EARLY STREAMER EMISSION TERMINALS FROM THE HIGH VOLTAGE ENGINEERING PERSPECTIVE

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Abstract: Two basic constructions of Early Streamer Emission terminals were shown: terminals with enhanced ionization and terminals with internal coil. The simplified theoretical background of these lightning terminals was explained. The paper shows the difficulties related to testing active lightning terminals in a laboratory. The limitations of applied conditions recommended in the NF C 17 – 102 standard were discussed: a) electrode arrangement plate-rod, b) very short 1 m distance between them, c) switching impulse with DC voltage bias. With the help of the air breakdown theory it was shown that the protection zone of the Early Streamer Emission terminals practically cannot be greater than the protection zone of classical Franklin terminals.

1 INTRODUCTION

A lightning rod was discovered over 260 years ago. Especially during the last 100 years our know-how in the field of the lightning phenomenon and the theory of lightning protection has increased considerably. However, the external lightning protection has changed only a little since Benjamin Franklin (the Franklin lightning rod) and Michael Faraday's times (the Faraday cage). Obviously, there were and still are different trials to improve the classical lightning protection. Yet no trial was completed with generally recognized success. The most well-known examples are radioactive lightning rods proposed soon after the Radium discovery [1] and Dissipator Active Systems DAS also called the Charge Transfer Systems CTS. These systems will supposedly prevent protected objects from lightning strikes. The discussion and controversy about active lightning terminals have lasted for over 20 years, the first papers dealing with new generation terminals appeared in 1992 [2]. In spite of negative opinions of nearly all experts and extensive evidence from the field showing no better properties than classical terminals, thousands of active lightning terminals were installed in different countries. This is a very troubling situation because the application of lightning protection systems that do not have the parameters claimed by their manufacturers can have even catastrophic consequences [3].

2 RADIOACTIVE TERMINALS

Leo Szilard, a distinguished physicist and co-worker of Maria Skłodowska-Curie, proposed in 1914 to improve the Franklin rod by adding a radioactive element near its tip. The first radioactive terminals were manufactured in France before WW II [1]. The radioactive elements were also used in high voltage engineering to improve small protective air gaps with the electrode distance in the range of 3 mm [4]. A radioactive element, e.g. Radium with a weight of 0.1 mg emits radiation that ionises air molecules and increases the ion and free electron density between electrodes. Without the radioactive element the ion density is smaller and ionisation is caused by cosmic rays and by radiation from radioactive elements contained in the Earth's crust. In atmospheric air this natural ion density is in the range $11/\mathrm{cm}^3\cdot\mathrm{s}$ [4]. The increased density of free electrons contributes to the shortening of the statistical development time of electrical discharge and the standard deviation decrease of breakdown voltage. It should be underlined that the value of breakdown voltage does not change. Nowadays, it is forbidden to use radioactive elements in protective air gaps. They were replaced by UV or gamma rays [5]. Obviously, there are enormous differences between small protective air gaps and lightning terminals. The electrode distances in protective air gaps are small, in the range of 1 – 10 mm, and the electrical field is uniform. The so called last stroke distance between the lightning terminal tip and the downward leader is several dozen meters and the electrical field between the rod and rod electrodes is very non-uniform. The application of the idea which is useful in small protective air gaps for the improvement of Franklin lightning rods is absolute nonsense for every high voltage engineer. The radioactivity source would have to be so powerful that a large protection area would be needed around it, like in the case of the Chernobyl nuclear power station. No wonder that already in 1965 the British Standard Committee rejected the use of radioactive lightning rods [6]. Afterwards in the 1980s the use of them was banned in many countries due to possible human exposure to harmful radiation.

3 ACTIVE TERMINALS WITH ENHANCED IONIZATION AT THEIR TIP

In the new types of lightning rods which replaced old radioactive terminals, the increased ionization was implemented borrowing the idea used in trigatrons. Trigarons are often applied in high voltage engineering among other things as convenient remote control of surge generators. Usually there are air gaps with one sphere divided into two isolated parts (Figure **1**). The voltage impulse of 10 - 30 kV from an additional small generator is delivered to the divided sphere. A spark between two divided electrodes considerably decreases the electrical strength between two main electrodes (by about 30%), it causes spark gaps ignition at other stages and the surge release of a whole generator. The breakdown voltage reduction of a trigatron by a spark results from an increase in air temperature, the delivery of a great number of free electrons and a decrease in electrical field uniformity.

