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The Electromagnetic Compatibility Research Group: research questions

Grupo de Investigación en Compatibilidad Electromagnética: preguntas de una investigación

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ABSTRACT

This paper summarises the Universidad Nacional de Colombia's Electrical and Electronic Engineering Department's Electromagnetic Compatibility Research Group (EMC-UNC) activities during the last 30 years. The group was involved in developing experimental tools during the early 1980s, such as constructing high-voltage apparatus, developing high-voltage practical work for students and observing electrical discharges. These tools enabled the group to spend a decade focused on resolving one of the Colombian electrical sector's main EMC problems: distribution transformer's failures caused by lightning. For almost a decade this investigation was focused on understanding the causes of the extremely high failure index in Colombian rural areas, especially in the Rionegro basin. The main result of this investigation was a reduction by one order of magnitude in mean 10% distribution transformer failure rate. During this research work a noticeable pattern was observed of several electrically-isolated metallic bodies immersed in an electric field (i.e. *floating electrodes*). This was led to initiating floating electrode studies and formulating a new scientific question, *"How do corona electrical discharges interact with floating electrodes?"* This new research question was dealt with during the second half of the 1990s and the first decade of the 2000s. This investigation was related to using electrostatically-accumulated charge on a floating electrode. This question opened up four research areas: gas discharge physics, generating fast current impulses, harvesting energy from the electric field and the possibility of high impedance current sources. This paper has summarised the most relevant work done by the EMC-UNC group on these topics. This floating electrode research work started by formulating four patents. Fresh research questions for the 2010s were related to measuring lightning electromagnetic pulses (LEMP), intentional electromagnetic interference (IEMI) studies, measuring picoseconds-rise-time impulses, cleaning water by corona discharge and harvesting, accumulating and using small amounts of energy extracted from electric and electromagnetic fields. The future of the EMC-UNC group is closely related to interaction with other groups.

Keywords: electromagnetic compatibility, high voltage technology, lightning, distribution transformer failures, LEMP, IEMI, floating electrode, impulse current generator, gas discharge physics, corona discharge, pulsed power, high power microwaves.

RESUMEN

Este artículo resume las actividades desarrolladas por el Grupo de Investigación en Compatibilidad Electromagnética —EMC— de la Universidad Nacional de Colombia, Departamento de Ingeniería Eléctrica y Electrónica, durante los últimos 30 años. A principios de los años ochenta, y durante un lustro, el grupo se concentró en el desarrollo de herramientas experimentales como la construcción de aparatos de alta tensión, prácticas docentes para estudiantes y observación de las descargas eléctricas. Con estas herramientas pudo enfocarse, durante una década, en la solución de uno de los mayores problemas de compatibilidad electromagnética del sector eléctrico colombiano: las fallas de los transformadores de distribución causadas por los rayos. Por cerca de diez años esta investigación se enfocó en entender las causas del extremadamente alto índice de fallas de transformadores de distribución en las zonas rurales colombianas, especialmente en la vertiente del río Negro. El principal resultado de esta investigación fue la reducción, en un orden de magnitud en la tasa promedio de falla de los transformadores de distribución, del 10%. En este trabajo se observó un comportamiento notable de diversos objetos metálicos eléctricamente aislados e inmersos en un campo eléctrico, los llamados electrodos flotantes. Ese fue el inicio de los estudios de electrodos flotantes y la formulación de una pregunta científica: *¿cómo interactúan las descargas eléctricas con los electrodos flotantes?* Ésta nueva pregunta se enfrentó en el segundo lustro de los años noventa y la primera década del 2000. El estudio estaba relacionado con el uso de la carga acumulada en un electrodo flotante, y la pregunta abrió cuatro áreas de investigación: física de la descarga en gases, generación de impulsos rápidos, recolección de la energía presente en el campo eléctrico y posibilidades de las fuentes de alta impedancia. En el presente trabajo se resume lo más relevante hecho por el Grupo EMC-UN en dichos frentes. La investigación de los electrodos flotantes se inició con la formulación de cuatro patentes. Las nuevas preguntas para la década del 2010 están relacionadas con la medición de impulsos electromagnéticos producidos por los rayos (LEMP), estudios en interferencia intencional (IEMI), medición de impulsos de corriente con tiempos de ascenso en el rango de los pico-segundos, limpieza de agua mediante la aplicación de ozono generado por descargas eléctricas; y recolección, almacenamiento y uso de las pequeñas cantidades de

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energía extraídas de los campos eléctricos y electromagnéticos. El futuro del Grupo de Compatibilidad Electromagnética está fuertemente relacionado con la interacción con otros grupos de investigación.

Palabras clave: compatibilidad electromagnética, tecnología de alta tensión, descargas Eléctricas atmosféricas, fallas de transformadores de distribución causadas por los rayos, LEMP, IEMI, electrodos flotantes, generadores de impulsos de corriente, física de la descarga en gases, descargas tipo corona, generación de ozono, potencia pulsante, microondas de alta potencia.

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Introduction

This paper describes the main areas of activity facing the electromagnetic compatibility (EMC) research group in Colombia during the last three decades. Additionally, the questions formulated in defining the research fields and present and future challenges are examined in this publication. The intention was also to raise awareness concerning the interaction between topics being investigated and the scientific products written about in more than 200 documents (including undergraduate and postgraduate research work).

The main activities performed during three decades of research may be described as follows. The group was involved in developing experimental tools for observing high-voltage phenomena during the first part of the 1980s. After this initial stage of observation, a decade was dedicated to applying the new tools so developed in understanding and solving a specific Colombian EMC-problem: *Distribution transformer failures caused by lightning*. The research question for solving this topic was, "*How can Colombian distribution transformers' extremely high failure-index be understood*?" This question was related to lightning activity in Colombia, the lightning protection standards being used and protection of devices (an EMC problem). A decade was spent on this investigation, focused on understanding the causes of the extremely high failures index in Colombian rural areas, especially in the Rionegro basin in Cundinamarca (Colombia's central area). This question was solved with experimental and theoretical work. The experimental work was directed towards measuring lightning electromagnetic pulses (LEMP) while the theoretical work was focused on obtaining numerical models of both protecting devices and LEMP interaction with transmission lines. Reducing distribution transformer´s failure rate to 1% was the main result of this investigation (Mejía *et al*., 1985). The results of this work were recognised by COLCIENCIAS as being one of the most successful research works having a practical application (Colciencias, 2006).

The group had been involved in floating electrode studies and their application in several original devices during the third research decade (the first decade of the 2000s). This work was mainly focused on developing different devices based on floating electrodes' properties, such as impulse current generators, electric field measuring devices and high impedance current sources. Additionally, a method was proposed for extracting energy from the electric field. This research work has produced four patents (Román, 2004, 1999c, 1999b, 1999a, 2001c). Finally, ozone generation based on corona discharges and radiating electromagnetic pulses generated by the impulse current generators so constructed were the main research focus during the last part of this decade.

New research questions for the 2010s are related to measurement and protection against LEMP, EMC intentional electromagnetic interference (IEMI) studies, understanding and reconstructing conducted and radiated impulse current in the picosecond range, harvesting and using small amounts of electric field energy and applying ozone in cleaning water using double dielectric layers.

Development tools for observing high-voltage phenomena

The research question which arose at the beginning of this investtigation was related to our own possibility of constructing HV-devices. The first activity performed by the EMC-UN group during the 1980s was directed towards resolving this question which was positively resolved by several pieces of graduate students' work. Different high voltage components and equipment, such as that mentioned in publications, were constructed as part of students' graduate thesis (Amórtegui *et al*., 1984; Melo *et al.*, 1984; Román *et al.,* 1985a, 1985b, 1988a, 1988b; Amórtegui and Cano, 1986; Díaz *et al.,* 1987; Luna *et al.,* 1987; Bohórquez and Zambrano, 1987; Godoy and Tique; 1987; Sánchez *et al.,* 1987; Román and Cuartas, 1988; Bulla *et al.,* 1988; Díaz and Pinzón, 1988; Cuartas, 1989; Becerra and García, 1989; Román, 1995b and 1989). Examples would be impulse voltage (Melo *et al.,* 1984; Román *et al.,* 1985b; Díaz *et al.*, 1987), current generators (Amórtegui *et al.*, 1984; Román *et al.,* 1985a), measuring devices (Díaz *et al.,* 1987; Luna *et al.,* 1987; Bohórquez and Zambrano, 1987; Godoy and Tique; 1987; Sánchez *et al.,* 1987; Román *et al.,* 1988a and 1988b; Cuartas, 1989; Becerra and García, 1989; Patiño *et al.,* 1989; Monsalve and Muñoz; 1989), lightning counters (Román and Cuartas, 1988; Cuartas, 1989), test cells for both polarities' corona discharge observations (Bulla *et al.*, 1988), HV-resistors (Díaz and Pinzón, 1988) and capacitors (Amórtegui and Cano, 1986). This effort was directed towards reinforcing the HV-test and practice abilities of students in the Electrical and Electronic Engineering Department. Studies performed since 1982 (Dams *et al.,* 1982; Román, 1982b, 1983, 1984, 1986, 1988a, 1995a; Abondano *et al.,* 1984; Román *et al.,* 1984, 1988c and 1988d; Solano and Suaza, 1986; Acosta *et al.*, 1986; Solano *et al.,* 1988; Torres *et al.,* 1987; Linares and Pava, 1987; Mosalve and Muñoz, 1989; Fajardo and Forero, 1990) were directed towards developing an HV-lab. Setting up an HV-teaching lab was proposed in a publication written in Spanish entitled, "Considerations about design, operation and security in an HV teaching lab" (Román, 1989). This work finished by developing an HV-lab for the Colombian Sector, supported by ISA and reviewed by CESI, Italy (INTERCONEXION ELECTRICA S.A., 1988).

