Investigations and studies on lightning air terminal shapes in relationship with the efficiency of a simple rod

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Abstract—
For many years, studies have been carried out concerning the shape of lightning air terminals in order to determine whether a blunt or sharp rod was more efficient. Their conclusions are depending on the authors and the parameters used for the study. In order to fully understand how a lightning air terminal behaves depending on its shape, this study is based on the analysis of the lightning phenomenon, the various theories on the upward leader initiation and development under thunderstorm conditions as well as the last research works performed on subject. A specific survey has then been conducted. It deals with different rod shapes maintained at potential zero under a uniform electric field. Simulation works, tests in laboratory and in real thunderstorm conditions have been conducted on the different types of air terminals. This study completes the previous studies conducted on the rods various shapes. It highlights the close relationship between the efficiency of a single rod air terminal and the surrounding conditions, more precisely the ambient electrical field value and its evolution. It also shows some possibilities of improving the efficiency of the rod.

Keywords—lightning rod, Corona effect, blunt shape, sharp shape, electric field, rod efficiency

I. INTRODUCTION

Many scientists looked into the behavior and the efficiency of the simple lightning rods according to their shape but often their conclusions diverge. We wanted to review on the state of art in this domain before trying to arrive at a consensus. This bibliographical work allowed us to define areas of study to go farther and complete the already realized works. These axes concerned a deepening of the physical theory, calculations and simulations but also tests in laboratory and in real thunderstorm conditions. Our results permitted coming to some clear rules about the functioning of lightning rods and the possibilities of improvement of their behavior.

II. BIBLIOGRAPHIC STUDY AND RESULTS PROCESSING

A. Introduction
The objective of the bibliographical study was to make the state of art in every field touching lightning. Different topics and reflection areas were defined:
- Understanding of the atmospheric phenomena (thunderstorms, lightning),
- Synthesis of the parameters of lightning (electric fields, currents, durations, speed,...),
- Understanding of natural corona effect,
- Study of the conditions of starting and development of the upward leader,
- Study of the possibilities of improvement of these conditions,
- Application to a lightning rod,
- Study of modeling, digitizing and existing simulations,
- Study and definition of the mathematical and computing tools, and of the tests in laboratory and in situ to implement, to verify and validate some principles.

B. Bibliographical Study
Bibliographical study was extensive and many documents were analyzed. We introduce here the points which seem to us the most important [1-11] for the understanding of treated subject.

1) Point effect and corona effect
The presence of sharp objects on the ground reinforces locally the electric field, by deformation of the E-field lines,
which can reach then values of some hundreds of kV/m. This is the point effect.

Fig. 1. Electric field distribution

If the electric field reaches locally approximately 30 kV/cm, an ionization of the air occurs owing to a phenomenon of electronic avalanche. It is the corona effect, precursory phenomenon of lightning strokes. A current becomes established during some tens of nanoseconds only. This phenomenon reproduces periodically (all the tens of milliseconds approximately). In fact, in the avalanche there is production of positive ions which are going to move in the direction of the field and to produce a positive space charge layer, which has the effect of decreasing the field in the neighborhood of the tip and of stopping ionization. Some people speak about shield effect, more important on the axis above the rod than on the sides [11].

Fig. 2. Space charge and electric field

As a result of the interactions with the other molecules, there is dissipation of the space charge layer and the field at the tip raises again after some tens of milliseconds. And then the process can restart again.

It is interesting to be able to have exact analytical solutions, found by mathematicians, which are going to allow studying a particular tip geometry. In the case of a simple rod, of which the equatorial plan is at potential 0, placed in a uniform field according to its north-south axis, there are exact solutions of the Laplace equation $\Delta V = 0$.

We can so calculate the electrical field at any point of the space and notably at the top and on the axis, according to the radius of curvature of the top. Thus it is possible to define the amplification factor of the tip and its evolution.

2) Streamer development

If the ambient field around the tip increases “fast enough”, a new avalanche of electrons can occur in the air, ahead of the positive space charge. So new positive ions are created, which themselves are going to create a new avalanche always by moving away from the tip, and so on.

Experimental data and theoretical calculations [4] give the limit of propagation of the streamer when the field becomes lower than 5 kV/cm.

3) Points accepted unanimously by the scientists

In the different consulted documents, we found several points which are unanimously accepted:

- With a sharpened rod, the intensity of the field is maximal but falls again to its surrounding nominal value at a shorter distance (of the top) than with a rounded off rod.
- The electronic avalanche goes on as long as the field created by positive ions does not weaken significantly the local field.
- Positive ions created by sharpened rods disappear faster than those created by rounded off rods.
- A minimal value of the ambient field is necessary for the development of a streamer in positive upward leader.