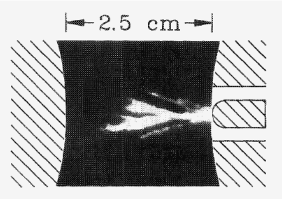

Figure 1: Trigatron's operation principle [7]. The right air gap electrode has an additional electrode connected to an auxiliary voltage source.

The adoption of a good solution, which are trigatrons serving for control breakdowns of small air gaps in the range of 1 cm, to the reduction of the electrical strength of long air distances with a very non-uniform field is yet another absurdity. How can a small spark influence the breakdown process of a long air distance? The inventor of such a solution was not a high voltage engineer. It is an attempt similar to the idea of "killing an elephant with an air-gun".

A few active terminal manufacturers are trying to utilize the trigatron working principle. There are, among others, Prevectron from Indelec (Figure **2a**), a similar solution are applied by TSTLP. The voltage source in these devices are small generators producing impulses to fire a spark between electrodes mounted near a terminal tip. In a Dynasphere terminal manufactured by Erico the spark ignites between a canopy-shaped electrode located at the floating potential and a grounding shaft (Figure **2b**). A large value resistor connects both electrodes. The oncoming downward leader causes the canopy potential to rise and spark ignition. The "true value" of Dynaspere terminal has been shown by Zaibal Hartono in Malaysia [8]. There were 12 lightning flashes on four building protected by Dynasphere terminals. One lightning flash struck a point only 10 m away from an active terminal.

Piezoelectric materials are also applied to ignite a small spark between two electrodes. The terminal Saint Elme AFB 1006 SE manufactured by Franklin France was fastened on a special bearing connected to a piezoelectric element (Figure **2c**). Terminal rocking was induced by the wind changing the pressure exerted on the piezoelectric element. The lightning terminal with a piezoelectric device for initiating the corona effect was patented in 1985 [9]. An ESE terminal equipped with a wind-driven voltage generator and a palm-sized laser device was also proposed [6].

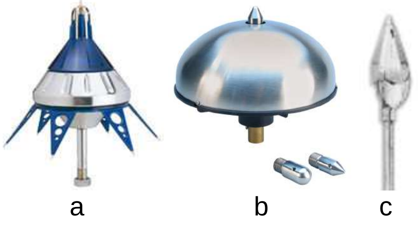

Figure 2: Terminals with axiliary electrodes, a - Prevectron, Indelec, b – Dynasphere, Erico, c – Saint Elme, Franklin France (source: catalogs of Indelec, Erico, Franklin France)

4 TERMINALS WITH INTERNAL COILS

The terminals with an internal coil have an entirely different design. The coil and a small air gap are contained in a metallic cylinder. The external protecting air gap is formed below the housing. The terminal outline and its electrical model are shown in Figure **3**. There are no additional electrodes for the generation of ionizing discharges. This terminal is not similar to the trigatron. When electrical field intensity violently rises due to an approaching downward leader, the internal air gap breaks down. The spark rapidly connects the coil and the capacitance between the downward leader and the terminal tip with the ground. As a result, oscillating transients with the maximum overvoltage factor equal to 2, typical in RLC circuits, appear. If oscillation frequency is appropriately selected, the overvoltage factor can be greater than 2 but smaller than 3.

Lightning terminals with an internal coil are manufactured by Helita and ORW-ELS companies (Figure **3c**, Figure **3d**). In this construction a slightly higher potential at the terminal tip is obtained compared with a potential at the Franklin terminal tip. The terminal with an internal coil is therefore a more interesting construction than terminals with small ionizing discharges trying to imitate the trigatrons. According to the standard [10] lightning terminals are tested in a laboratory using switching impulses. In this case it is possible to choose coil inductance in order to obtain the overvoltage factor close to 3. Under field conditions and the influence of an approaching downward leader, the potential at the terminal tip rises exponentially. Oscillation damping should therefore be as small as possible to keep the potential of the terminal tip high and to support the connection of the downward leader with the upward leader.

