INTERNATIONAL CONFERENCE ON LIGHTNING PROTECTION
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

Charge transfer in natural negative and positive downward flashes

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***Abstract* — The question of interest is the charge transfer of lightning flashes. On instrumented towers, it is possible to measure these values. In many countries there is no equipment installed on the towers in order to measure the charge transfer. The other fact is that there are just a few cases of downward flashes occurring in towers around the world. In this paper, a method for estimation of charge transfer will be present. We used data from Brazil, USA and Austria for the analysis and comparison.**

Keywords - charge transfer; downward flashes; eletric field sensor

I. INTRODUCTION

Charge transfer in downward flashes occur in two phases: an impulse phase (return stroke) and continuous phase (continuous current).

Continuous current is the persistence of charge flowing on the channel. Authors defined terms as “long”, “short” and “very short”, based on the duration of this process: longer than 40 ms, between 10 and 40 ms and equal to 10 ms but greater than 3ms, respectively.

The terms “continuous current” on downward flashes and “initial continuous current” on upward flashes are due to the similar characteristics: duration of hundreds of milliseconds and amplitude of some tens to some thousands of amperes [1]. As reported by Saba et al [2], a continuous current is the expansion of the channel inside of the cloud, collecting charges and maintaining the channel. Initial continuous charge is also the expansion of the channel through the air and then inside cloud.

As reported by previous works, continuous current are responsible for lightning damage associated with thermal effects, such as damage on windmill blades, blowing fuses used to protect distribution transformers, holes in the metal skins of aircraft, etc. [3-5]. Ishii [6] reported that 3 out of 4 cases of damage on wind turbines were due to flashes that transferred less than 300C.

Positive flashes are known as the most intense flashes but only a few studies about the charge transfer for positive downward flashes was reported. The charge transfer by negative flashes reported by the literature is in the range of a few coulombs. Table 1 shows a summary from many studies about charge transfer.

In this paper only the continuous current phase in downward flashes was analyzed.

A. Method

There is a model to estimate the charge transfer based on electric field sensors data. And the charge transfer (ΔQ) was based on the equation (1):

$$E_Q = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r_i^2}$$

$$E_T = \frac{2Q}{4\pi\varepsilon_0 r_i^2} cos\alpha$$

$$\Delta E_T = \frac{1}{2\pi\varepsilon_0}\frac{\Delta Q H}{[H^2+D^2]^{3/2}}$$

$$\Delta Q = \frac{2\pi\varepsilon_0 [H^2+D^2]^{3/2}}{H}\Delta E_T \quad (1)$$

The charge transfer (ΔQ) was calculated from ΔE, which is the electric field change due to the continuing current using, equation (1). The distance (D) between the ground contact point of the flash and the location of the electric field sensor was defined by the position provided by the LLS (Figure 1).

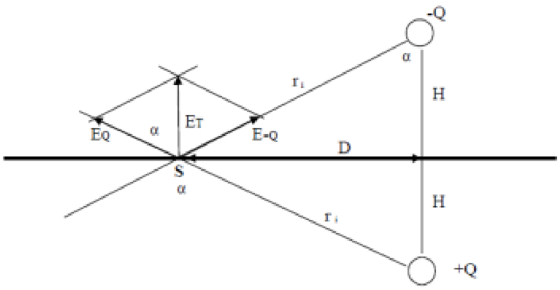

Figure 1: Image Method for Charge Transfer (adapted from [7])

The height of the negative charge center (H) was obtained by the radio sounding on the level of the -10°C isotherm for each day. The height of the positive charge center (H) was estimated to be 3km higher than the temperature level of -10°C (H-10°C+3km).

B. Charge center height and distance: the influence on the charge transfer results

In order to verify the influence of the distance and the charge center height on the charge estimated by the method described by (equation 1), the method was applied to one case reported by Brook et al., [8]. Brook et al., [8] measured the charge of a strike direct on the tower. From the given values of electric field change, distance, H and charge transfer, we varied the value of H in order to estimate how significant H is in the overall result. Figure 2 shows the analysis of sensitivity. On the horizontal axis, the height of the charge center is shown and on the vertical axis is the percentage difference found for the different heights.

