IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 8 December 2022, accepted 6 January 2023, date of publication 10 January 2023, date of current version 18 January 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3235874

RESEARCH ARTICLE

Studying Direct Lightning Stroke Impact on Human Safety Near HVTL Towers Considering Two Layer Soils and Ionization Influence

OSAMA E. GOUDA [1], ADEL Z. EL DEIN [2,3], SARA YASSIN OMAR [1,4], MATTI LEHTONEN [5], AND MOHAMED M. F. DARWISH [5,6], (Senior Member, IEEE)

[1]Department of Electrical Power Engineering, Faculty of Engineering, Cairo University, Giza 12613, Egypt
[2]Department of Electrical Power Engineering, Faculty of Energy Engineering, Aswan University, Aswan 81528, Egypt
[3]Faculty of Technological Industry and Energy, Thebes Technological University, Luxor 85863, Egypt
[4]Upper Egypt Electricity Distribution Company, Qena 11569, Egypt
[5]Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University, 02150 Espoo, Finland
[6]Department of Electrical Engineering, Faculty of Engineering at Shoubra, Benha University, Cairo 11629, Egypt

Corresponding authors: Osama E. Gouda (prof_ossama11@cu.edu.eg; prof_ossama11@yahoo.com), Mohamed M. F. Darwish (mohamed.m.darwish@aalto.fi; mohamed.darwish@feng.bu.edu.eg), and Matti Lehtonen (matti.lehtonen@aalto.fi)

This work was supported by the Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University, Espoo, Finland.

ABSTRACT A lightning strike is considered one of the most risky natural phenomena that can lead to human harmful and the surrounding soil layers. To tackle this issue, this article investigates the influence of direct lightning characteristics in terms of human body safety. Specifically, such investigation is carried out on the effect of resistivities of two-layer soils on human safety when lightning stroke hits the towers of the high voltage transmission lines (HVTLs). The merit of the proposed study is that the soil ionization phenomenon is taken into consideration. Further, the study focuses on the current passing through the human heart, when step and touch (contact) voltages are generated by grounding potential rise, caused by direct lightning strikes transmission tower and the produced potential rise that a person could be exposed. Also, studying the effects of peak current and time of lightning strokes are investigated. Additionally, the paper presents the effect of different reflection factors on human safety. For validation purposes, the ATP program is used in the simulation of the grounding system as well as the human body model. Numerous simulations were accomplished in order to examine the behavior of the current passing through with the human heart. Based on the simulation results, it was concluded that the soil characteristics have superior influences on the contact and step potentials and, accordingly, the survival threshold.

INDEX TERMS Human body safety, lightning strokes, human heart, ATP program, high voltage transmission lines, soil ionization, non-homogenous soil.

I. INTRODUCTION

Since mankind has used high and medium voltage networks for the transmission and distribution of electrical energy, the danger is increasing as a result of direct exposure to excessive overvoltage's of these networks on one hand, and to lightning strokes that may strike workers in these networks on the other hand, which may cause death or injuries in the best case. Effects of current on human beings and livestock are investigated by IEC/TR 60479-1-4 [1], [2]. Safety current limits for human beings are presented in IEEE Std. 80, Guide for Safety in AC substations [3].

Lightning is one of the most powerful natural phenomena that happen on earth [4], and it can be harmful to any devices on the rooftops and/or outdoor areas, such as deterioration in photovoltaic systems [5] and wind turbines [6] where it is necessary for providing effective lightning protection structures. Also, the lightning occurrence can cause human death and harm electrical devices and the environment [7]. Thousands of injuries produced by lightning have been

The associate editor coordinating the review of this manuscript and approving it for publication was Ahmed A. Zaki Diab.

reported from the start of humankind, resulting in fatalities and damage to humans with both acute and long-term consequences [8]. Further, to evaluate the risk caused by lightning-human interaction in the vicinity of humans, structures, and the surrounding earth, a sufficient Lightning Protection System (LPS) is designed and analyzed. The effectiveness of the grounding system and complex earthing models during lightning are utilized to evaluate the role performed by aspects such as earth electrode dimensions, soil resistivity, and the equivalent circuit nature elements. Moreover, the role of lightning strikes on humans caused by touch and step potential is determined by devising a lumped electrical model of human to evaluate its role and influence on wet and dry skin [9].

It is well known that influences of the amount of electrical current going through the human body are mostly determined by the duration, frequency, and amplitude of the event [7]. Over the last few decades, various efforts have been made to define reference limits and do studies relating to the impacts of electric current on humans and animals. However, the majorities of these researches only look at power frequencies and are mostly concerned with the study of sinusoidal current with frequency in the range of 15–100 Hz, which ended in the preparation of international standards actually in the use [8], [9], [10], [11]. Since there are no specified criteria for determining the maximum electric current, a human may suffer from lightning strokes. The IEEE Std 80 [3] is currently the most widely used standard for determining human-tolerated step and touch potentials and currents, although it is crucial to note that this standard is based on steady-state analysis at power frequencies, which is not ideal for transient investigations.

Unlike studies on the influence of alternating current at power frequencies and low magnitudes, research on lightning is extremely difficult to do because of the numerous experiments that must be completed. There is also minimal thought given to grounding systems, the effects of soil resistivity, and the variance in lightning characteristics. Furthermore, when lightning current flows through the network, the performance of the grounding electrodes in uniform soil is studied, where the frequency impact on the surrounding soil is considered [12], [13]. Recently, Gouda et al. investigated the impact of lightning strokes in uniform and two-layer soils on the step and touch potentials [14]. Based on the literature review and the authors' knowledge, most existing studies lack concerns with non-homogenous soil resistivity parameters that effectively change the touch and step voltages.

Based on this remark and to cover this gap in the literature, this paper investigates the effect of lightning current strokes on human safety. Further, this article focused on the current passing in the heart caused by step and touch (contact) voltages generated by first and subsequent lightning strokes when hit the transmission tower in case of non-homogenous soil resistivity. Also, the study of the parameters that affect the step and touch voltages such as different reflection factors, and different peaks and front times of lightning stroke currents are investigated.

TABLE 1. Data of 220 kV power line.

Item	Units	value
Transmission line capacity	MVA/circuit	158
Line voltage of the transmission line	kV(r.m.s)	220
Transmission line length	km	90
Positive and negative sequence impedance	per phase in ohm	3.6+ j 15.3
Zero sequence impedance	per phase in ohm	12.2+ j 50.95
Number of circuits per tower	-	2
Number of conductors per phase	-	2
Number of ground wires	-	1
Single conductor diameter	mm	27
Spacing between a conductor in the bundle	cm	30
Span between each two towers	meter	360

II. MATHEMATICAL MODELS FOR THE PROBLEM FORMULATION

In this part of the article, the simulation of the grounding system of the high-voltage transmission line towers is presented. The simulations of lightning current waveforms and the human body are also presented. The soil ionization phenomenon caused by lightning is also presented in this part of the article.

A. MODELING OF HVTL TOWERS GROUNDING

The grounding system of the HVTLs tower is shown in Fig. 1. Hence, Fig. 1.a illustrates the dimensions of the transmission line tower of 220 kV. The data of this line are illustrated in Table 1. The grounding system of the tower contains four vertical grounding electrodes, each electrode has a length of L=3 m and a radius of r=0.02 m. To model the transient behaviour of those vertical grounding electrodes, a transmission line method (TLM) with the aid of the ATP program [15] is used to compute the grounding impedance when lightning current is injected into those vertical grounding electrodes of the tower guiding system. In the TLM technique, any earthing electrode can be subdivided into M segments each one containing earthing resistance, inductance, and capacitance elements as shown in Fig. 1.b. The grounding resistance, R_g, capacitance C_g, as well as specified electrode inductance L_g of the vertical rod are computed by using the following equations (1):(3), respectively [16], [17].

