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Calculation of electric shock current caused by touch and step voltage in grounding grids including climatic conditions

Abstract. *Appropriately designed grounding should provide such a distribution of electrical potential on the ground surface to ensure the values of electric shock currents are at an acceptable level. The potential distribution depends on the design and size of the grounding system and the resistivity of the soil. The value of the electric shock current depends on the distribution of electrical potential on the ground surface determining the values of step and touch voltages and the impedance of the human body. The impedance value of the human body is affected by factors such as the condition of the epidermis, and the path of shock, but also environmental factors such as humidity and temperature. The article presents the results of calculations of human body impedance and electric shock current for different environmental conditions and different design variants of the grounding system, determining the values of step and touch voltages.*

Streszczenie: *Odpowiednio zaprojektowane uziemienie powinno zapewniać taki rozkład potencjału elektrycznego na powierzchni gruntu, aby zapewnić wartości prądów rażeniowych na akceptowalnym poziomie. Rozkład potencjału zależy od konstrukcji i rozmiaru systemu uziemienia oraz rezystywności gruntu. Wartość prądu rażeniowego zależy od rozkładu potencjału elektrycznego na powierzchni ziemi, określającego wartości napięć krokowych i dotykowych oraz impedancji ludzkiego ciała. Na wartość impedancji ciała człowieka mają wpływ takie czynniki jak stan naskórka, droga rażenia, ale także czynniki środowiskowe takie jak wilgotność i temperatura. W artykule przedstawiono wyniki obliczeń impedancji ciała człowieka i prądu rażenia dla różnych warunków środowiskowych i dla różnych wariantów projektowych systemu uziemienia, determinującego wartości napięć krokowych i dotykowych. (**Obliczanie prądu porażenia prądem wywołanym napięciem dotykowym i krokowym w sieciach uziemiających z uwzględnieniem warunków klimatycznych**)*

Keywords: electric shock current, step voltage, touch voltage, human body impedance, grounding grid
Słowa kluczowe: prąd rażeniowy, napięcie krokowe, napięcie dotykowe, impedancja ciała człowieka, uziom

Introduction

A properly functioning electrical power system should ensure the safety of people in contact with elements of the technical infrastructure. This contact may be unintentional and then the threat of electric shock is a particularly significant problem. This occurs when a person is near an element of the technical infrastructure of an electrical power system that is on the voltage. The value of the shock voltage, the time for the shock current to flow through the human body, and the impedance of the human body determine the pathophysiological effects of human electrocution [1 - 6]. The value of the shock voltage is affected by the value of the current flowing into the ground and the distribution of the electrical potential on the ground surface [1, 2, 7-12].

One of the technical measures of electric shock protection is grounding systems. The basic element of the grounding system is the grounding (earthing electrode), whose basic parameter is resistance. The ground resistance value is affected particularly by the design of the grounding system and the resistivity of the soil. Grounding resistance can be determined by analytical methods or by taking measurements for already existing objects [13-21]. The grounding resistance value also depends on changes in the soil resistivity depending on the impact of environmental factors such as humidity or temperature [22, 23] caused by atmospheric factors that depend on the season. The grounding system should be designed and constructed in such a way as to minimize the effect of corrosion of its essential structural components on the resistance value [24].

The shock voltage value depends on the distribution of electrical potential on the ground surface. The potential on the ground surface above the buried ground is caused by the flow of short-circuit current to the ground. Various methods, both analytical and numerical, can be used to calculate the electrical potential distribution on the ground surface [25-27]. Analytical methods can be used to calculate simple grounding system geometries. For more complex grounding system geometries, numerical methods, including the finite element method, are used. Knowing the distribution of electrical potential on the ground surface, it is possible to estimate the values of step U_{STEP} and touch U_{TOUCH} voltages [27, 28]. The flow time of the earthing current depends on the protection settings used in the electrical power system. Figure 1 presents the dimensions of the analyzed grounding grid, along with an illustration of the definition of touch and step voltage.

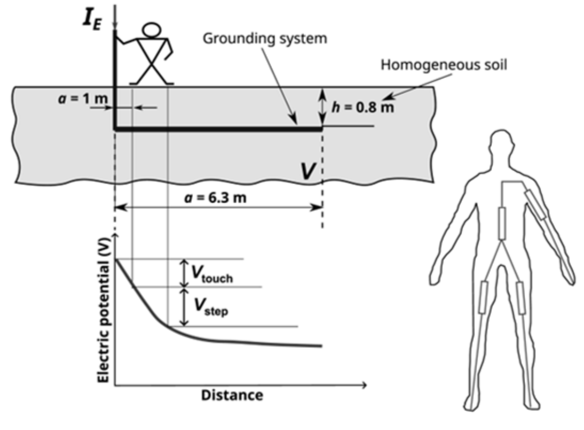

Fig.1. Dimension of analyzed grounding grid and definition of step voltage Vstep and touch voltage Vtouch.