From Figure 3, we can see that cases closer than 5 km have a large impact on the final value when the cloud charge center height varies. Therefore, only cases further than 5km and closer than 45 km were considered.

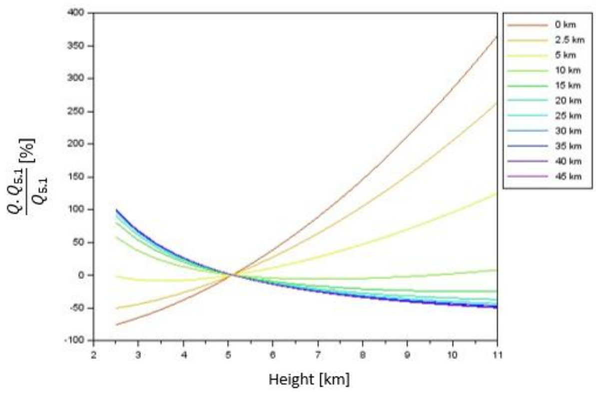

Figure 2: The variation of the height of the charge center has more influence on the charge values for cases closer than 5 km.

C. Algorithms

Two algorithms were used for the analysis. Both were developed in Scilab [9].

The input to the platform is composed by files of measurements recorded simultaneously by the sensors (with integrator amplifiers). The results are the compensated electric field waveforms where the distortion due to the antenna and the amplifiers is removed.

The first algorithm for compensation was developed by Kohlmann et al. [10]. It is the extension of the work of Rubinstein et al. [11] where the authors primarily developed a method to transfer the waveform measured with integrators from one time constant to another.

A second algorithm uses the compensated electric field waveforms from the first Scilab algorithm to calculate the charge transferred. This platform was used to generate the time intervals and to calculate the transferred charge (Q) with respect to the distance and the height of the charge center in the cloud.

In order to check the accuracy of the method, a case of a subsequent stroke that connected on Gaisberg Tower was used. Current measurement and electric field sensor data were used to compare the results from current waveform profile with the current waveform estimated by the method (Figure 3).

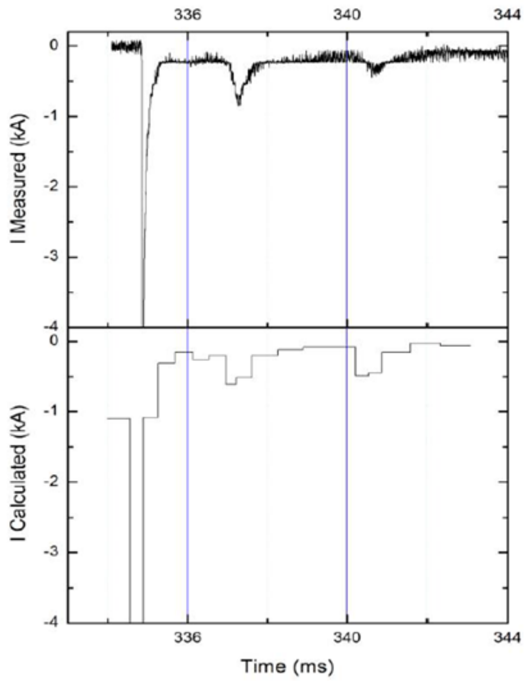

Figure 3. Shows the waveform of the current measured by shunt at Gaisberg Tower (top) and the current estimated by the method (bottom).

