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Lightning research in Colombia: Lightning parameters, protection systems, risk assessment and warning systems

La investigación del rayo en Colombia: Parámetros del rayo, sistemas de protección, evaluación de riesgos y sistemas de alerta

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Abstract

This paper summarizes the most important studies on lightning phenomenon in Colombia during the last 25 years. In order to give an in-depth treatment to specific aspects and advances in lightning research, this review has been divided in four sections: lightning parameters, lightning protection systems, risk assessment and warning systems. At the end of the paper, the advances and challenges on lightning research in Colombia are presented.

Keywords: electromagnetic fields, lightning discharge, lightning protection systems, measurement parameters.

Resumen

Este artículo sintetiza los estudios más importantes sobre la investigación del rayo en Colombia durante los últimos 25 años. Para dar un tratamiento detallado a aspectos específicos y avances relacionados con la investigación del rayo, esta revisión ha sido dividida en cuatro secciones: estudio de los parámetros del rayo, sistemas de protección, evaluación de riesgos y sistemas de alerta. El artículo finaliza con avances y retos futuros que presenta la investigación de rayos en Colombia.

Palabras clave: campos electromagnéticos, parámetros eléctricos, protección contra rayos, rayos.

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INTRODUCTION

The large lightning activity in tropical regions has been studied during the last decades. Colombia has particular geographical conditions because it is located in the intertropical convergence zone and has three mountain chains, presenting areas with a large lightning activity up to 35 strokes per square kilometer and large zones varying between 1 and 12 strokes per square kilometer [1]. These conditions make the country an exceptional place for lightning research.

Several studies about lightning have been performed in Colombia, including the following topics: measurement and modeling of lightning discharges, surges, lightning parameters and lightning protection systems [2]–[5]. Around 140 papers, 5 books and 6 standards published in Colombia and other countries have been identified. After a selection of the most relevant documents, 83 of them were taken into consideration in this paper. The parameters used for the selection of these references were the contribution level to the lightning research in Colombia and the knowledge provided to understand both the lightning process and the interaction between lightning and electrical, electronic and communication systems. In order to facilitate understanding of the reader, this review has been divided in four sections: lightning parameters, lightning protection systems, risk assessment and warning systems.

LIGHTNING PARAMETERS

In the year 2000, CIGRE ratified the lightning parameters of interest for engineering applications, which are classified in three groups: parameters of incidence (ground flash density, keraunic level, polarity, multiplicity, interstroke time interval and flash duration [6]), lightning return-stroke peak current and stroke current impulse shape. In order to measure, calculate and analyze some of the parameters of incidence, several studies have been performed in Colombia during the last 25 years.

Ground Flash Density (GFD) and Keraunic level (TD)

Torres *et al.* [7] describe the research project initiated in 1987 by the National Group on Lightning Research to measure and characterize lightning in Colombia. In 1990, the first lightning current detector MC-l00, a lightning counter RSA-10 and a TSS-420 sensor were acquired and implemented by the group.

Torres *et al.* [7], [8] proposed a methodology to correlate the keraunic level with rainfall measurements by using time series. Additionally, they proposed a division of the atmospheric electrical activity in Colombia in three zones, depending on displacement and latitude of the Intertropical Convergence Zone: North, Central and South.

In [9], it was established that in Colombia there are zones with high atmospheric electrical activity. Additionally, the authors indicate that lightning parameters differ from those reported by the international scientific community [10]-[12]. In [13]-[17], it is proposed and described a methodology using fuzzy set theory to analyze lighting data. Cardona *et al.* [18] [46]applied this methodology to the lightning data collected between 1995 and 2004 by the Colombian Lightning Location System (LLS). These authors establish that the performance characteristic of the LLS has an influence on the lightning parameters, which can be corrected using the Fuzzy Ground Flash Density (FGFD).

In other investigations [9], [12], [19], [20] it is indicated that, with some exceptions, GFD and TD obtained for the Colombian geographical conditions have a linear behavior. Latitudinal variations of lightning characteristics are also analyzed [12], [19]. The authors establish in [18] that there is a linear behavior between TD and GFD if calculated in annual periods. However, this is not the case on a monthly basis and therefore some lightning parameters have a temporal variation [21].

In [12], new equations to correlate GFD and TD are proposed for Colombia, discriminating between mountains and coastal zones and including a variation of GFD as a function of latitude. Using these equations, the authors calculated a maximum deviation of 41 % compared with 1568 % obtained with the CIGRE equations developed by de la Rosa *et al.* [6].

