Electric Shock in Presence of Water

"Compared to a dry fault, [in presence of water] current passes through a usually larger body surface."

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1. Introduction

Figure 1. The electrical conductivity of the internal tissues of a human body is higher than the conductivity of fresh water but lower than the one of sea water.

Electrical installations may be subject to earth faults, that is, small albeit dangerous currents that may find a way to ground throughout the body of a person. ABB white paper [1] is entirely dedicated to the protection against earth faults in general conditions. Risks increase in humid environments and, even more, in presence of water. The present guide is dedicated to electric shock when persons are totally or partially immersed in a volume of water, or when their skin is wet. Also in this case we refer to LV circuits. The reader is referenced to [1] for all the basic concepts, including a short account on Residual Current Devices (RCD).

1.1. Conductivity of water vs. human body

The presence of water is dangerous due to the increased electric conductivity of water compared to air. The conductivity of water ranges from 2×10^{-4} to 5×10^{-2} S/m for fresh water and up to 3÷6 S/m for sea saltwater. Water is hence much less conductive than metals ($>10^{6}$ S/m) and much more conductive than common insulation material ($<10^{-14}$ S/m). The average conductivity of an internal tissue in human body, that is wet and salty, ranges from 0.1 to 0.2 S/m, i.e., it is higher than the conductivity of fresh water. The internal body resistance from hand to feet is around 300÷500 Ω. The skin envelops the internal tissues and, when dry, has a relatively low conductance per unit surface, around 5÷10 S/m^{2}. As a result, the total resistance of a human body, inclusive of dry skin contribution, is around some kΩ. Despite dry skin offers a non-negligible barrier to electric conduction, the picture drastically changes when the skin is wet.

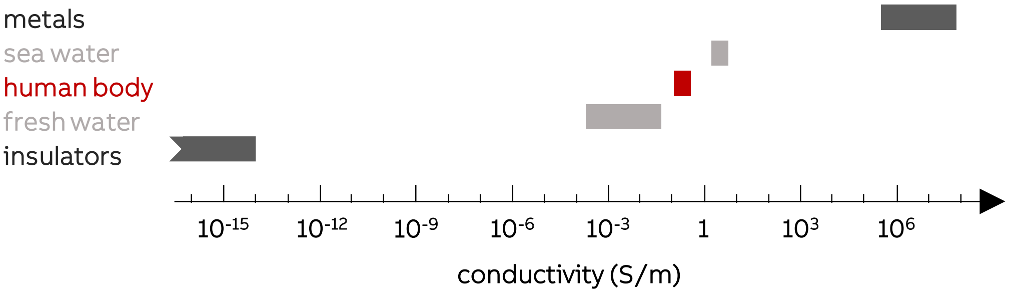

Figure 1.

1.2. Electric conduction across wet skin

The presence of water interposed between a live conductive part and a human skin strongly drops skin resistance. The reason is at least twofold. On the one side, water dissolves any salt, that may be present on the skin, into ions, that are charge carriers, thus increasing skin surfacic conductance (to more than 150 S/m^{2}). Saltwater clearly produces a larger effect. Furthermore, water fills air gaps in between contacting surfaces, thus enlarging the actual contact surface.

1.3. Electric conduction in a volume of water

The danger of water is furtherly increased when the body is immersed in it. If a live part is in contact with water, which is already in contact with ground (e.g., the basin bottom) or with another live conductor, then an electric field distributed throughout the volume of water will drive a current flow. While in an electric network the current flows along conductors, in water the current will distribute throughout the volume. A person in contact with an electric network adds an additional current path. A person partially or totally immersed in water alters the current flow through water, for some of the current flows through the body. This holds even if the person is not touching any conductor. See Figure 2 for a couple of reference and hypothetical cases, where Maxwell governing equations have been solved numerically by means of the finite element method (FEM).