Table 1 - Studies about charge transfer

		Authors	Country	Instruments	Values
Downward Flashes	Negative Flashes	Brook et al. [8] Kitagawa et al. [12]	New Mexico	Electric Field Sensors	3,4C to 29,2 C Average value 12C
		Williams and Brook [13]	New Mexico	Magnetometer	Charge Transf. 31C Average Current 184A
		Berger and Vogelsanger [14]	Switzerland	Tower measurement	50% dos cases transferred more than 25C Current from 100A to 300A
		Krehbiel et al. [15]	Novo Mexico	Multiples stations of electric field	Current from 50A to 580A
		Ferraz et al. [7]	Brazil	Electric Field Sensor	Charge transf. 1 to 370C Current from 30 to 1000A (Average: 292 A and Median: 198A)
		Silverio et al. [16] CIGRE [17]	Brazil	Tower Measurement	Charge Transfer First Stroke: 5.75C Charge Transfer Subs. Stroke: 1.44C
	Positive Flashes	Miyake et al. [18]	Japan	Tower's measurement	Values in order to 1000C
		Matsumoto et al. [19]	Japan	Direct measurements in Power line transmission towers	Values in order to 10kA with average duration of 35ms
		Schumann and Saba [20]	Brazil	Electric Field Sensor	Charge transf. 18 a 3070C Current de 100A to 11.4 kA
Upward Flashes	Negative Upward Flash	CIGRE [17]	Switzerland	Tower's measurement	Charge Transfer Median: 0.77C
		CIGRE [17]	Germany	Tower's measurement	Self Initiated flashes- Charge Transfer: 4.8 to 165C Triggered flashes – Charge Transfer: 46.6 C (Only case)
		CIGRE [17]	Brazil Cachimbo	Tower's measurement	Charge Transfer: 4.9C
		CIGRE [17]	Nikaho-kogen Wind Farm	Wind Turbine current measurement	Charge Transfer 20.8C Duration: 156 ms
	Positive Upward Flash	CIGRE [17]	Switzerland	Tower's measurement	Charge Transfer: 26C
		CIGRE [17]	Germany	Tower's measurement	Positive Triggered Leader: 9 to 18C Self-Initiated Pos. Leader: 20 to 249C Mean 105C and 58 ms duration
		CIGRE [17]	Austria	Tower's measurement	Charge Transfer: 58C Duration Average: 82ms
		CIGRE [17]	Switzerland Santis tower	Tower's measurement	Charge Transfer Average: 169C Flash Duration 80ms
		CIGRE [17]	Nikaho-kogen Wind Farm	Wind Turbine current measurement	Charge Transfer 30.2C Duration: 40 ms

II. EQUIPMENT, LOCATIONS AND DATA

For the analysis, data from 4 different high speed cameras were used: a Photron Fastcam 512 PCI (4,000 ips) and a Phantom v310 (10,000 ips) in Brazil, a Phantom v310 (10,000 ips) and a Miro 4 (1,000 ips) in USA and a Basler (200 ips) in Austria.

The cameras were used to determine the GPS time of the return stroke and the flash duration (the luminosity persistence interval on the images).

Defined as a fast electric field sensor, the system is composed of a flat plate antenna and integrator operating from 300 Hz to 1.5MHz and a time constant of 0.47ms. Measurements with this sensor were recorded with a 5MS/s digitizer.

For comparison between different integrators, the slow electric field sensor was used. This "slow" electric field sensor has a time constant of 1.7s.

Flashes simultaneously recorded with both measurement systems were compensated and consistent results between waveforms were obtained.

III. DESCRIPTION OF THE DATA RECORDED LOCATIONS

Brazil - Flashes were recorded in Sao Jose dos Campos, state of Sao Paulo. The electric field sensors were placed on top of a 27-meter tower. Data from 2008-2011 was analyzed. Simultaneous measurements were made at the top of the tower and at a flat area close to the tower. From this, an enhancement factor of 6.5 for the electric field was found and was considered for the results.

Austria - Flashes were recorded at different places in Austria. For all locations, the electric field sensor was set up on the ground and, therefore, no enhancement correction was necessary for the Austrian data.

USA - Data from 2011-2014 was analyzed. The same set of sensors was placed at three different locations during different data acquisition campaigns. The first location of the sensor was at ground level, thus an enhancement factor was not required. For the second and third locations where the sensors were installed on a hill and on a balcony (enhancement factors of 4.5 and 5.3 respectively) were present. The enhancement factor was not determined with simultaneous measurement as in Brazil. For the US, a comparison between the converted radiation peak of the lightning location system and the radiation peak measured by the fast electric field sensors was used to find the factor of enhancement.

The same method of comparison between the converted radiation peak of the lightning location system and the radiation peak measured by the fast electric field sensors was applied to the Austrian data.