It was also necessary to develop numerical tools to answer the aforementioned research question. The first attempts performed by the EMC-UN group at modelling electrical phenomena and electrical circuits and components were reported in student work and graduate theses (Román, 1982a, 1982c; Fajardo *et al.,* 1983; Castañeda *et al.,* 1984; Angarita, 1988; Monsalve and Muñoz, 1989). Finite difference and finite element computer programmes were used in these calculations. ATP programme applications in HV studies were investigated by the group in the following publications: Rincón *et al.* (1999), Arias and Bernal (1999), Muñoz and Velázquez (1999) and Román (1997c). A book entitled, "*Pro-*

*tection device modelling using ATP" (*Román, 1997c) was published in Spanish in 2008.

Observing electrical discharges was a first step in understanding gas discharge physics and lightning discharges. HV technology enables observing differences between positive, negative or AC gas discharges. Figure 1 shows some examples of photographical records of corona discharges performed in Fajardo and Forero (1990). Figure 1 shows a) a positive corona discharge, 1 b) a negative corona discharge and 1 c) an AC corona discharge. These examples of so-called corona discharges or external partial discharges were the first approach towards understanding the theory of floating electrodes and its industrial applications.

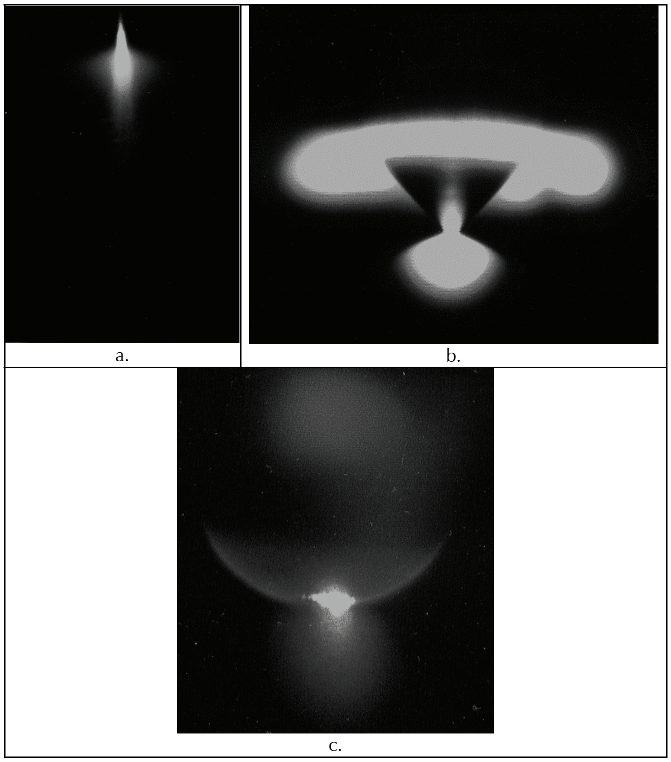

a.
b.
c.

Figure 1. Corona discharges: a) positive corona discharge in a conical electrode, 76.3 kV, exposure time: 20 sec., b) negative corona discharge in a conical electrode, 72 kV, exposure time: 1 min, c) AC corona discharge in a spherical cap electrode, 55 kV, exposure time: 1.5 min (Fajardo and Forero, 1990).

Another topic in which the EMC-UNC group was involved was related to contamination caused by low frequency electric and magnetic fields. Examples of this work are given in Jaimez *et al.* (1987), Román *et al*. (1987), Méndez and Román (1996), Rincón *et al.* (1999, 2001), Ramos *et al.* (2005) and Ramos (2006). The process for developing an electric field detector for human protection is mentioned in Ramos (2006) and Ramos *et al.* (2005). This device was constructed by the EMC-UNC group for the Cundinamarca Electricity Company (Empresa de Energía de Cundinamarca S.A. E.S.P).

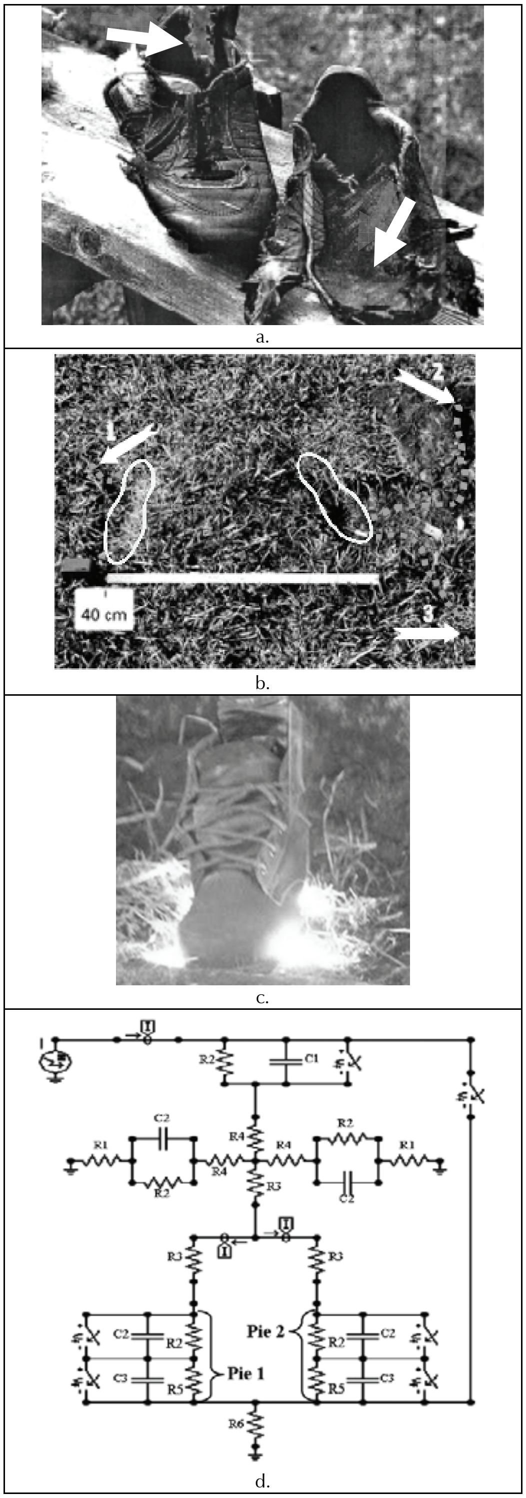
An interesting relationship between low frequency magnetic fields and electrocardiographic alterations in subjects exposed to these types of fields for several years in electricity substations was mentioned in Méndez *et al.* (1996). Additionally, accidents caused by lighting discharge was another topic of interest for the group, viewed from an EMC perspective of interaction between lightning currents and victims, as mentioned in Román and Lötberg (2000), Román *et al.* (2005), Santamaria *et al.* (2006c and 2008). Figure 2 shows the main results of an investigation for understanding the interaction between lightning discharge and victim. Figure 2 shows soccer shoes destroyed by direct lightning impact on the victim (a), while traces left by the lightning current in the ground and on the soccer shoes are shown (b). Numbers 1-3 in Figure 2 b) shows how the current path became split into several paths. The burned grass around the shoes was probably caused by impulsive corona discharges. Figure 2 c) is a still photograph taken during a lab experiment when a 16 kA lightning-like current was injected to a leader boot. Several sparks can be seen in this photograph, indicating that the applied current can follow several paths on its way to the ground. The human body model used in the numerical calculations to understand the lightning accident is presented in Figure 2 d). This EMC investigation into a lightning accident led to demonstrating that a lightning current striking a grounded body can split into several individual current paths. From an EMC point of view, this result can be understood as a resistive coupling between lightning current and victim, caused by the victim's shoes' grounding resistance. Explanations of this resistive coupling effect were given in papers (Sanchéz and Román, 2000; Díaz and Román (2005b), Santamaria *et al.,* 2005b, 2006a; Arévalo *et al*., 2006).