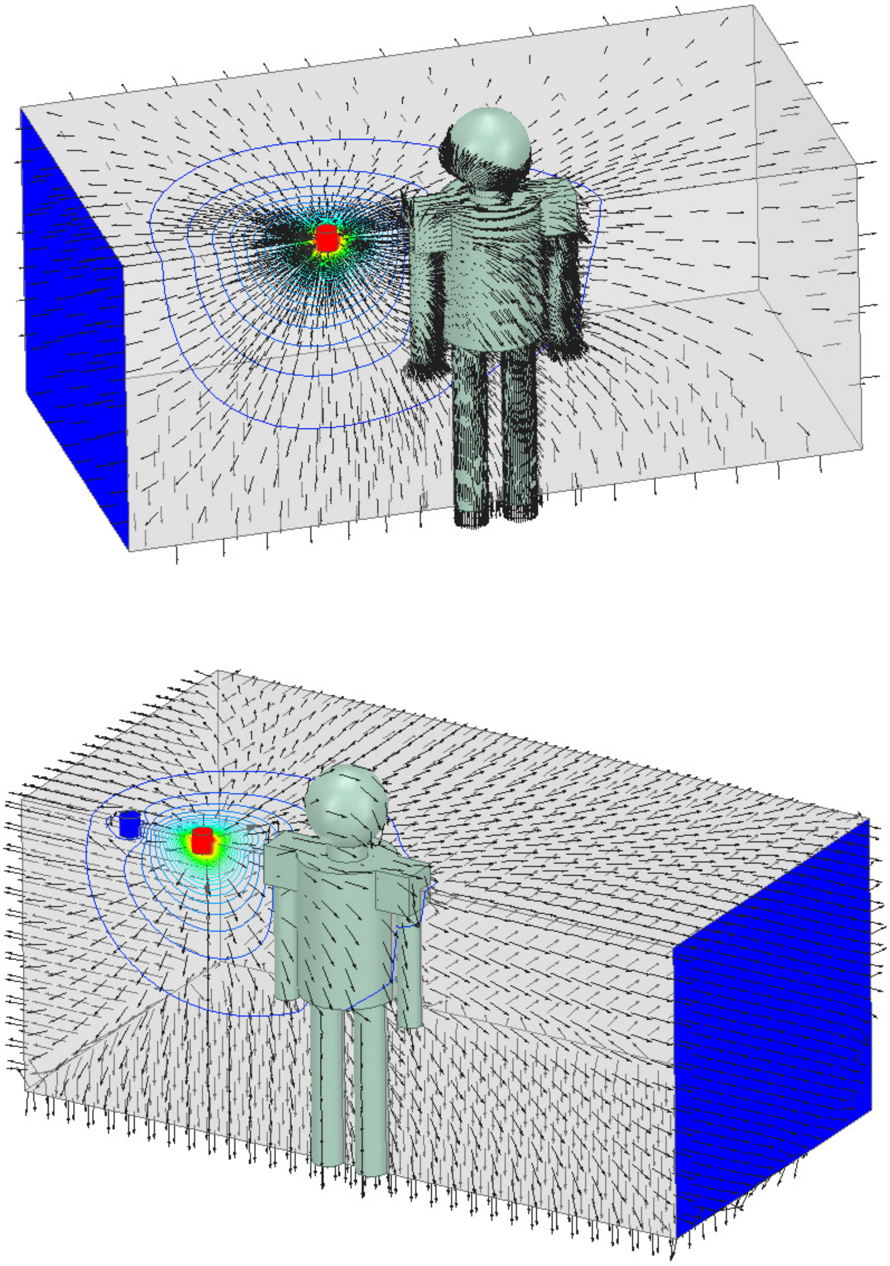

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Figure 2. Electric conduction in two reference and hypothetical cases, featuring a person (grossly approximated) standing and partially immersed to shoulders level in a box-shaped volume of fresh water (light gray, only half is shown, to focus on a vertical cross section through the person). Colors are representative of voltage, whose isovalue surfaces are outlined; black arrows represent current density flow. Basin sidewalls and bottom surface are at earth voltage (0 V, blue), a phase conductor (230 V, red) and, in the bottom picture, a neutral conductor (0 V, blue) touch water free surface (connecting cable not shown). Both cases have been solved numerically by means of the Finite Element Method (FEM), with the code Maxwell3D by Ansys®. As apparent, a significant portion of current flows back to source through person's body, even without any contact with a live part.

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Figure 2.

2. Earth faults in presence of water

Water-related electrical shocks generally occur according to a combination of three mechanisms, corresponding to different fault loops from the source (the substation transformer), to the victim and back to source.

2.1. Fault with direct or indirect contact to live part

Figure 3: Exemplary situations leading to electric shock with a person partially immersed in water touching a live part:
a) Person having a bath touching an electric appliance out of the water;
b) Person standing in a puddle while using a faulty electric tool (e.g. a drill).

