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Lightning Discharges and Discharges from Overhead Power Lines with Human Burn Injuries as Consequences

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Abstract: Discharges from overhead power lines and lightning discharges may severely endanger human life and health. If non-lethal, burn injuries may also last for a lifetime, so as Lichtenberg figures caused by lightning discharges. Some accidents with burns are discussed in this paper and recommendations given for safety reasons. Specific energy transferred by typical lightning strokes currents given in the standard IEC 62305 is calculated. The aim of the paper is to suggest a simple expression for the estimation of safe approach distances to overhead lines, especially if high temperatures and changes in terrain reduced the secure height above ground, or if carrying elevated objects. Results of these calculations are compared to safe approach distances given in regulations of different countries. Safe distances from railway power lines are also considered.

Keywords: Burn injuries, Lightning discharges, Overhead power lines, Safe approach distance.

1 Introduction

The paper analyzes human burn injuries due to discharges from high voltage overhead lines and lightning discharges, and suggests a simple way to calculate safe approach distances and to reduce the risk from these discharges. Besides being lethal, burns from natural discharges or artificial electricity present about 5% of admissions to burn units. The first death from an artificial source of electricity was reported already in XIX century in France, from 250 V AC generator (in 1879), and in the USA from a similar generator, in 1881 [1]. Lightning discharges have caused deaths of many people and animals already for ages, and the number of trees destroyed by lightning and such initiated fires in woods is enormous. For example, lightning causes 50-300 deaths and about 1000 victims suffering non-lethal injuries per year in USA. Work-related injuries from lightning are about 60% of those. Chances of being struck by lightning are increased by carrying metal objects such as fishing rods,

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umbrellas, axes, golf clubs, helmets or rifles. Fishermen carrying fishing rods are more endangered if passing under high voltage overhead lines. Just being by water, they are also more exposed to lightning threat. Campers, skiers, mountain hikers and joggers are common non-work related victims. About 80% of lightning victims are 25-45 age old men [2], as they are the majority of workers outdoors.

Most of lightning strikes happen in summer and in moist tropical climate regions, or in mountains. Data from "Instituto Superiore della Sanita" report an average of 1.6 million lightning strikes per year in Italy, especially during months of July and August, but this phenomenon may occur even in winter. The most affected areas in Italy are the Friuli, the region of Lombardy lakes, the area of Rome, and the foothills of the Alps and the Apennines mountains. More generally looking - there are no areas free of risk from lightning in Italy. Similar situation is in Serbia. There was also an unusual event of lightning noticed on a snowy day in January 2011. The lightning data are available from lightning detection networks such as LINET [3], which covers the whole Europe and also has two sensors in Serbia. By providing early warnings, lightning detection maps, statistics and weather forecast, LINET can be used to avoid or minimize damages from direct strokes or indirect lightning effects on different structures, power installations and transmission lines, electric devices and electronic circuits. Statistics of lightning characteristics in some region can be used in the design of lightning protection systems and in research of lightning discharges.

There is no place and no time without the risk from lightning in most of the countries throughout the world. The risk is greater in the areas with warm and moist climate, and decreases as geographic latitude increases.

2 Burn Injuries from Lightning Discharges

Lightning discharge to a person is usually lethal. If a lightning current finds path through the brain or heart of the victim, it causes death. Only in non-lethal cases the current passes through other paths, so that burn injuries happen. Burns are more common if a person touches or is near some object which is already the part of the discharge current flow. Side flashes may occur if the current on its way to the ground jumps from its primary struck object to the person. Step voltage is also very dangerous, if a person or animal has one foot closer to the strike point than the other foot, so that the discharge current flows through legs and body, instead through the ground. This often kills cattle and horses. Even some critically endangered animals were killed in South African forest reserve from lightning. By killing a few animals lightning caused elimination of a half of the Earth's population of that species. Cattle and wild animals can also get burn injuries from lightning caused fires in forests and plains.