Distribution transformer failures

The number of distribution transformer failures in most countries was extremely low for almost three decades (from the 1960s to the 1990s) compared to the same figures for Colombia. The first distribution transformer failure statistics in Colombia were presented to the international community by Román (1990). Compared to the statistics presented by Mundim and Zubludowaki (1990), figures in Colombia were extremely high; the distribution transformer failure index was higher than 51% in certain areas of Colombia in 1990 (western area of Cundinamarca), 43% (Cundinamarca, Pacho), 16% (Santander, Barbosa). Such figures were lower than 0.8% in the USA, 1974 (REA,1961). This critical situation was initially studied by the EMC-UNC group in Torres *et al.* (1987), Román *et al.* (1988c), Román and Cuartas (1988), Patiño *et al.* (1989), Jiménez *et al.* (1992), Catañeda and Lemus (1991) and Casteñeda y Villamil (1992).

A research question was proposed for explaining the large number of distribution transformer failures. The hypothesis was called the *Inductive-loops theory* (Román, 1990, 1991a, 1991b, 1991c, 1991d; Fajardo and Forero, 1990). The large number of distribution failures could have been explained by the long distances left between lighting arresters and transformers. Due to an inductive effect, a large derivative lightning current could produce a large voltage drop in the cables connecting lightning arresters and transformers. Colombian distribution transformer installation regulations were based on foreign regulations: USA rural electrification administration (REA) regulations (1961). Figure 3 shows a typical example of applying the aforementioned REA standard. Figure 3 a) shows the large distance left between the lightning arrester (indicated by the arrows) and the distribution transformer. The loop formed by the long conductors between arrester and transformer was called an *inductive loop*. These magnetic loops were responsible for generating over-voltages on the transformer windings, higher than their basic insulation level (BIL). The solution to this problem was just to install the lightning arresters close to the transformer bushings, as indicated in Figure 3b).

The REA regulations (1961) mentioned that distribution transformers protected by lightning arresters should fail less than 0.51% of the time every year, depending on the number of thunderstorm days and thunderstorm intensity. This was not the case for Colombia, a country having more than 110 thunderstorm days per year in certain areas such as the Rionegro basin.



a.

b.

c.

d.

Figure 2. Explaining a lightning accident. a) Soccer shoes after a lightning accident. Arrows show the destruction caused to both shoes by the lightning current. b) Where the victim was standing. Arrows and numbers 1-3 show the holes left by the three current paths. c) A still photograph taken during a lab experiment when a 16 kA lightning-like current was injected into a leather boot. Notice several sparks indicating that the applied current can follow several paths in its way to ground. d) Human body model used in numerical calculations (Sánchez *et al.,* 2000; Díaz and Román, 2005b; Santamaría *et al.,* 2005, 2006, 2008; Arévalo *et al*. 2006).

EMC-UNC group's work aimed at resolving the distribution transformer problem was initially reported by Román (1993b) to the Bogotá Electricity Company[2]. Final conclusions were presented in COLCIENCIAS' final reports by Mejía and Román (2002a, 2002b).

It was necessary to measure lightning currents to test the inductive loop theory. Induced voltage V_L in the inductive loops can be calculated using equation (1):

$$V_L - L \times \frac{di}{dt} \qquad (1)$$

Where:

L is the inductance of the inductive loops. A typical value of L is 4 to 6 μH. di/dt is the lightning current derivative.

The lightning di/dt value should be taken from the known literature or determined by measurements in an experimental transmission line. This was the origin of three projects financed by COLCIENCIAS and the Universidad Nacional de Colombia (Mejia, Román and Román 1993, 2002a, 2002b). Lightning measuring devices had to be developed for this work: lightning flash counters (Román and Cuartas, 1988; Cuartas, 1989), lightning current amplitude detectors (Luna *et al*., 1987) and di/dt measuring devices (Roncery and Cortés, 1991). A CGR3 lightning flash counter developed by Mackerras and Darveniza (1986) was also used in this project.

The activities performed in the experimental line and the statistics for measuring lightning current were presented in papers (Román 1992a, 1992b, 1993; Román and Mejía, 1992; Castro and Bello, 1992; Gonzáles *et al.,* 1992; Páez and Román, 1997; Román *et al.,* 1998c). The main conclusions of this body of research work were summarised as follows:

1- Inductive loops theory could explain several modes of distribution transformer failures, such as short circuits in three windings;

2- As derived from inductive loops theory, the regulations for installing distribution transformers used in Colombia and inspired by REA regulations were not feasible for Colombia due to the large inductive loops;

3- The measurements performed in the experimental distribution line showed that induced over-voltages could operate distribution transformer arresters. Frequent and violent thunderstorm activity in Colombia could explain the reduced life of lightning arresters in this mainly rural region;

4- Due to its geographical location, Colombia could be classified as being a thunder-stormy country;

5- Several products emerged from this investigation. Some of them were related to studies on lightning arresters (Lizarazo and Vega, 1991; Páez and Román, 1997; Román *et al.,* 1998c, 2001c, 2003a, 2003b, 2003c, 2003d, 2007; Román 1998a, 2000a, 2001b; Ramírez *et al*., 1998, 1999; Muñoz *et al*., 1999; Arias *et al.,* 1999; Arias and Bernal, 1999; Arias and Román, 2001a, 2001b; Ortiz and Román, 2001, 2003a, 2003b; Alarcón *et al.,* 2001, 2002; Román and Arias, 2001; Acero and Muñoz, 2003, 2004; Becerra *et al.,* 2003a, 2003b, 2003c; Acero *et al.,* 2004,

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[2] Román, F. Letter to Mauricio Cardenas Santamaría, General Manager, EEEB, 31 August 1993, Reference: "Preliminary Results of the Direct Lightning Characterization in Colombia", Activity: "Experimental Line for Lightning Studies: Project LEER". Computer Programme "Failures". Signed by Francisco Román Campos, PI of the Project "Lightning Characterization in Colombia"

2006; Montaño *et al.,* 2004; Díaz and Román, 2005a, 2005b, 2006, 2007; Ortíz *et al*., 2006; Alarcón and Román, 2007; Ortíz, 2005c; Arévalo, 2005; Mejía and Román, 2002b). The book by Arias *et al*., (2008) summarises several results obtained during this period.

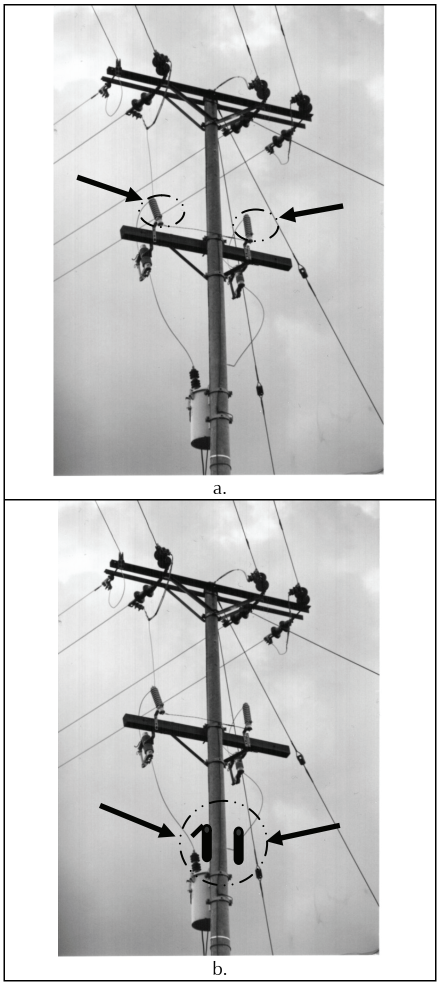


Figure 3. a) Example of a distribution transformer installed with inductive loops. Arrows show the lightning arresters. Notice the long distance between arresters and transformer. The area formed by the conductors is the so-called inductive loop. b) The cylinders shown by the arrows represent the correct location of the lightning arresters. Notice that inductive loops are strongly reduced with this new location.

Floating electrodes

A noticeable pattern was observed in several isolated metallic bodies during the campaign for resolving distribution transformer failures. A house having an isolated metal roof was struck by lightning, killing a small girl, several isolated metal pieces such as isolated lids from several distribution transformer tap changers were involved in lightning-related electrical discharges and a lightning accident involving an armed soldier left several unanswered questions about the interaction of floating electrodes and electrical discharges. The scientific questions formulated from this were: *"How is the interaction between corona electrical discharge and electrically-isolated metallic bodies immersed in an electric field?" "Could a metallic body attract an electrical discharge?"* These questions led to investigation into isolated metallic bodies or floating electrodes.