$$R_i = \frac{\rho_a}{2\pi} \ln(\frac{4l}{a} - 1) \tag{1}$$

$$C_i = \frac{\rho_a \varepsilon_g}{R_g} \tag{2}$$

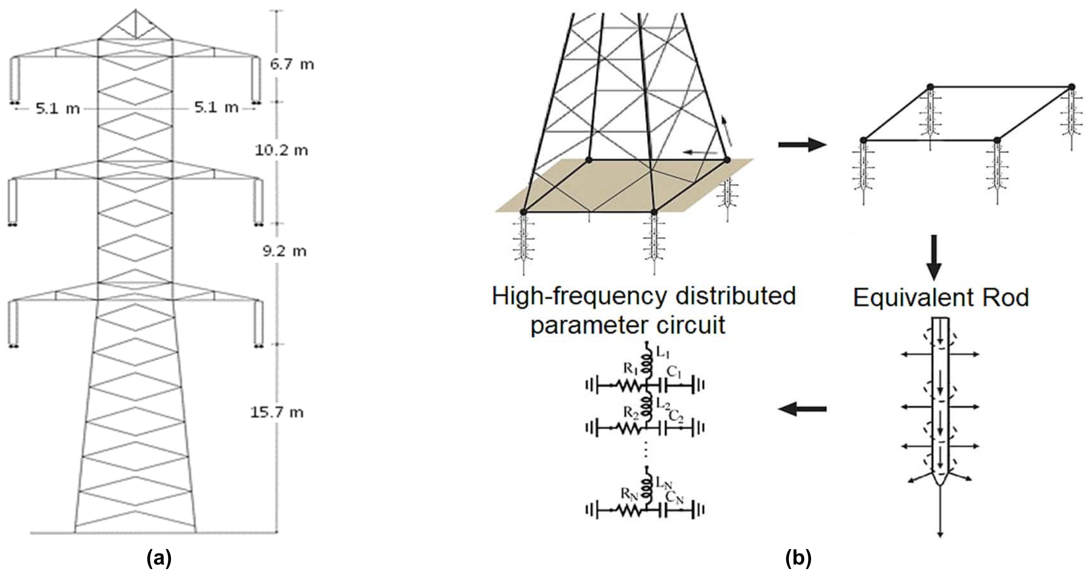

FIGURE 1. Geometric configuration of (a) transmission line tower dimensions of 220 kV, and (b) grounding electrode and its equivalent circuit.

$$L_i = \frac{\mu}{2\pi}(\ln\frac{2l}{\mathrm{a}} - 1) \tag{3}$$

where μ represents the soil permeability (H/m), a depicts the radius of the grounding electrode, which is replaced by r_i when the ionization process begins, ρ_a is the soil resistivity, ε_g represents the soil dielectric constant and l means the grounding electrode length.

B. SIMULATION OF LIGHTNING CURRENT WAVEFORMS

In this article, two lightning current waveforms equivalent to the first and subsequent lightning strokes are employed. The following Heidler's formula of lightning current function (HF) is selected to represent the current waveforms [18], [19], [20].

$$i(t) = \frac{I_0}{\eta}\frac{(\frac{t}{\tau_1})^n}{1+\frac{t}{\tau_1}^n}e^{(-t/\tau_2)} \tag{4}$$

$$\eta = e^{-(\tau_1/\tau_2)(n(\tau_2/\tau_1))^{1/n}} \tag{5}$$

where the time in second represents t, I_0 means the current pulse amplitude, followed by τ_1 that depicts the front time constant. Further, τ_2 means the decay time constant, as well as n refers to the exponent having values within range of 2 to 10, finally η means the amplitude correction factor [19].

C. HUMAN BODY SIMULATION

The impedances of human body elements depend on the degree of moisture of the skin, skin temperature, current path duration, touch (contact) or step voltages, and the body's physical properties. According to IEC/TS 60479-1 and other standards and studies, the human body has been simulated by two impedances (internal and external) [7]. The human body can be simulated by a combination of resistive and capacitive elements. Simplified simulations are carried out by many researchers [21], [22], [23], [24], [25], [26], [27]; one of these is shown in Fig. 2 [21]. Some adjustments have to be made for the evaluation of the electric current passing through the heart. The contact resistance $R_{contant}$ in between the feet of a person and the soil surface can be estimated by using equation (6) [23].

$$R_{contact} \cong 3.\rho \tag{6}$$

The impedances of human body elements based on reference [21] are illustrated in Fig. 2. The simulated equivalent circuit of the human body is used to examine the behavior of the current passing through the heart considering the step and touch (contact) potentials. This current is created from the change of potential in the soil between two specified points on its surface in case of step potential and between the touch point and point on the soil surface in case of touch (contact) voltage.

The simulation of the human body model in the case of step potential is illustrated in the equivalent circuit given in Fig. 2.a. Hence, Figure 2.b illustrates the simulation of the touch (contact) potential mechanism. The models given in Fig. 2 can be used to estimate the current in the heart.

D. SOIL IONIZATION

Due to lightning current, soil ionization happens when the dissipated current in the soil surpasses its critical value. The soil ionization occurrence by lightning current indicates an increase in the grounding electrode radius and subsequently; it decreases the ground resistance, step and touch (contact) potentials, and transient impedances. Manna and Chowdhuri in reference [27], which is one of many that dealt with this topic, proposed a relation between the critical breakdown

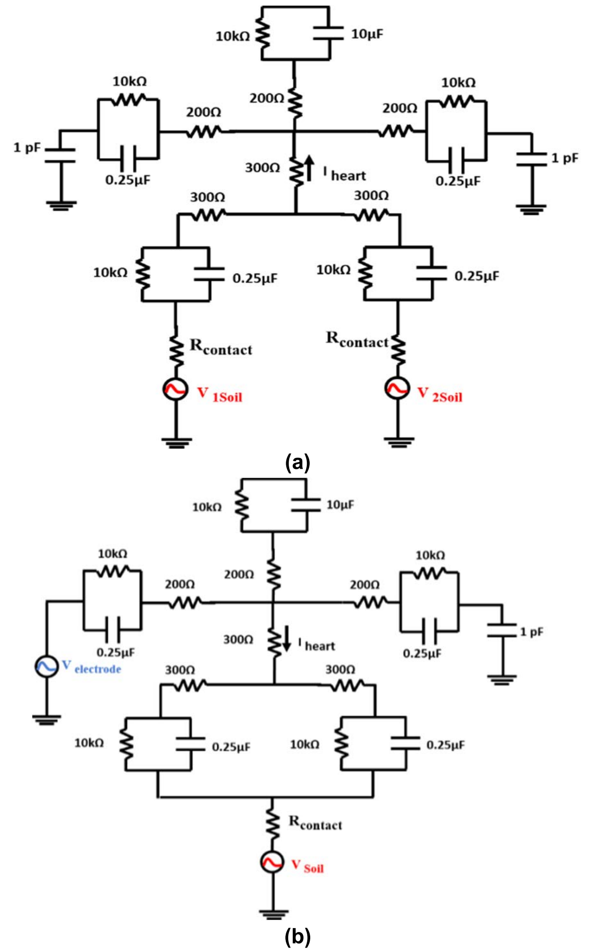

FIGURE 2. **Equivalent circuit of the human body, (a) in case of (a) step potential, (b) touch (contact) potential [21].**

field strength (E_c) as well as the soil dielectric constant ε_g and its conductivity σ_g as presented in equation (7).

$$E_c = 8.6083\varepsilon_g^{-0.0103}\sigma_g^{-0.15264} \tag{7}$$

The new effective grounding electrode radius r_i in meter is suggested by equation (8) [28], [29].

$$r_i = \frac{\rho I_m}{2\pi E_c l} \tag{8}$$

III. CALCULATION OF GROUND POTENTIAL RISE

This section explains gauss–Sedial method [30] that is used to estimate earth surface potential (ESP) in non-homogenous soil that is injected into human feet when walking near the grounding system of the 220 kV tower. Also, in this paper Gauss–Sedial method is used also in the calculations of step and touch (contact) potentials that are affecting the person near the towers of HVTLs. After calculating all the aforementioned parameters, the transient behavior of current passing through the human heart can be obtained by the use of ATP-EMTP [15].

The grounding fault current is i_g, which is discharged from the grounding system into the earth according to equation (9):

$$i_g = \sum\nolimits_{m=1}^{nn} i_m \tag{9}$$

i_m is the current of element $m = 1, \ldots\ldots, nn$

Two lightning current waveforms as given in equations (4) and (5) are used. The resistance of the grounding system will be:

$$R = \frac{u}{i_g} = \left(\sum\nolimits_{k=1}^{n} \frac{i_m}{u}\right)^{-1} \tag{10}$$

The potential of the grounding system is:

$$u = Ri_g \tag{11}$$

The electric potential u_T at any point (T), caused by the grounding system element buried in non-homogenous soil can be calculated by super-position of potential from an infinite sequence of images as follows:

$$u_T = \sum\nolimits_{k=1}^{n} r_{mT} i_m \tag{12}$$

where r_{kT} is the mutual resistance of grounding system element m and point (T) is on the surface of the upper soil layer. The reflection factor g is defined as:

$$g = (\rho_2 - \rho_1)\,.(\rho_1 + \rho_2)^{-1} \tag{13}$$

where ρ_1: is the resistivity of the upper soil, and ρ_2 is the lower soil resistivity.

