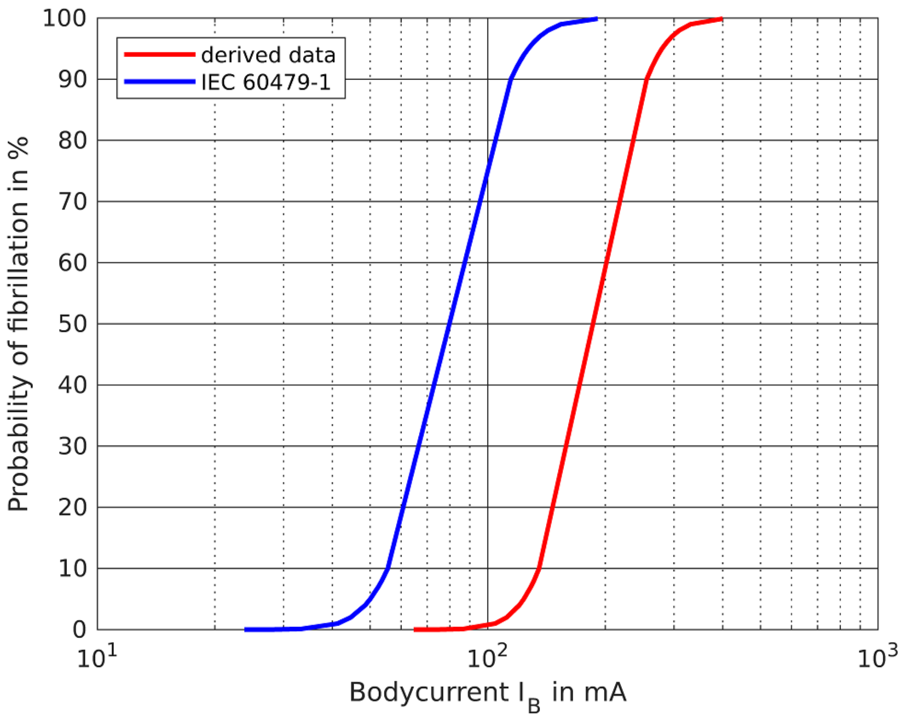


Figure 5.3: Probability surface distribution - derived data for $t_f \geq 300$ ms, IEC 60479-1 for $t_f = 10$ s

The values chosen in this work are now to be represented in a "body current I_{B}/fault duration t_{f}" characteristic curve. In order to be able to make a comparison with the other safety curves, especially the comparison with the curve "c-Kieback", since both "c-Kieback" and "c-proposed" are based on the figure A.1.The difference between "c-Kieback" and "c-proposed" lies in the way the values from figure A.1 for the long and short duration were taken over. In this work, as already described for figure 5.3 for the "long duration", the leftmost edge (higher safety) of the parallelogram was chosen for the values in figure A.1. In contrast to "c-Kieback", the values in the middle were chosen there. For the "short duration" of time, they have taken on extra security in their work, whereas in this work the results were taken directly from Buntenkötter's animal experiments. "c-proposed" was drawn for probability of fibrillation of 1 %.

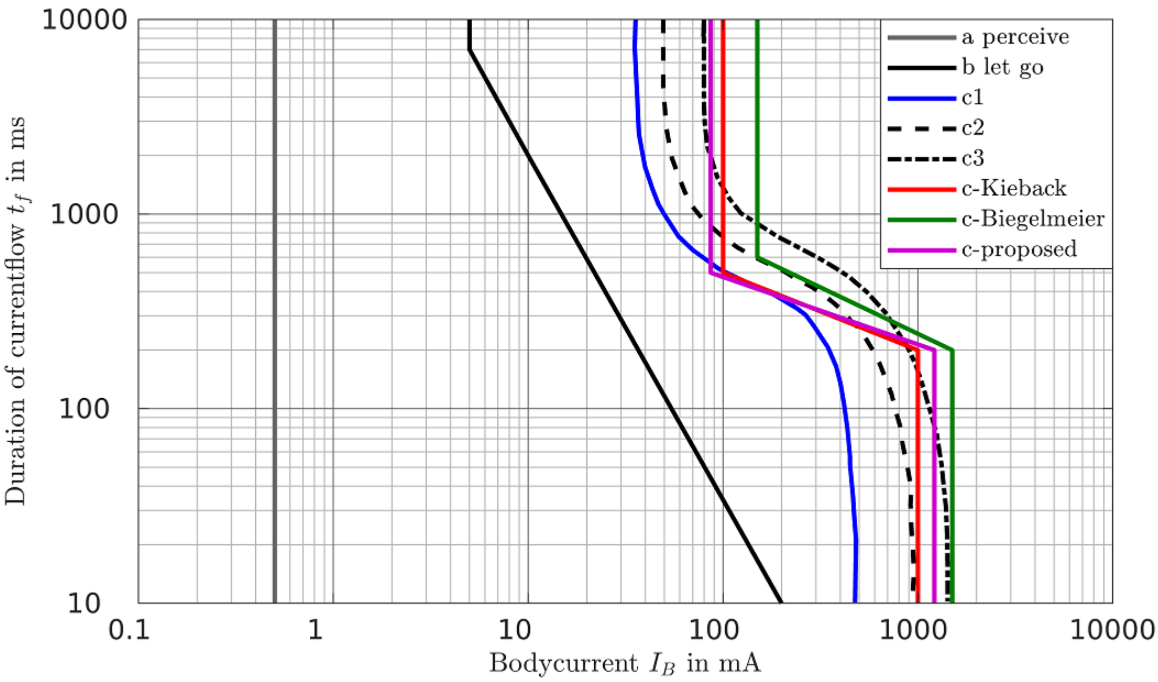


Figure 5.4: Comparison of the self-developed safety curve with existing ones

Chapter 6

Risk management structure

In Australia, a non-binding recommendation was published by the "Energy Network Association Australia", which bases the design of earthing systems on a risk analysis. The focus is on a probabilistic derivation of permissible voltage criteria and exposure under fault conditions.[8] In contrast to other countries where the earthing system is considered adequate if the impedance is below a fixed value, e.g. below 1 Ω. Other country's defined safe touch and step voltages for a fixed duration of time. The risk analysis evaluates a grounding system with the help of maximum values of the probability of fibrillation $P_{\text{fibrillation}}$ and the probability of coincidence $P_{\text{coincidence}}$.[3][8]

This process can be applied to any type of potential hazard that could result in injury or death to workers or the population.[3]

This section deals with the risk management of systems with different short circuits and configurations in different locations. How to transport or limit the energy in case of a fault in order to ensure the safety of people which come into contact with it, as well as the general system.

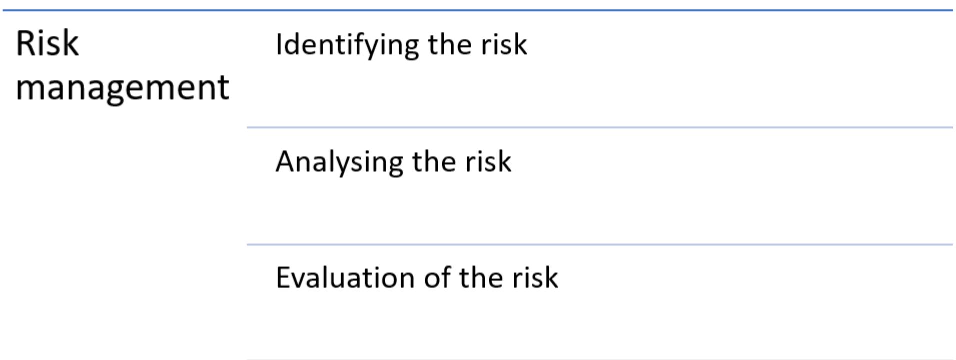


Figure 6.1: Risk management

The figure 6.1 has been designed according to existing risk assessment analysis methods in order to avoid confusion due to comparisons with similar or other works.[3][19][20]

The first step is to identify the risks in the overall system and to check whether they are so-called "tolerable risks". The risk is usually divided into three areas,[3][19]:

- intolerable risk
- risk that can be tolerated under certain circumstances and measures
- broadly accepted risk

The basic idea is that the earthing system is designed in such a way that any kind of touch or step voltage that is exposed to the workers or the rest of the population is either low enough that there is no danger or is switched off quickly enough.

When analyzing the risk, according to "Substation earthing system design optimization through the application of quantified risk analysis", the consequences of the risk are presented in their associated probability. This means that both the probability of coincidence and the probability of fibrillation are considered together. The variable that emerges and is checked is the probability of fatality. The exact criteria can differ from country to country and from company to company.[3]

The last step is to assess whether the values determined and analyzed are within the officially permissible limits for the faults mentioned and whether an improvement/modification of the safety measures is required. In doing so, we look at the three areas of general tolerability, table 6.1. In the middle band, there is the so-called ALARP criteria system, which means the Risk should be "as low as reasonably practicable". This will be dealt with in more detail in the following calculations.[3][19]

Probability of Single Fatality (per annum)	**Risk Classification for Public Death**	**Resulting Implication for Risk Treatment**
$\geq 10^{-4}$	High or Intolerable risk	Must prevent occurrence regardless of costs.
10^{-4}-10^{-6}	Intermediate or ALARP region	Must minimise occurrence unless risk reduction is impractical, and costs are grossly disproportionate to the safety gained.
$\leq 10^{-6}$	Low or Tolerable risk	Risk generally tolerable, however, risk treatment may be applied if the cost is low and/or a normally expected practice.

Table 6.1: Individual risk for ventricular fibrillation with fatal consequence [3]

The values described in figure 6.1 represent the individual tolerable limits of fatality. When calculating the probability of fatality, it is important to get at least into the middle band so that the safety concept can be reasonably updated to a satisfying degree looking at the cost performance comparison, otherwise needs to be completely revised.[3][8][19]

6.1 Probability of fatality

For a person to receive a lethal shock, they must be in contact with the live site at the moment a fault occurs. The fault needs to produces a body current of sufficient magnitude and duration for a ventricular fibrillation event to happen.
The equation for the probability of fatality P_{fatality} through indirect contact with the fault voltage may be expressed as described below.[3]

$$P_{\text{fatality}} = P_{\text{fibrillation}} \cdot P_{\text{coincidence}} \tag{6.1}$$

The probability of fibrillation is dependent on:

- all impedances in series with the body, Z_{s}: ref. to section 2.3
- contact configuration: ref. to section 3.1.1
- voltage applied, U_{T}: ref. to section 4.1
- fault duration, t_{f}: ref. to section 4.1.1

The probability of coincidence is dependent on:

- fault duration, t_{f}
- fault frequency, n_{f}
- contact duration, t_{b}
- contact frequency, n_{b}

Each of these values describes a variable in an assumed shock circuit. For these variables, a representative value must be chosen that influences the survival of the person in the selected scenario. Thus one can say that these values are probabilistic by nature.
Often in practice, a value of 1000 Ω for the total body impedance has been used in calculations, such as in IEEE Std. 80-2000 [16], BS 7354 [17] or ENA-TS 41-24 [18]. However, as seen in chapter 3, the value for Z_{T} can also deviate greatly, which can lead to dangerous cases if one wants to calculate the permissible contact voltages. In order to describe the probability of fatality, it is therefore necessary to have precise knowledge of the entire system, the shock circuit and all their dependencies.[3]

The purpose of the model below, figure 6.2, is to show which variables are related with each other in a simplified way. This is for the determination of the information needed to calculate the probability of fatality. The risk of exposure describes the probability that one or more persons touch a live part and simultaneously an earth fault occurs at said point.
The probability of failure, i.e. the probability of an ventricular fibrillation event, is determined with the probable contact configuration and the probable value for the contact voltage.
The applied voltage, or earth potential rise, depends on the level of the driving voltage and the specific contact of the body with the faulty place in the shock circuit. This means that in the scenario of touching the fault place without standing in a elevated potential, the full prospective voltage affects the person as contact voltage. However, there are different kinds of contact cases with different kinds of contact configurations, like the step scenario, in which only a part of the earth potential rise is applied to the body. The probability of such a fault occurring and the frequency of it must be checked statistically for similar or identical systems.[21]

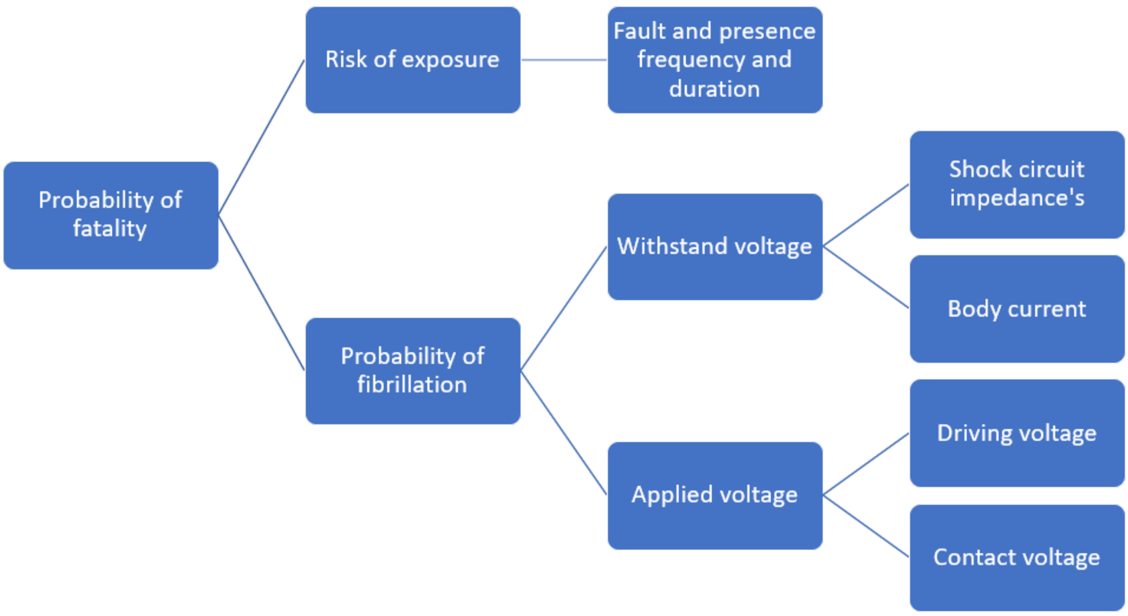


Figure 6.2: Probability of fatality [21]

The figure 6.2 is, according to today's standards, a simple version of a model to calculating fatal electricity accidents. The accuracy in comparison is very low when you look at today's computer models, whose accuracy goes at least to the fourth decimal digit. However, this models purpose is to serve as a simplified approach, also as a guide and checklist of the most important values required for the safety of the staff and the public.[21]

6.1.1 Calculation of the probability of fibrillation

As can be seen in chapters 3 and 4 on the behaviour of humans when voltage is applied and a current flows through the body, the survival of humans in contact with a fault essentially depends on two parameters, which are shown in the probabilistic figure 6.3.[3]

- the population current tolerances with respect to the fault duration.
- the population body impedance with respect to the voltage applied to the body.

