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Fundamental Concepts of Electrical Safety Engineering

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*I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I-
I took the one less traveled by,
And that has made all the difference.*

Robert Frost

1.1 Introduction

The renewable energy sector has been rapidly growing in the past decade [1–3], and so has been the number of accidents involving workers in “green” projects. Statistics in the United States reveal that injuries and death are caused by

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lack of safety training and safety procedures [4]. The *Electric* hazard, but also *Falls, Struck by* and *Caught in between* hazards, are always present during all photovoltaic, solar thermal, and wind tower construction projects, regardless of the magnitude of the job.

The culture of the *safety-by-design* [5, 6] seems to be the appropriate response to the increased risk offered by renewable energy systems (RES). RES may challenge the safety of workers because they are generally always *live*, and the system voltage may exceed 500 V d.c.¹

In addition to safety training and procedures, electrical safety may be conveyed through engineering measures that reduce the risk of electric shock below a threshold that is conventionally deemed acceptable by applicable standards. In fault-free conditions, the *basic* protection ensures that persons cannot come into contact with parts normally live (i.e., proper insulation of electrical components). In the case of failure of the basic insulation of components, the *fault* protection ensures defense against electric shock by automatic interruption of the fault current. In some scenarios, the fault protection may be obtained with alternative methods to the fault current interruption.

In general, the *safety-by-design* of RES [7] is achieved if hazardous energized parts are never accessible, and that equipment/appliances, also referred to as *exposed-conductive-parts* (ECPs), are never hazardous either under normal operations or in the event of single-faults. In essence, touch voltages and contact durations must be within the magnitudes deemed safe by applicable technical standards and codes.

1.2 Electric Shock

External electrical stimuli applied to the human body can prevent operational skeletal and cardiac muscles from properly operating, as well as destroy bodily tissues by thermal shock.[8]

External a.c. currents with frequency ranging from 50 to 100 Hz of magnitude around 10 mA for adult males and 15 mA for adult females, can override the internal electrical signals from the brain controlling the body muscles, render the person unable to “let go” of an energized part and cause painful muscle contractions.

For d.c. currents, thresholds of let-go cannot be positively defined. The circulation of d.c. current through the body only causes a sensation of warmth, and the person is subjected to painful muscle contractions only during making and breaking of the d.c. current.

¹ The system voltage of PV arrays is defined as $1.25V_{OC}$, where V_{OC} is the open-circuit voltage of the array.

Stevens' Law [9, 10] describes the perceived strength of a physical stimulus as a function of its intensity, expressed in its physical units. According to Stevens' Law, the perception of electric shock is *superlinear* with the stimulus, as varies as the 3.5 power of the a.c. voltage applied. The coefficient 3.5 relates the magnitude of the applied voltage to the perceived magnitude of the shock as current through the fingers; thus, a small increase in the applied voltage is perceived as a larger increase in the electric shock.

A 30 mA-current, if interrupted within 300 ms, can cause involuntary muscular contractions but usually no harmful electrical physiological effects. Longer disconnection time, up to 5 s, can cause muscular contractions, difficulty in breathing, reversible disturbances of heart function, but usually no organic damage.

Higher body currents inhibit internal muscle control, prejudicing the function of the muscles involved in the breathing process, thus causing asphyxia.

1.2.1 Ventricular Fibrillation

The ventricular fibrillation (V-fib) [11] is the loss of the normal heart rhythm. The V-fib causes the ventricles to *quiver*, or fibrillate, instead of contracting normally, preventing the heart from pumping blood and causing cardiac arrest. The ventricular fibrillation is the main cause of death in electric shock accidents.

The cardiac muscle, whose fibers have high contractile strength, specializes in pumping blood throughout the person's body. The contractions of the heart are stimulated by the *sinoatrial node* (SA), situated in the right atrium, which generates electrical impulses. The impulses propagate through the conductive tissues named *Bundle of His*, and *Purkinje fibers*, and reach the *atrioventricular node* (AV), situated in the center of the heart (Figure 1.1).

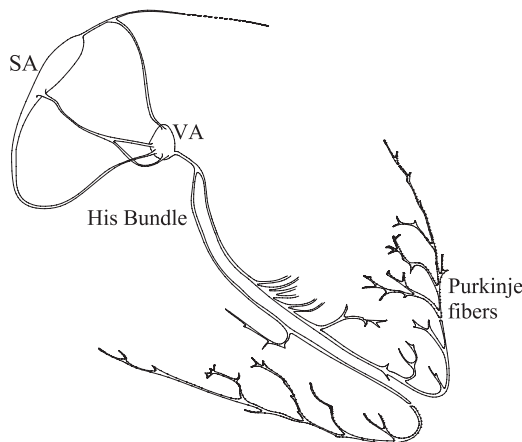


Figure 1.1 Electric conduction of the heart.

The Bundle of His, which departs from the AV, conducts the stimuli to the ventricles, which, after filling with blood, contract and push the blood through the arteries during the *systole*. After the contraction, the heart relaxes and fills up with blood again, awaiting further stimuli to contract again.

The net charge of the heart is zero; however, positive and negative charges are dynamically separated during each cardiac cycle and form an *electric dipole* vector that rotates and varies in magnitude with time. Thus, electric potential differences at different places along the person's body also change with time during each cardiac cycle, and this can be observed in an electrocardiogram (i.e., EKG or ECG) (Figure 1.2). Usually, *scalar* EKG measurements are performed: *vector* EKGs, which may more deeply describe the heart dipole rotation, are rarely performed. Typical potential differences showed in the EKG range between 30 and 500 μV .

During the P wave, the right and left atria contract; during the Q-R-S complex, the right and left ventricles contract (systole). The last event of the cycle, the S-T-U interval, is the repolarization of the ventricles: they return to the resting state; their walls relax and await the next signal. This complex procedure continues as the atria refill with blood and more electrical signals are sent by the SA; the heart-period duration is around 400 ms.

The superposition of external currents of larger magnitude to the normal bodily currents will override the control signals from the brain to the skeletal and cardiac muscles, which can no longer operate as intended, exposing persons to the risk of death.

The last half of the T wave is referred to as the *relative refractory period*, or the *vulnerable period*, which is known as the crucial time interval during which external electrical stimuli (i.e., electric shock) may induce the ventricular fibrillation.

For shock durations shorter than the cardiac cycle, the ventricular fibrillation may not occur, based on the lower probability that the external stimulus occurs during the vulnerable period of the heart.

