Estimation of Length Variation of Artificially Generated Electrical Arc in Out-Door Experiments

J. Talaisys, M.C. Tavares, C. Portela, A. Camara

Abstract-- **In the present paper the length results of 69 artificially generated arcs obtained through the analysis of both visual records generated with two cameras and the first pseudo-harmonic voltage between the arcs terminals are presented. An important contribution obtained with the analysis of the visual records of the arc and its harmonic content is presented.**

***Keywords*: Secondary arc, Arc length, Visual estimation, Harmonic content, Arc stabilization instant.**

I. Introduction

THE major part of faults in electrical system are single-phase and transitory [1] what makes possible to apply a maneuver called Single-Phase Auto-Reclosure Switching (SPAR) to normalize the system. There is a critical aspect to consider when using SPAR: the secondary arc must be extinguished before the reclosing to ensure that the switching succeeds [2 – 4].

Provided that such maneuver consists in opening just the faulty phase during a short time, minimizing the disturbance in the electrical system, the Brazilian Electrical Energy Regulatory Agency (ANEEL) has recommended that new transmission lines must be capable of carrying out such switching. Since then a mathematical model of electric arcs has been pursued in order to enable the development of an effective SPAR design [5]. The elongation of the electrical arc length is a significant factor related to the arc extinction and arcing duration, and therefore is an important parameter for the pursued model.

Laboratory experiments in a non-confined environment were conducted in order to make a detailed investigation into the physical processes involved during the occurrence of the secondary arc. In this paper the data provided by these experiments will be used for the estimation of length variation of long arcs in free air for different arc currents.

An innovative approach regarding the identification of the instant when the arc becomes stabilized is presented.

In the following sections the field tests will be described. Afterwards the methodology to estimate the arc length variation is presented, as well as the identification of the instant when the arc is stabilized and homogeneous through the harmonic content. Finally some results regarding the length variation for several arc current levels are presented.

II. Field Tests

The extinction of the secondary arc is imperative in studies for SPAR, as this phenomenon indicates when the faulted phase can be reclosed successfully. However, its behavior is very complex, influenced by a variety of parameters. The extinction time of the secondary arc depends on such parameters, which include: electric network-arc interaction, transmission line length, location of the fault occurrence along the line, line compensation levels, secondary arc current amplitude, line voltage level, line insulation and random weather-related variables such as wind, humidity and temperature.

The electric arc models available in the literature do not adequately represent the phenomena involved, especially as regards the time constants that describe the arc dynamics. Another characteristic of the arc that has not been correctly represented is its elongation.

In 2003, an important research project was initiated to evaluate and improve the performance of single-phase autoreclosing in transmission lines.

The main objective of that research project is to acquire and validate a robust model of secondary arc in air, enabling one to simulate the interaction between the arc and the network and determine the success (or failure) of the SPAR.

The database used in this study was produced by field tests conducted by the CEPEL High Power Laboratory [6]. These tests were conducted on an experimental section of 500 kV transmission line installed inside the facility, which represents actual transmission line conditions (fig. 1). The section is formed by three transmission towers, one anchor tower positioned between two suspension towers, and all the other elements such as insulator strings, shield rings, phases conductors and ground wires.

The tests consisted in generating the electric arc by imposing a sustained current of 60 Hz for 1 s. Despite the secondary arc current usually being less than 10^2 A_{rms} for relatively short lines, in the tests arc currents of up to

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10,000 A_{rms} were imposed, as the research project aims to obtain an arc model for up to this current level. When dealing with very long transmission trunk like half-wave length transmission higher secondary arc current levels of 10^3 A_{rms} are expected. The study involved the analysis of tests with the following current levels: 15 A_{rms}, 30 A_{rms}, 50 A_{rms}, 60 A_{rms}, 100 A_{rms}, 150 A_{rms}, 200 A_{rms}, 300 A_{rms}, 500 A_{rms}, 1000 A_{rms}, 3000 A_{rms} and 10,000 A_{rms}.

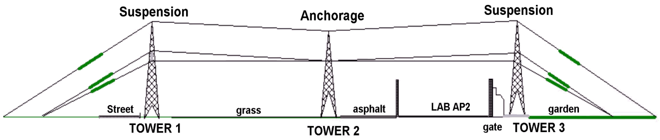

Fig. 1. 500 kV tower structure used in the experiments.

