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Electrodynamic Forces Affecting Lightning Protection System Components and Structures

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***Abstract* — Electrodynamic (ED) forces influencing upon lightning protection (LP) components in some typical LP system configurations and conditions are studied. These include: various angles between conductors, their finite lengths, round and flat bar cross-section, grid of conductors, various heights of conductor holders, placement of conductors above metallic cladding and reinforced concrete, various materials, etc. Some practical formulas and examples (grid; conductor going from roof to wall and other) are included, and the scale of stresses affecting the components is discussed. For various current magnitudes and waveforms according to [1], ED forces are estimated by analytical formulas and numerical simulation. In typical LP components, stresses may reach a few units, tens and up to ~180 kN/m, for maximal currents corresponding to LPL 1. For some fastening elements (screws, expansion anchors), the critical levels of current magnitudes (tens of kiloamperes), which able to pull out holders from typical base materials (wood, concrete/brick), are determined. Results are discussed and recommendations provided.**

Keywords - clamps; component; electrodynamic forces & stresses; fasteners; holders; lightning protection system; mechanical effects

I. INTRODUCTION

A lot of observations at actual structures and during laboratory tests have indicated serious mechanical damages caused by lightning-related electrodynamic (ED) forces and other effects to lightning protection system (LPS) components, and protected structures: crooking of bended conductors, destroying of various clamps and holders, damage to roofs, etc. Some clamps are designed and tested to overstand to large 10/350-µs lightning currents of up to 50 kA (normal duty), 100 kA (heavy duty) [2], and by some manufactures even of 200 kA [3]. In tests, two short (0.5 m) conductors are connected at the right angle (90^o) to each other, and such tests are usually accompanied with others, like ageing and mechanical tests.

Existing lightning protection (LP) normative documents contain minimal information related to mechanical stresses at lightning protection system (LPS) components [1, 4]. Some LP standards do not include related issues at all [5]. In Attachment D of [1], one can find simple formula for estimation of ED force between two parallel conductors of finite length and a plot of ED forces per length (f) profile for two 0.5-m conductors connected at the angle of 90^o and carrying current of 100 kA. Then it is shortly commented that in typical LPS configurations the ED forces can be neglected (due to certain relation between natural oscillation periods of the structure and time parameters of the lightning current impulse), but in some cases of using soft metal materials (aluminum, annealed copper) the ED forces can deform the conductors in corners and loops. Thus, these influences must be taken into account in tests of LPS (and, of course, in their design). But no more specific recommendations on estimation of discussed forces in various typical LPS configurations or for other current's or conductors' parameters are present in [1].

In [4], related to requirements on conductor fasteners, there are some indications regarding mechanical tests. In one of the test, it is recommended to place conductor horizontally in two holders spaced by 250 mm and apply mechanical load of 200 N in the middle of conductor for some time (5…6 min – for metallic fasteners, 60…61 min – for non-metallic ones). While indicated loads are static, as a first approach these can be at least compared to stresses caused by ED forces affecting conductors and fasteners.

Approaches on ED forces calculations for various power apparatus applications are well covered in literature [6-9]. Mostly these are related to stresses during short-circuit regimes. In case of LPS, much larger current magnitudes can be expected [1], and some other peculiarities to be taken into account. Unfortunately, for the LP applications not too many works can be found on discussed issue.

The aim of this paper is to present results of the study on ED forces influencing upon LP components in some typical configurations and conditions possible in actual LPS. These include: various angles between conductors, their finite lengths, round and flat bar cross-section, grid of conductors, various heights of conductor holders, conductors placed above metallic cladding and reinforced concrete, various materials, etc. Some practical formulas and examples (grid; conductor going from roof to wall and other) are included, and the scale of stresses affecting the components is discussed. ED forces are estimated for various current magnitudes and waveforms, according to [1], by existing or derived formulas, analytical method (AM), and numerical simulation (NS). For some fastening elements (screws, expansion anchors), which are usually recommended in catalogs of LP products for various holders installation, the critical levels of current magnitudes that can pull out these elements from typical base materials (wood, concrete/brick) are evaluated.

