STUDY OF OPERATION CONDITIONS FOR THE HIGH-VOLTAGE INSULATED LIGHTNING DOWNCONDUCTOR SEALING UNIT

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Abstract: The model of the high-voltage insulated down-conductor sealing unit insulation and procedure for electric field distribution analysis in conditions related to action of lightning strike are presented. Simulation is performed by a program based on a finite element method. Initial investigations of approaches for obtaining of a suitable electric field strength distribution in the sealing unit area and determination of maximum current value acceptable for this unit under normal operation were done. First, the influences of cover electrical conductivity and of frequency of the voltage (100 kV) between head piece and earthing clamp are explored. Obtained results show that the maximum values of electric field strength, both near the earthing clamp and within the semiconductive cover, are decreasing to their minimum values when the cover conductivity is increasing. Further enhancement doesn’t improve these values. Second: (a) the amplitudes of currents having different frequencies and creating a unit voltage drop of 100 kV between the head piece and the earthing clamp are estimated; (b) the operation conditions for sealing unit insulation during current injection of 100 kA are analyzed. Preliminary results show possible appearance of dangerous electric field stresses at the sealing unit for relatively low currents. This indicates the need of consideration of specific test procedures in a future standard for insulated lightning downconductors.

1 INTRODUCTION

Lightning protection (LP) systems based on insulated downconductors (IDC) are progressively widely used during last decade. Among their advantages are diverting of lightning currents from the structure earthed elements and solution of the separation distance problem [1-4].

Some types of IDC are using coaxial cables having metallic sheath, other – semiconductive ones. Latest type of IDC has some advantages [1]. Characteristics, construction and test results for this IDC type are described, for example, in [3, 5]. Design and installation of these IDC should provide: (a) a suitable electric field distribution, especially in the area of its sealing unit (active part, between head and clamp, Fig. 1), in order to exclude flashover or breakdown during conducting of lightning current; and (b) elimination of large inductive loops formed by central conductor and sheath of IDC, and conductive parts of protected structures.

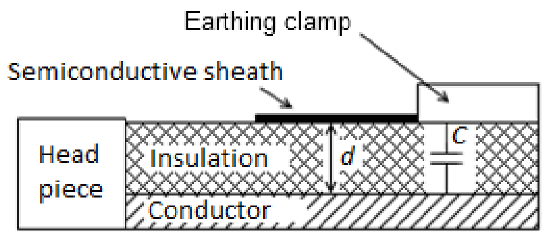

Figure 1: Sealing unit of insulated downconductor

There are various methods of field control that can be used for IDC sealing unit (capacitive, resistive, etc. [5, 6]). The use of semiconductive sheath (resistive method), is one of effective method for discussed purpose, Fig. 1 [3, 6]. Semiconductive sheath (cover) can have linear or non-linear characteristics [7]. Using of semiconductive sheath helps to achieve more homogeneous electric field distribution and reduce stresses in sealing unit insulation. Also, several connections of sheaths to the earthed parts of protected installations allow reducing the inductive loop and induced voltage, and current in it [3].

Some previous works are reporting results on laboratory tests of insulated downconductors by impulse voltages [1, 3, 5]. As a first approach, they allowed: (a) experimental estimating of IDC electric strength; (b) determining of conditions for surface discharges within IDC’s sealing unit; (c) validating of selected sheath’s conductivity value; (d) estimating separation distance, (e) validating of sealing unit dimensions, etc.

A theoretical analysis of conditions for surface currents and discharges [5] and of induced voltage in inductive loop [2, 3] was already developed. But, to the best of our knowledge, the detailed analysis of electric field distributions for sealing units was not presented yet. While some simplified formulas are available for estimating electric field strength at joint point between the clamp and semiconductive cover in case of applied harmonic voltage [6], the design of actual sealing units requires using of detailed analysis on the basis of numerical algorithms and modern software.

The parameters of currents for LP system (LPS) that should provide protection of a certain standard level are indicated in [8]. As the lightning downconductors are part of LPS and designated to conduct large and steep lightning currents, one can expect that the tests of IDC and theoretical analysis of operation conditions for their insulation should include also the aspects related to currents. Perhaps, more accurate approaches could lead to obtaining different characteristics and parameters than those obtained previously by voltage tests. Recently, the work started on standard for test of components of isolated LPS [9].