A floating electrode is an electrically-isolated metallic body immersed in an electric field. Figure 4 show examples of floating electrodes. The spherical electrode shown in Figures 4 a) and b) has its electric field concentration in the upper and lower side of the floating electrode. However, Figures 4 c) and d) show the electric field concentration when the spherical electrode has a protrusion. Electric field enhancement at the protrusion creates a corona current source in a region called primary gap region (see Figure 4 c). Corona ionic currents charge the spherical floating electrode, thereby increasing the electric field in the secondary gap region show in Figure 4 c). A discharge occurs when the electric field in the secondary gap region surpasses its breakdown electric field. This forms a floating electrode switch.

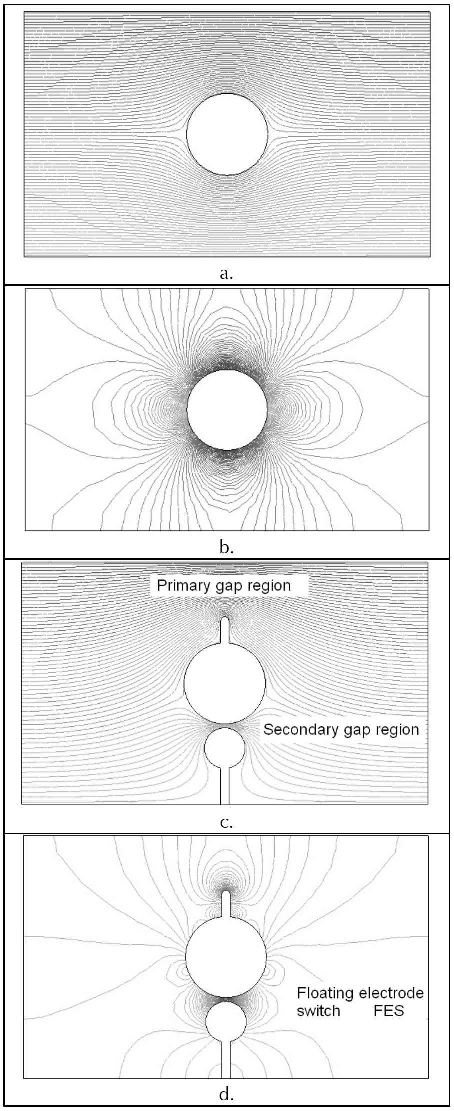


Figure 4. Examples of floating electrodes. a) Calculated potential distribution in spherical floating electrode, b) Calculated equielectric field lines in the spherical floating electrode. Note the electric field concentration in the upper and lower part of the spherical floating electrode. c) Equipotential field lines in a spherical floating electrode having a protrusion. Note the electric field enhancement at the protrusion which creates a corona current source. The corona source produces ionic currents which charge the spherical floating electrode and d) floating electrode with a protrusion close to a grounded sphere forming a floating electrode switch. Note the electric field enhancement in both the protrusion and secondary gap. A discharge occurs when the electric field surpasses the breakdown electric field in the floating electrode switch (Román *et al.*, 1994, 1995; Román, 2001a.

An electrostatically-accumulated charge on a floating electrode could have practical applications. This simple idea led to work in the following four research areas (Román, 1997c): *Gas discharge physics and corona discharges, generating fast current impulses, developing a high impedance current source and harvesting energy from an electric field*. This work resulted in developing four patented devices: An impulse current generator (Román, 1999b), an electric field measuring device (Román, 1999a; Román *et al.,* 1997a), a high impedance DC current source (Román, 2001c) and a method for extracting energy from an electric field (Román, 1999c). Intensive work was initiated during the second half the 1990s and the first decade of the 2000s to solve scientific questions related to floating electrodes. The characteristics of insulated metallic bodies in very intense electric fields were studied in Román *et al*. (1994, 1995, 1996a, 1996b, 1998b), Román and Scuka (1995), Valencia and Velázquez (1998), Román, (1995b) and Valencia (2009).

Gas discharge physics and corona discharges

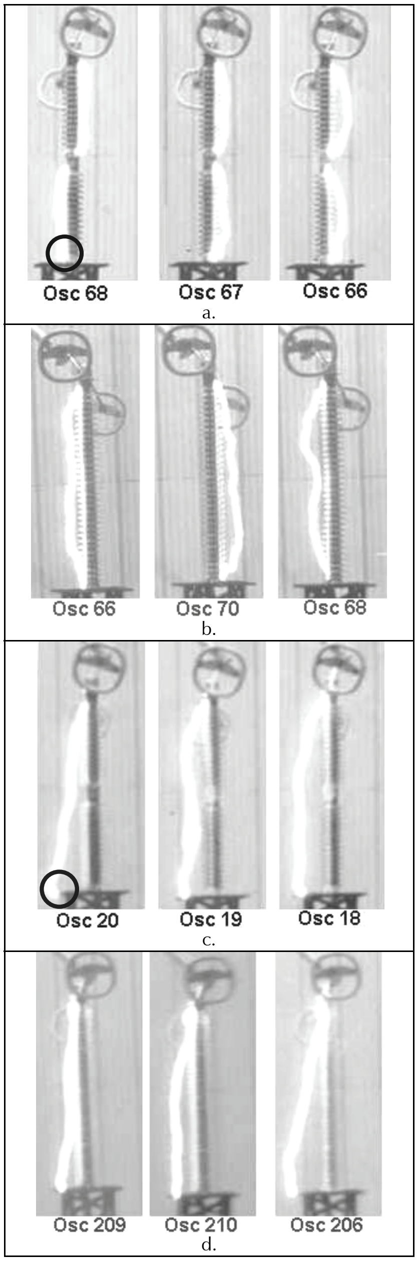
As mentioned above, gas discharge physics studies were initiated by simple observation of electrical phenomena (Solano and Suaza, 1986, 1988; Román *et al*., 1988d; Bulla *et al.,* 1988; Torres and Zamudio, 1989; Fajardo y Forero, 1990; Román, 2001a). Later on, gas discharge physics theory and numerical methods for its calculation was studied (Román, 1982a, 1982b, 1988a; Fajardo *et al.,* 1983; Castañeda *et al.,* 1984; Amortegui *et al.,* 1988; Castillo *et al.,* 1990; Monsalve and Muñoz, 1989; Verbal, 1989; Román and Castillo, 1990; Díaz, 1991; Román *et al.,* 1994, 1995, 1996a, 1998b, 1999a; Román and Scuka, 1995; Gomes *et al.,* 1999; Bogoya *et al.,* 1999a and 1999b; Arévalo *et al.,* 2003a).

This initial work on gas discharge physics led to formulating a possible way of calculating breakdown voltage in long gaps in the so-called single stress method (SSM) (Román *et al.,* 1997b, 1998a, 1999b, 2001a, 2001b; Román, 1995b, 1997c, 1998b, 2000b; Becerra *et al.,* 1998, 1999a, 1999b; Gomes *et al.,* 1999; Sánchez and Vargas, 1999; Sánchez *et al.,* 2000; Becerra and Román, 2002b). Figure 5 shows how this method can be applied to investigating the breakdown voltage of two glass insulating columns using SSM (Becerra and Román, 2002a).

In, Becerra and Román (2003b) demonstrated that this method was not feasible for obtaining 50% probability breakdown voltage.

A new numerical calculation was initiated by Becerra in different works (Becerra and Román, 2002a, 2003a; Moreno *et al.,* 2003). Corona numerical calculations were performed by Arévalo in Díaz and Arévalo (2002), Arévalo *et al.* (2003b, 2003c, 2004, 2005a, 2005b, 2005c, 2005d, 2005e, 2005f, 2006, 2008), Gomez *et al.* (2005), Díaz *et al.* (2007), Román and Arévalo (2007), Román *et al*. (2008b) and Arévalo (2005) following these studies. Some other efforts were directed towards obtaining canonical geometries' correction constants for breakdown voltage in the atmospheric conditions pertaining to Bogotá, Colombia (Bejarano and Romero, 2002; Romero *et al.,* 2003; Bejarano *et al.,* 2010; López and Gómez, 2003).

Corona experimental work was directed towards understanding the behaviour of corona sources in high voltage electric fields (Osorio and Rosero, 2003; Rojas *et al.,* 2005; Forero *et al.,* 2005; Mora *et al*., 2007; Alarcón *et al*., 2009; Alarcón, 2010). This work was directed towards capturing and accumulating the energy obtained from the electric field in batteries (Rojas, 2010).



a.

b.

c.

d.