II. Components' Geometry and Approaches

Geometries of some considered problems are presented in Figs. 1 and 2. Other configurations and associated sketches are referred later, in corresponding sections. Forces for bended or crossed conductors (Fig. 1 and other) and in 2D-problems of round conductor above the flat metal sheet for various current waveforms are evaluated analytically. Also problems of 2D- and 3D-geometry are solved by numerical simulation using special software (Elcut, Comsol Multiphysics). In these cases, actual materials characteristics (electric conductivity, magnetic permittivity) were taken into account. Lightning currents, having waveforms 10/350, 1/200, and 0.25/50 µs [1], when used for the 2D-models, were approximated by regular bi-exponential functions (sum). And for the 3D-models these were approximated by harmonic waveforms having characteristic frequencies corresponding to impulse front time and peak value as in impulse.

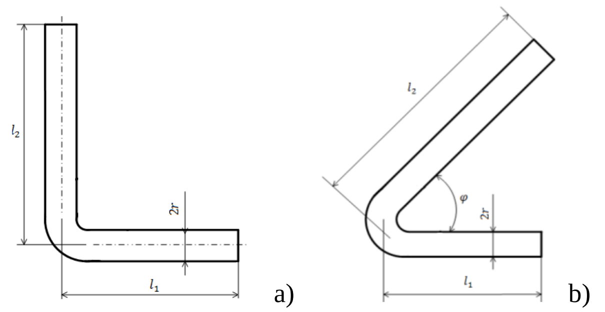

Figure 1. Bended or crossed conductors: a – angle 90°; b – other angles

III. Results

A. Conductors Bended or Connected at Various Angles

Various practical configurations on the use of round conductors bended or connected at different angles are considered, including that indicated in [1, 2].

1) Angle 90°: Herein formulas for estimation calculations of ED forces per unit length (f) and total force (F) affecting conductors in configurations shown in Fig. 1a and Fig. 3, and some related results are presented.

a) General and partial formulas: ED forces per unit length distributed along conductor part l_1 from interaction with conductor l_2, when these conduct currents I_1 and I_2 (Fig. 1a):

$$f_{21}(l_1) = \frac{\mu_0 I_1 I_2}{4\pi} \cdot \frac{l_2}{l_1 \cdot \sqrt{l_1^2 + l_2^2}} \quad (1)$$

The total force, applied to conductor l_1, is:

$$F_{21} = \int_r^{l_1} f_{21}(l_1) dl_1 = \frac{\mu_0 I_1 I_2}{4\pi} \ln\left(\frac{l_1}{r} \frac{\sqrt{r^2 + l_2^2} + l_2}{\sqrt{l_1^2 + l_2^2} + l_2} \right) \quad (2)$$

For partial case, when l_1 is rather long, it is reduced to:

$$F_{21} = \frac{\mu_0 I_1 I_2}{4\pi} \ln \frac{\sqrt{r^2 + l_2^2} + l_2}{r} \quad (3)$$

For another partial case, when l_2 is rather long:

$$F_{21} = \frac{\mu_0 I_1 I_2}{4\pi} \ln \frac{l_1}{r} \quad (4)$$

Main portion of these stresses is applied to conductors at close distances to point of crossing and of clamps location.

These formulas are applied to LPS grid in next paragraph.

b) Clamp at the edge of the LPS grid: Typical LPS grid contains conductors crossing at the right angles (Fig. 3). At the