The first mechanism of shock involves a person, partially in touch with or immersed in water and in contact with earth potential, reaching out of water and contacting a live conductive part (direct contact) or the metal enclosure of an appliance that had become hazardous live due to an internal loss of insulation (indirect contact). Figure 3 shows two possible examples.

As described in Section 1, water reduces the impedance of the body to true earth, by enlarging the real contact surface and by diminishing the interface resistance. Larger water-wet body parts and higher salt content result into higher currents. Additional factors, such as the presence of metal pipes, the insulation of the soil, grout lines and many more, contribute to making fault currents hard to predict. If the entire body is water-wet, the total body resistance from hand to feet may reduce to only 300÷600 Ω, implying currents higher than 500 mA in a 230 V network.

Assuming that a high sensitivity RCD be installed and depending on the total fault loop resistance (including the highly unpredictable resistance R_c of the contact between hand and energized object), three circumstances may occur. If current is lower than 10 mA, the risk of immobilization is low, the person can detach his hand from the electrified object and interrupt autonomously the electrical shock. If current is high enough (e.g., ≥ 30 mA), the RCD trips quickly and strongly reduces the risk of an electrical injury.

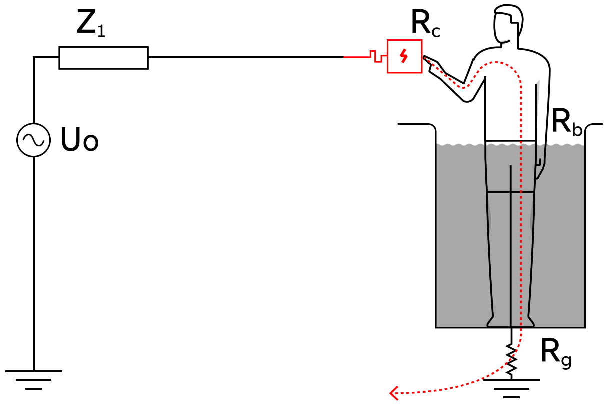

Figure 3a.

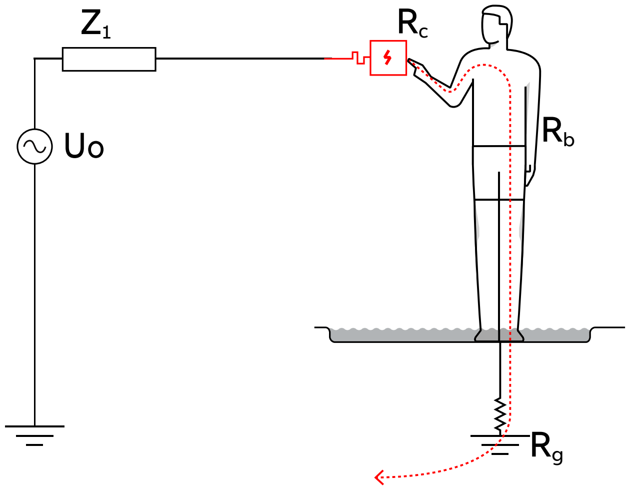

Figure 3b.

2.2. Contactless fault with one live part

The second shock mechanism occurs when a live conductive part (e.g., 230 V) is in contact with a volume or a film of water in which a person is totally or partially immersed or enveloped. Figure 4 shows some examples. In all illustrated cases, the person is not in direct contact with a live conductive part but is subject to the voltage gradient of the electrified water. Water plays the role of an interposed resistor electrically bridging the live part to the person and to ground. A strong enough voltage gradient results into a dangerous current through the human body.

If the electrified water volume is large compared to the body (e.g., a swimming pool), the voltage gradient across the body may be rather low, the surface of the body is substantially equipotential and little current pierces it (meaning, current finds others ways around the person). On the other hand, for the same applied voltage, a small water extension (e.g., a bathtub) creates a higher voltage gradient and thus higher current through the body. Consequently, the higher risk for human life occurs when a person is having a bath or a shower. Indeed, most deaths by electric shock in home environments occur in the bathroom. The role of a continuous film of water to envelope the body and create a large interface surface, for instance when having a shower, must not be underestimated. A somewhat similar case may be a person wearing soaked clothes, for instance because of the rain. Electric current may also easily enter a water-wet body through mucous membranes, such as the mouth.

