Current and Voltage Harmonic Content of Artificially Generated Electrical Arc in Out-Door Experiments

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

Abstract--**This study involves the application of the Windowed Discrete Fourier Transform in order to obtain the harmonic content of the current and voltage between the terminals of 543 artificially generated electric arcs. This harmonic content can be used to identify the moment at which the arc is stabilized in the air. A statistical analysis of the results, considering only the period for which the arc is stabilized, enabled the establishment of the harmonic signature of the electric arcs.**

***Keywords*: Secondary arc, harmonic analysis, single-phase autoreclosing, non-permanent faults.**

I. INTRODUCTION

Most disturbances of an electrical system occur in the transmission lines. These disturbances are mainly single-phase and transitory, the latter characteristic being even more accentuated in extra-high voltage lines [1]. Single-phase autoreclosing (SPAR), which consists in opening only the faulted phase, is the most recommended switching procedure to eliminate this kind of fault, offering the highest level of stability to the system.

However, 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]. Some research groups around the world continue to search for a consistent electric arc model. A more reliable representation of the arcs during a fault is of utmost importance for the development of an effective SPAR design [5].

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. One of the results obtained during the treatment of the data from these tests was the harmonic content of the arc current and of the voltage between the arc terminals.

By using this harmonic content one can identify the harmonic signature for the arc [6]. Additional results, covering a greater number of sustained arc current levels are presented, consolidating this harmonic signature.

Furthermore, the harmonic analysis allows the identification of the instant at which the electric arc is stabilized in the air and the collected data can be used to ascertain the sought mathematic model.

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 [7]. 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.

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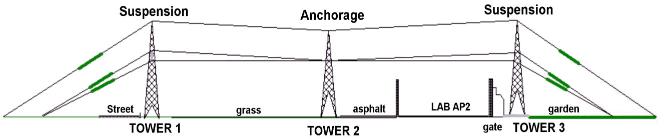

Fig. 1. 500 kV tower structure used in the experiments.

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 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}.

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 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 treated tests, but some V-shaped strings were also used.

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

To evaluate the arc dynamic behavior and investigate the associated time constants, current impulses with different waveforms, polarities and amplitudes have been injected into the sustained arc at different specific time within the period of the arc power frequency current. Impulse current front times of 1 μs, 5 μs and 10 μs, with peak values of 5, 10 and 20 % of 60 Hz current component amplitude, and of positive and negative polarity, have been used. In the present paper only low-order pseudo-harmonics are analyzed. Some results regarding the arc dynamic response and the time constants related to arc model can be found in [7].

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. The meteorological conditions during the test are also recorded.

III. ANALYSIS OF THE VOLTAGE AND CURRENT MEASUREMENTS

Due to the large volume of data, numerical pre-processing was required so as to verify the consistency and separate the desired information from the data. Fig. 3 shows the voltage between the arc terminals and the sustained current of the arc during a complete test of current rating 200 A_{rms}. The voltage increase between the arc terminals is apparent as it elongates as the test progresses.

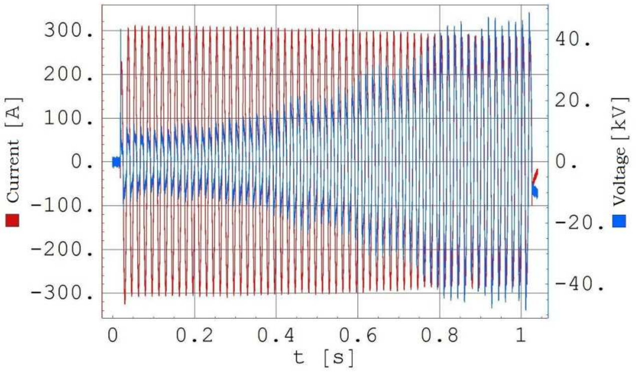

Fig. 3. Voltage and sustained current obtained from a field test of arc rating 200 A_{rms}.

Fig. 4. Images of the test of arc rating 200 A_{rms}.

Some images of this test of current rating 200 A_{rms} are shown in fig. 4. These photographs give one a better idea of the speed of the arc variation during the test. Although in chronological order, the intervals between each image are not necessarily constant.

More details of the voltage and current of this test can be found in fig. 5 and 6. As the test involved the imposition of a sustained current (60 Hz), it can be noted that the current amplitude is maintained practically constant throughout the test. Meanwhile, the voltage between the arc terminals increases, although its wave shape remains similar, indicating that the "pseudo-harmonic" content did not vary during the experiment.

