

TOUCH AND STEP VOLTAGE HAZARD ANALYSIS

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Abstract

This article analyzes the risks associated with electric shock, specifically focusing on the effects of touch and step voltage, which can lead to severe injury or death. Citing international studies, the research confirms that older individuals typically exhibit a body resistance between 1000-2000 Ω , with exposure to 230 V potentially causing dangerous currents. The study highlights key factors influencing shock severity, including current magnitude, duration, body resistance, and current path. Additionally, the article explores the understudied phenomenon of step voltage, which arises from lightning strikes or electrical faults, and poses significant risks to both humans and animals. Despite theoretical analysis, the lack of real-world data on step voltage's impact on the human body is emphasized. The paper presents a novel approach to evaluating and mitigating these risks by considering soil resistance, current flow, and physiological effects. The reliability of the studies cited is supported by extensive theoretical research, but the article calls for further investigation and the implementation of improved grounding systems and safety protocols to better protect high-risk environments, such as industrial sites and military installations. The findings contribute valuable insights into the understanding of lightning-induced hazards and propose new safety measures for minimizing step voltage dangers.

Key words: touch voltage, step voltage, lightning strikes, electrical resistance, grounding systems, lightning protection, electrical hazards, voltage distribution, nervous system damage, safety protocols, power surges, soil resistivity.

I. Introduction

Electric shock occurs when a person touches an electrically charged object and at the same time comes into contact with another surface that can conduct electric current to the ground. Common sources of electric shock include bare and damaged wires, electrical machines, appliances, conductive cables, and other electrical installations. Proper grounding and the use of electrical safety devices can help prevent electric shock.

According to international studies, 95% of older people have a total body resistance (impedance) in the range of 1000-2000 Ω . When a person with a body resistance of 1000 Ω is exposed to a voltage of 230 Volts, a current of up to 230 milliamperes can pass through the body [1-3]. This current poses a serious and potentially fatal risk (figure 1).

The curves in figure 1 are explained as follows, zone: AC-1 - generally has no effect on humans; AC-2 - generally is not dangerous for the human body; AC-3 - generally has no effect on the body. However, if the current lasts more than 2 seconds, there is a possibility of muscle contraction and respiratory difficulty; AC-4 - with increasing intensity and duration of the current, pathophysiological effects such as cardiac arrest, respiratory arrest and severe burns may occur. AC-4.1 - the probability of ventricular fibrillation of the heart is about 5%; AC-4.2 - the probability of ventricular fibrillation of the heart is about 50%; AC-4.3 - the probability of ventricular fibrillation of the heart is more than 50%.

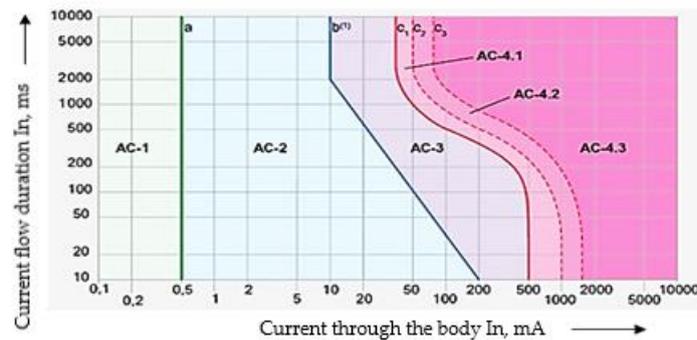


Figure 1. Ampere-time curve showing the effect of alternating current with a frequency of 10-100 Hz on a person

To understand the risk posed by electric current, the following five factors must be taken into account:

- the magnitude of the current;
- the duration of the current;
- the path it takes through the human body;
- the resistance of the body;
- frequency of the power supply.

According to the IEC 61140 standards, two types of dangerous contact are defined: direct contact and indirect contact [22]. Direct contact refers to a person who makes contact with a conductor that is normally under voltage. Indirect contact refers to a person who makes contact with any part of an electrical circuit that is not under voltage but is conductive as a result of accidental damage to the insulation or any other fault.