The arc is formed between the top point of the insulator string, connected to the tower structure, which is grounded, and the bottom point of the string, connected to the phase, with the use of a fuse wire connected in parallel to the insulator string (fig. 2). The insulator string length is 4.05 m. The arc ignition is enabled by the current passing through this wire. The fuse wire then vaporizes. After 1 s of arc ignition, the sustained current is interrupted. I-shaped insulator strings were used in the vast majority of the tests analyzed in the present study, but some V-shaped strings were also used.

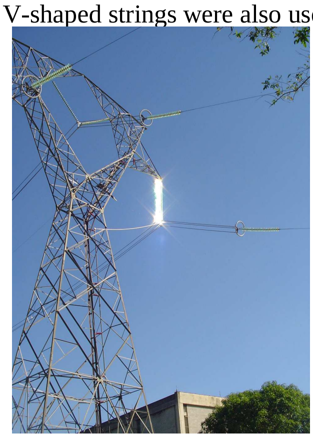

Fig. 2. Former instants of electric arc ignition along the insulator string.

The samples are acquired and stored by a system developed by the CEPEL. This acquisition system is in constant development and is currently capable of processing 20 million samples per second through 4 independent channels.

Visual record of each test is made with two cameras. The meteorological conditions during the test are also recorded.

III. Initial Data Treatment and Harmonic Content

The data collected during the tests were initially verifyed and any inconsistence encountered was corrected, specifically for the fundamental frequency arc current and the voltage between the arc terminals. Following, the harmonic content of the arc current and of the voltage between the arc terminals were obtained by applying the Windowed (or Short-Time) Discrete Fourier Transform (WDFT). The WDFT is acquired by splitting the signal by a window function. Then the spectrum of each segment is determined by the Discrete Fourier Transform. To this end a rectangular type window was applied, with a width equivalent to a 60 Hz period and moving in steps of 20 μs.

Further details about the acquisition, considerations and results of the harmonic content of the analyzed tests are described in [7] and [8].

IV. Arc Length Estimation Methodology

A. *Arc Properties in Stabilized Conditions*

Considering the arc electrical properties in stabilized conditions, some equations relating the voltage between the arc terminals (U_a) and the arc length (L) have been empirically obtained in earlier studies. The most known approach was developed by Ayrton [9]:

$$U_a = \left(A + \frac{B}{I}\right) + \left(C + \frac{D}{I}\right)L \qquad (1)$$

In (1) the former term represents the voltage drop due to anode and cathode regions, while the second term is the voltage drop along the arc column. In long arcs, as the ones analyzed in the present paper, the anode and cathode regions are very small when compared with the remainder of the arc and its influence may be discarded. This results in:

$$U_a = \left(C + \frac{D}{I}\right)L \qquad (2)$$

For arcs with constant current or with high current, the arc length depends mainly of the voltage between the arc terminals:

$$L = kU_a \qquad (3)$$

However, in the present paper the arc current range analyzed varies from low current (10^1 A_{rms}) up to high current (10^3 A_{rms}). And although the aim was to have a constant current experiment, a small variation of the arc current was observed for some tests, mainly when the elongation was too extreme. This current variation could reach 15 % in some experiments, mainly at the final part of the tests.

In order to take the current variation into account, a relation as the proposed by Warrington [10] was used:

$$L = kU_a I^{\alpha} \qquad (4)$$

Nevertheless, the values of $\boldsymbol{k}$ and α to be used in (4) will not match the values originally presented by Warrington, since some improvements in those data are needed [11].

The $\boldsymbol{k}$ parameter will need to be obtained in order to estimate the arc length for any test time instant, once the voltage between the arc terminal and the arc current are field-measured data. The factor α is not constant for all the current range, but at this stage of the study it was assumed $\alpha = 0.25$ for all the treated cases.

In this study instead of using the voltage between the arc terminal and the arc current to derive the arc length, it was used the first pseudo harmonic order of the voltage between the arc terminals and of the arc current to obtain the arc length based on (4).

B. *Arc Stabilization*

Just after the arc ignition in the tests, the arc does not have its electrical characteristics stabilized and (4) cannot be utilized. This is due to mainly one or more of the following reasons:

- influence of the metallic vapors resulting from the fuse wire used in the arc ignition;

- direct contact of the electric arc with the insulator string, causing heat transfer from the arc to the string;

- insufficient time for plasma stabilization.

This means that only after arc stabilization ***k*** parameter in (4) can be obtained.