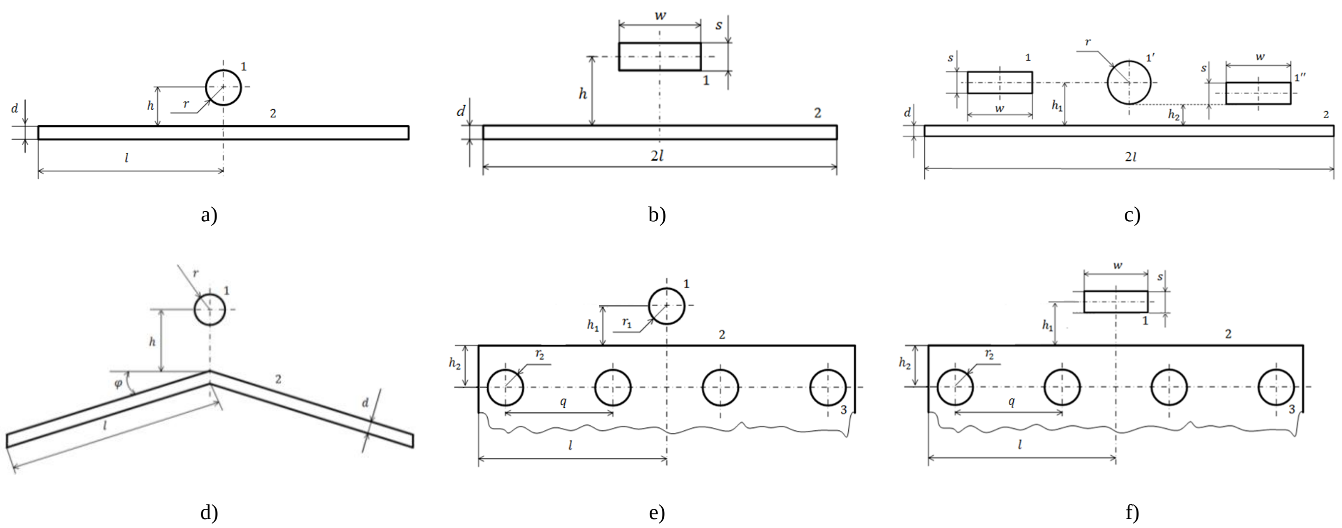

Figure 2. Model configurations of various conductors (1, 1', 1") above metal surfaces (2), cases a, b, c, d, and reinforced concrete (2, 3), cases e, f

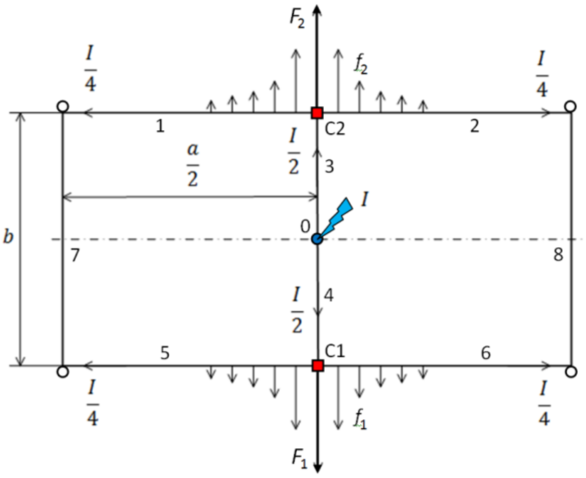

Figure 3. Sketch for the problem on ED stresses in LPS grid

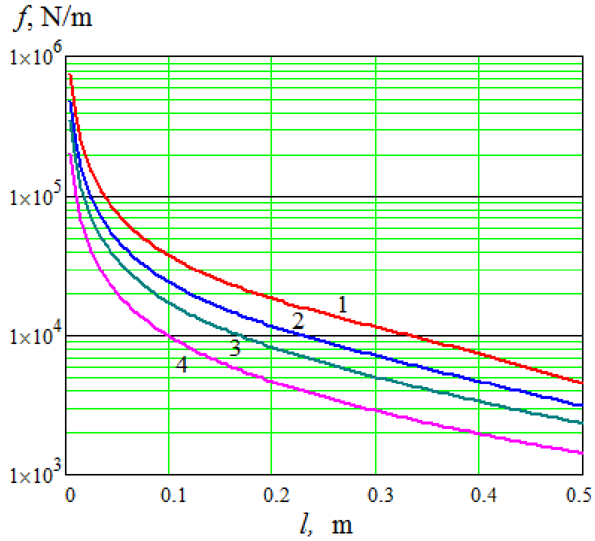

Figure 4. ED stresses f at conductors of Fig. 1b for some angles φ ($l_1 = l_2 = 0.5$ m, I =100 kA): 1 to 4 – φ = 30°, 45°, 60°, 90°, respectively

