A MODERN PERSPECTIVE ON DIRECT STRIKE LIGHTNING PROTECTION

by

Dr. F. D'Alessandro, B.App.Sc., B.Ed., PhD, MIREE, GradIEAust

ERICO Lightning Technologies, Australia

This paper reviews some of the latest lightning protection research results and the research being carried out by ERICO. It also addresses some of the issues being widely discussed at present, such as conventional and non-conventional air terminals, high voltage laboratory testing of terminals and lightning protection design methods. It is intended to follow up the letter recently published by ERICO as well as looking toward the future in lightning protection design methodology and hardware.

1. ERICO's Position

ERICO's position as a supplier of lightning protection systems and solutions is bipartisan. It offers conventional or "passive" systems in accordance with international standards such as NFPA 780 and BS 6651, as well as non-conventional or "active" systems based on an enhanced air terminal and screened, insulated downconductor. These systems are marketed by ERICO as System 2000 and System 3000 respectively. ERICO's is totally dedicated to providing the best lightning protection solution for a given situation, whether this involves the use of conventional or non-conventional systems, or a hybrid design employing particular aspects of both systems.

However, ERICO recognises that current conventional protection systems and design methodology, as prescribed in various Codes of Practice, can be improved. It also recognises that sound scientific principles must be at the heart of any non-conventional system. This is why ERICO has invested, and is continuing to invest, in basic and applied lightning protection research, employing theoretical, computer modelling, laboratory and field investigation techniques.

2. Overview

Building and structure protection is an essential part of any overall lightning protection system. One of the key components of any system is the type of *air terminal* placed on the structure. The primary purpose of an air terminal is to capture the lightning stroke at a preferred point, so that the discharge current can directed into the downconductor for connection to the earth system. A protection system where lightning misses the air terminals is a waste of money. Two related and equally important aspects that must also be considered are the: (i) *protection area* afforded by each air terminals, and (ii) *location* of the air terminals on the structure. Both of these aspects must be taken into account in the *lightning protection design method* that is used.

The lightning protection methodology and technology used to achieve the above should be guided by two key requirements:

(A) An objective, fundamental, theoretical and scientific basis.

(B) Adequate experimental or field research, conducted in a systematic, objective manner.

The results of modern research into the physics of lightning and its attachment to a ground point, along with laboratory studies of long spark discharge and leader development are now available to provide the fundamental basis to meet requirement (A). Furthermore, requirement (B) is met by performing *valid* testing of the air terminals, whether they are passive or active.

Both of these requirements are now discussed further in the context of modern, contemporary research into the lightning protection problem.

3. Lightning Protection Design Methods

3.1 Introduction

A fundamental aspect is the lightning protection "design method" used to identify the most suitable location(s) for the air terminal(s), based on the area of protection afforded by each terminal. A number of methods have been proposed, some of which are in common use, such as Cone of Protection, Faraday Cage and Rolling Sphere.

The Cone of Protection method is a result of poorly applied and unquantifiable physics principles (Moore *et al* 1981). Indeed, on structures protected by Franklin rods using this design method, it is not unusual to find places where lightning has struck well within the hypothetical zone of protection (Sakurano *et al* 1995).

There is no guarantee that the metallic strips used in the Faraday Cage method will be struck by lightning in preference to some other nearby exposed point. The dielectric strength of construction materials is such that the lightning strike may flash over to the nearest element of the structural steel, with unpredictable consequences. Furthermore, protection of exposed items such as communication dishes is virtually impossible.

3.2 Rolling Sphere Method

The Rolling Sphere method is undoubtedly the most common one in Standards documents. It originated from the electric power transmission industry, i.e., lightning strike attachment to phase and shield wires of lines (Lee 1978) and is based on the Electrogeometric Model (EGM). The EGM relates striking distance to the prospective peak stroke current. To apply this technique, an imaginary sphere, typically 45 m (150 ft) in radius, is rolled over the structure. All surface contact points are deemed to require protection, whilst the unaffected volumes are deemed to be protected.

It is claimed that the main advantage of the Rolling Sphere method is the simplicity of its application. This may be the case for simple structures but for more complex ones it is almost impossible to apply by hand, requiring sophisticated 3D numerical modelling software. The fundamental technical problem with the method is that it assigns an equal leader initiation ability to all contact points on the structure. That is, for a given prospective peak stroke current or, alternatively, protection level, the striking distance is a constant value. This over-simplification results in over-design on flat horizontal and vertical surfaces and under-design when structural points with significant electric field intensification are outside the sphere radius in a so-called protected zone.

Furthermore, it can be shown that the standard 45 metre rolling sphere, which is derived from a peak return stroke current of 10 kA, is inappropriate for flat surfaces. Using a nominal air breakdown value of 3 MV/m for plane geometries, breakdown will be initiated by a 3000 m long downward leader when it carries a charge of approximately 12 C. This charge corresponds to a peak return stroke current in the range 60-170 kA, depending on which charge-current relation is used. Conversely, it can be shown that 45 m / 10 kA is too high for points that have a very high leader initiation or strike probability.

Hence, a more physically-based method, able to differentiate between points on a structure having high and low leader initiation probability, is necessary for some of the more complex, modern-day lightning protection designs. In this way, more reliable and efficient lightning protection systems can be designed.

3.3 Recent models

Two studies that have certainly progressed toward the realisation of a design method with a sound physical basis are the Leader Progression Model (Dellera & Garbagnati 1990, Bernardi et al 1996) and the Leader Inception Theory (Rizk 1989a,b, 1990, 1994a,b).

Both of these models were included in a recent report of the CIGRE committee on lightning interception (CIGRE 1997). This committee was given the task of reporting to the IEC TC81 on better methods of lightning protection design. So far, neither of these methods have been included in the new IEC draft standard on lightning protection.