Exposing a random person to a given voltage hazard will either result in that individual surviving or dying because of ventricular fibrillation. Having heard that, it may not initially appear to make sense to talk about the 'probability of fibrillation', because calculating it for a single Person, it will always result as either true, i.e. 100 % or false, i.e. 0 %. However, this is only correct for a specific individual considered. Instead, the probability of fibrillation calculated here, is interpreted as the probability that an individual selected at random from the population enters ventricular fibrillation as a result of the voltage hazard.[3]

This interpretation of the fibrillation probability associated with a voltage hazard could be said to be the average individual probability, and is equivalent to the fraction of the population that would enter ventricular fibrillation if the entire population was exposed to the voltage hazard.[3]

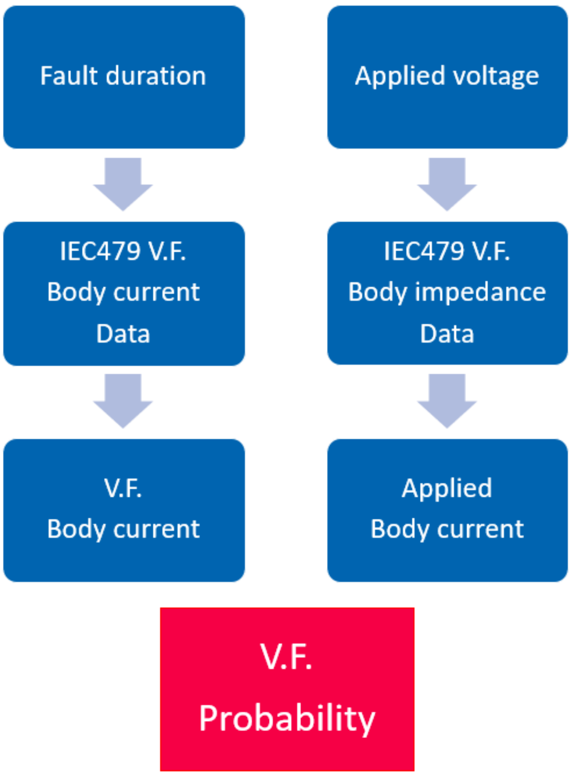


Figure 6.3: Calculation method for the probability of fibrillation [3]

For demonstration, the comparison between the EN 50522 curve at section 4.1.1 and a new one is to be made. In figure 6.4, you can see how the prospective permissible touch voltage changes with different body impedances not exceeded by a certain percentage of people. The curve for 5 percent of the population is clearly lower than for 50 percent, which means for 5 percent of the population the probability of fibrillation is higher than for 50 percent. This would be reversed if we looked at the 95 percent column.

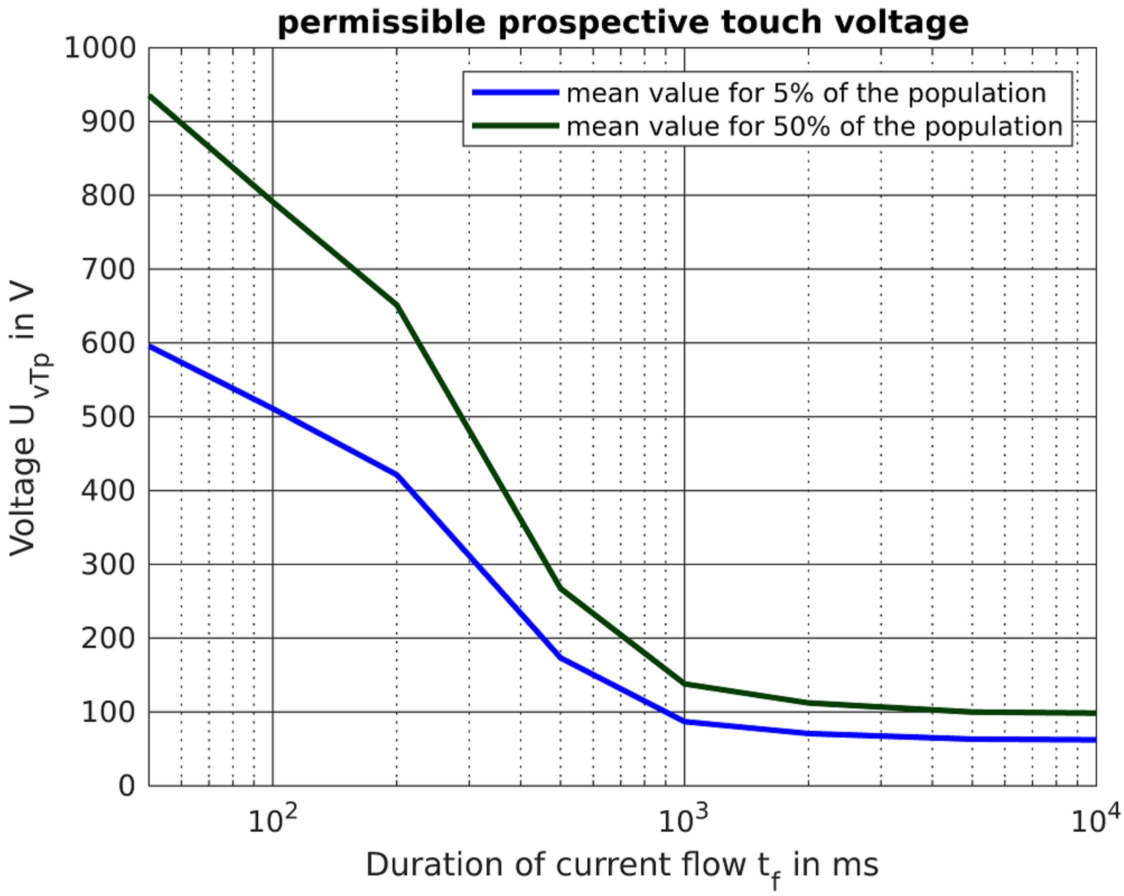


Figure 6.4: Comparison of U_{vTp} for $Z_{\mathrm{T}}(5\%)$ and $Z_{\mathrm{T}}(50\%)$ - IEC 60479-1 curve "c2"

SHORT AND SIMPLIFIED EXAMPLE

This is determined with a worst-case scenario condition, resulting in:

- maximum touch or step voltages.

Using the maximum value of the:

- prospective voltage

and the discrete values of the:

- body impedance
- footwear resistance
- soil resistivity
- ...

The maximum current I_B flowing through the human body in this scenario is calculated from the touch voltage U_T divided by the total body impedance Z_T adapted with BF to the configuration:

$$I_\mathrm{B} = \frac{U_\mathrm{vT}}{Z_\mathrm{S} + Z_\mathrm{T}} \tag{6.2}$$

For U_T in the numerator, the equation 2.1 for the prospective touch voltage was used. In the denominator the body impedance is for 50 percent of the population for the value of the touch voltage calculated in the numerator.
Then, for an assumed fault duration for the current flow depending on the clearing time of the used protective device, the probability of ventricular fibrillation is determined by examining where the value of body current multiplied by HF lies in relation to the published curves of ventricular fibrillation. IEC 60479-1 $t_\mathrm{f} = 200$ ms.

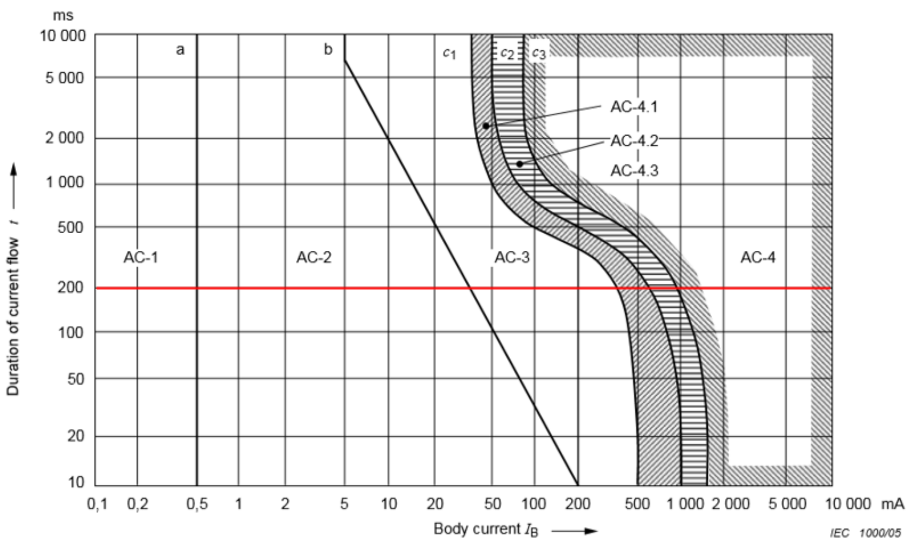


Figure 6.5: Conventional time/current zones of effects of a.c. currents [9]

6.2 Probability of coincidence

The probability of coincidence depends on four variables, the fault and contact frequency and duration.[21]
The coincidence is a variable that represents the degree to which the probability of a single-pole short circuit leading to dangerous consequences for others. This means the coincidence calculation can be carried out for the scenario of a single person coming into contact with the faulty point as well as for the scenario of several different people coming into contact with the faulty point.[3]

The individual risk: The annual risk of fatality for an exposed individual.[8]

- The risk associated with an individual is usually calculated for a single hypothetical person who is a member of the exposed population. Individual risk assessments do not account for the danger to an exposed population as a whole.[8]

The societal risk:

- The risk associated with multiple, simultaneous fatalities within an exposed population. When considering the impact on society it is usual to consider the annual impact upon a 'typical segment' of society. Societal risk may be a determining factor in the acceptability of the risk associated with a hazard for areas where many people congregate.[8]

Of course, the simplest case that can occur is the individual risk. There is one faulty place and one person who comes into contact with it. This means that the equation 6.3 only requires knowledge of how often the person passes the possible fault location, touches it and how often an earth fault occurs in this scenario, calculated over a whole year. The equation 6.3 and table given below have been simplified according to "EG-O 'Power System Earthing Guide- Part 1: Management principles".[8]

$$P_{\mathrm{coincidence}} = \frac{n_{\mathrm{f}} \cdot n_{\mathrm{b}} \cdot (t_{\mathrm{b}} + t_{\mathrm{f}}) \cdot T}{(365 \cdot 24 \cdot 60 \cdot 60)\frac{\mathrm{s}}{\mathrm{a}}} \tag{6.3}$$

variable	explanation
n_{b}	Frequency of contact per individual per year (1/a)
n_{f}	Fault frequency per year (1/a)
T	Period under consideration (a)
t_{b}	Contact duration (s)
t_{f}	Fault duration (s)

These two events are approximated by the POISSON distribution. The average time between the events is important to know, but they are often randomly spaced. We may have failures one after the other, or years may pass between failures due to the randomness of the process.[8][22]
In order to use the equation derived from the POISSON distribution according to [22], its criteria for use must be fulfilled:

- events are independent of each other. The occurrence of one event does not affect the probability another event will occur.
- the average rate (events per time period) is constant.
- two events cannot occur at the same time.

The second point means that if, in the calculation, there are different numbers of contacts with the possibly live part or different numbers of earth faults each month, the calculation must be made for the individual months and added up to a year at the end.

