Secondary Arc Voltage and Current Harmonic Content for Field Tests Results

A. A. Montanari, M. C. Tavares, C. M. Portela, A. B. Câmara

Abstract--**In this paper the harmonic content of measured secondary arc current and voltage between the arc terminals were analyzed by the application of the Short Time Discrete Fourier Transform (STDFT). The algorithm is based on shifting a window on the signals (voltage and current) and computing the coefficients of the STDFT. The measurements were performed on a large number of field tests realized at CEPEL High Power Laboratory in Brazil. It was possible to identify a harmonic signature of the "secondary arc" produced in the field tests and some extrapolation can be made for actual secondary arc.**

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

I. Introduction

It is well-known that most frequent faults on high voltage overhead lines are single-phase faults, which are mainly non-permanent type of fault. To improve system reliability Single-Phase Auto Reclosure (SPAR) is a widespread technique employed.

An accurate prediction of the fault transients requires a detailed and comprehensive representation of all the components in a system. A realistic simulation of fault arcs is extremely important in the successful design and development of SPAR [1].

Although SPAR is widely employed, a critical aspect of its design is the prediction of the secondary arc extinction before successful reclosure [2, 3, 4]. A reliable arc model is still pursued by several research groups all over the world [5, 6, 7].

Field tests have been carried out aiming the investigation of the secondary arcing process in details. As intermediate result, the harmonic characteristics of the arc current and voltage between the arc terminals during the field tests have been obtained.

In the following sections the field test is briefly described and some tests results are present. Furthermore, the harmonic content of current and voltage is presented for the field tests analyzed up to now.

With the harmonic signature of the arc, it was possible to propose a new Fast Adaptative SPAR which can reclose the opened phase as soon as the secondary arc extinguishes. The proposed procedure is properly described in a companion paper [8].

II. Secondary Arc

Secondary arc extinction is the most important phenomenon in transmission line SPAR studies. Various experimental studies and field tests have shown that the overall process of the secondary arc is an extremely complex phenomenon and it is influenced by various parameters.

The secondary arc extinction time depends on several factors, and among them it can be listed: magnitude of secondary arc current, recovery voltage, line compensation level, line voltage level and line length. At the same time, those factors are affected also by weather conditions such as: temperature, humidity, pressure and wind speed.

A. Field Tests

Significant research has been conducted to assess and improve the performance of single-phase switching of overhead transmission lines.

A test infrastructure was established at CEPEL High Power Laboratory in Brazil, including an outdoor actual 500 kV line structure formed by three towers and two spans and the necessary measuring systems, where arcs have been generated and monitored (Fig. 1).

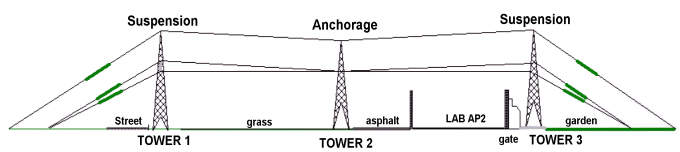

Fig. 1. 500 kV experimental spans.

The tests consist of generating an arc imposing a sustained 60 Hz current during 1s. In the test a wide range of current amplitudes were imposed, but for the present work only some data were analyzed, being: 60 A_{rms}, 100 A_{rms}, 150 A_{rms}, 200 A_{rms}, 300 A_{rms}, 500 A_{rms} and 3000 A_{rms}.

As the secondary arc is basically composed of fundamental frequency, the field test imposes the dominant component frequency of the secondary arc behavior as if it were originated by sound phases coupling. However, when an arc is established in a transmission system there will be a dominant 60 Hz component of the arc current and the voltage between

The work of authors was partially supported by CNPq - National Council of Scientific and Technological Development from Brazil - and FAPESP - The State of São Paulo Research Foundation.