3.4 Collection Volume Method

To facilitate inclusion in Codes of Practice, a new design method must be technically sound (and this means that it may be complex) *but relatively simple to implement*. In this respect, the improved EGM first proposed by Eriksson (1979, 1980, 1987), and sometimes called the Collection Volume Method (CVM), is a strong candidate. Following is a short description of the method.

The CVM takes a more physical approach than the basic EGM by using the well-known fact that the striking distance, d_s, is dependent on both the peak stroke current (or downleader charge) **and** the degree of electric field enhancement, hereafter termed the "field intensification factor", K_i, of the prospective strike point. For structures, the K_i is determined to a large extent by the height and width, but the shape and radius of curvature of the structure or structural features are also important. In the case of air terminals, the K_i depends on the height and tip radius of curvature as has been demonstrated in numerous papers by Moore (e.g., Moore 1981, Rison *et al* 1998, Moore *et al* 1999). When air terminals are placed on buildings, the K_i's are multiplied up by a factor which depends on the structure dimensions.

Hence, an improved approach to lightning protection design is to assume all points on a structure are able to launch an intercepting upward leader, but to differentiate those points based on the local field intensification factor. The field intensification factor is computed relatively easily using numerical techniques such as the finite element method (e.g., see D'Alessandro & Gumley 1998).

The CVM originated with the work of Eriksson (1979, 1980, 1987) and has since been successfully developed and improved, with application to any 3D structure installed with air terminals. The method considers the approach of the lightning downward leader to a structure and, using the K_i of the air terminals and structural features, determines the point at which an upward leader will be launched. The criteria for leader inception will be described in Section 4.1.

The CVM goes beyond the above fundamental improvement of the basic EGM by stipulating that interception will occur only if an adjacent competing feature does not "win the race" to interception with the downward leader. This criterion introduces a "time" variable is which is taken into account by the *ratio of downward and upward leader velocity*, K_v. From field observations of natural lightning, this ratio is typically of the order of unity (Yokoyama *et al* 1990, Miyake 1994). In a recent paper, Chalmers *et al* (1999) also used a velocity ratio (rather than an absolute upward leader velocity).

The above analysis results in the definition of a parabolic-like volume above a feature (structure, structural features or air terminals) which represents the capture volume of that feature. Hence, the commonly used term, "collection volume". Figure 1 is an example of the output from such an analysis.

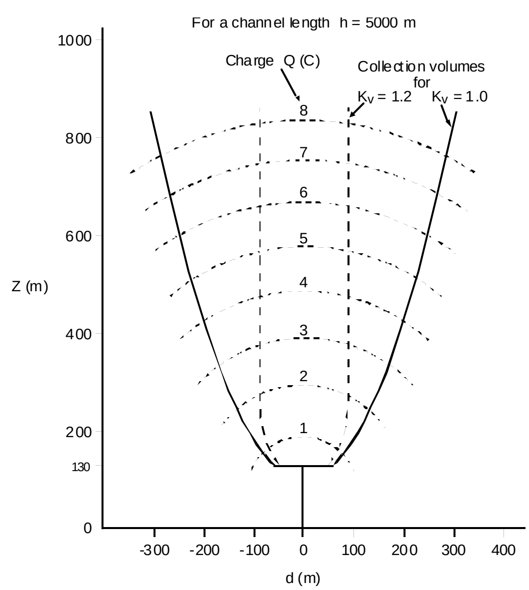

Figure 1: The Collection Volume of a slender structure 130 m high for different downward leader charges and velocity ratios.

In terms of the model, for a particular leader charge and velocity ratio, a downward leader will only terminate on the structure or air terminal if the striking distance is attained **and** the leader path is contained within the outer boundaries of the collection volume. This information is often summarised in the form of an "attractive radius", R_a, which is simply the radius of the collection volume at the height specified by the striking distance surface. The attractive radius is perhaps the most important output parameter of a collection volume analysis as it can then be used to compute the "attractive", "capture" or "protective" area of a given structure, structural feature or air terminal.

Eriksson (1987) validated the CVM by performing a series of iterative calculations over a broad range of structure heights (10 - 200 metres) and lightning parameters. It was then possible to derive a generalised relationship between attractive radius, structure height and peak current for a given velocity ratio. For $K_v = 1$, he found that

$$R_a = 0.84\, I_p^{\,0.74}\, H^{\,0.6}$$

Note that K_i does not appear directly in this particular equation since $K_i \propto H^b$ for slender structures.

3.5 Three dimensionalisation of the CVM

Eriksson's basic model has been successfully extended to the protection of extended 3D structures. An illustration of a lightning protection design using the CVM is shown in Figure 2. Strike 1 is assumed to have a larger leader charge (2 C). Upon entering the 2 C striking distance surface, it initiates an upward intercepting leader from point A before critical conditions occur on other parts of the structure. In strike 2, the leader charge is less (1 C) and it approaches closer to the structure. Point A is bypassed because the downward leader is outside its collection volume, even though it may initiate an upward leader. Hence, point B is the most likely strike point.

