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A statistical study using lightning data in Portugal from a Lightning Location System

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***Abstract*—This paper presents a study on lightning statistics over the continental territory of Portugal during a period from 2003 to 2014, using the data collected by the national Lightning Location System. Being part of the EUCLID (European Cooperation of Lightning Detection) project, this European grid is presented and its performance validated over the European continent. With the measured and then processed data, an overall ground flash density map is built, as well as a mean peak current map. In addition, a cumulative probability distribution curve is obtain and compared to the widely used CIGRE curve, followed by the application of both curves to a case study where IEEE Flash software is used.**

Keywords-Lightning location system, ground flash density map, median peak current map, CIGRE distribution curve.

I. INTRODUCTION

Flashover caused by lightning activity has been one of the greatest factors, which seriously affects the safety operation of overhead transmission lines. The knowledge of lightning parameters has crucial importance in the design of protection systems for those structures.

Since its publication, in 1991, CIGRE Document 63 "Guide to procedures for estimating the lightning performance of transmission lines", [1], has been the reference, setting the lightning parameters for the project and design of the protection of transmission lines. Using the data from direct current measurement obtained by instrumentation towers, supplemented by less accurate indirect lightning current measurements using magnetic links, two main distributions of lightning peak currents for negative first strokes were obtained, the IEEE and CIGRE distributions curves (Figure 1).

For the CIGRE distribution, 98 % of peak currents exceed 4 kA, 80 % exceed 20 kA, and 5 % exceed 90 kA.

For the IEEE distribution, the "probability to exceed" values is given by the following equation (Eq. 1)

$$P(I) = \frac{1}{1 + (\frac{I}{31})^{2,6}} \qquad (1)$$

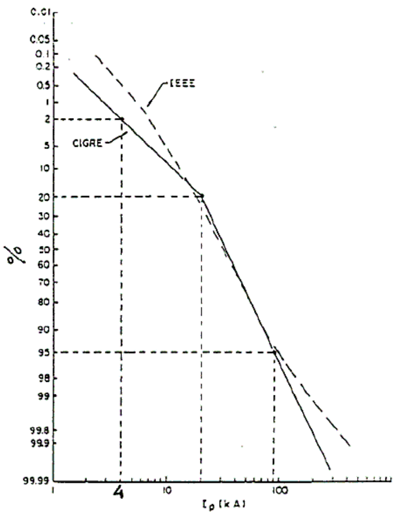

Figure 1. Cumulative statistical distributions of peak currents for negative first strokes adopted by IEEE and CIGRE [3]

There are different methods to obtain experimental data from lightning:

1. Lightning Location Systems (LLS);
2. Lightning to instrumented towers;
3. Rocket-triggered lightning;
4. Video and E-field records of lightning discharges.

Instrumentation towers systems, which allow for direct measurements, are used in many countries like Russia, South Africa, Canada, Germany, Japan, Austria and Switzerland, and have provided important data, as the one presented in Figure 1.

Rocket-triggered lightning, used for example in Camp Blanding (USA), allows for the direct measurement of lightning discharges.

LLS have been installed worldwide to monitor lightning activity. These systems are in use worldwide and the main ones are the U.S. National Lightning Detection Network (NLDN) and the European Cooperation for Lightning Detection (EUCLID). Portugal is a member of the EUCLID project.

Due to the enormous amount of data that can be gathered by the Lightning Location Systems, these represent a promising source of experimental data to be used for the upgrade of standards related with the protection of power systems against lightning. As a consequence, it is essential to validate the performance of the LLS. A direct comparison of LLS data with ground truth data is the best way to validate the performance of these systems.

The performance of the LLS can be evaluated by at least 3 parameters:

- Detection Efficiency, DE.
- Location Accuracy, LA.
- Peak current estimates.