Generally, a human body impedance value of 1000Ω is assumed in the calculation of electric shock currents, according to IEEE 80 [29]. The standard [29] also defines permissible step and touch voltages for human body weights of 50kg and 70kg.

A number of models of impedance or resistance of the human body are described in the literature [1- 4]. Impedance or resistance values calculated with the models are used to calculate the electric shock current flowing through the human body to estimate pathophysiological effects. One of the more interesting methods of determining the impedance of the human body is that described by S. Gierlotka in [4]. The described method takes into account, the path and value of the shock voltage, and the effect of climatic conditions. The value of climate in special units is measured with Hill's catathermometer. It is dependent on temperature, humidity, and air velocity. In this way, it is possible to estimate the effect of climatic conditions on the human body impedance of a person performing work, for example, in the open area of a substation.

The paper presents the results of an analysis of the potential risks to humans from the effects of electric shock currents on their bodies. Calculations of electric shock currents were made for different design variants of a simple grounding system and climate values. For the calculated values of the impedance of the human body, taking into account climatic conditions, the values of electric shock currents were calculated. The value of the electric shock current determines the pathophysiological effects caused by its flow through the human body.

Determination of human body impedance

Relationship (1) taken from [4], by using can be calculated the value of the human body impedance as previously mentioned takes into account, in addition to the path and value of the shock voltage, the effect of climatic conditions.

$$Z_B = \frac{0.24 \cdot K^{2.3}}{\sqrt[3]{U} \cdot \xi} \tag{1}$$

where: Z_B – human body impedance in (kΩ), U – shock voltage, in (V), K – climate defined in special humidity degrees, in (°K$_W$), ξ – path of shock current transformation factor (hand-hand ξ=6, hand-feet ξ=10, hand-torso ξ=9).

Calculation result

In the first stage of the analysis, calculations were made of the electric potential distribution on the ground surface over a buried grounding system made in the form of a 6.3 x 6.3m grid. The grounding system was buried at a depth of h = 0.8m. A detailed description of the grounding system construction and calculation method is described in [30]. Potential distribution calculations were performed for six grounding system variants. The first variant (variant 1) of the grounding system can be regarded as a reference variant because the calculations were made for homogeneous soil, with no technical measures used to shape the potential distribution on the ground surface. In variant 2, a surface material of 8.3 x 8.3 m placed on the ground surface, with a thickness of h_s = 3cm, and a resistivity of ρ_s =1 Ωm, was used to shape the potential distribution. Surface material with a dimension of 8.3 x 8.3 m, the thickness of h_s =3cm, and resistivity of ρ_s =2000 Ωm was placed on the ground surface in variant 3. In variants 4 and 5, insulating screens placed on the ground surface above the grounding system with the following parameters were used to shape the potential distribution. Variant 4 uses an isolation screen of 8.3 x 8.3 m and resistivity ρ_{sn} = 10e+12 Ωm. The screen was buried at a depth of h_{sc} =0.4m. An isolation screen with dimensions of 3 x 3 m and resistivity ρ_{sn} =10e+12 Ωm buried at a depth of h_{sc} = 0.4m was used in variant 5. In the last 6 variants, the potential distribution is shaped with a metal screen of 3 x 3 m and a depth of burial in the ground equal to h_{sc} = 0.4m.

Based on numerical calculations performed in ANSYS, the potential distribution for the above grounding system variants was calculated, from which the step and touch voltages were determined. For the case of the considered grounding system, it can be assumed that the values of step and touch voltages are equal to U_{step} = U_{touch}. Calculations were made for an earthing current equal to I_E=40A. The values of step and touch voltages were used to calculate the human body impedance and the value of the electric shock current flowing along the foot-to-foot and hand-to-feet paths. The calculated values of shock voltages are: for variant - 1 - 112.32 V, for variant 2 - 62.64 V, for variant 3 - 117.49 V, for variant 4 - 129.66 V, for variant 5 - 115.18 V and variant 6 - 60.45 V. A range of catastopic changes from 8°K$_W$ to 22°K$_W$ was assumed for the calculations. The obtained results of the calculations for each variant are presented in Figures 2 through 7. The values of the human body impedance were determined from equation (1).