In the case of natural lightning discharge an impulse current flows through the interior of the body (tissues and organs) and through its exterior surface (skin). This results in proportional heating of tissues, and in wide burn areas of skin, sometimes resulting in carbonization. Heating of tissues causes electrothermal burn injuries which depend on the resistance of a tissue, its moisture, temperature and other tissue properties. Nerves, muscles, mucous membranes and blood vessels have high water and electrolyte content, so they have low resistance and behave like good conductors. On the contrary - bones, fat and tendon have high resistance, so they heat up and coagulate, but don't transmit electrical current well. Skin is a primary resistor for the current flow. Dry skin represents an intermediate conductor, but conductivity values given in literature differ [4, 5]. On the inside arm its specific resistance is about 300 Ωm, but heavily calloused palm may have 50 times greater specific resistance [1]. This may result in significant amount of energy being dissipated at the skin surface, causing burn injuries, but less internal damage to deep tissues and organs. However, it results in skin burns and blisters, and further in decreased resistance. Sweat and moisture decrease skin resistance. According to the literature [1] (Schwan & Kay, Kaufman&Johnson), specific resistance is about 10 Ωm for lung, about 7 Ωm for muscle, heart and liver, about 15-50 Ωm for fatty tissue, about 2 Ωm for blood, etc. Often used values ([4, 5]) for calculations of induced currents and fields in human tissues at 50 Hz are given in **Table 1**.

Table 1

Specific conductivity and relative permittivity of human tissues at 50 Hz.

Tissue	Conductivity [4] [S/m]	Relative permittivity [4]	Conductivity [5] [S/m]	Relative permittivity [5]
Muscle	0.23	$17700 \cdot 10^3$	0.86	$434.93 \cdot 10^3$
Bone	0.02	$8.88 \cdot 10^3$	0.04	$12.32 \cdot 10^3$
Skin	0.0002	$1.14 \cdot 10^3$	0.11	$1.14 \cdot 10^3$
Heart	0.083	$8660 \cdot 10^3$	0.5	$352.85 \cdot 10^3$
Blood	0.7	$5.26 \cdot 10^3$	0.6	$5.26 \cdot 10^3$
Lung	0.068	$5750 \cdot 10^3$	0.04	$145.10 \cdot 10^3$
Liver	0.037	$1830 \cdot 10^3$	0.13	$85.67 \cdot 10^3$

The nature and severity of electrical burn injuries depend on the magnitude of the current, resistance of the path, and duration of the current flow and the path itself. Thermal power represents Joules losses following equation:

$$W(t) = \int_0^t R\, i^2(t)\,\mathrm{d}\,t\,, \tag{1}$$

where $i(t)$ is the current flowing through resistance R in a time interval t.

Lightning current may take the path which is not possible to predict, and in fact lethal or non-lethal outcome of that current flow mostly depends on the selected path. In cases of lightning injuries important vital functions always have to be taken care of, before considering any burns.

The resistance of a human body is non-linear, depending mainly on voltage and frequency, and varies a lot for different persons. For the frequency of 50 Hz and 25 V it may vary from 1750 to 6100 Ω, for 100 V from 1200 to 3200 Ω, for 220 V from 1000 to 2125 Ω, and for 1000 V from 700 to 1500 Ω [6]. The first values are not exceeded in 5% of population, and the second are not exceeded in 95% of population. Human body also has dielectric properties (**Table 1**), thus in total presenting impedance for the current flow. In the case of lightning discharge currents there is a wide spectrum of frequencies from Hz to MHz, so it is difficult to estimate the dissipated energy.

The specific energy can be calculated as:

$$W(t)/R = \int_0^t i^2(t)\,\mathrm{d}\,t\,, \tag{2}$$

so if human body or another struck object is modeled with some average resistance, the transferred energy can be calculated roughly for lightning currents of typical strokes as specified in the standard IEC 62305.