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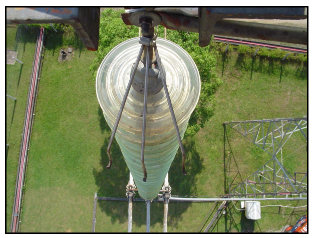
Paper submitted to the International Conference on Power Systems Transients (IPST2009) in Kyoto, Japan June 3-6, 2009

arc terminals and also others harmonics components, quite exclusively odd ones, which also can appear both in arc current and voltage between arc terminals, depending on the systems interaction with the arc response at the arc terminal. It is expected that the voltage harmonic content is much bigger than the current harmonic content for actual field secondary arc.

Secondary arc current in regular lines are normally lower than 10^2 A_{rms} for not very long lines, but in the field tests arc currents up to 3000 A_{rms} were generated. In the research project an arc model for higher current will be obtained.

The arc tests were produced over a vertical “I” insulator string at the tower. A fuse wire was stuck with hooks in parallel to the insulator string and it was utilized to provide the arc ignition (Fig. 2).

(a)



(b)

(c)

(d)

Fig. 2. Insulator string details: (a) view from below, (b) view from above, (c) lower hooks , (d) upper hooks.

The secondary arc current flows through the wire and it burns out igniting the secondary arc. After 1 s from the arc ignition, the sustained current is switched off. The arc current and arc voltage are A/D converted and measured.

The main purpose of this research project is to obtain and validate a robust model of the secondary arc in the air, allowing to simulate the interaction between the arc and the network, at arc terminals, and the evaluation of SPAR success (or not). When analyzing the data, the harmonic signature emerged as an useful result.

B. *Voltage and Current Measured*

The system measurement acquires, stores and processes 10 million samples per second for each measurement. It was necessary to implement a pre-processing in order to verify the quality of the measurements, to filter data and to separate the desired information. In Fig. 3 to Fig. 5 the measured voltage between arc terminals and the sustained arc current of a 300 A_{rms} current class arc test are presented. Two detailed graphics of the voltage and current are presented in Fig. 4 and Fig. 5 to show the voltage waveform along the test. It can be observed that the current has rather the same magnitude all over the test while the voltage between the arc terminals increases, although it does not change the relative waveform, meaning that the relative harmonic content should be similar.

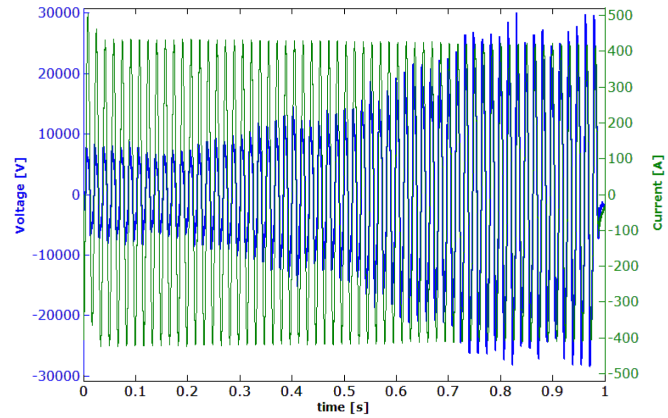


Fig. 3. Measured voltage and current of a 300 A_{rms} current class secondary arc field test simulation on a 500 kV transmission line.

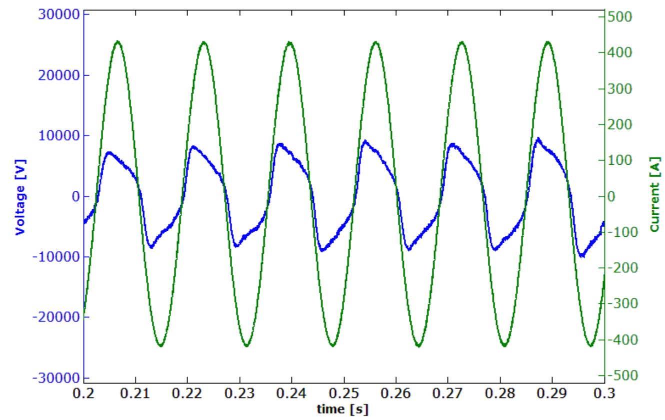


Fig. 4. Detail of the measured voltage and current of a 300 A_{rms} current class secondary arc field test simulation on a 500 kV transmission line - Time interval 200 to 300 ms.