Figure 5: Photographs of impulse voltage test on glass insulated columns with and without flanges. a) Positive lightning impulse voltage on a glass column with, and b) without flanges. c) Negative switching impulse voltage on a glass column with d) and without flanges (Becerra and Román, 2002a). Notice the effect of the flange in the discharge.

Additionally, spark channel resistance was initially investigated in the EMC-UNC group in (Rodríguez *et al.,* 1998; Rodríguez and Ospina, 1998). Later on, this work was directed towards model gas discharge switches (Díaz *et al.,* 2008; Santamaria, 2010).

Lightning protection structures

One of the topics of interest when investigating distribution transformer failure concerned how to characterise the electromagnetic environment in the Rionegro basin. The aforementioned papers, as well as those mentioned in Román (1988f, 1990, 1991b, 1991d, 1992a), Patarrollo *et al*. (1988), Torres *et al.* (1989), Román and Mejía (1992), Castro and Bello (1992), Gonzáles *et al*. (1992), Díaz (1992), Román and Arias (2001), Becerra *et al*. (2003a) and Mejía and Román (2002a), were orientated towards instrumentation of an experimental transmission line for studying lightning and understanding the interaction between lightning and distribution transformer failure. However, some other activities were performed for understanding the physics of lightning. A lightning measurement campaign was undertaken in 2005 (Santamaria *et al.,* 2005a); electric field devices were developed during this campaign (Santamaria *et al.,* 2006b). Later on, the measured waveforms were compared to lightning signatures in Sri Lanka (Santamaria *et al.,* 2006b) and Sweden (Santamaria, 2006).

Applications of this investigation orientated by Becerra (2007 and 2008) were performed in Miranda (2006), Becerra *et al.* (2006, 2008a and 2008b).

An example of a numerical calculation for a lightning channel using the software developed by Becerra (2008a, 2008b) is presented in Figure 6.

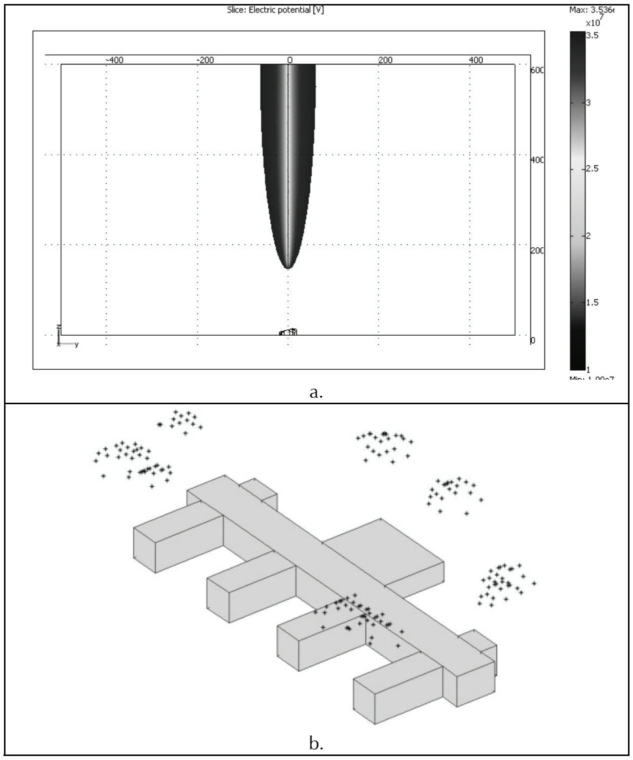


Figure 6. a) Numerical calculation of a lightning channel approaching the Engineering building at the Universidad Nacional de Colombia. Computer software published by Becerra (2007, 2008a, 2008b) and applied in Miranda (2006). b) Lightning striking distance for the same building by Miranda (2006).

New work in this field corresponds to noise reducing lightning electric field signals using wavelets (Santamaria *et al.,* 2009).

Impulse current generators

From the original ideas on current generators proposed in Román's patent (1999b) and in Román (1997c), new generators were developed as in Muñoz *et al.* (1999) and Muñoz and Velázquez (1999) to increase the amplitude of impulse current generators (Diaz and Román, 2005a, 2005b, 2006; Díaz, 2005). Figure 7 a) show the original 6 A, 3 ns rise in time current impulse generated by a floating electrode impulse current generator similar to that shown in Figure 4 d) (image taken from Román, 1997c). Figure 7 b) shows a 1,200 A, 5 ns rise time current impulse produced by the *Román generator* (RG) mentioned in Román *et al.* (2003b, 2003c) and Montaño *et al.* (2004). Figure 7 c) shows a 3,2 kA signal produced by the RG version constructed by Diaz and shown in Figure 7 d) (Díaz, 2005; Forero *et al.,* 2005; Díaz and Román, 2005b, 2006, 2007; Díaz *et al.,* 2008.

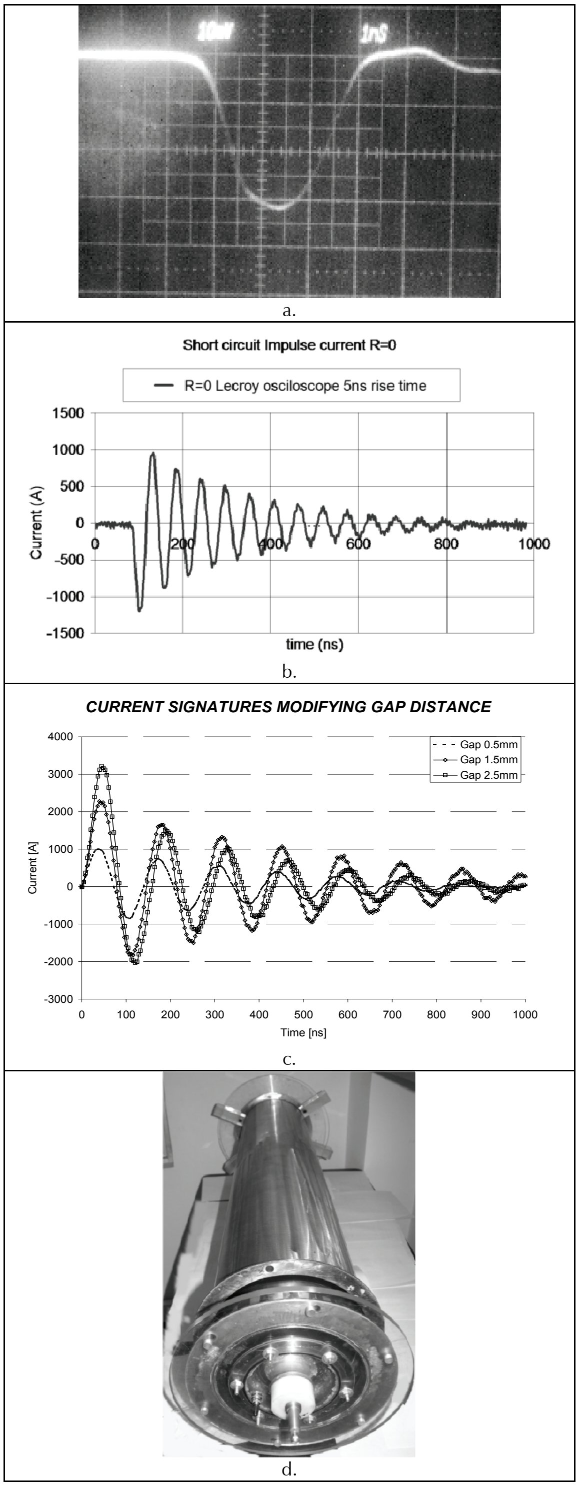
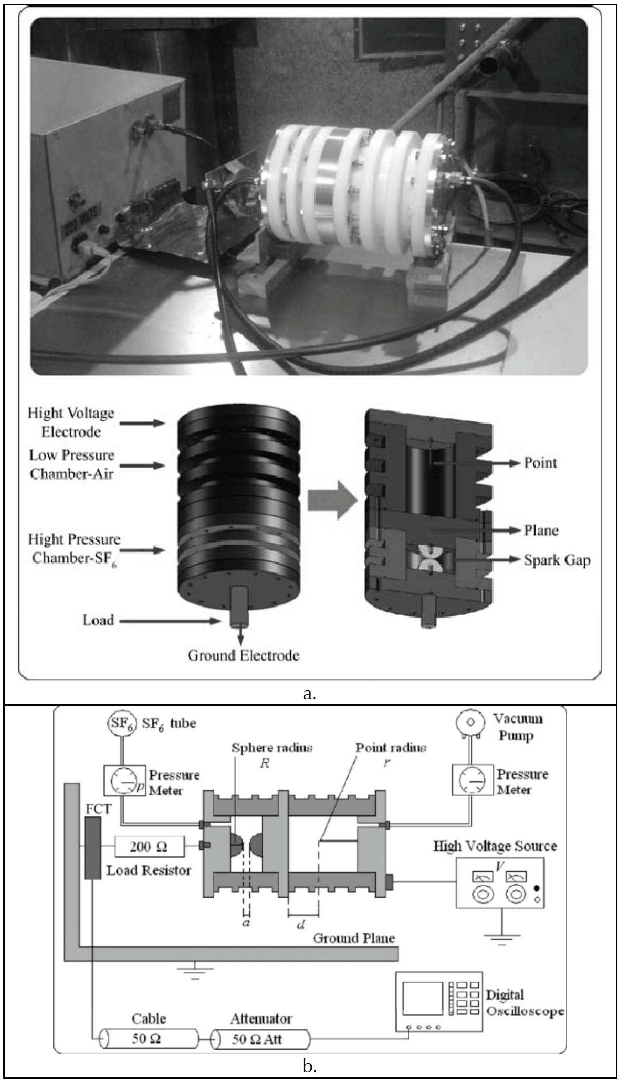