The mutual resistance of element m and point T is given by:

$$r_{mT} = \frac{\sum_{s=0}^{\infty} Q_{mT}(s)}{i_m} \tag{14}$$

The integer s represents the general index of the image sequences. $Q_{mT}(s)$ is representing the voltage potential caused by terms s of the image sequences.

$$Q_{mT} = \begin{cases} \frac{\rho i}{4\pi l} ln\frac{G+1}{G-1}, & G > l + \frac{d^2}{2l} \\ \frac{\rho i}{4\pi l} ln(\frac{2l}{d})^2, & G \le l + \frac{d^2}{2l} \end{cases} \tag{15}$$

where $G = \sqrt{(P,T)} + \sqrt{(Q,T)}$

$$\begin{aligned} r_{mT} = \frac{\rho_1}{4\pi l_m}\{A_{mT}(0) + B_{mT}(0) + \sum\nolimits_{s=1}^{\infty} k^s[A_{mT}(s) \\ + B_{mT}(s) + C_{mT}(s) + D_{mT}(s)]\} \end{aligned} \tag{16}$$

P, Q are being the endpoints of the conductor. Symbols i, l, d denote the conductor's current, length, and diameter of grounding electrode respectively and ρ is the soil resistivity.

IV. RESULTS AND DISCUSSION

A. THE IMPACT OF SOIL IONIZATION ON THE STEP AND TOUCH POTENTIALS AND CURRENT PASSING THROUGH THE HUMAN HEART

The stochastic characteristics of a lightning surge and current peak values in the range of 4 to 250 kA are considered [31]. Based on the mathematical simulation and Gauss–Sedial

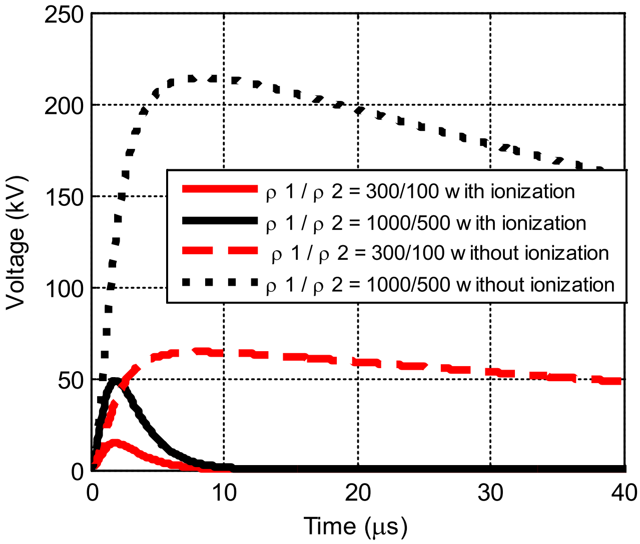

FIGURE 3. Step potential above the grounding system affecting the human body at a first lightning model with and without soil ionization.

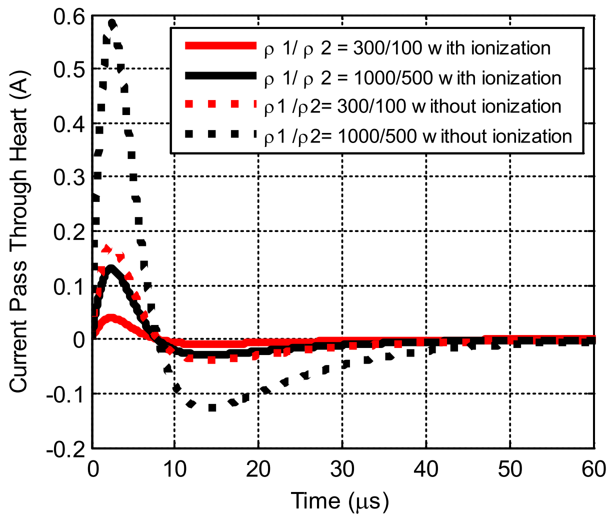

FIGURE 4. Current passing through the heart when step potential affects the human body at a first lightning stroke with and without soil ionization.

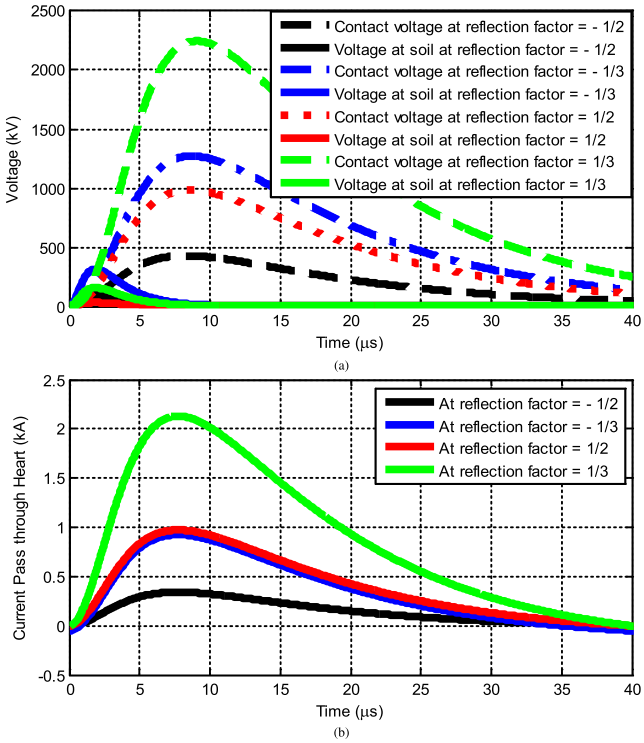

FIGURE 5. Contact potential submitted in the body model at different reflection factors (a) first stroke, (b) subsequent return strokes.

method considering the soil ionization impact it is possible to estimate the passing current through the human heart. The steps of the calculation of touch (contact) and step potentials as well as the current passing through the human body are as follows:

1) Insert equivalent circuit of the human body model in case of step potential in the ATP program, ρ_1, ρ_2, start point and end point of each element, and effective radius of electrode considering ionization.

2) Calculate V_{1soil}, V_{2soil}, $V_{soil,}$ and $V_{electrode}$ illustrated in Figs. 2(a) and (b) by the use of equation (12).

3) Insert in ATP V_{1soil} and V_{2soil} in the human body model as given in Fig. 2.a in case of step potential and V_{soil} and $V_{electrode}$, as given in Fig. 2.b in case of contact potential.

Figure 3 illustrates the behaviour of step potential that a person suffers from grounding potential rise when located above the grounding system of the tower at two-layer soils due to the first lightning stroke when the lightning surge current peak was 100 kA. The dielectric constants of the soils are considered between 6 and 20 depending on the soil composition, and the thickness of the upper layer was 10 meters [29]. The thickness of the upper layer is considered 10 meters. The figure shows the step voltages with and without considering the soil ionization at a distance of one meter from the tower foot.

It is seen that step potential affects a person decreases when the soil ionization phenomenon is considered by values of 71% and 80% at $\rho_1/\rho_2 = 300/100$ and $\rho_1/\rho_2 = 1000/500$, respectively.

Figure 4 illustrates the influence of soil ionization phenomena on the current that passes through the heart when step potential affects the human body at a first lightning stroke in two-layer soils. It is observed that soil ionization has helped in reducing the current value that affects the human heart if the person is stationed above the tower grounding system in the event of a lightning-stroke earth fault, and this is expected due to the reduction of the step voltage in this case. It is observed that the soil ionization phenomenon helps in the decrease of the current by about 74% - 73.5 % depending on ρ_1/ρ_2. It is also noted that with the increase in the resistivity of the upper layer of soil, the value of the current pass-through heart of humans increases. The touch or contact voltage is calculated