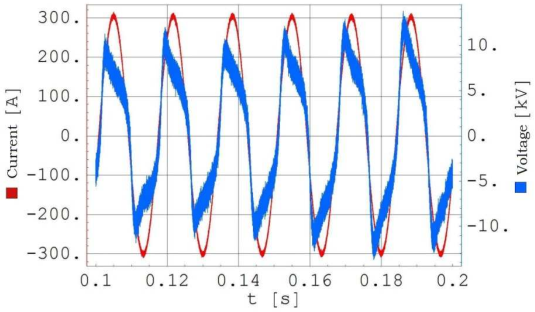

Fig. 5. Voltage between the arc terminals and sustained arc current obtained from a field test of arc rating 200 A_{rms} between 100 ms and 200 ms.

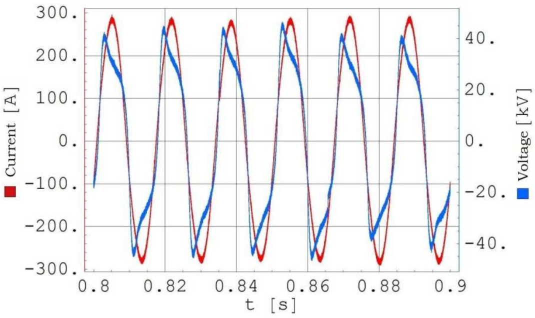

Fig. 6. Voltage between the arc terminals and sustained arc current obtained from a field test of arc rating 200 A_{rms} between 800 ms and 900 ms.

IV. HARMONIC SIGNATURE

The pseudo-harmonic contents of the current and of the voltage between the terminals of secondary arcs measured in the tests were obtained by applying the Windowed (or short-time) Discrete Fourier Transform (WDFT). The WDFT is acquired by splitting the signal into smaller segments, by multiplying the original signal by a window function. Then the spectrum of each segment is determined by the Discrete Fourier Transform. To this end a retangular type window was applied, with a width equivalent to a 60 Hz period and moving in steps of 20 μs.

Continuous analysis of these spectra reveals the evolution of the frequency content over time, characterizing a time-frequency distribution.

Pseudo-harmonics were calculated up to the 15th order of the field test secondary arcs. The term "pseudo" is used due to the fact that the current and voltage are not perfectly periodic functions in time, however it is assumed that for each window of time these signals can be treated as periodic. At this stage of the work no comparison was performed regarding different methods to obtain the pseudo-harmonic content.

From this analysis it was possible to identify a pseudo-harmonic signature for these arcs.

A. *Analysis of the Current Rating 200 A_{rms} Test*

This section presents the results obtained from the WDFT analysis of the current rating 200 A_{rms} arcs. Fig. 7 shows the amplitudes of the first order pseudo-harmonic of the voltage between the arc terminals, $Varc_1$, and of the arc current, $Iarc_1$.

Fig. 8 shows the amplitudes of the other odd order pseudo-harmonics of voltage calculated for this test.

Fig. 9 shows the relation between the amplitudes of the odd order pseudo-harmonics of the voltage between the arc terminals and the amplitude of the first order pseudo harmonic of this voltage. The odd order pseudo harmonics are very significant, however gradually drop as the harmonic order increases. By the 15th order, the amplitude of the pseudo harmonic of voltage is already insignificant.

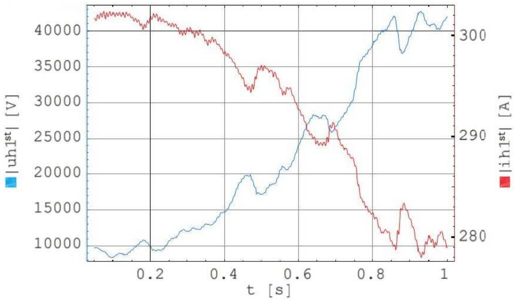

Fig. 7. Amplitude of the 1st order pseudo-harmonic of voltage between the src terminals and of current of a 200 A_{rms} rating arc.

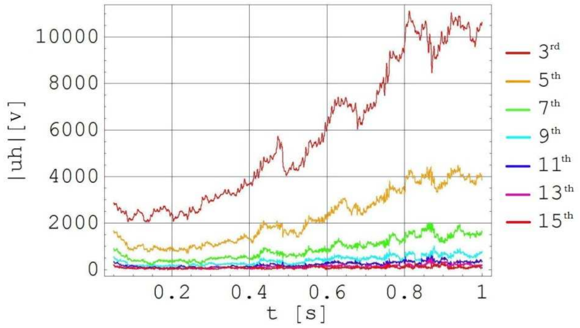

Fig. 8. Amplitude of the odd order pseudo harmonics of the voltage of a 200 A_{rms} rating arc.

