Adaptative Single-Phase Autoreclosing Based on Secondary Arc Voltage Harmonic Signature

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

***Abstract*--This paper presents an adaptative Single-Phase Auto Reclosure (SPAR) scheme to minimize protection dead time. The proposed method detects the extinction of the secondary arc. Computer simulation and secondary arc field tests were combined to improve the performance of adaptative SPAR for various secondary arc current levels. The PSCAD/EMTDC program together with measured secondary arc data were used to simulate secondary arc on the system. The harmonic content of the secondary arc voltage was analyzed with Short Time Discrete Fourier Transform (STDFT). The proposed algorithm is based on the characteristics of the odd order harmonics of the faulted voltage. The algorithm determined the secondary arc extinction and gave the order to reclose the circuit breaker. A properly designed control can be responsible for taking the decision on whether the fault is a permanent one or a transient fault, and if the transient one has extinguished, i.e. whether to trip the other sound phases or to reclose the faulted phase after the secondary arc extinction.**

***Keywords:* Adaptative autoreclosing, secondary arc extinction, dead time, harmonic analysis, non-permanent faults.**

I. INTRODUCTION

Single-phase autoreclosing (SPAR) is widely employed to eliminate single-phase to ground faults, which constitutes the overwhelming majority of faults at transmission lines. Conventional SPAR assumes fixed dead time reclosure, that is, the breaker recloses after a defined period. However, if this period between the tripping operation and the reclosure of the faulted phase breakers is not optimized, there may be an unnecessary delay to reclose the phase after the arc extinction or the phase may be reclosed with the fault still existing.

Using invariable time delay for SPAR has some disadvantages. The main problems related with the conventional reclosure scheme are: the risk of a fault restrike due to an insufficient time to extinguish the fault; the risk of a second shock to the system in the case of a permanent fault; and the possibility of greater oscillations. These problems could jeopardize the system stability and reliability and cause serious damages with negative impact on utility equipment. Therefore, a method that determines when the arc is extinguished is very important for upgrading the performance of the reclosure techniques [1-4].

The efficiency of the SPAR may be significantly increased if SPAR had capability to trace, in real time mode, the status of the secondary arc in order to close the faulted phase after the arc is extinguished. The valuable information indicating the existence of the arc can be used to implement an adaptative autoreclosure scheme. A criteria based on the harmonic characteristics of the secondary arc [5], specifically the harmonic content of the faulted phase terminals voltages, is presented in this paper.

II. BASICS OF SPAR

Faulted phase conductor is coupled with other phases' conductors by mutual capacitance and inductance, besides the shunt compensation reactors, if present. These connections feed fault current and support the fault arc after the faulted phase trips.

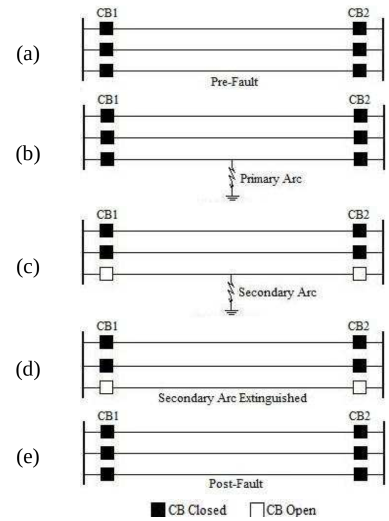

Fig. 1. Principle of the SPAR.

Fig. 1 depicts the stages of SPAR process. Normal system operation is represented in Fig. 1 (a). Further, Fig. 1 (b) presents a single line to ground fault occurrence. Short circuit current flows through the wires, typically with a high current arc (10^1 kA_{rms}) in air (primary arc). After a short time, protective relays open the faulted phase. Primary arc quenches by opening faulted phase breakers completely. Nevertheless, because of the coupling between faulted and healthy phases, lower amplitude current arc (normally < 10^2 A_{rms}) is

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established (secondary arc) (Fig. 1 (c)).

III. Secondary Arc

Secondary arc extinction is the most important phenomenon in transmission line SPAR studies. It is a highly complex phenomenon and it is influenced by various parameters [6, 7].