Figure 7. a) 6 A, 3 ns rise time current impulse generated by a floating electrode impulse current generator similar to that shown in Figure 4 d) Image taken from Román (1997c). b) 1,200 A, 5 ns rise time current impulse produced by the RG mentioned in Román *et al.* (2003b, 2003c) and Montaño *et al.,* 2004. c) 3.2 kA impulse current produced by the generator constructed by Diaz and shown in d) (Díaz, 2005; Forero *et al.,* 2005; Díaz and Román, 2005b, 2006, 2007; Díaz *et al.,* 2008).

Figures 8 a) and b) show the experiments performed by Vega (2010) and Mora (2009) on a gas insulated switch to obtain an electrical model of the RG (Mora *et al.,* 2008; Vega *et al.,* 2009b). Vega *et al.* (2009b) and Mora (2009) predicted the RG impulse repetition frequency in their thesis work by developing an electromagnetic model of the corona source (called a corona tube by the latter).

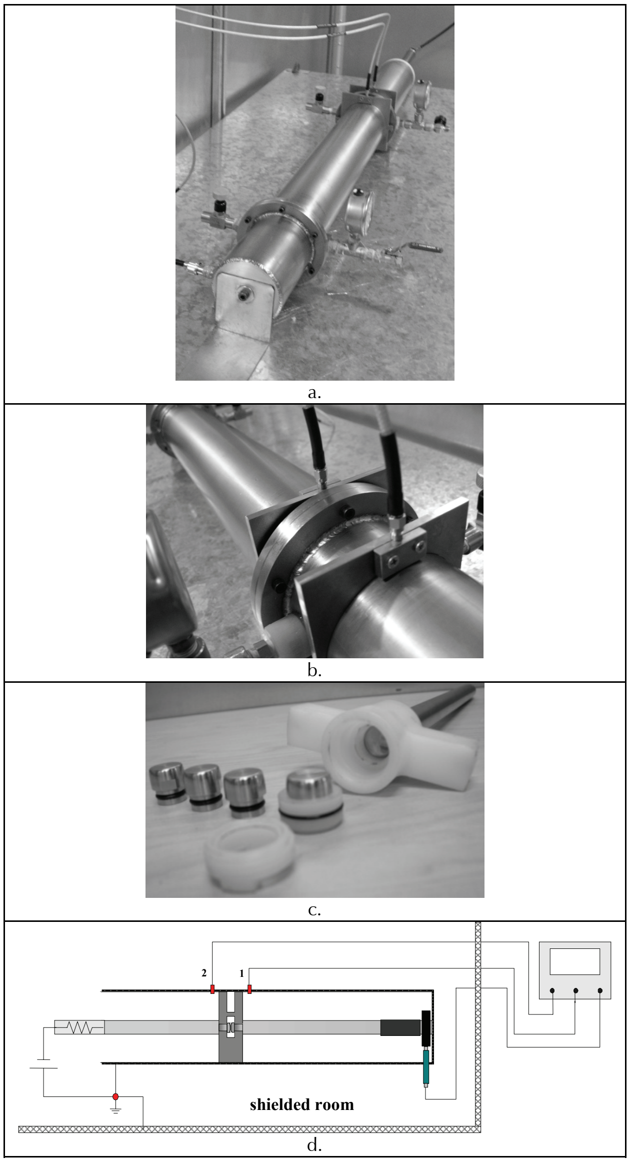


a.

b.

Figure 8 a) Román generator (RG) constructed in EPFL by Vega, b) RG measuring system (Vega *et al.,* 2009b) used by Mora (2009) to predict RG pulse repetition frequency.

Investigation by Santamaría (2010) aimed at understanding the dynamic behaviour of electrical discharges in micro-gaps was focused on understanding arc channel dynamic impedance. Such discharge channel pattern was studied as a function of interelectrode distance and both gas type and pressure. The experimental set-up shown in Figures 9 a), b) and d) was constructed to perform this investigation. Figure 9 a) shows the coaxial current generator while b) shows details of the D-dot measuring probe connection. Figure 9 c) shows some construction details while d) shows the equivalent circuit. The voltage drop across the switch and current in the circuit were measured to obtain the arc channel's dynamic impedance. Voltage was thus obtained from electric field measurements before and after the switch. An example of the measure voltage and current signals is given in Figures 10 a) and b). Notice that current rise time was less than 1 ns in Figure 10 a. Figure 10 b) shows rise time dependence on gas pressure.



a.

b.

c.

d.

Figure 9. a) Coaxial impulse current generator developed for obtaining the discharge channel dynamic characteristics of a micro-gap. b) Details of the D-dot measuring probe connection, c) shows some switch construction details and d) a schematic representation of the measuring circuit. D dot probes are indicated by numbers 1 and 2.

Ozone generation from corona discharges

Corona discharges have been used for generating ozone. The objective of an investigation sponsored by COLCIENCIAS (Román *et al.,* 2006) was to optimise ozone generation by producing electrical discharges in dielectric barriers (Mora, 2010; Rojas, 2010). Figure 11 shows aspects of the experimental setup for generating ozone using a double dielectric barrier reactor. Corona electrical discharges were investigated in a coaxial configuration having different conductor lengths. Figure 12 shows a good correlation between corona current and ozone concentration. Mora (2010) has focused his work on investigating the correlation between corona current shape and ozone concentration. These results are of importance for future investigations into ozone generation for cleaning water.

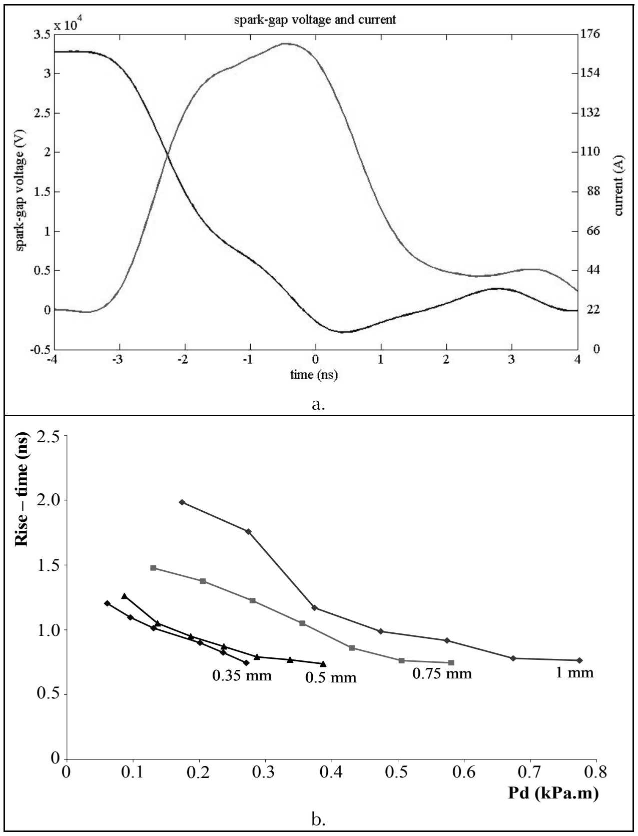


Figure 10 a) Voltage and current signals measured in the experimental set-up shown in Figure 9. b). Notice that current rise time was less than 1 ns. b) shows rise time dependence on gas pressure.