For d.c. currents, experiments on animals and data derived from electrical accidents demonstrate that the threshold of V-fib for a downward current is

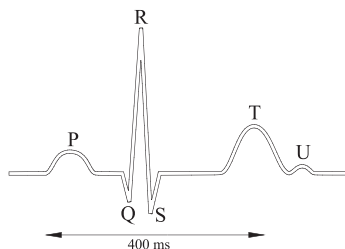


Figure 1.2 A normal electrocardiogram (EKG).

about twice as high as for an upward current; therefore, downward currents are less hazardous than upward currents.

For shock durations longer than the cardiac cycle (e.g., 0.5–1 s), the threshold of fibrillation for d.c. is several times higher than for a.c. However, for shock durations shorter than 200 ms, the threshold of d.c. fibrillation is approximately the same as for a.c. (measured in r.m.s. values).

1.2.2 The Heart-current Factor

The probability that the V-fib is induced is dependent upon the pathway of the body current. To compare the danger of different current paths through the body, standard IEC 60479-1² defines the *heart-current factor* F [12] (Eq. 1.1).

$$F = \frac{I_{ref}}{I_h} \quad (1.1)$$

I_{ref} is the body current that determines V-fib for the path left hand to feet, and I_h is the fibrillation current for different body paths, as shown in Table 1.1.

The larger is the heart-current factor; the more dangerous is the current pathway through the body.

As an example, a current of 225 mA hand-to-hand has the same likelihood of producing ventricular fibrillation as a current of 90 mA left hand-to-both feet. Therefore, the hand-to-hand pathway is less hazardous than the left hand-to-both feet.

Table 1.1 Heart-current factor F for different current paths

Path	Heart-Current Factor F	
	IEC	Simulated
Left hand–feet	1	1
Hands–feet	1	0.85
Left hand–right hand	0.4	0.75
Right hand–feet	0.8	0.88
Hands–seat	0.7	0.84
Left foot–right foot	0.04	0.01
Left hand–right foot	1.00	1.00
Left hand–left foot	1.00	1.00
Right hand–right foot	0.88	–
Right hand–left foot	0.8	0.89

2 (International Electrotechnical Commission) IEC/TS 60479-1: “Effects of Current on Human Beings and Livestock - Part 1: General Aspects”.

The IEC does advise that the published heart-current factors must be considered as a rough estimation of the relative danger of the various current paths with regard to ventricular fibrillation. The IEC formulation of the heart-current factor is, in fact, based on experiments on corpses, animals and volunteers, or data from electrical accidents. Trials on animals produce results whose extrapolation to humans may not always be reliable, due to the obvious anatomical differences. In addition, exhaustive information about electrical accidents may not be available; therefore, it may not be possible to evaluate the magnitude of the body current affecting the injured and have reliable data.

A possible alternative computation for F can be obtained through *human phantoms*, which are computerized models that allow the numerical simulation [13] of the current pathways through the human body when subjected to external stimuli, as shown in the last column of Table 1.1.

The comparison between the two sets of heart-current factors shows that the IEC may underestimate the magnitude of F for pathways involving the right hand, probably due to the extrapolation of the results of measurements on animals to humans.

The same heart current factors are also applicable to d.c. currents.

1.3 The Electrical Impedance of the Human Body

The electrical impedance Z_B of the human body is capacitive in nature [14] due to the capacitance C_s of the skin (Figure 1.3); therefore, it depends on the frequency of the applied touch voltage. R_{Bi} is the internal body resistance; R_{cs} represents the resistance of the skin at the surface area of contact, which takes into account the

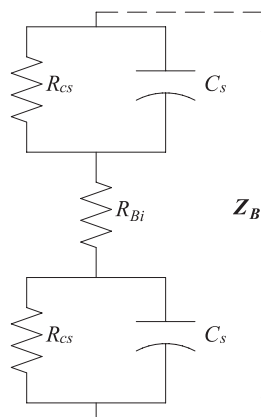


Figure 1.3 Impedances of the human body.

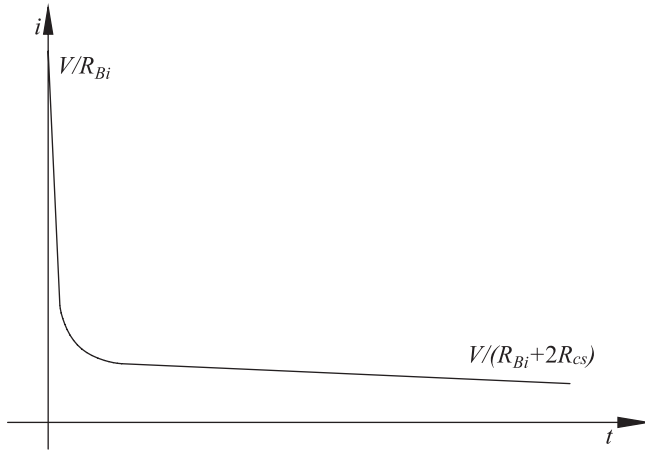


Figure 1.4 Current response of human body to d.c. voltage.

presence of the pores, which are small conductive elements; R_{cs} is strongly variable with environmental and physiological conditions (e.g., sweaty hands).

The model of Figure 1.3 has been validated on cadavers by analyzing the current response to a d.c. voltage V [15] (Figure 1.4).

When the d.c. touch voltage occurs, the capacitances C_s are not charged, and become short-circuits during the initial transient, bypassing the contact resistances R_{cs} ; therefore, the ratio of the touch voltage V to the current peak equals R_{Bi} . After the transient expires, the capacitances of the skin become an open circuit, and the current reaches the steady-state value of $V / (R_{Bi} + 2R_{cs})$, where the denominator is the total body resistance.

The impedance of the skin is the primary barrier against the flow of the body current, providing that the voltage is not high enough to puncture it (i.e., below 200 V), and the skin is not wet. Voltages greater than 200 V exceed the dielectric strength of the skin, C_s “fails” and short-circuits the contact resistance R_{cs} , reducing the resistance of the human body to R_{Bi} : the body current can cause greater damages to the internal organs.

In addition, at 50/60 Hz, the capacitive reactance of the skin is practically an open circuit, and $Z_B \approx R_{Bi} + 2R_{cs}$.