Thus, the goal of this work is to rise and initially explore the question of considering current effects in analysis of operation conditions for insulation of IDC and, in particular, of its sealing unit. The tasks will include numerical electric field simulation for sealing unit having actual dimensions and parameters, both for cases of applying high voltages and of current injection. Also comparison to results of previous tests and analysis by other researchers will be provided.

2 MODEL, APPROACH AND CONDITIONS

The high-voltage insulated (HVI) lightning down-conductor sealing unit taken for modeling is shown in Fig. 2 [10]. Some parameters for modeling are as follows: (a) internal conductor is from copper 5 mm (20mm^2); (b) main insulation is from polyethylene – thickness of 6.15 mm, dielectric permittivity ε = 2.3, electrical conductivity $\sigma \approx 10^{-14}$ S/m; (c) PVC covering at the head and sheath joint – thickness of 1 mm, ε = 4, $\sigma \approx 10^{-12} \ldots 10^{-14}$ S/m; (d) semiconductor sheath's resistance per unit length in some sealing units can be assumed of about 10 kOhm/m [2]; this parameter was varied in this study; ε = 4.

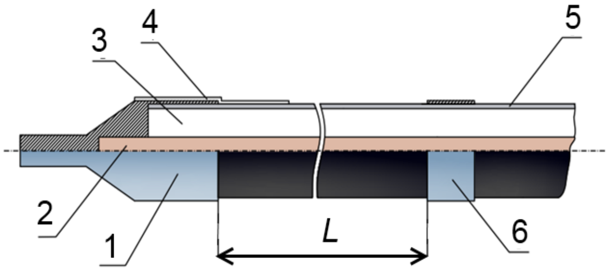

Figure 2: HVI lightning down-conductor sealing unit: 1 – head piece, 2 – conductor, 3 – high-voltage main insulation, 4 – PVC covering, 5 – semiconductive sheath, 6 – EB clamp (earthing)

For simulations, the 2D CAD-model having an axial symmetry was developed. The length is 2 m in total: 1.5 m between head and equipotential bonding (EB) clamp and additional 0.5 m is behind that clamp. The sealing unit was numerically modeled in a cylindrical air volume having a 0.7 m radius, the number of nodes in a triangle-elements' grid is about $137 \cdot 10^3$.

The frequency *f* of the applied voltage or currents was varied. It corresponds to different lightning current components front steepness [8, 11]: (1) f=50 Hz is partly related to continuous currents; (2) f=25 kHz corresponds to first return stroke (RS) components having front times of about 10 μs [8]; (3) f=250 kHz corresponds to some subsequent RS components having front times of about 1 μs. In LP and ECM Standards, and in technical literature one can meet some other impulse parameters [5, 8, 11], thus, simulation were performed also for higher frequencies (~10^6 kHz).

The studies of electric field distributions and maximum field strength values (Table 1, Fig. 3) for the sealing unit insulation were performed for various specific volume conductivities σ of sheath: 10^{-14} and in the range of 0.0001 – 100 S/m.

Table 1: Electric field strength under research

Notation	Location
E_1	In the air along of the cover between head piece and the connection element
E_2	In the high-voltage insulation (0.5 mm about conductor)
E_3	In the semiconductive sheath

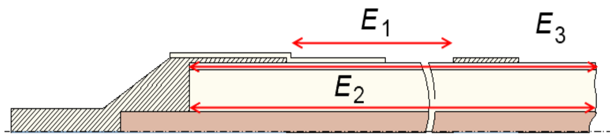

Figure 3: Notation of estimated maximum electric field strength values (see Table 1)

Depending on the problem considered, the potential of 100 kV is applied or various currents are injected to conductor. The EB clamp was assumed to have zero potential or connected to remote earth (structure's earthed parts) through the 3-m wire (aluminum is assumed).