For the evaluation of the frequency n_b you need to know the exact scenario. For example, assume that the live part at work is touched once a day for 40 seconds, only on working days. So for 52 calendar weeks, the value for n_b can be calculated with:

$$n_\mathrm{b} = 52 \text{ weeks/year} \cdot 5 \text{ days/week} = \underline{\underline{260 \text{ days/year}}}$$

In case of the variable n_f, it does not only have to refer to the fault itself, but can also stand for a structure that is under voltage as a result of a fault. A high voltage tower would be such structure. To calculate this, you have to know how often a fault occurs, at for example point A of the high-voltage line B, in one year. Then you have to find out at how many points on the high-voltage line B the fault can occur. The last point to check is how many power lines are present which have an influence on the tower with their faults.[8]

$$n_\mathrm{f} = (no._\mathrm{f}/\text{Time period (in years)}) \cdot (no._\mathrm{h}/no._\mathrm{t})$$

variable	explanation
$no._\mathrm{f}$	Number of faults on the line within the time period
$no._\mathrm{h}$	Number of hazardous structures per fault
$no._\mathrm{t}$	Number of transmission structures in line

A SIMPLE EXAMPLE to illustrate the process:

People go to the university every morning during the week to work on projects or jogging. When they enter the area through the revolving door at the back entrance, they have contact with the metal part next to the door for about 1 second. The risk of an earth fault occurring and the metal part being live changes with the seasons, but always lasts about 1 second. The data from last year's incidents were evaluated and written down in the following table.

The average duration of exposure: $t_{\mathrm{b}} = 1$ s
The average duration of fault: $t_{\mathrm{f}} = 1$ s

Month	fault rate (n_{f})	exposure rate (n_{b})
Jan. - Mar.	$1.6 \cdot 10^{-3}$	1200
Apr. - Jun.	$2.8 \cdot 10^{-3}$	1000
Jul. - Sep.	$3 \cdot 10^{-4}$	1600
Oct. - Dec.	$8 \cdot 10^{-4}$	800

Table 6.2: fault rate and exposure rate over a year

These four cases must now be calculated separately from each other in order to guarantee the second condition of the POISSON distribution. What exactly changes in the calculation when it has to be split is explained here. Since the fault rates and the exposure rate are only related to one season, they have to be extended to a whole year in order to be able to calculate them with the equation 6.3, i.e. $n_{\mathrm{f}} \cdot 4$ and $n_{\mathrm{b}} \cdot 4$. The result $P_{\mathrm{coinc(n)}}$ must then be divided by 4 to relate it again to only one season.

$$\begin{aligned} P_{\mathrm{coinc1}} &= n_{\mathrm{f}} \cdot n_{\mathrm{b}} \cdot (t_{\mathrm{b}} + t_{\mathrm{f}}) \cdot \frac{T}{(365 \cdot 24 \cdot 60 \cdot 60)\frac{\mathrm{s}}{\mathrm{a}}} \\ &= 1.6 \cdot 10^{-3}\frac{1}{\mathrm{a}} \cdot 1200\frac{1}{\mathrm{a}} \cdot (1\mathrm{s} + 1\mathrm{s}) \cdot \frac{4 \cdot 1\mathrm{a}}{(365 \cdot 24 \cdot 60 \cdot 60)\frac{\mathrm{s}}{\mathrm{a}}} = \underline{\underline{0.487 \cdot 10^{-6}}} \end{aligned} \tag{6.4}$$

$$\begin{aligned} P_{\mathrm{coinc2}} &= n_{\mathrm{f}} \cdot n_{\mathrm{b}} \cdot (t_{\mathrm{b}} + t_{\mathrm{f}}) \cdot \frac{T}{(365 \cdot 24 \cdot 60 \cdot 60)\frac{\mathrm{s}}{\mathrm{a}}} \\ &= 2.8 \cdot 10^{-3}\frac{1}{\mathrm{a}} \cdot 1000\frac{1}{\mathrm{a}} \cdot (1\mathrm{s} + 1\mathrm{s}) \cdot \frac{4 \cdot 1\mathrm{a}}{(365 \cdot 24 \cdot 60 \cdot 60)\frac{\mathrm{s}}{\mathrm{a}}} = \underline{\underline{0.71 \cdot 10^{-6}}} \end{aligned} \tag{6.5}$$

$$
\begin{aligned}
P_{\text{coinc3}} &= n_\text{f} \cdot n_\text{b} \cdot (t_\text{b} + t_\text{f}) \cdot \frac{T}{(365 \cdot 24 \cdot 60 \cdot 60)\frac{\text{s}}{\text{a}}} \\
&= 3 \cdot 10^{-4}\frac{1}{\text{a}} \cdot 1600\frac{1}{\text{a}} \cdot (1\text{s} + 1\text{s}) \cdot \frac{4 \cdot 1\text{a}}{(365 \cdot 24 \cdot 60 \cdot 60)\frac{\text{s}}{\text{a}}} = \underline{\underline{0.121 \cdot 10^{-6}}}
\end{aligned} \tag{6.6}
$$

$$
\begin{aligned}
P_{\text{coinc4}} &= n_\text{f} \cdot n_\text{b} \cdot (t_\text{b} + t_\text{f}) \cdot \frac{T}{(365 \cdot 24 \cdot 60 \cdot 60)\frac{\text{s}}{\text{a}}} \\
&= 8 \cdot 10^{-4}\frac{1}{\text{a}} \cdot 800\frac{1}{\text{a}} \cdot (1\text{s} + 1\text{s}) \cdot \frac{4 \cdot 1\text{a}}{(365 \cdot 24 \cdot 60 \cdot 60)\frac{\text{s}}{\text{a}}} = \underline{\underline{0.162 \cdot 10^{-6}}}
\end{aligned} \tag{6.7}
$$

For the total probability the results of equation 6.4, 6.5, 6.6 and 6.7 need to be added up.

$$
\begin{aligned}
P_{\text{coinc}} &= P_{\text{coinc1}} + P_{\text{coinc2}} + P_{\text{coinc3}} + P_{\text{coinc4}} \\
&= 0.487 \cdot 10^{-6} + 0.71 \cdot 10^{-6} + 0.121 \cdot 10^{-6} + 0.162 \cdot 10^{-6} \\
&= \underline{\underline{1.473 \cdot 10^{-6}}}
\end{aligned} \tag{6.8}
$$

6.2.1 Calculation with coincidence location factor

The other way to calculate the coincidence probability, according to "EG-O 'Power System Earthing Guide- Part 1: Management principles", is to start from known scenarios where the event rate is already predicted and therefore it is easy to quickly calculate the probability using the coincidence location factor, in equation 6.9.

$$P_{\mathrm{coinc}} = CM \cdot n_{\mathrm{f}} \cdot T \tag{6.9}$$

variable	explanation
CM	Coincidence multiplier
n_{f}	Fault frequency per year (1/year)
T	Period under consideration (year)

Location scenario	n_b	t_b	Coincidence multiplier (10^{-4}) for fault duration (s)						
	1/Year	s	0.2	0.4	0.6	0.8	1	2	4
Backyard	416	4	0.554	0.588	0.607	0.633	0.660	0.791	1.06
Urban interface	100		0.133	0.140	0.146	0.152	0.159	0.190	0.254
Remote	10		0.0133	0.0140	0.0146	0.0152	0.0159	0.0190	0.0254
MEN	2000		2.66	2.79	2.92	3.04	3.17	3.81	5.07

Table 6.3: Coincidence location factor [8]

However, for such a table to work properly, a lot of data is needed to be able to include possible deviations and changes.

6.3 Risk limits to be met

This brings us back to the "tolerable risks". The aim is to keep the risk as low as possible without having to invest too much financial or human resources. We always try to be in the first band for a minimum risk-level, for this at least one of the two variables $P_{\text{fibrilation}}$ or $P_{\text{coincidence}}$ must be low enough.[21]

$$P_{\text{coinc-permissible}} = \frac{10^{-6}}{P_{\text{fibrillation}}} \tag{6.10}$$

$$P_{\text{coinc}} \leq P_{\text{coinc-permissible}}$$

With the equations 6.10 and 6.11 and with the probability of ventricular fibrillation known, it is possible to calculate the maximum permissible probability of coincidence and thus see in advance what target must be reached so that the probability of a fatality remains within the permissible range. If the risk is too high, we are either in the middle or lowest band. In the lowest band, there must be a revision of the safety concept, as safety is obviously not guaranteed. If we are in the middle band, we are in the so-called ALARP zone, where it is possible to get the risk back into the first band by carrying out risk reduction procedures.[3]

$$P_{\text{coinc-ALARP}} = \frac{10^{-4}}{P_{\text{fibrillation}}} \tag{6.11}$$

$$P_{\text{coinc}} \leq \frac{10^{-6}}{P_{\text{fibrillation}}} < P_{\text{coinc-ALARP}} \leq \frac{10^{-4}}{P_{\text{fibrillation}}}$$

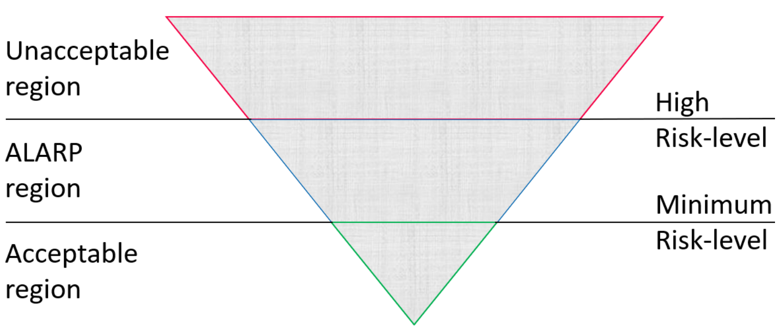


Figure 6.6: Risk-bands

For the coincidence calculation, it is reasonable to use the value of the coincidence probability as the target requirement for safety compliance. After calculation of the earth current and the possible contact configurations, only the contact configuration and finally the probability of chance can change the probability of a fatal accident.[8]

First of all, the probability of someone coming into contact with the fault must be derived. In combination with the maximum permissible probability of fatality (10^{-6} or 10^{-4}) and the probability of fibrillation, which is equivalent to the current, as shown in figure (here, figure from chapter 5), the probability of a fatal accident can be adjusted either by making the system remote or by adapting the safety concept to ensure safe operation of the system for bystanders.[8]

Of course, the inverted scenario can also be used, provided there is knowledge about coincidence probability. In this case, the relationship of the permitted fatal events can be used to infer the permitted ventricular fibrillation probability from the coincidence probability.

Negligible risk and remote locations

If the coincidence probability is less than the allowable societal limits the hazard is of an acceptable level fault independent of the fibrillation probability. This condition is met for some low fault frequency cases (for example, some transmission structures without shieldwires) or for 'remote locations' where people rarely make contact. In such instances the earthing system specifications are dictated by system reliability requirements (for example, insulation coordination and protection operation) or equipment damage requirements (for example, telecommunications plant, pipeline insulation's, railways signalling equipment). In some cases a standard design procedure may still be followed if the cost is low and the action expected.[8]

6.3.1 Risk reduction measures

Reduction of the dangerous voltage and duration

There are several ways to reduce the touch and step voltage or to increase the tripping speed of the safety devices, according to [3] page 72:

- modification of the current distribution
- changing the settings or type of the safety devices
- installing a equipotential bonding
- reduce the short-circuit current

Reduction of the contact frequency and duration

The value of how often and how long someone comes into contact with a live part cannot be given exactly. These values are approximations or rough averages over a month or year. These parameters are often determined by simple observation and counting, which can be used to estimate approximately how often the live part comes into contact with someone at a particular location. Due to this, inaccuracies or erroneous estimates occur. To counteract this, the coincidence reduction factor was introduced in "EG-O 'Power System Earthing Guide- Part 1: Management principles",[3][8]:

$$P_{\text{coinc-new}} = P_{\text{coinc}} \cdot CRF \tag{6.12}$$

The coincidence reduction methods are barriers and safety measures to reduce the likelihood of someone coming into contact with the potential point of failure. At the beginning of a calculation, unless otherwise stated, the variable CRF = 1. Below are a few of the most commonly and easily used reduction factors from [8] page 39.

Coincidence reduction method	CRF
install barrier fence	0.1
install insulation covering	0.4
restricted access, PPE and SWMS	0.5
install sign	0.8

Table 6.4: Coincidence Reduction Factor

Chapter 7

Case study and its adaptations

The theoretical findings, the various methods, their simplifications and adaptations are now explained for a basic example.

First, the conventional calculation of the permissible touch voltage is presented, which parameters influence this calculation and how these parameters are obtained. Some of them cannot be determined in advance, such as: the clothing, the contact configuration, the condition of the skin, etc.. However, there are worst case scenarios that can be found in the system and allow a targeted increase in safety measures in the facility.

The next step in this work is the probabilistic theory. Instead of worst case parameters of the shock circuit, the probability of occurrence is considered. It therefrom is possible to calculate the probability of a fatal event and compare it with the permissible boundaries. How these values can be modified for safety concepts and what possible extensions there may be is explained below.

7.1 Baseline case study

In this example the possible contact voltages and their risks for the staff and the public in a public swimming pool is calculated. Near this public swimming pool is an earth fault compensation coil. For an earth fault in the distribution network, the coil compensates the earth fault current with a maximum current of 400 A. Due to the proximity of the station with the earth fault compensation coil to the public swimming pool, a connection is made via PEN conductor. The prospective contact voltage in the bath is 80 V.