The electric shock current values are derived from the calculated shock voltages [29] and are determined based on knowledge of the basic laws of electrical engineering. Knowing the value of the human body impedance and the value of the shock voltage, the electric shock current was calculated from equation (2).

$$I_S = \frac{U}{Z_B} \tag{2}$$

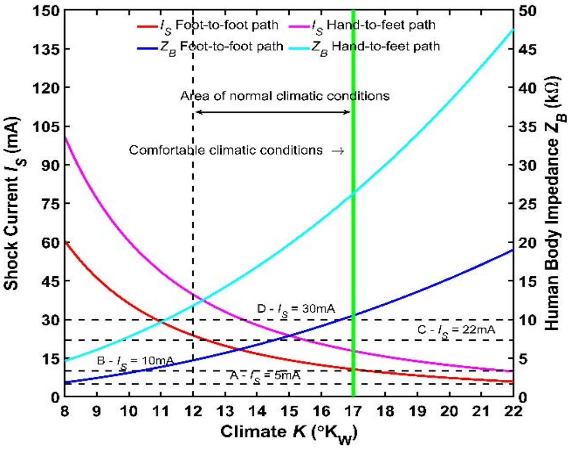

Fig.1. Dependence of human body impedance and shock current on climatic conditions for variant 1

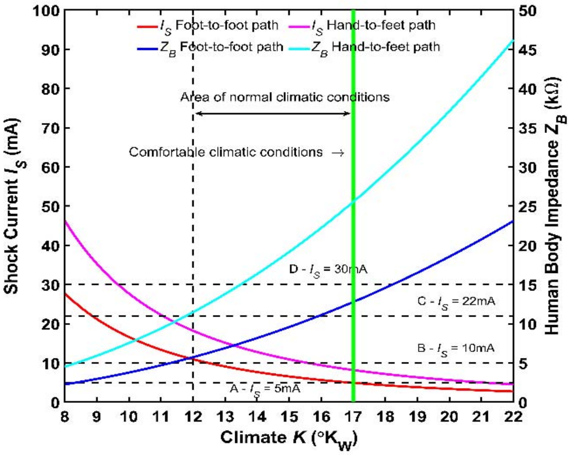

Fig.2. Dependence of human body impedance and shock current on climatic conditions for variant 2

Analyzing the values of electric shock currents, it is first necessary to describe the characteristic values resulting from the analysis of the impact of electric current on the human body. The 5 mA value of the electric shock current can cause severe hand cramps and numbness in the hands. Its increase to a value of 10 mA results in possible contractions of the muscles of the arms and forearms and an increase in blood pressure. The flow of 22 mA of current through the human body causes strong and painful contractions in the muscles of the hands. The characteristic limit value of electric shock current that causes an immediate threat to human life by causing ventricular fibrillation of the heart is equal to 30 mA. These characteristic values are shown in Figures 2 to 7 to facilitate analysis of the obtained results.

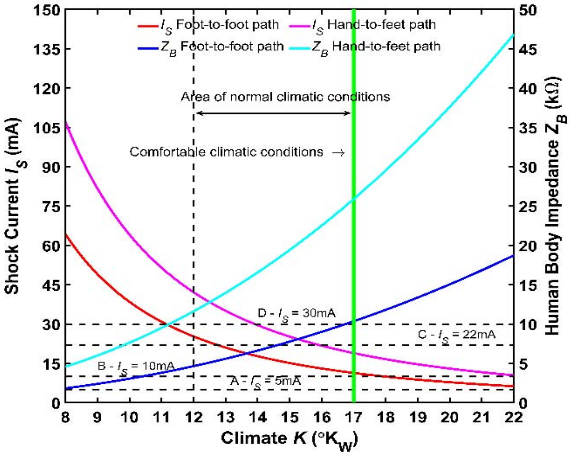

Fig.3. Dependence of human body impedance and shock current on climatic conditions for variant 3

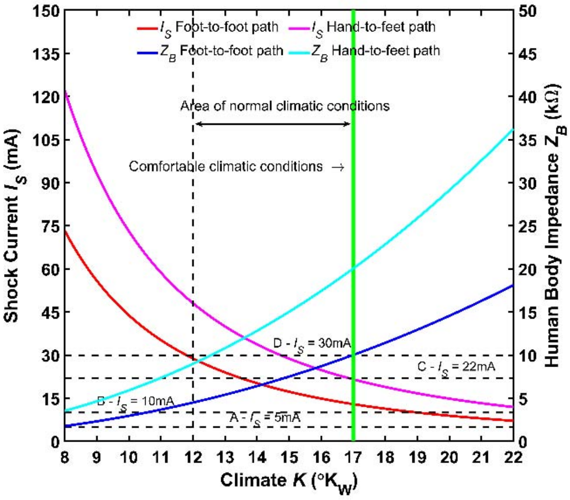

Fig.4. Dependence of human body impedance and shock current on climatic conditions for variant 4