Analytical expression for the channel-base current NCBC given in [7] is:

$$i(t) = \begin{cases} I_m\, \tau^a \exp\left[a(1-\tau)\right], & 0 \le \tau \le 1, \\ I_m \sum\limits_{i=1}^{n} c_i\, \tau^{b_i} \exp\left[b_i(1-\tau)\right], & 1 \le \tau < \infty, \end{cases} \tag{3}$$

for parameters a and b_i, weighting coefficients c_i (so that $\sum\limits_{1}^{n} c_i = 1$), normalized variable $\tau = t/t_m$, rise-time t_m to the maximum current value I_m, and selected number of expressions n in the decaying part of the function. NCBC function is presented in Fig. 1. For $n = 1$, $c_1 = 1$ and $b_1 = b$ this function has just four parameters I_m, t_m, a and b. Parameters are calculated according to the standard IEC 62305 lightning currents of the first negative strokes, subsequent negative strokes and positive strokes.

Specific energy is calculated from the following expression [8]:

$$\frac{W(t)}{R}=\int_0^t i^2(0,t)\,\mathrm{d}t=$$

$$=\begin{cases} I_m{}^2 t_m \dfrac{\exp(2a)}{(2a)^{2a+1}}\gamma\left(2a+1,2at/t_m\right), & 0\le t\le t_{\mathrm{m}}, \\ I_m{}^2 t_m \left\{\dfrac{\exp(2a)}{(2a)^{2a+1}}\gamma\left(2a+1,2a\right)+\right. & \\ \quad +\displaystyle\sum_{i=1}^{n} c_i{}^2 \dfrac{\exp(2b_i)}{(2b_i)^{2b_i+1}}\left[\gamma\left(2b_i+1,2b_i t/t_m\right)-\gamma\left(2b_i+1,2b_i\right)\right]+ & \\ \quad +2\displaystyle\sum_{\substack{j,k=1\\ j\neq k}}^{n} c_j c_k \dfrac{\exp(b_j+b_k)}{(b_j+b_k)^{b_j+b_k+1}}\left[\gamma\left(b_j+b_k+1,(b_j+b_k)t/t_m\right)-\right. & \\ \quad \left.\left.-\gamma\left(b_j+b_k+1,b_j+b_k\right)\right]\right\}, & t_m\le t<\infty \end{cases} \tag{4}$$

where the incomplete Gamma function (Euler function of the second kind) is $\gamma(a+1,x)=\int_0^x t^a\exp(-t)\,\mathrm{d}t$.

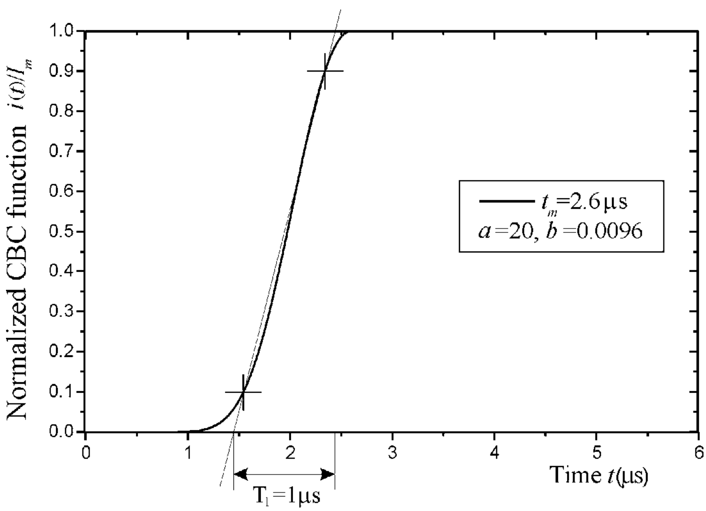

Fig. 1 – *The rising part of the first negative stroke current* 1/200 μs.

For the first negative strokes 1/200 μs parameters of the NCBC function are $t_m = 2.6$ μs, $a = 20$, $b = 0.0096$, and for $I_m = 100$ kA the specific energy calculated from (4) is about 1.45 MJ/Ω for the time interval long enough so that current approximately decreased to zero (calculated for 2 ms). For current waveshapes 2/200 μs and 3/200 μs the same results are obtained and given in Fig. 3, so changes in the rising part are not so important for this value.