As the voltage wave (fig. 5 and 6) is approximately symmetrical in relation to the abscissa, the harmonic frequencies present will primarily be odd multiples of the fundamental frequency. Therefore, the even order pseudo harmonics of the voltage between the arc terminals are very small [6].

The harmonic level of the current is much smaller than that of the voltage. This low harmonic content of the current is explained by the fact that throughout the whole test the current signal is imposed with an approximately "pure" sustained signal of 60 Hz. Beside that, the harmonic current content that appears is due to interation between the arc and the source frequency response.

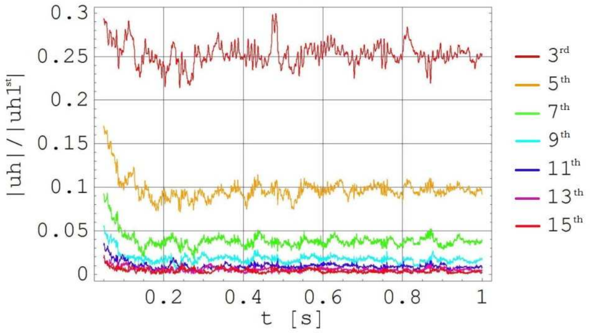

Fig. 9. Relation between the amplitudes of the odd pseudo harmonics and the amplitude of the first order pseudo harmonic of the voltage between the arc terminals of a 200 A_{rms} rating arc.

It should be pointed out that the secondary arc current that arises during single-phase opening is fed by the capacitive coupling between the healthy phases that remain energized and the open phase. As the voltages of the healthy phases are fed by the 60 Hz system (industrial frequency), the current will predominantly be a signal on that frequency. There will, however, be some harmonics due to the harmonic content of the voltage between the arc terminals that will generate low amplitude voltage harmonics in the healthy phases by coupling. These low amplitude harmonics will generate small current harmonics by coupling in the secondary arc.

Based on the foregoing, one can consider that the secondary arc current that emerges in a transmission system during SPAR for a non-solid fault is predominantly a 60 Hz current. The harmonic content of the secondary arc current in a transmission system should be formed primarily by odd-numbered harmonics of low amplitude, which reduce even more as the harmonic order progresses. It can also be expected that there are both current harmonics and voltage harmonics between the arc terminals, although the voltage harmonic content will be much greater than that of the current.

Based on this, the approach made in the presented experiments is not far from reality. The electric arc artificially generated formed by basically fundamental frequency current can have a small error due to not representing the odd pseudo-harmonic current that would be generated due to arc-network interaction.

These characteristic harmonics, here named the “pseudo-harmonic signature”, can be used to identify the existence of the secondary arc [8].

V. STABILIZATION OF THE ELECTRIC ARC

For an interval of time after its formation in the experiment, the arc remains without stabilized electrical characteristics. This is due primarily to 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.

It was observed [9] that for some arcs analyzed in this study the expected relation between the arc elongation with the first order pseudo harmonic of its voltage did not occur. However, considering only the period when the relations between the pseudo harmonics with the first order pseudo harmonic of the arc voltage were almost constant, the expected relation between the arc elongation and arc voltage is confirmed.

Therefore, analysis of the harmonic content is shown to be an effective tool to determine the instant at which the electric arc becomes stabilized. Fig. 10 shows the relations between the odd-numbered pseudo harmonics of the voltage and the first pseudo harmonic of four distinct tests, demonstrating the variable relations at the beginning of the test, tending toward a flat profile when the arc is then considered stable in the test, free of the cited influences. For the majority of the tests analyzed in this study, this instant occurred between 150 ms and 300 ms.