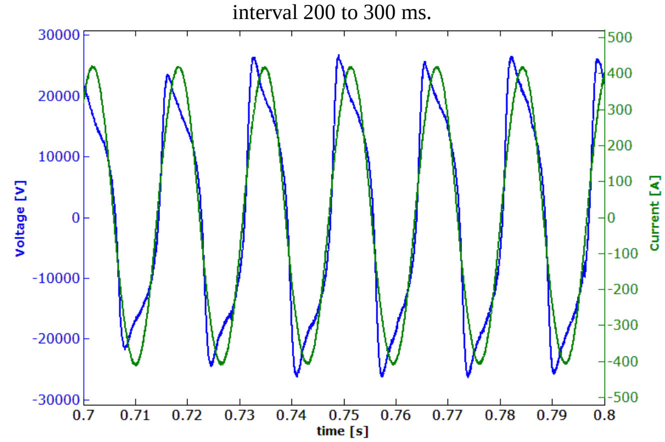


Fig. 5. Detail of the measured voltage and current of a 300 A_{rms} current class secondary arc field test simulation on a 500 kV transmission line - Time interval 700 to 800 ms.

Fig. 6 depicts images of the 1 s duration 300 A_{rms} current class field test. The pictures give more detailed information of the fast variation of the arc during the test. Only some images are presented and the time interval between each image is not the same. These images were chosen to show the arc behavior during the test.

III. Harmonic Signature

The harmonic content of the measured secondary arcs current and voltage were analyzed by the application of Short Time Discrete Fourier Transform (STDFT). The proposed algorithm is based on shifting a window along the signals. Using known sampling measured data, the coefficients of the STDFT can be calculated by:

$$\hat{V}_h = \sum_{k=0}^{N-1} \frac{V_k exp(- j\omega hk)}{N} \qquad (1)$$

where V is the voltage between the arc terminals, $\hat{V}_h$ is the complex pseudo-harmonic voltage, $\omega=2\pi f$ is the reference pulsation (frequently named angular velocity, a non-physically robust terminology), f is the reference frequency, h is the pseudo-harmonic order, k is the sample sequential ordinal number, N is the number of samples per pseudo-cycle, and $j = \sqrt{-1}$ is the imaginary unity. The word *pseudo* emphasizes the fact that current and voltage are not exactly periodic functions at $-\infty < time < +\infty$.