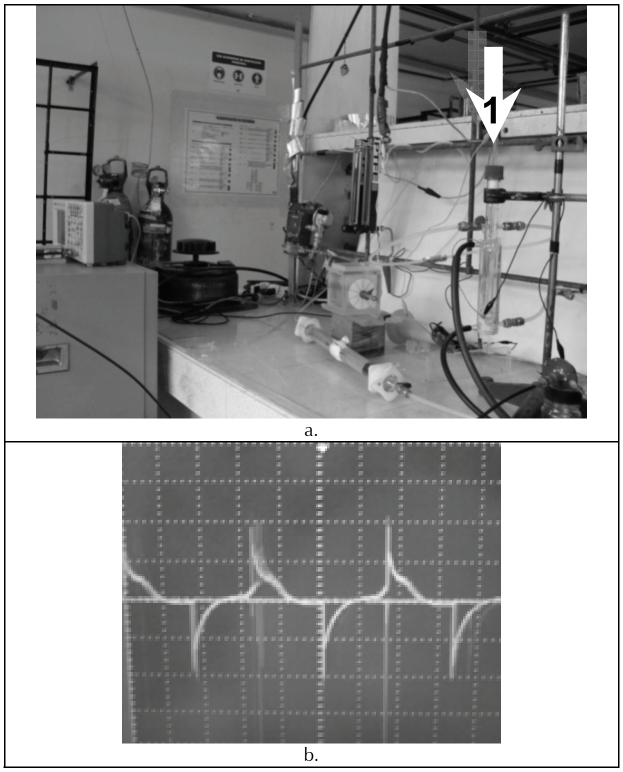


Figure 11. a) Experimental setup used to generate ozone in a double dielectric barrier reactor indicated by arrow numbered 1, b) applied voltage waveform (Mora, 2010).

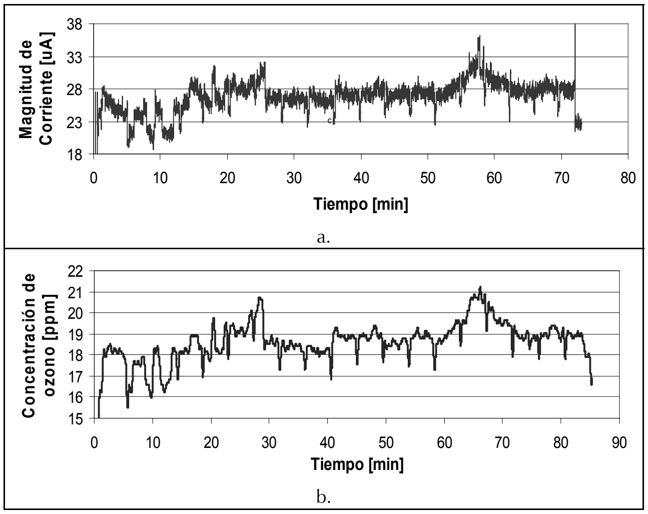


Figure 12. a) Current amplitude as a function of time measured in a coaxial configuration and b) ozone concentration in ppm as a function of time. Both signatures were taken simultaneously. See Rojas (2010).

Energy from the electric field

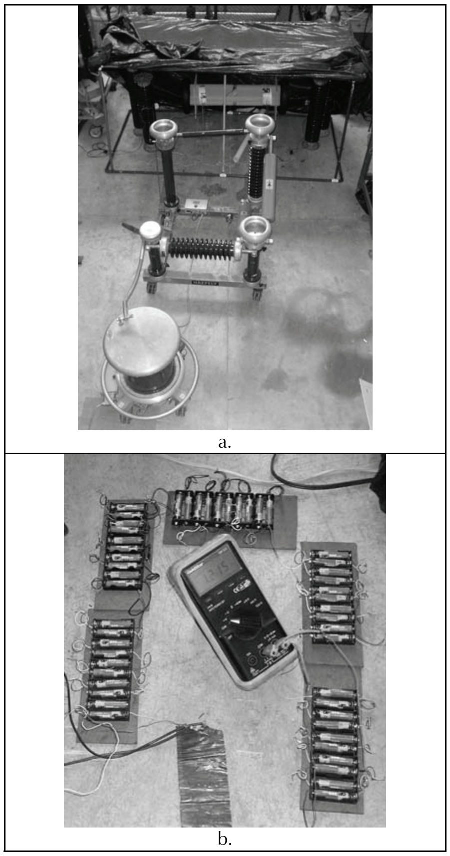
The main idea in this investigation was to apply corona discharges to obtaining energy from the electric field. A. Rojas and Sanchez (2004) and Rojas (2005) and Mora *et al.*, (2007) have investigated the simultaneous charging process of 50 rechargeable AA batteries using a corona source in a configuration called high impedance current source (ETHICS in Spanish) (Rojas and Sánchez, 2004; Rojas *et al.,* 2005 and 2007). Figures 12 a) and b) taken from Rojas (2004) show, respectively, the experimental set up for activating the corona current source and the charged batteries (Rojas and Sánchez, 2004). This work concluded that this source can charge all series connected batteries with the same amount of charge. This conclusion is important for extrapolating this result to natural electric field sources.

Figure 14 shows a comparison of corona current produced by two types of corona electrodes. These electrodes will be used as an application of the previously explained experiment for charging batteries from the electric field. Ariza *et al.* (2010) compared a cactus-like electrode pattern to a single-needle electrode. It was concluded that both had similar behaviour in similar wind conditions. However, the advantage of using the former is its simplicity of construction, as can be seen in Ariza *et al.* (2010).

Radiating electromagnetic energy

As mentioned above, the EMC-UNC Group has been involved in generating fast current and voltage impulses. The limits reached by the group are in terms of amplitude (several kA) and in terms of rise-time the present limits is around 500 ps. It is well-known that devices in EMC practice should withstand different amplitudes from radiated electromagnetic fields. This was the origin of a new research question and a challenge for the EMC-UNC group: *"Could the generated current impulses be radiated?" "Are there efficient ways of matching ultra wide antennas (UWA) to the generator, in such a way that generator electromagnetic energy can be efficiently radiated?"*

Several research activities have been initiated to solve these questions. Vega (2010) focused his work on designing a high-power ultra wideband system using a fast impulse current generator. The first results were presented at URSI 2008 (Vega *et al.*, 2008) in designing a mesoband high power electromagnetic radiator using a switched oscillator and a corona current generator. Vega *et al.* (2009a) has design and simulated an electromagnetic lens for a half impulse radiating antenna to match the antenna to the generator. Additionally, an UWB antenna fed by a corona source was tested as a source of interference. Figure 15 a) shows a radiating broad-band pulse generator with corona charging mechanism used for radiating the current impulse shown in Figure 15 b). Notice that measured electric field rise time at 20 m was 1.6 ns whilst amplitude was 110 V/m (Becerra *et al.,* 2008a.


a.

b.

Figure 13. a) Experimental set-up for generating corona discharges as a battery charging current source. b) battery set-up to be connected to the current source in a). Notice that batteries are connected in series.

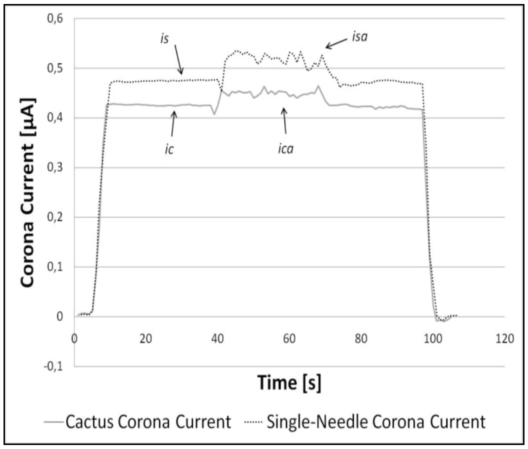
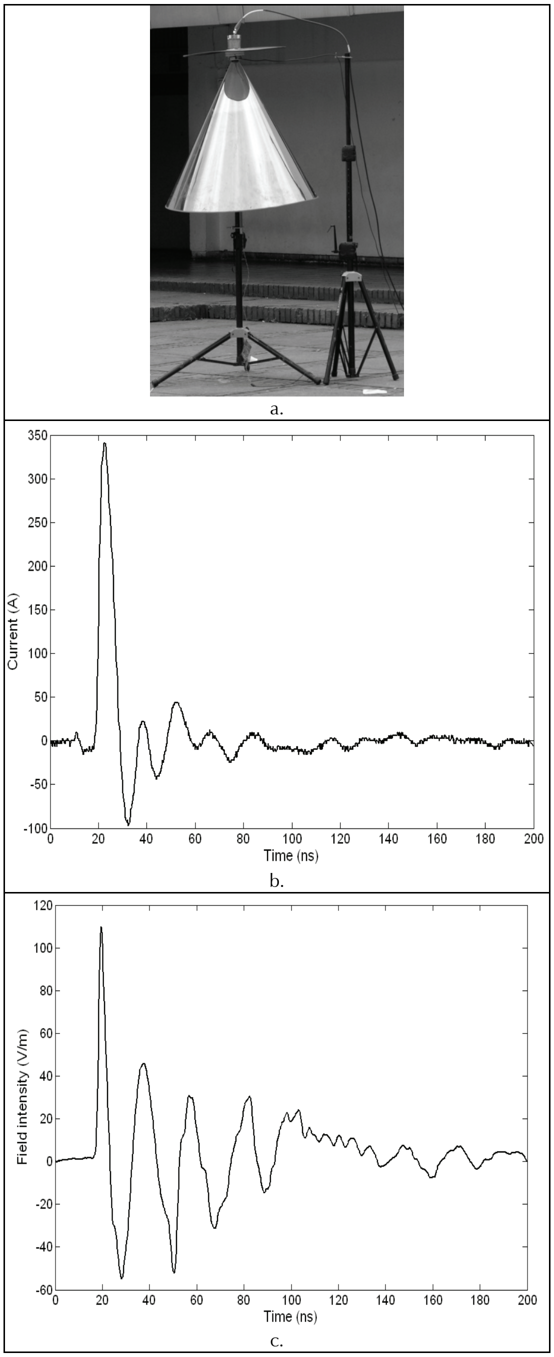