In a first investigation (Section 3), the sealing unit was studied under application of voltage U = 100 kV between head 1 and clamp 6 (Fig. 2). Analysis was performed in quasi-static time-harmonic approach. Secondly (Section 4), the current injection was considered. An approach of transient analysis for electric currents was used. In that case, for modelling of a long cable part behind the clamp, an additional equivalent circuit was connected to initial model of the sealing unit (Fig. 4). Its parameters were calculated using regular formulas [12, 13] and presented in Table 2. In Fig. 4: $R_{\_cover1}$ is the sheath resistance, it was varied; in presented simulations assumed $R_{\_earth}$= 0 and R_x = 10^{20} Ohm. Current generator is connected to nodes 1 and 0 (earth).

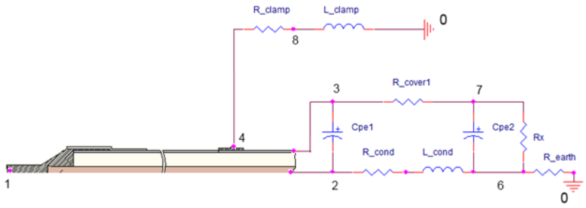

Figure 4: The model including equivalent electric circuit of long cable part in case of current injection

Table 2: Calculated parameters of equivalent electric circuit for long cable part (see Figure 4)

f, Hz	$R_{\_cond}$, Ohm	$L_{\_cond}$, H	$R_{\_clamp}$, Ohm	$L_{\_clamp}$, H	$C_{\_pe}$, pF
50	0.014	$2.59\cdot10^{-5}$	0.004	$4\cdot10^{-6}$	0.768
$25\cdot10^{3}$		$2.52\cdot10^{-5}$			
$25\cdot10^{4}$					

3 RESULTS OF SIMULATION IN CASE OF APPLICATION HIGH VOLTAGE

Main results of simulation in case of application high voltage to the sealing unit of insulated downconductor are presented in Table 3 and Figs. 5 to 9.

Table 3: Results of electric field intensity simulation in case of applied voltage of 100 kV (sheath: ε=4)

Test	*f*, Hz	Electrical conductivity of sheath σ, S/m	Maximum values of electric field strength (see Table 1), V/m		
			E_1	E_2	E_3
1	50	$1\cdot10^{-14}$	$9.00\cdot10^{6}$	$2.54\cdot10^{7}$	$1.20\cdot10^{7}$
2		0.0001	$1.66\cdot10^{6}$	$2.70\cdot10^{7}$	$2.4\cdot10^{5}$
3		0.001	$1.00\cdot10^{6}$	$2.70\cdot10^{7}$	$7.50\cdot10^{4}$
4		0.01	$9.50\cdot10^{5}$	$2.70\cdot10^{7}$	$6.60\cdot10^{4}$
5		0.1	$9.50\cdot10^{5}$	$2.70\cdot10^{7}$	$6.60\cdot10^{4}$
6		1	$9.50\cdot10^{5}$	$2.70\cdot10^{7}$	$6.60\cdot10^{4}$
7		10	$9.50\cdot10^{5}$	$2.70\cdot10^{7}$	$6.60\cdot10^{4}$
8	$25\cdot10^{3}$	$1\cdot10^{-14}$	$9.00\cdot10^{6}$	$2.60\cdot10^{7}$	$1.20\cdot10^{7}$
9		0.0001	$5.30\cdot10^{6}$	$2.70\cdot10^{7}$	$5.20\cdot10^{6}$
10		0.001	$4.32\cdot10^{6}$	$2.70\cdot10^{7}$	$1.75\cdot10^{6}$
11		0.01	$2.70\cdot10^{6}$	$2.70\cdot10^{7}$	$6.00\cdot10^{6}$
12		0.1	$1.27\cdot10^{6}$	$2.70\cdot10^{7}$	$1.60\cdot10^{4}$
13		1	$9.50\cdot10^{5}$	$2.70\cdot10^{7}$	$7.00\cdot10^{4}$
14		10	$9.50\cdot10^{5}$	$2.70\cdot10^{7}$	$6.65\cdot10^{4}$
15	$25\cdot10^{4}$	$1\cdot10^{-14}$	$9.00\cdot10^{6}$	$2.59\cdot10^{7}$	$1.20\cdot10^{7}$
16		0.0001	$8.60\cdot10^{6}$	$2.68\cdot10^{7}$	$1.10\cdot10^{7}$
17		0.001	$6.60\cdot10^{6}$	$2.70\cdot10^{7}$	$5.30\cdot10^{6}$
18		0.01	$4.32\cdot10^{6}$	$2.70\cdot10^{7}$	$1.80\cdot10^{6}$
19		0.1	$2.70\cdot10^{6}$	$2.70\cdot10^{7}$	$6.00\cdot10^{5}$
20		1	$1.20\cdot10^{6}$	$2.70\cdot10^{7}$	$1.60\cdot10^{5}$
21		10	$9.00\cdot10^{5}$	$2.70\cdot10^{7}$	$6.86\cdot10^{4}$
22		100	$9.00\cdot10^{5}$	$2.70\cdot10^{7}$	$6.65\cdot10^{4}$

