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BONDING VERSUS ISOLATING APPROACHES IN LIGHTNING PROTECTION PRACTICE

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Abstract - A review of the recent (the last 20 years or so) literature on the safety distance in the soil is given. The review is motivated in part by apparent controversy or misunderstanding regarding the bonding and isolating concepts in lightning protection practice.

1. INTRODUCTION

The twofold objective of lightning protection against direct strikes is (1) to force the current flow where one wants it to go and (2) not to allow the development of hazardous potential differences. A difference of potential of 2 MV is sufficient for a sideflash of over 1.8 m (6 ft) in air (NFPA 780, Annex C, p. 35) or arcing through the soil over 5.4 m (18 ft) or so (Mousa, 1994). Once arcing takes place, an unplanned and uncontrolled current path is created. The arc is likely to turn moisture in the soil or structural material to steam with potentially damaging hydrodynamic effects. Destructive arcing between exposed or buried elements of the lightning protective system (LPS) and nearby metallic objects can be prevented by either (1) equipotential bonding or (2) adequate electrical isolation (IEC 61024-1, p. 27). If direct bonding is not acceptable, it should be done via a surge protective device (SPD) with suitable characteristics (IEC 61024-1, p. 29).

Ideally, when lightning current causes a properly protected system's potential to rise momentarily to as much as some megavolts, all points of bonded conductors "rise" together (neglecting traveling-wave effects that occur on electrically long conductors), and no hazardous potential differences are created (Hasbrouck, 1989, p. 22). This scenario is somewhat similar to that of a bird sitting on a high-voltage wire unaware that it is at a potential of over 1 kV, which is changing several times a second (NFPA 780, Annex C, p. 36).

2. LIGHTNING SAFETY DISTANCE IN THE SOIL

We review below the recent (the last 20 years or so) literature on the safety distance in the soil, in chronological order. In doing so, we neglect the so-called surface arcs that were observed to occur when lightning peak current exceeds 15 kA or so (depends on soil conductivity and on availability and type of man-made grounding) and to carry about 5% of the total lightning current (Rakov et al., 1998). This phenomenon is in need of further research.

A. R.H. Lee, Grounding and Lightning Protection. Seminar Notes, Edition #2, 1986

Lee (1986) considered sideflashes in air on p. L-45 of his Seminar Notes. He stated that "in the past" the sideflash distance (also called safety distance or bonding distance) was assumed to be equal to 6 ft (1.8 m), regardless of height above ground. We estimate that the corresponding arcing distance through the soil should be about a factor of 3 greater, 18 ft (5.5 m), because the breakdown electric field in the soil is about a factor of 3 lower than that in air (Mousa, 1994).

Lee (1986) also gave an equation for sideflash distance in feet based on more recent research:

$$D_{air} = 0.3R + \frac{\ell}{2n} \quad (\mathrm{ft}) \tag{1}$$

where R is measured resistance of the grounding system in ohm, ℓ is the length of downconductor from point of possible sideflash to the grounding system in feet, and n is number of downconductors spaced at least 50 ft apart. If the point of interest is located in the immediate vicinity of ground surface, $\ell \approx 0$ and equation (1) reduces to

$$D_{air} = 0.3R \quad (\mathrm{ft}) \tag{2}$$

Further, if the point of interest is below ground surface (although this case was not considered by Lee), where breakdown electric field is about a factor of 3 lower than that in air, the value of safety distance given by equation (2) should be multiplied by 3, so that

$$D_{soil} = 0.9R \quad (\mathrm{ft}) \tag{3}$$

If we assume that R = 25 Ω, D_{soil} = 0.9 x 25 = 22.5 ft ≈ 6.9 m. If the separation between the LPS conductor (grounding electrode) and another conductor in the soil (e.g., a buried metallic pipe) is less than D_{soil}, equal to 6.9 m, the two conductors must be bonded in order to avoid arcing between them.