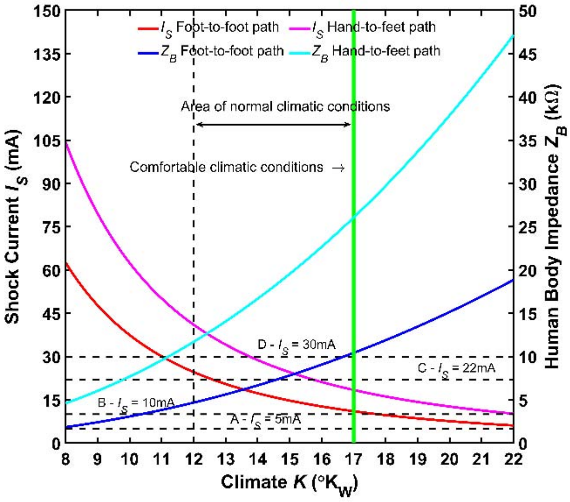

Fig.5. Dependence of human body impedance and shock current on climatic conditions for variant 5

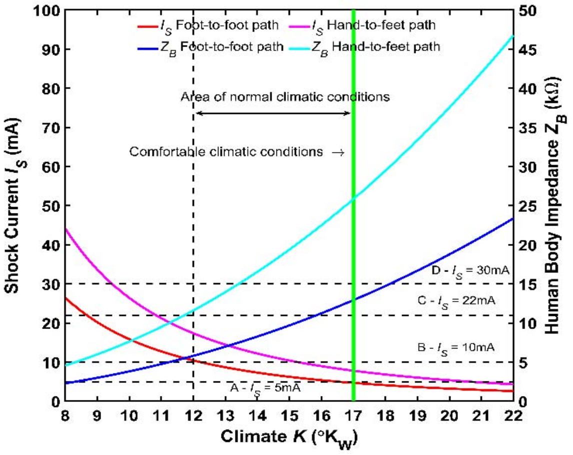

Fig.6. Dependence of human body impedance and shock current on climatic conditions for variant 6

The shock currents, regardless of the path of their flow, decrease with increasing degree K, and this relationship is nonlinear. For normal climatic conditions (K in the range of 12 to 17 °K_W), the value of the shock current in the hand-feet path achieves a maximum value of 37 mA for variant 1. The lowest values of shock current were obtained for variants 2 and 6 and are 17 and 16 mA, respectively. By appropriately shaping the potential distribution on the ground surface, the values of shock currents can be significantly reduced. Other grounding systems variants do not offer such possibilities

For variants 2 and 6, the values of shock currents for K = 22°K_W are less than 5 mA.

From the point of view of the electrocution consequences, the other characteristic value of the electric shock current is the self-release current. For men, its value is 10 mA, and for women it is equal to 6 mA. Under normal climatic conditions for the adopted grounding system design and earthing current values, the calculated shock current values are greater than 10 mA. Thus, for these conditions, a person will not be able to self-relieve himself from the exposure to the shock current.

For all considered grounding system variants, the highest values of shock current were obtained for K = 8°K_W. The highest value of shock current occurred for variant 4 and reached a value of more than 120 mA. For both paths considered, the values of shock current exceed 30 mA for all considered variants of grounding system.

Therefore, it can be concluded that the effect of climate on the shock current values and thus on pathophysiological effects is significant. As the value of climate K decreases, the human body impedance increases, and thus the values of the electric shock current decrease.

Conclusion

A properly designed and constructed grounding system should ensure safety for those in its immediate vicinity, both bystanders and qualified personnel. The risk factors determining the degree of electric shock risk are the touch and step voltages and the human body impedance. The shock voltage values depend on the distribution of the electric potential on the ground surface and are greater the more uneven this distribution. In order to reduce these voltages, technical measures are used to improve the uniformity of electrical potential distribution on the ground surface.

As previously mentioned, a number of human body models have been described in the literature using which the human body impedance value can be calculated. The model used in the article, which takes into account climatic conditions, is useful in particular for analyzing the effects of electrocution on those doing the work. The model makes it possible to calculate the human body impedance values for given climatic conditions and thus to calculate the shock currents. Based on the calculations, it can be concluded that climatic conditions have a significant impact on the values of shock currents. The highest values of shock currents occurred for climate values of $K = 8\ ^{\circ}\mathrm{K_W}$ and for all analyzed grounding systems variants. And these are values exceeding 30 mA, that is, the flow of such a current through the human body will cause serious pathophysiological effects and may even be the cause of death.

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