C. *Preliminary Arc Length Variation Estimation*

To evaluate the relation between the arc length with the first pseudo harmonic order of the voltage between the arc terminals ($Varc_1$) for each experiment, or in other words, to identify ***k*** parameter in (4), the arc length had to be known at some instant. The identification of this arc length was obtained through visual inspection of the videos made from the tests. The error of this measurement is not small at this stage of the research and more elaborated procedure is being developed [12].

At the present the arc videos were decomposed in several pictures and each pair of pictures was analyzed. The videos were not synchronized and that can increase the error. Beside that the arc length measurement was made observing the pictures and to reduce the error only the tests where the arc elongate mainly in the plane captured by the camera were treated. That reduced the universe of tests from 543 available arcs to 69.

As stated in the previous section, the expected relation between $Varc_1$ and the estimated arc length can only be obtained after the arc is stabilized. This instant was supposed to occur just after the arc went free in the air, so that no arc could be seen still linked to the insulator string where it initiated. This length measurement should introduce less error, as the arc would not have twisted around itself, making the visual length estimation more difficult.

The former approach was that when the arc no longer had contact with the insulator string it would be eventually stabilized and that frame would be selected to measure the initial arc length (L_0).

Fig. 3 shows the former instants of one of the arcs selected for the present study, being the last frame the one selected to visually measure the arc length. The frame rate of the cameras used was 30 frames/second (f/s).

Relating the arc length obtained through visual inspection with $Varc_1$ at that time instant (this time was supposed to be the initial arc time – t_0), from (4) the arc length could be estimated for the remainder of the experiment. This approach was applied to all the arcs analyzed.

However, the results obtained with this procedure were not consistent. It was observed that in an important number of experiments the expected relation between $Varc_1$ and the arc length did not occur. That could easily be identified in some experiments were the arc elongation did not correspond to $Varc_1$ increase. In fig. 4 this inconsistence can be seen: the frames correspond to two instants of an experiment were $Varc_1$ at the second instant is almost twice the former instant and the arc elongation does not indicate such a high length variation.

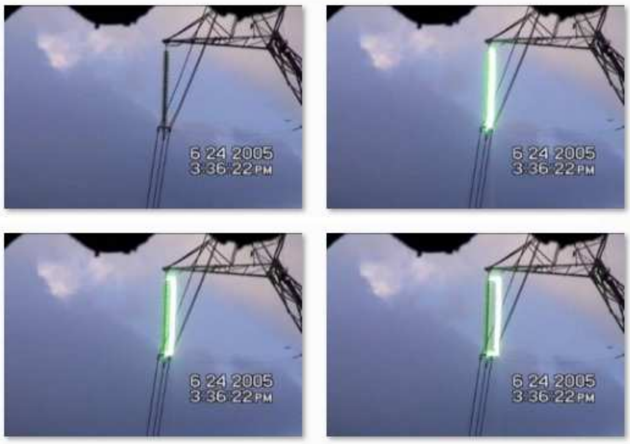

Fig. 3. Former instants of 60 A_{rms} rating arc.

D. *Identifying Arc Stability*

The inconsistence found for some experiments in the previous section suggested that the arc was not stabilized when the relation between $Varc_1$ and the arc length was obtained. This means that identifying the instant when the arc became completely free in the air was not enough to find t_0.

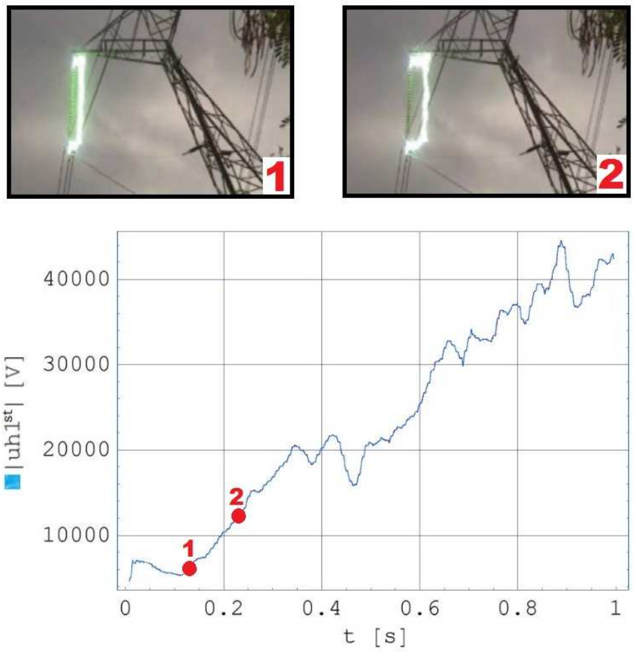

Fig. 4. Identifying coherence between arc elongation and first pseudo harmonic voltage between arc terminals.