For this prospective contact voltage, is assumed to be fix with the following parameters are varied for risk evaluation:

- contact configuration - touch or step
- moisture - wet or dry
- soil resistivity
- contact resistivity - 1000 Ωm (Tills), 3000 Ωm (crushed rock) and 10 000 Ωm (Asphalt) [23]
- additional series impedances such as footwear and gloves
- touch configuration: hand - hand, right hand - left foot, left hand - both feet and both hand - both feet
- fault duration

In figur 7.1 the principle overview of the earth fault case and its compensation by means of the earth fault compensation coil in the star point of the transformer substation.

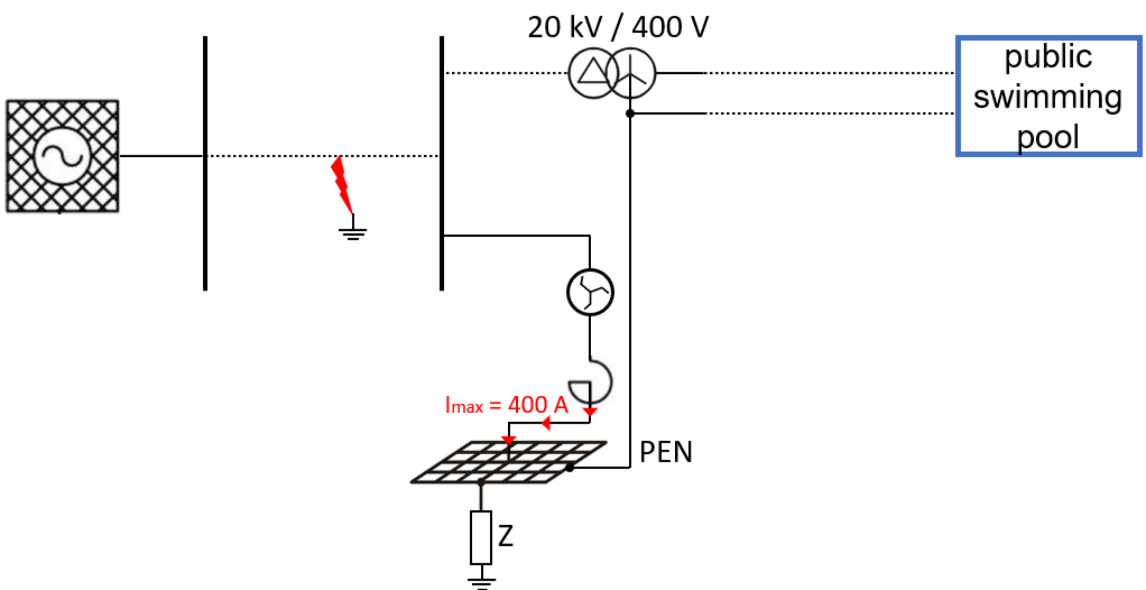
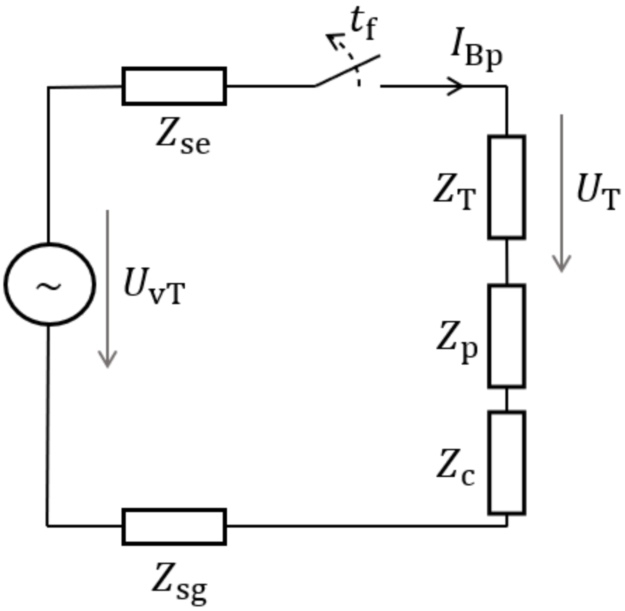
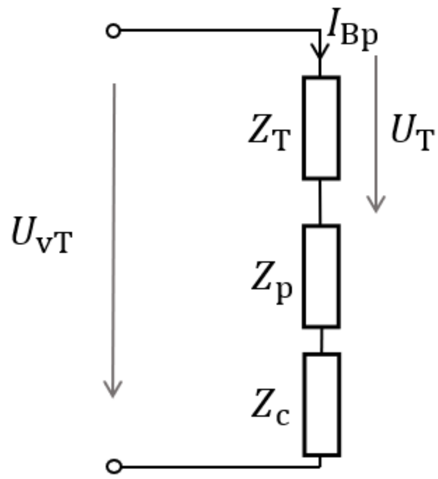


Figure 7.1: General system

The impedances Z_{se} and Z_{sg} are neglected. Which reduces the equivalent circuit as given in figure 7.2b and in the calculation. I_{Bp} describes the magnitude of the current that actually flows through the shock circuit. I_B is the current that can be used to determine the probability of fibrillation as a function of the fault duration t_f and the heart current factor HF.



(a) Shock circuit



(b) Simplified shock circuit

Figure 7.2: Shock circuit for a worst-case scenario [8]

The equation 2.1 therefor is simplified to:

$$\begin{aligned} U_T &= \frac{Z_T}{Z_{se} + Z_p + Z_c + Z_{sg} + Z_T} \cdot U_{vT} \\ &= \underline{\underline{\frac{Z_T}{Z_p + Z_c + Z_T} \cdot U_{vTp}}} \end{aligned} \tag{7.1}$$

The permissible prospective touch voltage U_{vTp} comes to:

$$\begin{aligned} U_{vT} &= U_T + I_{Bp} \cdot (Z_p + Z_c) \\ &= I_{Bp} \cdot \frac{1}{HF} \cdot (Z_T(U_T) \cdot BF + Z_p + Z_c) \end{aligned} \tag{7.2}$$

Adjustment for the protection and contact impedance according to [3][8]

This example evaluated for touch and step voltage and for direct contact with the surface or with a layer between the person and the surface.

For the step voltage with direct contact with the surface, the additional impedances of the soil Z_c and the shoes Z_p come into play. In this case, if one shoe got the impedance of Z_1 than:

$$Z_c = 6\ \mathrm{m}^{-1} \cdot \rho_E$$

$$Z_p = Z_1 \cdot 2 \tag{7.3}$$

In the case of touch voltage and with direct contact with the surface, the equation 2.3 is used and in this situation the calculation of the protective impedance is based on the equation:

$$Z_c = 1.5\ \mathrm{m}^{-1} \cdot \rho_E$$

$$Z_p = \frac{Z_1}{2} \tag{7.4}$$

If the person is standing on a surface that has a different resistivity than the earth below, the equation 2.5 must be taken into account. The values for the different impedances for different kinds of shoes can be found in [8] on page 68.

7.1.1 Influence of the parameters on the permitted contact voltage

For the calculation of the permitted prospective contact voltage that occurs in the event of a fault, only a few parameters can be changed preemptively to ensure a better chance of survival. Thus, the configuration of the contact with the fault as well as in many cases the cladding is left to the probability. However, the surface of the soil around a probable fault location can be modified to avoid dangerous contact voltages due to high contact impedance.

7.1.2 Contact impedance

At first, a closer look at the equations for the contact impedance to see how each variable affects it.

Soil resistivity ρ_E

If there is no layer between the person and the soil, the relationship between the soil resistivity and the resulting contact impedance is linear , as shown in (7.5).

$$\begin{aligned} Z_c &= 1.5\ \text{m}^{-1} \cdot \rho_E - \text{In case of a touch scenario} \\ Z_c &= 6\ \text{m}^{-1} \cdot \rho_E - \text{In case of a step scenario} \end{aligned} \tag{7.5}$$

Covering layer - specific resistivity ρ_1

If there is a covering material in the shock circuit, the resistivity of the material of the covering ρ_1 and its thickness h_s, can be considered with the factor F_s according to the equations 7.6.

$$F_s = 1 - \frac{0.09\ \text{m} \cdot \left(1 - \frac{\rho_E}{\rho_1}\right)}{2 \cdot h_s + 0.09\ \text{m}} \tag{7.6}$$

Resulting in the equation below for the touch and step voltage:

$$\begin{aligned} Z_c &= 1.5\ \text{m}^{-1} \cdot F_s \cdot \rho_1 - \text{In case of a touch scenario} \\ Z_c &= 6\ \text{m}^{-1} \cdot F_s \cdot \rho_1 - \text{In case of a step scenario} \end{aligned} \tag{7.7}$$

For illustration of the effects of the parameter ρ_1, the figure 7.3 was created. With a body current of 70 mA and a resistivity of $\rho_1 = 3000\ \Omega$m (crushed rock), the permissible prospective contact voltage is calculated with variable ρ_E and a constant $h_s = 2$ cm, and compared with no covering material of $\rho_1 = \rho_E$.

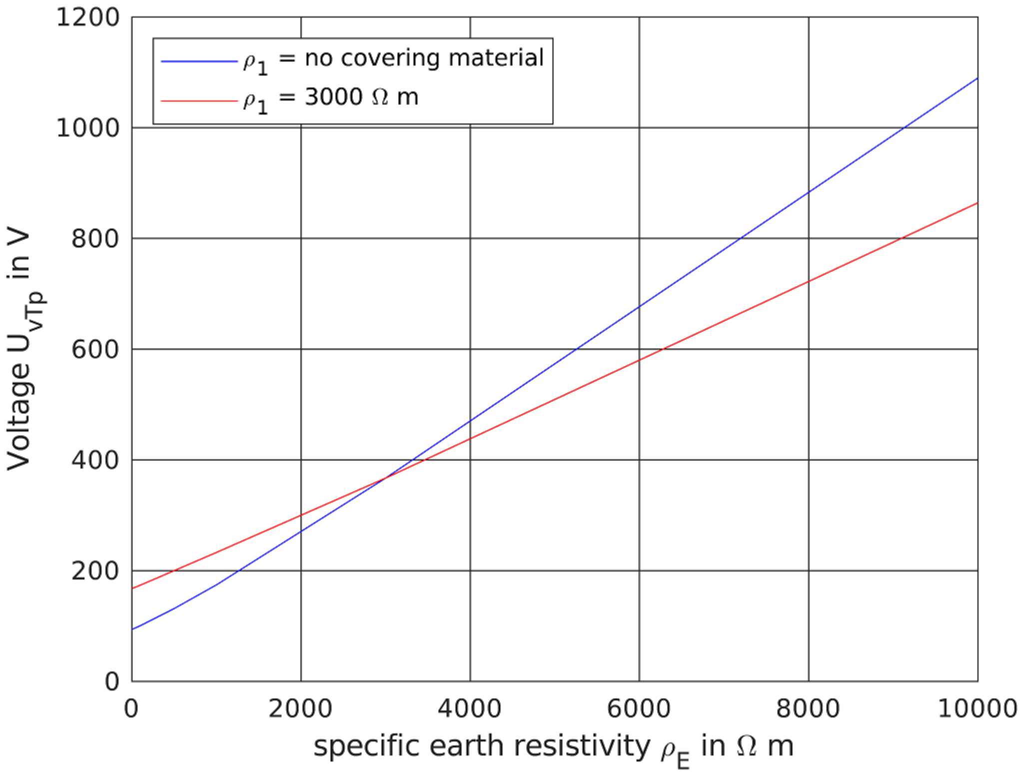


Figure 7.3: U_{vTp} for a soil ρ_E and a conducting material ρ_1 with a thickness of h_s

In figure 7.3, to the left of the intersection, it is easy to see that the bigger the difference between ρ_1 and ρ_E, the better the safety. To the right of the intersection point, the contact material is more conductive than the soil, so the voltage of the blue line is higher from this point on.

If parameter h_s is changed for the same body current, with constant $\rho_E = 50\ \Omega$m and variable ρ_1, we obtain the different lines in figure 7.4. Here the influence of thickness h_s for different materials ρ_1 can be seen.