A. Field Tests

A test infrastructure was established at CEPEL High Power Laboratory in Brazil, including an outdoor actual 500 kV line, with three towers and two spans and the necessary measuring systems, where arcs have been generated and monitored. The tests consist of generating an arc imposing a sustained 60 Hz current during 1s. In the tests several current amplitudes were imposed, but for the present work only some data were used, being: 60 A_{rms}, 100 A_{rms}, 150 A_{rms} and 200 A_{rms}.

The measured arc voltage and current of a 100 A_{rms} current class arc are presented in Fig. 2.

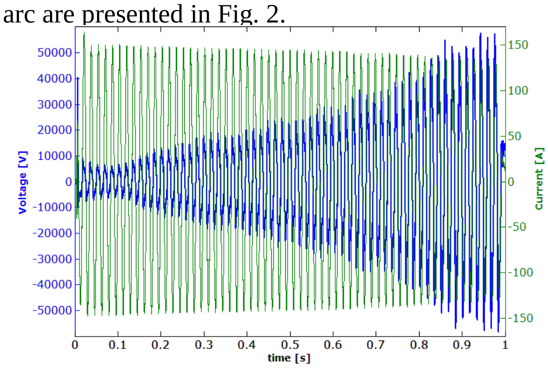


Fig. 2. Measured voltage and current of a 100 A_{rms} current class secondary arc field test simulation (Test 4) on a 500 kV transmission line.

The arc was produced over a vertical "I" insulator string at the tower. A fuse wire in parallel to the string was utilized to provide the arc ignition.

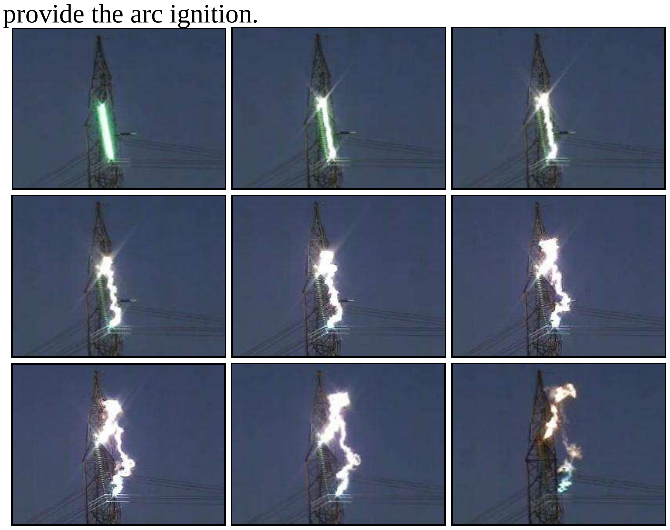


Fig. 3. Captured images of a 200 A_{rms} current class secondary arc field test (Test 8).

Fig. 3 depicts images of a 200 A_{rms} current class field test. From arc voltage and current measurements, it is possible to acquire the harmonic characteristics of the arc during the tests.

B. Harmonic Signature

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

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

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 $-\infty < time < +\infty$.

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

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

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

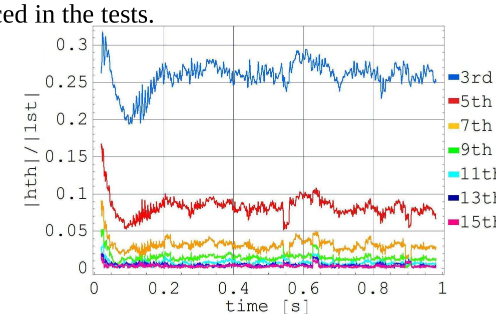


Fig. 4. Ratios between the magnitude of the odd order pseudo-harmonics and the magnitude of the first order pseudo-harmonic of the measured voltage between the arc terminals.

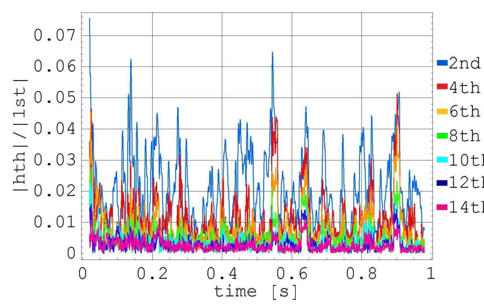


Fig. 5. Ratios between the magnitude of the even order pseudo-harmonics and the magnitude of the first order pseudo-harmonic of the measured voltage between the arc terminals.