1.3.1 The Internal Resistance of the Human Body

R_{Bi} in Figure 1.3 represents the internal resistance of the human body, which depends on the chosen current pathway [16]. IEC 60479-1 expresses the resistance R_i of different segments of the body, ignoring the skin contribution at

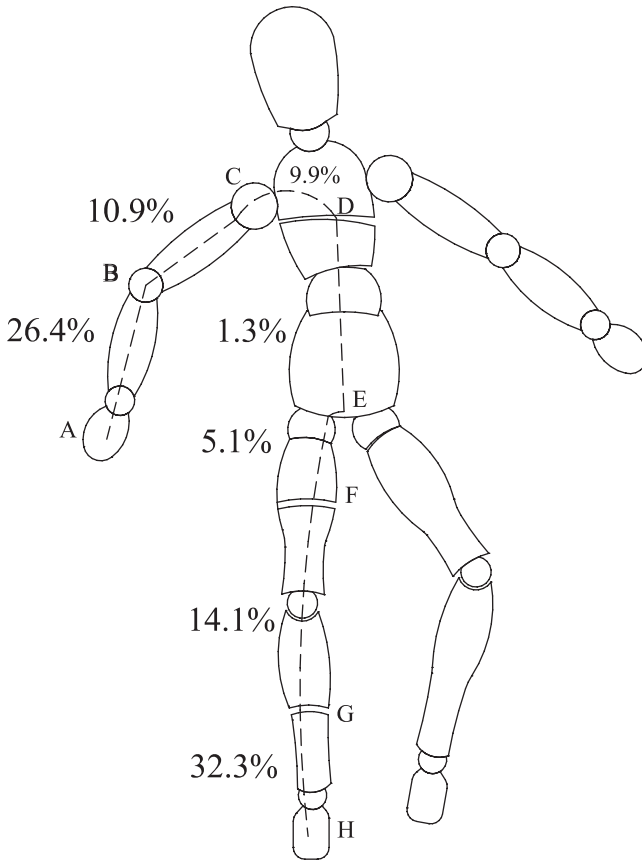


Figure 1.5 Internal partial impedances of the human body (no skin contribution).

50/60 Hz, as a percentage of the internal resistance of the human body related to the path hand-to-foot (Figure 1.5).

For example, the partial impedance of the trunk (i.e., segment D-E) is only 1.3% of the total body impedance hand-to-foot, due to large amount of conductive fluids normally present in the trunk.

The resistance R_i of the segment are determined as $R_i = \rho l / S$, where ρ is the segment tissue mean resistivity, l the mean length of the segment, and S its mean cross-sectional area. The cross-sectional area of the body segment plays a crucial role in determining its resistance: fingers and joints, such as elbow and knee, have higher resistance values due to their relatively small cross-sectional areas, even though they are made of well-conductive tissues.

The total body impedance for a given current path is obtained by adding the resistances R_i of the body segments for that path and the impedances of the skin at the surface areas of contact.

To underscore the role of the skin as the primary barrier against the flow of the body current, the US NIOSH³ states that “*under dry conditions, the resistance offered by the human body may be as high as 100,000 Ω. Wet or broken skin may drop the body’s resistance to 1,000 Ω*”.

IEC/TS 60479-1 affirms the variability of the body impedance Z_B and body resistance R_B related to the touch voltage, both a.c. (50/60 Hz) and d.c., and provides impedance values for the hand-to-hand pathway, in the case of dry skin and large contact areas (i.e., order of magnitude 100 cm²), herein shown in Table 1.2.

Table 1.2 shows Z_B and R_B in the population percentile; for instance, for a touch voltage of 50 V, 95% of the population has an impedance of 4,600 Ω or less.

The body resistance for direct current (i.e., $f = 0$) is higher than the body impedance for alternating currents (i.e., $f = 50/60$ Hz) for touch voltages up to approximately 200 V, thanks to the blocking effect of the capacitances of the skin (i.e., they are open circuits at steady state); for a.c. contacts, the capacitances C_s are instead in parallel to the contact resistances R_{cs} .

For durations of current flow longer than 0.1 s, the skin will rupture, and Z_B approaches R_B .

The total body impedance Z_B depends on the area of contact with the energized part. Surface areas of contact are defined as *large*, *medium*, and *small*, with order of magnitude respectively of 100 cm², 10 cm², and 1 cm², and characterized by dry, water-wet, and saltwater-wet conditions.

Table 1.2 Body impedances and resistances for a current path hand-to-hand

Touch Voltage (V)	Z_B (Ω)			R_B (Ω)		
	5%	50%	95%	5%	50%	95%
25	1750	3250	6100	2100	3875	7275
50	1375	2500	4600	1600	2900	5325
150	850	1400	2350	875	1475	2475
200	800	1275	2050	800	1275	2050
225	775	1225	1900	775	1225	1900
400	700	950	1275	700	950	1275
500	625	850	1150	625	850	1150
1000	575	775	1050	575	775	1050

3 National Institute for Occupational Safety and Health. Publication 98-131: “*Worker Deaths by Electrocutation - A Summary of NIOSH Surveillance and Investigative Findings*”.

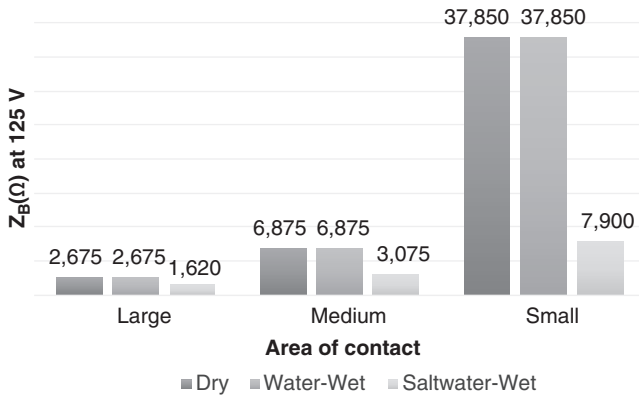


Figure 1.6 Body impedances at 1250 V for a path hand-to-hand vs. the area of contact.

In Figure 1.6, values of impedances not exceeded by the 95% of population, for a current path hand-to-hand and for a 125 V touch voltage (a.c. 50/60 Hz), are shown as a function of the surface areas of contact.

It can be observed that Z_B increases with polynomial law when the area of contact decreases. For a given area of contact, no appreciable differences in Z_B are present in dry and water-wet conditions for a touch voltage of 125 V.

The effect on Z_B of the surface area of contact increases when the touch voltage decreases; this is because touch voltages exceeding 200 V may rupture the capacitance of the skin and short-circuit the contact resistance.

In sum, Z_B is different from person to person and is dependent on several factors, including [17] but not limited to:

- the touch voltage;
- the supply frequency;
- the duration of the current flow;
- the conditions of wetness of the skin and surface area of contact;
- the general environment.