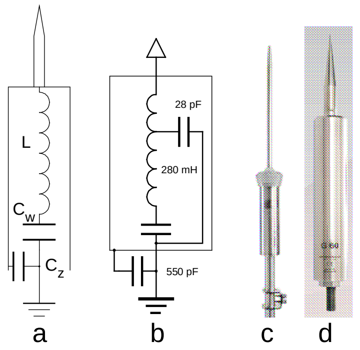

Figure 3: Design of a terminal with internal coil (a) and its equivalent electrical scheme [11]. Pulsar manufactured by Helita (c), Gromostar made by ORW-ELS (d)

Let us assume that the overvoltage factor $k_m = 3$ and terminal height is 1 m like in [10]. Before lightning flash development the electrical field intensity under the storm cloud Eo = 20 kV/m. Therefore, the potential rise of the terminal tip due to oscillation is equal to 60 kV. Let us take into account a lightning with a very small return current of 5 kA. The decision distance $R_m = 10 \cdot 5^{0,65} = 28$ m and the voltage needed for the breakdown of such a long air gap is about 3 MV. The overvoltage with an amplitude of 60 kV that is generated in RLC circuit is only 2% in comparison with 3 MV. The situation is quite different during the test conducted according to the standard [10] with an electrode arrangement plate – rod separated by 1 m. The breakdown voltage amounts here to about 0.5 MV. The overvoltage with an amplitude of 60 kV makes even 11.5% of this value. No wonder that under such conditions a terminal with an internal coil can perform better than the Franklin terminal [12]. For a lightning with greater current the overvoltage generated by such an active terminal is still smaller than 2% of the enormous voltage needed for the breakdown of a very long air distance (longer than 28 m). Summing up: under field conditions the terminals with an internal coil are only slightly better than Franklin rods. The long protection radiuses given in the technical data of active lightning terminals are simply a misunderstanding.

5 ACTIVE TERMINALS WITH UNKNOWN CONSTRUCTION

The constructions of some active terminals are unknown. Their manufacturers dose information in such a way that we can suspect it is a deliberate action. It is quite possible that such strategy may result from an intention to keep some information secret. It seems that the concealment of sensational patented construction does have any sense. Quite the contrary, a simple product description presenting its working principle seems to be the best advertising. Now only one mysterious construction of an active terminal: Interceptor ESE i-Series manufactured by Erico (Figure **4**) will be presented. Similarly to other terminals, three types of this construction are manufactured: SI25i, SI40i and SI60i with the time advantage of active terminal ΔT equal to appropriately: 25, 40 and 60 μs, respectively. Parameter ΔT is defined in [10]. Thanks to an internal control circuit this lightning terminal enables supposedly earlier streamer emission than a classical terminal. Interseptor ESE i Series generates voltage impulses with a given amplitude and frequency. This confirms oscillations similar to transients in terminals with an internal coil. The terminal tip is on a floating potential. However, some questions arise: Is the high voltage section a voltage source ? Is it a coil ? Why does the terminal tip have such a peculiar shape ? Why is the insulating ring so thin ?

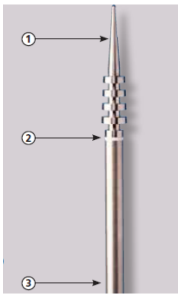

Figure 4: Interseptor i Series manufactured by Erico, 1 - terminal, 2 - insulating ring, 3 – high voltage control section [13]

6 THEORETICAL ANALYSIS OF TERMINALS WITH INTERNAL COIL

The authors of an interesting paper [12] have proposed an electrical model of a terminal with an internal coil placed below a great plane high voltage electrode (Figure **5**). The capacitance between the terminal and the plane electrode C_a, the capacitance between terminal tip and ground C_0 as well as coil and ground resistance R were taken into account. After a breakdown, the internal air gap C_i is short circuited by a switch. The authors placed the internal air gap above the coil (in fact the internal air gap is situated below the coil). Mikes built a similar electrical model of a terminal with additional capacitance between the coil and the metallic housing (Figure **3b**).

The authors [12] have considered the state before and after the internal air gap breakdown. The external electrical field E_0 changes from a relatively weak DC stationary field produced by storm cloud charges 22 kV/m to the strong impulse field generated by approaching the downward leader. In stationary field E_0 charge Q_0 collected on the Franklin terminal tip

$$Q_o = -C_a \cdot U_a \qquad (1)$$

C_a, U_a – are marked in Figure **5**.

Whereas the charge collected on the ESE terminal tip

$$Q_m = k_m \cdot Q_o \tag{2}$$

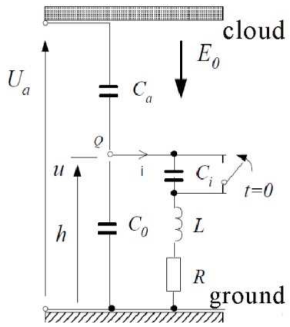

Figure 5: Equivalent circuit diagram of an active terminal [12] placed under high voltage electrode and tested according to standard [10].