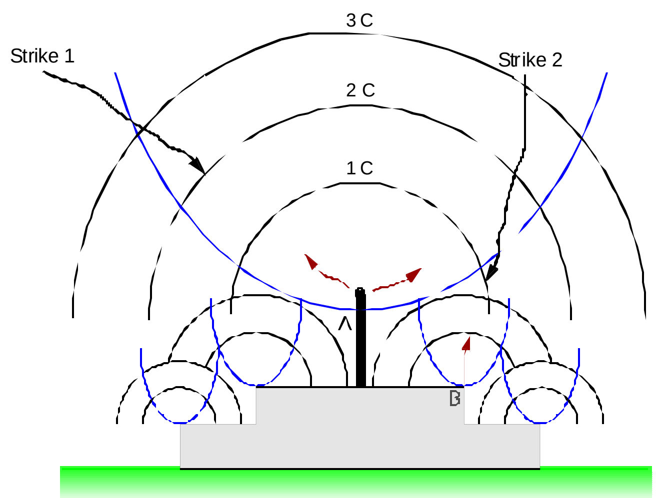

Figure 2: Illustration of lightning protection level design using the CVM.

The two key points regarding the three-dimensionalisation of Eriksson's original model can be summarised as follows:

- *3D Electric Field Modelling*: Modern desktop computers, along with modelling software that utilises the finite element or charge simulation methods, or a combination of both (Abdel-Salam 1990, Beasley 1979, Schmidt et al 1996, Singer et al 1974, Steinbigler 1979), have made it possible to compute with relative ease the electric field distribution over and around a structure and its microgeometry. This can be done in either 2D XY plane, 2D RZ plane, or full 3D, depending on the particular geometry that is to be modelled. Hence, field intensification factors can be computed for all prospective competing features, for input to the CVM design.

- *Competing features*: A collection volume is computed for each structural feature, including air terminals, masts, antennae etc. There are two ways in which competing features can be compared, namely by computing the collection volume (i) relative to adjacent flat ground, as per Eriksson (1979); or (ii) relative to all other competing features, including the adjacent ground. Method (i) is more simple from a computational point of view. Method (ii) is more calculation-intensive and results in non-symmetrical volumes. Method (i) is equivalent to method (ii) provided a conservative approach is used. "Worst case" collection volumes are compared for overlap to determine whether any parts of the structure are not protected (hence requiring additional air terminations). An example of a collection volume design for a three dimensional structure is shown in Figure 3.

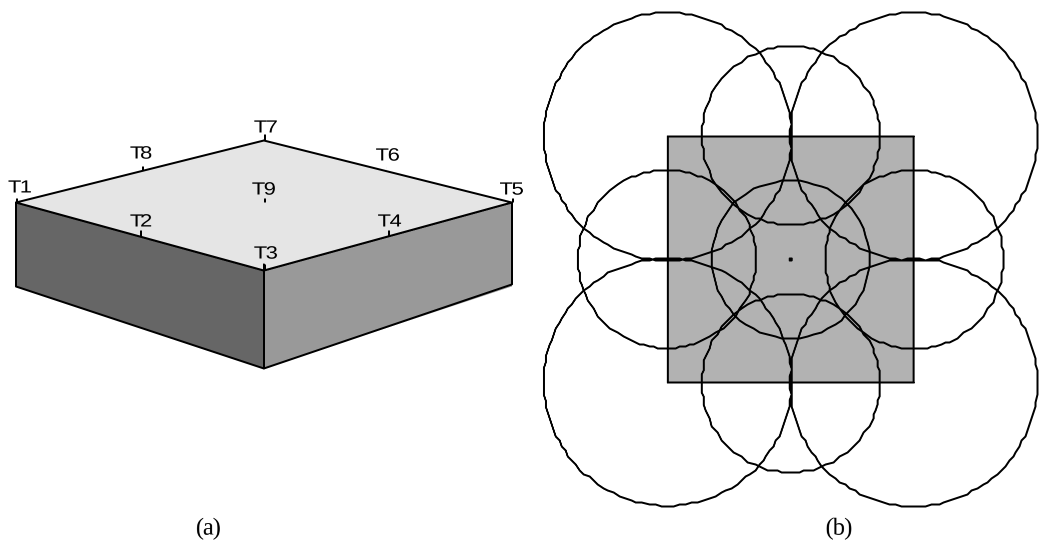

Figure 3: Example of the Collection Volume design method. Protection of a building 20 m high and 50 m wide and deep, using conventional finials 1 m high, 15 mm in diameter and with a tip radius of curvature of 1 mm.
(a) 3D view. (b) Plan view.

Since the application of the CVM to 3D structures more than a decade ago, more than 7000 structures worldwide have been successfully protected through the use of CVM designs. In an unprecedented study, ERICO has gathered lightning strike data from several hundred real field installations in Hong Kong in order to assess the performance of the CVM under real lightning conditions. A preliminary statistical analysis has so far been carried out (D'Alessandro 1998, 1999), and a more in-depth analysis is in progress. The results show that reliable and efficient lightning protection solutions can be provided by using the CVM.

The CVM is best implemented as a computer program, although manual calculation (for simple designs at least) is also possible. The advantages of using computer software relate to flexibility. For example, the site altitude, cloud base height, leader charge (protection level), structure height and shape, field intensification factors, leader velocity ratio are stored or easily computed within the program and are readily available when an optimised lightning protection design is requested by a customer (at a specified level). As new research results come to hand, the models, equations etc. used in the program can be easily updated.

Finally, it is important to note that the Collection Volume design method can be used for any air termination system designed to *capture* lightning, whether it is "conventional" or "non-conventional". Designs involving the former terminals are the most simple. If the latter air terminals are used, any claimed enhancement of their capture ability is above and beyond the passive Collection Volume Method of design described in this paper. The CVM provides a more rigorous and scientific basis to the placement of air terminals. In essence, it is an improved version of the basic Electrogeometric / Rolling Sphere method.