Figure 14. Comparison between positive corona current measured in the cactus-like electrode (lower line) and in the single-needle electrode (upper line) at 6.2kV/m and 9.65m/s. Is and Ic are the respective corona currents in the single-needle and in the cactus-like electrodes.


a.

b.

c.

Figure 15. a) Discone antenna, a radiating broad-band pulse generator with corona charging mechanism. Notice the high voltage source connected to the upper part of the antenna. b) Radiated 341 A, 2 ns current impulse c). Calculated electric field waveform at 20 m distance: 110 V/m, 1.6 ns (Román *et al.*, 2008a, 2008c).

However, Vega (2010) will soon publish the final version of the system he has developed for radiating electromagnetic impulses using pulse forming line (PFL)-based types of generators.

It has been necessary to develop an EMC-lab to perform the EMC studies mentioned here. Figure 16 shows some aspects of the EMC-lab constructed with the support of the following companies: CODENSA, ECOPETROL, EEB, EMGESA, EPM, ISA, ISAGEN and the Universidad Nacional de Colombia. The shielded rooms represent the main experimental facility in this lab where measurements can be taken without electromagnetic noise.

a.

b.

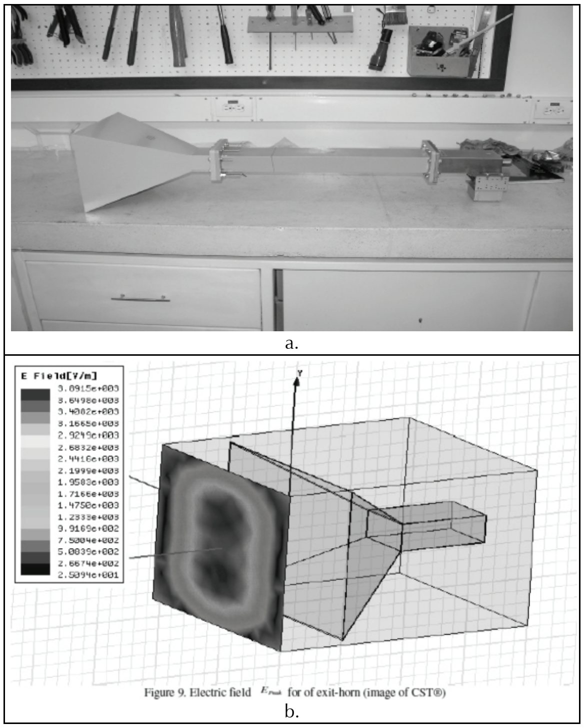
Figure 16. Universidad Nacional de Colombia's Electromagnetic Compatibility (EMC) lab. a) First floor. Notice the shielded rooms in the background. b) Second floor. Notice the areas for experimental work and the meeting room.

Future research activities

The EMC-UNC group's future research activities are related to applications involving gas discharge physics and generation and measuring fast current impulses in the picosecond range in pulsed power and intentional electromagnetic interference (IEMI) problems. This topic is of interest to stay in contact with Uppsala University. The group will increase its ability for developing measuring systems to help investigate electromagnetic interference in electrical and electronic systems as being important aspects of EMC-immunity problems. This topic is of interest for the international cooperation agreement with the EPFL EMC group in Switzerland. The interaction of equipment and microwaves will be also investigated, especially by reinforcing experimental and numerical simulations of radiating such electromagnetic waves. Figure 17 shows an example of the calculations performed by the group regarding this topic. This work will increase present interaction with the GEST research Group of Prof. Nestor Peña at los Andes University in Colombia and Prof. K. Baum at the University of New Mexico, USA.

Several characteristics of lightning electromagnetic pulses (LEMP) in Colombia are still unknown, especially those related to lightning at high altitude compared to lightning at sea level. Collaboration with research groups in Uppsala, Stockholm and Gothemburg in Sweden, Switzerland, Sri Lanka, Mexico and Malaysia and Dr. Marley Becerra will continue. The final product of this research is to increase the protection capacity of lightning protection systems. Incorporating new techniques like wavelets (Santamaria *et al.*, 2009) and other numerical techniques will be investigated in depth in the near future.

The investigation into harvesting energy from an electric field using electrical discharges will continue until this technology's real possibilities have been revealed. In the case of ozone production for cleaning water, the group will apply this technology to concrete cases. Finally, the possibility of increasing the internal impedance of high impedance current sources will be investigated to find some industrial applications for this.



a.

b.

Figure 17. a) a) Waveguide and horn antenna of an LPM system and b) calculated electric field in the near field for a horn antenna. Calculation performed by Carlos Rivera and Felix Vega.

All EMC-UNC group activity is transferred to education in the Electrical and Electronics Department's graduate and postgraduate courses at the Universidad Nacional de Colombia. New books will be written on the research topics mentioned here to increase such activities.

Conclusions

The EMC-UNC group research activity's which has been carried out for almost three decades can be summarised as accumulating knowledge obtained by performing experiments, investigating gas electrical phenomena and solving a few research questions.

This investigation started by constructing experimental tools for observing high-voltage phenomena: electrical discharges in gases. The start made with simple tools involved the photographic recording of DC corona discharges. Later on, more sophisticated tools were developed and used for observing more complicated phenomena, such as lightning-induced currents. The increase in observation tool complexity was accompanied by developing computational modelling ability. The first stage finished by developing HV electrical equipment, such as voltage sources, and circuit components, such as resistors, inductors and capacitors.

A second stage involved resolving concrete EMC-problems, such as the destruction of equipment caused by lightning. The first research question posed was: *"How can the extremely high Colombian distribution transformer failure-index be understood*?" Directly observing damaged units provided the answer; damage was being caused by very high overvoltages. The *inductive loop* hypothesis was the correct answer to this question; the *inductive loops theory* involving reducing the inductive loops was formulated to solve this problem. Another solution was to reduce the induced overvoltages by using arresters along the line. The properties of wood were used to extract these overvoltages from the distribution lines. This work finished with a reduction of one order of magnitude in the distribution transformers' failure index. The group continues its studies into lightning discharges to solve a basic research question about the nature of lightning at high altitudes and a practical question on better lightning protection technologies.

Observing interacting floating electrodes with lightning discharges provided the origin for a second group of questions: *"How do corona electrical discharges interact with floating electrodes?"*

"How is the interaction between corona electrical discharges and electrically-isolated metallic bodies immersed in an electric field?" "*Could a metallic body attract an electrical discharge*?" Several hypotheses were formulated to answer these questions. The answer lay in understanding gas discharge physics. Corona discharge in a floating electrode was the main reason for the interaction between electrical discharges and isolated bodies. The electrostatically-accumulated charge on a floating electrode could be used in several applications. Four patented devices were developed following this idea.

Formulating new impulse generators was the origin of new research questions: "*Could generated current impulses be radiated*?" "*Are there efficient ways of matching ultra wide antennas (UWA) to a generator in such a way that the generator's electromagnetic energy can be efficiently radiated*?" The answers to these questions led to developing impulse radiating systems and led the EMC-group towards the field of pulsed power technology. A device based on the use of pulse forming lines (PFL) will be presented at the end of this year.

Another answer led to studying harvesting energy from an electric field. The present interest in this study lies in evaluating the possibilities of this source as a feasible energy source.

Another derived investigation has been related to ozone production, directed related to the knowledge gained in gas discharge physics.

The radiating energy derived from pulse power technology has directed the EMC-UNC research group towards becoming involved in microwave technologies for radiating energy in a more efficient way.

Acknowledgements

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