B. RD 34.21.122-87, Russian Lightning Protection Design Code for Buildings and Structures, 1987

This code requires (see Fig. 2) that the distance through air between the LPS conductors and the protected object exceeds the safety distance D_{air}, which depends on object height and soil resistivity, ρ. For structures less than 30 m in height,

$$D_{air} = 3 \text{ m for } \rho \le 100\ \Omega\text{m}; \tag{4}$$

$$D_{air} = 3 - 12 \text{ m (depending on grounding system type) for } 100 < \rho \le 1000\ \Omega\text{m} \tag{5}$$

Clearly, D_{air} increases with increasing ρ, because this results in an increase in the grounding resistance. For taller structures D_{air} must be increased by 1 m per every 10 m of height in excess of 30 m.

The code also requires (see Fig. 2) that the distance in the soil between the LPS grounding system and buried metallic services (including electrical cables) is to be greater than the safety distance D_{soil} in meters. For Category I (highest protection level) buildings and structures

$$D_{soil} = D_{air} + 2 \quad (\mathrm{m}) \tag{6}$$

Thus,

$$D_{soil} = 5\,\mathrm{m} \text{ for } \rho \le 100\,\Omega\,\mathrm{m} \tag{7}$$

$$D_{soil} = 5 - 14\,\text{m} \;\; \text{for}\, 100 < \rho \leq 1000\,\Omega\,\text{m} \qquad (8)$$

To summarize, buried cables must be placed at a distance exceeding 5 m from the LPS grounding system in order to avoid arcing between them. If the distance is less than 5 m, the two must be bonded, regardless of soil resistivity.

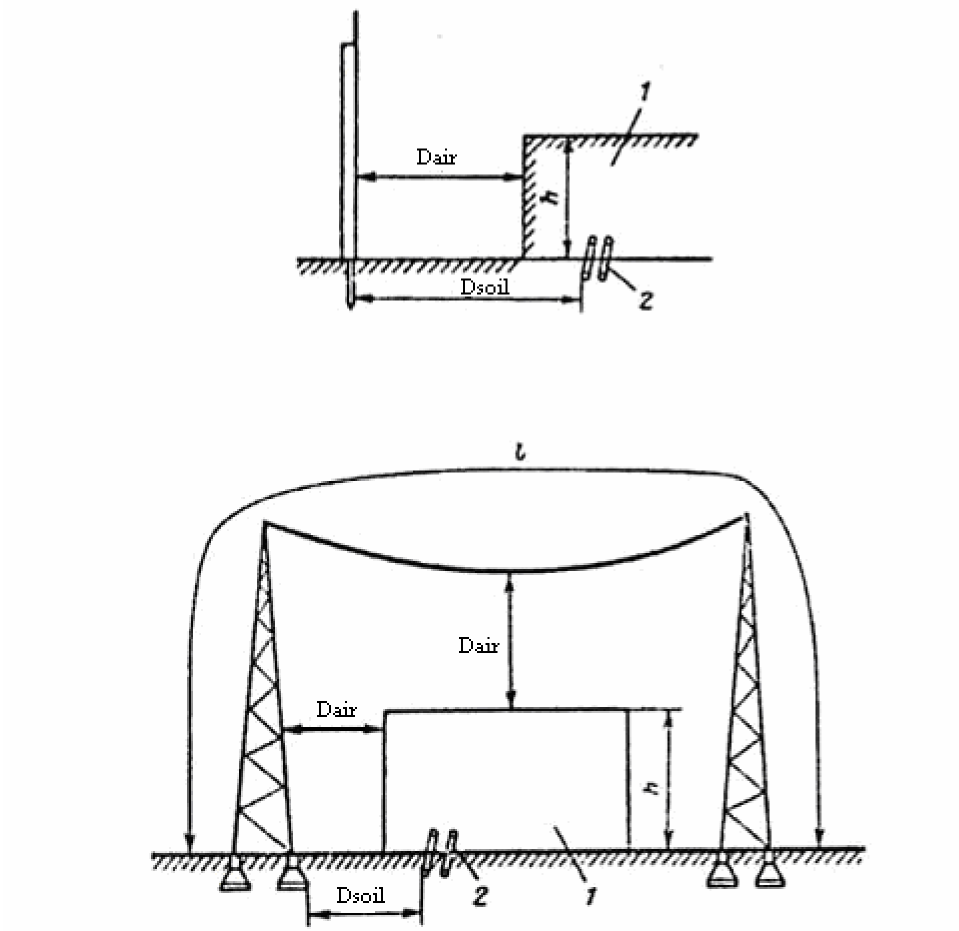

Fig. 2. Safety distances in air (D_{air}) and in the soil (D_{soil}) in RD 34.21.122-87. 1 - protected object, 2 - metallic services. Taken from RD 34.21.122-87.