Has a part of the EUCLID network, the Portuguese LLS system uses the same technology and have the same technical issues. So it is relevant to present and describe the EUCLID project. Nevertheless, the dataset used for this work were provided by IPMA, which in terms of software settings are slightly different from the EUCLID settings, because they are adapted for the Portugal LLS grid.

This paper is structured as follows: Section II presents and validates the performance of the EUCLID network. Section III shows the results obtained by the Portuguese LLS system. The final Section (IV) applies the LLS distribution curve in a case study and compares its results with those obtained using the CIGRE curve. The simulations were performed using IEEE Flash software. Has a part

II. EUCLID PROJECT

A. *EUCLID Network characterization*

In 2001 several countries (Austria, France, Germany, Italy, Norway and Slovenia) started a cooperation named EUCLID. The goal of this cooperation is to provide to European end users wide lightning data with high and nearly homogeneous quality. Meanwhile, also Spain, Portugal, Finland, Sweden and Belgium joined EUCLID.

The EUCLID cooperation is special as it is the merge of independent national networks and the individual partners are highly motivated to run their local networks with state-of-the-art lightning detection sensors.

EUCLID network had 149 sensors, 7 LPATS, 10 IMPACT, 31 IMPACT ES/ESP, and 101 LS700x sensors, when listed in order from the oldest to the newest sensor version, in December 2014. EUCLID network is showed in Figure 2 and the sensors location is represented as red dots.

Besides national LLS, data from all 149 sensors are processed in real-time using a central processor, which also provides daily performance analyses reports for each of the sensors. This assures that the resulting lightning data are as consistent as possible throughout Europe [5].

Figure 2. EUCLID network configuration for 2014. Sensor locations are shown as red dots [5]

Since the beginning of the cooperation the performance of the EUCLID network has been steadily improved. Enhancements are the result of employing more advanced location algorithms, installing state of the art sensor technology, and relocating sensor positions in case of poorly performing sensor sites.

B. *EUCLID Network Performance Validation*

The performance validation of the EUCLID network, which is presented in [5], is achieved by the comparison of the LLS EUCLID with ground truth data collected from the Gaisberg Tower (GBT) and the video and field recording system (VFRS).

1) *Gaisberg Tower (GBT) – Austria*

Since 1998, direct lightning strikes to a radio tower have been measured at Gaisberg (Figure 3), a mountain near Salzburg in Austria. This 100 m high tower is located on the top of the mountain Gaisberg (1287 m above sea level). [5]

Figure 3. Gaisberg Tower in Austria

Initially created to validate the performance of the Austrian LLS (ALDIS), this project was also recently used to validate the performance of the EUCLID system, because it is installed in the borderland between Austria and Germany. The lightning data is collected by a number of sensors from the EUCLID system, located at different distances from the GBT.

2) Video and field recording system (VFRS)

To collect video and E-field data of individual lightning discharges it has been used a mobile video and field recording system (VFRS) consisting of a flat plate antenna, an integrator, a fiber optic link and a camera. [5]

3) Performance validation

a) Location Accuracy (LA)

All the improvements over the years result in an actual median LA of 89 m for the last 100 strokes recorded at the GBT. For greater areas, the LA spatial estimation by use of the semi major axis of the 50 % confidence ellipses is used. The ground truth data shows that the LA determined from the distribution of the 50 % confidence ellipses is representative for the real LA and hence the LA for the EUCLID network is better than 500 m in the majority of the network.

b) Detection Efficiency (DE)

A DE of 96 % and 70 % for negative flashes and strokes (for peak currents greater than 2 kA), respectively, determined from data to the GBT, is in good agreement with the DE determined from VFRS data in Austria (98 % and 84 % for flashes and strokes, respectively).

c) Peak current estimates

LLS tend to overestimate the peak current of strokes to so-called electrically tall towers. A tower is considered electrically tall when the rise time of the lightning current is smaller than the current wave propagation time along the tower, and therefore, the current injected into the tower top reaches its peak before the arrival of any ground reflections. Correction factors have been derived and implemented. Therefore, it is possible to assume that peak current errors are positive (the arithmetic mean and the median are 3 and 4 %, respectively) which means that the EUCLID LLS overestimates the peak current, with a small error.