The concentration field factor at the Franklin terminal [12]

$$K_e = \frac{E_m}{E_o} = \frac{h}{r} \tag{3}$$

E_m – maximum electrical field at the Franklin terminal tip.

Assuming a very blunt but high lightning terminal with the radius tip r = 0.25 m, the height h = 25 m we obtain K_e = 100, that means that the electrical field at the Franklin terminal tip is 100 times greater than on the ground. If the terminal tip is sharp (r = 1 mm) K_e achieves a very high value of 25000. The electrical field at this Franklin terminal has a value of 25 kV/cm (which is close to ionization onset 30 kV/cm) even under the so called fair weather conditions where E_0 = 100 V/m. The ESE terminal is at the floating potential V_h (it is isolated from the ground by an internal gap) therefore its conditions are different. If the potential at height h is high enough, then the air gap ignites. As a result, the oscillations with overvoltage factor k_m occur (Figure **6**). Their frequency depends on RLC circuit parameters. In a circuit consisting of a voltage source and LC elements the overvoltage factor reaches a value of 2. After the ignition of internal air gap C_i the circuits consists of R, L, C_a/C_o (Figure **5**). Due to the isolation between ground and the ESE terminal tip, and transients generation after the breakdown of the internal air gap, the real electrical field intensity increase at the ESE terminal tip is achieved.

7 LABORATORY TESTING OF LIGHTNING TERMINALS

No high voltage test is able to reproduce the field conditions during a storm because the nominal voltage value of the available Marx impulse generators is too small. Nevertheless, the test described in the standard [10] should be changed. There are at least two reasons.

-The electrode arrangement plate-rod models only the conditions for the upward leader that develops from high objects higher than 100 m. In the case of lower objects the discharge lightning develops in the arrangement similar to rod-rod electrodes. Therefore, the rod-rod arrangement is much better than plate-rod electrodes. This opinion is shared by many experts [14].

-The electrode distance had to be increased to a minimum of 2 m because at the distance of up to 1 m discharges develop generally as streamers not leaders. Additionally, at shorter electrode distances the discharges are usually not stable. It causes a greater standard deviation of test results [15].

When switching impulses and plate-rod electrodes are used, there is no influence of the DC bias on breakdown voltages if the air gap distance is greater than 30 cm. In other words, the impulse voltage practically does not depend on the intensity of corona discharges [16]. Comparing the breakdown voltages with or without corona discharges from the Franklin rod tip, one can say that this “ionising” corona discharges does not influence the breakdown voltage [17]. Conclusion: DC voltage application during the impulse tests of Franklin rods seems senseless and it only makes these tests more complicated. On the contrary, if a terminal with an internal coil is tested under switching impulses, the DC bias voltage can have an influence on the results. After the impulse breakdown of an internal air gap, the DC voltage keeps “the oscillation symmetry axis” at the same potential as before the breakdown. When DC voltage is not applied, the oscillations run around a zero potential. The shift of the oscillation axis causes the rise of the overvoltage factor from 2 to even 3 if the amplitude time of occurrence and the oscillation frequency are appropriately matched (Figure **6**).

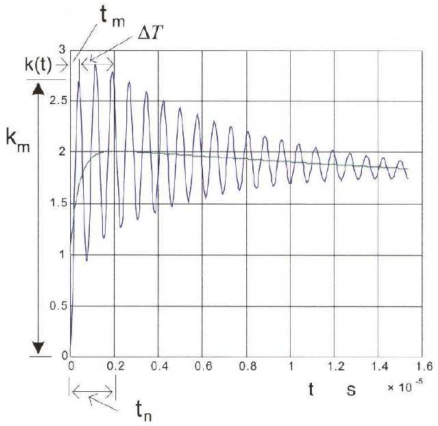

Figure 6. Instantaneous curve of oscillation function k(t) of terminal with internal coil and lightning impulse 1,2/50 μs [18]

When the downward leader approaches the lightning terminal, the potential at its terminal increases exponentially. Unfortunately, there are not high voltage generators that were able to deliver the voltage with such a shape. The standard [10] requires the application of switching impulses. The voltage speed in switching impulses 250/2500 μs is slower than under field conditions. Therefore, the use of standard lightning impulses seems to be an interesting proposal. However, the oscillation frequency in such a test should be changed to take into account the different lightning impulse shape. Oscillation frequency (radial frequency ω) depends on RLC parameters.