A new criterion to identify when the arc was finally stabilized in the air was then pursued. Observing the arcs where the relation arc length - $Varc_1$ were adequate and the ones where this did not occurred as expected, it could be verified that for the former arcs the harmonic content was stabilized, what did not happened with the latter experiments. Fig. 5 and fig. 6 show the harmonic content of an experiment with valid arc length - $Varc_1$ relation and another with inconsistent result, respectively, with the instant when the arc was supposed to be stabilized.

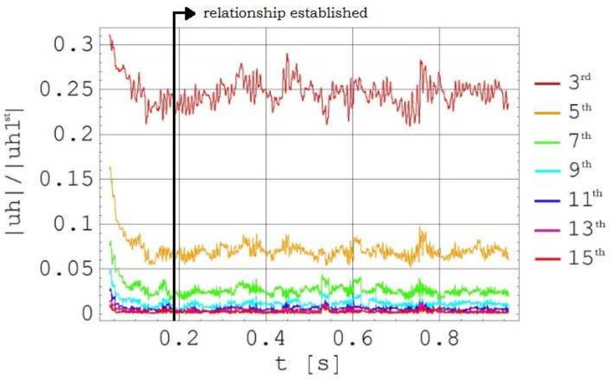

Fig. 5. Ratio between odd pseudo harmonics and first order pseudo harmonic of the voltage between the arc terminals for the experiment with consistent result, with the instant when relation between arc length and $Varc_1$ was adopted.

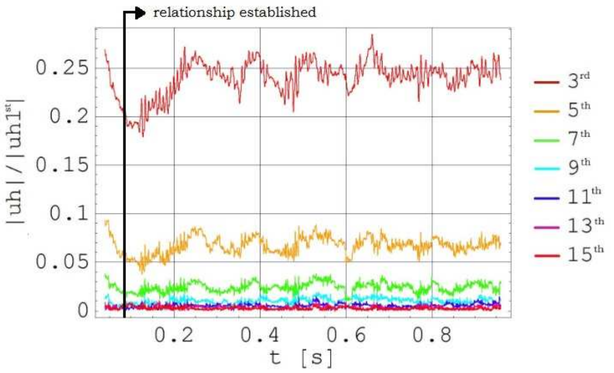

Fig. 6. Ratio between odd pseudo harmonics and first order pseudo harmonic of the voltage between the arc terminals for the experiment with non-consistent result, with the instant when relation between arc length and $Varc_1$ was adopted.

Analyzing the previous results arose the hypothesis that the instant when the arc harmonic content was stabilized corresponded to the instant when the arc would have its electric characteristics also stabilized, which means finding t_0.

The new approach to find t_0 was applied to all the experiments. For the majority of the experiments this instant occurred between 150 and 300 ms. In fig. 7 it is shown the stabilizing arc instant for 4 experiments with distinct current class, where it can be seen the harmonic content variation in the former instants of the experiments, tending towards a flat profile after the arc is stabilized.

The length variations obtained with this hypothesis were much more consistent with the visual records, indicating that the approach that identified the arc stabilization instant through its harmonic content was adequate. The new results are presented in the following.

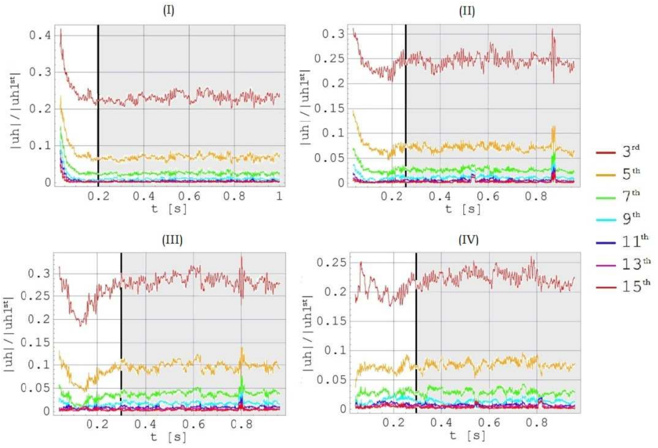

Fig. 7. Instant when the electric arc becomes stabilized of four distinct tests: (I) 30 Arms rating arc, (II) 60 Arms rating arc, (III) 100 Arms rating arc and (IV) 500 Arms rating arc.