1.4 Thermal Shock

The current i passing through the human body during the contact time t with an energized part produces a physiological damage due to the generation and transfer of heat, per the Joule effect, to the biological tissues. An *electric burn* is defined as the burning of the skin or of an organ caused by the flow of an

electric current along its surface or through it. Electric burn injuries account for 4% to 6% of all admissions to burn-care facilities [18].

The amount of heat generated in the tissue depends on the current density and the tissue conductivity. However, the conductivity is in turn determined by the heat generated in the tissue; since the tissue ionic conductivity increases with the increasing temperature, a further intensification in current density and temperature occurs. Thus, the thermal injury is determined as the result of a feedback mechanism; however, the conductivity change is not considered in burn models due to the complexity of the resulting nonlinear equations.

For the calculation of the amount of energy w delivered by a current i during the time t to a homogeneous volume of biological tissue of length l , cross-sectional area and ionic conductivity σ (Eq. 1.2), it is conservatively assumed an *adiabatic* process. Such a process calls for no heat removal into neighboring tissues by blood flow or by conduction and/or convection into the air, but it is presumed that all the heat stays within the tissue.

$$w = \frac{l}{\sigma S} i^2 t. \quad (1.2)$$

Vues of ionic conductivity of some biological tissues are listed in Table 1.3 [12].

The thermal injury will depend on the duration t of the contact and the temperature rise ΔT that the passing current will impose [19]. The thermal energy expressed in Eq. 1.2 is related to the temperature rise ΔT to which the volume of tissue is subjected. We can write the thermal balance equation (Eq. 1.3),

Table 1.3 Electrical conductivity σ of biological tissues

Tissue	σ (S/m)
Blood	7.00E-1
Bone	8.07E-2
Cartilage	1.71E-1
Fat	4.04E-2
Heart	8.27E-2
Kidney	8.92E-2
Muscle	2.33E-1
Nerve	2.74E-2
Skin (dry)	2.00E-4
Skin (wet)	4.27E-4

which describes the exchange of heat between the heat delivered w and the heat accumulated in the volume of tissue, assuming σ independent of the temperature.

$$w = \frac{1}{\sigma S} i^2 t = cS\Delta T \quad (1.3)$$

c is the volume-specific heat capacity, defined as the heat necessary to increase the temperature of a unit volume of a substance by 1°C.

The temperature rise ΔT is given by Eq. 1.4

$$\Delta T = \frac{J^2}{\sigma c} t \quad (1.4)$$

Equation 1.4 shows that the temperature rise ΔT depends on the square of the current density J and on the duration t of the current circulation.

The skin has the lowest conductivity among the biological tissues, and the current density is higher at the point of contacts on the body (referred to as *entry* and *exit* sites); therefore, for a given current, the highest temperature rise is achieved on the skin, which therefore suffers the greatest level of damage.

Thermal injury of the human skin occurs when the temperature rise persists for a sufficient length of time: for instance, to cause cutaneous injury, a temperature of the skin of 45°C requires a contact duration of 2 h; 51°C requires a contact duration of 2 min; and 60°C requires a contact duration of 3 s⁴ Current densities of a few mA/mm² for a duration of about 0.5 to 1 s can cause burns, whereas a current density of a few tens of mA/mm² for a few seconds, will cause third-degree burns with destruction of deeper tissues and possible necrosis.

Thermal shock can also be caused by the heat released by electric arcs, which are accompanied by the vaporization of metal to form a superheated toxic gas.

1.5 Heated Surfaces of Electrical Equipment and Contact Burn Injuries

Burns can also be triggered by unintentional contact with hot surfaces of electrical equipment, which may be readily accessible during normal operations (e.g., the surface of a PV module) [20, 21].

4 Henriques, F.C. and Moritz, A.R. (Sep. 1947). Studies of Thermal Injury II. The Relative Importance of Time and Surface Temperature in the Causation of Cutaneous Burns. *The American Journal of Pathology* 23 (5): 695–720.

According to Stevens' Law, the perception of temperature is also *superlinear* with the stimulus, as varies as the 1.6 power of the temperature (i.e., experimentally analyzed by using a heated metal on a person's arm).

Most apparatus and appliances in industrial, commercial, and residential environments are thermally insulated unless the insulation would prevent their functions (e.g., the bottom surface of a flatiron). However, superficial temperatures of insulated equipment may still be high enough to cause burns from contact with readily accessible parts. The severity of such burns will depend on the thermal resistivity of the material of the touchable surface, and the pressure and duration of the contact.

An effective protection against burns can be established based on the acceptable contact period and on the level of acceptable injury.

According to the CENELEC Guide 29⁵ for adults, a minimum contact period ranging between 0.5 s and 1 s should be used, based on the type of the equipment and where they are to be used (e.g., restrictive locations); however, extended reaction times may be considered based on the age of users that may possibly come into contact with the hot surface (Table 1.4).

Once the maximum operating temperature of readily accessible surfaces is determined, by direct measurement or calculation, the potential injury level may be established through the graph of Figure 1.7, which shows the relationship between surface temperature and exposure time.

The bottom curve T_B is the locus of the pairs temperature and exposure time representing the limit of the reversible epidermal injury; T_B describes the acceptable injury level as a first degree burn, that is, a burn where the temperature and/or duration are not sufficient to cause necrosis of the epidermis but

Table 1.4 Standard contact durations

Age Group	Exposure time (s)
Adults	0.5–1
age < 2 years	15
2 years < age < 6 years	4
6 years < age < 14 years	2
Elderly persons	1–4
Physical disabilities	According to nature of disability

5 NELEC Guide 29: "Temperatures of hot surfaces likely to be touched. Guidance document for Technical Committees and manufacturers". Ed. 1, 04-2007.

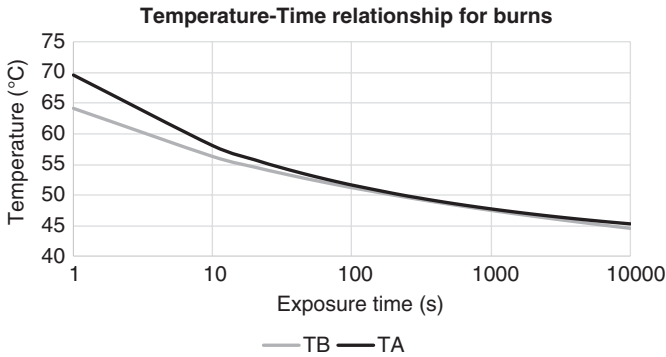


Figure 1.7 Temperature–Time Relationship for burns.

only reddening of the skin. T_A is the locus representing the complete trans-epidermal necrosis.