II. Formulation of the problem

The value of the maximum allowable current, depending on the duration, can be calculated analytically using the following expressions (1), (2).

$$I_b = \frac{0.116}{\sqrt{t_s}} \quad (\text{body mass } 50 \text{ kg}) \quad (1)$$

$$I_b = \frac{0.157}{\sqrt{t_s}} \quad (\text{body mass } 70 \text{ kg}) \quad (2)$$

Equations (1) and (2) were determined based on experiments conducted by Dalziel and it was estimated that 99.5% of the participants could withstand the shock without suffering from ventricular fibrillation. Dalziel's experiments were conducted for a contact time of 0.03÷3 sec. [6-9].

Main part. Touch voltage (U_{touch}) is the potential difference between an object under voltage (for example, the housing of electrical equipment) and the foot of a person touching this object. When a person touches the grounded housing of the equipment in contact with one of the phases, part of the grounding current passes through the person, and if the housing is not grounded, the grounding current passes completely through the person (unipolar touch) [4]. The value of the touch voltage for a person who is on the ground and touches a grounded housing under voltage can be considered as the difference between the potentials of his hand (housing) and his foot (ground) (figure 2). When the current is closed to the case of any equipment, the potential on the ground surface is distributed along a hyperbolic curve (figure 3 and 4).

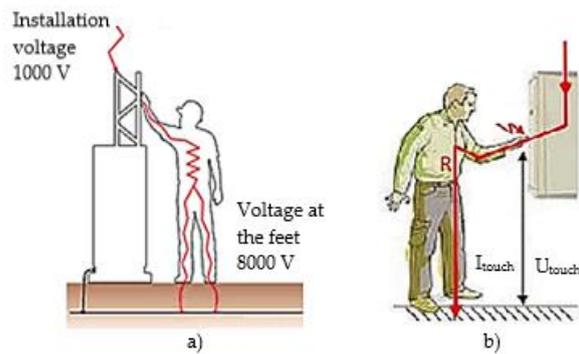


Figure 2. Touch voltage, when the equipment is a) grounded and b) ungrounded

In this case, touch voltage is the difference in potentials between the case of electrical equipment (for example, an electric motor) and the points of the ground surface touched by a human foot [5].

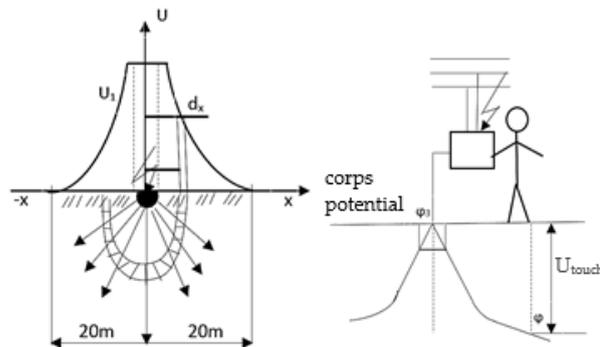


Figure 3. Hemispherical grounding conductor and potential distribution curves on the ground surface

The further the electrical equipment is from the earthing conductor, the greater the touch voltage U_{touch} to which the person is exposed, and vice versa, the closer to the earthing conductor, the lower the touch voltage (figure 4). Outside the current propagation zone (≥ 20 m), the touch voltage is equal to the voltage on the housing of the electrical equipment [11].

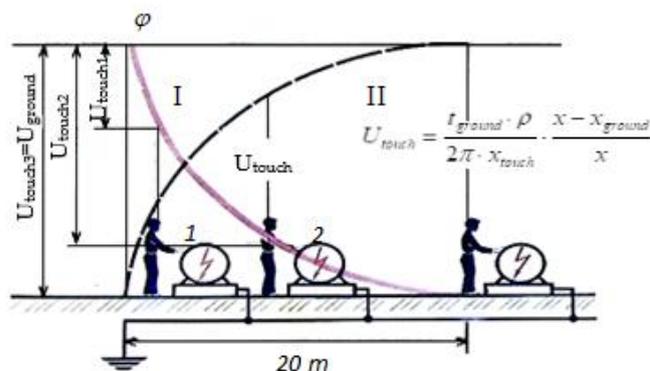


Figure 4. Grounded electrical equipment and touch voltage.
I – Potential distribution curve on the ground surface; II – Touch voltage curve