4. Air Terminals

4.1 Modern research

Two fundamental concepts have emerged from the recent research effort that are directly applicable to air terminals, namely:

1. Air terminals that produce copious amounts of corona are likely to be far less efficient in the interception of a lightning downward leader. The resulting space charge layer can greatly inhibit the development of a responding upward leader from the air terminal. The reader is referred to the papers by Boutlendj et al (1991), Moore (1983), Rison et al (1998), Moore et al (1999), and Allen et al (1998) for more details. Furthermore, the variable effects of wind on the space charge layer tends to make corona-producing air terminals unreliable at best and, as a consequence, inefficient. A corollary of this is that "dissipation air terminals", which are supposed to prevent lightning striking them, are also unreliable.

2. An efficient air terminal is one which launches an upward streamer under the optimum conditions. Whilst the criteria for the optimum conditions are relatively complex, two key pieces of information have come out of theoretical analyses and laboratory experiments on the physics of long sparks that simplify the conclusions:

    - The electric field required to initiate and sustain stable upward leader propagation is in the range 300 - 500 kV/m for a positive leader and ~ 1 MV/m for negative leaders (e.g., see Petrov *et al* 1994, Petrov & Waters 1995, Berger 1995, Rizk 1994, Bondiou & Gallimberti 1994, Les Renardieres Group 1972-1986, and references therein).
    - Streamers must have a minimum length of 0.7 - 1 m before they can be converted into a stable leader discharge (Petrov & Waters 1995, Chernov *et al*, 1991, and references therein).

The implication of these results is that an air terminal with the ability to launch a streamer "early" is not necessarily the most efficient. Rather, it is important to launch a streamer at a time when it can convert into a stable, propagating leader. This can only occur when the field strength in the first metre above the air terminal tip is larger than the threshold values mentioned above. This can be understood from basic physics principles – energy density in an electric field is proportional to the square of the electric field strength. Streamers and leaders derive the required propagation energy from the electric field, so if the field strength is too low, the streamer or leader will cease to propagate and simply dissipate into a space charge.

Hence, air terminal geometry **is** important. This conclusion has been confirmed by long term field research (Moore et al 1999). Consider Figure 4, which compares the space charge-free electric field decay in the first metre above a blunt and sharp lightning rod. The electric field above the blunt lightning rod remains at a higher level than the field above the sharp rod. Hence, the leader inception criterion for a blunt rod will be met in lower ambient electric fields. On the other hand, sharp rods produce corona in much lower ambient fields and hence will suffer the debilitating effects of space charge.

Figure 5 compares the space charge-free electric field decay in the first metre above a lightning rod with a scenario in which a space charge volume of average density 0.25 $\mu C m^{-3}$ exists above the point. Even in the presence of strong winds, in which case the space charge layer may be blown away and hence make space charge a non-issue, the more rapid electric field decay above the sharp point is a major disadvantage with respect to lightning capture.

Of course, the lightning protection problem is more complicated than this simplified description. For example, there exists an optimum height to radius ratio for air terminals that is a function of several variables, such as structure height and dimensions, and the location of the air terminal on the structure. These particular issues will be addressed in a forthcoming paper.

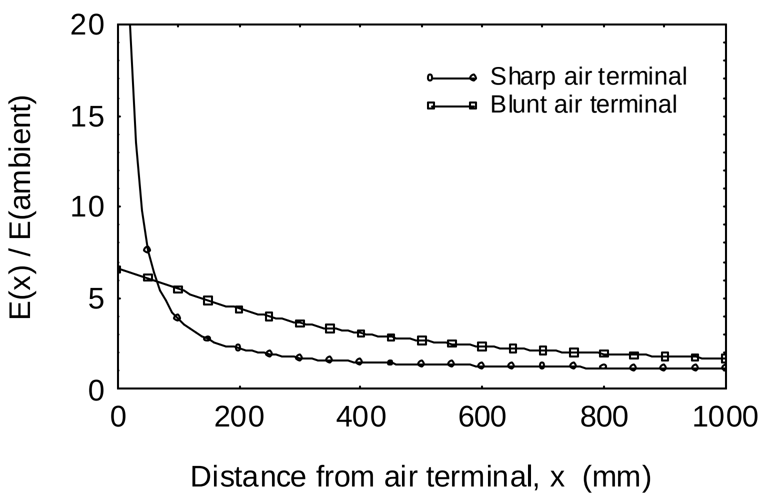

Figure 4: Comparison of the space charge free electric field decay for air terminals.

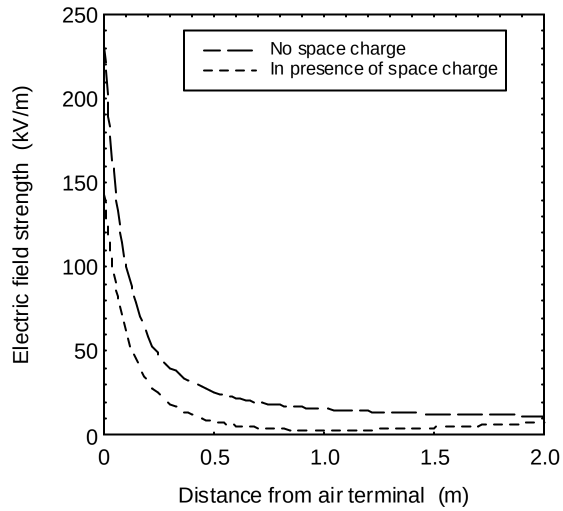

Figure 5: Field distribution above a lightning rod with and without the influence of a space charge volume of average density 0.25 μCm^{-3}.

4.2 Laboratory Testing

Considerable insight has been gained about the physical nature of lightning from laboratory-scale studies of electrical breakdown and spark formation in "long" air gaps, with typical gap spacings of 2 to 15 m (Les Renardières 1972, 1974, 1977, 1981). However, laboratory testing has a number of disadvantages that make the interpretation of any results very difficult.