C. J. Wiesinger and W. Zischank, Lightning Protection, in Handbook of Atmospheric Electrodynamics, vol. II, ed. H. Volland, pp. 33-64, Boca Raton: CRC Press, 1995

According to Wiesinger and Zischank (1995), the safety distance, D_{soil}, in meters, between the LPS grounding system and nearby buried metallic services (pipes or cables) that are not bonded to the grounding system is

$$D_{soil} = IR/E_b \qquad (\text{m}) \qquad (9)$$

where I is the lightning peak current, R is the grounding resistance, and E_b is the breakdown electric field in the soil. If we assume I = 30 kA (typical first-stroke peak current), R = 25 Ω, and E_b = 300 kV/m (Mousa, 1994),

$$D_{soil} = 30 \text{ x } 25/300 = 2.5 \text{ m} \tag{10}$$

For a larger peak current, say, 60 kA, D_{soil} = 5 m.

If buried metallic services are located at a distance that is less than D_{soil} from the LPS grounding system, they must be interconnected (bonded). Bonding of external services entering protected structure is illustrated in Fig. 3.

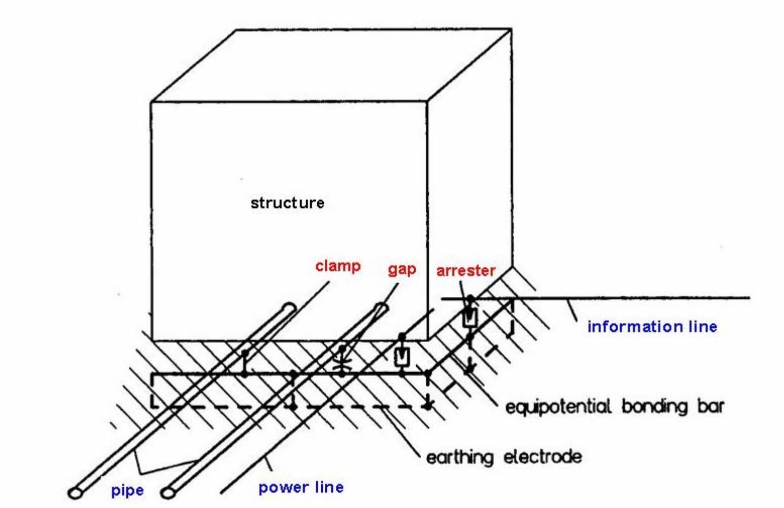

Fig. 3. Bonding of external services near ground level. Taken from Wiesinger and Zischank (1995).

D. I.P. Kuzhekin, V.P. Larionov, and E.N. Prokhorov, Lightning and Lightning Protection, 300 p., Moscow: Znak, 2003

According to Kuzhekin et al. (2003), the distance between an LPS down-conductor and the protected object in air should be greater than D_{air} given in meters by

$$D_{air} = 0.12Z + 0.1l \text{ (m)} \tag{11}$$

where Z is the impedance of LPS grounding system under direct lightning strike conditions (transient impedance, which can be either smaller or larger than the dc grounding resistance, R) and ℓ is the distance between the point of interest and the LPS grounding system. For a point in the immediate vicinity of ground surface, ℓ ≈ 0 and equation (11) reduces to

$$D_{air} = 0.12\,Z \text{ (m)} \tag{12}$$

If Z = 25 Ω, D_{air} = 0.12 x 25 = 3 m.