C. Portuguese LLS network

The LLS was installed in Portugal in 2002 by IPMA("Instituto Português do Mar e da Atmosfera"), being part of the EUCLID European project. The Iberian system is composed by 18 sensors, 4 of which are located in Portugal, as seen in Figure 4. The Portuguese LLS receives the information from the 5 Spanish sensors closer to its border, improving the quality of the processed data.

For the continental territory of Portugal the LLS software manufacturer guarantees a detection efficiency greater than 90 % for the first lightning discharges with a peak current greater than 5 kA, and a location error smaller than 500 m, considering the 50 % confidence ellipse.

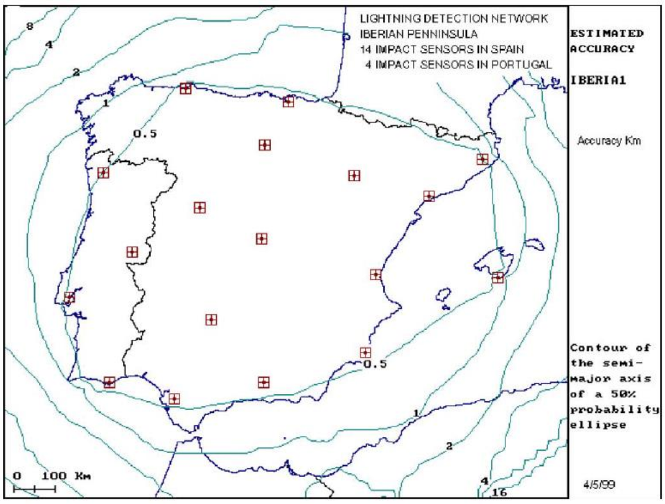

Figure 4. Iberian LLS [4]

III. METHODOLOGY AND STATISTICAL RESULTS

The data provided by the Portuguese LLS refers to an operation period between 2003 and 2014, the 2002 data were excluded, because the technology was still under testing. The area under investigation fully covers the continental territory of Portugal, limited in longitude by -9.6º ≤ long. ≤ -6.2º and in latitude by 36.9º ≤ lat. ≤ 42.2º. The LLS not only provide the location and peak current of a lightning discharge, but also important information about the detection precision and reliability.

The data provided is composed by:

- Date – hour, minute, second, nanosecond – UTC
- Lon – longitude
- Lat – latitude
- I [kA] – peak current
- Nb – multiplicity (number of subsequent strokes)
- Mode – type of location (when it assumes the value 6, the radius is valid);
- Intra – 0 (cloud-ground), 1 (cloud-cloud)
- Ax [km] – semi-axis of the elipse error
- Ki^2 – reliabitlity parameter of the location
- Other information

In order to increase the confidence on the data provided, it is necessary to preprocess the data, following different criteria:

- Mode = 6 (optimized location detection, with angle information and time of discharge)
- Ki2 ≤ 5 (the lower this parameter is, the better the location gets)
- Ax ≤ 20 km
- Only first strokes (no subsequent) to ground, located on the continental territory of Portugal.

After this filtering process, it is possible to obtain the overall ground flash density map, as well as the ground flash median current map and the distribution curves for the peak current.

A. *Ground flash density map*

The overall ground flash density (GDF) map is shown in Figure 5. In this map, the country is divided into 0.01º x 0.01 (~1,11km x 1,11km) squares. GFD is calculated by counting lightning flashes that occurred in the period 2003-2014 and dividing this number by the incidence area and by the number of years considered. Although the procedure followed was different form the one specified in the Standard IEC 62858, the filtering process guarantees the quality of the data.