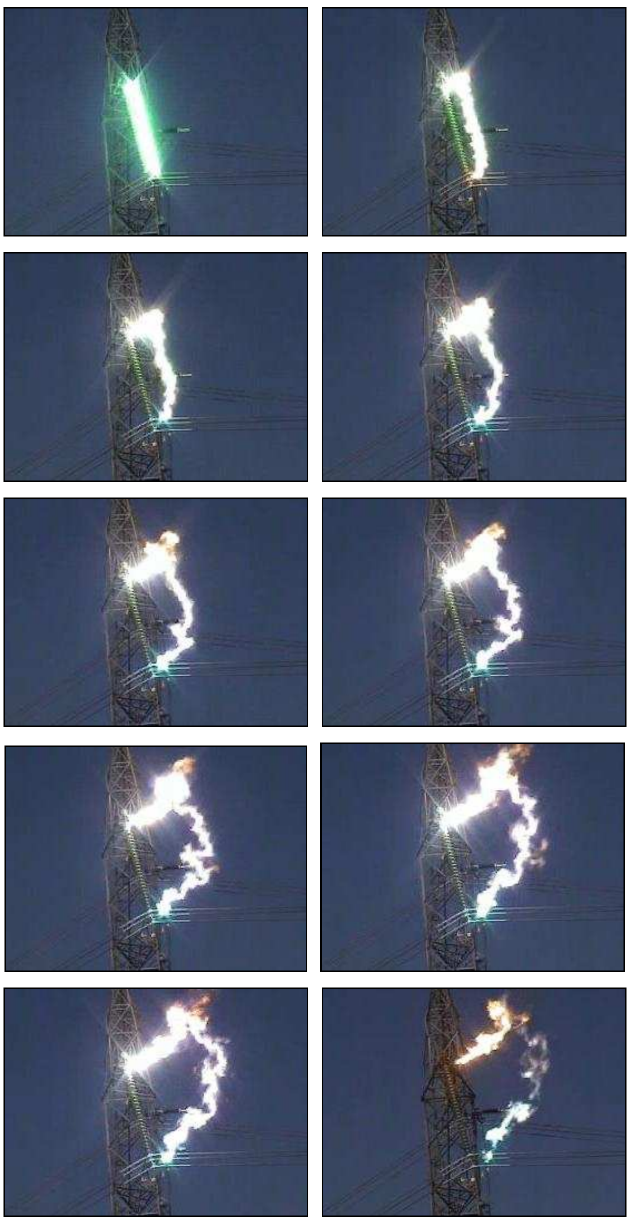


Fig. 6. Captured images of a 300 A_{rms} current class secondary arc field test.

The magnitude of *h-th* pseudo-harmonic order V_h is obtained by:

$$V_h = \left|\hat{V}_h\right| = \sqrt{Re^2\{\hat{V}_h\} + Im^2\{\hat{V}_h\}} \qquad (2)$$

The analysis provides frequency and time information. As a large harmonic range of the fundamental frequency was analyzed (1^{st} - 15^{th} order) it was possible to identify a harmonic signature of the secondary arc produced in the test.

The currents data were computed with the same expressions (1) and (2).

A. 300 A_{rms} Current Class Test Analysis

This section shows results of the STDFT analysis. Fig. 7 depicts the first order pseudo-harmonic current and voltage between the arc terminals of the 300 A_{rms} current class field test presented.

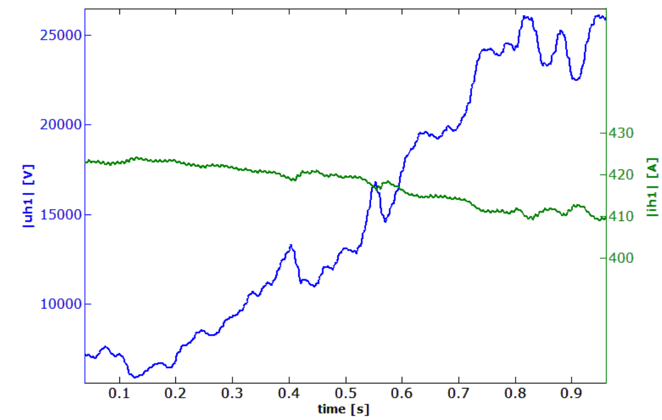


Fig. 7. Magnitudes of the first order pseudo-harmonic of the measured voltage between the arc terminals and of the measured sustained arc current.

Fig. 8 shows the magnitudes of the odd order pseudo-harmonics of voltage (except 1^{st} order).

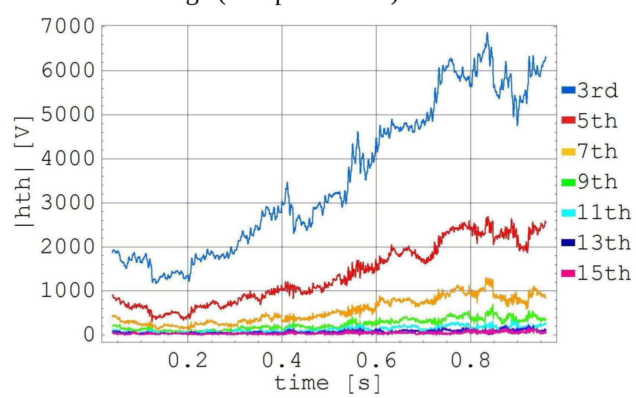


Fig. 8. Magnitude of the odd order pseudo-harmonics (except 1st order) of the measured voltage between the arc terminals.

Fig. 9 and Fig. 10 show results concerning the relation between the odd order and even order pseudo-harmonics and the 1^{st} order pseudo-harmonic measured voltage between the arc terminals, respectively.