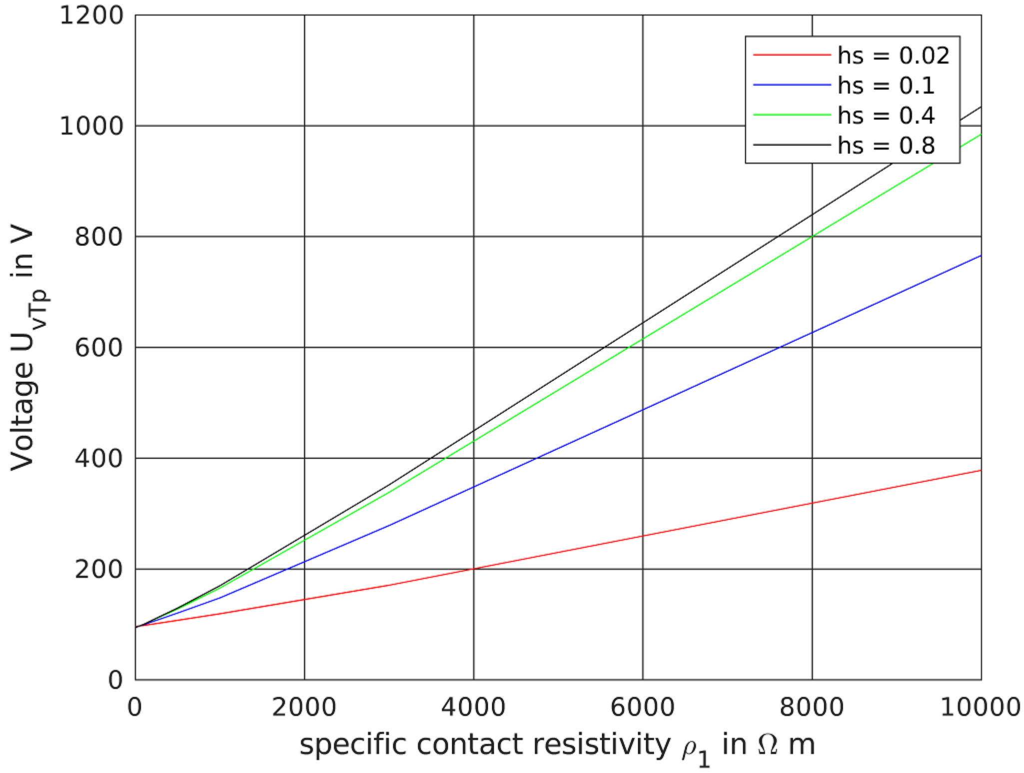


Figure 7.4: U_{vTp} for a variable ρ_1, a soil $\rho_E = 50\ \Omega$m and a variable thickness of the covering layer h_s

7.1.3 First case: Calculation of the body current with additional series impedances

For an example the relationship between the touch voltage and the prospective touch voltage is shown, taking into account possible additional resistances.

- prospective touch voltage $U_{\mathrm{vT}} = 80$ V
- contact configuration: left hand - both feet
- contact condition: dry, big area
- soil resistivity $\rho_{\mathrm{E}} = 50\ \Omega\mathrm{m}$
- covering material resistivity $\rho_1 = 1000\ \Omega\mathrm{m}$, with a thickness $h_{\mathrm{s}} = 2$ cm
- additional series impedances: typical public footwear according to [8]
- fault duration of $t_{\mathrm{f}} = 2$ s

Calculation of the impedances in the shock circuit

Contact Impedance:

$$\begin{aligned} F_{\mathrm{s}} =& 1 - \frac{0.09\ \mathrm{m} \cdot \left(1 - \frac{\rho_{\mathrm{E}}}{\rho_1}\right)}{2 \cdot h_{\mathrm{s}} + 0.09\ \mathrm{m}} \\ =& 1 - \frac{0.09\ \mathrm{m} \cdot \left(1 - \frac{50\ \Omega\mathrm{m}}{1000\ \Omega\mathrm{m}}\right)}{2 \cdot 0.02\ \mathrm{m} + 0.09\ \mathrm{m}} \\ =& \underline{\underline{0.34}} \end{aligned} \tag{7.8}$$

$$\begin{aligned} Z_{\mathrm{c}} =& 1.5\ \mathrm{m}^{-1} \cdot F_{\mathrm{s}} \cdot \rho_1 \\ =& 1.5\ \mathrm{m}^{-1} \cdot 0.34 \cdot 1000\ \Omega\mathrm{m} \\ =& \underline{\underline{510\ \Omega}} \end{aligned} \tag{7.9}$$

Protective Impedance:
According to statistics of the "EG-O Power System Earthing Guide- Part 1: Management principles: Version 1", 16 % of the population use shoes made of dry used black rubber, in the worst-case scenario with an Impedance for one shoe $Z_1 = 1000\ \Omega$.[8]

$$\begin{aligned} Z_{\mathrm{p}} =& \frac{1000\ \Omega}{2} \\ =& 500\ \Omega \end{aligned} \tag{7.10}$$

With these values, the touch voltage can now be calculated by means of interpolation.

- additional resistance $Z_c + Z_p = 1010\ \Omega$
- $Z_T(80\ V) = 1945\ \Omega$
- BF = 0.75

$$U_T = \frac{80\ V}{1945\ \Omega \cdot 0.75 + 1010\ \Omega} \cdot 1945\ \Omega \cdot 0.75 = 47.3\ V$$

$$Z_T(47.3\ V) = 2581\ \Omega$$

$$= \frac{80\ V}{2581\ \Omega \cdot 0.75 + 1010\ \Omega} \cdot 2581\ \Omega \cdot 0.75 = 52.6\ V$$

$$Z_T(52.6\ V) = 2448\ \Omega$$

$$= \frac{80\ V}{2448\ \Omega \cdot 0.75 + 1010\ \Omega} \cdot 2448\ \Omega \cdot 0.75 = 51.6\ V \quad (7.11)$$

$$Z_T(51.6\ V) = 2468\ \Omega$$

$$= \frac{80\ V}{2468\ \Omega \cdot 0.75 + 1010\ \Omega} \cdot 2468\ \Omega \cdot 0.75 = 51.75\ V$$

$$Z_T(51.75\ V) = 2465\ \Omega$$

$$= \frac{80\ V}{2465\ \Omega \cdot 0.75 + 1010\ \Omega} \cdot 2465\ \Omega \cdot 0.75 = \underline{\underline{51.7\ V}}$$

Thus, the current through the shock circuit I_{Bp} can now be calculated:

$$\begin{aligned} I_{Bp} =& \frac{U_T}{Z_T} \\ =& \underline{\underline{27.96\ mA}} \end{aligned} \quad (7.12)$$

The Heart current factor (HF) for this configuration is 1. To check whether this is a dangerous current for humans, the current I_{Bp} must be multiplied by the factor HF.

$$I_B = I_{Bp} \cdot HF \quad (7.13)$$

Now this current I_B can be compared with existing boundaries, for example with the conservative figure 3.3. 27 mA are to the left of "c1", therefore there is no risk of fibrillation over the whole fault duration t_f .

7.1.4 Second case: Comparison of permissible prospective touch voltages for different body currents with equal probability of fibrillation.

In order to show the influence of different body configurations with which people can come into contact with the fault location. As well as the difference between the characteristic curves from figure 5.4. For this configuration, the maximum permissible touch voltage is calculated as an example according to the safety characteristic for the current and the values for the body impedances of IEC60479-1 and the safety characteristic of the current from the paper of "Kieback 2009" in chapter 5.[9][15]

- prospective touch voltage - $U_{\mathrm{vT}} = 80$ V
- contact configuration: left hand - both feet
- contact condition: dry, big area
- soil resistivity $\rho_{\mathrm{E}} = 100\ \Omega\mathrm{m}$
- covering material resistivity $\rho_1 = 0\ \Omega\mathrm{m}$
- additional series impedances: $Z_{\mathrm{c}} + Z_{\mathrm{p}} = 0\ \Omega$
- fault duration of $t_{\mathrm{f}} = 2$ s

Z_{p}, for the case of barefoot is omitted. For the contact resistance without additional surface resistance, the variable Z_{c} is described as follows:

$$\begin{aligned} Z_{\mathrm{c}} &= 1.5\ \mathrm{m}^{-1} \cdot 100\ \Omega\mathrm{m} \\ &= 150\ \Omega \end{aligned} \tag{7.14}$$

Both iteration start with the prospective touch voltage of 80 V, with an fault duration $t_{\mathrm{f}} = 2$ seconds. In the first issue, IEC 60479-1 is used for the two following values.[9]

- $Z_{\mathrm{T}}(80\ \mathrm{V}) = 1945\ \Omega$ for 50 % of the population
- $I_{\mathrm{B}}(2\ \mathrm{s}) = 54.35$ mA for a probability of ventricular fibrillation of 5 %

In the second issue, we use the probability surface distribution figure 5.3 for the following current values and the IEC 60479-1 for the values of the body impedance.[9][15]

- $Z_{\mathrm{T}}(80\ \mathrm{V}) = 1945\ \Omega$ for 50 % of the population
- $I_{\mathrm{B}}(2\ \mathrm{s}) = 123.4$ mA for a probability of ventricular fibrillation of 5 %

The contact configuration is left hand to both feet, which means the total body impedance Z_{T} and the body current I_{B} have to be converted.

- HF = 1
- BF = 0.75

$$U_{\mathrm{vTp}} = I_{\mathrm{B}}(t_{\mathrm{f}}) \cdot \frac{1}{HF} \cdot (Z_{\mathrm{T}}(U_{\mathrm{Tp}}) \cdot BF + Z_{\mathrm{c}}) \tag{7.15}$$

To determine the values of the impedances for the calculated voltages, Table 1 of IEC60479 was interpolated in Matlab®.

<u>The first issue:</u>

$$\begin{aligned}
U_{\mathrm{vTp}} &= 54.35\ \mathrm{mA} \cdot \frac{1}{1} \cdot (1945\ \Omega \cdot 0.75 + 150\ \Omega) = 87.4\ \mathrm{V} \\
Z_{\mathrm{T}}(87.4\ \mathrm{V}) &= 1863\ \Omega \\
&= 54.35\ \mathrm{mA} \cdot \frac{1}{1} \cdot (1863\ \Omega \cdot 0.75 + 150\ \Omega) = 84.1\ \mathrm{V} \\
Z_{\mathrm{T}}(84.1\ \mathrm{V}) &= 1899\ \Omega \\
&= 54.35\ \mathrm{mA} \cdot \frac{1}{1} \cdot (1899\ \Omega \cdot 0.75 + 150\ \Omega) = 85.5\ \mathrm{V} \\
Z_{\mathrm{T}}(85.5\ \mathrm{V}) &= 1884\ \Omega \\
&= 54.35\ \mathrm{mA} \cdot \frac{1}{1} \cdot (1884\ \Omega \cdot 0.75 + 150\ \Omega) = 84.9\ \mathrm{V} \\
Z_{\mathrm{T}}(84.9\ \mathrm{V}) &= 1891\ \Omega \\
&= 54.35\ \mathrm{mA} \cdot \frac{1}{1} \cdot (1891\ \Omega \cdot 0.75 + 150\ \Omega) = \underline{\underline{85.2\ \mathrm{V}}}
\end{aligned} \tag{7.16}$$

<u>The second issue:</u>

$$\begin{aligned}
U_{\mathrm{vTp}} &= 123.4\ \mathrm{mA} \cdot \frac{1}{1} \cdot (1945\ \Omega \cdot 0.75 + 150\ \Omega) = 198.5\ \mathrm{V} \\
&= \ldots\ldots \\
&= 123.4\ \mathrm{mA} \cdot \frac{1}{1} \cdot (1711\ \Omega \cdot 0.75 + 150\ \Omega) = \underline{\underline{149\ \mathrm{V}}}
\end{aligned} \tag{7.17}$$

In figure 7.5 and figure 7.6 , the IEC60479-1 [9] and "Stromunfälle, Herzkammerflimmern und Letalität by Kieback 2009" mean for the resulting permissible prospective touch voltage are given.[15]

The same four contact configuration cases which were already used in section 4.1.1 are to be presented as a comparison over the entire fault duration with the values for the body current from chapter 5.

Conditions:

- contact configuration : table 4.1
- serial impedance: $Z_c = 150\ \Omega$
- body impedance value is not exceeded by 50 % of the population
- probability of ventricular fibrillation shall be about 5 %.