Fig. 4 and Fig. 5 show results of the STDFT analysis concerning the odd order and even order pseudo-harmonics, respectively, of the measured voltage of the 100 Arms current class field test presented in Fig. 2. It is possible to notice that the odd order far outweighs the even order. This harmonic content is originated by the basic field test characteristic of imposing a sustained 60 Hz current during all tests.

However the harmonic signature characteristic of the secondary arc current obtained in the tests can be partially extrapolated and applied to simulations in order to propose a method for the identification of the secondary arc existence. Analysis results for different current classes tests were depicted in Tab. I. For each current class, it was chosen two field tests with different voltages root mean square value.

TABLE I
SECONDARY ARC FIELD TESTS CHARACTERISTICS - MAIN ODD ORDER PSEUDO-HARMONICS VOLTAGE (3^{RD}, 5^{TH} AND 7^{TH}) MEAN VALUE RELATED WITH THE FIRST (1^{ST}) ORDER PSEUDO-HARMONIC VOLTAGE.

Current Class (A_{rms})	Test	Current (A_{rms})	Voltage (kV_{rms})	$\overline{\left(\frac{\lvert 3rd \rvert}{\lvert 1st \rvert}\right)}$	$\overline{\left(\frac{\lvert 5th \rvert}{\lvert 1st \rvert}\right)}$	$\overline{\left(\frac{\lvert 7th \rvert}{\lvert 1st \rvert}\right)}$
60	1	63.80	10.03	0.2568	0.0760	0.0289
	2	66.04	19.14	0.2528	0.0744	0.0274
100	3	101.64	8.86	0.2676	0.0930	0.0361
	4	98.71	20.18	0.2610	0.0810	0.0303
150	5	151.50	8.24	0.2760	0.1079	0.0432
	6	148.77	14.99	0.2730	0.1050	0.0419
200	7	195.91	5.74	0.2592	0.1019	0.0420
	8	196.58	15.51	0.2507	0.0955	0.0375

The test secondary arc current had a low harmonic content since a sustained 60-Hz current was "imposed" in the field test. In normal field conditions of a typical transmission system, before secondary arc extinction, there should be odd pseudo-harmonics in the voltage between arc terminals and, also, in secondary arc current. The relative values of such pseudo-harmonics are defined by the interaction between the network impedance seen at the arc terminals and the arc during the fault. Then, while the secondary arc exists, there will be a source of odd harmonics (secondary arc) that will be measured at the open phase terminals voltages. After secondary arc extinction, typically, the odd pseudo-harmonics in both open phase terminals voltage will be much lower than before secondary arc extinction.

IV. ADAPTATIVE RECLOSURE SCHEME

The method proposed relies on a tracking scheme to detect the existence of the secondary arc based on the harmonic signature of the tests results previously presented. Computer simulation and secondary arc field tests were combined to find ways to improve the performance of adaptative SPAR for various secondary arc current levels. The PSCAD/EMTDC program together with the measured secondary arc data were used to simulate an arcing fault on the system.

The non-linear characteristic (harmonic signature) of the secondary arc propagates through the transmission system allowing the identification of the secondary arc by monitoring the voltage at the extremes of the opened phase. The voltage harmonic content that appear at sound phases due to secondary arc harmonic content and electromagnetic coupling among line phases, due to the mutual inductance and capacitance of the transmission line and due to shunt reactors, is too low to be of some interest for arc extinction identification. However, the voltage waveform of the faulted phase while the secondary arc exists is greatly distorted compared with the same voltage after the secondary arc extinction. After the secondary arc is extinguished, very low harmonic content is expected in the opened phase voltage.

A. Systems Studied

The transmission system used in this study had data obtained from the Brazilian National Grid. The simulation of a typical 500 kV transmission system was set up. The test line implemented is similar to North East-South East (NE-SE) interconnection trunk. The transmission system modeled consists of a generator, a step up transformer and a transmission line. The line characteristics used are summarized in Fig. 6. The power frequency soil resistivity was supposed 4000 Ω.m. The conductors' data are summarized in Tab. II and Tab. III. The simulation performed consisted of the line energization under single-phase fault.

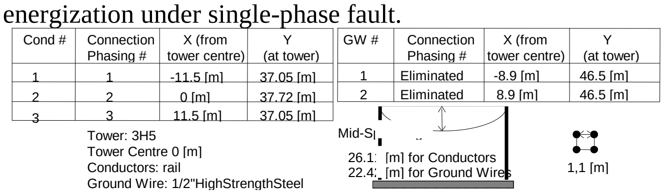


Fig. 6. NE-SE Tower Data.