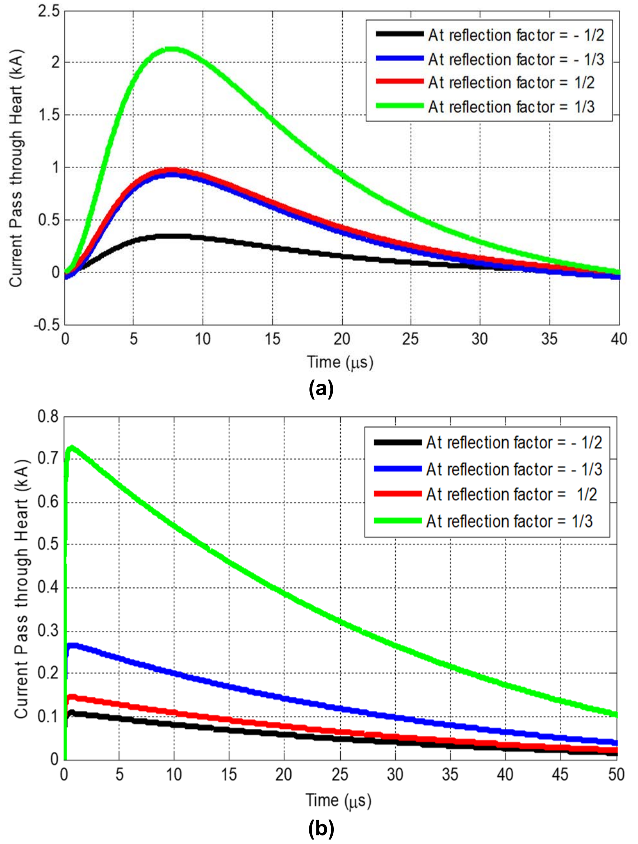

FIGURE 6. **Current passing through the heart when contact potential is submitted to the human body at (a) first lightning stroke, (b) subsequent return strokes.**

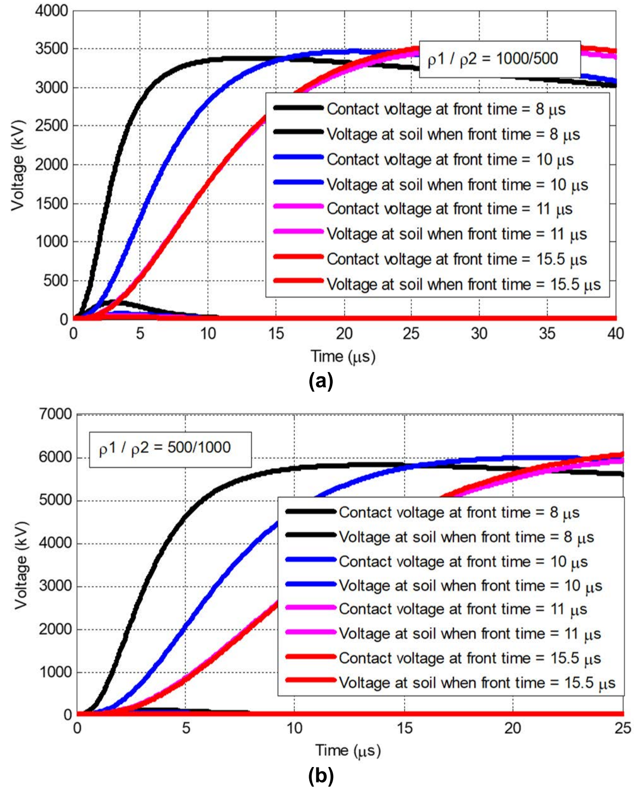

FIGURE 7. **Contact potential submitted in the body model at the current peak of lightning stroke = 100 kA (a) negative reflection factor, (b) positive reflection factor.**

by the use of the human body model given in Fig. 2.b. The calculations of touch or contact voltages are carried out considering soil ionization. The contact potential, and the ground potential in cases of first lightning and subsequent return strokes for different reflection factors considering the ionization procedure with the first peak wave current was 100 kA are given in Figures 5(a) and (b).

The corresponding currents passing through the heart are illustrated in Figures 6(a) and (b). It is noticed that the positive reflection factors gave higher peak values of touch or contact voltage and current pass through the human heart compared with the negative reflection factor.

The obtained results are in agreement with those that were reached in reference [21], and the differences are due to the fact that in this article the study was done in the case of two-layer soils and that the ionization state in the soil was considered.

By comparing the results of the step voltage and those of the touch voltage, we find that in the first case, the step voltage increases with a negative reflection coefficient, while the opposite happened in the case of the touch voltage. Perhaps this is due to the fact that the current in the latter case tends to pass through the second layer due to the necessity of passing through the ground

B. THE INFLUENCE OF THE STROKES FRONT TIME ON THE CURRENT PASSING THROUGH THE HUMAN HEART

Figures 7(a) and (b) show the influence of the front time of the first lightning strokes on the contact potential submitted in the body model at negative and positive reflection factors and the current peak of lightning stroke = 100 kA. The corresponding currents passing through the heart are illustrated in Figures 8(a) and (b) when soil ionization is taken into account. The created current in the body is progressing from the difference of potential between the soil surface and contact point, considering the feet are together, besides 1 m apart from the touch tower.

From Figure 8, it is observed that when contact potential is submitted to the human body current pass through the heart increases when the resistivity of the second layer of soil is higher than the upper layer's resistivity. Also, it is noted that when the front time of lightning current increases, the current pass-through the heart takes a long time to reach its peak value. It is also observed that the current magnitudes are higher than that produced by step potential. Moreover, it is observed that in the positive reflection factor, the current passing in the human heart is much higher than the similar current in the case of negative reflection factors. Again, it is monitored that the soil resistivity of the second layer plays an effective role in increasing the contact voltages and currents.

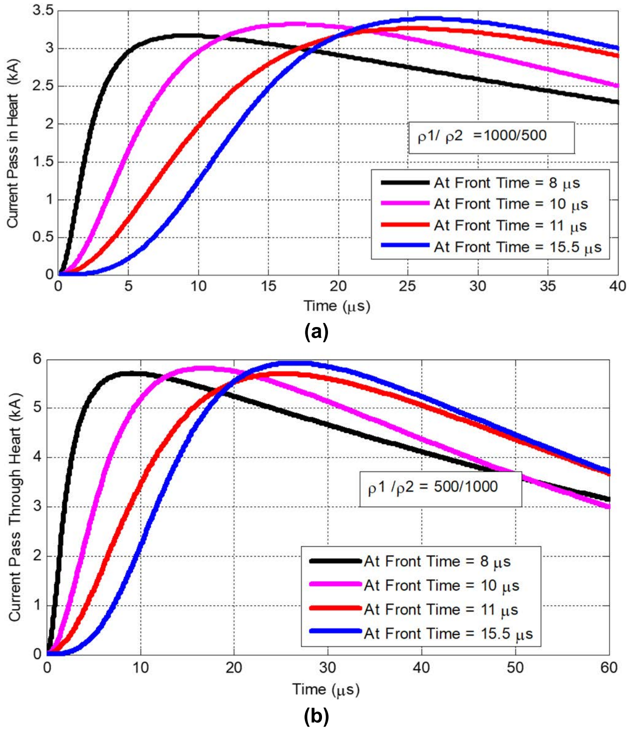

FIGURE 8. Current passing through the heart when contact potential is submitted to the human body at (a) negative reflection factor, (b) positive reflection factor, the current peak of lightning=100 kA.

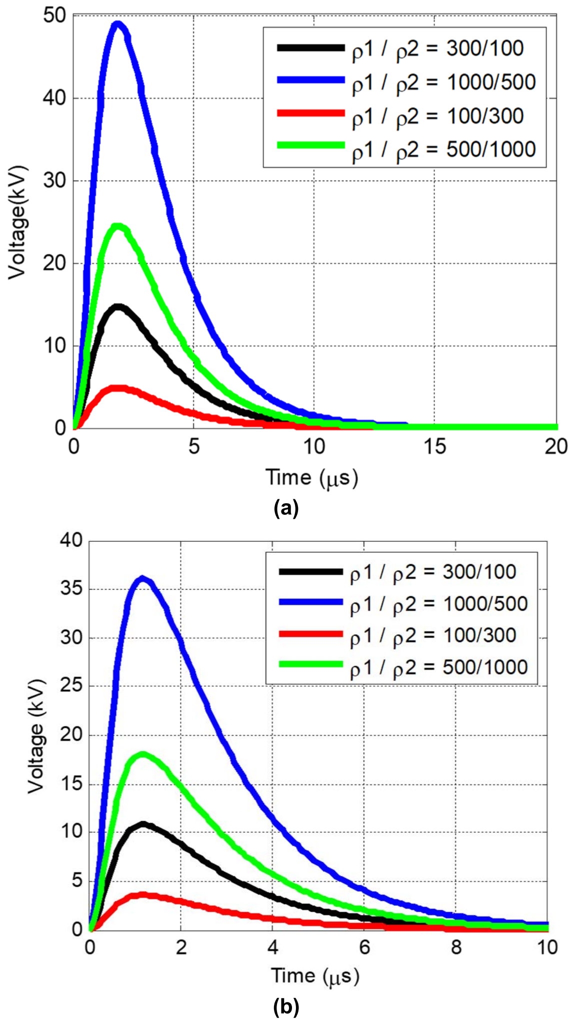

FIGURE 9. Step potential submitted in the body model (a) at a first lightning stroke and (b) subsequent return stroke.