As the average resistivity of a wet human body is slightly lower than the resistivity of fresh water, at the boundary between body and water current preferably enters the body, instead of sliding tangentially (a human body “attracts” electricity). The problem is made complex by several factors, most notably by the salinity of water. Therefore, if the person is having a bath in the sea, owing to the high conductance of saltwater, which is greater than that of human body, current may flow around instead of throughout the body. Nonetheless, for the same applied voltage, salt increases total current flow and therefore it reduces but does not eliminate the possibility of electrical injury.

Compared to a dry fault, here current passes through a usually larger body surface. Furthermore, the current path generally involves head and chest, thus electrifying vital organs such has brain, heart, and respiratory muscles. Consequently, the “conventional” current paths through the body (i.e., hand to feet, hand to hand), based on two limited contact areas, are no more realistic. Likewise, the traditional safety current thresholds (i.e., 10 mA for immobilization, 30 mA for ventricular fibrillation), based thereon, are not rigorously applicable. Pathological, lethal effects of electricity (tetanic contraction, respiratory paralysis, ventricular fibrillation, etc.) may occur for currents lower than in ordinary conditions. If the water volume is large enough (e.g., a sea, a lake, a large bathtub, a swimming pool), the electric shock, even if not lethal per se, may cause loss of muscle control and lead to death by drowning.

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Figure 4: Exemplary situations leading to electric shock with a person partially or fully immersed in water but not directly touching a single live part:
a) A person having a bath with an electric appliance (e.g., a hairdryer) connected to 230 V ssocket-outlet and falling into the water;
b) A person swimming near a marina with water electrified by a faulty boat, connected to the marina’s power supply;
c) A wall mounted electric equipment (e.g., a wall switch or a water heater) without appropriate IP protection, under a sustained water dripping creating an electrified water layer that covers the equipment itself, the wall, the floor, and a person having a shower (or under the rain); d) A puddle electrified by a faulty underground cable, with a person walking or standing over and being subject to the voltage difference between feet, termed step voltage.

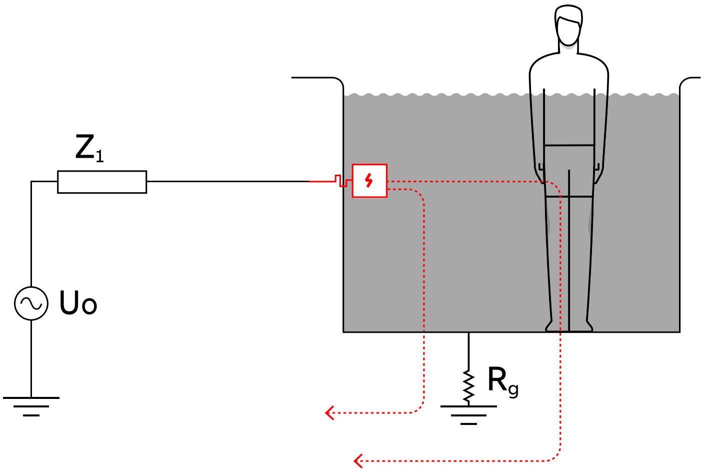

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Figure 4a.

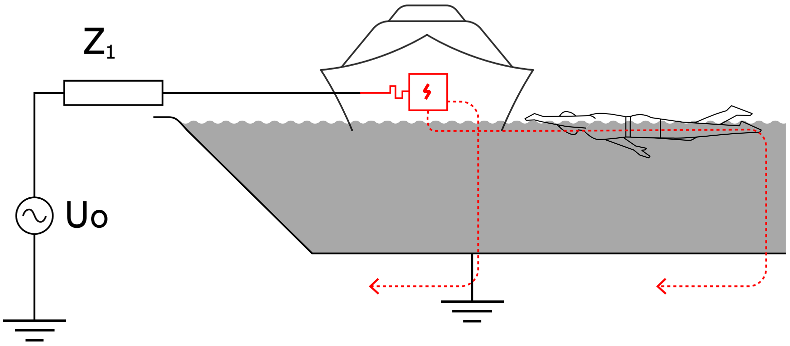

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Figure 4b.