V. RESULTS

The amount of cases treated was restricted to 69 experiments, with current level varying from 15 A_{rms} to 1000 A_{rms}. In table I it is presented the number and the current class of the analyzed arcs. Beside that the relative arc elongation and the effective arc lengths are also presented. The relative arc elongation is the relation between the maximum arc length during the experiment and the initial arc length (L_0).

TABLE I
ARC LENGTH ESTIMATION

Arc Rating (A_{rms})	Number of Tests	Relative Length			Maximum Length (m)		
		Average	Minimum	Maximum	Average	Minimum	Maximum
15	4	4.67	2.99	6.10	36.83	20.32	45.14
30	8	3.57	2.35	4.55	25.22	18.31	34.16
60	31	3.16	1.91	4.96	26.97	18.30	39.33
100	5	2.79	2.13	4.54	24.22	19.40	38.60
150	2	3.15	2.19	4.10	26.58	19.52	33.64
200	3	2.85	2.60	2.97	25.49	24.08	27.93
300	14	2.78	2.22	3.45	25.28	20.91	33.13
500	1	2.92	*	*	21.91	*	*
1000	1	2.09	*	*	22.12	*	*

In fig. 8 the average relative maximum length elongation for each arc rating with the larger number of treated cases is presented. The cases with higher current elongates less, what can be explained by its interaction with the air (heat exchange and influence of weather conditions). However this relation tends to a constant for higher currents.

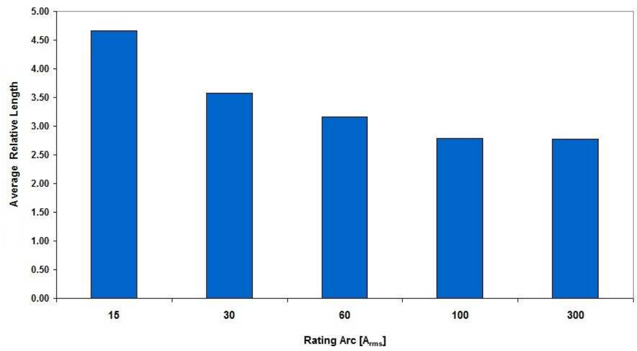

Fig. 8. Average relative length elongation for several rating arcs.

It is difficult to obtain the length variation of higher current arcs through the proposed method, for instance, for arcs up to 10 kA_{rms} that were generated, due to the high luminosity generated by such arcs, what saturates the images captured by the cameras, preventing the initial visual analysis. Experiments made with recently acquired cameras will overcome this problem.

Fig. 9 and fig. 10 show the length variation of all the arcs analyzed for 60 A_{rms} and 300 A_{rms} arcs rating, respectively. In fig. 11 and fig. 12 only three curves are presented for each of these current classes: the ones that had the maximum and the lowest length variation, and an experiment with an intermediate length variation.

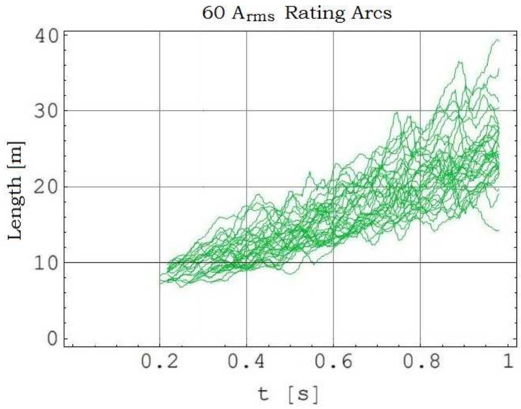

Fig. 9. Estimated length of the 60 A_{rms} arcs rating.

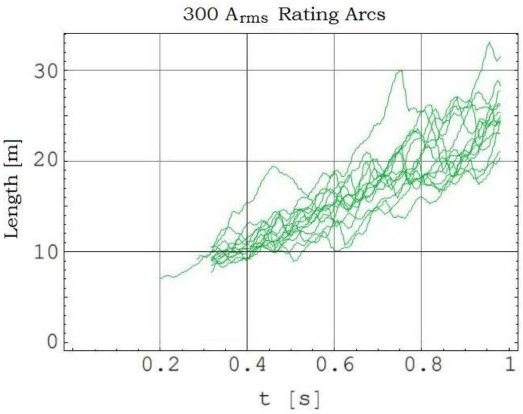

Fig. 10. Estimated length of the 300 A_{rms} arcs rating.