TABLE II
CONDUCTOR DATA OF NE-SE LINES.

Conductor	Resistance [Ω/km]	External Radius [m]	Internal Radius [m]	μr
RAIL	0.06114	0.014795	0.0037	1
GW - EHS	3.51	0.004572	-	70

TABLE III
PER UNIT SERIES AND SHUNT PARAMETERS CALCULATED AT 60 HZ – NE-SE.

Sequence	Resistance [Ω/km]	Reactance [Ω/km]	Susceptance [μS/km]
Zero	0.3576402	1.4283469	3.5237035
Positive	0.0159706	0.2734496	6.0457682

Two transmission lines configurations (500 km and 900 km) are employed. Fig. 7 depicts these configurations.

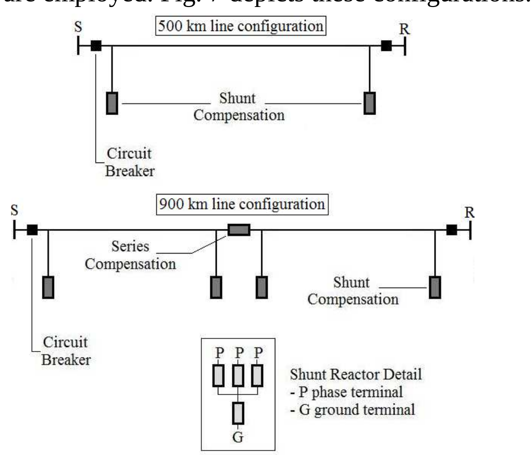


Fig. 7. Line basic schemes, including series and shunt compensation.

B. Fault Implementation

Formerly, a single-phase short-circuit was simulated by connecting a 10 Ω resistance between the faulted phase and the ground. The secondary arc was simulated by opening the faulty phase circuit breakers at the line terminals. This process was implemented to adjust the line length and the value of a neutral reactor that would match the secondary arc current level of each test presented in previous section (Tab. I).

When the circuit breakers of the faulty phase were opened, the 10 Ω resistor was disconnected and the secondary arc voltage signal recorded from the field tests was injected. The faulted phase was tripped at both side at 1.25 s (considering duration of 1 s of the measured data) and the arc was considered self extinguished at 2.25 s. Fig. 8 illustrates the time events described before.

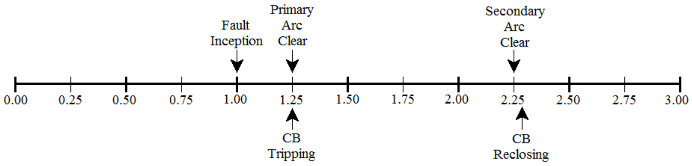


Fig. 8. Fault events simulation.

C. 100 A_{rms} Current Class Test Analysis

A single-phase fault was simulated at the middle of the transmission line system of 500 km. The voltages measured on the line side of the circuit breakers are shown in Fig. 9.

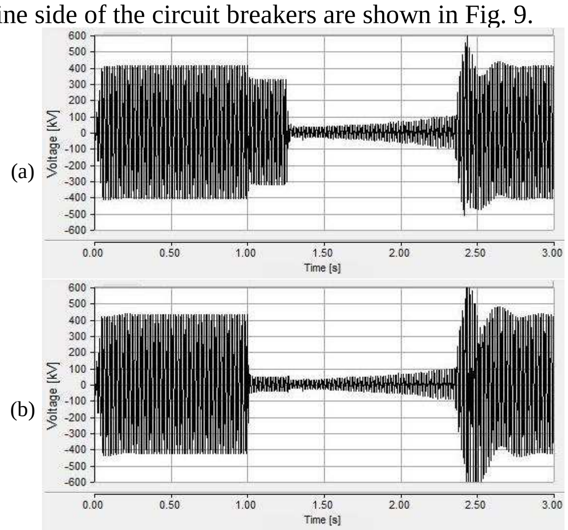


Fig. 9. Voltage waveform measured on line side of the circuit breaker: (a) at the S side, and (b) at the R side.