$$\omega_o = \sqrt{\omega^2 - \alpha^2} \qquad \omega = \frac{1}{\sqrt{LC}} \qquad \alpha = \frac{R}{2L} \qquad (4)$$

At constant C value, it is possible to match the L and R values to the test voltage shape (Table **1**). The calculations are simple for different aperiodic impulses, such as standard lightning impulse, standard switching impulse or for an impulse with different parameters T1/T2 (time to peak/time to half value). However, under natural conditions the electrical field over a lightning terminal increases exponentially unlike in laboratory tests with application of Marx generators. These changes were already considered earlier by Berger who carried out first laboratory tests of ESE terminals [2].

Table 1: RLC parameters vaues for lightning and switching impulses [18]

Impulse type	R Ω	C pF	L mH	ω_o MHz
Lightning 1.2/50μs	8.0	6.0	7.0	1.4
Switching 650/6500 μs	152	66	105	1.2

Beccera and Cooray proposed the model of self-maintaning leaders showing the importance of the electrical field distribution at a lightning terminal tip [19]. Even when an early streamer originates, it has to disappear if the external local field is too small to maintain this discharge. As a result, Cooray and Bazelyan argue that active terminals should have at least an 0.5 MV generator to enable early streamers development [20, 21].

The construction of an Early Streamer Emission terminal equipped with an 0.5 MV generator is technically possible. However, such a lightning terminal would be too expensive and too complicated for common use. Research aimed at the "improvement of classical lightning protection" should and can be continued because even small improvements of the traditional Franklin rod or the Faraday cage are very important.

8 LABORATORY TEST RESULTS

Own laboratory experiments [1] and studies made by other independent researchers did not show any better properties of active terminals over the classical ones. In the above mentioned measurements the high voltage electrodes had the form of rods [1, 21-23]. A very good result for radioactive terminals was published in [24] and for a terminal with an internal coil in [12], they were connected with the application of a plane high voltage electrode and the relatively small air gap distance of 3.6 m [24] and 1 m [12]. The explanation why such excellent results achieved in [12] were possible was given in part 4.

9 OBSERVATIONS IN THE FIELD

Over 100 observations proving that the active terminal protection zone is considerably smaller than that declared by their manufacturers were collected by Hartono in Malaysia [8]. Some cases suggest that the protection zone of ESE terminals is equal to the protection zone of Franklin rods. It is not known how many documented ESE failures concern active terminals with an internal coil. The author knows only three lightning strikes of objects that were incorrectly protected by terminals with an internal coil: family house in Kamieniec Wrocławski in Poland (Figure **7**), biogas station in Malsice in the Czech Republic [25] and church tower in Sigolsheim in France [26]. Lightning struck the objects in the points removed from a terminal with an internal coil by 18 m [1], 26 m [25] and only 6 m [26], respectively.

Figure 7: Wieczorkowski family house in Kamieniec Wroclawski [1]

A lightning strike in a hotel in Odry, Czech Republic, with a wooden structure had a very grave effect [27]. The lightning "successfully" struck an active terminal, however, in spite of that the hotel was set on fire. The active lightning terminal was connected to only one down conductor and only one earthing resistance. The spark originated from grounding wire ignited wooden boards. This example shows how dangerous is a single lightning terminal connected to only one down conductor and only one earthing resistance.

10 CONCLUSIONS

Early Streamer Emission terminals with ionizing small discharges between electrodes are designed without any basic knowledge of high voltage engineering.

Active terminals should contain an additional generator with the impulse amplitude of at least 0.5 MV to efficiently emit early upward streamers (leaders). However, such lightning terminals would be too expensive and too complicated for common use.

Lightning terminals with an internal coil are a very small improvement (2% or less) of Franklin terminals.

The laboratory testing of terminals with an internal coil should be carried out with impulse voltage delivered to a rod electrode and with DC bias voltage delivered to a plane electrode. The distance between the terminal tip and the rod electrode should be greater than 2 m.

The oscillation frequency of terminals with an internal coil should be matched with impulse time to amplitude. The frequency can be practically changed by inductance adjusting.

The two above conclusions show the limitations of this interesting solution, that is the lightning terminal with an internal coil.

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