The voltage waveform (Fig. 4 and Fig. 5) is approximately symmetrical above and below its average centerline, with a time translation of half-period, in a fixed length window of 1 period at 60 Hz (16,67 ms). Thus, the harmonic frequencies will be odd integer multiples of the fundamental, with no important even integer multiples. The half-wave symmetric waveforms have no even order harmonics. Even pseudo-harmonics (from 2nd to 14th) are absent or only minimally present.

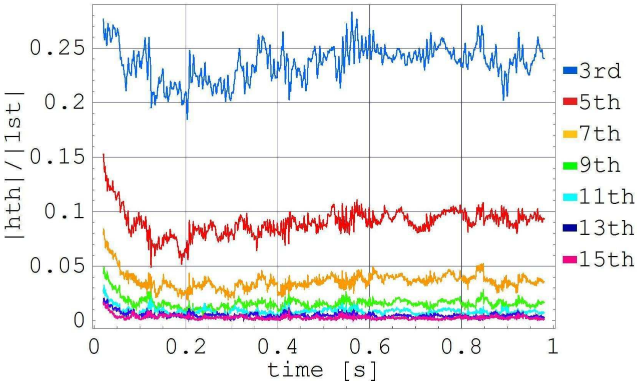


Fig. 9. Relations between the magnitude of the odd order pseudo-harmonics and the magnitude of the first order pseudo-harmonic of the measured voltage between the arc terminals.

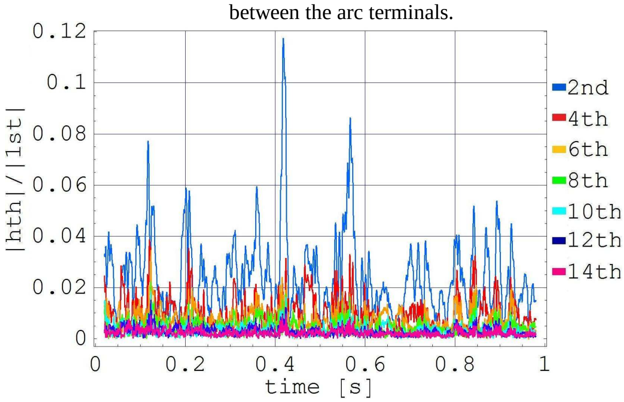


Fig. 10. Relations between the magnitude of the even order pseudo-harmonics and the magnitude of the first order pseudo-harmonic of the measured voltage between the arc terminals.

Fig. 9 and Fig. 10 confirm this analysis, showing that the odd order far outweigths the even order. Only very low magnitude even order pseudo-harmonics are present. The odd order pseudo-harmonics are quite high, but the magnitude decreases as the harmonic order increases. By the 15th order, the magnitude of the pseudo-harmonic is negligible.

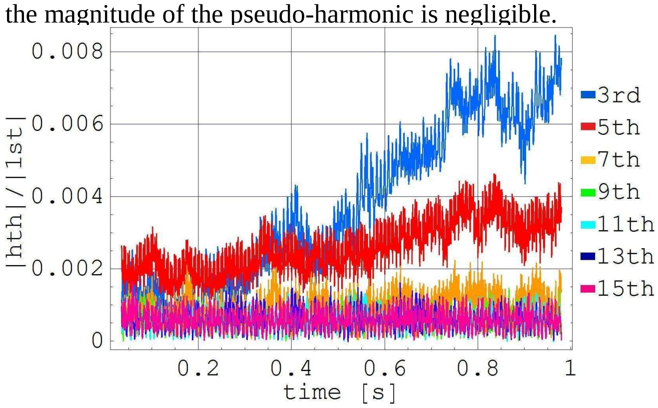


Fig. 11. Relations between the magnitude of the odd order pseudo-harmonics and the magnitude of the first order pseudo-harmonic of the measured current imposed.

Fig. 11 and Fig. 12 show results of the STDFT analysis concerning the odd order and even order pseudo-harmonics, related to the 1st order pseudo-harmonic measured current, respectively.