Aranguren *et al.* [22] report that ten VLF/LF magnetic field antennas were installed on several places of Colombia, between 0 and 2800 MSL. Based on the lightning data recorded from January 2012 to December 2013, GFD and other parameters were studied. According to this information, very high

GFD values (until 60 flashes/km^2 year) were observed in the Catatumbo region located between Colombia and Venezuela [23]. On the other hand, analyzing the data recorded in some American tropical regions [24], it was observed that the highest lightning activity zones in South America are located between latitudes of 8° and 10° north, it means between Colombia and Venezuela, which fits with what has been reported by NASA.

In order to estimate the TD in Colombia, in [24] the authors assumed that a TD is a day when at least one CG or IC flash is detected, which is not the standard definition of TD. However, this data was used to study the changes in the relation between TD and GFD for the different terrain conditions in Colombia. TD values are between 90 and 160 and fit with previous values calculated from historic data of 30 years.

Polarity and multiplicity

In Colombia, several works have been developed with the aim to identify and analyze some lightning parameters. Results show that polarity and multiplicity of lightning flashes change according to geographic location. With respect to polarity, the most relevant results are presented in table 1.

Table 1. Polarity of flashes recorded in different zones of Colombia

Location	Date	Positive flashes	Negative flashes
Colombia [12]	1997-2001	33 %	67 %
Bogotá [12]	1997-2001	10 %	90 %
Bogotá [25]	2004-2006	1.5 %	98.5 %
Medellin [18]	1995-2000	6 %	92 %
Medellin [18]	2001-2004	28 %	72 %

In the table above, from 69 lightning electric field signals recorded in the city of Bogotá by Santamaria *et al.* [25], 68 are negative flashes and only one is positive. This parameter is also analyzed in [12], finding 90 % of negative flashes and a 10 % of positive ones in Bogota. For Colombia, the distribution of negative and positive flashes is 67 % and 33 %, respectively.

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In [18], an increment in the number of positive flashes registered during the nine years of the study is described for the city of Medellin and surroundings. In the first period of the study, the percentage of positive flashes is 6 %, while in the last period this value reaches 28 %. For the complete study, 20 % of flashes are positive and the remaining negative.

Time parameters

With respect to time features of lightning flashes, the parameters showed in table 2 were analyzed obtaining the following results [12], [25], [26]:

Table 2. Time parameters of flashes recorded in Colombia

Parameter	Occurrence	Average duration
Occurrence of subsequent strokes [12]	Before 20 ms (2.1 %) Before 120 ms (62.5 %) Before 300 ms (90 %)	N/A
Time between the first stroke and the first subsequent stroke [25]	N/A	32 ms
Time between subsequent strokes [25]	N/A	26 ms
Flash duration [25]	N/A	105 ms

The interstroke time interval was analyzed in [12] with data recorded between 1997 and 2001. From this work, 2.1 % of subsequent strokes occurred before 20 m, 62.5 % before 120 ms and 90 % before 300 m. On the other hand, the average time between the first stroke and the first subsequent stroke, and the average time between subsequent strokes in Bogotá computed by Santamaria *et al.* were 32 m and 26 m, respectively [25]. These results are similar to the 32.4 m accepted by international standards [26]. Additionally, the authors in [25] reported an average flash duration of 105 m for 68 negative flashes recorded in 2004, lower than the 167 ms reported in IEC 62305-1.

Lightning current

Lightning peak current analysis depends on direct measurements and data derived from LLS. The former introduces low estimation errors, but there are a few number of registers while there are many indirect registers, but with a large uncertainty. The cumulative probability distribution function of lightning peak current is analyzed in [12]. The current peak value is estimated based on electromagnetic field measurements made by the Colombian Lightning Location Network (RECMA in Spanish). However, this method can introduce deviations in the calculation of this parameter [27], [28]. In [18], the cumulative frequency distribution function of lightning peak current measured in the city of Medellin shows deviations up to 92 % from the measured values.

The relationship between GFD and peak current is presented in [12] and [29]. It is observed that zones with high lightning flash densities usually have low current magnitudes and vice versa. Younes *et al.* obtained differences between their proposed equations for lightning currents as a function of GFD of 25 % and 28 % for positive and negative lightning peak current polarities, respectively [12].