The surface of photovoltaic arrays in full sun can exceed the ambient temperature by 30°C or more, which may easily produce temperature greater than 60°C. It is therefore apparent that PV modules' surface with temperatures exceeding 64°C can only be contacted for 1 s before skin injury occurs.

IEC 60364-4-42⁶ requires that accessible parts of electrical equipment within arm's reach do not attain temperatures exceeding the limits given in Table 1.8, to prevent burns caused by contact with heated surfaces.

The above temperature limits vary according to whether the part is intended to be hand-held or touched during normal use, and are based on the nature of the material of the accessible surface; they do not apply to equipment for which a maximum temperature is specified in the relevant product standard.

The temperature limits of Table 1.8 are rather large, and it would be prudent to be well below those values; if not possible, the equipment in question might be fitted with guards to prevent accidental contact.

1.6 Ground-Potential and Ground-Resistance

A ground electrode is a conductive part, embedded in the soil or in another conductive medium (e.g., concrete), which is in electrical contact with the earth [22].

⁶ IEC 60364-4-42: "Low-voltage electrical installations – Part 4-42: Protection for safety – Protection against thermal effects".

Table 1.8 Temperature limits in normal service for accessible parts of equipment

Accessible parts	Material of accessible surfaces	Maximum temperatures (°C)
A hand-held part	Metallic	55
	Non-metallic	65
A part intended to be touched but not hand-held	Metallic	70
	Non-metallic	80
A part that does not need to be touched for normal operation	Metallic	80
	Non-metallic	90

A connection to the ground can also be made through metalwork not forming part of the electrical installation, such as structural steelwork, metal, water supply pipes, or other buried metalwork. Such metalwork, however, should not be relied upon as an electrode, as it could be removed or replaced without any warning to users. The safety purpose of ground-electrodes is to effectively dissipate fault-currents into the soil.

To illustrate the relationship between ground-potentials, ground-resistances, and ground-currents, we study a hemispherical electrode, as this will allow the understanding of the performance of electrodes of different geometry.

We consider a hemisphere of radius r_0 embedded in a boundless and uniform soil of resistivity ρ , buried at a sufficient distance from a receiving electrode, and that the ground-current i leaking from this electrode flows radially into the soil (Figure 1.8).

The current density \vec{J} , identified as a vector quantity, through a surface S in the soil of infinitesimal thickness dl , placed at the distance r from the center of the hemisphere, is related to the uniform leakage current i through the flux operator expressed in Eq. 1.5.

$$i = \iint_S \vec{J} \cdot \vec{u}_n dS = J2\pi r^2 \quad (1.5)$$

Equation 1.5 yields:

$$\vec{J} = \frac{i}{2\pi r^2} \hat{r}, \text{ for } r > r_0 \quad (1.6)$$

where \hat{r} is the unit vector in the radial direction.

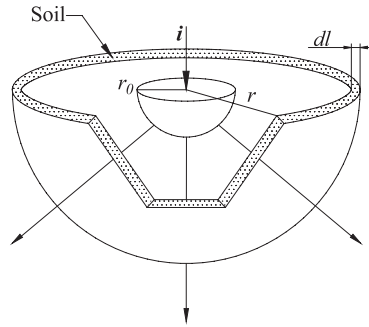


Figure 1.8 Hemispherical ground-electrode.

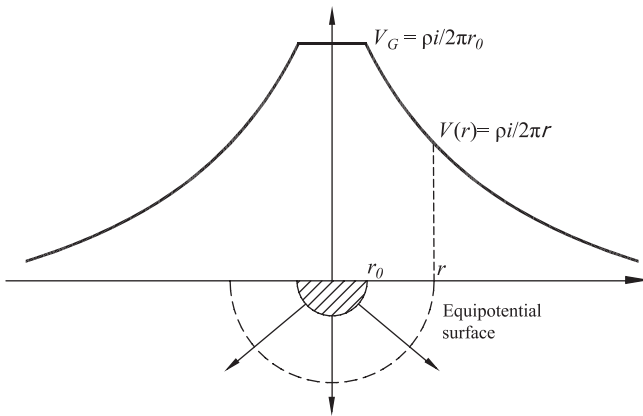


Figure 1.9 Hyperbolic distribution of the ground-potential $V(r)$ over the soil.

The electric field \vec{E} at any distance r from the center of the hemisphere can be determined as:

$$\vec{E}(r) = \rho \vec{J}, \text{ for } r > r_0 \tag{1.7}$$

The *ground-potential* on the soil surface at any distance r from the center of the hemisphere, which is taken zero at infinity, is:

$$V(r) = -\int_{\infty}^r \vec{E} \cdot d\vec{r} = -\rho \int_{\infty}^r \vec{J} \cdot d\vec{r} = -\rho \frac{i}{2\pi} = \int_{\infty}^r \frac{1}{r^2} \cdot d\vec{r} = \rho \frac{i}{2\pi r} \tag{1.8}$$

The ground-potential $V(r)$ features a hyperbolic distribution through the soil, with the coordinate axes as asymptotes (Figure 1.9).

The equipotential surfaces are hemispheres, including the actual surface of the electrode. Points belonging to the same equipotential surface have equal potential both on the surface and deep in the soil. Current lines are perpendicular to such surfaces.

The *ground-potential rise* on the surface of the hemisphere, that is, the potential at the distance r_0 from its center, is

$$V_G = V(r_0) = - \int_{\infty}^{r_0} \vec{E} \cdot d\vec{r} = - \rho \int_{\infty}^{r_0} \vec{J} \cdot d\vec{r} = - \rho \frac{i}{2\pi} = \int_{\infty}^{r_0} \frac{1}{r^2} \cdot d\vec{r} = \rho \frac{i}{2\pi r_0} \quad (1.9)$$

We define the resistance R_G of the hemisphere-electrode to earth (from now on the *ground-resistance*) as the ratio of the ground-potential rise V_G to the leakage current i (Eq. 1.10).

$$R_G = \frac{\rho}{2\pi r_0} \quad (1.10)$$

The ground-resistance of a ground-electrode can be seen as an equivalent one-port (Figure 1.10): one terminal of the one-port is the metal connection to the electrode (generally named *grounding electrode conductor* in codes and standards), whereas the other terminal represents a point at zero potential (i.e., a point at sufficient distance from the electrode where the potential is negligible).

The ground symbol (from IEC 60417 “*Graphical symbols for use on equipment*,” symbol 5017) does not represent the soil, but a point at sufficient distance from the electrode where the surface potential is negligible.