III. Problem solution

When a person standing on the ground touches a grounded body that is under voltage, the contact voltage can be calculated using the following expression (3) [12-15]:

$$U_{touch} = \varphi_{hand} - \varphi_{ground}, \quad (3)$$

where φ_{hand} is the potential of the hand and body (4):

$$\varphi_{hand} = U_{ground} = \frac{I_{ground} \cdot \rho}{2\pi \cdot x_{ground}}; \quad (4)$$

φ_{ground} is the potential of the ground on which the person is standing (5):

$$\varphi_{ground} = \frac{I_{ground} \cdot \rho}{2\pi \cdot x}; \quad (5)$$

ρ is the specific resistance of the ground. Taking into account the value of potentials (6):

$$U_{touch} = \frac{I_{ground} \cdot \rho}{2\pi} \cdot \left(\frac{1}{x_{ground}} - \frac{1}{x} \right) = \frac{I_{ground} \cdot \rho}{2\pi \cdot x_{ground}} \cdot \frac{x - x_{ground}}{x} = U_{ground} \cdot a_1. \quad (6)$$

Here $a_1 = (x - x_{ground})/x$ is the coefficient of contact voltage for a hemispherical ground electrode (figure 2). A similar coefficient (β_1) is calculated for step voltage. These coefficients are determined experimentally for particularly complex group ground electrodes, which are distinguished by their hemispherical shape. This expression allows calculating the contact voltage without taking into account the resistance of the supporting surface of the foot (R_{foot}) and the resistance of the shoe (R_{shoe}). The influence of these resistances can be determined by the coefficient a_2 . This coefficient takes into account the voltage drop across additional resistances in the human circuit (7):

$$a_2 = \frac{R_{body}}{R_{body} + R_{foot} + R_{shoe}} = \frac{R_{body}}{R_{total}}, \quad (7)$$

where R_{body} is the resistance of the human body, R_{total} is the total resistance.

The analog coefficient (β_2) calculated for step voltage is 4 times smaller than the coefficient a_2 calculated for touch voltage (8), i.e.:

$$a_2 = 4 \cdot \beta_2. \quad (8)$$

The full expression for the touch voltage is (9):

$$U_{full.touch} = U_{touch} \cdot a_1 \cdot a_2. \quad (9)$$

If there is a grounding conductor for electrical equipment (figure 4), when a person touches electrical equipment outside the zone where the current flows, the touch coefficient $a_1=1$, then $U_{touch}=U_{max}=U_{ground}$ (not taking into account the coefficient a_2).

Touching a housing that is under voltage and outside the field distribution is the most dangerous situation for a person.

The current flowing through a person exposed to touch voltage can be calculated as (10):

$$I_{body} = I_g \cdot \frac{R_{ground}}{R_{body}} \cdot a_1 \cdot a_2, \quad (10)$$

where R_{ground} is the resistance of the grounding conductor.

In the indicated cases, a step voltage (U_{step}) also arises. The greatest step voltage arises near the grounding conductor, especially when a person stands on the grounding conductor with one foot. On the same equipotential line or outside the potential distribution area ($x > 20$ m), the step voltage is equal to zero. The value of the step voltage is much less than the touch voltage [19].

Experience shows that:

- if the distance between the person servicing the electrical installation and the grounding conductor is equal to or greater than 20 m (figure 4, case 3 $x \geq 20$ m), then the potential in the base (ground) will be equal to zero. In this case, the touch voltage is maximum and equal to the grounding potential;

- if the distance x is zero (figure 3, case 1, $x=0$); then the potential at the base is equal to the potential at the grounding conductor, and the touch voltage will be zero.