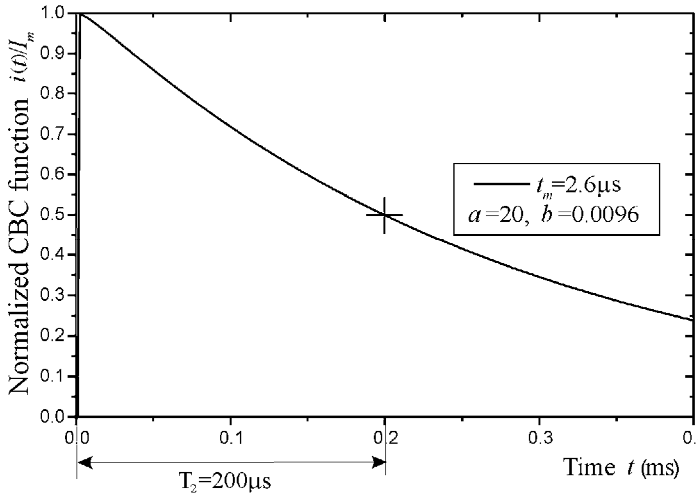

Fig. 2 – *The decaying part of the first negative stroke current* 1/200 μs.

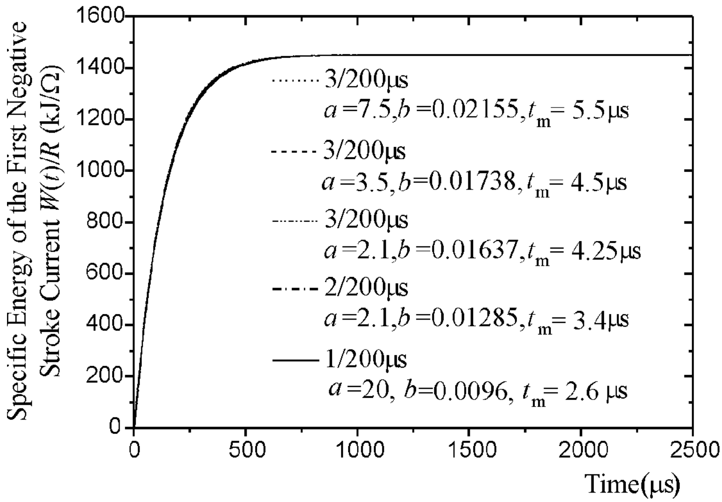

Fig. 3 – *Specific energy of the first negative stroke currents* 1/200 μs, 2/200 μs *and* 3/200 μs.

For the subsequent negative stroke 0.25/100 μs, parameters are t_m = 0.65 μs, a = 20, b = 0.00467, and for I_m = 50 kA, the specific energy calculated from (4) is 0.18 MJ/Ω for the time interval long enough so that current approximately decreased to zero (1 ms). Results are given in Fig. 4.

For the positive stroke 10/350 μs parameters are $t_m = 0.26$ μs, $a = 20$, $b = 0.0665$, and for $I_m = 200$ kA the specific energy calculated from (4) is 12 MJ/Ω (Fig. 5) for the time interval long enough so that current approximately decreased to zero (3.5 ms).

Peaks of lightning channel-base currents for cloud to ground lightning strokes are measured from a few kA to hundreds of kA [2].

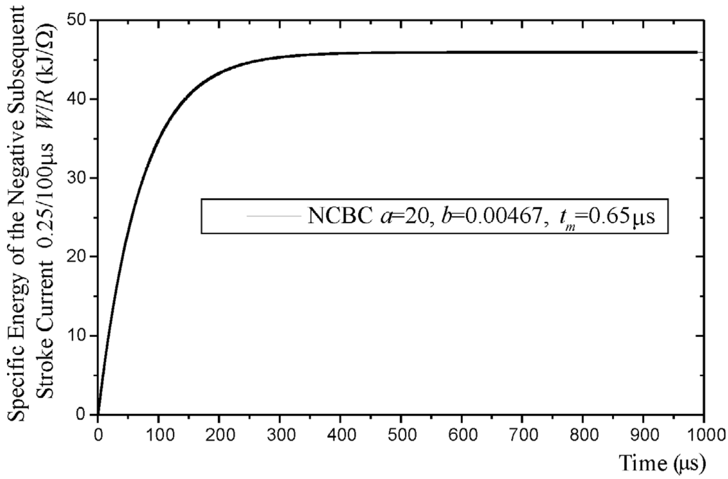

Fig. 4 – *Specific energy of the subsequent negative stroke current* 0.25/100 μs.