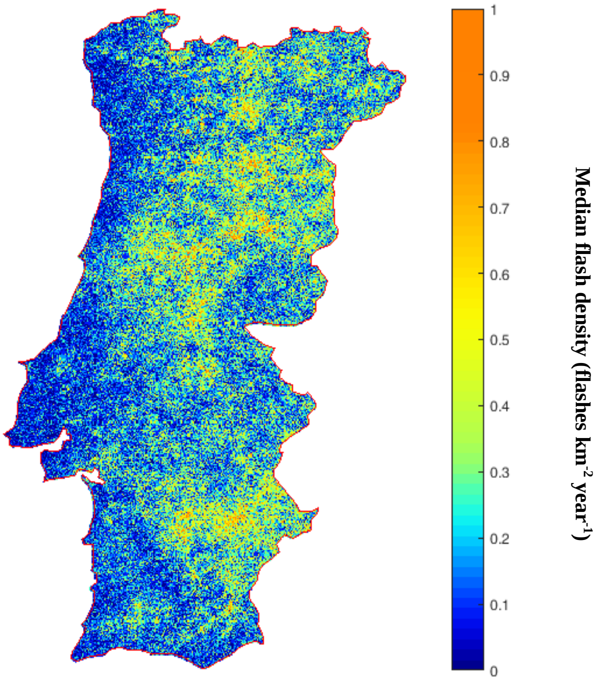

Figure 5. Overall GFD map between 2003-2014

The results in Figure 5 show that, for the continental territory of Portugal, it is possible to obtain a mean ground flash density of 0.22 flashes.km^{-2}.year^{-1}, which is similar to the result of 0,24 flashes.km^{-2}.year^{-1} achieved in [6], for the 2003-2009 period and considering a 0.2º x 0.2º grid. This result shows that Portugal is a low-risk country for lightning related incidents.

The GFD map characterizes the overall lightning threat to a power system, allowing to estimate how often the electrical installations are exposed to direct and indirect strokes. Hence, the GFD map has a very important role in evaluating the risk level associated with the potential location of any structure.

B. *Peak current map and distribution curves*

Also important for the transmission lines project and design, as well as for the *post-mortem* incident analysis is to estimate the peak current values affecting those lines. With the data provided by the LLS it is possible to build a map, similar to the one presented in Figure 5, where in every square of the grid is represented the mean peak current value for that region. The overall mean peak flash current is represented in Figure 6, with a square grid of 0.02º x 0.02º, for better visualization and comprehension. The value of the lower current detected was not provided by the manufacturer, but it is well known that the detection efficiency it's better for higher peak currents.

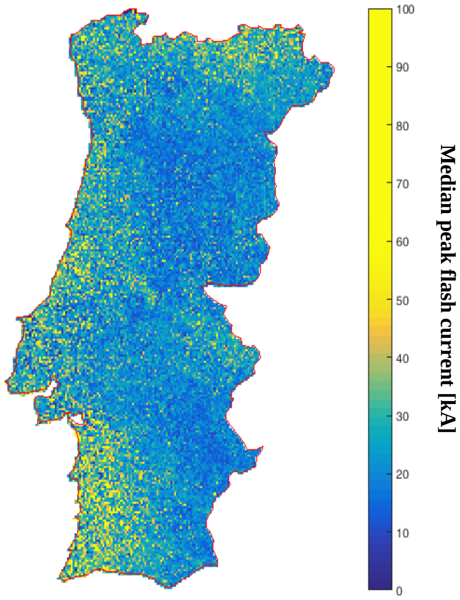

Figure 6. Overall median peak flash current map between 2003-2014

As it can be seen, peak current values are higher on the Portuguese coastline.

Splitting the flashes using the polarity criteria, the distribution curves presented next are obtained.