joints, clamps (C1, C2) are subjected to large ED stresses. This is shown by example calculations for a grid a x b = 10x5 m, made of round conductor (r = 4 mm), and for injected I = 200 kA. Taking into account interactions (attracting and repulsing) of all conductors in Fig.3 (but 7, 8, which do not have currents), it is found that the total F_1 applied together to conductors 5 and 6 (and similarly F_2 – to 1 and 2) is of about 5.74 kN. If, for example, conductors 5 and 6 are fastened by holders/supports at the distance x = 1 m from the clamp C1, the pull out force at this node will be of 5.14 kN. If x = 0.15 m, one can expect reducing of force at the clamp C1 to 3.6 kN.

2) Other angles (Fig. 1b): ED forces per unit length distributed along conductor part l_1 from interaction with conductor l_2, when these conduct currents $I_1 = I_2 = I$, are:

$$f_{21}(l_1) = \frac{\mu_0 I^2}{4\pi \cdot sin(\varphi)}\left(\frac{cos\,(\varphi)}{l_1} + \frac{l_2 - l_1 \cdot cos\,(\varphi)}{l_1\sqrt{l_1^2 - 2l_1 l_2 \cdot cos\,(\varphi) + {l_2}^2}}\right) \quad (5)$$

The total force, applied to conductor l_1, is:

$$F_{21} = \frac{\mu_0 I^2}{4\pi \cdot sin(\varphi)}\int_{r/sin(\varphi)}^{l_1}\left(\frac{cos\,(\varphi)}{l} + \frac{l_2 - l \cdot cos\,(\varphi)}{l\sqrt{l_2^2 - 2l_2 l \cdot cos\,(\varphi) + l^2}}\right)dl \quad (6)$$

This integral can be taken, but the final formula is too large. It is easy to calculate it by special mathematic software.

For partial case, when l_2 is rather long, stresses at l_1 are:

$$f_{21}(l_1) = \frac{\mu_0 I^2}{4\pi \cdot sin(\varphi)}\left(\frac{cos\,(\varphi) + 1}{l_1}\right) \quad (7)$$

For the same partial case, total force affecting l_1 is:

$$F_{21} = \frac{\mu_0 I^2 (cos\,(\varphi) + 1)}{4\pi \cdot sin(\varphi)} \ln\left(\frac{l_1 sin(\varphi)}{r}\right) \quad (8)$$

Calculation results for several angles are summarized in Fig. 4.

3) Roof-to-wall transition (Fig. 5a): Conditions and results for considered sample configuration are presented in Table I. F_{12} and F_{32} are ED total forces affecting the conductor 2 (transition) due to intercation with conductors 1 (at the roof) and 3 (at the wall). Plot of loading profile f (per unit length stresses) at conductor 2 is shown in Fig 5b. These forces are trying to rotate conductor 2 clockwise around point B (located about ~0.34 m from the wall conductor).

TABLE I. FORCES AT CONDUCTOR l_2 AT THE ROOF-TO-WALL TRANSITION CAUSED BY INTERACTION WITH CONDUCTORS l_1AND l_3, FOR 10/350 μs, l = 0.5 m, r = 4 mm, d = 0.5 mm, α = 30°

φ, degrees	**F_{12}, kN**		**F_{32}, kN**	
	100 kA	***50 kA***	***100 kA***	***50 kA***
0	-18.02	-4.51	4.83	1.21
30	-8.61	-2.15	2.87	0.72
60	-5.52	-1.38	1.48	0.37

B. *Conductor Above the Flat Metal Surface (Fig. 2a, b, c)*

Following results are obtained by using NS. Thus, electrical characteristics of materials are taken into account.