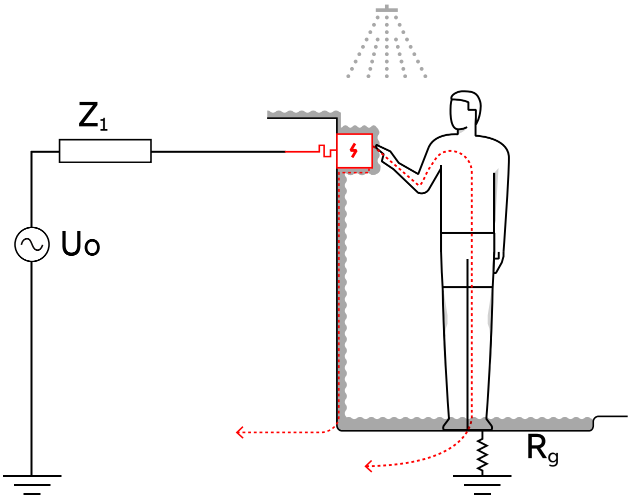

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Figure 4c.

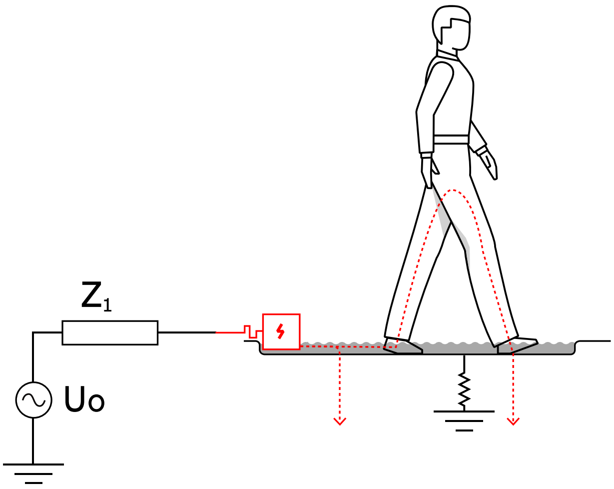

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Figure 4d.

2.3. Contactless fault with multiple live parts

The third shock mechanism is similar to the second one but with the important difference that water is electrified by the contact with two or more live conductive parts having different voltage. Figure 5 shows the typical case of an appliance (e.g., a hairdryer) connected to phase (230 V) and neutral (0 V) that has fallen into water. If both phase and neutral come in touch with water, then the latter creates and electrical bridge from phase to neutral, while only a fraction of the total fault current flows back to source through water and earth. Similar conclusions hold in the (less common) case of three phase appliances, the role of neutral possibly being played by a second phase.

As the impedance of the neutral is generally way lower than the impedance of earth, most of the current actually flows back to source through water and neutral, undetected by RCDs; See [1] for reason and detail. In some cases, the electrified water could be totally or largely insulated from earth (e.g., a bathtub made of insulating material, not connected to walls, pipes, or floor) and no or little current flows to earth. In general, the size of water region affected by the phase-to-neutral reclosing path is proportional to the distance between the two conductive parts (i.e., roughly, to the dimension of the immersed equipment). If a person immersed in water is close enough to such region, it may be affected by a body current undetectable by RCDs. This situation is similar to a well-known bipolar direct dry contact, when the RCD cannot trip.

In conclusion, the danger of the third mechanism depends on the share of undetectable residual current (phase-to-neutral) vs. phase-to-earth, and on the collocation of the person with respect to both fault paths. As for other factors, such as the presence of salt, similar considerations hold as for the second mechanism, contributing to make the scenario rich in complexity.

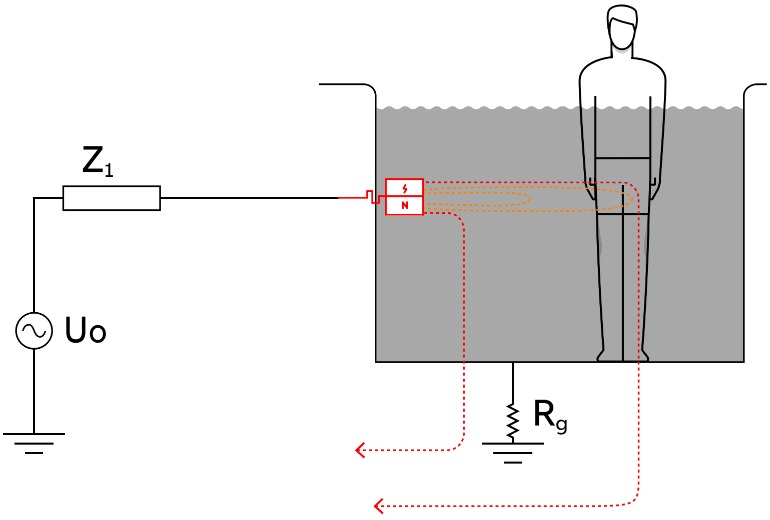

Figure 5.