Thus, considering the step voltage and touch voltage, the following conclusions can be drawn:

- the exposure of a person to danger depends on his distance from the grounding conductor. As this distance decreases, the danger from step voltage increases, while the danger from touch voltage decreases, and vice versa, as the distance increases, the danger from step voltage decreases, while the danger from touch voltage increases;

- in general, touch voltage is more dangerous than step voltage, since the maximum value of the touch voltage coefficient is equal to unity $\alpha_{max}=1$, and the maximum value of the step voltage coefficient is less than unity $\beta_{max} < 1$. In addition, the flow of current through the touch voltage along the "hand-to-foot" path is more dangerous than the flow through the "foot-to-foot" path.

In order to reduce the danger of people from touch voltage, grounding conductors should be installed as close as possible to electrical installations in production areas [16-18].

In engineering standards, the touch distance for calculating the touch potential is taken as 1 m, in dangerous places - 2 m, and in especially dangerous places - even 3 m.

In industrial areas, a technical protection measure is taken to reduce the danger from touch voltage and step voltage at the same time - the potential of the core is equalized. For this, contour grounding with a group of grounding conductors in the form of a grid is used. Vertical grounding conductors are placed at a distance equal to or less than their lengths from each other, i.e. $S \leq L$ (figure 5).

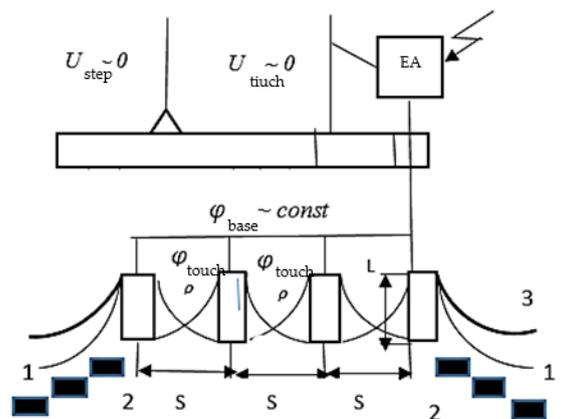


Figure 5. Contour grounding with a group of earthing conductors
1 – natural potential curves; 2 – metal tires; 3 – low-slope potential curves

When the phase is closed to the housing of an electrical installation (EA) connected to a group of earthing conductors, current begins to flow from them along mutually intersecting potential curves 1 (figure 5), their potentials are summed up to form the group potential sum φ_{qr} [7, 8]. As a result, at each point of the foundation of the production area, an almost identical potential is created, equal to the potential of the EA housing: $U_{base} \approx \text{const}$. Thus, the values of the touch and step voltages will be close to zero: $U_{touch} \approx 0$ and $U_{step} \approx 0$. To reduce the step voltage outside the contour, additional metal tires 2 are laid in the ground along the transitions, as a result of which the potential decrease goes along a more sloping curve [20].

In order to protect against various types of hazardous conditions, the following measures should be taken: do not assume that a fallen wire is safe just because it is in the ground or does not create a spark; don't assume that any insulated wires are just telephone, television or fiber optic cables; low-hanging wires are still live even if they are not touching the ground, so don't touch them; never approach a fallen electrical appliance or a downed power line. Always assume that it is live. Touching it can be fatal; electric current can travel in a circular pattern from the point of contact to the ground. The greater the distance from the center, the greater the voltage difference; never drive over downed power lines. Assume that they are live; if you are in a car and come into contact with a live power line, stay calm and do not get out unless the car is on fire. Call for help if possible; if you have to leave any equipment for fire or other safety reasons, try to jump completely clear, making sure not to touch the equipment or the ground at the same time.

To minimize the path of the electric current and avoid electric shock, land on both feet and walk away in small steps. Be careful to maintain your balance [12].