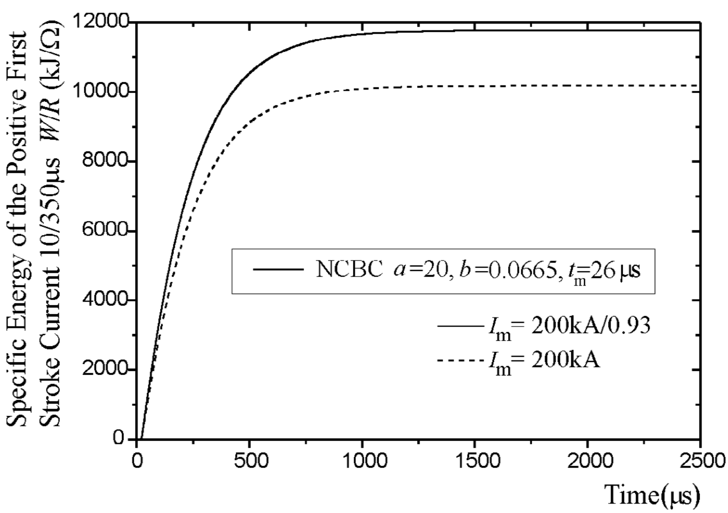

Fig. 5 – *Specific energy of the first positive stroke current* 10/350 μs.

If the current is flowing through the resistor $R = 1$ kΩ calculated values of energy are of GJ values. This energy may cause burns of fourth degree and carbonization of a human body. A victim of the lightning strike may also get Lichtenberg figures on skin, either he was lucky to survive as in Fig. 6, or not.

Fig. 6 – ***Lichtenberg figure on skin*** **[9].**

Fig. 7 – ***Burns from high-voltage installations*** **[10].**

3 Burn Injuries from Overhead Power Lines

Burn injuries often happen in household while using electrical appliances with malfunctions or with wet hands, due to cords defects or bad electrical installations in bathroom. There is a constant presence and threat from high voltage installations in certain living areas and at some working places. These are the most dangerous of all electrical installations as they can cause damages from a distance by an electric arc. In the cases of low voltages, electrical injury burn marks can appear, but death can happen even without them, as happens in about 20% of cases. Ears, sculls, and hands - fingers, palms, wrists, elbows or shoulders may be contact points to AC sources and ground contact points can be feet or other.

In non-lethal cases, discharges from high voltage installations result usually in the second to fourth degree burns (Fig. 7). Second degree burns result in erythematous skin, deeply and severely damaged. There are blisters and significant swelling. Third degree burns cause damage to all layers of the skin down to the tissue under the skin. They destroy nerves and burnt skin looks white or charred. Victims with such burns have multiple complications and they require prolonged hospitalization. Extensive burn scars following lightning burns may develop into squamous cell carcinoma.

Electrical installations can have direct current (DC) or alternating current (AC). DC contact usually causes single muscle spasm, thus throwing victim from the electrical source. It can also result in cardiac disturbances. AC exposure to the same voltage is more dangerous than DC (approximately three times), as it causes long duration contraction of muscles. Values of dangerous currents and voltages depend primarily on the type of current and its path through the body, and in the case of AC on frequencies. 5 Hz is dangerous frequency, but very high frequencies are not - and they may result just in surface skin heating which is used for medical treatments.

For 50 Hz (in Europe) or 60 Hz (in the USA), AC currents greater than "let-go threshold" prevent victims to release from current sources due to muscular tetany. Above this, thoratic tetany occurs and results in respiratory arrest [11 – 14]. Ventricular fibrillation occurs for 60–120 mA currents, and cardiac arrest follows. It is possible that the current > 50 mA stops the heart, but if it vanishes in about 0.1 s time, the heart may continue without consequences, so as for the current > 150 mA, if it vanishes in 0.02 s time. However, these values are different for humans, and present statistical values.