The distance between the LPS grounding system and buried metallic services should be greater than D_{soil} given by

$$D_{soil} = IZ/E_b\,,\ \text{m} \tag{13}$$

where I is the lightning peak current, and E_b is the breakdown electric field in the soil. Kuzhekin et al. (2003) assumed I = 60 kA (approximately 10% value, which is recommended for lightning protection studies in Russia) and E_b = 300 kV/m, so that

$$D_{soil} = 0.2\ Z,\ m \tag{14}$$

If Z = 25 Ω, D_{soil} = 0.2 x 25 = 5 m. Whatever the value of Z, Kuzhekin et al. (2003) recommend that $D_{air} \geq 5$ m and $D_{soil} \geq 3$ m ($D_{air} > D_{soil}$ due to the inductance of down conductors). It follows that buried electrical cables within 3 m of an LPS grounding system must be bonded to that system. An insulated single-wire cable can be bonded either via SPD or via an enclosing metallic pipe. Kuzhekin et al. (2003) state that the capacitance between the cable and pipe is sufficiently large, so that the capacitive impedance between them under direct lightning strike conditions is very small. As a result, the wire and pipe become effectively bonded (at the high frequencies characteristic of lightning current), this effect saving cable's insulation from electrical breakdown.

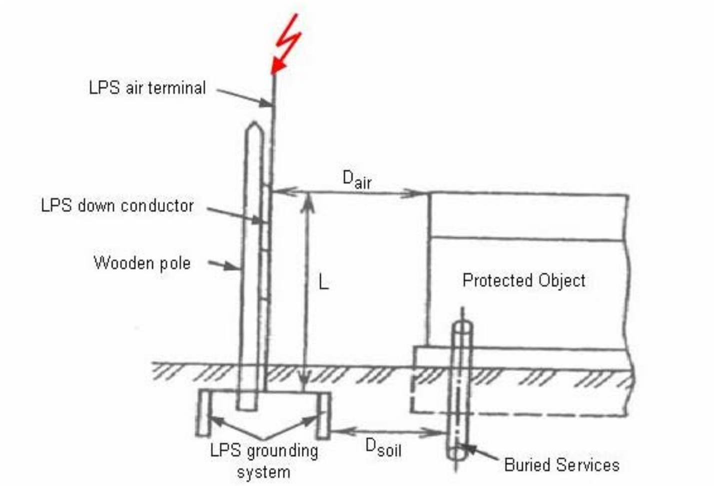

Fig. 4. Illustration of safety distances in air (D_{air}) and in the soil (D_{soil}). L = ℓ. Taken from Kuzhekin et al. (2003).

3. STATISTICAL DISTRIBUTIONS OF LIGHTNING PEAK CURRENT

According to equation (13), which is the most general of all equations for the safety distance, in the soil,

$$D_{soil} = IZ/E_b\ ,\ m \tag{15}$$

where I is the lightning peak current, Z is the impedance of LPS grounding system, and E_b is the breakdown electric field in the soil. D_{soil} in equation (15) is the distance from the lightning current injection point into the ground to a nearby buried object. It follows from equation (15) that the lightning safety distance in the soil depends on (1) the magnitude of the lightning peak current, (2) the breakdown electric field in the soil, and (3) the impedance "seen" by the lightning at its attachment point. In this section, we consider the magnitude of the lightning peak current, with E_b being examined in Section 4. Clearly D_{soil} increases with increasing I.

Lightning peak currents for first strokes vary by a factor of 50 or more, from about 5 kA to 250 kA (e.g., Rakov and Uman, 2003). The probability of occurrence of a given value of peak current rapidly increases with increasing I, up to 25 kA or so, and then slowly decreases. In designing lightning protective schemes, it is customary to consider, as the "worst case", moderately severe strokes that still have an appreciable probability of occurrence, so that the object is protected against the overwhelming majority of strokes (up to the "worst case"). As we will show below (see Table 1), it seems to be reasonable to consider lightning strokes with peak currents up to 60 kA, which constitute about 85% of the population. In this case, D_{soil} = 5.0 m. If one would like to assure protection against strokes up to 80 or 100 kA, which constitute about 92.2 or 95.5% of the population, respectively, the corresponding values of D_{soil} will be 6.7 or 8.3 m.