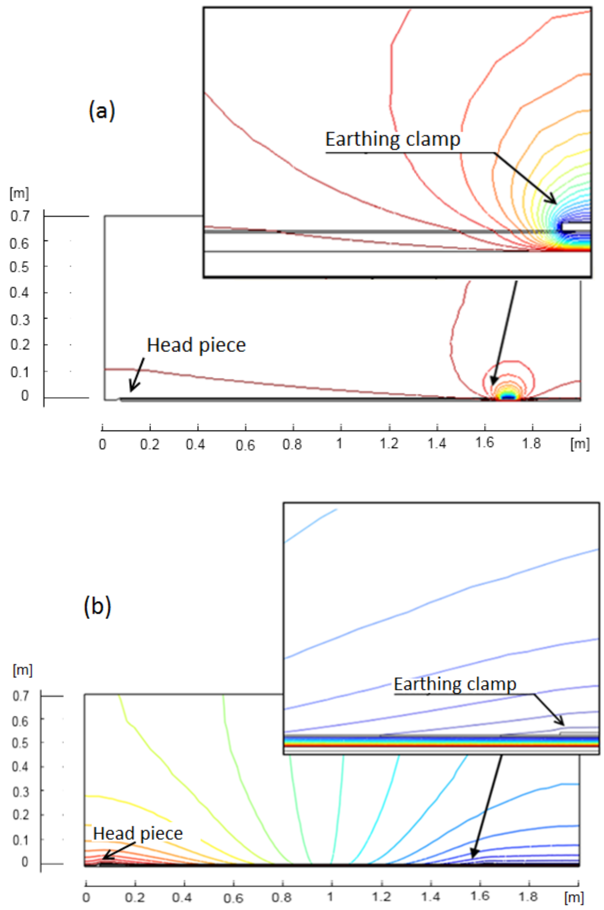

Figure 5: Electric field equipotential lines in the seal unit zone: (a) without, and (b) with field control

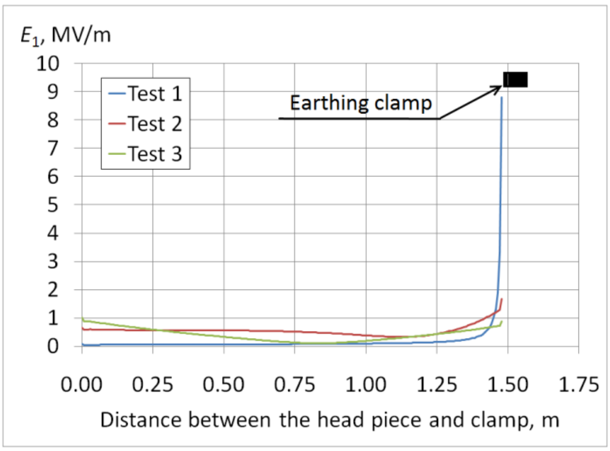

Figure 6: Electric field strength distribution in air, E_1 (test variants – see Table 3)

In Table 3, the cells with E_3 that correspond to certain sheath's conductivity values, when field homogeneity within sheath achieves 80-100 %, are marked in blue. The cells marked in green correspond to the minimal peak values of E_1 in air for the above homogeneous conditions; with the sheath's conductivity increasing these peak values are saturated and observed already near the head piece. These tendencies are also demonstrated in Figs. 5 and 6. With sheath's conductivity increasing, the values of E_2 in main insulation are growing slowly. Selection of certain conductivity values, for example, allows obtaining conditions (E_1) for the absence of surface discharges in air (Fig. 6, tests 2 and 3). Of course, the distribution of E_1 depends on several other parameters (frequency, dielectric permittivity, its thickness, etc.).