Firstly, there is a large difference in the scale size of the problem. Even the largest laboratory air gaps are more than two orders of magnitude smaller than the height of a thundercloud above the ground. This complicates the extrapolation from laboratory to nature (see Suzuki *et al* 1981).

Secondly, there is presently no provision to simulate the significant statistical variability exhibited by natural lightning in such parameters as current, striking distance, angle of approach etc. Hence, there is no single acceptable test configuration that can be used to completely characterise the performance of all lightning protection devices.

Thirdly, variations in atmospheric parameters such as air pressure, humidity, and wind can only be simulated in the laboratory by using sophisticated test apparatus.

Despite the present limitations, laboratory tests conducted with high speed electrical and optical techniques do offer a means of gaining information in a relatively short period of time on the physical mechanisms, operation and performance of some lightning protection devices.

Importantly, one aberration that can create erroneous results is the simulation of lightning electric fields in a high voltage laboratory using a Marx-style generator. This generator can produce RC-type waveforms with various rise and decay times. The output waveform is measured across a shunt capacitor which is series connected via a resistor to a stepped voltage increase. This type of generator is excellent for simulating the impulse current from a lightning discharge *after* the cloud-ground connection is complete, but it is not able to simulate the electric fields observed by ground points *during the approach phase* of a lightning discharge. In this case, the descending electric charge on a downward leader creates a rapidly escalating waveform. Figure 5 illustrates the difference between the two waveforms.

With the known dependence of air breakdown parameters on waveshape, it may therefore not be valid to test air terminals with RC-type wavefronts. For a laboratory leader propagating over a distance of metres, such wavefronts present an ever decreasing rate of voltage rise, contrary to the natural wavefront which is rapidly increasing. Furthermore, the Marx wavefront does not present the air terminal with the initial slowly rising fields that are evident in natural events.

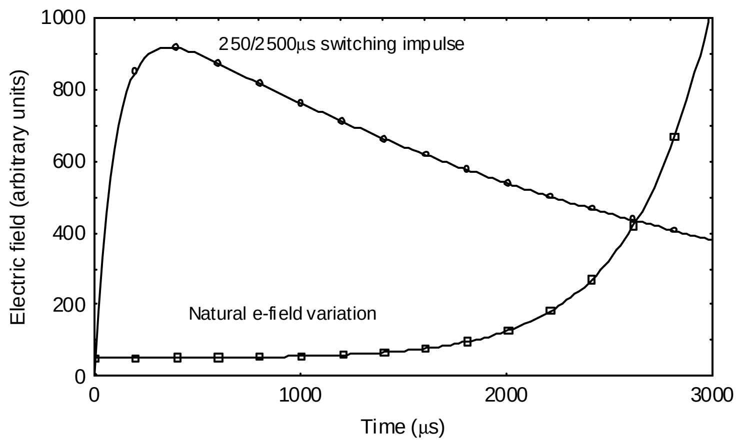

Figure 5: Comparison of a typical waveform obtained from a Marx-style generator with that observed in nature (e.g., Beasley et al 1982) from a progressing lightning downleader.

Herein lies an important principle - if the correct (natural) waveshape can be produced, then the major limitation of laboratory testing is removed. A prototype impulse generator with this capability is now available (Gumley *et al*, 1998). This high voltage arbitrary waveform generator (HVAWG) has a number of features which can revolutionise wavefront generation for testing air terminals, as well as other devices such as insulators, and for tests such as EMC and strike probabilities to transmission lines.

The HVAWG is capable of producing any monotonically increasing voltage waveform, e.g., RC-type, natural escalating, or linearly rising, up to a peak voltage of ~ 150 kV, with rise times exceeding 1 kV/m/µs. The present prototype comprises a series stack of ten modules, each capable of producing PWM step voltages of 15-20 kV. Delays inserted between the PWM signals to these modules enable a smooth waveform to be created. This “interleaving” principle is shown in Figure 6. A schematic of the generator is shown in Figure 7.

Once a set of desired waveshapes is created, the computer control basis of the generator allows switching from one shape to another in a matter of seconds, as well as the recall of a desired waveshape at a later date to repeat a series of tests.

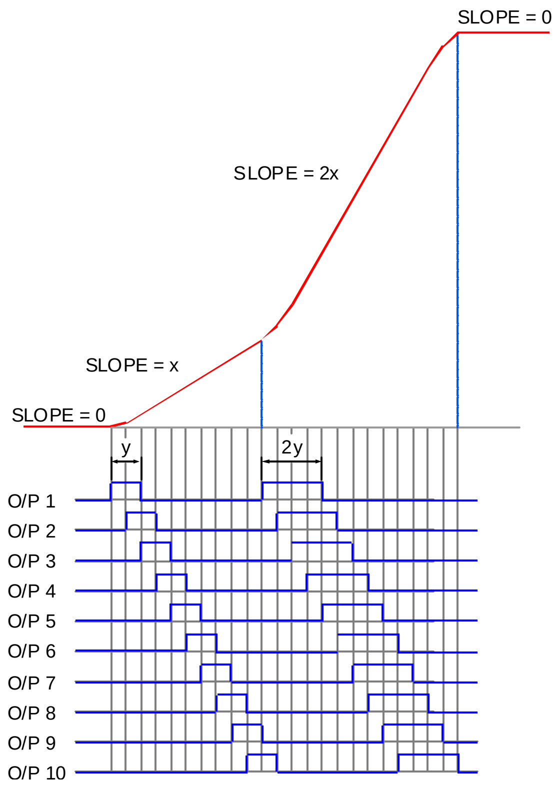

Figure 6: Simplified example of the "interleaving" principle of the HVAWG. The waveform slope is approximately proportional to the duty cycle.