Based on direct measurements, [24] reports that the average probabilistic lightning peak current value adopted by CIGRE [6] and IEC [26] is 30 kA, whereas the average probability value based on direct and indirect measurements in Brazil, Colombia and Rhodesia is about 42 kA [30].

LIGHTNING PROTECTION SYSTEMS

The knowledge of gas discharge physics and lightning parameters in some regions of Colombia has allowed the development of extensive research to improve the performance of Surge Protection Devices (SPDs). Additionally, the aim of some of these works is to increase the immunity of equipment and systems (electrical, electronic, communications, etc.) against lightning direct impacts, and reduce transient overvoltages and lightning induced overvoltages. In this paper, lightning protection systems have been divided in five categories: protective devices, grounding systems, transmission and distribution lines, transformers and protection of buildings and structures.

Protective devices

Some papers describe different alternatives to design and analyze the behavior of protective devices against lightning overvoltages and the selection criteria of Lightning Protection Systems components (LPS) [31]-[33]. Avendaño *et al.* [31] described a methodology to design high-energy SPDs required for the protection of low voltage electric systems highly exposed

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to lightning direct impacts by using a combination of metal oxide surge arrestors. In [32], [33] engineering principles, recommendations and practical approaches to select components, design, install and preserve the LPS were presented. These papers describe a theoretical-experimental study of thermodynamic, mechanic, electrochemical and electric behavior of the materials and components of the external LPS.

On the other hand, Pineda *et al.* [5] presents experimental studies using granular materials for the development of low voltage protecting devices used in electrical networks. These studies demonstrated that hygroscopic materials could be a good alternative to improve the protection systems for rural networks [5]. Additionally, Avendaño *et al.* [34], [35] propose additional alternatives to select SPDs for low voltage AC electrical facilities highly exposed to direct lightning impacts based on ATP/EMTP simulations.

The dissipated energy and the response of low voltage protective devices in the presence of current impulses and induced voltages generated by subsequent strokes were analyzed in [36]-[38]. Pérez *et al.* [39] presented a feasible technical and economical solution to optimize the location of surge arresters on distribution networks by implementing a genetic algorithm technique.

Grounding systems

The main cause of transmission line failures is lightning, being the direct strike to shielding wires one of the most frequent origin of lightning overvoltages. Among other factors, the parameter with the biggest influence in the direct lightning strikes overvoltages is the Grounding System (GS) [40]-[42]. For this reason, some Colombian electric companies have centered their attention in the study of grounding systems in power systems and distribution networks [41]-[43].

In Rondon *et al.* [42] and Montaña *et al.* [43] an evaluation of the most suitable way to analyze transient phenomena in transmission lines using ATP/EMTP and applying two models of a transmission tower for the lightning-surge analysis was presented. In these papers, different GS models, e.g. linear resistance model, nonlinear resistance model and reduced circuit model, were implemented.

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On the other hand, Moreno *et al.* [41] presented an electromagnetic model to evaluate the transient behavior of the grounding system and its effect in the calculation of lightning overvoltages. Based on this model, a computational tool (GTIERRAS) developed to determine the grounding system impedance for random configurations and their behavior against lightning impulses, overvoltages and other typical transients associated with electromagnetic compatibility problems is described in [44].

Practical recommendations for designing grounding systems as part of an integral protection system against lightning strikes are presented in [45]. In addition, the influence of grounding systems in the failure rate of transmission lines due to lightning is analyzed in [40]. Finally, last year, the inductive voltages and other effects produced by lightning when an impulse current of 100 kA (10/350) strikes a grounded mast are computed using a computational program based on finite techniques [46].

Transmission and distribution lines

Besides the studies related to grounding systems and the design and characterization of protection devices against lightning, several studies about the lightning performance of transmission lines and distribution networks have been developed [47], [48].

Younes *et al.* [48] presented a comparative study of two methodologies to evaluate the lightning performance of transmission lines in tropical zones, while Martinez *et al.* [49] described an ATP/EMTP application to analyze the behavior of a transmission line if surge arresters are included in different parts of the system. A procedure to compute the lightning performance of distribution lines using two methodologies for computing GFD, the traditional and a new concept using fuzzy strategies, is presented by Soto *et al.* [47].

A study case to evaluate the effect of nearby lightning strokes on an overhead distribution line in Medellin is presented in [50]. Results show the influence of lightning peak current, distance from lightning strike point and front time, in the induced distribution network overvoltages.