From the graph of the ground potential of Figure 1.9, it can be observed that the radius r_0 of the hemisphere identifies the point from where the hyperbolic distribution starts. For a given hemisphere, different values of the product ρi determine different hyperbolae, whose distance for the horizontal axis depends on the soil resistivity and the fault-current.

The rate-of-change of the potential with the distance r from the hemisphere (i.e., the potential gradient) is defined in Eq. 1.11.

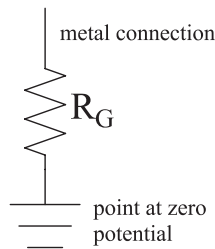


Figure 1.10 Electrode ground-resistance as an equivalent one-port.

$$\frac{dV}{dr} = -\frac{\rho i}{2\pi r^2} \quad (1.11)$$

which shows that the maximum variation of the ground potential occurs in proximity of the hemispherical electrode (i.e. $r \approx r_0$).

1.6.1 Area of Influence of a Ground-electrode

The electric field is a *long-range* field and is zero only at infinite distance from its source, and so is the *ground potential*. In engineering practice, however, the design of ground electrodes is based on the *area of influence*, which defines the zone beyond which the ground potential can be considered negligible. If we evaluate the ground potential at the distance $r = 5r_0$, we obtain:

$$V(5r_0) = \frac{V_G}{5} \quad (1.12)$$

At a distance $5r_0$ from the center of the hemisphere, the ground potential reduces to 20% of the ground potential rise, and this result has a general validity, independently of the shape of the electrode. It can conventionally be assumed that the hemispherical volume of the earth of radius $5r_0$ is the area of influence of the electrode. For differently-shaped electrodes (e.g., rods, rings, grids, etc.), their maximum dimensions can be used in lieu of the radius; for instance, for grounding grids, the largest diagonal can be employed to identify the area of influence.

Two unconnected ground-electrodes are defined as independent from each other if they are outside of their respective areas of influence.

1.7 Hemispherical Electrodes in Parallel

Two identical hemispherical electrodes of radius r_0 are connected in parallel into a uniform soil of resistivity ρ , and each leaks the current $i/2$. The electrodes are buried at a distance d .

The hemispheres attain the same ground-potential rise, which can be calculated by superimposing the potentials of each electrode, supposed isolated from the other (Eq. 1.13).

$$V_G = \rho \frac{i/2}{2\pi r_0} + \rho \frac{i/2}{2\pi(d-r_0)} = \rho \frac{i}{4\pi r_0} \frac{1}{1 - \frac{r_0}{d}} \quad (1.13)$$

Thus, the total ground resistance is given by Eq. 1.14.

$$R_G = \frac{\rho}{4\pi r_0} \frac{1}{1 - \frac{r_0}{d}} \quad (1.14)$$

If $d > 5r_0$, the second factor in Eq. 1.14 is ≈ 1 , and R_G is mathematically expressed by the formula of the parallel of the ground resistances of each electrode.

If the electrodes are closer than $5r_0$, they are not independent from each other, and their total resistance is greater than their mere parallel (Figure 1.11).

1.8 Hemispherical Electrodes in Series

Let us consider two identical hemispheres embedded into the soil at the distance $d \geq 5r_0$ center-to-center, so that they can be considered independent from each other. The first electrode leaks the current i , whereas, the second electrode receives the same current (Figure 1.12).

The resulting surface potential $V(r)$ at a generic point r along a line joining the two hemispheres is given by the superposition of the potentials imposed by each electrode (Eq. 1.15).

$$V(r) = \rho \frac{i}{2\pi r} - \rho \frac{i}{2\pi(d-r)} = \rho \frac{i}{2\pi} \left(\frac{1}{r} - \frac{1}{d-r} \right). \quad (1.15)$$

If $r = d/2$, which is the center point between the two hemispheres, the value of the surface potential is $V(d/2) = 0$.

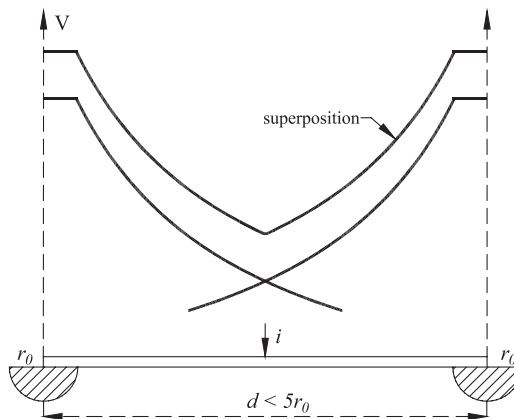


Figure 1.11 Ground-electrodes in parallel.

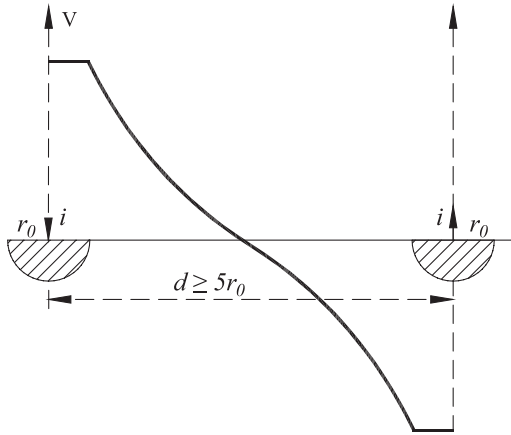


Figure 1.12 Hemispherical electrodes connected in series.

The point of the soil at which the ground potential is zero is the location that must be identified for the correct measurement of the ground resistance R_B of an electrode, as further elaborated.

1.9 Person’s Body Resistance-to-ground and Touch Voltages

In the case of the pathway hands-to-feet, the current will flow into the soil through the feet, and its amount will depend on the series between the body resistance R_B and the person’s resistance-to-ground R_{BG} . The person’s resistance-to-ground limits the circulation of the body current, therefore is beneficial for the electrical safety of individuals.

For an approximate calculation of R_{BG} , the adult human foot can be modeled as a circular plate of radius $r_f = 0.08$ m, laying on a surface of resistivity ρ . The expression in ohms of the ground resistance R_f of such electrode is given in Eq. 1.16.

$$R_f = \frac{\rho}{4r_f} \cong 3\rho \tag{1.16}$$

If we assume that the two feet act as ground electrode in parallel, and that the plates do not interfere with each other, the body resistance-to-ground R_{BG} equals 1.5ρ .