Figure 5: Exemplary situation leading to electric shock with a person partially or fully immersed in water electrified by two (or more) live parts: a hairdryer falls into a bathtub; most of the current (yellow) flows from the phase to neutral, undetected by RCDs, and only part (red) flows to ground.

3. Installation recommendations

Not surprisingly and owing to the increased electric shock risk, international standards dedicate specific and more severe requirements and recommendations to the design, erection, and verification of low-voltage electrical installations in presence of water. General provisions are in IEC 60364 [2]. National standards, based thereon, may modify or complete such stipulations, not infrequently making them stricter.

3.1. Bathrooms

As mentioned, bathrooms are, within a household, the places most prone to electric shock. They are discussed in IEC 60364-7-701 [3], where zones are defined with progressively stricter provisions, basing on proximity and exposition to water; See Figure 6 and refer to national standards for exact details. The zonal approach controls if the placement of electrical devices is limited or forbidden, as outlined in the following. As it will be apparent, the “usual” electrical appliances commonly installed in dwellings, including socket-outlets, switches, etc., cannot be installed within zones 0, 1 or 2.

Zone 0, area that can hold an amount of water where a person is expected to be immersed or enveloped, partially or totally (e.g., bathtub interior, shower tray). Generally, no current-using equipment may be installed. The only accepted exceptions are explicitly declared suitable to zone 0. They must be supplied by a Safety Extra Low Voltage (SELV) source (not exceeding 12 V AC or 30 V DC) located outside of zones 0 and 1. The degree of protection must be at least IPX7 (i.e., the product can be immersed in water up to 1 meter for 30 minutes).

Zone 1, area directly above zone 0, not immersed but under water splashing, occupied by persons having a bath or a shower. Electrical installations are limited to equipment explicitly declared suitable to zone 1. Examples include luminaires, water heaters, ventilation equipment, hydromassage, lifts for the disabled and the like, along with needed junction boxes and fittings. They may be supplied at 230 V, provided that they are permanently connected. Socket-outlets or equipment supplied by Safety Extra Low Voltage (SELV) or Protective Extra Low Voltage (PELV) source (not exceeding 25 V AC or 60 V DC), the source being located outside zones 0 and 1, may be also installed. The degree of protection must be at least IPX4 (i.e., the product has water splash resistance from any direction). Notice that not all IPX4 appliances are suitable to zone 1; Consult manufacturer’s declaration and install according the attached instructions.

Zone 2, area aside zone 1 (up to 60 cm from the border, horizontally), still likely to get wet. Generally, permanently connected equipment with a degree of protection at least IPX4 may be installed. Same limitations as in zone 1 apply for socket-outlets, with the further exemption of shaver supply units complying with IEC 61558-2-5 [5].

Anywhere in bathrooms, electrical equipment that is likely to be exposed to water jets shall have a degree of protection at least IPX5 (water jet resistance from any direction).