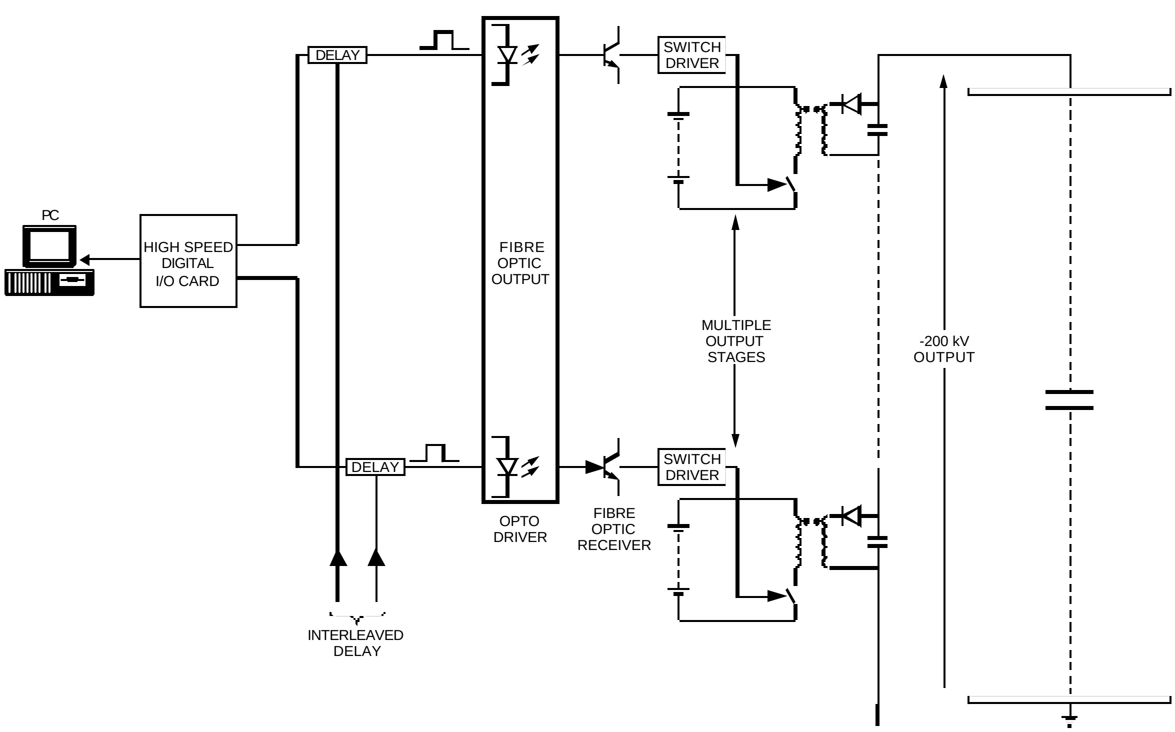

Figure 7: Schematic of the 150 kV prototype high voltage arbitrary waveform generator (HVAWG).

Some of the other characteristics of the prototype generator include: (i) superior speed of testing and recording (existing generators ~ 20 shots per hour, HVAWG > 100 shots per hour, limited only by space charge clearance time); (ii) the potential to generate multiple impulses with delays that match those of natural lightning (10 – 200 ms); (iii) generation of more complex wavefronts such as those due to a laterally descending, stepped downward leader or "angled" lightning, where the electric field waveform depends on the lateral distance between object and downleader - this is calculable and can be downloaded from the computer.

ERICO would welcome any individuals or organisations interested in a collaborative arrangement for the development of a full-scale version of this novel generator, e.g., capable of producing 1-2 MV.

5. The NFPA-781 debate

We now turn our attention to the NFPA-781 (ESE) debate. In light of some of the latest scientific research outlined above, a number of comments can be made.

Firstly, NFPA 781 is now out of date - Δt and ΔL debate aside, the lightning protection design method may be flawed. For example, the ΔL extension assumes the upward leader moves vertically upwards, and the protective area for structures appears to be based on a "cone of protection" concept. Also, the combined effect of the field enhancement afforded by the air terminal *and* the building does not appear to have been taken into account in the method. It is not valid to test at ground level and then assume the same behaviour on top of a structure.

Secondly, it is generally accepted that field testing is one of the most valid methods of assessing air terminal performance. What is often forgotten is that this method is very much a long term proposition, perhaps taking as long as 20-30 years to obtain indisputable "proof". And, as any research scientist knows, when taking measurements in the real world, there is no such thing as indisputable "proof" !! Perhaps a better approach is one in which air terminals already installed are instrumented and assessed under real conditions of protecting a structure against lightning. Rocket triggered lightning (RTL) is not suitable for reproducing the electric fields due to the first natural lightning attachment event - it is widely accepted that RTL only accurately reproduces subsequent strokes (Rubenstein *et al* 1995, Barker *et al* 1996). RTL is also a long-term proposition when compared to, for example, laboratory testing.

Thirdly, much has been said and written about laboratory testing of air terminals in recent times. ERICO believes that laboratory testing can be useful, *provided* suitable waveshapes are used. The waveshapes should closely replicate the waveforms obtained from field measurements of *primary* attachment events in natural lightning.

In light of all the information above and other correspondence on this issue, it appears that the most appropriate course of action is not to have a separate NFPA 781 standard for "ESE" terminals but rather to see a broadening of the scope of NFPA 780 to embrace newer terminal designs and better Electro-Geometric Models, backed by scientific research. In this way, the people who count most, namely the end users, can receive the safest and most cost-efficient lightning protection designs possible with the present knowledge base.