Essentially all national and international lightning protection standards (e.g., IEEE Std 1410-1997; IEEE Std 1243-1997; IEC 61024-1) include a statistical distribution of peak currents for first strokes in negative lightning flashes (including single-stroke flashes). This distribution, which is one of the cornerstones of most lightning studies, is largely based on direct lightning current measurements conducted in Switzerland from 1963 to 1971 (e.g., Berger, 1972; Berger et al., 1975). The resultant cumulative statistical distributions of lightning peak currents, giving percent of cases exceeding abscissa value, are presented in Fig. 5. The distributions are assumed to be lognormal and given for (1) negative first strokes, (2) positive first strokes, (3) negative and positive first strokes, and (4) negative subsequent strokes.

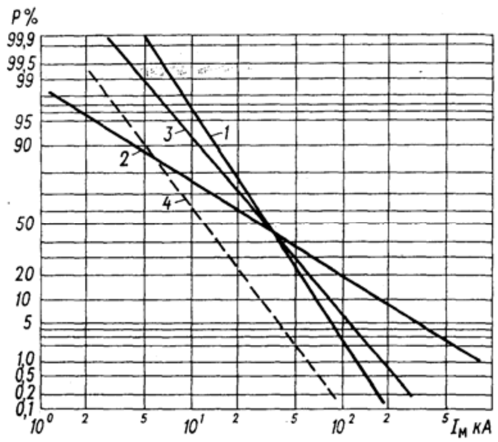

Fig. 5. Cumulative statistical distributions of lightning peak currents, giving percent of cases exceeding abscissa value, from direct measurements in Switzerland (Berger, 1972; Berger et al. 1975). The distributions are assumed to be lognormal and given for (1) negative first strokes, (2) positive first strokes, (3) negative and positive first strokes, and (4) negative subsequent strokes. Adapted from Bazelyan et al. (1978).

Only a few percent of negative first strokes exceed 100 kA, while about 20% of positive strokes have been observed to do so. On the other hand, it is thought that less than 10% of global cloud-to-ground lightning is positive. About 95% of negative first strokes are expected to exceed 14 kA, 50% exceed 30 kA, and 5% exceed 80 kA. The corresponding values for negative subsequent strokes are 4.6, 12, and 30 kA, and 4.6, 35, and 250 kA for positive strokes. Subsequent strokes are typically less severe in terms of peak current and therefore often neglected in lightning protection studies. According to Fig. 5 (line 3), slightly more than 5% of lightning peak currents exceed 100 kA, when positive and negative first strokes are combined.

Berger's peak current distribution for negative first strokes shown in Fig. 5 is based on about 100 direct measurements and, as of today, is apparently the most accurate one. In lightning protection standards, in order to increase the sample size, Berger's data are often supplemented by less accurate indirect lightning current measurements obtained using magnetic links. There are two main distributions of lightning peak currents for negative first strokes adopted by lightning protection standards: the IEEE distribution (e.g., IEEE Std 1410 – 1997; IEEE Std 1243 – 1997; Anderson, 1982; IEEE, 2005) and CIGRE distribution (e.g., Anderson and Eriksson, 1980; IEC 61024 – 1). Both these distributions are presented in Fig. 6 (taken from CIGRE Document 63).

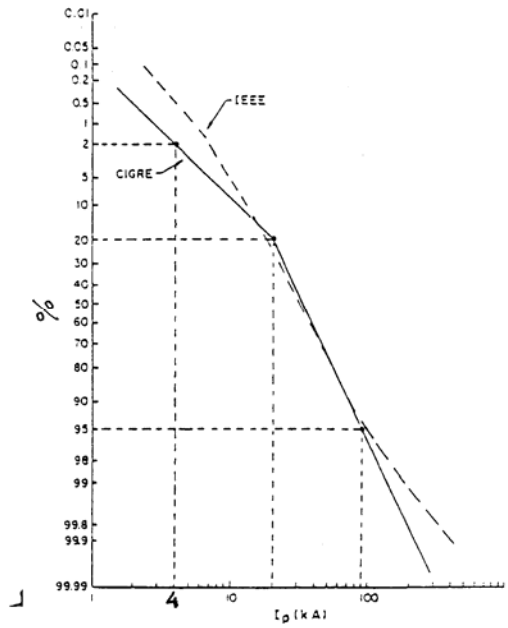

Fig. 6. Cumulative statistical distributions of peak currents (percent values on the vertical axis should be subtracted from 100% to obtain the probability to exceed, as in Fig. 5, the peak current value on the horizontal axis) for negative first strokes adopted by IEEE and CIGRE and used in various lightning protection standards. Adapted from CIGRE Document 63 (1991).