Both people and animals can get blunt trauma from falls, as happened to a bear that climbed up an electrical mast as if it was a tree. Victims may be thrown away from electrical sources by sudden and intense contractions of muscles caused by current flowing through their bodies which causes injuries.

Thresholds and ranges of current values for some physical effects at 50/60 Hz are given in **Table 2**.

Table 2
Physical effects of some currents.

Physical effect	AC current [mA] 50/60 Hz	DC current [mA]
Tingling sensation	about 1	about 5
Let-go current for children	4	-
Let-go current for women	7	-
Let-go current for men	9	-
Freezing to circuit	10-20	-
Respiratory arrest from thoracic muscle tetany	20-50	-
Ventricular fibrilation	> 50 (for $t > 0.1$ s)	300-500

A case was reported last year in Serbia of a man passing under the 35 kV line with an Al-rod for tracing the road. He was terribly burnt due to the current discharge which passed through the rod to the ground, but partially also through his arm and leg. The line was lower due to the change of terrain which was upraised with ground works for more than 1m after line's installation. A current jumped from the line and passed from his hand to his leg and went out his foot, so that he got third degree burns. He had amputation of the leg and his son gave him skin for the operation. Another man was carrying irrigation pipe in an upraised position and thus approached to 10 kV overhead line more than he should, so he suffered a high-voltage discharge.

Height under the line may be reduced from the tower height due to sags [15], so that relative reduction of the height may be great, as illustrated in Fig. 8. The power line is lowered to just a few meters height, which is obvious from its position where passing in front of another mast placed at the agricultural terrain.

Severe injuries are sometimes consequences of bad installations of high voltage lines, but mostly of the absence of precaution. In the place Pasipoljana near Niš a high voltage line was lowered due to high ambient temperature of about 40^{o}C. Additionally, houses were built there under the power line which was at 6 m height upraised forty years before, when there were no buildings in that area, instead at 7 m which is a secure height in built area according to regulations. In summer sags can be problem together with changes of terrain and accidents are reported in many countries all over the world. The cases should be properly analyzed because of fatal consequences.

Fig. 8 – *High voltage line sag due to heat.*

4 Railway Power Lines

There are various high voltage lines in all countries for railways and subways. In Serbia, a special case that one should be aware of is that railway 25 kV single-phase power lines are passing above ground at 5.5 m height. A person may be at some distance from high voltage line but still endangered, as current can flashover through the air to the nearest object. Danger places under such lines are bridges and railway stations, especially in the case when old wagons are left there and they seem like a nice place for children playing.

In April 2013, a 12-years old boy was trying to make graffiti with his friends and climbed up on an old wagon in the railway station in Niš (Serbia). Thus he approached to the railway 25 kV line, current flashed over to his body and he was also thrown away. His skin was 90% burnt and one part was carbonized (fourth degree burns). He lived until the next day. The place is shown in Fig. 6. Simple calculation shows that head of any upraised person who climbed on the roof of a wagon under such line is not at the safe distance.

Fig. 9 – *Railway station with* 25 kV *overhead line.*

In April 2007 a 14-years old boy, also in Niš (Serbia) and not far from the same station, was passing the railway bridge under the 25 kV single-phase line. He was going fishing. He approached standard railway line height of 5.5 m as he had a fishing rod in his hand. The rod material itself is not so important as its proximity to the line. When the discharge occurred, he was literally put on fire and fortunately saved by a man who saw what was happening. The boy got terrible burns all over his body (70% of his skin) and had several surgeries to save his life. In years after that he had transplantation in the hospital in Italy using skin developed from his own skin cells. The operations succeeded and he is well now, but he had suffered a lot. The bridge (a) and the pedestrian path (b) (without any sign of warning) are shown in Fig. 9.