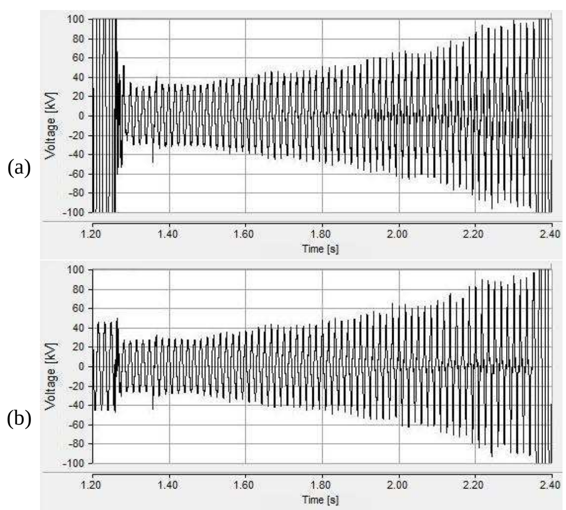


Fig. 10. Voltage waveform measured on line side of the circuit breaker (secondary arc detail): (a) at the S side, and (b) at the R side.

The described phases of SPAR showed in Fig. 1 are clearly visible on Fig. 9, where voltage of faulted phase opened terminals is given. Fig. 10 shows the same result of Fig. 9 focusing on the secondary arc duration.

Fig. 11 presents the sustained secondary arc current response of the system and the current measured in the field test. These two signals were adjusted in order to inject the field test in phase with the sustained system response. After identifying the necessary time delay the secondary arc test voltage was applied between the system "arc terminals" as an external source voltage, "reproducing" a secondary arc fault (Fig. 12).

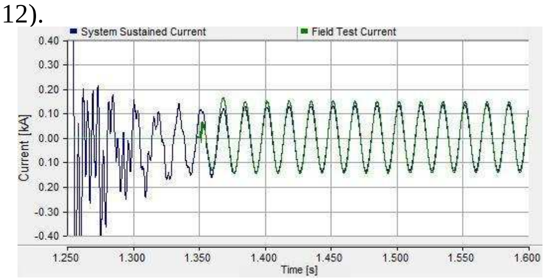


Fig. 11. Simulated sustained secondary arc current and field test secondary arc current.

In Fig. 12 it can be observed that the field test secondary voltage was applied in phase with the expected sustained power frequency secondary arc current.

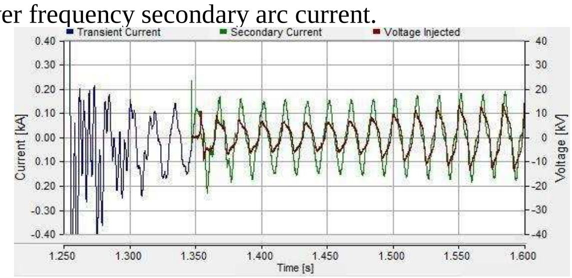


Fig. 12. Field test voltage injected in the fault location "reproducing" a secondary arc.

Due to the system response the secondary arc current is no longer a 60 Hz dominant signal, but has harmonic content originated by the secondary voltage field test harmonics. When a secondary arc occurs in a transmission system, the ratio the harmonics will divide between the secondary arc current and the arc voltage depends on the impedance response at the fault location and the harmonic immitance between the fault location and the opened phase extremities. Nevertheless it is expected that a high content of odd harmonics will appear at the open phase terminals voltage, produced both by the harmonic content of the arc current and of the arc voltage. The results presented in the present simulations have some approximations as field tests with specific characteristics are being used.

The harmonic content is evaluated by the STDFT ((1) and (2)) with a moving window of 16.67 ms. The harmonic contents of the terminals voltages depicted in Fig. 9 (a) and Fig 9 (b) are shown in Fig. 13 (a) and Fig. 13 (b), respectively.

The analysis of the presented data shows that the status of the secondary arc may be determined through tracing the voltage of the open phase and comparing it with the harmonic signature of the secondary arc.

By processing the voltage depicted in Fig. 9, the Harmonic Factor (*HF*) is calculated as:

$$HF = \frac{\sqrt{V_7^2 + V_5^2 + V_3^2}}{V_1} \tag{3}$$

where V_h is the magnitude of the *h* pseudo-harmonic voltage.