1) Round conductor and influence of sheet material, thickness, distance to surface, and current waveform: Conditions and simulation results on stresses f for various

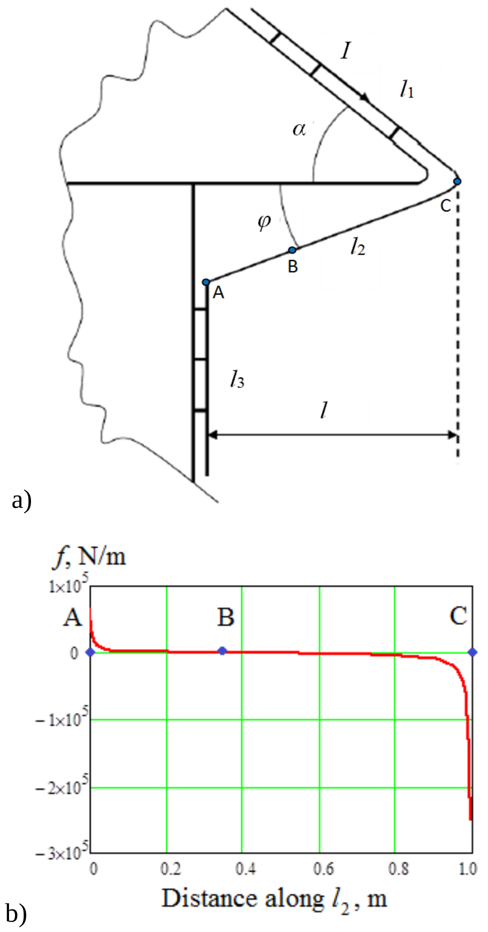

Figure 5. Sketch for the roof-to-wall problem (a) and loading profile for l_2 (b)

materials of conductor and conductive surface, sheet thickness *d*, height *h* of the conductor's axis above the surface are gathered in Table II.

TABLE II. FORCES PER UNIT LENGTH AT ROUND CONDUCTOR ABOVE FLAT CONDUCTIVE SURFACE FOR VARIOUS MATERIALS, THICKNESS *d*, HEIGHT *h*, AND *I* = 100 kA, 10/350 µs, *r* = 4 mm

h, mm	*d*, mm	*f*, kN/m			
		Copper	*Aluminum*	*Steel (µ=1)*	*Steel (µ=800)*
20	0.5	47.63	47.51	47.12	45.86
	4.0	47.71	47.55	47.12	45.61
30	0.5	30.07	30.02	29.86	26.67
	4.0	30.09	30.04	29.85	29.13
55	0.5	12.11	12.13	12.08	11.03
	4.0	12.18	12.14	12.08	11.86

The influence of current waveform time characteristics is shown in Table III. These are obtained by analytical method of moving sources [8] and by NS. For *h* = 20 mm and large currents of 100 to 200 kA, huge stresses can be expected (50 to 180 kN/m).

Magnitudes of currents that can produce critical forces and pull out from base material the specific screws and anchors, which are keeping holders, are presented in Table IV. In practice, for LPS are often recommended fastening components, which have permissible tensile loads of 0.69…1.39 kN for screws and 0.8 kN for 8x40 mm polyamid anchores, that are much lower than mentioned in Table IV.

TABLE III. FORCES PER UNIT LENGTH AT ROUND CONDUCTOR ABOVE FLAT CONDUCTIVE SURFACE FOR VARIOUS CURRENT WAVEFORMS AND MAGNITUDES, COPPER, *r* = 4 mm, *d* =0.5 mm, AND *h* = 20 mm

I, kA	*f*, kN/m					
	10/350 µs		*1/200 µs*		*0.25/50 µs*	
	AM[a]	*NS*[a]	*AM*[b]	*NS*	*AM*[b]	*NS*
200	196.0	182.8	-	-	-	-
100	48.8	45.6	49.1	46.6	-	-
50	12.2	11.4	12.5	11.6	12.4	11.7
25	3.1	2.9	3.3	2.9	3.2	2.9

a. AM – analytical method, NS – numerical simulation; b. For waveforms 1/200 and 0.25/50 µs, the use of AM is not too correct due to relation between skin depth and sheet thickness