For the CIGRE distribution, 98% of peak currents exceed 4 kA, 80% exceed 20 kA, and 5% exceed 90 kA. For the IEEE distribution, the "probability to exceed" values are given by the following equation

$$P_I = \frac{1}{1 + \left(I/31\right)^{2.6}} \tag{16}$$

where P_I is in per unit, and I is in kA. This equation applies to values of I up to 200 kA. Values of P_I for I varying from 5 to 200 kA, computed using equation (16), are given in Table 1. The median (50%) peak current value is equal to 31 kA. Also given in Table 1 are values of D_{soil} computed using equation (15), assuming that Z = 25 Ω and E_b = 300 kV/m.

Table 1. The IEEE peak current distribution given by equation (16) and corresponding values of D_{soil} given by equation (15).

Peak current, I, kA	5	10	20	40	60	80	100	200
Percentage exceeding tabulated value, $P_I \cdot 100\%$	99	95	76	34	15	7.8	4.5	0.8
D_{soil}, m (Z = 25 Ω, E_b = 300 kV/m)	0.42	0.83	1.7	3.3	5.0	6.7	8.3	17

As stated above, a reasonable value of I in equation (15) is 60 kA, and the corresponding value of D_{soil} = 5 m.

4. BREAKDOWN ELECTRIC FIELD IN THE SOIL

The breakdown electric field in the soil, also referred to as “soil ionization gradient” and “breakdown gradient of the soil”, has been reviewed in detail by Mousa (1994). A summary of E_b values based on measurements of impulse resistance, taken from Mousa (1994), is given in Table 2.

Table 2. Breakdown electric field in the soil obtained from impulse resistance measurements.

Reference	Sample Size	Electrode Type	Soil Type	Soil Resistivity, Ωm	E_b, kV/m	
					Range	Average
Towne (1929)	5	Rods	Gravel	130-686	29-104	75
Bellaschi (1941)	28	Rods	Shale, Clay	93-100	160-519	333
Bellaschi et al. (1942)	27	Rods	Gravel, Sand	77-90	50-350	160
Liew and Darveniza (1974)	4	Rods and hemispheres	Clay, Sand, Gravel	50-310	110-300	230
Norinder*	2	Concentric cylinders	-	-	330-360	343
Berger*	6	Hemispheres	-	1000	490-540	513
Armstrong (1953)	6	Rods	Sand, Clay	52-495	330-480	432
Dick and Holliday (1978)	19	Rods	-	12-25	13-221	71

* Taken from Petropoulos (1948).

After considering possible errors and uncertainties in the experimental data presented in Table 2, Mousa (1994) concluded that E_b (E_o in his nomenclature) should be taken equal to 300 kV/m for typical soils. The value of E_b = 400 kV/m recommended by CIGRE (1991) is also usable. Geri (1997), using impulse resistance measurements, found values of E_b that are “compatible” with those suggested by Mousa (1994) and CIGRE (1991). Kuzhekin et al. (2003, p. 204) quotes a range of E_b from 300 to 550 kV/m, and Wiesinger and Zischank (1995, p. 47) recommend E_b = 500 kV/m. Annenkov (1995) uses E_b = 300 kV/m in estimating the safety distance in the soil. Sekioka et al. (2005, p. 1574) found that, on average, E_b = 580 kV/m, but stated that the actual value should be “a few hundred kV/m” to account for the neglected resistivity of the soil ionization zone.

Mousa (1992) distinguishes between the “soil ionization gradient”, E_o = 300 kV/m, associated with the “volume breakdown” in the immediate vicinity of the current injection point, and the “breakdown gradient in the soil”, E_b = 50 kV/m, associated with the formation of a “discrete arc channel” in the soil. In this approach, illustrated in Fig. 8, the safety distance increases by a factor of 7 ($1 + E_o/E_b$) relative to the value estimated using equation (15) with E_b = 300 kV/m, in which radially uniform soil breakdown (see Fig. 9) is assumed. As stated by Rakov and Uman (2003, p. 620), for a non-uniform current distribution in the soil longer arcs will occur. Thus, values of D_{soil} given by equation (15) are rather conservative.