The electric field control can also be done by a capacitive method (for example, by variation of the sheath's ε) [7]. The influence of capacitances can also seen in Fig. 7, where in test 1 (related to larger insulation thickness) the field E_2 maximum is lower than in test 3.

The influence of frequency f and sheath's conductivity σ upon electric field values is demonstrated in Table 3, and Figs. 8 and 9. Fig. 8 includes results also for frequencies larger than those mentioned in Table 3. For example, in case of σ = 0.001 S/m and f = 50 Hz, the electric field strength at the critical point near the clamp reaches up to E_1 = 10 kV/cm, and for f = 25 kHz it could theoretically reach up to 43 kV/cm, which significantly exceeds the breakdown level of air (simulation tests 3 and 10, in Table 3).

Results of simulation show (Fig. 9), that, for all three frequencies considered, the value of electric field strength E_1 will not exceed the critical discharge level (assumed of E_o= 30 kV/cm) if the sheath's conductivity σ is of 0.1 S/m or larger. The strength E_1 is noticeably (nonlinearly) decreasing with the increase of discussed conductance (and more rapidly for larger frequencies) and finally approaching to minimal values; for example, in case of σ=1 S/m, E_1 do not exceeds 12 kV/cm. For slightly larger frequencies (~1 MHz), the observed tendency allows to expect that E_1 will still remain lower than E_o. These results are almost in agreement with the estimations made in [2] (while these are related to somewhat different approach), which predict that similar sealing unit of 10-m conductor can withstand to standard short impulses (0.25 μs front duration) having voltage peak value of about 150 kV, in case of σ=1.54 S/m (that corresponds to resistance per unit length of 10 kOhm/m used in [2]).

Thus, for approach considered, it was obtained that operation conditions for sealing unit insulation become more difficult under stress of high frequency (steep front) lightning components. In further studies, a non-static approach and impulse action can be considered. This can include taking into account the dependence of electrical strength of sealing unit insulation components on time of voltage application (voltage-time characteristics [14]). Actual electric withstand capabilities of IDC and models presented should be verified by experimental tests.

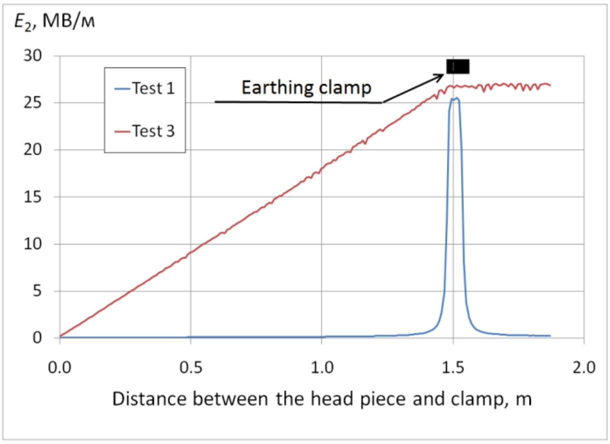

Figure 7: Electric field strength distribution in main insulation, E_2 (test variants – see Table 3)

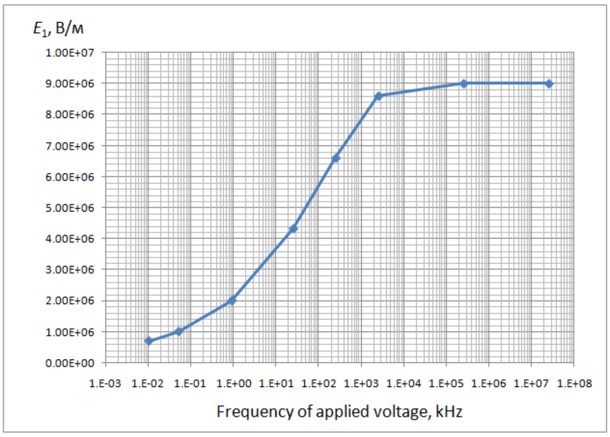

Figure 8: Dependence of the maximum electric field strength E_1 in air near earthing clamp on the frequency of applied voltage (sheath's conductivity is 0.001 S/m)