Cuarán *et al.* [51] uses the Self-consistent Leader Inception and Propagation Model (SLIM) to analyze the lightning attachment to EHV and UHV transmis-

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sion lines in Japan. The authors noted that the phase conductors are slightly more vulnerable to be struck by lightning during the positive voltage semi-cycle and the transmission line is placed over mountainous terrain.

Transformers

In Colombia, the high ratio of rural distribution transformer failures due to lightning is a critical matter in several regions [52]. For this reason, extensive research has been conducted to reduce this problem. However, many of these works have been developed within research projects supported by Colombian electrical companies whose results are not public domain. Because of this, few experiences have been published.

Research conducted in the period between 1992 and 2001 show a relationship between transformer failures and their geographical location. Failure rates tend to decrease towards the south of the country and towards the high mountain areas. Regions located between 1000 and 2500 MSL are the most affected zones by distribution transformer failures, being them especially critical in areas close to 1500 MSL, which are related with the formation of thunderstorm clouds in tropical countries [5].

In recent years, the effects of lightning on distribution transformers have been analyzed by Aranguren *et. al.* [53], taking into account the relationship between weather conditions and the high lightning activity. From this work, it can be observed that average failure rates are closer to the adverse weather conditions related with thunderstorm days. Data comparison shows that about 27 % of the power transformers are located in high and very high lightning activity regions, and their failure rates increase respectively to an average of 13 and 45 times higher with respect to the normal weather conditions [53].

In Colombia, the reduction of distribution transformer failures has been addressed in several ways [5], [54]: the development of new protection devices and optimal protection schemes, proper design and construction of an optimal distribution transformer for tropical zones, optimization of distribution transformers to make them more robust against high short-circuit currents and the adequate characterization of the lightning parameters. In addition, for the optimal protection of distribution transformers, some

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works have been development to improve the insulation coordination of the power networks and the optimal selection of protection devices without modifying the Basic Impulse Level (BIL) of the transformers [5], [52].

Protection of buildings and structures

With respect to lightning protection schemes applied to structures, Torres *et al.* [55], [56] and Montaña *et al.* [57] describe a methodology for LPS in petroleum facilities and petroleum exploration sites in high lightning activity zones in Colombia. Measurements obtained by Colombian and international researchers are employed in these designs [56]-[58].

Other studies in Colombia related to protection of structures against lightning are presented in [59]-[64]. Some of these studies deal with the analysis and application of the electromagnetic compatibility standards for lightning protection of electric and electronic devices [59], external protection of buildings [60] and the analysis of transient voltages and current distribution in structures, due to lightning direct strikes [62]. In addition, recent years special attention has been paid to evaluating the striking distances and lightning attachment in common structures [63] and complex structures [61], [64]. These studies propose an alternative method to estimate the lightning striking distance and to compare its results provided by empirical application of the rolling sphere method and the collection volume method.

RISK ASSESSMENT AND WARNING SYSTEMS

Risk assessment in Colombia involves some research works and methodologies focused in the analysis of risk levels [65]-[70] and the development of warning alarm systems [71]-[74]. Lightning generates high currents and overvoltages that can produce dangerous voltages (step and touch voltages), affecting the isolation of equipment or cause fires in presence of flammable materials [66]. These events can be generated under specific conditions and depend on the lightning impact and the type of electromagnetic coupling [26].

Torres *et al.* [65] and Gallego *et al.* [66] used fuzzy logic to compute the quantity of harmful events that can occur. They also proposed a computational tool capable of combining numeric and linguistic variables in order to estimate if a risk level is acceptable. Avendaño *et al.* [67], [68] present a procedure including the use of a software for lightning failure risk as-

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sessment in low voltage systems. This piece of software determines the system vulnerability and specifies the design parameters for the lightning protection system. Besides, a correlation between the keraunic level in the city of Bogotá and damages of electric and electronic equipment produced by strikes are presented in [69], [70].

In recent years, warning systems based on electric mills have been developed in Colombia. These systems are located in different places and their measurements have been used as a methodological way to propose warning criteria to reduce human risk and prevent damages in devices and systems. Thus, a methodology evaluated in several regions of Colombia for tracking thunderstorm cells is presented in [71]. Afterwards, Lopez *et al.* [72] uses a LLS and complement its information using measurements provided by electric field mills in order to improve warning systems in mountainous regions. In this work, experimental data were taken from regions with latitude between 1500 and 2200 MSL and compared them using four selection criteria to demonstrate the improvement of thunderstorm alarms efficiency. Results show that the proposed method provides better results that those obtained from the traditional method (two area method).