In general, it may be conservatively assumed that the person does not wear shoes or gloves, and that there is no floor to limit the body current. However,

standard EN 50522⁷ allows, for calculation purposes, additional known resistances in series to the body resistance (e.g., gloves, footwear, standing surface made of insulating material, such as gravel, asphalt, etc.); EN 50522 identifies in 1 k Ω the average value for old and wet shoes. Typical shoe resistances are 5–10 k Ω for wet leather soles, 100–500 k Ω for dry leather soles, and 20 M Ω for rubber soles.

To calculate the body current, we determine the parameters of a Thevenin equivalent circuit, V_{th} (i.e., equivalent voltage source) and R_{th} (i.e., equivalent resistance), as seen from the point of contact of the body with the energized part, and the ground (Figure 1.13).

R_{th} is generally negligible if compared to $R_B + R_{BG}$, and therefore can be conservatively ignored; the fault source can be thought of as an ideal voltage generator.

In these conditions, the body current i_B can be calculated with Eq. 1.17.

$$i_B = \frac{V_{th}}{R_B + R_{BG}} \quad (1.17)$$

In Figure 1.12, V_{ST} is the *prospective touch voltage*, which is defined as the potential difference between simultaneously accessible conductive parts, when those conductive parts are not being touched by a person. V_T is the (effective) *touch voltage*, defined as the potential difference between accessible conductive parts when touched simultaneously by a person (one part can be the ground) [23–27]. The value of the effective touch voltage is affected by the persons' body resistance, greatly variable, and the person's resistance-to-ground. Consequently, the same touch voltage may correspond to different body currents, and this makes the touch voltage a rather ineffective indicator of hazard.

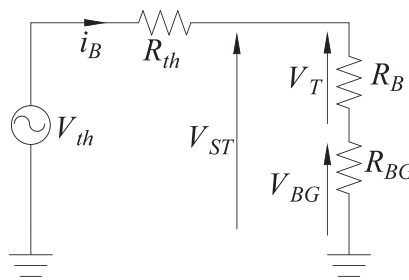


Figure 1.13 Equivalent circuit for the computation of body currents due to a touch voltage.

⁷ EN 50522:2010-11: “Earthing of power installations exceeding 1 kV a.c”.

Thus, for the purpose of designing protective measures against electric shock, technical standards identify a conventional body resistance of $1\text{ k}\Omega$.

The *step voltage* is defined as the voltage between two points on the earth's surface that are 1 m distant from each other, which is considered the standard stride length of a person.

In the worst-case scenario, prospective touch voltages may equal the ground potential rise V_G . To better clarify the concept, let us assume that in the event of a fault, a hemisphere of radius r_0 , and resistance-to-ground R_G leaks to ground the current i . Let us also assume a person standing in a region at zero potential; the person is touching a metallic structure electrically connected to the hemisphere for grounding purposes (Figure 1.14).

The hemisphere attains the ground potential rise $V_G = iR_G$, and so does the metallic structure: the person's hand is at the potential V_G , whereas their feet are at zero potential. The prospective touch voltage V_{ST} equals the ground potential rise; however, the effective touch potential V_T is a lower value, equal to the voltage drop on the person's body resistance R_B , as established by the voltage divider between R_B and R_{BG} (Figure 1.13).

The distribution of the ground potential $V(r)$ over the soil is shown in Figure 1.15. It can be seen that in correspondence with the persons' feet, the surface ground-potential rises up from (almost) zero to the value V_{BG} , which accordingly lowers the touch voltage.

The other possible scenario is the person standing in a non-zero potential region, at a distance r from the center of the hemisphere less than $5r_0$ (Figure 1.16).

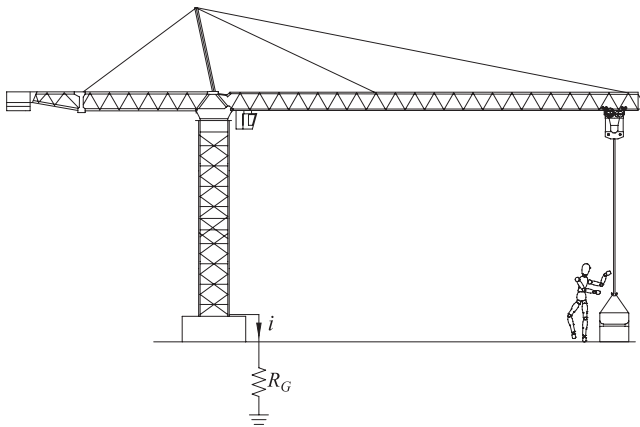


Figure 1.14 Person standing in a region at zero potential.

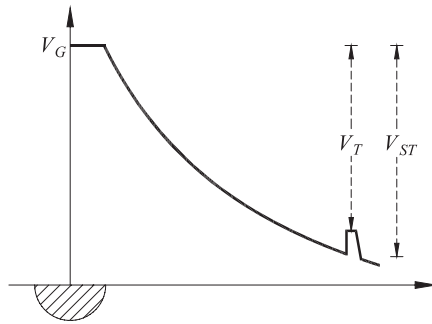


Figure 1.15 Distribution of the ground-potential with a person standing in a region at zero potential.

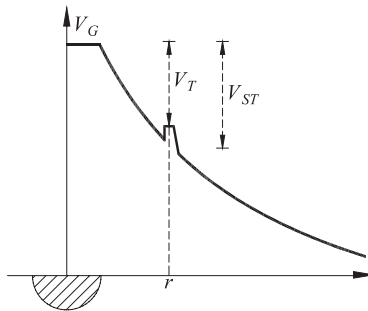


Figure 1.16 Distribution of the ground-potential with person standing in a region at non-zero potential.

In this case, the prospective touch voltage V_{ST} is less than V_G , even though the person's hand is still at the potential V_G . The person's feet, in fact, will be at a higher potential, with an evident reduction of both prospective and touch voltage.

A possible hazardous situation is when the person, although standing in a non-zero potential area, may also be in contact with a conductive part at zero potential. Such parts, defined as *Extraneous-Conductive-Parts* (EXCPS) [28, 29], may include water pipes, exposed metallic structural parts of the building, etc.

EXCPS may have a very low resistance-to-ground R_{EX} , such that $R_{EX} \ll R_{BG}$, therefore, if contacted, they may completely bypass the person's body resistance-to-ground. The person is therefore subjected to a greater touch voltage, and if R_{EX} were zero, the touch voltage would equal V_{ST} (Figure 1.17).

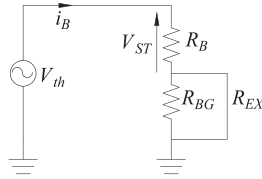


Figure 1.17 Equivalent circuit for the computation of body currents in the presence of an EXCP.