4) Arguments against sharpened rods

Some scientists give their preference to the rounded off rods rather than to the sharpened rods.

According to them, a streamer going out of a rounded off electrode has a higher probability to be converted into a stable upward leader and so into a capture discharge more efficient than a discharge going out of a rod with a sharp tip.

C.B. Moore [6] says that, in order to initiate the propagation of a positive streamer, the E-field has to grow quickly enough so that the limitation created by the current of positive ions has no important repercussion.

In low ambient field, there are corona current pulses separated by time $t$ which corresponds to the necessary time so that positive ions disappear and for the return to initial conditions.

The smaller the radius of curvature of the tip, the higher the frequency of pulses is.

Also, if the field increases, frequency increases. From a certain value of E-field, the pulsed pattern is transformed into continuous pattern (glow).
C.B. Moore says that it must be long enough so that the increase of the ambient field is important enough when positive ions are still present, so as to maintain the electronic avalanche and a column of positive ions. He reports a value of 50 μs.

The basic idea is that the increase of the external electrical field must compensate the masking effect of the field due to the space charge layer.

C.B. Moore also bases his reasoning on tests results in real thunderstorm conditions. He speaks about a compromise on the radius of curvature but there is no real physical foundation.

5) Arguments in favor of sharpened rods

Other scientists, as P. Lalande [4], give their preference to sharpened rods rather than to round-ended rods.

In laboratory, for identical height, he states that the rod with the smallest radius is likely to develop a positive leader having the highest probability to reach the upper plane electrode.

The time of breakdown is equal to T1+T2+T3 with :

T1 = time of appearance of the first corona ;
T2 = time to appearance of the leader ;
T3 = time taken by streamers to reach plane electrode.

T1 decreases when the radius of curvature R decreases.
T2 increases when R decreases.
T3 is nearly independent of R.

For low radius, the first corona forms very early but his length and his charge are small and insufficient to allow transition into leader. Several coronas have to start to form the leader.

With a larger radius, the first corona forms later but evolves faster in leader.

On the other hand, (T1+T2) decreases when R decreases. P. Lalande introduces the notion of stabilization field (figures 3 and 4).

This is the ambient minimal E-field to be reached so that the space charge effects are counterbalanced by the lengthening effect of the leader. Indeed, when the field at the head of the discharge reaches a continuous growth pattern, the leader moves quickly enough to compensate for the effect of the space charge deposited in the head corona region. It is a dynamic balance which becomes established according to the propagation and which is only little influenced by the conditions of superficial local ionization field at the top of the electrode. It is therefore logical that this field does not practically depend on the radius of curvature, under reserve of course that the local conditions of ionization of the first corona are satisfied. It is the case when the radius of curvature is lower than the so-called “critical radius”.

By contrast, for large radius, superior to the critical radius, the field at the head of the electrode is not very divergent and the condition of formation of the first corona is then more restrictive than the stabilization one. In that case, any formation of the first corona will lead automatically to the development of a stable leader.

If the field is lower than the stabilization field, discharge performs some steps then stops.

If the field is equal or upper to the stabilization field, discharge propagates in a stable way.

![Fig. 3. Evolution of the stabilization field as a function of the radius](image)

C. Results Processing

In a general way we want to favor the creation and the development of the upward leader.

We know that a minimal value of the ambient field is necessary to achieve the development of a streamer into a positive upward leader ; we shall call the field corresponding to this value “development field”.

Purpose is to make sure that a corona effect is transformed into an upward leader. Therefore any pulsed mode is useless because as soon as pulses are occurring, it means that corona effect switches off periodically and does not evolve into leader. On the other hand, if this functioning mode is not efficient, it is not embarrassing since pulses are also the proof of the periodic disappearance of space charges at the tip.

Dealing with P. Lalande’s work, we notice that for values of radius of curvature lower than a critical value, we have a pulsed pattern. The critical radius corresponds at case the first corona evolves in leader. Thus using a lower radius is finally useless.

C.B. Moore states that the radius of curvature has to be such as the first corona persists enough for a long time so that the development field could be reached.

Finally, with different points of departure and different demonstrations, C.B. Moore and P. Lalande converge to the same conclusion.

In fact, it is necessary to take a radius of curvature which is such as the first corona starts as early as possible and persists a time long enough so that the ambient field evolution makes that the development field is reached.
We exclude from the reasoning tips with a radius of curvature upper to the critical radius of Lalande because in that case the development field grows with the radius, what is completely uninteresting.