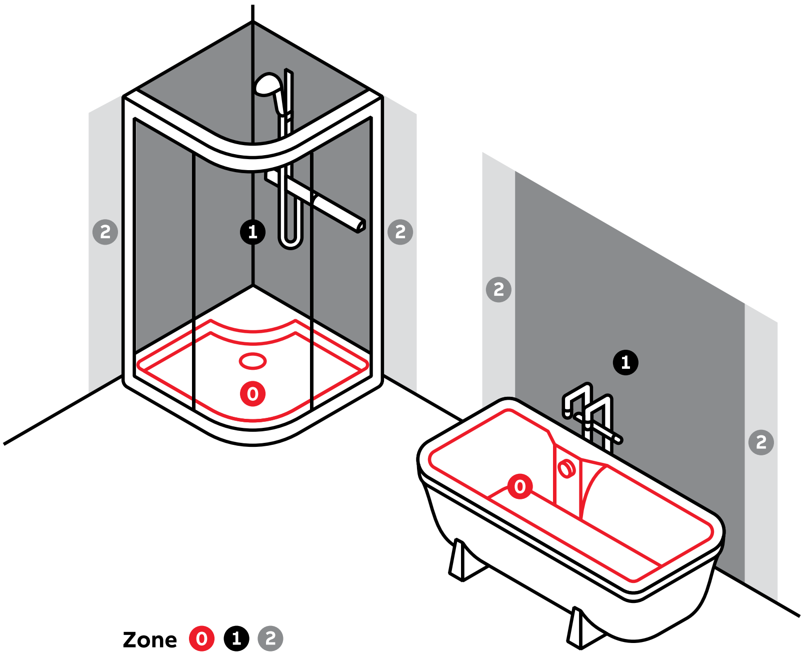

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Figure 6.

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Figure 6. Partition of bathrooms into zones, according to IEC 60364 [2]: as for electrical installations, progressively stricter provisions apply basing on proximity and exposition to water.

3.2. Other areas with presence of water

In some national standards, a similar, zone-based approach applies to washbasins, sinks, bidets, or the like. Generally, these areas are less hazardous because the body is generally not completely water-wet or immersed. Anyway, some reasonable distance between electrical equipment and any washbasins or tap is advisable.

As per IEC 60364-7-702 [4], zones are likewise defined for swimming pools, natural waters, other similar areas and their surroundings, where people presence is expected for bathing, swimming and paddling. Once again, readers are encouraged to refer to their national rules for correct requirements.

3.3. The three-layer protection strategy and the role of RCDs

Provisions according to the zonal approach above are aimed at preventing electric shock by suitably separating electricity from water. This is clearly a first key set of measures, they could be seen as additional measures respect to the ones termed basic protection in the frame of a three-layer protection strategy; See, e.g., ABB white paper [1] and references therein. On top of basic protection, standards prescribe fault protection. In all locations containing a bathtub or a shower, protective equipotential bonding must be installed within the location between all exposed and extraneous metal parts (e.g., metallic pipes or metallic bathtubs). This provides a necessary (but not sufficient) condition for RCDs to operate and grant fault protection by automatic disconnection of supply; See [1].

Finally, on top of fault protection and as further safety provisions in case of failure of basic protection and fault protection, or in case of carelessness by the users, IEC prescribes additional protection: In all locations containing a bathtub or a shower, all circuits shall be protected by RCDs having a rated residual operating current not exceeding 30 mA, or protected by a separation transformer, or by Extra Low Voltage. We shall focus on the first and most common option, i.e., high sensitivity RCDs. When an RCD operates as additional protection, it does not prevent electric shock but, in case, it lowers the risk of injury or death. The 30 mA limit for additional protection was selected by IEC because it prevents ventricular fibrillation, i.e., the main cause of death by electrocution.

As discussed above, the presence of water has the double effect of increasing both person vulnerability to electric shock and the probability of electric shock, due to additional fault mechanisms not occurring in dry conditions. We observed that water or humidity generally increase the total earth fault current. Nonetheless we also outlined the possibility, for instance with the third fault mechanism discussed in section 2 (contactless fault with multiple live parts), that a non-negligible amount of the earth fault current flowed back to source without passing through the ground. As a result, it may happen that the earth fault current detected by an RCD rated 30 mA be below its trip threshold. Still, a person may be subject to a permanent current able to induce strong muscular contractions, pain, respiratory difficulties, and inability to move autonomously. Furthermore, indirect effects shall be considered in water, as inability to leave the bathtub or drowning.

For these reasons, it is advisable for additional protection in applications involving the risk of water related electric shock, to use RCDs rated 10 mA, particularly in presence of more vulnerable persons like children, old people, or sick people. Even if the use of such RCDs is not a general requirement in IEC standards, it is recommended by some country regulations or guidance. To preserve continuity of supply, it is not advisable to protect by a single 10 mA RCD a large amount of equipment or the whole installation. A more convenient practice is to use 10 mA RCDs only for more sensitive applications such as, e.g.:

- 230 V appliances permanently installed in zones 1 or 2 of bathrooms, like water heaters or hydromassage.
- Socket-outlets rated 230 V anywhere in bathrooms (likely to supply portable appliances, such as hairdryers). Locations containing a bath or a shower.
- Socket-outlets rated 230 V likely to supply portable appliances close to water basins or similar, e.g., in the kitchen.