4 RESULTS OF SIMULATION IN CASE OF CURRENT INJECTION

The problem of current injection to conductor was subdivided into two tasks: (1) to determine the current value needed to obtain voltage of about 100 kV between head and clamp of the sealing unit (for comparison to studies on voltage tests and results of electric field simulations presented in Section 3); 2) to determine the voltage and electric field strength conditions related to injection of current having parameters according to LP standards, including current amplitude of 100 kA (same as indicated for LP levels III and IV in [7]). For both tasks, the model includes the sealing unit of length 1.5 m and 15-m long HVI cable conductor (Fig. 4).

4.1 Currents that create voltage of 100 kV

Results related to the first task, for sheath's conductivity σ=0.01 S/m, are shown in Table 4. In this case, the sheath's resistance $R_{\_cover}$ = 18.96 Ohm. As one can see, for higher frequencies the lower injected currents are required to cause the same voltage of 100 kV. When f = 250 kHz, the current amplitude is only 2.5 kA, and the electrical strength E_1 in air is exceeding the critical value.

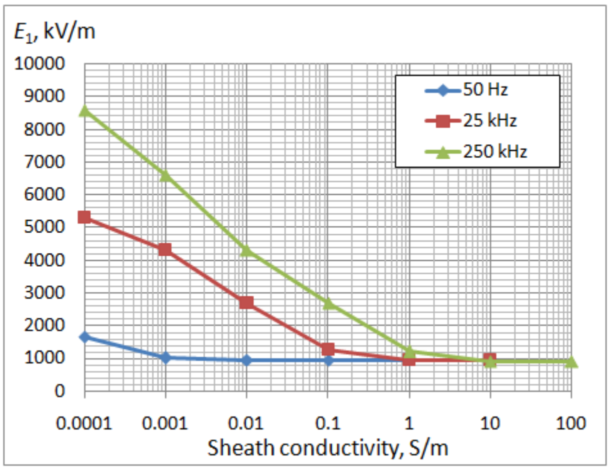

Figure 9: Dependence of the electric field strength maximum value near earthed EB clamp in air (E_1) on the sheath conductivity and voltage frequency

Table 4: Injected current for obtaining voltage of 100 kV (sheath: ε=4, σ=0.01 S/m)

f, Hz	Injected current, kA	Maximum values of electric field strength, V/m		
		E_1	E_2	E_3
50 $25{\cdot}10^3$ $25{\cdot}10^4$	$6{\cdot}10^3$ 26 2.53	$1{\cdot}10^6$ $2.5{\cdot}10^6$ $4.4{\cdot}10^6$	$2.7{\cdot}10^7$ $2.7{\cdot}10^7$ $2.7{\cdot}10^7$	$7{\cdot}10^4$ $5.62{\cdot}10^5$ $1.8{\cdot}10^6$

Comparison of results presented in Tables 3 and 4 show that values of E_1, E_2 and E_3 of corresponding variants of two problems are rather similar. This fact indicates the similarity of electric field distribution determined in both approaches (application of voltage and injection of current).

4.2 Injection of current 100 kA

Results of the second task are presented in Table 5, for sheath's conductivity σ = 0.001 S/m, which corresponds to $R_{\_cover}$ = 189.6 Ohm. As one can see, even for f = 25 kHz the electric field

Table 5: Voltage and electric field intensities caused by injected current of 100 kA (sheath: ε=4, σ=0.001 S/m)

f, Hz	Estimated voltage between head piece and earthing clamp, kV	Maximum values of electric strength, V/m		
		E_1	E_2	E_3
50 $25{\cdot}10^3$ $25{\cdot}10^4$	1.82 400 4000	$2{\cdot}10^4$ $2.1{\cdot}10^7$ $2.65{\cdot}10^8$	$4.5{\cdot}10^5$ $1.1{\cdot}10^8$ $1.1{\cdot}10^9$	$2.5{\cdot}10^3$ $1.1{\cdot}10^7$ $2.2{\cdot}10^8$

strength in air E_1 exceeds E_0 by seven times; this will result in discharge along sealing unit. For f = 250 kHz and current of 100 kA, significant exceeding of field strength above acceptable values will be observed not only in air (E_1), but also for main polyethylene insulation: the calculated value E_2= $1.1{\cdot}10^9$ V/m is about three times larger than estimated strength of usual polyethylene for such conditions ($3.5{\cdot}10^8$ V/m [14]).