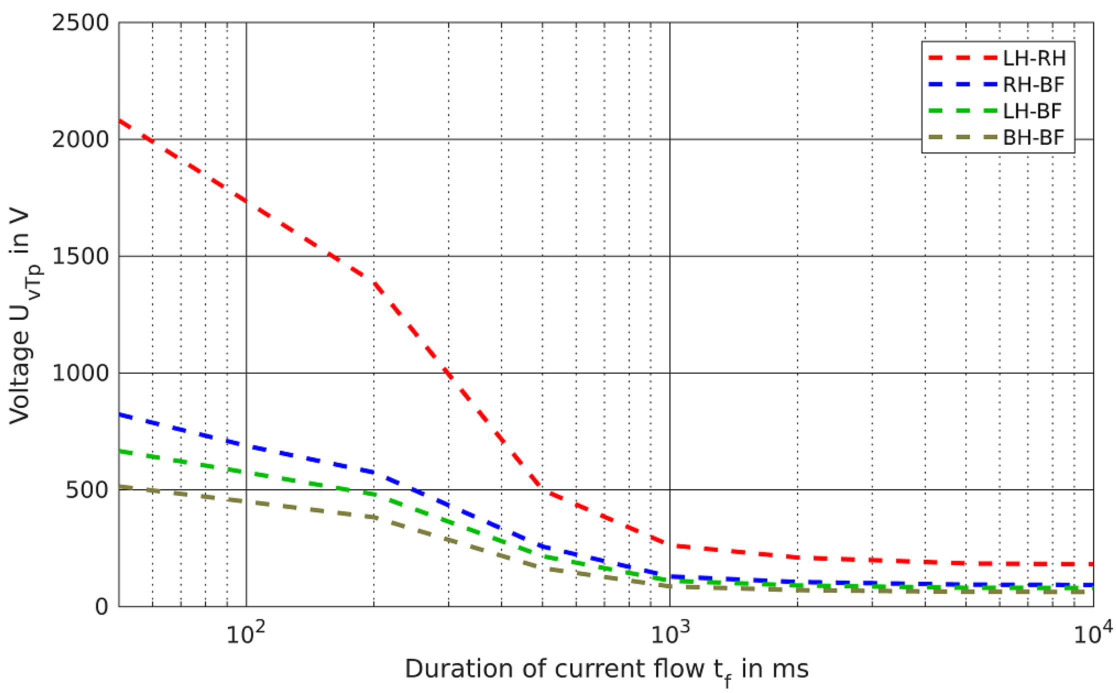


Figure 7.5: U_{vTp} for I_{B} ("c-2"-5% probability) and Z_{T} (50 % of the population) - IEC 60479-1

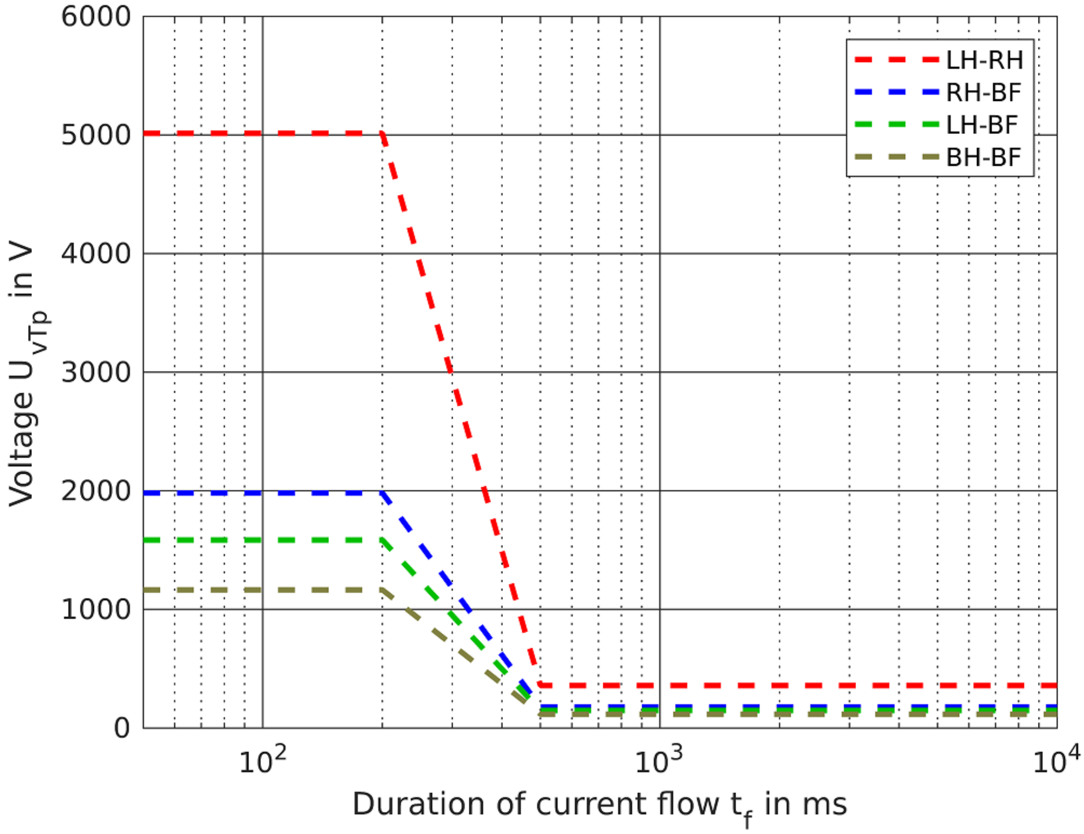


Figure 7.6: U_{vTp} for I_{B} (5% probability) and Z_{T} (50 % of the population) - Kieback 2009

This is to illustrate that according to: "Kieback 2009"[15], the probability of ventricular fibrillation at the same value of the prospective touch voltage is significantly lower than with the conservative curves used according to IEC60479-1.[9]
This means that even if the values for the total body impedance of 5 % of the population are used to create the figure 7.6, so that the impedance is about half, one would still be in the safe range with the new characteristic curve according to the international standard 60479-1.[9]

7.1.5 Thrid Case: Calculation of the probability of fatality

In the second method, we go directly to the probability calculation in order to be able to make statements about whether the probability of occurrence of a fatal accident is so high that it requires an improvement of the safety concept.
For this example, a public swimming pool with 8000 visitors a year is considered, 25% of the visitors come into contact with a potentially live part for 3 seconds on the way between the entrance gate and the changing rooms.
Note: The path from the changing room to the exit gate is a different one.

The primary protection clearance time for overhead lines in a voltage range of 11-33 kV (line to line) is according to [8] on average 1 second and for a compensated network around 3600 seconds. This results in a prospective voltage of 80 V.
There are between 10 - 40 faults per 100 km of OHL per year. Therefrom a 10 km section, there are 1 - 4 faults per year.
For this calculation 1 is chosen because the values were recorded for Australia, i.e. for stronger storms that occur at a higher rate than in Austria. These data can be found in the work "EG-O 'Power System Earthing Guide- Part 1: Management principles".[8]

- n_b = 2 000 contacts/year
- n_f = 1 fault/10km/year
- t_b = 3 s
- t_f = 2 s or 0.3 s / 3600 s (compensated network)

Design for the calculation process

As already described in chapter 6, the officially permissible tolerable limits be complied with, i.e. in the best case the probability of a fatal incident should not exceed the value 10^{-6}.
Here, the starting point of the calculation is to begin with the probability of coincidence and in the following to infer the probability of fibrillation via the permissible limits. At the end we will conclude if the prospective permissible touch voltage is in the safe boundary's.

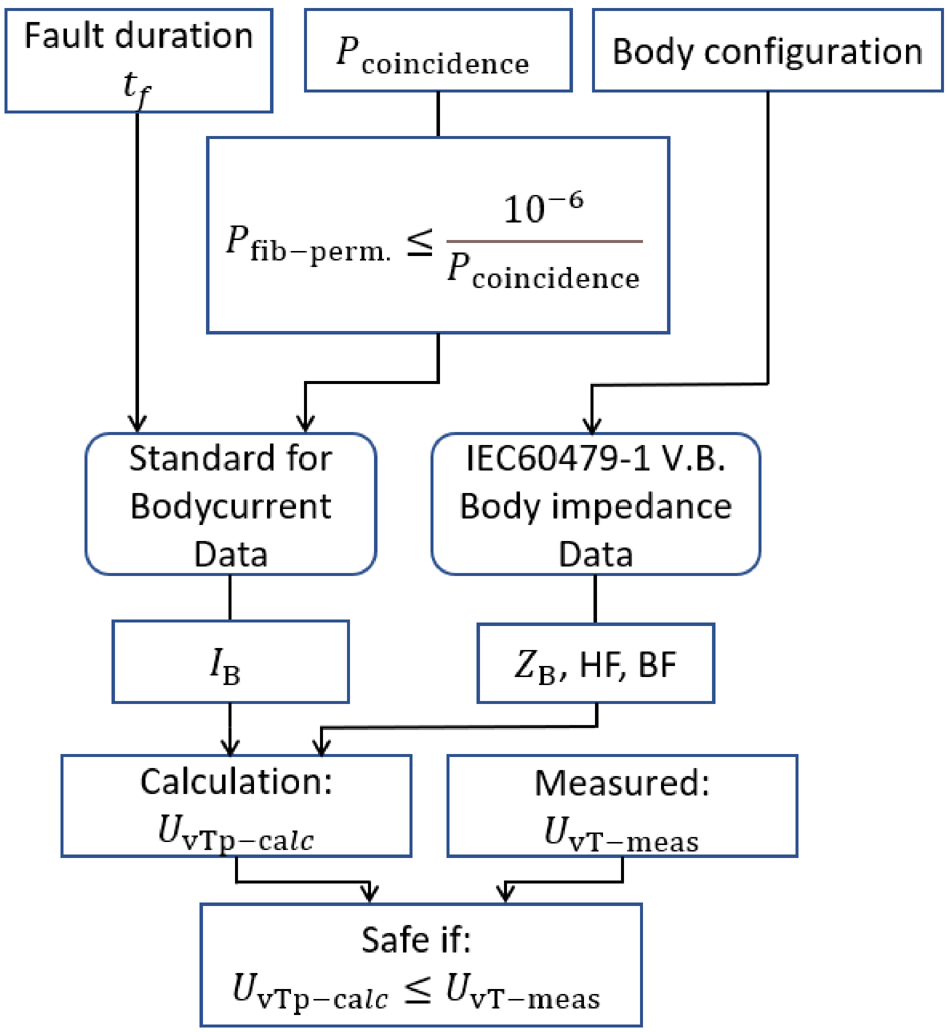


Figure 7.7: Comparing the permissible prospective touch voltages

Probability of coincidence

$$\begin{aligned} P_{\text{coincidence}} &= \frac{n_\text{f} \cdot n_\text{b} \cdot (t_\text{b} + t_\text{f}) \cdot T}{(365 \cdot 24 \cdot 60 \cdot 60)\frac{\text{s}}{\text{a}}} \\ &= \frac{1\frac{1}{\text{a}} \cdot 2000\frac{1}{\text{a}} \cdot (3\ \text{s} + 3600\ \text{s}) \cdot 1\text{a}}{(365 \cdot 24 \cdot 60 \cdot 60)\frac{\text{s}}{\text{a}}} \\ &= 2.28 \cdot 10^{-1} \end{aligned} \tag{7.18}$$

Therefrom the maximum $P_{\text{fib-permissible}}$ can be calculated:

$$\begin{aligned} P_{\text{fib-permissible}} &\leq \frac{10^{-6}}{P_{\text{coincidence}}} \\ &\leq \frac{10^{-6}}{4.5 \cdot 10^{-2}} \\ &\leq 4.37 \cdot 10^{-6} \end{aligned} \tag{7.19}$$

A Matlab® script was used to convert the probability of fibrillation into values for the body current for the different fault duration times.

Self generated curve from figure 5.2 and 5.3:

For $t_\text{f} > 300$ ms and $P_{\text{fib-permissible}} = 4.37 \cdot 10^{-6} \;\Rightarrow\; I_\text{B} \leq 49.35$ mA

For $t_\text{f} \leq 300$ ms and $P_{\text{fib-permissible}} = 4.8 \cdot 10^{-3} \;\Rightarrow\; I_\text{B} \leq 878.3$ mA

Calculation of the prospective touch voltage

To start the calculation of the prospective voltage, the body configuration of the person touching the fault location and all additional resistances in the shock circuit according to figure 7.2 must be determined.

For $t_f = 3600$ s

- iteration start voltage = 25 V
- $I_B = 49.35$ mA
- additional resistance $Z_c + Z_p = 0$
- HF = 1
- BF = 0.75

$$\begin{aligned} U_{vTp} &= I_B(t_f) \cdot \frac{1}{HF} \cdot (Z_T(U_{Tp}) \cdot BF + Z_c + Z_p) \\ &= 49.35 \text{ mA} \cdot \frac{1}{1} \cdot (3250\ \Omega \cdot 0.75) \\ &= .... \\ &= \underline{\underline{74.3 \text{ V}}} \end{aligned} \tag{7.20}$$

additional $Z_c + Z_p = 1510\ \Omega$

$$\begin{aligned} &= 49.35 \text{ mA} \cdot \frac{1}{1} \cdot (3250\ \Omega \cdot 0.75 + 1510\ \Omega) \\ &= .... \\ &= \underline{\underline{130.6 \text{ V}}} \end{aligned}$$

For the additional resistance, a soil resistivity of 50 Ωm, a contact resistivity of 1000 Ωm (tiles) and conventional shoe soles made of dry used black rubber with additional conservation, 2000 Ω, are assumed.[8]
The result of the calculation without additional impedances shows that the permissible prospective voltage must not exceed 74.3 V in this scenario. This boundary almost doubles with the additional impedances.

The specification states that in this example there is a prospective touch voltage of 80 V. This means that risk reduction methods would have to be applied. Although the EN 50522 [13] indicates a max U_{vTp} for $t_f > 10$ s of 80 V, which means $U_{vTp} = 74.3$ V would be a safe value.

For $t_f = 300$ ms

- iteration start voltage = 25 V
- $I_B = 878.3$ mA
- additional resistance $Z_c + Z_p = 0$
- HF = 1
- BF = 0.75

$$\begin{aligned} U_{vTp} &= I_B(t_f) \cdot \frac{1}{HF} \cdot (Z_T(U_{Tp}) \cdot BF + Z_c + Z_p) \\ &= 878.3 \text{ mA} \cdot \frac{1}{1} \cdot (3250\ \Omega \cdot 0.75) \\ &= .... \\ &= \underline{\underline{548 \text{ V}}} \end{aligned} \tag{7.21}$$

additional $Z_c + Z_p = 1510\ \Omega$

$$\begin{aligned} &= 878.3 \text{ mA} \cdot \frac{1}{1} \cdot (3250\ \Omega \cdot 0.75 + 1510\ \Omega) \\ &= .... \\ &= \underline{\underline{1836 \text{ V}}} \end{aligned}$$

If the fault can be switched off within the first 300 ms, the boundary to be respected is so high that there are no problems in terms of danger to people.