It is possible to show that, at some field level, a rod with a more rounded off tip maintains positive charges longer and gives a corona effect more stable compared with a sharpened tip and on the other hand this last one starts a corona effect earlier that a rounded off tip but maintains it fewer time.

Therefore, we can deduct that the sharpened tip will be more efficient if the field varies strongly in a very short period of time (dE/dt great) ; otherwise corona effect will stop and the more rounded off tip will then be better although corona effect starts later. When the leader has started, positive charges will be more easily created by corona effect at the tip if this one is sharpened. Figure 4 illustrates this comment.

Thus, no ideal shape, it depends on the field and on its evolution.

The shape of the "ideal" lightning conductor would be the one which could fit automatically onto the surrounding electric field.

A possible example should be a rod tip "more or less rounded off" at first, according to dE/dt, to allow a starting up supported by good conditions, with an important range, but then a rod tip sharpened to allow the evolution of the upward leader.

A sphere (or half sphere) topped with a sharp tip would behave in this same way.

However the ideal way would be to transform the shape of a rod according to electric conditions.

How to achieve such a challenge ?

Our concept is based on the fact that the difference, from an electrical point of view, between a sharpened and a rounded off rods lies in the distribution of the E-field and potential lines near the top, consequence of the different E-field amplification factor values.

Figure 6 shows the map of potential lines for two shapes of rods.

Concerning the choice of the rod shape, it will be necessary to take into account the fact that the creation of positive ions above the tip creates an antagonistic field which decreases the resultant one, but also the variation of the electric field on the ground, according to the distance with regard to the ground of the head of the downward precursor (figure 5).

To change the behavior of a rod, it would thus be necessary to succeed in varying the amplification factor.

To achieve this goal, the concept which we highlight would be to modify the distribution of potential lines by introducing a variable auxiliary polarization potential to change the amplification factor of the tip and to transform fictitiously a blunt tip into a sharp tip or vice versa. So, we would obtain a rod which we can call "variable-geometry rod" and which take into account real time electrical field conditions.

### III. STUDY ON THE SHAPE OF RODS - SIMULATION WORKS

#### A. Introduction

To verify if the suggested theory above is correct, we realized several simulations by using the finite element calculation software ATILA. From a well defined meshing
and from various calculations, we were able to determine the electric characteristics to the neighborhood of a rod (potential and electric field lines, amplification zone of the field) and the field on the symmetry axis according to the distance with regard to the top of the rod.

In order not to overload this present document, we do not expose here all the obtained results.

![Image](image1.png)

**Fig. 7.** Rod samples used for simulation

B. Works on rod at potential 0 with polarized disk

1) Study configuration

We introduced a metallic disk near the top of the rod, to which we apply a DC high voltage to modify the distribution of potential lines.

![Image](image2.png)

**Fig. 8.** Geometrical configuration of the study

Figure 9 represents the transformation of potential lines according to the polarity of the DC potential applied to the disk.

![Image](image3.png)

**Fig. 9.** Meshing and potential lines

2) Simulation results

**Comparison between rod + polarized disk and simple rod**

We defined the reduced field as the quotient of the E-field at any point of the symmetry axis by the E-field applied between the 2 metallic electrodes. The calculation of the reduced field as a function of the distance from the top of the rod shows that the presence of the disk disrupts the functioning of the rod itself (figure 10). To recover the same performance of simple rod, it is necessary to polarize the disk at about -1 KV. Then, with a higher negative voltage the rod becomes more sharpened.

On the contrary, by using a positive polarization, we undoubtedly get a blunter rod.

Moving away from the tip (figure 11), we observe that process is reversed. Indeed, the field amplification, even if it is lower on a blunt rod, operates on a more important zone than with a sharp rod.

![Image](image4.png)

**Fig. 10.** Reduced field as a function of the distance to the tip for various rod configurations

The influence of disk position and disk diameter was also studied.

The disk position (located at 3 or 4 cm from the top of the rod) has a limited influence. However, in positive polarization, it has more influence when closer to the top.
The disk diameter (6 or 8 cm) has a little influence in negative polarization. In positive polarization, the more the diameter is important, the more it has influence.

Fig. 11. Reduced field as a function of the distance to the tip for various rod configurations

Comparison between rod + polarized disk and passive rod with complex shape

By polarizing the disk at +4 KV we manage to modify the electrical characteristics of a simple rod.