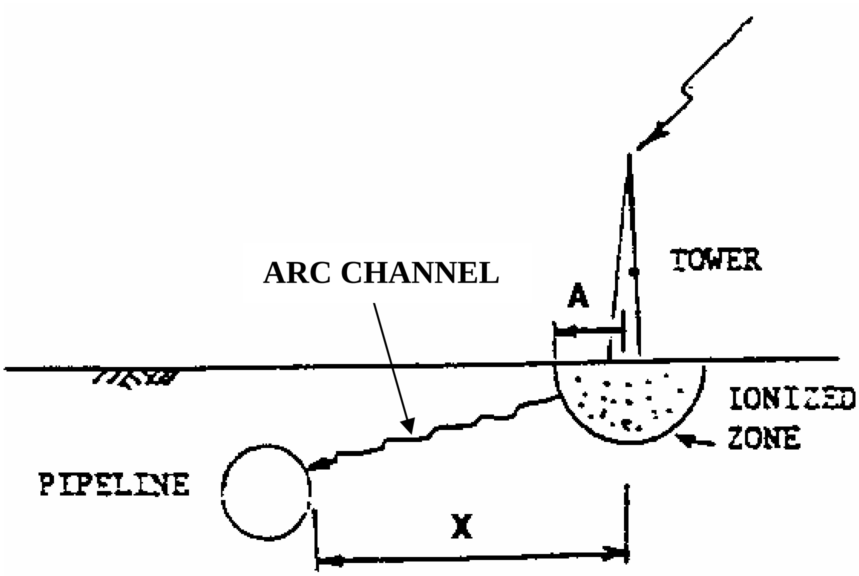

Fig. 8. Arcing through the soil from a tower struck by lightning to a nearby buried pipeline. Adapted from Mousa (1992).

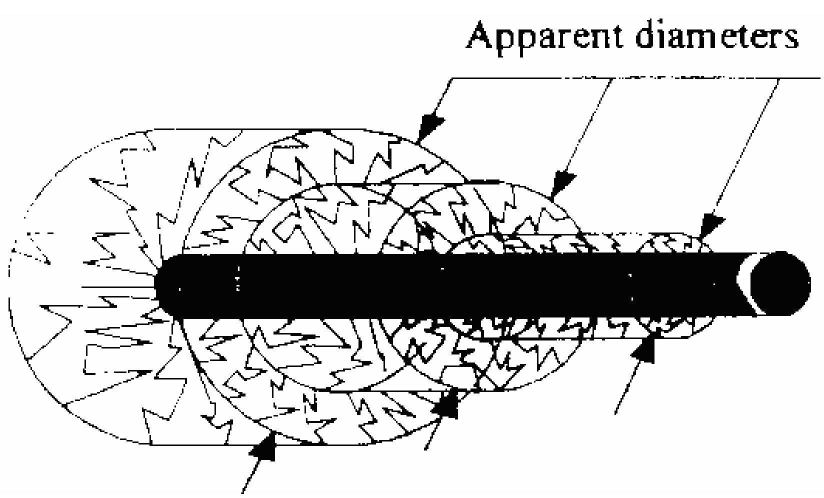

Fig. 9. Radially uniform soil breakdown around a buried horizontal wire subjected to a lightning strike. Adapted from Geri (1997).

It appears that a reasonable value of E_b in equation (15) is 300 kV/m.

5. SUMMARY

The choice between the bonding and the isolating approaches usually depends on whether it is possible or not to separate LPS conductors and other conductors of the system by distances that are larger than the so-called safety distance (e.g., IEC 61024-1, p. 28). This safety distance depends on the breakdown electric field (which is different in air and in the soil), the magnitude of the lightning current (also the current rate-of-rise when the inductance of down-conductors is involved), and the impedance "seen" by the lightning at its attachment point (which depends on the soil resistivity, the geometry of the grounding electrode, and, in the case of sideflash in air, on the inductance between the point of interest and the grounding system).

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