Figures 9(a) and (b) show the behaviors of the step potential at a person located above the grounding system of the 220 kV tower in non-homogenous soil due to first and subsequent lightning strokes, respectively.

It is noticed that the step potential of the first stroke is higher than that of the subsequent lightning strike by about 35%.

Figures 10(a) and (b) illustrate the influence of the first and subsequent lightning strokes on the current passing through the heart of a human when step potential is submitted into the body model in non-homogenous soil when the soil ionization phenomenon is taken into account. It is seen that the current passing through the heart of humans decreases at subsequent return strokes much higher than its value at the first stroke due to the high values of the step potential. Also, it is seen that when the reflection factor is negative the current pass-through of the heart increases. Finally, it is noticed that the time of current pass-through the heart reaches zero quickly in the first lightning stroke.

Figures 11(a) and (b) illustrate the behavior of step potential of a person stationed above the tower grounding system at non-homogenous soil resistivity when a soil ionization phenomenon is taken into account. The front time of the lightning waves is changed as shown in the figure. It is seen that the step potential that is submitted to a person increases when the front time of lightning stroke is decreased. Again, it seems that with the increase of the resistivity of the upper layer of soil, the step potential that is submitted to a person increases.

C. THE INFLUENCE OF THE WAVE PEAKS ON THE CURRENT PASSING THROUGH THE HUMAN HEART

Figures 12(a) and (b) show the effect of the current peak values of lightning pulse on step potential at a person stationed above the tower grounding system on non-homogenous soil resistivity with a positive reflection factor when soil ionization phenomena are considered. It is seen that step potential as well as the current increase when the current peak of the lightning pulse increases. Similar results are obtained in Figure 13 with a negative reflection factor when a soil ionization phenomenon is considered a soil negative reflection factor.

Comparing Fig. 12 with Fig. 13, it can be seen that the current pass in the heart of the human as well as the step potential values are higher in the case of a negative soil reflection factor ($\rho_1/\rho_2 = 1000/500$) in comparison with the positive flection factor ($\rho_1/\rho_2 = 500/1000$). This reflects

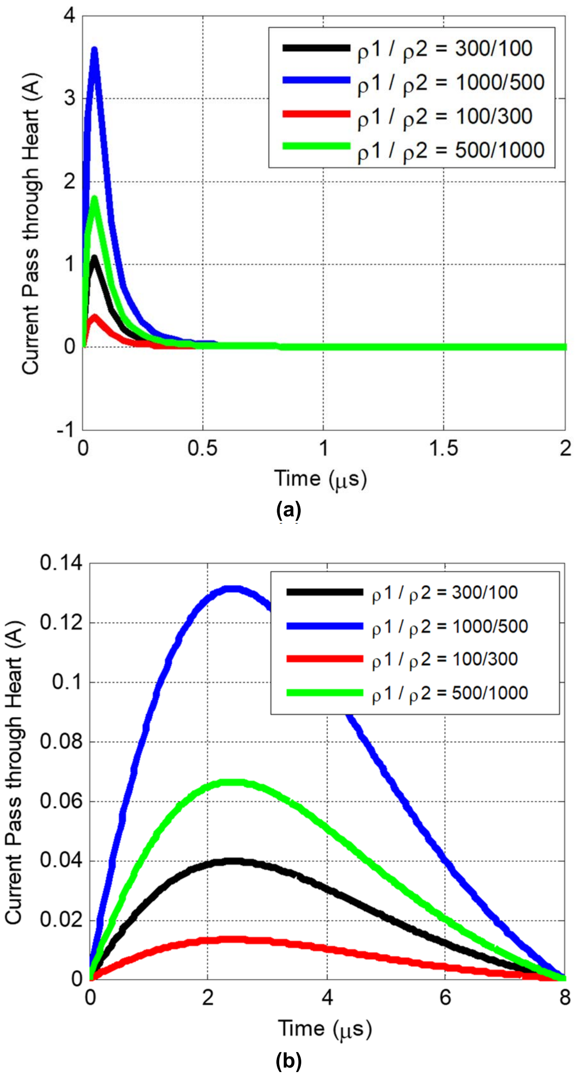

FIGURE 10. Current passing through the heart when step potential at (a) first lightning stroke and (b) subsequent return stroke.

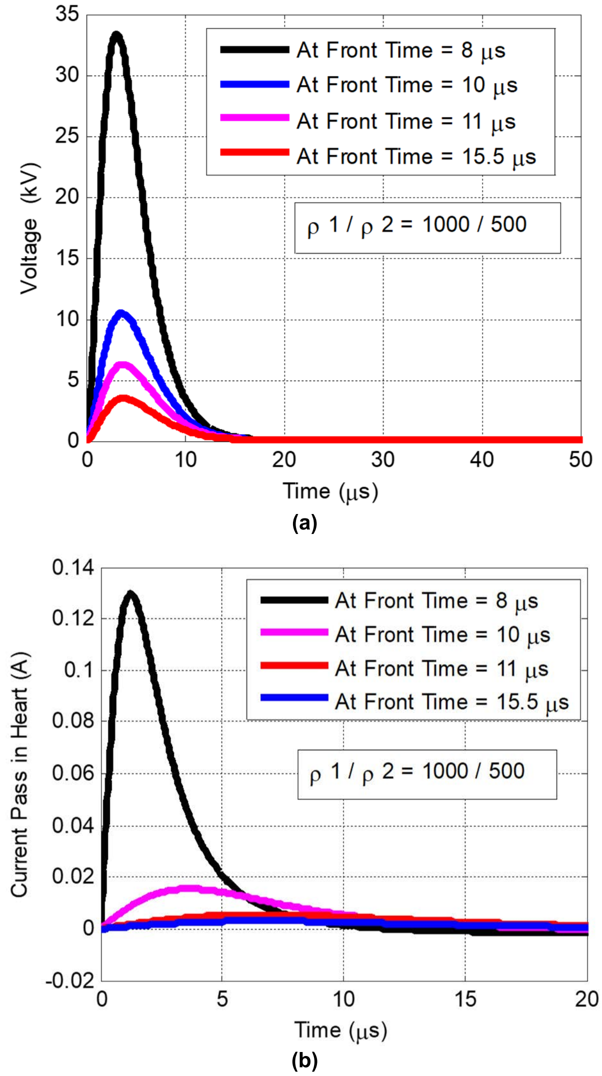

FIGURE 11. (a) Step potential submitted into the body model, (b) Current passing through the heart when the current peak of lightning =100 kA and the soil layers have a negative reflection factor.

the effect of the soil resistivity of the upper layer. Also, it is seen that when the upper layer of soil resistivity is high, the current passing in heart of a human is increased. Finally, it is observed that at the different current peaks of lightning pulse, the current passing through the heart reaches zero at a time equal to 10 μ sec. This means that the peak value of the current passing through the human heart may not be significant in terms of the time period.

The confirmation of the obtained results cannot be achieved practically, as it is not possible to expose people to the influences of lightning strikes for the electric shock measurements, because these people will be exposed to certain death. Therefore, the modeling process is the only method for conducting such studies. In any case, it is possible to compare the results obtained with that reported by others [21], [31], [32], [33]; especially those who used the same model of human representation [21].

The contact potentials with negative and positive reflection factors for different wave peaks considering soil ionization are given in Figures 14(a) and (b).

The corresponding currents passing through the heart are illustrated in Figures 15(a) and (b).

By comparing the results obtained in this study with those obtained in a reference [21], it is found an agreement in the case of touch voltage. Also, the quantitative comparison of the step and touch voltages, and the current passing through the heart proved to match the results between what was obtained in this article and the previous study in the reference [21], taking into account that in this article the study was done in the case of non-homogenous soils considering the ionization process in the soil.