IV. DATA

A total of 165 negative flashes and 100 positive flashes were used for this analysis. Only flashes with a duration of more than 40ms (i.e. flashes with long continuing current) were analyzed. And as mentioned above, only flashes striking at a distance greater than 5 km were selected.

59 cases from Brazil, 70 cases from Austria and 36 cases from USA were negative flashes (-CG). 20 cases from Brazil, 35 cases from Austria and 45 cases from USA were positive flashes (+CG). For all locations, the mean CC duration found for positive flashes and negative flashes were 221 ms and 161 ms respectively. Individual values for each location is shown in Table 2.

The charge transferred was determined from a starting point of 5 ms after the return stroke GPS time until the last moment of the channel luminosity. The first 5 ms starting point was considered due to the time resolution of the slowest camera used to register the flashes (Basler).

V. RESULTS AND DISCUSSION

All waveforms of the flashes were analyzed and only cases with no saturation during continuing current events were included in the dataset. Each case was compensated for the integrator time constant that was used.

For all regions, the mean charge transferred during the continuing current phase was 14.8 C and 102.3C for negatives and positive flashes respectively. The transferred charges (AM, minimum and maximum) by –CG and +CG flashes for each location are shown in Table 2.

Berger et al. [21] reported that the mean negative cloud to ground return stroke charge transfer is about 4 C.

Comparing the present work to the literature values (table 1) the method used in this work provides results within a comparable range of charge.

The charge transferred by negative flashes in Brazil was twice as much as those found in the other regions. Even though the mean calculated duration was similar to USA (about 180ms).

As the results for the negative flashes are comparable with direct measurement, we applied the same method for the positive flashes. The results for positive flashes are in the range of 5 to 10 times larger if compared with negatives flashes that occurred in the same region. The maximum value of the transferred charge for positive flashes in Brazil is 1329 C while the maximum value in the other regions are in the order of 400C. Both positive and negative charge transfer values are in the range of what was scarcely reported in past studies shown in Table 1.

Figure 4 shows an accumulative frequency distribution for negative and positive flashes independent of the region.

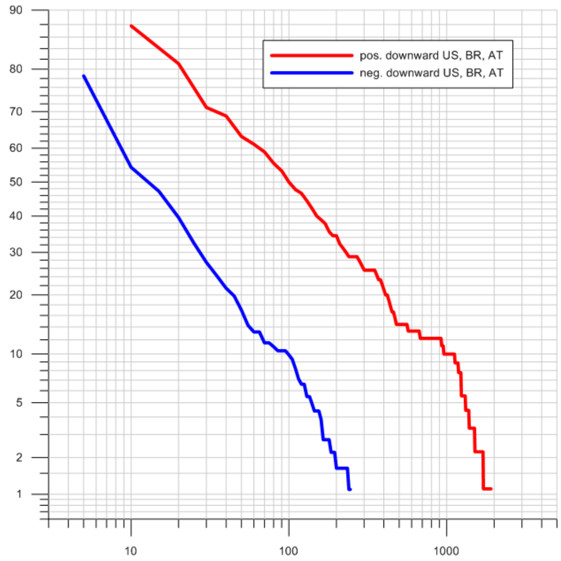

Figure 4 - Accumulative charge transferred by negative and positive flashes for all regions.

The average continuing current was 96 A for negative flashes and 445A for positive flashes during the time of calculation (161ms for negative flashes and 221ms for positive flashes).

Some cases present intensification of the current (Figure 5). Part of them was correlated with the intensification of the luminosity on the channel. Other part of the intensification was correlated with activity in the cloud confirmed by video.