4. Safety tips for end users

Rigorous electrical standards and the adoption **of high sensitivity RCDs** have significantly reduced the risk of fatal or harmful incidents. Nevertheless, every year hundreds of people across the world die from accidents involving water and electricity. These tragedies are often caused by carelessness by the users, who do not keep electricity and water separate enough. Once that electrical installations and equipment are correctly selected, erected and verified by a skilled electrician according to applicable standards, the next step is to follow common-sense tips able to avoid any residual risks.

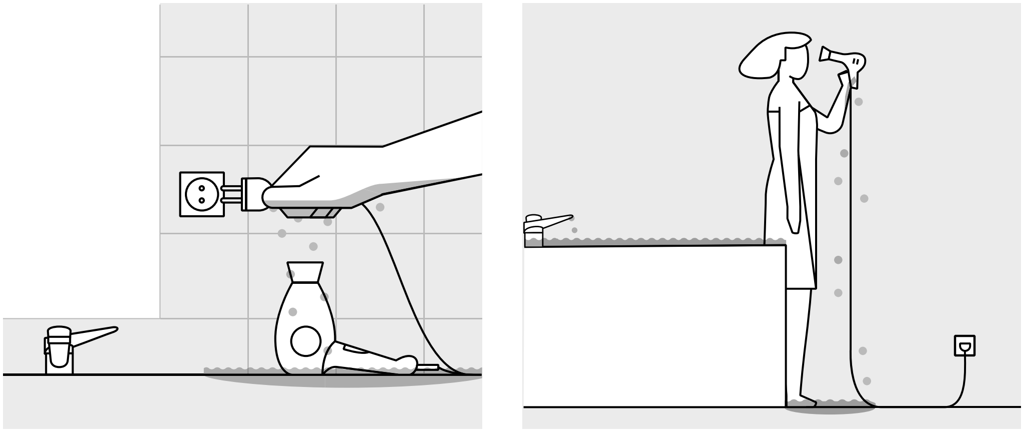
As for **children,** given their natural curiosity and inherent unawareness, given the attractiveness of water and of playing with it or with electrical appliances, parents are encouraged to **educate** them about the dangers of mixing electricity with water.

More generally, caution must always be used when using electric devices and appliances around water, unless the equipment is specifically intended for this condition (refer to instructions). **Never use portable pluggable devices when having a bath or a shower.** Even if installation standards require some distance between socket-outlets and bathtub, shower or swimming pool, the supply cable is long enough to allow the user to move, say, a hairdryer, close to the water. This is a very dangerous situation if a person is immersed or water-wet; See Figure 7, left.

Do not handle plugged appliances if your hands are wet; See Figure 7, right. Mobile phone chargers are also reported to be responsible for electrocutions and must not be used close to a bathtub or shower. Albeit their output voltage should be Safety Extra Low Voltage (SELV), unfortunately, due to the frequently low quality of these cheap devices, the separation from 230 V voltage often fails. **In the kitchen,** keep mobile tools, like a mixer, away enough from sink. In case an electric appliance connected to 230 V socket-outlet falls into a bathtub, pool, or sink, **do not touch** anything and, first of all, **disconnect** supply by unplugging it or by turning the protective circuit breaker off in the electric panelboard (be sure to switch the right breaker!).

Outdoor, do not use any pluggable electric tools, like a mower, **if it is raining or the ground is wet.** This does not apply to device specifically intended for such use like, e.g., outdoor EV charging equipment. Attention shall be given to extension cords or multi-sockets left in the garden.

While swimming in natural water (lakes or seas), keep away from marinas and moored boats with connection for electricity: in case of fault, the boat or the connection cable may leak a fault current through the water, possibly causing muscle paralysis and then drowning.



— Figure 7.

— Figure 7 . Dangerous behaviors to be avoided!

5. References

[1] Earth Fault Protection, ABB Bulletin, 2021 https://campaign.abb.com/l/501021/2021-05-05/t8nzf2

[2] IEC 60364 (series), Low voltage electrical installations.

[3] IEC 60364 (series), Low voltage electrical installations.

[4] IEC 60364-7-701, Electrical installations of buildings - Part 7-701: Requirements for special installations or locations – Locations containing a bath or shower.

[5] IEC 61558-2-5, Safety of transformers, reactors, power supply units and combinations thereof - Part 2-5: Particular requirements and test for transformer for shavers, power supply units for shavers and shaver supply units.

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