As can be seen from Fig. 11 and Fig. 12, the current harmonic levels in the tests are much lower than the voltage harmonic levels, i.e., the secondary arc current harmonic content is very low, apart from imperfections, due to the fact that this signal is imposed and sustained by the test system. The 2nd order pseudo-harmonic is around 1 % of the fundamental frequency current. As explained, this harmonic content is originated by the basic field test characteristic of imposing a sustained almost pure 60 Hz current during all test.

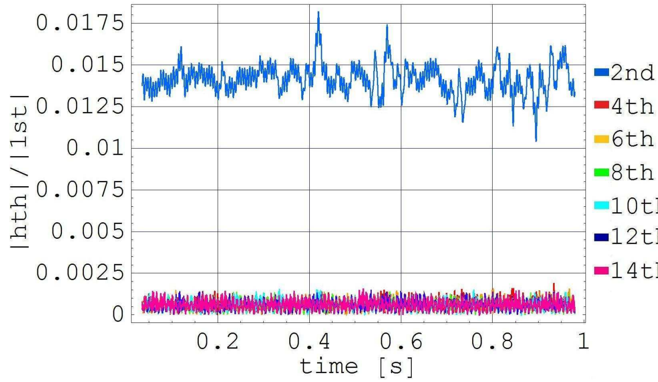


Fig. 12. Relations between the magnitude of the even order pseudo-harmonics and the magnitude of the first order pseudo-harmonic of the measured current imposed.

However, it is expected that the harmonic content of an actual secondary arc in a transmission system is formed dominantly by odd harmonics, that will have decreasing magnitude as the harmonic order increases and that can have harmonic componentens both in the arc current and the voltage between the arc terminals, depending on the system response at the arc terminals. The voltage harmonic content in an actual field arc should be much bigger than the current one as the secondary arc current originates from the phase coupling and the sound phases voltage are basically 60 Hz.

This harmonic "signature" of test arcs can be applied for the identification of the secondary arc existence.

B. *Other Tests Results*

In the presented study, 348 field tests were analyzed. A probabilistic approach was applied to the data in order to achieve the harmonic signature.

The relation between the magnitude of the pseudo-harmonics and the magnitude of the first order pseudo-harmonic of the measured voltage between the arc terminals was calculated for each test and may be written as:

$$\overline{\left(\frac{\left|h^{th}\right|}{\left|1^{st}\right|}\right)} = \frac{1}{N}\sum_{k=1}^{N}\frac{V_{h_k}}{V_{1_k}} \qquad (3)$$

where h is the pseudo-harmonic order, 1^{st} is the first order pseudo-harmonic, N is the number of samples, V_h is the voltage and k is the sample.

The average value of this relation (3) was computed for each rms current class test:

$$\overline{\left(\frac{\left|h^{th}\right|}{\left|1^{st}\right|}\right)}_{N_T} = \frac{1}{N_T}\sum_{i=1}^{N_T}\overline{\left(\frac{\left|h^{th}\right|}{\left|1^{st}\right|}\right)} \qquad (4)$$

where N_T is the number of tests.