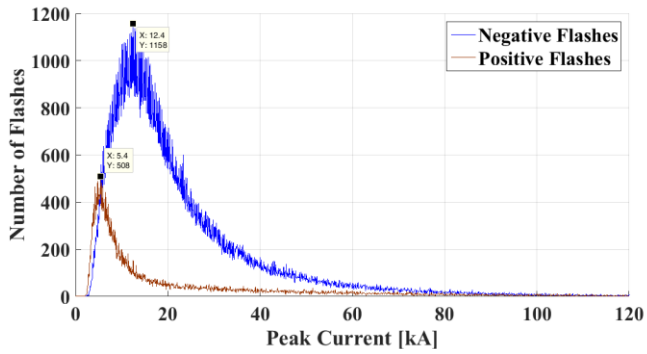

Figure 7. Peak current flash distribution between 2003-2014

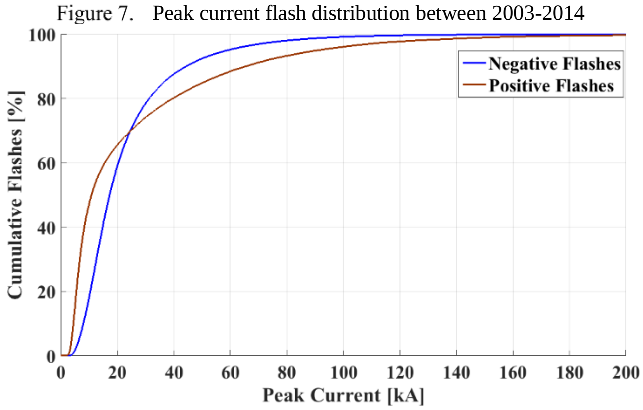

Figure 8. Cumulative peak current distribution curves between 2003-2014

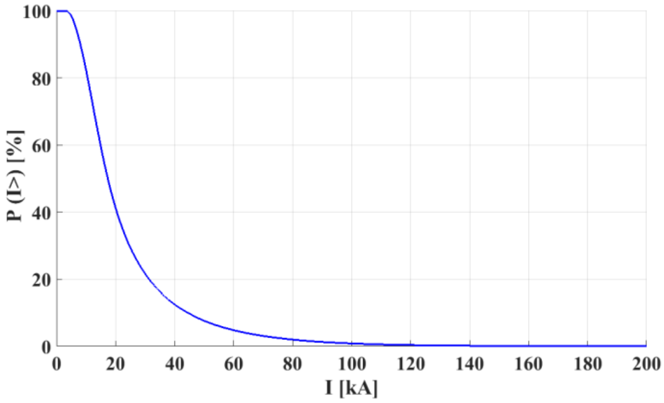

Figure 9. Cumulative probability distribution of lightning for negative first strokes between 2003-2014

Figure 7 illustrates the flash to ground peak current distribution, considering its polarity, while Figure 8 represents the same data in the cumulative form. Figure 9 shows the cumulative distribution curve for negative first strokes inverted, which is aimed for the comparison between CIGRE and IEEE distribution curves (Figure 1).

The positive discharges have their peak at 5.4 kA, while for negative ones the peak is around 12 kA, (Figure 7). According to the cumulative distribution curves (Figure 8) 59 % of the negatives flashes have peak values below 20 kA, while in the positive case this value is around 66 %.

Considering the average and median values, it can be seen that positive polarity flashes will have an average value of 25 kA and a median around 11 kA. For negative flashes the average value is 23 kA, and the median 17 kA. This means that a great number of positive flashes features low peak current values, while some have very high amplitudes, which shifts the average for higher values. The total average current peak value is set at 23.4 kA due to the greater number of negative discharges in comparison with the positive.

Considering the CIGRE curve (Figure 1) only 20 % of first cloud-to-ground strokes have a peak current lower than 20 kA. However, for the Portuguese situation (Figure 9) 20 % of the first strokes have a peak current that is lower than 10 kA, which is in accordance with the results achieved in [4].

The comparison between the cumulative distribution of peak current inferred by LLS and the ones given by IEEE and CIGRE standards should be carefully made. Note that the LLS provides current amplitude reports that may be affected by several uncertainties.