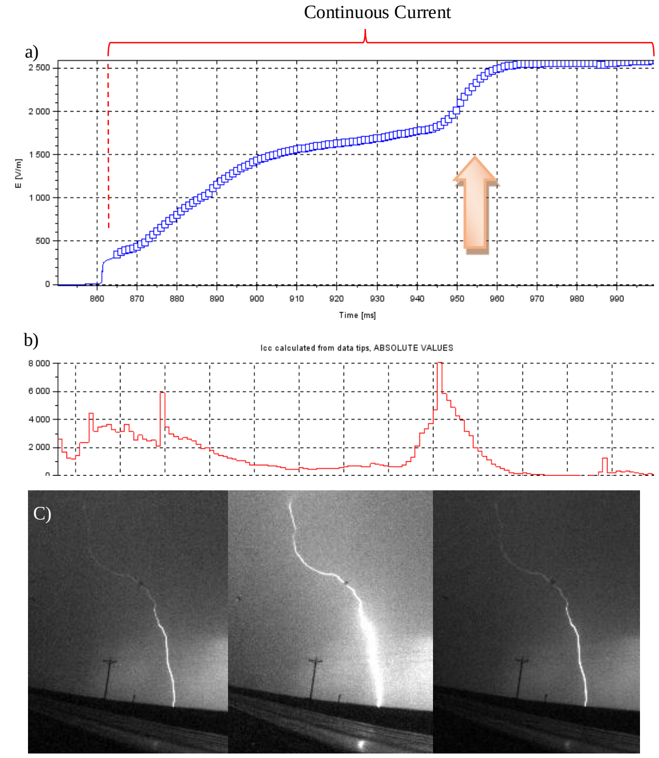

Figure 5 a) Shows the electric field (in blue) for the return stroke b) the current profile for the continuous current (in red) and the c) the central image is when the intensification on the channel occurs (950ms) (red arrow indicates on the current profile).

	-CG			+CG		
	Brazil	**Austria**	**USA**	**Brazil**	**Austria**	**USA**
Number of cases	59	70	36	20	35	45
Distance Min (km)	5.0	5.5	5.0	6.9	6.5	9.8
Distance Max (km)	35.0	34.1	35.4	44.1	32.8	35.5
Charge Transfer Average (C)	21.2	11.6	10.5	255.4	50.1	74.9
Charge Transfer Min (C)	0.6	0.4	0.2	2.5	2.9	1.7
Charge Transfer Max (C)	127	115	46	1329	434	358
Icc (Q/dt) (A)	140	83	50	866	458	2482
Icc (Q/dt) Min (A)	11.4	7.4	3.5	21.0	14.7	27.2
Icc (Q/dt) Max (A)	845	828	165	3258	4573	1096
CC Duration (ms)	185.1	133.0	197.1	262.0	124.0	290.6
CC Duration Min* (ms)	42.0	40.0	41.0	40.0	40.0	43.0
CC Duration Max (ms)	570.0	580.0	527.0	800.0	355.0	689.0
Ip Average (kA)	-11.8	-12.2	-16.3	49.8	34.2	51.8
Ip Min (kA)	-3.0	-2.5	-7.1	12.7	7.0	10.6
Ip Max (kA)	-25.8	-68.7	-58.4	142.0	207.6	169.5
Hcloud Average (m)	6501	5702	5848	9266	8818	8683
Hcloud Min (m)	6120	4564	5182	8683	7970	8182
Hcloud Max (m)	7043	5906	6809	9896	9115	9618

VI. SUMMARY

In this paper, it was possible to estimate these values based on the electric field sensor data and to compare results for different regions. It was possible to verify and compare the method used with the direct measurement. The data used were from United States, Austria and Brazil.

Results for continuous current phase in cases registered in Brazil, Austria and U.S.A were found. The results for negative flashes were satisfactory and comparable with values in the literature. Applying the same method to positive flashes, charge transferred values 5 to 10 times larger were found. The average found was 14.8 C and 102.3 C for negatives and positive flashes respectively.

Brazil presented charge transfer values twice higher than Austria and U.S.A. for negative flashes and three times higher for positive flashes. In Brazil, a maximum value of 1329 C was found for a positive flash.

The values in Brazil were larger than in USA and in Austria, even though the same measuring system was used. The cloud height does not present any difference on the results.

ACKNOWLEDGMENT

This research has been supported by the FAPESP through the projects: 2012/15375-7, 2013/05784-0 and 2014/10299-6; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) through the project: 302706/2008-9; CAPES/PROEX and National Science Foundation that support project: ATM – 0813672. Our sincerely thank to Raphael B. da Silva and Shailine F. Viegas, for the help on gathering all data for this work. We also thank the members of the Atmospheric Electricity Group, ELAT at INPE for their support.

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