Risk reduction for $t_\mathrm{f} = 3600$ s

Since the previous result is only 5.7 V below the prospective voltage which is applied, it is possible to leave the danger zone with the coincidence reduction methods (CRF) in order to get within the permitted range for safety. For this purpose, a barrier fence at the fault location is created here according to table 6.4.

- $P_\mathrm{coincidence} = 2.28 \cdot 10^{-1}$
- CRF $= 0.1$

$$\begin{aligned} P_\text{coinc-new} &= P_\text{coincidence} \cdot CRF \\ &= 2.28 \cdot 10^{-1} \cdot 0.1 \\ &= \underline{\underline{2.28 \cdot 10^{-2}}} \end{aligned} \tag{7.22}$$

$$\begin{aligned} P_\text{fib-permissible} &\leq \frac{10^{-6}}{P_\text{coinc-new}} \\ &\leq \frac{10^{-6}}{2.28 \cdot 10^{-2}} \\ &\leq \underline{\underline{4.36 \cdot 10^{-5}}} \end{aligned} \tag{7.23}$$

- iteration start voltage $= 25$ V
- $I_\mathrm{B} \leq 54.95$ mA
- additional resistance $Z_\mathrm{c} + Z_\mathrm{p} = 0$
- HF $= 1$
- BF $= 0.75$

$$\begin{aligned} U_\mathrm{vTp} &= I_\mathrm{B}(t_\mathrm{f}) \cdot \frac{1}{HF} \cdot (Z_\mathrm{T}(U_\mathrm{Tp}) \cdot BF + Z_\mathrm{c} + Z_\mathrm{p}) \\ &= 54.95 \text{ mA} \cdot \frac{1}{1} \cdot (3250\ \Omega \cdot 0.75) \\ &= .... \\ &= \underline{\underline{80 \text{ V}}} \end{aligned} \tag{7.24}$$

With the value of 80 V, the safety of the system for persons and workers is exactly at the boundary of the permitted range. This could be further adapted with different variations of obstacles that make it more difficult to touch the fault location or the location is better signposted.

7.1.6 Fourth Case: Different probabilities of the contact cases

For this purpose, the probability of coincidence of case three was used as a starting point, so that the permitted prospective voltage can be calculated for the four contact configurations from case two, table 4.1. For these four scenarios, the statistical evaluation of 3640 incidents of the Cologne Institute is now to be used to determine the frequency of occurrence of the different contact configurations, table 5.1[15]. This probability of the specific configuration is added in the following.

- $P_{\text{coincidence}} = 2.28 \cdot 10^{-1}$
- $P_{\text{fibrillation}} = 4.37 \cdot 10^{-6}$
- for $t_{\text{f}} = 3600$ s
- $I_{\text{B}} = 49.35$ mA
- additional resistance = 0
- iteration start voltage = 25 V

hand - hand

$$\begin{aligned} U_{\text{vTp}} &= 49.35 \text{ mA} \cdot \frac{1}{0.4} \cdot (3250\ \Omega \cdot 1) \\ &= .... \\ &= 166 \text{ V} \end{aligned} \tag{7.25}$$

left hand - left foot

$$\begin{aligned} U_{\text{vTp}} &= 49.35 \text{ mA} \cdot \frac{1}{1} \cdot (3250\ \Omega \cdot 1) \\ &= .... \\ &= 90 \text{ V} \end{aligned} \tag{7.26}$$

left hand - both feet

$$\begin{aligned} U_{\text{vTp}} &= 49.35 \text{ mA} \cdot \frac{1}{1} \cdot (3250\ \Omega \cdot 0.75) \\ &= .... \\ &= 74 \text{ V} \end{aligned} \tag{7.27}$$

both hand - both feet

$$\begin{aligned} U_{\mathrm{vTp}} &= 49.35\ \mathrm{mA} \cdot \frac{1}{1} \cdot (3250\ \Omega \cdot 0.5) \\ &= .... \\ &= 58\ \mathrm{V} \end{aligned} \tag{7.28}$$

Based on the LH-BF and BH-BF cases, which account according to table 5.1 for 400 of the 3640 incidents, there is a probability of 10.97 % that the system does not meet the permissible safety conditions. Therefore, I would like to introduce a third variable into the probability calculation for these cases using the statistics, table 5.1. The probability that a particular contact configuration will occur, $P_{\mathrm{configuration}}$.[15]

$$P_{\mathrm{fatality}} = P_{\mathrm{fibrillation}} \cdot P_{\mathrm{coincidence}} \cdot P_{\mathrm{configuration}} \leq 10^{-6} \tag{7.29}$$

The third case (left hand - both feet) and the fourth (case both hands - both feet) are to be recalculated.

left hand - both feet

This contact configuration occurred according to table 5.1 in 294 of the 3640 incidents, that is, in 8.07 % of the cases. For $P_{\mathrm{configuration}} = 0.0807$, the permissible probability of fibrillation $P_{\text{fib-permissible}}$ comes to:

$$\begin{aligned} P_{\text{fib-permissible}} &\leq \frac{10^{-6}}{P_{\mathrm{coincidence}} \cdot P_{\mathrm{configuration}}} \\ &\leq \frac{10^{-6}}{2.28 \cdot 10^{-1} \cdot 0.0807} \\ &\leq \underline{\underline{5.4 \cdot 10^{-5}}} \end{aligned} \tag{7.30}$$

therefrom with the body current $I_{\mathrm{B}} \leq 55.52$ mA from figure 5.3 for $t_{\mathrm{f}} > 300$ ms and the impedance from the IEC60479-1[9] it comes to:

$$U_{\mathrm{vTp}} = \underline{\underline{81\ \mathrm{V}}} \tag{7.31}$$

So it can be said by taking into account the probability of configuration $P_{\mathrm{configuration}}$ this touch case with the prospective touch voltage of 81 V is in the permissible range of safety.

both hand - both feet

This contact configuration occurred according to table 5.1 in 106 of the 3640 incidents, that is, in 2.9 % of the cases. For $P_{\text{configuration}} = 0.029$, the permissible probability of fibrillation $P_{\text{fib-permissible}}$ comes to:

$$
\begin{aligned}
P_{\text{fib-permissible}} &\leq \frac{10^{-6}}{P_{\text{coincidence}} \cdot P_{\text{configuration}}} \\
&\leq \frac{10^{-6}}{2.28 \cdot 10^{-1} \cdot 0.029} \\
&\leq \underline{\underline{1.5 \cdot 10^{-4}}}
\end{aligned}
\tag{7.32}
$$

the body current $I_{\text{B}} \leq 58.2$ mA from figure 5.3 for $t_{\text{f}} > 300$ ms and the impedance from the IEC60479-1[9] it comes to::

$$
U_{\text{vTp}} = \underline{\underline{64 \text{ V}}} \tag{7.33}
$$

The fourth and last configuration both hands - both feet shows that at the permissible prospective voltage of 80 V safety is not given, but again additional risk reduction factors are required to get out of the ALARP boundaries.

Chapter 8

Discussion

When generating the IEC60479-1 curve in figure 5.2 and figure 5.3, it was recognized during the calculation of the probit straight line equation that the values for "c1probit" for 1 % probability do not lie on the straight line. Since it doesn't follow the normal distribution, the variable "c1" isn't the 1 % curve. It is assumed that certainties were taken into account when creating the "c1" curve. This is the reason that when converting the curve "c1" as described in chapter 5, it does not coincide with figure 5.2 and figure 5.3.

The four cases discussed in this thesis all assume the same base model, figure 7.1, with a measured prospective touch voltage $U_{\mathrm{vT}} = 80$ V. In the first two cases, the worst case calculation was performed. Table 8.1 and 8.2 show the parameters and results for this two cases.
In the first case the body path current I_{Bp} is calculated, without the influence of one of the characteristic curves, for the body configuration left hand to both feet. This makes it the second most dangerous among the four configurations used in this work, according to figure 4.2. Nevertheless, I_{B} ($I_{\mathrm{Bp}} \cdot \mathrm{HF}$) does not reach the threshold "c1" for fault duration t_{f} (figure 5.4). The same calculation with the additional impedance $Z_{\mathrm{c}} = 150\ \Omega$ ($\rho_{\mathrm{E}} = 100\ \Omega\mathrm{m}$) and without Z_{p} results in $I_{\mathrm{B}} = 47.5$ mA. This body current is to the left of the threshold "c2" (figure 5.4). Thus, according to deterministic calculation, this configuration is considered safe.

In the second case, assuming that the person is standing on the floor unclothed at the time of contact, all four body configurations were considered. As shown in the results of table 8.2, the only situation with higher risk occurs with both hand to both feet, according to IEC60479-1 [9]. Comparison of figure 7.5 with figure 7.6 shows that the probability of fibrillation is lower in figure 7.6 than in figure 7.5 for the same permissible prospective touch voltage U_{vTp}. Assuming values of 5 % of the population for the calculation of the permissible prospective touch voltages U_{vTp} according to Kieback 2009 [15] for the total body impedance $Z_T(5\%)$, the permissible voltages would still be higher than in figure 7.5.

In the third case, as in case one, the body configuration left hand to both feet was used for the calculation. In table 8.3 it is shown that the permissible probability of fibrillation $P_{\text{fib-permissible}}$ is very small. This is due to the fact that the coincidence probability $P_{\text{coincidence}} = 2.28 \cdot 10^{-1}$ is very high, as a result of the long

fault duration $t_f = 3600$ s. Therefore, the calculation of the permissible prospective touch voltage 1.1 (table 8.3) leads to a value with higher risk, smaller than 80 V, which must be avoided. However, according to EN 50522, a prospective touch voltage $U_{vT} \leq 80$ V for $t_f \geq 10$ s would be safe. Using the IEC60479-1 [9] for this calculation, a body current of $I_B = 17.49$ mA is obtained, according to figure 5.3. Calculating the permissible prospective touch voltages U_{vTp} with this current (17.49 mA), all body configurations would be below 80 V, except for the scenario left hand to right hand. That is unsafe according to probability theory but safe according to EN 50522 [13]. To increase the calculated permissible prospective touch voltage to a safe level, the reduction factors CRF are included.
To compare the probabilistic calculation of case three with the deterministic calculation of case two, $t_f = 2$ s was chosen for the body configuration left hand to both feet. This results in the permissible prospective touch voltage $U_{vTp} = 51.96$ V, according to table 8.3, and shows that for this scenario safety is not guaranteed. On the other hand, the result of table 8.2 shows that safety is guaranteed for the worst case calculation, for the same specifications, with a permissible prospective touch voltage $U_{vTp} = 85.2$ V. Compared to the probability calculation, important parameters, like the probability of coincidence, are not included in the deterministic calculation. This results in a higher danger probability that can be overlooked in the worst case calculation.

In case four the parameter of case three were used. Here the problematic cases left hand to both feet and both hand to both feet for $t_f > 300$ ms are used, to improve the permissible prospective touch voltage in the safe range by a possible specification (table 8.4). In table 5.1 it is evident that the most dangerous cases (BH-BF, LH-BF) are also the rarest. With the introduction of the parameter $P_{\text{configuration}}$, the permissible prospective touch voltage, which was already calculated in case three (U_{vTp}(LH-BF) = 74V), is now in the safe range (U_{vTp}(LH-BF) = 81V) without using reduction factors.