TABLE I

HARMONIC SIGNATURE - STATISTICAL RESULTS

		Current Class (A_{rms})	**60**		**100**		**150**		**200**		**300**		**500**		**3000**	
		N_T (Number of Tests)	80		53		51		57		52		49		6	
		$\overline{I_{rms}}$ (A_{rms})	64.907		103.132		153.766		203.153		295.092		519.731		2927.872	
		$\overline{V_{rms}}$ (kV_{rms})	16.314		12.436		10.740		9.655		8.953		7.559		6.860	
		$\overline{\left(\frac{\lvert h^{th}\rvert}{\lvert 1^{st}\rvert}\right)}$ (%) and σ	$\overline{\left(\frac{\lvert h^{th}\rvert}{\lvert 1^{st}\rvert}\right)}$	σ	$\overline{\left(\frac{\lvert h^{th}\rvert}{\lvert 1^{st}\rvert}\right)}$	σ	$\overline{\left(\frac{\lvert h^{th}\rvert}{\lvert 1^{st}\rvert}\right)}$	σ	$\overline{\left(\frac{\lvert h^{th}\rvert}{\lvert 1^{st}\rvert}\right)}$	σ	$\overline{\left(\frac{\lvert h^{th}\rvert}{\lvert 1^{st}\rvert}\right)}$	σ	$\overline{\left(\frac{\lvert h^{th}\rvert}{\lvert 1^{st}\rvert}\right)}$	σ	$\overline{\left(\frac{\lvert h^{th}\rvert}{\lvert 1^{st}\rvert}\right)}$	σ
Voltage	**Odd Order**	**3rd**	**25.012**	1.111	**27.930**	1.038	**26.813**	0.596	**25.634**	0.676	**23.768**	0.410	**21.744**	0.573	**21.239**	0.897
		5th	**7.279**	0.740	**9.605**	0.772	**10.260**	0.525	**10.099**	0.585	**9.159**	0.387	**7.832**	0.371	**7.588**	0.834
		7th	**2.756**	0.388	**3.741**	0.442	**4.063**	0.361	**4.072**	0.344	**3.719**	0.239	**3.209**	0.210	**3.398**	0.484
		9th	**1.225**	0.194	**1.737**	0.235	**1.938**	0.174	**1.849**	0.218	**1.672**	0.129	**1.473**	0.113	**1.907**	0.352
		11th	**0.654**	0.120	**0.954**	0.153	**1.015**	0.144	**0.998**	0.134	**0.886**	0.090	**0.777**	0.070	**1.190**	0.193
		13th	**0.421**	0.080	**0.590**	0.138	**0.609**	0.099	**0.595**	0.104	**0.524**	0.049	**0.493**	0.049	**0.854**	0.158
		15th	**0.324**	0.066	**0.407**	0.122	**0.399**	0.088	**0.421**	0.099	**0.351**	0.038	**0.351**	0.038	**0.616**	0.108
	Even Order	**2nd**	**2.542**	0.267	**2.522**	0.457	**2.479**	0.404	**2.527**	0.528	**2.533**	0.257	**2.789**	0.510	**4.227**	0.520
		4th	**1.272**	0.147	**1.431**	0.238	**1.331**	0.209	**1.387**	0.275	**1.229**	0.134	**1.321**	0.255	**2.020**	0.263
		6th	**0.778**	0.091	**0.915**	0.204	**0.893**	0.171	**0.962**	0.183	**0.834**	0.088	**0.868**	0.136	**1.241**	0.188
		8th	**0.558**	0.072	**0.652**	0.172	**0.608**	0.131	**0.671**	0.166	**0.567**	0.062	**0.605**	0.079	**0.848**	0.131
		10th	**0.433**	0.059	**0.498**	0.133	**0.464**	0.111	**0.519**	0.148	**0.422**	0.046	**0.440**	0.043	**0.642**	0.107
		12th	**0.359**	0.050	**0.409**	0.113	**0.366**	0.091	**0.420**	0.130	**0.335**	0.036	**0.353**	0.036	**0.513**	0.083
		14th	**0.312**	0.046	**0.344**	0.102	**0.313**	0.076	**0.345**	0.125	**0.281**	0.032	**0.294**	0.031	**0.431**	0.072
Current	**Odd Order**	**3rd**	**1.191**	0.248	**0.654**	0.166	**0.482**	0.122	**0.383**	0.107	**0.382**	0.083	**1.455**	0.294	**1.244**	0.217
		5th	**0.272**	0.068	**0.286**	0.061	**0.295**	0.040	**0.243**	0.091	**0.317**	0.050	**0.522**	0.079	**0.496**	0.061
		7th	**0.098**	0.025	**0.093**	0.051	**0.084**	0.048	**0.090**	0.042	**0.126**	0.016	**0.154**	0.020	**0.212**	0.021
	Even Order	**2nd**	**0.883**	0.503	**1.024**	0.237	**1.108**	0.173	**1.264**	0.427	**1.420**	0.105	**1.157**	0.112	**1.889**	0.422
		4th	**0.135**	0.040	**0.088**	0.067	**0.079**	0.050	**0.105**	0.059	**0.131**	0.021	**0.174**	0.024	**0.311**	0.027
		6th	**0.102**	0.033	**0.062**	0.050	**0.058**	0.043	**0.071**	0.044	**0.089**	0.016	**0.108**	0.016	**0.200**	0.013

The sample mean rms value for each rms current class test was obtained with:

$$\overline{V_{rms}} = \frac{1}{N_T}\sum_{i=1}^{N_T} V_{rms} = \frac{1}{N_T}\sum_{i=1}^{N_T}\sqrt{\frac{1}{N}\sum_{i=1}^{N} V_k^{\,2}} \qquad (5)$$

The currents data were computed with the same expressions (3) to (5), using the current data instead of voltage.