TABLE IV. CRITICAL CURRENT MAGNITUDES THAT ENOUGH TO PULL OUT THE HOLDER'S SCREW OR ANCHOR ABOVE CONDUCTIVE SURFACE AND WALL/ROOF BASE FOR VARIOUS CURRENT WAVEFORMS, AND HEIGHTS: COPPER, ROUND CONDUCTOR *r* = 4 mm, SHEET *d* =0.5 mm

h, mm	Screw KOH- 5x25, base – timber [10][a]			Anchor KPR-FAST 10 mm, base – whole brick/concrete (C12/15) [10][b]		
	I, kA			*I*, kA		
	10/350 µs	*1/200 µs*	*0.25/50 µs*	*10/350 µs*	*1/200 µs*	*0.25/50 µs*
20	19.4	19	18.9	27.6	27.4	27.2
30	23.8	23.6	23.4	34.2	34.1	33.9
55	38.8	38.6	38.5	54.4	54.3	54.2

a. permissible tensile load – 1.79 kN; b. permissible tensile load – 3.5 kN

2) Influence of cross-section type – flat bar (20x2.5mm) vs round conductor (Φ8) comparison: The models for NS are shown in Fig. 2c, where d = 0.5 mm, h_1 = 20 mm, h_2 = 16 mm, 2l = 140 mm. Conductors have the same cross-section areas of 50 mm^2. Other conditions: copper, 100 kA, 10/350 µs. Results on obtained ED forces per unit length: case of conductor 1 – 40.29 kN/m, 1' – 45.63 kN/m (max), and 1" – 42.75 kN/m.

3) Conductor above the roof ridge (Fig. 2d): This configuration studied for various materials, ridge pitch angles φ and heights of conductor holders. Conditions and results of calculation stresses *f* are shown in Table V and in Fig. 6. In Fig. 6 results are presented for copper and were simulated for selected values of angle φ = 0, 15^o, 30^o, 45^o, and 60^o.

4) Round conductor and influence of connection to the sheet (Fig. 7): This simulation was performed in Comsol. ED forces affecting conductor were studied for two cases: F_1 – when conductor was insulated from the metallic surface 1 at the area of holder 4, and F_2 – when the holder 4 was metallic (or shorted by channel of electrical discharge).

TABLE V. FORCES PER UNIT LENGTH AT CONDUCTOR ABOVE ROOF RIDGE FOR VARIOUS MATERIALS, HEIGHTS AND $\varphi = 30^o$, 100 kA, 10/350 µs, r = 4 mm, d = 0.5 mm

h, mm	***f*, kN/m**			
	Copper	***Aluminum***	***Steel (µ=1)***	***Steel (µ=800)***
20	21.64	21.56	21.34	20.66
30	12.55	12.53	12.40	12.00
55	2.89	2.88	2.82	2.74

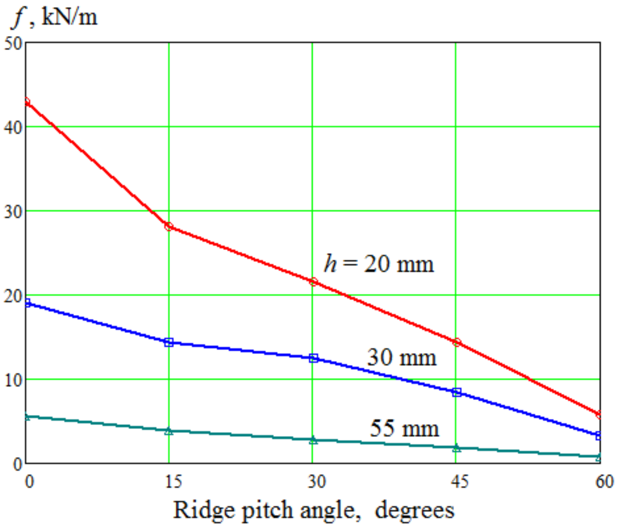

Figure 6. Forces per unit length at conductor above the ridge for various pitch angles φ, heights h of conductor, and 100 kA, 10/350 µs, r = 4 mm, d = 0.5 mm