Parameters	Details	Values	Results
prospective touch voltage	U_{vT}	80 V	
soil resistivity	ρ_E	50 Ωm	
contact resistivity	ρ_1	1000 Ωm	
additional series impedances	Z_1	1000 Ωm	
fault duration	t_f	2 s	
contact configuration	LH-BF	BF=0.75, HF=1	
contact condition	dry, big area		
contact impedance	Z_c		510 Ω
protective impedance	Z_p		500 Ω
touch voltage	U_T		51.7 V
total body impedance	Z_T	2465 Ω · 0.75	1848 Ω
body current	I_{Bp}		27.96 mA
fibrillation current	I_B	27.96 mA · 1	27.96 mA

Table 8.1: Details and results of the first case

Parameters	Details	Values	Results
prospective touch voltage	U_{vT}	80 V	
soil resistivity	ρ_E	100 Ωm	
additional series impedances	Z_1	0	
fault duration	t_f	2 s	
contact configuration:			
left hand - right hand	LH-RH	BF=1, HF=0.4	
right hand - both feet	RH-BF	BF=0.75, HF=0.8	
left hand - both feet	LH-BF	BF=0.75, HF=1	
both hand - both feet	BH-BF	BF=0.5, HF=1	
contact condition	dry, big area		
contact impedance	Z_c		150 Ω
body current (IEC60479-1, 5%)	I_B		54.35 mA
per. pros. touch voltage 1			
LH-RH	U_{vTp}		195 V
RH-BF	U_{vTp}		99 V
LH-BF	U_{vTp}		85.2 V
BH-BF	U_{vTp}		67 V
body current (derived data, 5%)	I_B		123.4 mA
per. pros. touch voltage 2			
LH-RH	U_{vTp}		359 V
RH-BF	U_{vTp}		176 V
LH-BF	U_{vTp}		149 V
BH-BF	U_{vTp}		117 V

Table 8.2: Details and results of the second case

Parameters	Details	Values	Results
prospective touch voltage	U_{vT}	80 V	
exposure rate	n_{b}	2 000 contacts/a	
fault frequency per year	n_{f}	1 fault/10km/a	
contact duration	t_{b}	3 s	
fault duration	t_{f}	0.3 s / 3600 s	
contact configuration	LH-BF	BF=0.75, HF=1	
contact condition	dry, big area		
soil resistivity	ρ_{E}	50 Ωm	
contact resistivity	ρ_1	1000 Ωm	
additional series impedances	Z_1	2000 Ω	
contact impedance	Z_{c}		510 Ω
protective impedance	Z_{p}		1000 Ω
fault duration	t_{f}	3600 s	
probability of coincidence 1	$P_{\text{coincidence}}$		$2.28 \cdot 10^{-1}$
probability of fibrillation 1	$P_{\text{fib-permissible}}$		$4.37 \cdot 10^{-6}$
body current 1 (derived data)	I_{B}		49.35 mA
per. pros. touch voltage 1.1	U_{vTp}		74.3 V
per. pros. touch voltage 1.2	U_{vTp}		130.6 V
fault duration	t_{f}	0.3 s	
probability of coincidence 2	$P_{\text{coincidence}}$		$2.09 \cdot 10^{-4}$
probability of fibrillation 2	$P_{\text{fib-permissible}}$		$2.8 \cdot 10^{-3}$
body current 2 (derived data)	I_{B}		878.3 mA
per. pros. touch voltage 2.1	U_{vTp}		548 V
per. pros. touch voltage 2.2	U_{vTp}		1836 V
fault duration	t_{f}	3600 s	
coincidence reduction factor	CRF	0.1	
probability of coincidence 3	$P_{\text{coinc-new}}$		$2.28 \cdot 10^{-2}$
probability of fibrillation 3	$P_{\text{fib-permissible}}$		$4.36 \cdot 10^{-5}$
body current 3 (derived data)	I_{B}		54.95 mA
per. pros. touch voltage 3	U_{vTp}		80 V
fault duration	t_{f}	2 s	
probability of coincidence 4	$P_{\text{coincidence}}$		$3.17 \cdot 10^{-4}$
probability of fibrillation 4	$P_{\text{fib-permissible}}$		$3.2 \cdot 10^{-3}$
body current 4.1 (derived data)	I_{B}		68.96 mA
per. pros. touch voltage 4.1	U_{vTp}		93.12 V
body current 4.2 (IEC60479-1)	I_{B}		28.15 mA
per. pros. touch voltage 4.2	U_{vTp}		51.96 V

Table 8.3: Details and results of the third case

Parameters	Details	Values	Results
prospective touch voltage	U_{vT}	80 V	
fault duration	t_{f}	3600 s	
probability of coincidence	$P_{\mathrm{coincidence}}$	$2.28 \cdot 10^{-1}$	
probability of fibrillation	$P_{\text{fib-permissible}}$	$4.37 \cdot 10^{-6}$	
body current (derived data)	I_{B}	49.35 mA	
contact configuration:			
left hand - right hand	LH-RH	BF=1, HF=0.4	
left hand - left foot	LH-LF	BF=1, HF=1	
left hand - both feet	LH-BF	BF=0.75, HF=1	
both hand - both feet	BH-BF	BF=0.5, HF=1	
contact condition	dry, big area		
per. pros. touch voltage			
LH-RH	U_{vTp}		166 V
LH-LF	U_{vTp}		90 V
LH-BF	U_{vTp}		74 V
BH-BF	U_{vTp}		58 V
probability of configuration			
LH-RH	$P_{\mathrm{configuration}}$	79.42 %	
LH-LF	$P_{\mathrm{configuration}}$	9.58 %	
LH-BF	$P_{\mathrm{configuration}}$	8.07 %	
BH-BF	$P_{\mathrm{configuration}}$	2.91 %	
LH-BF			
probability of fibrillation	$P_{\text{fib-permissible}}$		$5.4 \cdot 10^{-5}$
body current (derived data)	I_{B}		55.52 mA
per. pros. touch voltage	U_{vTp}		81 V
BH-BF			
probability of fibrillation	$P_{\text{fib-permissible}}$		$1.5 \cdot 10^{-4}$
body current (derived data)	I_{B}		58.2 mA
per. pros. touch voltage	U_{vTp}		64 V

Table 8.4: Details and results of the fourth case

Chapter 9

Conclusion and Outlook

There are different standards that consider various aspects as important when developing a safety concept. The approach seems to be subjective, for example the value for total body impedance is often assumed to be $Z_{\mathrm{T}} = 1000\ \Omega$ like in IEEE Std. 80-2000 [16],BS 7354 [17] or ENA-TS 41-24 [18]. On the other hand, IEC60479-1 [9] and EN 50522 [13] take the voltage-dependency of the body impedance into consideration. The EN 50522 [13] in particular uses the voltage depended body impedance, not to be below 50 % of the population, value curve of the maximum permissible prospective touch voltage for safety.
At the beginning of this work the behaviour of persons in the circuit as well as the behaviour of the circuit itself was examined. The current safety regulations, i.e. the characteristic curves as well as the permissible risk levels were discussed. This knowledge was used in the calculation methods presented to formulate the framework for the analytical calculation and to describe the basis for the probability theory. In the elaboration of the basics of the scenario dealt within this work, first of all, the parameters influencing the permissible prospective contact voltage were discussed, in particular the influence of the soil and the surface on which the person is standing in the moment of contact with the faulty location. It was determined which parameters can be neglected and what influence an approximate knowledge of the surface at the fault location, the knowledge of the soil resistivity and the possible presence of tiles or gravel for example, often found at public swimming pools, can have. In case one and two, four contact configurations were examined by analytical observation within the given safety limits, by IEC60479-1 and the self-generated curves, for the simplified shock circuit. To see if they exceed the prospective voltage of 80 V is described in figure 7.1.

In case three the probability calculation is examined. The aim is to implement objective parameters, i.e. focusing on the probabilities of people's behaviour. The probability distribution in figure 5.2 and figure 5.3 were created using data from IEC60479-1 [9] and Kieback 2009 [15]. Therefore it is possible to select the equivalent values for the body current I_{B} for different values of the fibrillation probability $P_{\mathrm{fibrillation}}$ as a function of the fault duration t_{f}. The "c-proposed" curve in figure 5.4 was calculated for 0.1 % risk. Nevertheless the risk is indicated as a 1 % curve because the remaining risk according to Biegelmeier is too large [15]. The curves in IEC60479-1 [9] assume higher probabilities of fibrillation for the same body current than in Kieback 2009 [15] or in this work. The permissible prospective touch voltage U_{vTp} was calculated and compared with the permissible value of $U_{\mathrm{vTp}} = 80$ V for $t_{\mathrm{f}} \geq 10$ s, according to EN 50522[13]. Using the probability calculation, the permissible prospective touch voltages U_{vTp} of the four body configurations were calculated for the body current $I_{\mathrm{B}}(t_{\mathrm{f}} \geq 10\ \mathrm{s})$, according to IEC60479-1 [9]. All body configurations except the left hand to right hand have a prospective touch voltage $U_{\mathrm{vTp}} \leq 80$ V. This means according to EN 50522 [13] the values are in the safe range, but according to the probability theory the probability is higher than 10^{-6} and therefore not acceptable without measures.

The fourth scenario was used to further specify the probability calculation. Based on the elaborated data of Kieback 2009 [15] table 5.1, it is possible to classify the body configurations, mainly used in this work, according to their probability of occurrence. Thus, a new variable $P_{\mathrm{configuration}}$ can be defined. Therefore a better differentiation and prioritisation of the individual scenarios while maintaining the acceptable risk of 10^{-6} is possible.

In this work, the thresholds for dangerous body currents for different fault duration were investigated shown in figure 5.4. The curve from the IEC60479-1 [9], compared with Biegelmeier [6], Kieback 2009 [15] or this work, shows a higher probability of fibrillation than the others for the same body current. With the statistical evaluation in Kieback 2009 [15], deviations of the transfer factor f_{v} used in Biegelmeier [6] and the IEC60479-1 [9] were found. If the safety curves of IEC60479-1 [9] are considered, it is evident that the more the accident statistics are taken into account, the more the safety curves shift to the right [15]. That is, to higher and longer body currents [15].
The probabilistic calculation and the calculation with precisely defined preconditions (worst case) were analysed, showing the advantages and adaptability of the probabilistic theory in contrast to the worst case calculation. Using the mean value of the individual permissible contact voltage curves in figure 4.2 for safety check, a comparison with the probability calculation was made in the discussion. It shows that individual contact configuration scenarios can occur, which may not exceed the safety of the EN 50522 [13], 80 V ($t_{\mathrm{f}} \geq 10$ s), and still be considered unsafe. The probability calculation with its individual probabilities gives more information about the overall risk than the worst case evaluation according to the standards, especially if the limits given in these standards are reached under very rare events with low coincidence. Further the reduction factors enable targeted adaptations of the safety concept in contrast to a complete revision of the safety concept.

Questions that have not been addressed in this work, but would be relevant in the sense of an outlook:

- What would be the impact of changing the curves to newer/more profound curves in the IEC60479-1[9]?
- Investigation of more statistics of electrical incidence to generate more accurate curves with less residual risk.
- Further exploration into new probability variables such as $P_{\mathrm{configuration}}$, which allow probably dangerous scenarios to be examined more closely.

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Appendix A

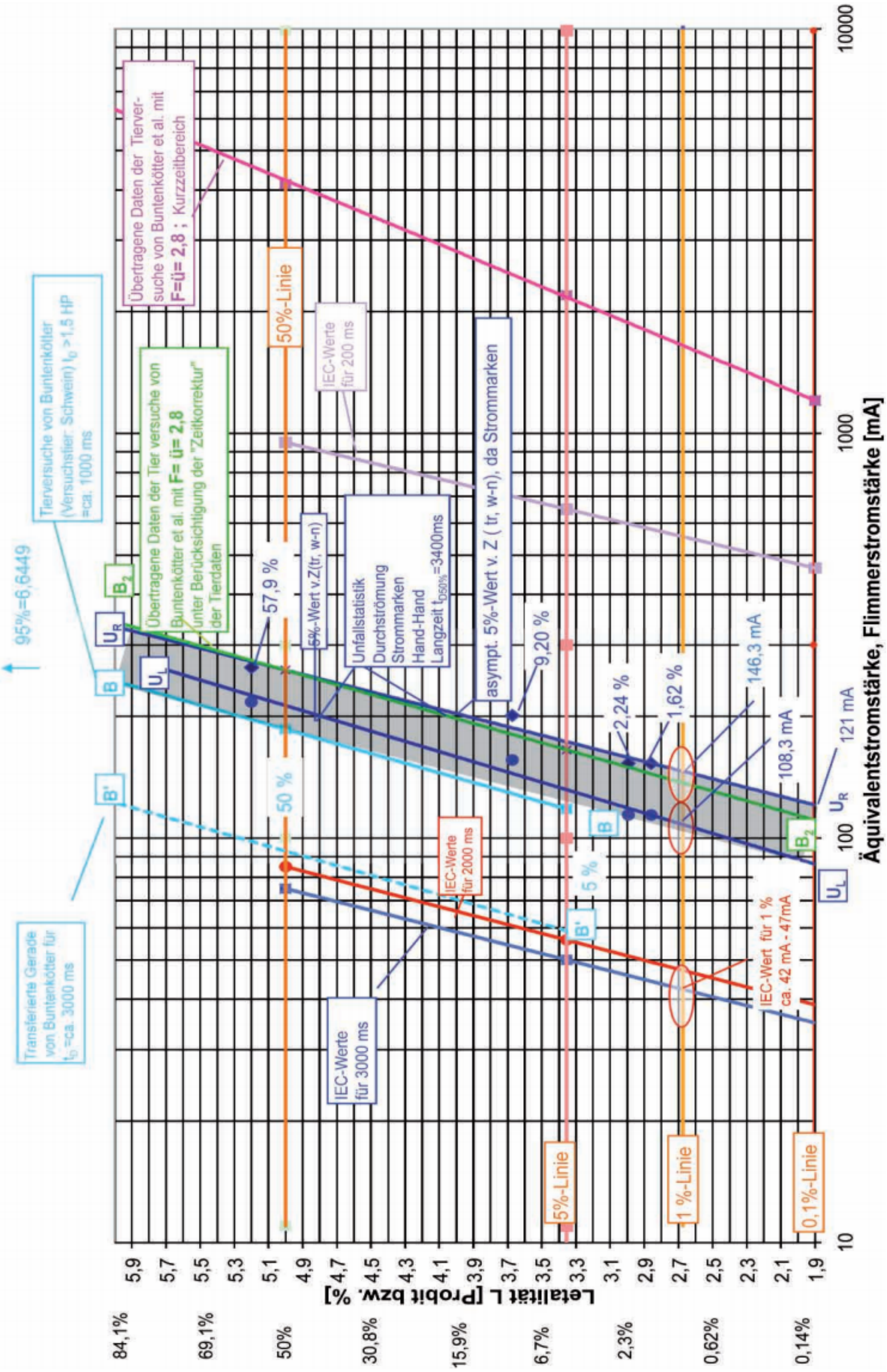

Figure A.1: Comparison of animal experiments and accident statistics [15]