5 DISCUSSION

The tests of insulated lightning downconductors were previously performed in laboratories by using voltage impulses having amplitudes up to 700…800 kV and front time of 0.4…0.5 µs [3, 5]. Thus, the equivalent frequency is about 625 kHz, for 0.4 µs.

As the frequency dependence of voltage caused by injected current is practically linear (see Table 5), for f = 625 kHz and current of 100 kA, it can be expected appearance of voltage between head and clamp of about 10 MV. On reverse, it could be concluded that the discussed test voltages of 800 kV corresponds to a current values of about 8 kA for the investigated cable length. This value would be significantly smaller than current amplitudes indicated in LP standards (100…200 kA [8]).

Thus, it looks that the laboratory tests of insulated downconductors by voltage pulses having amplitude up to 800 kV, perhaps, are not enough to conclude on their ability to safely conduct the standard currents having extreme amplitudes or steepnesses and long cable length. On the other hand, some types of polyethylene and air could have better impulse strength characteristics than assumed here.

In [3] a test procedure was proposed taking the requirements on separation distance according to IEC 62305-3 and the increase of insulation strength into consideration. Currently IEC TC81 is developing an international standard for components of isolated lightning protection systems [9]. To support the presently ongoing standardization work for the voltage tests of such downconductors, we suppose that further theoretical and experimental studies should consider also the discussed aspects of current injection and take these results into account during work on a test standard.

Introducing of *current* tests for *lightning current* downconductors will allow additionally exploring such characteristics as: permissible total length of downconductors, voltages between head and clamp related to different current steepnesses, amplitudes, and earthing system parameters, etc. Then, obtained voltages for different conditions could be used for determination of separation distances and for comparison of these values to those obtained previously in impulse voltage tests of insulated downconductors.

6 CONCLUSION

In paper, the operation conditions of insulated lightning downconductor sealing unit are studied using numerical simulation for cases of applied high voltages and injected currents having various frequencies, which are characteristic for different lightning RS current components.

1. For various frequencies of applied voltage (100 kV), the distribution of electric field and maximal values of its intensities in different areas (air, main insulation, sheath) are varied. This feature should be taken into account in design of insulated downconductors.

2. For approach considering the high voltage application, a certain level of sheath's conductivity is found (0.1…1 S/m), which corresponds to achievement of electric field homogeneity for typical lightning current components' frequency characteristics (50 Hz…1 MHz). For lower conductivity values, for example of 0.001 S/m, the field intensities in sealing unit will be too high, and the discharge will occur for both, first and subsequent, lightning return strokes.

3. Simulation studies on current injection into sealing unit of the 15-m long insulated downconductor were presented in two solved tasks (Section 5).

3.1. In first task, it was found that, for obtaining voltage of 100 kV between the head and clamp of sealing unit, the currents to be injected are: 6 MA for current frequency of 50 Hz, 26 kA – for 25 kHz, and 2.5 kA – for 250 kHz (case of sheath's conductivity 0.01 S/m).

3.2. In second task, for injected currents of 100 kA (related to LP levels III and IV) and sheath's conductivity 0.001 S/m, it was found that the electric field intensity in air along sealing unit E_1 is significantly exceeding the acceptable level (E_0=30 kV/cm) for both, first and subsequent, lightning RS (frequencies of 25 kHz and above). For subsequent strokes (250 kHz and above), the electric field stresses could also exceed the acceptable levels for main insulation made of usual polyethylene.

4. It appears that tests on applying high voltage impulses to insulated downconductors [3, 5] do not provide a complete answer on their ability to conduct lightning current with parameters that are indicated in LP standards for different LP levels [8]. Actually, further theoretical studies and experiments are needed to verify existing and to create new, more accurate, models of downconductors and their sealing units. This is also important for possible development of related test standards for insulated downconductors, which seems should include tests by currents.

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