Example 1.1 A hemispherical electrode of radius $r_0 = 2$ m is buried in the ground of resistivity $\rho = 200 \text{ } \Omega\text{m}$ and connected to a tower crane (Figure 1.13). A person is standing 10 m away from the center of the hemisphere and holding a metal hook electrically connected to the hemisphere. A ground-fault causes a current $i = 100$ A to flow into the earth through the hemisphere. Determine the electric current i_B through the person’s body in the case of touch, assuming a conventional body resistance of 1 k Ω .

Solution

From Eq. 1.9, the ground potential rise of the hemisphere is:

$$V(r_0) = \rho \frac{i}{2\pi r_0} = 1,592.4 \text{ V}$$

The touch voltage is $V(r_0) - V(r)$, where $V(r)$ can be calculated with Eq. 1.8 with $r = 10$ m.

$$V(r) = \rho \frac{i}{2\pi r} = 477.7 \text{ V}$$

$$V_t = V(r_0) - V(r) = 1114.6 \text{ V}$$

From Eq. 1.16, the body current with $R_B = 1 \text{ k}\Omega$, and $R_{BG} = 1.5\rho = 300 \text{ } \Omega$, is:

$$i_B = \frac{V_{th}}{R_B + R_{BG}} = 857.4 \text{ mA}$$

1.10 Identification of *Extraneous-Conductive-Parts*

With the purpose of reducing touch voltages, applicable standards require that in each installation main protective bonding conductors connect to the main ground busbar the EXCPs, which may include: metal installation pipes for gas,

water, heating, etc.; non-insulating floors and walls; exposed metallic structural parts of the building. These items are mere examples of conductive parts that may require the protective equipotential bonding; the identification of EXCPs is crucial for safety and a verification if conductive parts are EXCPs is necessary before connecting them to the ground busbar.

BS 7671⁸ defines an EXCP as “a conductive part liable to introduce a potential, generally earth potential, and not forming part of the electrical installation.”

The term *earth potential* is generally assumed to be zero volts and introduced by the general mass of the earth into the installation. This definition implies that such conductive parts would originate outside the building and be in contact with the ground. If this can be verified by visual inspection, the part in question should be bonded as close as practicable to their point of entry within the building. It is important to clarify that for bonding purposes, the point of connection of pipework should take place along the section of the pipe from the meter into the building, which is owned by the user, and not on the section that comes in from the road into the meter. This prevents corrosion issues to the service pipework.

If it is not possible to verify by visual inspection alone that a conductive part is an EXCP, a measurement of the resistance R_{EX} between the conductive part in question and the main ground busbar should be performed. If the measured resistance R_{EX} satisfies Eq. 1.18, based on the circuit of Figure 1.16, the conductive part in question is not to be considered an EXCP.

$$R_{EX} \geq \frac{V_{th}}{I_{BM}} - R_B \quad (1.18)$$

V_{th} is the nominal voltage to ground of the installation (in V); R_B is the standard value of body resistance of 1 k Ω ; I_{BM} (A) is the maximum value of body current that is deemed acceptable to the designer. Threshold values for I_{BM} may be 0.5 mA (i.e., the threshold of perception), 10 mA (the threshold of let-go), or 30 mA.

However, the designer should assess if the measured resistance to the ground of the concerned conductive part may change (i.e., decrease) throughout the lifetime of the installation.

If, for example, the chosen threshold of safe current is 30 mA with $V_{th} = 230$ V, and the measured resistance between a conductive part not forming part of the electrical installation (a presumed EXCP) and the ground is greater than 6.67 k Ω , then no connection to the main ground terminal of the metal part in question would be required.

⁸ BS 7671:2018 “Requirements for Electrical Installations”.

It is important to recognize that the indiscriminate connection to the ground terminal of mere conductive parts that are not EXCPs may cause fault potentials to be transferred throughout the installation. This can cause the risk of electric shock for persons standing outside of the installation that is in contact with the presumed EXCP that has become live (e.g., a metallic fence).

1.11 Measuring Touch Voltages

Measurements after construction of the installation can verify the adequacy of the electrical design of the substation [30]. Measuring touch voltages [31–33] includes two choices: measure the prospective touch and step voltages, by using a high-impedance voltmeter, or measure the effective touch and step voltages occurring across an appropriate resistance of 1 k Ω , which represents the human body.

For touch voltage measurements a current injection method may be used (Figure 1.18).

An alternating voltage of approximately the system frequency is applied between the facility ground electrode and an auxiliary ground electrode, located far enough to guarantee separate zones of influence (e.g., 4 or 5 times the maximum dimension of the facility ground electrode). A test current i_m is injected into the facility grounding system, which causes a measurable ground potential rise.

The test current should be so high that the measured touch voltage, referred to as the test current, is greater than possible disturbance voltages; according to EN 50522, this may be ensured for test currents of at least 50 A. Always according to EN 50522, the measuring electrodes for the simulation of the feet, connected in parallel, must have a total area of 400 cm², lie on the ground with a minimum

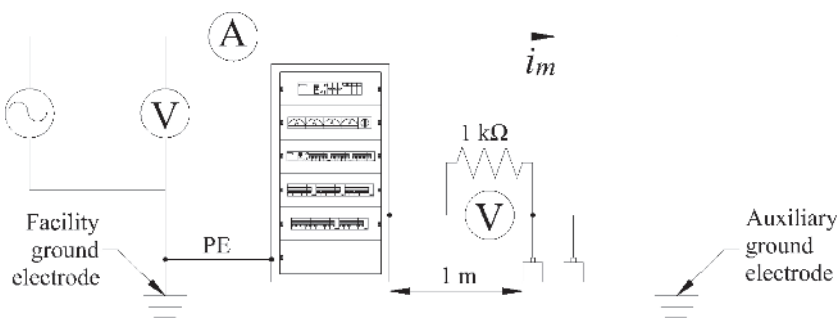


Figure 1.18 Touch voltage measurement with the current injection method.

total force of 500 N, and placed at a distance of 1 m from the equipment of the installation, or from an EXCP. During the test, the auxiliary ground electrode may assume a dangerous ground potential rise, and therefore should be guarded.

The tip-electrode for the simulation of the hand touching the equipment, or an EXCP, must be capable of penetrating a paint coating (not insulation).

The reading of the voltmeter, which is referred to as the test current, must then be scaled up by multiplying it by the ratio of the effective ground-fault current provided by the utility to the test current.

The touch voltage measurement should be performed in the substation, as a sampling test, keeping in mind that higher magnitudes for the touch voltages may be found around the edge of the ground grid.

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