(a) **(b)**

Fig. 10 – (a) *Railway bridge*; (b) *Pedestrian path on the railway bridge without any sign of warning.*

5 Estimation of Safe Approach Distances to Overhead Lines

Although there are different regulations in each country and various types of installations, we should all consider wisely approaching to high voltage lines and installations. Safe distances from power installations for living, building or working are given for normal persons and other values for workers on installations in the safety regulations of each country. Technically educated persons can estimate high voltage of an overhead line just by looking at the tower carrying the line, insulators, number of conductors, and knowing nominal voltages in that country.

A simple expression to calculate the safe distance from the power line of some nominal voltage is proposed in this paper as the following:

$$d = a \log_{10} 3U , \tag{5}$$

for U in kV, and the constant a depending on the regulations of some country showing how rigorous they are. For example, this constant should be chosen as $a = 0.8$ m for Serbian, and $a = 2$ m for Australian regulations. The expression is applicable to voltages greater than 1 kV. The results of calculations using (5) and regulations values are given in the following tables.

Table 3
Safe approach limits for some voltages given in Serbian regulations.

Nominal voltages [kV]	Approach limits from Serbian regulations [m]	Approach limits [m] calculated from (5) for a = 0.8 m
< 1	0.8	**0.4**
10	1.2	**1.2**
20-35	1.5	1.4 – 1.6
110	2	2.0

Table 4
Safe approach limits for some voltages given in Australian regulations.

Nominal voltages [kV]	Approach limits from Australian regulations [m]	Approach limits [m] calculated from (5) for a = 2 m
< 1	3	**1**
7.6 – 11	3	**2.7-3**
19-33	3	3.5 – 4
66	4	4.6
132	5	5.2
275	6	5.8

Table 5
Minimum approach distances for live work and surge voltages.

Surge voltages [kV]	Minimum approach distance [m] from Atlani formula (6) for D_E = 0.5 m	Minimum approach distance [m] calculated from (5) for a = 0.35 m
10	0.55	0.52
20 – 35	0.60 – 0.675	0.62 – 0.71
50	0.75	0.76

Table 3 gives safe approach distances of persons from power lines at 50 Hz for some voltages given in Serbian regulations, and **Table 4** for Australian regulations. The constant a is different for various countries, but there is a good agreement of results shown even in cases where these distances are roughly given in regulations.

For approximate calculation of minimum safe approach distance (MAD) for live working (for surge voltages and for 50 Hz) Atlani formula given in [16] and [17] is:

$$D_a = D_U + D_E \,, \tag{6}$$

for $U = 200D_U$ [kV] and D_U [m], electric distances $D_E = 0.3$ m for low voltages, and $D_E = 0.5$ m for high voltages. For some voltages results of Atlani formula are given in **Table 5** and compared to results calculated from (5) for the value $a = 0.35$ m.

High voltage installations have precaution warnings that should be strictly obeyed, but non-work related people are usually not well informed about these. High voltage overhead lines deserve more precaution and require responsibility not only from people working on them, but also from other people who can be at risk from them. For both lightning threat or if passing under power lines, it is danger to hold conductive or other objects high in the hands (pipes, fishing rods, scythes, axes, golf clubs, umbrellas or other conductive objects with sharp edges) and thus reduce safe distance.

6 Conclusion

In general, lightning discharge is an unpredictable natural phenomenon, but if there is a lightning threat a person should minimize the risk by finding a safer place and following some safety recommendations [18 – 20]. Safety rules can only reduce the risk from potential damage and losses, but regardless of the action in accordance with the rules, lightning discharges are dangerous, unpredictable, and security is never absolutely guaranteed.

Vicinity of lightning threat or high voltage installations always requires responsibility and caution from people at risk. There is not enough public attention to this danger, except when accidents occur, but public knowledge about these risks should be improved by constant education, lightning brochures and warnings where needed. In this paper the analysis of burn injuries from high voltage overhead lines and lightning discharges is presented in order to avoid such risks for human health and life. Specific energy transferred by some typical lightning strokes currents is calculated and shows good agreement with values from the standard IEC 62305. An expression is proposed for the estimation of safe distances from high voltage overhead lines. It should be noticed that safe distances may be reduced from many reasons and also depend on wind, temperature, and other weather conditions.

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