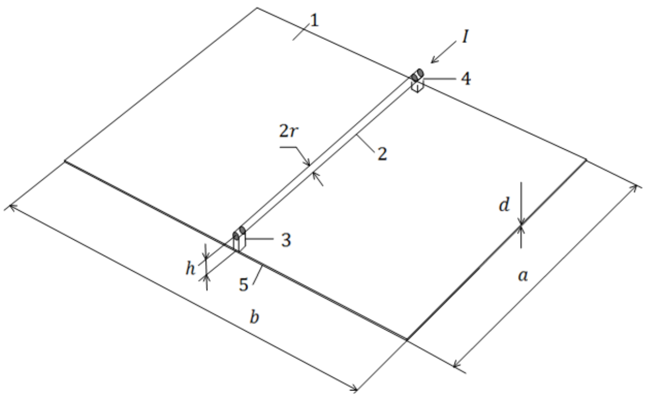

Figure 7. Model for conductor having contacts to the metal cladding: 1 – metallic sheet; 2 – conductor; 3 – holder, where conductor's end is permanently connected close to the edge 5 of 1 and earthed; 4 – holder (conductive/non-conductive) at point of current I injection

Other conditions and results of simulation are summarized in Table VI. I_c and I_p are portions of current I flowing into conductor and plane in the second case (conductive holder 4). Results show that for considered conditions, forces in the first case are 13 to 18 times larger than in case 2. In case 2, conductor is attracted to the sheet. The signs of forces in two cases are different. Actually, case 1 is more probable for characteristic frequencies of the first positive stroke, while for the first and subsequent negative strokes one can expect overflash at the non-conducting holder 4. This can result in perforation of the thin cladding sheet.

TABLE VI. CURRENT DISTRIBUTION BETWEEN CONNECTED COPPER CONDUCTOR (I_C) AND PLANE CLADDING (I_P), AND FORCES AT CONDUCTOR FOR I = 100 kA, 25 kHz, r = 4 mm, d = 0.5 mm, a = b = 1 m, COPPER

h, mm	**I_c, %**	**I_p, %**	**F_2, kN**	**$\|F_1 / F_2\|$**
20	37.4	62.6	3.8	13.5
30	37	63	1.5	12.8
55	36	64	0.4	18.2

C. *Conductor Above the Reinforced Surface (Fig. 2e, f)*

Interaction of conductor placed above the reinforced concrete is studied (NS) for four its types: round conductors of r = 4 and 8 mm; flat bars 20x2.5 and 30x3.5 mm. Conditions: current – 100 kA, 10/350 us; material of metal parts – regular steel, µ = 800; conductor's distance to the surface h_1 (10 to 55 mm) and step between the rebars (q = 100, 50, 25 mm) were variety parameters. Corresponding to these q values, number of rebars considered: 2, 4, 8. Some conditions and simulation results on ED stresses f are presented in Tables VII to X.

TABLE VII. FORCES PER UNIT LENGTH AT ROUND CONDUCTOR ABOVE REINFORCED WALL FOR VARIOUS STEPS q, HEIGHTS h_1, AND $r_1 = r_2$ = 4 mm, h_2 = 14 mm

h_1, mm	***f*, kN/m**		
	q = 100 mm	***q = 50 mm***	***q = 25 mm***
10	3.40	8.42	14.06
15	3.20	4.10	5.60
20	2.50	3.04	3.12
30	1.10	1.34	1.55
55	0.21	0.33	0.39