Step voltage is the potential difference between two parts of the earth. This physical effect has not been sufficiently studied, despite the fact that the surge voltage that occurs between parts of the earth due to lightning strikes, breaks and falls of power lines to the ground and other causes is very dangerous. Since the specific electrical resistance of the soil is not zero, the current in each case "flows" in the soil, creating a zone of high potential. If there is a conductor on the ground, an electrical short circuit may occur. Such a conductor can also be a person on the ground, in which case the current enters one leg and exits the other, turning the human body into an "electric charge". This is very dangerous, since high voltage can cause muscle paralysis. As a result, a person can fall to the ground on his hands, and with subsequent lightning discharges, the current can pass through the heart area, increasing the risk of cardiac arrest. When a person's head touches the ground, the risk of irreversible damage to the central nervous system increases. Step voltage is more dangerous for large horned animals, because the distance between the front and hind legs of these animals is very large, and accordingly, the voltage falling on this distance is also high. There are not many cases of death from step voltage in such animals. Note that if the earth's surface has a high resistance (rocky or dry sandy area, etc.), the voltage can instantly spread over a wider area when lightning strikes, and animals can die at a greater distance from the lightning strike. The specific electrical resistance of some parts of the earth's surface is shown in Table 1 [4-6].

Table 1. Specific electrical resistance of some parts of the Earth's surface ($\Omega \cdot m$)

| | |
|------------------------|---------------------|
| Sand | 400 - 1000 and more |
| Sandy clay | 150 - 400 |
| Clay | 8 - 70 |
| Garden soil | 40 |
| Black soil | 10 - 50 |
| Peat | 20 |
| Stony clay | 100 |
| Limestone, coarse sand | 1000 - 2000 |
| Rock, stones | 2000 - 4000 |
| River water (plain) | 10 - 80 |
| Sea water | 0,2 |
| Tap water | 5 - 60 |

Although there are algorithms for accurately determining the step voltage near lightning rods and tall objects, additional knowledge is needed to determine the safety zone. In most cases, lightning strike victims believed that they were not in danger and that their property was protected by lightning rods. Theory is very important, but the decisive parameter for practice is the distance from the arrester at which the step voltage is guaranteed to be safe. It is important to report on the installation of lightning rods and voltage distribution grids. Unfortunately, there is little research on this topic, and in this case, military research in the field of lightning is of great importance. This is due to the fact that in military units of different countries, in different climatic zones and weather conditions, lightning often strikes lightning rods in armories, near tents where equipment and military personnel are located. Accurate recording of these events allows us to collect useful statistics. The 2002 US Army TRADOC Lightning Protection Guidelines state that there have been deaths from power surges within 10-20 m of a lightning strike. In most cases, the lightning strike was not caused by the direct impact of a lightning discharge, but by a power surge and arc discharges from devices [7].

The calculation of the expected step voltage value is provided by a special warranty program and the corresponding service of specialists. Step voltage, as we have already mentioned, depends on the current strength and the specific resistance of the earth. Dangerous power surges can occur near the grounding of electrical equipment during an emergency shutdown. Therefore, the permissible resistance value of grounding devices and the specific resistance of the soil should be standardized [21-23].

As we have already mentioned, when loading a step, the leg muscles contract strongly, as a result of which a person falls to the ground, and as a result, the current begins to flow through new points of support - for example, from the hands to the feet, which can lead to death [18].

The likelihood of being struck by a power surge can be reduced by observing the rules of behavior in the danger zone. To do this, you must be free of potentials on the ground. Therefore, the distance between the legs should be reduced to a minimum and in no case should you touch the ground or various objects (steel supports, reinforced concrete walls, etc.) with your hands. In emergency situations, i.e., if lightning suddenly strikes a lightning rod or tall objects, if you are near them, you should move away in very short and tight steps ("walk like a goose"). Sometimes it is recommended to stand on one leg, but in this case, an unstable body position can lead to falling on your hand or instinctively grabbing an object. Due to the above physiological reasons, it is absolutely forbidden to allow current to flow along the head-to-leg or arm-to-leg circuit, since this can damage the brain and heart. Therefore, in such conditions, you must stand with your legs tightly pressed together. The voltage step depends on the resistance of different soil layers, although it can be roughly calculated. The short-circuit current in the event of a break in one phase of the high-voltage wire and a fall to the ground can be calculated using expression (11):

$$I_q = \frac{U_f}{\sqrt{3(R_0 + R_{cont})}}, \quad (11)$$

where U_f is the phase voltage, R_0 is the resistance of the neutral to the operating voltage (several Ω), R_{cont} is the resistance to the flow of current at the contact point (usually 12 Ω) [12].