To demonstrate the need for the latter approach, consider the fact that sharp Franklin rods have been used for centuries. Even with the benefit of modern research, these terminals still have not been tested and verified as the optimum configuration in laboratory and field experiments. There is a multitude of photographic evidence showing buildings minus their corners that are supposedly protected by these sharp rods. Even though there is substantial evidence suggesting that they are not the optimum configuration, they are still recommended in NFPA 780. The excellent, long-term research conducted by Moore, Rison and others at New Mexico Tech provides ample evidence to back these statements. Their work shows that air terminal geometry and fundamental physical parameters such as field intensification factors play an important role in the reliable and efficient capture of lightning strokes.

The Rolling Sphere method is another example. It produces satisfactory results for simple geometric structures of relatively low height. However, the deficiencies of the method make it difficult to apply to more complex or taller structures and result in over-design. As a result, many users of today's Standards only comply with the *intent* of the Standard, since cost and aesthetic considerations take priority. The opportunity now exists for the inclusion of improved methods in NFPA 780 for designing reliable, safe and cost-efficient direct strike lightning protection systems.

6. Conclusions

This paper has focussed on the implications of the latest lightning research results for designing efficient protection systems. In particular, it has been shown that the Collection Volume Method is a significant improvement of the basic Electrogeometric Model / Rolling Sphere Method because it is based on physical principles for determining leader initiation and strike probabilities for all potential strike points. It also considers the dependence of the effective capture volume on the relative progress velocity of the propagating leaders. Finally, the method is generic enough to allow the physical parameters and criteria to be easily updated as new research results come to hand.

ERICO takes a bipartisan, solution-driven approach to lightning protection. The aim is to provide the best solution for a given application. By "best" we mean the most reliable, efficient and safest system. Some applications are best protected with conventional systems, whilst other protection problems are best solved with enhanced air terminal designs. How does one protect sensitive microwave dishes and other antennae on high rise roof tops with conventional finials and flat copper tape ? Add to this factors such as aesthetic acceptability and, importantly, the preferences of customers, and it becomes immediately obvious that both types of air termination hardware as well as modern design methods are needed. ERICO also envisages that hybrid designs may offer the best lightning protection solution is some cases, such as the tall slender structures being constructed around the world today.

With respect to air terminals, the two basic generic concepts are commonly known as conventional and non-conventional. The former relates to systems of finials and conductive tapes. The latter seems to have acquired the "Early Streamer Emission" label. This nomenclature is often incorrectly applied, irrespective of the technology used.

We now know that the early streamer emission of many commercial air terminals may be too early and that any failed attempt to launch an upward leader will leave behind a space charge. Its presence prior to the approach of a downward leader can delay the establishment of a stable, propagating upward leader when close leader approach occurs. The optimum air terminal launches an upward streamer at a point in time when the ambient electric field strength is sufficient to convert the streamer into a leader and to sustain the propagation of the latter.

Finally, there is now sufficient evidence to suggest that optimisation of air terminals and valid assessment of air terminal performance in general, can only be performed in a high voltage laboratory if the ground observed electric fields due to an approaching downward leader are more accurately simulated than is presently possible with Marx-style generators.

7. References

Abdel-Salam, M., 1990, "Electric Fields", Chapter 2 in *High Voltage Engineering: Theory and Practice*, Dekker, 1990.

Allen, N.L. & Faircloth, D.C., 1998, "Some factors relating to the early streamer emission principle", ERA Technologies Conference on Lightning Protection, pp. 3.1.1-3.1.10.

Allen, N.L., Huang, C.F., Cornick, K.J. & Greaves, D.A., 1998, "Sparkover in the rod-plane gap under combined direct and impulse voltages", *IEE Proc. A*, **145**, pp. 207-214.

Barker, P.P., et al, 1996, "Induced voltage measurements on an experimental distribution line during nearby rocket triggered lightning flashes", *IEEE Trans.Pow. Del.*, **11**, 980-995.

Beasley, W.H., et al, 1982, "Electric fields preceding cloud-to-ground lightning flashes", *J. Geophys. Res.*, **87**, 4883-4902.

Berger, K., 1972, "Methoden and Resultate der Blitzforschung auf dem Monte San Salvator bei Lugano in den Jahren 1963-1971", *Bull. Schweiz. Elektrotech. Ver*., **63**, 1403-1422.

Berger, G., 1995, "Inception electric field of the lightning upward leader initiated from a Franklin rod in a laboratory", *11th Int. Conf. Gas Disch. Appl.*, pp. 234-237.

Bernardi, M., Dellera, L., Garbagnati, E. & Sartorio, G., 1996, "Leader progression model of lightning: Updating of the model on the basis of recent test results", *Proc. 23th ICLP*, Florence, pp. 399-407.

Bondiou, A. & Gallimberti, I., 1994, "Theoretical modelling of the development of the positive spark in long gaps", *J. Phys. D: Appl. Phys.*, **27**, 1252-1266.

Boutlendj, M., Allen, N.L., Lightfoot, H.A. & Neville, R.B., 1991, "Transitions in flashover characteristics of rod-plane gaps under direct voltages in humid air", *Proc. 7th Symp. on High Volt. Eng*., Dresden, paper 42.17.

Chalmers, I.D., Evans, J.C. & Siew, W.H., 1999, "Considerations for the assessment of early streamer emission lightning protection", *IEE Proc. - Sci., Meas. & Techn*., **146**, pp. 57-63.

Chernov, E.N., Lupeiko, A.V. & Petrov, N.I., 1991, "Investigation of spark discharge in long air gaps using Pockel's device", *Proc. 7th Symp. on High Volt. Eng*., Dresden, pp. 141-144.

D'Alessandro, F., 1998, "A statistical analysis of strike data from real installations which demonstrates effective protection of structures against lightning", *Australasian Universities Power Engineering Conference '98*, Hobart, Australia, pp. 632-637.