These uncertainties are related mainly to the following issues: 1) LLS infers current amplitude from the measurement of magnetic fields and using an empirical formula that relates the measured peak fields with peak currents. Two strokes with the same peak value but different return stroke velocities would result in the same inferred current amplitude, while it is known that, for two different return stroke velocities, two different current amplitudes are needed to get the same field. However, and despite of the above, the statistical estimation (e.g., using mean values and standard deviations) should be less affected by the variability of the return stroke speed [4];

2) The LLS are only able to detect lightning strokes with a peak current superior to 3-4 kA, which affects the cumulative distribution;

4) The LLS have, a well known, misclassification effect between CC and CG flashes for low peak currents, which can affect the results by giving lower median and mean values for the peak distributions (CC have usually lower currents);

3) Ground propagation effects and calibration errors may also have a great influence, but it’s difficult to implement those effects in any LLS;

4) IEEE and CIGRE distributions are based on current measurements of the lightning striking instrumented towers; it is known that this causes the so-called “tower effect,” namely, the presence of the tower tends to bias toward higher values of the lightning current amplitudes, while LLS refers to lightning striking the soil at ground level and, therefore, the relevant statistics do not suffer this bias [4];

5) As it is shown in Figure 6, the peak current values have a variation over the continental territory of Portugal, which allow us to conclude that the distribution curves for a certain region of country will be shifted from the one present in Figure 9.

IV. Simulation Results

Figure 10 shows the tower design for the line tested in this paper. It is a 400 kV line, with two conductors per phase and two shield wires, whose characteristics are provided in TABLE I.

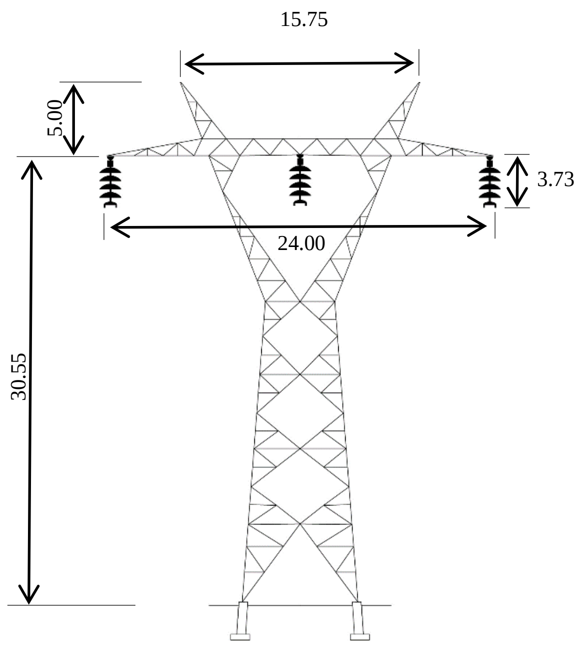

Figure 10. 400 kV line configuration

TABLE I. LINE CONDUCTOR CHARACTERISTICS

	Type	Diameter (mm)	Resistance (Ω/km)
Phase conductors	2xZambeze	31.80	0.0562
Shield wires	Dorking/OPGW	16.02	0.2985

This case study aims to calculate the lightning performance indexes for the line above, the shielding failure and back flashover rates, using the widely used IEEE Flash software. Simulations will be performed using the IEEE distribution curve (Figure 1) and the distribution curve for Portugal (Figure 9) for comparison. For that purpose, the test line reference currents were calculated:

- minimum flashover current = 10.2 kA (IFO, blue line);
- maximum shielding failure = current of 20 kA (ISF, green line);
- minimum back flashover current = 54 kA (IBFR, red line).

Figure 11 shows the distribution curves with the reference currents for the test line. In addition, the shielding failure zone (green) and the back flashover zone (red) are represented, as well as the current range that does not cause incidents (yellow, 20-54 kA).