The potential of the contact point at any point x on the earth's surface is given by expression:

$$\varphi_x = U_x = \frac{I_q \cdot \rho}{2 \cdot \pi \cdot x}, \quad (12)$$

where p is the resistance of the ground layer. Considering that $\rho = k = \text{const}$. Obtain expression (13):

$$\varphi_x = U_x = \frac{k}{x}. \quad (13)$$

The expression (13) is a hyperbolic equation, meaning that the potential of points on the earth's surface varies according to a hyperbolic law.

When lightning strikes a lightning rod or the housing of electrical equipment falls under the AG, the potential of point t on the surface of the grounding device (voltage on the grounding device) will have a maximum value, which is shown in expression (14):

$$\varphi_t = \varphi_{\max} = U_t = \frac{I_q \cdot \rho}{2 \cdot \pi \cdot x_t} = I_t \cdot R_t, \quad (14)$$

where $R_t = \rho / 2 \cdot \pi \cdot x_t$ - is the resistance of the grounding conductor.

The step voltage between points x and x+a can be calculated according to expression (15):

$$U_{step} = \varphi_x - \varphi_{x+a} = \frac{k}{x} - \frac{k}{x+a} = k \cdot \frac{a}{x \cdot (x+a)} = \varphi_x \cdot \frac{a}{(x+a)} = \frac{I_q \cdot \rho \cdot a}{2 \cdot \pi \cdot x \cdot (x+a)}, \quad (15)$$

where p is the soil resistivity (several hundred $\Omega \cdot m$), x is the distance from the lightning strik point or the point where the YG wire falls, a is the length of the step [19-22].

Highly resistive stony, frozen, etc. types of soil are especially dangerous due to their low permeability. When lightning strikes them, very high voltages arise. A person can be struck by tens of thousands of volts of voltage in a normal stride [16].

Being near a building is also dangerous, because the step voltage can spread through the foundation. As can be seen from the graph (figure 2), at a lightning current of 30 kA, the step voltage at a distance of 5 m on a reinforced concrete foundation slab is 4.5 kV. Let us consider that this voltage is within the normative grounding resistance (4 Ω) [12].

In industrial areas, to reduce the danger of step voltage, technical protection measures are taken - they equalize the potential of the core. For this purpose, loop grounding with a grounding group in the form of a grid is used. Vertical grounding conductors are placed at a distance equal to or less than their length, i.e. $S \leq L$ (figure 6).

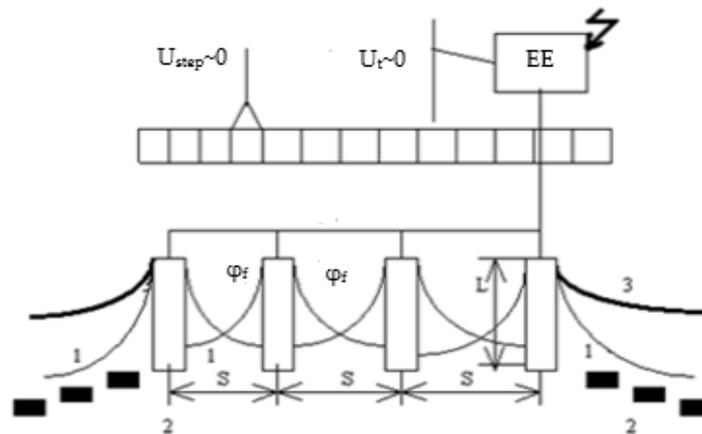


Figure 6. Contour grounding with a group of grounding electrodes

When a phase is shorted to the body of electrical equipment (EE) combined with a group of grounding electrodes, current 1 begins to flow from them along mutually intersecting potential curves (figure 6), their potential is collected and the group potential φ_f is collected. As a result, at each point of the structure of the production zone, a practically identical potential is created, equal to the foundation potential: $U_f \approx \text{const}$. Therefore, the value of the touch and step voltage will be close to zero: $U_{step} \approx 0$ and $U_t \approx 0$. To reduce the step voltage outside the circuit, additional metal

buses 2 are placed along the transitions to the ground, as a result of which the potential drop occurs along a flatter curve.