D'Alessandro, F., 1999, "A preliminary assessment of the long-term performance in the field of an enhanced air terminal and the lightning protection design method", *11th International Conference on Atmospheric Electricity*, Alabama, USA, submitted.

D'Alessandro, F. & Gumley, J.R., 1998, "Electric field modelling of structures under thunderstorm conditions", *24th International Conference on Lightning Protection*, Birmingham, U.K., pp. 457-462.

Dellera, L. & Garbagnati, E., 1990, "Lightning stroke simulation by means of the leader progression model. Part I. Description of the model and evaluation of exposure of free-standing structures", *IEEE Trans. on Power Delivery*, **5**, 2009-2022.

Eriksson, A.J., 1979, "The lightning ground flash - an engineering study", *PhD thesis*, University of Natal, Pretoria, South Africa (CSIR Special Report ELEK 189).

Eriksson, A.J., 1980, "Lightning striking dstances - an analytical study", *Proceedings of the 6th International Conference on Gas Discharges and their Applications*, Edinburgh, pp. 143-146.

Eriksson, A.J., 1987, "The incidence of lightning strikes to power lines", *IEEE Trans. Pow. Del.*, **PWRD-2**, 859-870.

CIGRE Task Force 33.01.03, 1997, "Lightning exposure of structures and interception efficiency of air terminals", Report 118.

Gumley, J.R., D'Alessandro, F. & Kossmann, C.J., 1998, "Development of a high voltage arbitrary waveform generator capable of simulating the natural electric fields arising from stepped downleaders", *Proceedings of the 24th International Conference on Lightning Protection*, Birmingham, U.K., pp. 888-892.

Lee, R.H., 1978, "Protection zone for buildings against lightning strokes using transmission line practice", *IEEE Trans. on Indust. Appl.*, **IA-14**, 465-470.

Les Renardières Group: 1972, Electra, **23**, 53-157.
1974, Electra, **35**, 49-56.
1977, Electra, **53**, 3-153.
1981, Electra, **74**, 67-216.
1986, IEE Proc. A, **133**.

Moore, C.B., Brook, M. & Krider, E.P., 1981, "A Study of Lightning Protection Systems", Office of Naval Research, Arlington, VA, AD-A158258.

Moore, C.B., 1983, "Improved configurations of lightning rods and air terminals", J. Frank. Inst., 315, pp. 61-85.

Moore, C.B., Rison, W., Mathis, J. & Aulich, G., 1999, "Lightning rod improvement studies", *J. Appl. Met*., in press.

Miyake, K., 1994, "Development of measuring system on lightning discharge and explication for characteristics of winter lightning", CRIEPI Report No. T36, Japan.

Petrov, N.I. & Waters, R.T., 1995, "Determination of the striking distance of lightning to earthed structures", *Proc. R. Soc. Lond. A*, **450**, 589-601.

Petrov, N.I., Avanskii, V.R. & Bombenkova, N.V., 1994, "Measurements of the electric field in the streamer zone and in the sheath of the channel of a leader discharge", *Tech. Phys*., **39**, pp. 546-551.

Rison, W., Moore, C.B., Mathis, J. & Auchlin, G.D., 1998, "Comparative tests of sharp and blunt lightning rods", *Proc. 24th ICLP*, pp. 436-441.

Rizk, F.A.M., 1989a, "A model for switching impulse leader inception and breakdown of long air-gaps", *IEEE Trans. on Power Delivery,* **4**, 596-606.

Rizk, F.A.M., 1989b, "Switching impulse strength of air insulation: Leader inception criterion", *IEEE Trans. on Power Delivery,* **4**, 2187-2195.

Rizk, F.A.M., 1990, "Modeling of transmission line exposure to direct lightning strokes", *IEEE Trans. on Power Delivery,* **4**, 1983-1990.

Rizk, F.A.M., 1994a, "Modeling of lightning incidence to tall structures. Part I: Theory", *IEEE Trans. on Power Delivery,* **9**, 162-171.

Rizk, F.A.M., 1994b, "Modeling of lightning incidence to tall structures. Part II: Application", *IEEE Trans. on Power Delivery,* **9**, 172-193.

Rubenstein, M., et al, 1995, "Characterization of vertical electric fields 500 m and 30 m from triggered lightning", *J. Geophys. Res*., **100**, D5, 8863-8872.

Sakurano, H., Katsuragi, Y. & Nakamura, K., 1995, "Discussions on striking distance and lightning protection failure to a radome structure in winter thunderstorm", *9th International Symposium on High Voltage Engineering*, Graz, pp. 6766-1 – 6766-4.

Schmidt, S., Zech, G. & Otto, W., 1996, "Fast and precise computation of electrostatic fields with a charge simulation method using modern programming techniques", *IEEE Trans. on Magnetics*, **32**, 1457-1460.

Singer, H., Steinbigler, H. & Weiss, P., 1974, "A charge simulation method for the calculation of high voltage fields", *IEEE Trans. Pow. App. Sys.*, **PAS-95**, 1660-1668.

Steinbigler, H., 1979, "Combined application of finite element method and charge simulation method for the computation of electric fields", *3rd International Symposium on High Voltage Engineering*, Milan, Italy, paper 11.11.

Suzuki, T., Miyake, K. & Kishizima, I., 1981, "Study on experimental simulation of lightning strokes", *IEEE Trans. PAS*, 4, 1703-1711.

Yokoyama, S., Miyake, K. & Suzuki, T., 1990, "Winter lightning on the Japan sea coast - development of measuring system on progressing feature of lightning discharge", *IEEE Trans. Pow. Deliv*., **5**, 1418-1425.