Analyzing fig. 9-12 it can be observed the complex arc behavior what is also evident in its length variation. An important influence for the arc elongation is the wind, but up to now the wind measures treated were in a low time rate, which were not adequate to the fast length/voltage variation. New equipments already acquired will enhance the length variation analysis in a near future.

It can be noted that the initial arc length L_0 is greater than the insulator string length, as it corresponded to the stabilized arc length. For the 60 A_{rms} cases L_0 varies from 7 to 10 m, while the insulator string was 4.05 m. Also it can be observed that the arc length L(t) is not a monothonic curve, as it decreases and increases during the experiment. The length reduction occurs when the arc twists around itself and makes a clew, and this arc section is abruptly separated from the remainder of the arc.

The present arc length results can be applied to arc models.

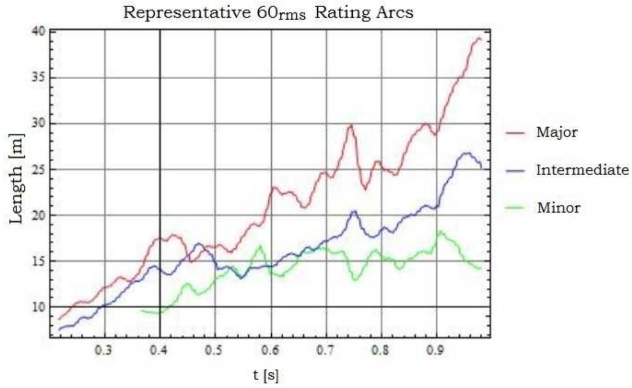

Fig. 11. Estimated length of three selected arcs of the 60 A_{rms} arc rating.

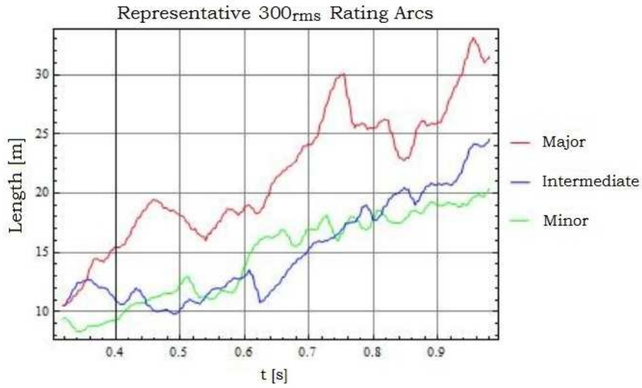

Fig. 12. Estimated length of three selected arcs of the 300 A_{rms} arc rating.

VI. Conclusions

In the present paper the arc length variation for 69 electric arcs artificially generated in non-confined environment were presented. The length estimation was based in visual analysis of the arc at its initial stage, when it was stabilized in the air. From this former arc length L_0 it was possible to obtain its length L(t) during the remainder of the experiment based on the first pseudo harmonic order of the voltage between the arc terminals and of the arc current.

A new method to identify the initial arc stabilizing instant was proposed. The results obtained for the arc length variation were coherent with the voltage between the arc terminals variation and corroborate the methodology.

The results demonstrated that there is a great variation of the arc elongation, even within the same current rating arcs.

Low current arc had higher length variation, while high current arcs had almost the same length variation. Specifically, 15 A_{rms} arc current class had a mean variation of 4.7 times its initial length (obtained when the arc was stabilized), while 300 A_{rms} arc current class had a mean variation of 2.9 times L_0. When compared to the arc length when it ignites, the variation would increase, respectively, to 9.1 times and 6.2 times.

In near future new results related to higher current class arcs will be presented, and also more data regarding weather factors, specially wind effect to arc elongation will be provided.

VII. Acknowledgment

Professor Carlos Portela had his former results related to arc experiments in the 80's and since then has pursued a more robust arc model. In the beginning of 2000 decade he managed to start a new project with field experiments in actual high voltage line towers specially built for the tests. The main objective was to develop a robust arc model to apply for SPAR studies. Important contributions to the field will be presented in the next years based on Professor Portela's suggestions and ideas. Professor Portela passed away in November, 2010.

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