As a validation process for the article results, calculations are done considering uniform soil and other data that are reported by Reference [21]. In the simulations produced here,

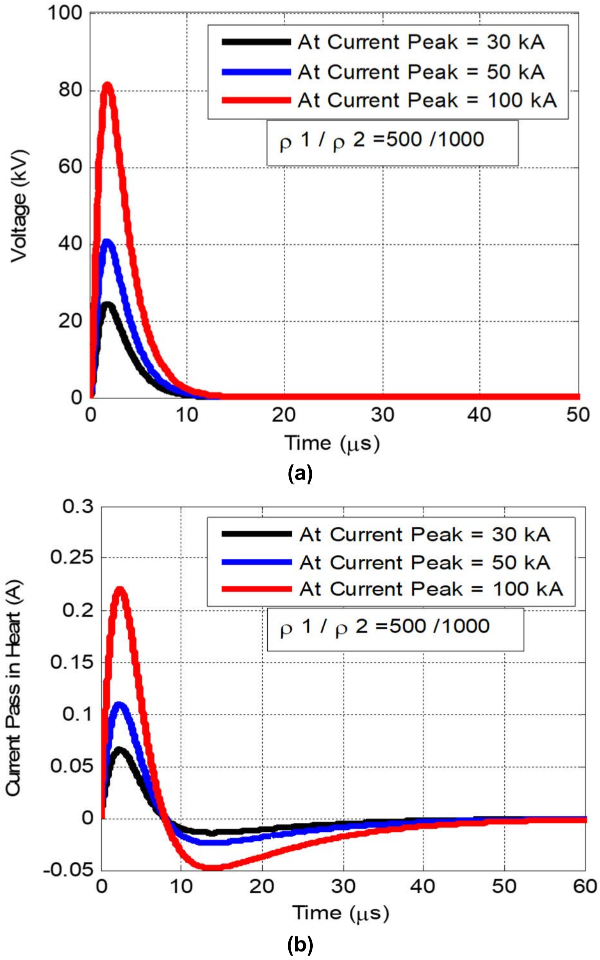

FIGURE 12. (a) Step potential submitted into the body model, (b) Current passing through the heart with different values of the current peak of lightning and the soil layers has a positive reflection factor.

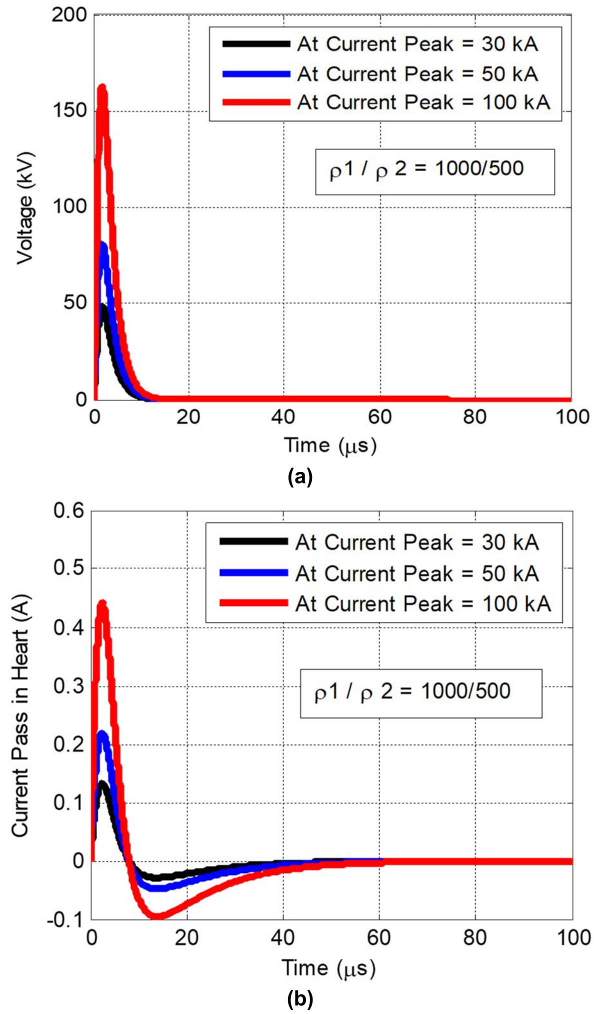

FIGURE 13. (a) Step potential submitted into the body model with soil negative reflection factor, (b) Current passing through the heart with different values of the current peak of lightning, and the soil layers have a negative reflection factor.

a standard horizontal electrode with 7.5 mm of radius, with 9 m length, as well as buried at 0.5 m depth in homogeneous soil is implemented. A slow wave shape, double exponential with 5 kA (8 × 20) s is used in the calculations. The soil resistivity was 500 Ω.meter. An agreement is noticed between the paper results as well as Reference [21] results as illustrated in Fig. 16. The differences are related to considering the soil ionization procedure in this article.

D. ELECTRICAL ENERGY GENERATED IN THE HUMAN BODY

To evaluate the impact of soil construction and lightning characteristics on the risky electrical energy that affects the person during step and contact voltages due to lightning strokes, the estimated current passing through the heart can be used. Equation (17) can be utilized in the estimation of such this energy per unit ohm of the current path:

$$E_e = \int_0^t i^2 dt \; (j/\Omega) \tag{17}$$

TABLE 2. Electrical energy generated due to step potential mechanism at first lightning and subsequent return strokes when soil ionization takes place.

ρ_1/ρ_2	I_{Max} (A) pass in heart due to first lightning	E_e (j/Ω) due to first lightning	I_{Max} (A) pass in heart due to subsequent return lightning	E_e (j/Ω) due to subsequent return lightning
300/100	0.0395	6.1028e-09	1.0641	8.5049e-08
100/300	0.1312	6.7133e-08	0.3566	9.5504e-09
1000/500	0.0132	6.8371e-10	3.5909	9.6843e-07
500/1000	0.0662	1.7105e-08	1.7780	2.3743e-07

where E_e (j/Ω) is the energy per unit ohm and i is the current passing through the heart in Ampere during time t in seconds.

Table 2 shows the quantities of generated energy due to the step potential procedure at first and subsequent return strokes when soil ionization takes place. Table 3 shows the quantities of the electrical energy generated due to the contact potential

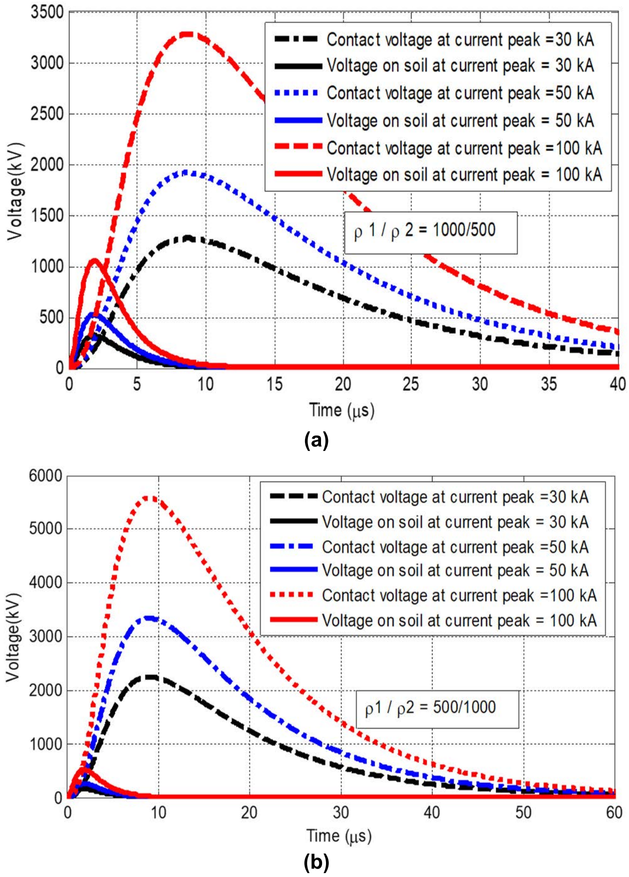

FIGURE 14. Contact potential submitted in the body model when the lightning stroke has a different peak current, (a) at negative reflection factor, and (b) positive reflection factor.

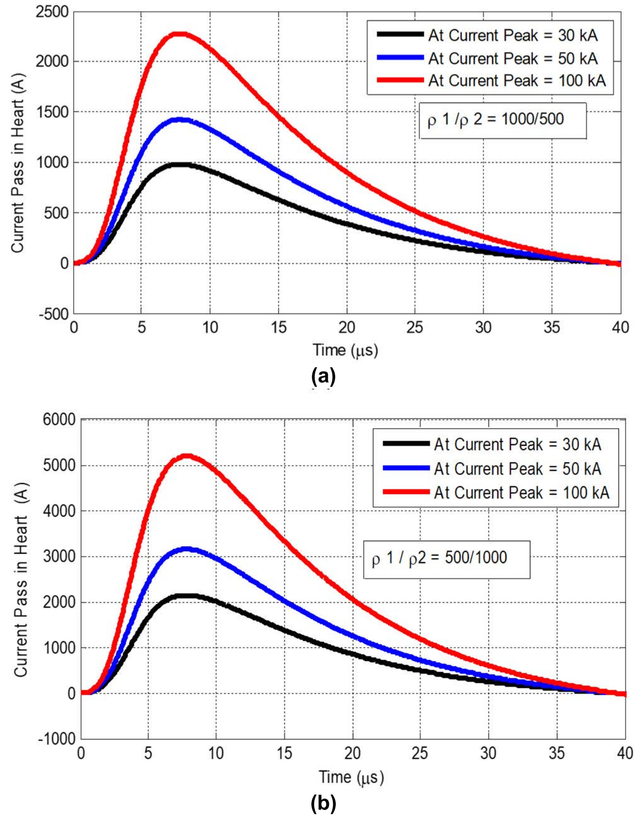

FIGURE 15. Current passing through the heart when contact potential is submitted into the human body at (a) negative reflection factor, (b) positive reflection factor.