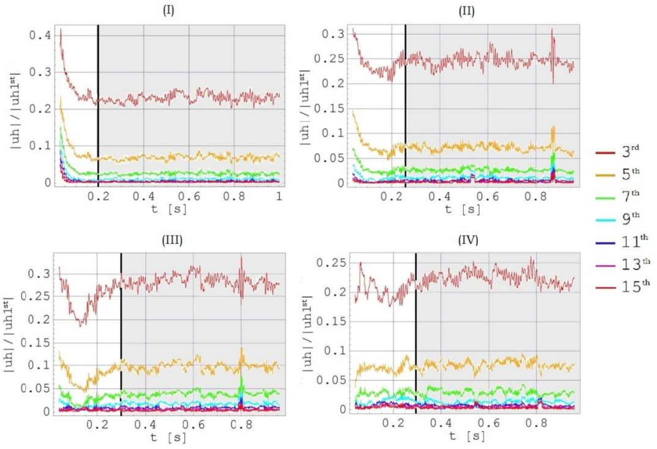

Fig. 10. Instant at which the electric arc becomes stabilized of four distinct tests: (I) 30 Arms rating arc, (II) 60 Arms rating arc, (III) 100 Arms rating arc and (IV) 500 Arms rating arc.

VI. HARMONIC CONTENTS

Harmonic analysis was made on a total of 543 arcs generated in the field tests. The harmonic signature can be identified after statistical treatment of the harmonic contents obtained.

For these results, a procedure similar to that presented by [8] was used, and also the same database was employed. In relation to the procedure, the major difference is the fact that the first 300 ms of all the tests were discarded, in order to analyze the arc in stable conditions, as per exposed above. The database, meanwhile, was increased with 195 new treated tests, including new current ratings analyzed.

The statistical results for the harmonic content (average relation of the pseudo harmonics with the first order pseudo harmonic, and standard deviation) of all the analyzed tests are presented in Tables 1 and 2. The orders of pseudo harmonics omitted in these tables presented average relation values of less than 1%.

It was analyzed a sufficient number of tests to provide a

TABLE I

HARMONIC SIGNATURE - STATISTICAL RESULTS - PART I

Current Rating (A_{rms})			**15**		**30**		**50**		**60**		**100**		**150**	
Number of Tests			28		32		15		102		71		51	
I_{rms} (A_{rms})			13.867		36.429		54.884		63.882		106.23		153.766	
V_{rms} (kV_{rms})			22.535		19.043		16.143		16.579		12.334		10.74	
$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$ **(%) and σ**			$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$	σ	$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$	σ	$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$	σ	$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$	σ	$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$	σ	$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$	σ
Voltage	**Odd Order**	**3ª**	**27.51**	0.60	**22.33**	0.71	**22.71**	0.91	**25.32**	1.07	**27.07**	1.24	**27.25**	0.60
		5ª	**10.87**	0.48	**6.42**	0.45	**5.97**	0.46	**7.31**	0.70	**9.07**	0.81	**10.49**	0.53
		7ª	**4.87**	0.32	**2.29**	0.24	**1.98**	0.20	**2.71**	0.37	**3.49**	0.43	**4.17**	0.36
		9ª	**2.37**	0.22	**0.92**	0.14	**0.83**	0.12	**1.17**	0.19	**1.60**	0.22	**1.95**	0.17
	Even Order	**2ª**	**3.30**	0.58	**2.75**	0.29	**3.16**	0.22	**2.51**	0.41	**2.87**	0.59	**2.60**	0.40
		4ª	**1.99**	0.38	**1.30**	0.15	**1.49**	0.10	**1.22**	0.21	**1.46**	0.35	**1.31**	0.21
Current	**Odd Order**	**3ª**	**1.63**	0.28	**0.95**	0.17	**0.93**	0.17	**1.27**	0.30	**0.71**	0.16	**0.48**	0.12
	Even Order	**2ª**	**1.21**	0.15	**1.21**	0.08	**0.84**	0.08	**1.08**	0.53	**1.00**	0.22	**1.11**	0.17