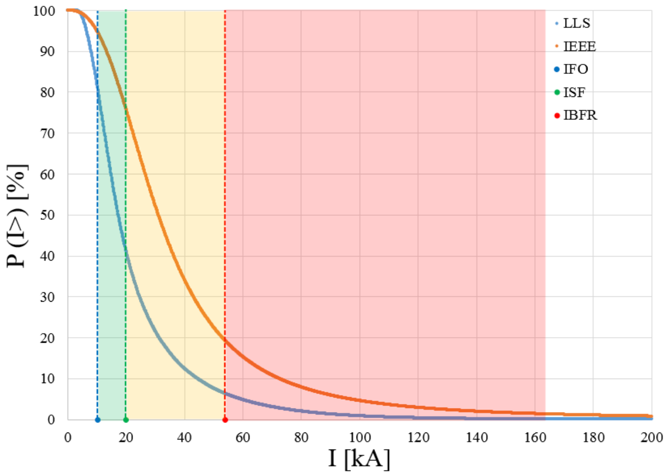

Figure 11. Probability distribution curves, and reference currents for the test line

Considering a 350 m line span and 100 foot resistance, the test line was simulated using the two distribution curves, IEEE and LLS. The flashover rates were calculated assuming that the flash ground density was $N_g = 0.25$ flash per km^2 and year. The results are present in TABLE II.

TABLE II. SIMULATION RESULTS

	SF	BFR
CIGRE curve	0.01032	0.78
LLS curve	0.02138	0.25
Variation	107%	-68%

The results clearly show the enormous influence of the distribution curve on the performance indexes calculation, which was expected. For the LLS curve, the shielding failure rate doubles the value obtained for the IEEE curve, while the backflashover rate lowers for around 30 % of the value. This happens because the CIGRE curve shielding failure zone only has 10 % of its discharges, while for the LLS curve this value is around 41 %. For the backflashover zone those values are 20 % and 7 % respectively.

Note that the low SF values were obtained because the IEEE Flash software only considers vertical lightning discharges and also due to a low phase exposition area.

CONCLUSIONS

This paper presents the lightning data obtained with LLS in Portugal over an 11 year period. Being part of the EUCLID project, this European grid is presented and its performance validated over the European continent in terms of location accuracy, detection efficiency, and peak current estimates. After the validation and processing of the Portuguese LLS data obtained in the period 2003-2014, an overall ground flash density map is presented, as well as a median peak current map. The information of both maps, flash density and peak current, provides essential data in the design of adequate protection measures for vital power systems.

In addition a cumulative distribution current curve was obtained and compared with the widely used CIGRE curve. The influence of both curves in the calculation of a test line lightning performance was tested using the IEEE Flash software, and it was clear that this is a relevant subject to be address in future standards.

Hence, this paper greatly improves the knowledge of the lightning activity in Portugal and its application to the project, design and *post-mortem* incident analysis in the electrical grid.

REFERENCES

[1] CIGRE Report 63 (1991), “Guide to Procedures for Estimating the Lightning Performance of Transmission Lines”, WG 33.01

[2] CIGRE Brochure nº 376 (2009), “Cloud-to-ground lightning parameters derived from lightning location systems – The Effects of System Performance”, WG C4.404

[3] CIGRE Brochure nº 549 (2013), “Lightning Parameters for Engineering Applications”, WG C4.407

[4] R. B. Rodrigues, V. M. F. Mendes, J. P. S. Catalão (2010), “Lightning Data Observed With Lightning Location System in Portugal”, IEEE Trans. Power Del.

[5] W. Schulz, G. Diendorfer, S. Pedeboy, D. R. Poelman (2015), “The European lightning location system EUCLID – Part 1: Performance validation”

[6] M. L. C. Sandra (2012), “Análise de padrões temporais e espaciais de descargas elétricas atmosféricas em Portugal Continental