TABLE 3. Electrical energy generated due to contact potential mechanism at first lightning and subsequent return stroke when soil ionization takes place.

ρ_1/ρ_2	I_{Max} (A) pass in the heart due to the first lightning	E_e (j/Ω) due to the first lightning	$I_{Max\,(A)}$ pass in the heart due to subsequent return lightning	E_e (j/Ω) due to subsequent return lightning
300/100	340.7706	1.4000	107.9977	0.1785
100/300	975.1190	11.4631	144.9161	0.3215
1000/500	972.3712	11.3986	267.3263	1.0940
500/1000	2.1290e+03	54.6424	725.6813	8.0616

procedure at first and subsequent return strokes when soil ionization is considered.

It is noted that the ratio between the soil resistivities for each of the first and second layers plays a sensitive role in the values of the current passing through the heart and, accordingly, the amount of generated electrical energy for each unit of its resistance. Considering that the heart resistance is in the range between 25 and 150 ohms, it can be concluded that the generated energy has significant values, especially in the case of touch (contact) potential. It can be concluded that the touch (contact) potential will be fatal [34].

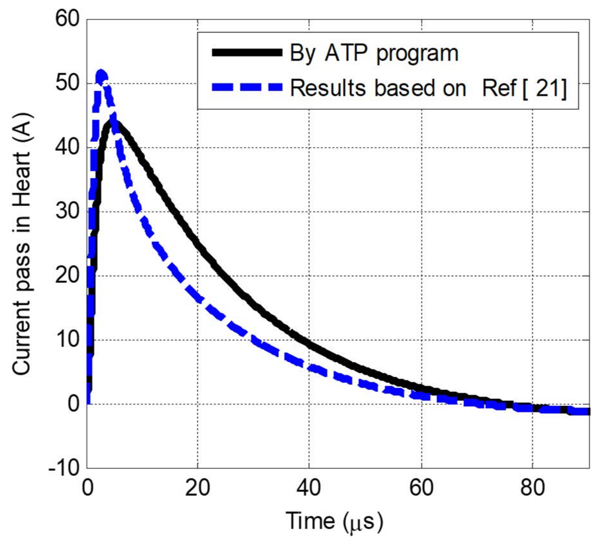

FIGURE 16. Comparing results between Reference [21] and ATP as the validation process.

V. CONCLUSION

This paper investigates the impact of direct lightning strikes on human safety near towers of HVTLs considering soil ionization influence. The article studies the current pass–through the heart of the human in cases of step and touch voltages in non-homogenous soil. In the present study, the first stroke and subsequent return stroke were considered, and the evaluation is carried out for lightning with a short duration. It is concluded that the step and touch potentials as well as the current pass-through heart in non-homogenous soil depend mainly on the resistivity of the upper layer, i.e., the negative reflection factors gave higher values in step potential and current more than positive reflection factors, while in touch potential the opposite has happened. This may be due to the difference in the path of the current in both cases.

It is observed that soil ionization plays an influential role in reducing the step and touch (contact) potentials as well as the values of the current pass-through heart. It is seen that the front time of lightning stroke affects the time to reach by the current pass-through heart to its beak value. The current pass-through of the heart of humans increases when the current peak of the lightning pulse increases, also when the reflection factor is positive the current pass–through the heart is decreased in case of step potential and increased in touch potential.

ACKNOWLEDGMENT

This work was supported by the Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University, Espoo, Finland.

REFERENCES

[1] *Effects of Current on Human Beings and Livestock—Part 4: Effects of Lightning Strokes on Human Beings and Livestock*, document IEC/TR 60479-4, Edition 1.0, 2004.
[2] *Effects of Current on Human Beings and Livestock—Part 1, General Aspects*, document IEC/TS 60479-1, Edition 4.0, 2005.
[3] *Guide for Safety in Ac Substation Grounding*, New York, NY, USA, Standard IEEE 80, 2000.
[4] D. R. Koont, *Lightning*. London, U.K.: Headline, 2015.
[5] I. Hetita, D.-E.-A. Mansour, Y. Han, P. Yang, and A. S. Zalhaf, ''Experimental and numerical analysis of transient overvoltages of PV systems when struck by lightning,'' *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–11, 2022.
[6] A. S. Zalhaf, D.-E.-A. Mansour, Y. Han, P. Yang, and M. M. F. Darwish, ''Numerical and experimental analysis of the transient behavior of wind turbines when two blades are simultaneously struck by lightning,'' *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–12, 2022.
[7] V. Cooray, C. Cooray, and C. J. Andrews, ''Lightning caused injuries in humans,'' *J. Electrostatics*, vol. 65, nos. 5–6, pp. 386–394, May 2007.
[8] N. R. Misbah, M. Z. A. A. Kadir, and C. Gomes, ''Modelling and analysis of different aspect of mechanisms in lightning injury,'' in *Proc. 4th Int. Conf. Model., Simul. Appl. Optim.*, Kuala Lumpur, Malaysia, Apr. 2011, pp. 1–5.
[9] S. Sreedhar and V. Indragandhi, ''A comprehensive framework for direct lightning-structure-human interaction modelling in heritage monuments and safety assessment,'' *Energies*, vol. 15, no. 19, p. 7053, Sep. 2022.
[10] *Effects of Current on Human Beings and Livestock—Part 4: Effects of Lightning Strokes on Human Beings and Li*, Vestock, document IEC/TR 60479-4, Edition 1.0, 2004.
[11] *Effects of Current on Human Beings and Livestock—Part 1: General Aspects*, document IEC/TS 60479-1, Edition 4.0, 2005.
[12] D. Cavka, N. Mora, and F. Rachidi, ''A comparison of frequency-dependent soil models: Application to the analysis of grounding systems,'' *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 1, pp. 177–187, Feb. 2014.
[13] R. Alipio and S. Visacro, ''How the frequency dependence of soil parameters affects the lightning response of grounding electrodes,'' in *Proc. Int. Conf. Lightning Protection (ICLP)*, Vienna, Austria, Sep. 2012, pp. 1–4.
[14] O. E. Gouda, A. Z. E. D. Mohamed, M. M. Al-Harthi, S. Y. Omar, and S. S. M. Ghoneim, ''Performance of grounding electrodes under lightning strokes in uniform and two-layer soils considering soil ionization,'' *IEEE Access*, vol. 10, pp. 76855–76869, 2022.
[15] W. S. Meyer and T.-H. Liu. *ATP Rule Book 1987–1992 by Canadian/American EMTP User Group*. Portland, OR, USA. Accessed: May 19, 2022. [Online]. Available: https://kupdf.net/download/rulebook_5af689ce e2b6f5ac65d31504_pdf
[16] G. Leonid, ''Modeling of grounding electrodes under lightning currents,'' *IEEE Trans. Electromagn. Compat.*, vol. 51, no. 3, pp. 559–571, Aug. 2009.
[17] J. Nahman and L. Paunovic, ''Resistance to Earth of earthing grids buried in multi-layer soil,'' *Elect. Eng.*, vol. 88, no. 4, pp. 281–287, 2006.
[18] L. Grcev, ''Impulse efficiency of ground electrodes,'' *IEEE Trans. Power Del.*, vol. 24, no. 1, pp. 441–450, May 2009.
[19] F. Heidler and J. Cvetić, ''A class of analytical functions to study the lightning effects associated with the current front,'' *Eur. Trans. Electr. Power*, vol. 12, no. 2, pp. 141–150, Mar. 2002.
[20] F. Rachidi, W. Janischewskyj, A. M. Hussein, C. A. Nucci, S. Guerrieri, B. Kordi, and J.-S. Chang, ''Current and electromagnetic field associated with lightning-return strokes to tall towers,'' *IEEE Trans. Electromagn. Compat.*, vol. 43, no. 3, pp. 356–367, Aug. 2001.
[21] D. S. Gazzana, A. S. Bretas, G. A. Dias, M. Telló, D. W. Thomas, and C. Christopoulos, ''A study of human safety against lightning considering the grounding system and the evaluation of the associated parameters,'' *Electr. Power Syst. Res.*, vol. 113, pp. 88–94, Aug. 2014.
[22] J. O. S. Paulino, W. D. C. Boaventura, A. B. Lima, and M. F. Guimarães, ''Transient voltage response of ground electrodes in the time-domain,'' in *Proc. Int. Conf. Lightning Protection (ICLP)*, Vienna, Austria, 2012, pp. 1–6.
[23] M. Becerra and V. Cooray, ''On the interaction of lightning upward connecting positive leaders with humans,'' *IEEE Trans. Electromagn. Compat.*, vol. 51, no. 4, pp. 1001–1008, Nov. 2009.
[24] G. Ala and M. L. D. Silvestre, ''A simulation model for electromagnetic transients in lightning protection systems,'' *IEEE Trans. Electromagn. Compat.*, vol. 44, no. 4, pp. 539–554, Nov. 2002.
[25] C. Portela, ''Frequency and transient behavior of grounding systems. II. Practical application examples,'' in *Proc. IEEE EMC, Austin Style IEEE Int. Symp. Electromagn. Compat. Symp. Rec.*, Aug. 1997, pp. 385–390.
[26] A. P. Meliopoulos, *Power System Grounding and Transients*. New York, NY, USA: Marcel Dekker, 1988.
[27] T. K. Manna and P. Chowdhury, ''Generalised equation of soil critical electric field EC based on impulse tests and measured soil electrical parameters,'' *IET Gener., Transmiss. Distrib.*, vol. 1, no. 5, pp. 811–817, 2007.
[28] Y. Q. Liu, N. Theethayi, R. Thottappillil, R. M. Gonzalez, and M. Zitnik, ''An improved model for soil ionization around grounding system and its application to stratified soil,'' *J. Electrostatics*, vol. 60, no. 2–4, pp. 203–209, 2004.
[29] M. Mokhtari, Z. Abdul-Malek, and G. B. Gharehpetian, ''A critical review on soil ionization modeling for grounding electrodes,'' *Arch. Elect. Eng.*, vol. 65, no. 3, pp. 449–461, 2016.
[30] (Sep. 28, 2022). *Gauss–Seidel Method*. [Online]. Available: https://math.libretexts.org/Bookshelves/Linear_Algebra/Introduction_to_Matrix_Algebra_(Kaw)/01%3A_Chapters/1.08%3A_Gauss-Seidel_Method
[31] (Dec. 14, 2019). *Effects of Lightning Strikes on the Human Body*. Cardiac Arrest Brain Injury Seizures Spinal Cord Damage Amnesia. [Online]. Available: https://www.prevention.com/health/a32851873/struck-by-lightning-effects
[32] C. Andrews, ''Electrical aspects of lightning strike to humans,'' in *The Lightning Flash*, V. Cooray, Ed. London, U.K.: IEEE Press, 2003, pp. 548–564.
[33] M. A. Cooper, R. L. Holle and C. J. Andrews, ''Distribution of lightning injury mechanisms,'' in *Proc. 30th Int. Conf. Lightning Protection (ICLP)*, Cagliari, Italy, 2010, pp. 1–4.
[34] J. D. Bronzino, *The Biomedical Engineering Handbook*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2000.