TABLE II

HARMONIC SIGNATURE - STATISTICAL RESULTS - PART II

Current Rating (A_{rms})			**200**		**300**		**500**		**1000**		**3000**		**10000**	
Number of Tests			85		52		49		21		29		8	
I_{rms} (A_{rms})			204.573		295.092		519.731		932.226		2954.47		8707.255	
V_{rms} (kV_{rms})			10.69		8.953		7.559		9.425		8.275		7.142	
$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$ **(%) and σ**			$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$	σ	$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$	σ	$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$	σ	$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$	σ	$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$	σ	$\overline{\left(\left\lvert\frac{h^{th}}{1^{st}}\right\rvert\right)}$	σ
Voltage	**Odd Order**	**3ª**	**25.36**	0.77	**24.03**	0.41	**21.20**	0.57	**20.46**	0.74	**20.62**	0.94	**18.90**	0.93
		5ª	**9.70**	0.67	**9.27**	0.39	**7.64**	0.37	**6.81**	0.46	**6.93**	0.66	**6.34**	0.81
		7ª	**3.83**	0.36	**3.70**	0.24	**3.08**	0.21	**2.67**	0.26	**2.93**	0.39	**2.92**	0.63
		9ª	**1.72**	0.21	**1.62**	0.13	**1.37**	0.11	**1.20**	0.15	**1.50**	0.26	**1.61**	0.43
	Even Order	**2ª**	**2.30**	0.45	**2.32**	0.26	**3.34**	0.51	**2.22**	0.21	**3.24**	0.49	**3.21**	0.62
		4ª	**1.15**	0.24	**1.09**	0.13	**1.39**	0.26	**0.93**	0.14	**1.36**	0.26	**1.33**	0.39
Current	**Odd Order**	**3ª**	**0.51**	0.24	**0.38**	0.08	**1.46**	0.29	**2.38**	0.43	**1.28**	0.26	**1.13**	0.39
	Even Order	**2ª**	**1.12**	0.48	**1.42**	0.11	**1.16**	0.11	**1.69**	0.09	**1.46**	0.39	**1.09**	0.12

statistical approach for almost all current ratings, except only for the arcs of current ratings of 10,000 A_{rms}. The presence of this current rating in Table 2 is merely for informative purposes, and should be better studied in future.

The arrangement of the insulator strings used in the tests, either "I-shaped" or "V-shaped", did not significantly influence the results. Therefore, no distinction has been made in relation to this fact.

Tables 1 and 2 show that even after discarding the measurements relative to the first 300 ms of the tests, the values obtained for the average relation of the pseudo harmonics with the first order pseudo harmonic were very close to those obtained by [6] for the corresponding current ratings, with equally small standard deviations.

The values obtained for the new current ratings analyzed in this study (15 A_{rms}, 30 A_{rms}, 50 A_{rms} and 1000 A_{rms}) are in accordance with the expected harmonic signature, with the average relation between the voltage 3rd order and 1st order pseudo harmonics lying in the range of 20 % to 27 %, the average relation of the voltage 5th order and 1st order pseudo harmonics between 7 % and 11 % and the relation of the voltage 7th and 1st order between 3 % and 5 %.

The graphs of fig. 11 and 12 highlight the average values of the two most relevant pseudo harmonics in relation to the first order pseudo harmonic of the voltage between the arc terminals. Note the declining trend in these harmonics as from the tests of rating 150 A_{rms}. However, for tests with sustained currents below that rating such a trend was not verified.

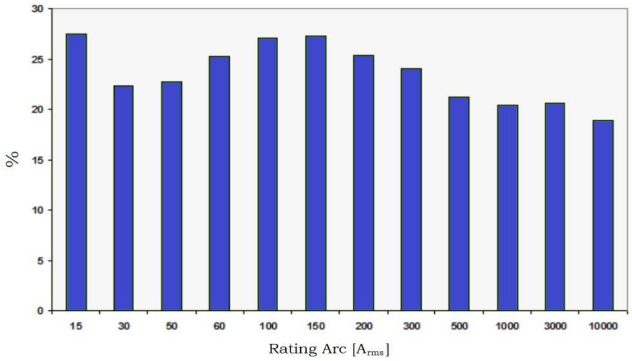

Fig. 11. Average relation of the amplitudes of the 3rd order pseudo harmonics of the voltage and the amplitude of the first order pseudo harmonic of the voltage between the arc terminals for the different current ratings.

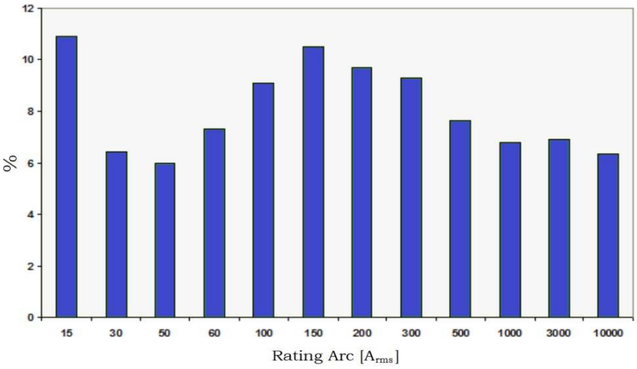

Fig. 12. Average relation of the amplitudes of the 5th order pseudo harmonics of the voltage and the amplitude of the first order pseudo harmonic of the voltage between the arc terminals for the different current ratings.