Thus, the step voltage still remains an additional dangerous effect of a lightning strike. The effect of such microsecond, multiple impulse voltages on the body has been poorly studied. Therefore, a special attitude should be paid to lightning protection and the study of the rules of behavior in risky conditions of a step voltage strike.

Modern technologies allow to significantly reduce the risk of step voltage. Some equipment has an automatic blocking function in case of damage to the electrical network. Such capabilities allow to significantly increase the level of safety and reduce the number of accidents at the enterprise.

In combination, methods of reducing step voltage give excellent results. Automated enterprises working with innovative equipment almost never encounter emergency situations.

The article studies touch and step voltage, a phenomenon caused by the distribution of electrical potential in the ground following lightning strikes or electrical faults [13-15].

The dangerous physiological effects of step voltage are highlighted, in particular its unpredictable and potentially fatal consequences for the human body. It is noted that even low voltages, such as 36 V, can cause serious injuries, including muscle paralysis, cardiac arrest, and damage to the nervous system. The lack of a clearly defined "safe" step voltage threshold is emphasized, indicating the complexity of human resistance and the impact of lightning-induced currents on the body.

The behavior of step voltage as it propagates through the ground is investigated as a function of soil resistivity.

It highlights how different soil types (e.g. rocky, sandy, or frozen soil) affect the step voltage hazard zone, resulting in different distances at which the voltage can affect both humans and animals.

Environmental factors such as soil type can influence the degree of hazard caused by step voltage. In areas with highly resistive soil, the voltage can spread over a larger area, increasing the risk to people and animals further from the lightning strike point.

The availability of theoretical algorithms for calculating step voltage highlights the lack of real-world data on lightning protection systems, especially in areas such as military installations and high-risk industrial environments.

Practical risk reduction measures are suggested, such as the use of grounding systems, metal meshes, and dielectric materials to create zones of equal potential. However, it highlights the need for better designed protective infrastructure to ensure safety.

Placing additional metal bars in the ground along the transitions to reduce the off-loop voltage step results in a steeper potential drop curve.

Overall, the article advances the discussion by highlighting the lack of research on the real-world effects of step voltage, both physiologically and in terms of its wider environmental effects. It suggests more in-depth study and more effective protective measures to prevent fatalities caused by lightning-related surges.

IV. Conclusions

In conclusion, the article provides a comprehensive analysis of the dangers posed by various hazardous electrical conditions, emphasizing the importance of precautionary measures to prevent fatal accidents. It underscores that both direct contact with electrical appliances or downed power lines, as well as indirect hazards such as step voltage, present significant risks to human safety. The article highlights the unpredictability and potentially deadly effects of step voltage, even at low voltages, and its capacity to affect both humans and animals, with the severity of the risk influenced by environmental factors such as soil resistivity.

The reliability of the conclusions drawn from the article is supported by the detailed exploration of the phenomenon of step voltage, the physiological effects it has on the body, and the

analysis of the factors influencing the hazard zone. However, the article also points out the lack of real-world data on the effectiveness of current lightning protection systems and suggests that further research is required to fully understand the environmental and physiological implications of step voltage, particularly in high-risk environments like military and industrial settings.

From a broader perspective, the article calls for a more refined approach to the design of protective measures, emphasizing the need for improved infrastructure, such as better grounding systems and dielectric materials, to minimize the risks associated with electrical hazards. The absence of clear safety thresholds for step voltage indicates a significant gap in the existing safety protocols, suggesting that more robust and scientifically informed safety guidelines are essential to mitigate the risks of electrical hazards.

Overall, the article provides valuable insights into the dangers of step voltage and other electrical hazards, urging for further research, better-designed protective systems, and enhanced public awareness to prevent fatalities and injuries caused by electrical accidents.

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