OSAMA E. GOUDA a was born in 1951. He received the B.Sc. degree in electrical engineering and the M.Sc. and Ph.D. degrees in high voltage from Cairo University, Egypt, in 1975, 1979, and 1982, respectively. From 1988 to 1993, he was an Associate Professor at the Department of Electrical Power Engineering, Faculty of Engineering, Cairo University. In 1988, he was at the Department of Electrical Engineering, Kema Institute, Arnhem, The Netherlands, where he was a Research Fellow. Since 1993, he has been a Full Professor with the Electrical Engineering Department, Cairo University. He is currently the Head of the High Voltage Group, Electrical Power Engineering Department, Cairo University. He published more than 140 papers. He was a supervisor for about 70 M.Sc. and Ph.D. degrees. His research interests include high-voltage phenomena, cable insulation, protection of power systems, and electromagnetic transients.

ADEL Z. EL DEIN was born in Egypt, in 1971. He received the B.Sc. and M.Sc. degrees in electric engineering from the Faculty of Energy Engineering, Aswan, Egypt, in 1995 and 2000, respectively, and the Ph.D. degree in electric engineering from Kazan State Technical University, Kazan, Russia, in 2005. From 1997 to 2002, he worked as a Teaching Assistant at the Faculty of Energy Engineering, Aswan. From 2002 to 2005, he was at the Kazan Energy Institute, Kazan, and Kazan State Technical University. From 2005 to 2011, he was a Staff Member at the Department of High Voltage Networks, Faculty of Energy Engineering, Aswan University, Aswan. From 2011 to 2016, he was an Associate Professor at the Department of High Voltage Networks, Faculty of Energy Engineering, Aswan University. In 2014, he joined the Department of High Voltage Engineering (Hikita Laboratory), Kyushu Institute of Technology (KIT), Japan, as a Researcher. Since 2016, he has been a Full Professor of high voltage engineering with the Department of High Voltage Networks, Faculty of Energy Engineering, Aswan University. In October 2022, he becomes the President of New Thebes Technological University, Luxor, Egypt. His research interests include the calculation of electric and magnetic fields and their effects and the comparison of numerical techniques in electromagnetics. He is a Regular Reviewer for IEEE TRANSACTIONS ON POWER DELIVERY, *Electric Power Systems Research*, and *IET Generation, Transmission & Distribution*.

SARA YASSIN OMAR was born in Egypt, in 1989. She received the B.Sc. degree in electric engineering from the Faculty of Energy Engineering, Aswan, Egypt, in 2011, and the M.Sc. degree in high voltage engineering from the Faculty of Engineering, South Valley University, Qena, Egypt, in 2017. She is currently pursuing the Ph.D. degree with the Faculty of Engineering, Cairo University, Giza, Egypt. From 2012 to 2016, she was a Laboratory Engineer at the Electric Engineering Department, Industrial Technical Institute, Qena. In 2020, she joined Upper Egypt Electricity Distribution Company, Qena, as a Project Engineer. Her research interests include the transient performance of grounding systems under soil ionization effect and frequency effect.

MATTI LEHTONEN received the master's and Licentiate degrees in electrical engineering from the Helsinki University of Technology, Finland, in 1984 and 1989, respectively, and the Doctor of Technology degree from the Tampere University of Technology, Finland, in 1992. He was at VTT Energy, Espoo, Finland, from 1987 to 2003. Since 1999, has been a Full Professor and the Head of the Power Systems and High Voltage Engineering Groups, Aalto University, Espoo. His research interests include power system planning and assets management, power system protection including earth fault problems, harmonic related issues, high voltage systems, power cable insulation, and polymer nanocomposites. He is an Editor of *IET Generation, Transmission & Distribution* and an Associate Editor of *Electric Power Systems Research* journal.

MOHAMED M. F. DARWISH (Senior Member, IEEE) was born in Cairo, Egypt. He received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the Faculty of Engineering at Shoubra, Benha University, Cairo, in May 2011, June 2014, and January 2018, respectively. From 2016 to 2017, he joined as a Ph.D. student at the Department of Electrical Engineering and Automation (EEA), Aalto University, Finland, and Prof. M. Lehtonen's Group. Since January 2023, he has been working as an Associate Professor with the Department of Electrical Engineering, Faculty of Engineering at Shoubra, Benha University. He is also a Postdoctoral Researcher with the Department of EEA, School of Electrical Engineering, Aalto University. He has coauthored several international IEEE journals and conferences. His research interests include high voltage, cable insulation, fault diagnosis, nano-fluids, partial discharge, DGA, renewables, applied machine learning, the IoT, and industry 4.0. He is currently a Young Editoral Board Member in *Applied Energy* journal and a Topic Editor in *Catalysts* Journal, also becomes a guest editor for many special issues in numerous journals. He received the Best Ph.D. Thesis Prize that serves industrial life and society all over the Benha University Staff for the academic year (2018–2019). Furthermore, in 2022, he got also the Prestigious Benha University Encouragement Award in engineering sciences and technologies for the academic year (2021–2022). Recently, he was nominated as an Associate Editor in *IET Generation, Transmission & Distribution*, *Electric power components and systems*, and *Frontiers in Energy Research* journals.