Indeed, it shifts from a simple rod shape to a rod bearing electric characteristics appreciably equivalent to those exhibited by a more complex rod, for example a sphere with a small tip on the top (figure 12).

Fig. 12. Reduced field as a function of the distance to the tip for various rod configurations

Comparison of different cones (from 2 to 10 cm) with or without polarization of + or - 3 KV

For example, we observe that a 5 cm cone with a disk polarized at +3 KV is equivalent to a 2 cm cone (amplification factor of 400), and that a 5 cm cone with a disk polarized at -3 KV is equivalent to a 8 cm cone (amplification factor of 550).

It would be also possible to show that this auxiliary polarization is able to change a cone geometry into an ellipse geometry and vice versa.

Other works were accomplished with a metallic tube instead of the disk and ended with similar results.

Fig. 13. Reduced field as a function of cone sizes for two disk polarizations

C. Rules ensuing from simulations results

According to the obtained results, we were able to establish various rules:

- By polarizing an element near the tip with a voltage of the same sign as the ambient field, "the tip gets more sharpened".
- By polarizing an element near the tip with a voltage of sign opposite to the ambient field, "the tip gets more rounded off".
- Starting from a sharpened tip, the variation range of the amplification factor of the field as a function of the polarization is larger than starting from a rounded off tip.
- It seems easier to shift a tip to a more rounded off one than a more sharpened one.
- The higher the ambient field, the lesser effective the effect of the polarization is.
- In the interesting values of field, it is necessary to apply a polarization voltage above 1 kV to induce a significant effect.

IV. STUDY ON THE SHAPE OF RODS - TESTS IN HIGH VOLTAGE LABORATORY

A. Introduction

To validate in laboratory the simulation and calculations results, we used the same test configuration of the figure 8, with the rods illustrated at figure 14.
A test equipment was purposely designed for this study allowing us to count current pulses concerning the corona effect on each tip.

B. Results

1) Simple rods

We observe that the more the field increases the more the number of corona pulses increases (figure 15). We also notice that this number gets larger as the rod sharpens.

2) Rods with polarized disk

We observe on the figure 16 that we were able to change fictitiously the shape of the rod simply by modifying the polarization of the auxiliary disk.

We also compared the effect of various disks placed in different positions.

The disk was then replaced by a tube. Results complied with our expectations.

C. Conclusion

Comparing the results obtained during simulations to those obtained in laboratory, we note that they are in good agreement.

Tests in laboratory thus allowed confirming the results obtained by calculation.

We were able to observe the real "transformation of the shape" of studied rods by addition of a polarized auxiliary element.

V. STUDY ON THE SHAPE OF RODS - TESTS IN REAL THUNDERSTORM CONDITIONS

A. Introduction

Measurement campaigns were led in Florida and Brazil to validate, in situ, results described above.

Tests were set up to compare the behavior of different rods subjected to an electrical thunderstorm field and to highlight the influence of a high voltage polarization applied to an element located near the top of the rod.

4 rods were subjected to tests:

- Rod 1: 10 cm cone;
- Rod 2: 5 cm cone;
- Rod 3: 10 cm cone with polarized tube (11 cm tube placed at 3 cm from the top of the rod), or with polarized disk (disk of diameter 6 cm placed at 3 cm from the top of the rod).
- Rod 4: 5 cm cone with polarized tube or disk.

B. Results

Figure 17 shows the comparison between rods 1, 2 and 4 (5 cm cone with disk polarized at -3KV and situated at 3 cm from the top). Owing to the disk, the rod 2 gets transformed
into a "more sharpened" element, practically equivalent to a 10 cm cone (rod 1).

Figure 17 shows the comparison between rods 1, 2 and 3 (10 cm cone with disk polarized at + 3 KV and situated at 3 cm from the top). Owing to the disk, the rod 1 gets transformed into a "more rounded off" element than the 5 cm cone (rod 2).

C. Conclusion

The measurements performed on the various rods are in good agreement with the results of calculations, simulations and tests in high-voltage laboratory.

VI. GENERAL CONCLUSION

Works described in this paper allowed us to find a consensus on the functioning of the simple lightning rods. We highlighted the difference of behavior and efficiency of these rods as a function of the electrical characteristics of ambient environment.

We also came up with a principle that gives the ability to modify the answer of rods to electrical thunderstorm conditions by the addition of a metallic polarized part near the tip. This principle, validated on one hand by calculation and simulation and on the other hand in high-voltage laboratory and in real conditions, consists in modifying in a virtual way the geometry of rods to adapt them to ambient conditions ("variable-geometry rods") and so to improve their efficiency.

REFERENCES