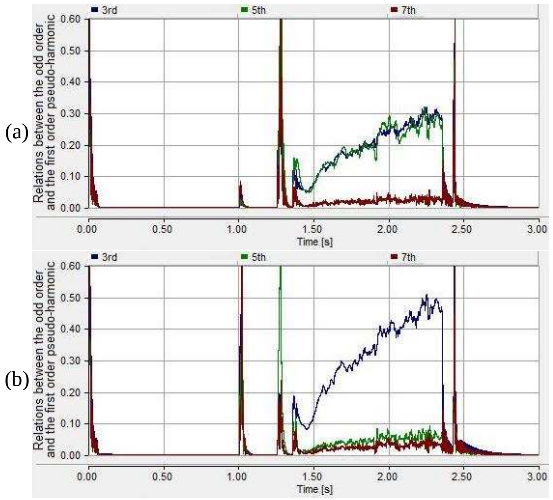
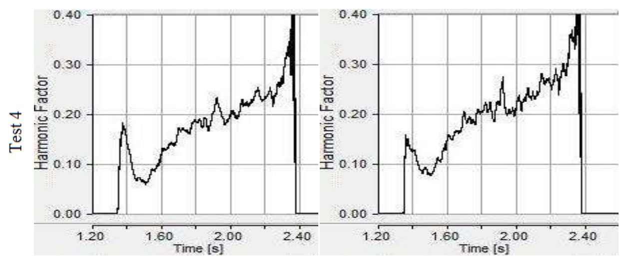


Fig. 13. Magnitude of the odd order pseudo-harmonics of the voltage on line side of the circuit breaker:(a) at the sending side, and (b) at the receiving side.

Fig. 14 shows that the *HF* decrease defines the moment of the secondary arc extinction.



(a) (b)

Fig. 14. Harmonic Factors of the voltage on line side of the circuit breaker: (a) at the S side, and (b) at the R side.

The algorithm is activated when the breaker trip is identified. Once the fault is identified to be permanent or not having extinguished after the protection dead time, a signal is sent to trip the other two healthy phases and lock out the SPAR. A transient fault can be distinguished from a permanent fault (high impedance) by detecting the harmonic content.

The proposed algorithm is based on shifting a window on voltage signal and computing the *HF* value. It is possible to conclude that the moment of the secondary arc extinction is defined by the decrease of the *HF*.

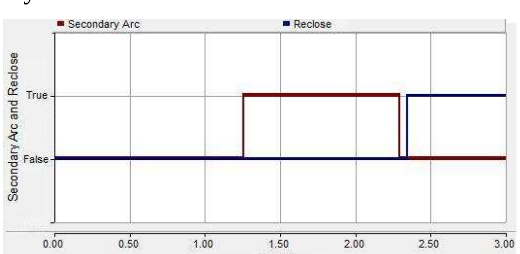


Fig. 15. Secondary Arc Duration and Reclosure Signal.

Fig. 15 shows that the algorithm can determine the secondary arc duration and the optimum reclosure time. However, although the secondary arc extinction time provides a good indication of when to reclose, reclosure of the circuit breakers immediately after arc extinction will normally result in a restrike of the fault. This is the reason why a further delay is required to allow the fault arc path to deionise completely.

In the proposed method the Harmonic Factor of both voltage sides is compared with a predefined threshold in every interaction. When the *HF* of both voltage line terminal are lower than a threshold for a determined period of time, then after 2 cycles (33.3 ms - 60 Hz) the circuit breakers are reclosed. The threshold was established between 0.1 and 0.2.

TABLE IV

SYSTEMS CONFIGURATIONS.

Tests	Line Length (km)	Fault Location (km)	Compensation			Current (A_{rms})
			Shunt		Series (%)	
			Phase Reactor (%)	Neutral Reactor (R_h)		
1, 2	500	250	75.9	4.27	-	63.64
3, 4	500	250	75.9	1.01	-	101.12
5, 6	900	50	81.1	3.57	50	151.46
7, 8	900	850	81.1	2.27	50	200.82

D. Other Tests Results

Eight tests were conducted, in order to verify the availability and applicability of the proposed criterion. For each secondary arc current level, it was chosen two different voltage levels. A summary of the tests performed is given in Table IV, and the Harmonic Factors in Fig. 16. The algorithm was tested using different configurations and different secondary arc data.