The operational analysis of an electric field mill system, performing a set of measurements during 2010, is presented in [73]. In this case, the behavior of the electric field changes was analyzed in order to obtain a relationship with respect to the distance pattern. Results show that this methodology can be used in other geographic conditions.

Based on the performed studies and the IEC 62305 standard series, Colombia has developed a national standard, including the lightning parameters adopted for a tropical zone [1]. These parameters (TD and GFD) were included by Sarmiento *et al.* [75] in a piece of software developed to determine the risk assessment for structures and people according to the IEC 62305-2 [76]. A comparison between the national standard NTC 4552 and IEC 62305 to analyze the risk in urban buildings and structures smaller than 20 meters is presented in [77]. In addition, to determine the most appropriate standard to be applied in Colombia, a comparison of the results obtained from the application of NTC 4552 and IEC 62305 using a building as case study is presented in [78]. Finally, through measurements obtained by lightning detection systems based on LINET sensors, five facilities were evaluated based

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on IEC 62305-2 standard, showing a diminution of the risk with respect to other methodologies that do not use a thunderstorm warning system [74].

To establish the importance of lightning prevention programs, several works about lightning accidents based on media information and from the Colombian Institute of Legal Medicine have been reported [79]-[82]. Cruz *et al*. [79] presents an analysis about the accidents occurred at the Colombian National Army as a vulnerable group, establishing an events classification for the period from 2003 to 2012 and obtaining a relationship between rainy seasons, keraunic level and ground flash densities.

In the same way, reliable statistics about lightning deaths and injuries in Colombia are presented in [80]. In this work, data collected from 2000 to 2009 are classified using different categories such as location of the event, date, age and gender. The analysis of data shows that the death rate for all Colombian territory was about 1.78/million/year. However, the highest mortality rate is located in the Vaupes Department with an average about 7.69/million/year [80]. These results promote the need to develop new lightning prevention programs, especially in rural areas.

As a topic in development, in [81] is reported the statistics of nonfatal lightning injuries, reporting through two examples (case studies) and simulation methods the reasons for avoiding mortal injuries and establishing a starting point for new lighting protection methods. Finally, Villamil *et al.* [82] presents a review of the main educational methodologies about lightning safety in Colombia for several population groups. This study illustrates the importance of the prevention methods, determining their requirements and public policies in order to minimize the accidents due to lightning.

DISCUSSION

Important contributions to the study of lightning parameters in Colombia have been done in the last 25 years. The results in terms of peak current, GFD and TD diverge significantly from the typical values adopted internationally by CIGRE [6] and IEC [26], among others. The average peak current value adopted by CIGRE [6] and IEC [26] is 30 kA, against the 42 kA reported for Colombia [24]. Based on the equations proposed for Colombia, a maximum deviation of 41 % in the GFD calculation was reported, compared with

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1568 % obtained with the classical CIGRE equations. Because of these efforts, the IEEE standard 1410 of 2010 suggests the use of different equations for tropical countries [83].

Despite the above, this study demonstrates the need for further direct and indirect measurements to determine the lightning parameters in Colombia with high confidence. The keraunic levels map was developed over 20 years ago and it is the basis of the standard for lightning protection. Then, it is expected that with the data recorded by LLS in recent years based on magnetic field sensors, this map will be updated in the coming years. However, the ability of the system to discriminate between IC and CG strokes must be verified.

CONCLUSIONS

Colombia has been an exceptional place for lightning research during the last 30 years due to its geographical location in the intertropical convergence zone, its mountain chains, and the high keraunic levels that can be registered.

Lightning parameters in Colombia show a special behavior in comparison with those recorded in other countries. More studies should be carried out in order to achieve a better understanding of the lightning phenomenon in countries with particular locations and characteristics.

Lightning research in Colombia has focused on understanding the phenomenon and analyzing its parameters to design efficient protection systems as a way to counteract the high lightning activity and its important consequences. However, it is necessary to carry out more studies in order to achieve the characterization of lightning in different regions of Colombia, especially in the more active zones and rural regions.

In the next years, lightning research in Colombia will focus on the prediction, detection and localization of lightning for reducing the risks and on improvement of protection schemes for electrical and industrial systems.

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