TABLE VIII. FORCES PER UNIT LENGTH AT ROUND CONDUCTOR r_1 = 8 mm ABOVE REINFORCED WALL FOR VARIOUS STEPS q, HEIGHTS h_1, AND r_2 = 4 mm, h_2 = 14 mm

h_1, mm	***f*, kN/m**		
	q = 100 mm	***q = 50 mm***	***q = 25 mm***
10	3.50	8.60	14.30
15	3.10	4.30	5.80
20	2.83	3.10	3.33
30	1.21	1.43	1.73
55	0.36	0.53	1.41

IV. DISCUSSION

Results show that significant ED stresses produced in LPS can appear in situations of LP conductors interaction between each other (Figs. 1, 3, 5) and also with the metal parts of the

TABLE IX. FORCES PER UNIT LENGTH AT BAR CONDUCTOR ABOVE REINFORCED WALL FOR VARIOUS STEPS q, HEIGHTS h_1, AND r_2 = 4 mm, h_2 = 14 mm, w x s = 20 x 2.5 mm

h_1, mm	*f*, kN/m		
	q = 100 mm	*q = 50 mm*	*q = 25 mm*
10	4.71	9.55	17.01
15	3.20	4.76	6.51
20	2.87	3.10	3.67
30	1.29	1.36	1.65
55	0.37	0.40	0.49

TABLE X. FORCES PER UNIT LENGTH AT BAR CONDUCTOR ABOVE REINFORCED WALL FOR VARIOUS STEPS q, HEIGHTS h_1, AND r_2 = 4 mm, h_2 = 14 mm, w x s = 30 x 3.5 mm

h_1, mm	*f*, kN/m		
	q = 100 mm	*q = 50 mm*	*q = 25 mm*
10	15.84	18.16	19.44
15	7.04	8.07	8.64
20	3.96	4.54	4.86
30	2.83	3.41	4.21
55	0.79	1.01	2.13

protected structure (Figs. 2, 6 and other data in paper). Thus, the design of LPS and structure itself should consider these effects.

Normative documents have some indications on the need of considering discussed issue of ED forces in design of LPS and in tests of its components. But these indications are related to very limited types of components and tests. The tests of connecting components are related only to configuration of two conductors, which are perpendicular to each other, and presently "heavy duty" tests are performed only for 100 kA. In practice, situations may often happen when full current of 200 kA (LPL I) to be considered, and it flows from lightning rod to the LP grid or to down conductors only through one wire (regular conductors from lightning rods near installations at the roof, insulated downconductors, etc.).

On the other hand, it looks that the effect of interaction between lightning conductors and metal structure parts is not discussed in standards. Possibility of overflashes at non-metallic holders and following puncturing of cladding is also requiring attention.

Also, when one look at obtained results for holders (for example, Table II to V and VII to X), it is clear that in many cases the ED stresses can be much larger than that allowed in static tests for holders/fasteners with conductor by a side load (approximately can be recalculated to 200 x 4 = 800 N/m). Similarly, it is also observed possibility of significant ED stresses exceeding the permissible tensile loads for screws and expansion anchors usually recommended for installation of discussed holders. Of course, it is not too correct to compare the static strength of LPS components and short dynamic influences. But at least, more configurations related to the use of LP components should be studied regarding considered issues, and, perhaps, other normative tests will be developed.

Simple formulas mentioned in part A do not consider the characteristics of materials and some other details, but can be used for practical evaluations.

VI. CONCLUSION

1. The scale of ED stresses at LPS components related to standard lightning current parameters is ranging from some units to several tens of kilonewtons, and up to ~180 kN. It is large enough to cause the damage of LPS designed according to present normative documents. The stresses for considered various conductive materials do not differ too much.

2. The possibility of overflash at non-metallic holders placed on thin metallic cladding by lightning discharge needs to be considered. In most lightning cases, this also will result in cladding damage.

3. Rather different requirements should be applied to LPS components at the same structure, depending on the accepted LP level, LPS configuration, structure and LPS materials, and location of the components. There is a need in further studies on the issue, in tests and standards development.

4. Discussed ED stresses have effect both on LPS components and structure. These should be considered in their design.

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