VII. CONCLUSIONS

The use of single-phase autoreclosing is justified in essence due to the very nature of the kind of fault to be eliminated, and the direct advantages of its use are mainly perceived as a consequence of the partial continuity of the supply, which also entails positive effects on dynamic aspects, the electro-mechanical and voltage stability, operational flexibility and reliability.

The most relevant phenomenon in the studies for implementation of single-phase autoreclosing is the extinction of the secondary arc. The better this phenomenon is modeled, the better the optimization will be, not only of the solution employed, but also of the installation and planning of the grid. Conservative or overly simplified analysis methodologies, as well as failing to point out genuinely optimized solutions, also run the risk of generating incorrect solutions.

This study presented the results of field test analyses of electric arcs conducted by the CEPEL High Power Laboratory, on an experimental stretch of 500 kV transmission line. In particular, the harmonic content analysis of the arc currents and voltages between the arc terminals were presented. Due to the large number of tests, it was possible to identify the harmonic content of the electric arcs with different characteristics.

With this harmonic content it is possible to identify the instant at which the arc can be considered stable in the air. This instant is determined by identifying when the relations between the pseudo harmonics and the first order pseudo harmonic of the arc voltage become approximately constant.

Considering the methodology of executing field tests involving the imposition of a sustained 60 Hz current on the arc with low-level harmonics, it was possible to characterize a harmonic signature of the arc by analyzing the pseudo harmonics of the voltage between the arc terminals. Only the period during which the arc is already stabilized in the air was considered.

The results were similar to those obtained in a previous study when the arc stability was not taken into account as the period disregarded was small when compared to the experiment period. It could be observed that the relation between the amplitude of the 3rd order and 1st order pseudo harmonics of the voltage between the arc terminals is between 20 % and 27 %. The amplitude of the 5th order pseudo harmonic in relation to the 1st order varies between 6 % and 10 %, and the relation between the amplitude of the 7th order pseudo harmonic and the 1st order is between 2 % and 5 %. The amplitudes of the other pseudo harmonics of the voltage between the arc terminals (higher odd-numbered all the even-numbered pseudo harmonics) are insignificant.

Due to the amount of tests and the variety of the electric arc current ratings analyzed, it can be expected that this harmonic signature is roughly maintained for secondary arcs of any current amplitude rating while they are in stable condition.

VIII. 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.

IX. REFERENCES

[1] J. Estergalyos, “The application of high speed grounding switches on EHV-UHV power systems to enhance single pole reclosing control and protection”, Proc. 1981 Western Protective Relay Conference, USA.

[2] K.H. Milne, “Single-pole reclosing tests on long 275 kV transmission lines”, IEEE Transactions on Power Apparatus and Systems, vol.82, pp.658-661, 1963.

[3] R. Luxenburger and P. Schegner, “Determination of secondary arc extinction time and characterization of fault conditions of single-phase autoreclosures”, Proc. 2005 International Conference on Future Power Systems, Amsterdam, Netherlands. pp.1-5.

[4] J. Giesbrecht, D. Ouellette, and C. Henville, “Secondary arc extinction and detection real and simulated”, Proc. 2008 International Conference on Developments in Power System Protection, Glasgow, Scotland. pp.138-143.

[5] C. Portela and M.C. Tavares, “Transmission system parameters optimization – Sensitivity analysis of secondary arc current and recovery voltage”. IEEE Transactions on Power Systems, Vol.19; pp.1464-1471, 2004.

[6] A. Montanari, M.C. Tavares, C. Portela, and A. Câmara, “Secondary arc voltage and current harmonic content for field test results”, Proc. 2009 International Conference on Power Systems Transients, Kyoto, Japan.

[7] A. Câmara, R. Gonçalves, M. Rodrigues, O. Oliveira, C. Portela and M.C. Tavares, “Single-phase autoreclosure studies: secondary arc model research including a 500 kV line experimental circuit”, Proc. 2008 International Conference on High Voltage Engineering and Application (ICHVE), Chongqing, China.

[8] A. Montanari, M.C. Tavares and C. Portela, “Adaptative single-phase autoreclosing based on secondary arc voltage harmonic signature”, Proc. 2009 International Conference on Power Systems Transients, Kyoto, Japan.

[9] J. Talaisys, M.C. Tavares, C. Portela, A. Camara, “Estimation of Length Variation of Artificially Generated Electrical Arc in Out-Door Experiment”, Proc. 2011 International Conference on Power Systems Transients, Delft, The Netherlands.