The statistical dispersion was analyzed by means of the standard deviation, indicating how widely spread the values of the experimental data were. The standard deviation was computed as follows (root-mean-square deviation of its values from the mean):

$$\sigma = \sqrt{\frac{1}{N_T - 1}\sum_{i=1}^{N_T}\left(x_i - \frac{1}{N_T}\sum_{i=1}^{N_T} x_i\right)^2} \qquad (6)$$

where σ is the standard deviation and x is the variable analyzed.

Analysis results for different current classes are depicted in Tab. I.

The number of each arc current class tests analyzed is between 50 to 80, for current class up to 500 A_{rms}, allowing a probabilistic analysis. For the 3000 A_{rms} current class, only 5 tests were analyzed, and this small set does not allow a pure probabilistic approach. The information presented in Tab. I for this last current class test is merely informative, and shall be improved in future works.

Apart the exception commented above, the voltage 3^{rd} order pseudo-harmonic has a small variation range, between 21 % to 28 % related to 1^{st} order pseudo-harmonic. The voltage 5^{th} order pseudo-harmonic varies from 8 % to 10 % related to 1^{st} order pseudo-harmonic and the following important pseudo-harmonic (7^{th}) varies from 3 % to 4 % related to 1^{st} order pseudo-harmonic. The remaining pseudo-harmonics have very low magnitude and are not important for the secondary arc signature. It is very important to observe that the standard deviation is rather small.

IV. CONCLUSION

Some results of outdoor secondary arc field tests realized on 500 kV actual tower structures in CEPEL Laboratory were analyzed. The results concerning harmonic content of sustained arc current and voltage between arc terminals were analyzed. The test results obtained allowed the establishment of the secondary arc harmonic content in an important range of conditions.

Specifically for the field test implemented, considering the basic approach of imposing a sustained 60 Hz arc current with very low harmonic content, the voltage 3^{rd} order pseudo-harmonic related to 1^{st} order pseudo-harmonic stays in a range between 21 % to 28 %. The voltage 5^{th} order pseudo-harmonic varies from 8 % to 10 % related to 1^{st} order pseudo-harmonic and the following important pseudo-harmonic (7^{th}) varies from 3 % to 4 % related to 1^{st} order pseudo-harmonic. The remaining pseudo-harmonics (all higher order odd pseudo-harmonics and all even order pseudo-harmonics) have very low magnitude and are not important for the secondary arc signature. The same statement can be presented to all orders of pseudo-harmonic current in relation to the 1st, with the exception of the 2nd order which is around 2 % of the 1st.

After analyzing the number of tests of this field experiment it seems that the harmonic signature of the secondary arc under the assumption of sustained 60 Hz current has been established for all classes of arc current magnitude. Some complimentary results will be presented for higher magnitude current tests in near future.

It is expected that when a secondary arc is established in a transmission system, the interaction between the system seen from the arc terminals and the arc itself will produce an arc that may have different harmonic content of the arc current and the voltage between arc terminals. However, those contents should be dominantly composed of odd harmonics, split between current and voltage, with ratios defined by the network impedance, for the harmonic frequency (except for power frequency), measured between the two network terminals between which secondary arc is established, and with magnitude decreasing, in principle, as the harmonic order increases. Low level of even harmonics both for arc current and voltage between arc terminals, and higher voltage harmonic content when compared to current harmonic content are expected.

V. Acknowledgment

The results presented in this paper have been obtained in the field tests realized in CEPEL High Power Laboratory, Brazil, and supported by FURNAS Centrais Elétricas S.A., Brazil.

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