The parameter chosen to select the basic characteristics of the neutral reactor is the ratio R_h [8],

$$R_h = \frac{Z_h}{Z_d} = \frac{Z_p + 3Z_n}{Z_p} = \frac{1/Y_p + 3/Y_n}{1/Y_p} \tag{4}$$

where Y_p, Y_n, respectively, are the reactors phase and neutral admittance, Z_p, Z_n are the corresponding impedance, and Z_d, Z_h, respectively, are the non-homopolar and homopolar impedance of the shunt compensation reactor (all in complex notation).

As can be observed in the results presented in Fig. 17, it was found that *HF* of at least of one side is always higher than a threshold (0.1 - 0.2) in different transient fault conditions.

This method shows how to perform the secondary arc extinction phenomenon detection for different arc current level and fault location. In all tests successful reclosure occurred, however in the presented results there is the approximation of using field tests, obtained under specific conditions, applied to a system which does not reproduce exactly the tests characteristics.

The change of current levels demonstrates that this scheme is well adaptative. As a consequence, the proposed adaptative autoreclosure scheme may identify an transeient arc and has higher reliability compared with the conventional scheme.

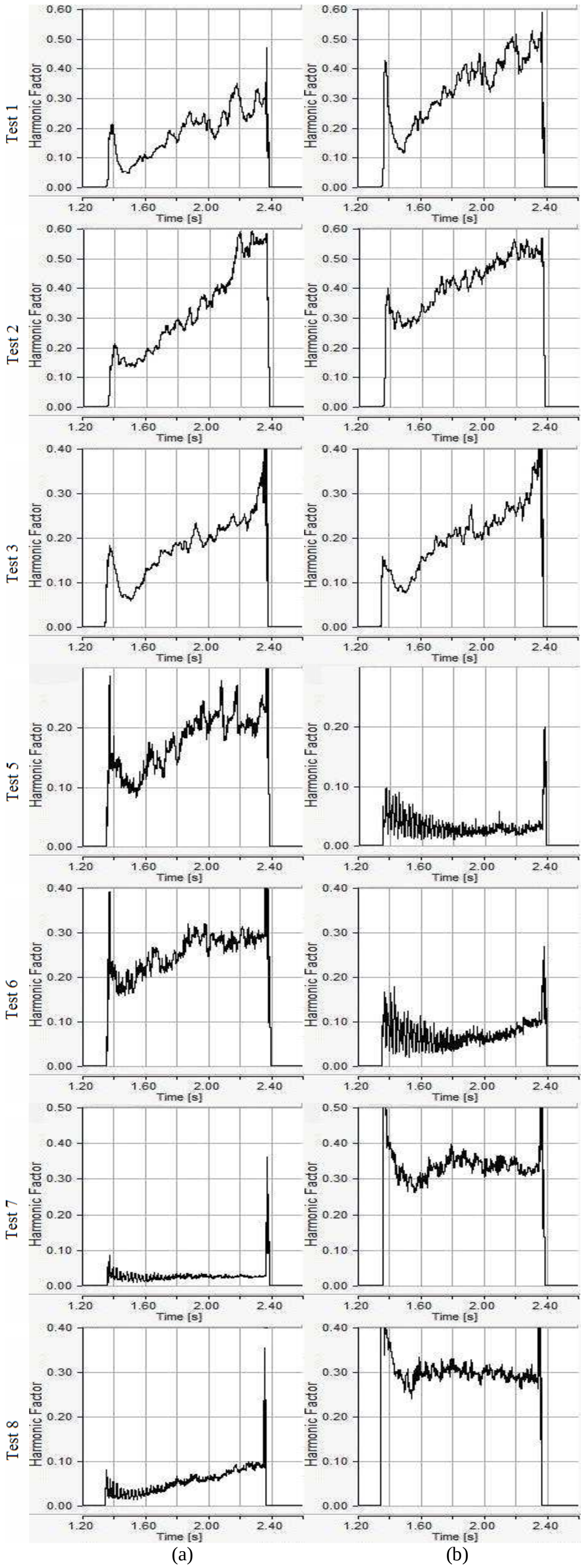


Fig. 16. Harmonic Factors of the voltage on line side of the circuit breaker: (a) at the S side, and (b) at the R side.

V. Conclusions

The main features of an algorithm for real time existence detection of secondary arc for fast adaptative SPAR on a transmission line have been proposed. The adaptive reclosure technique is important for improving the stability of power systems. The method is able to discriminate between permanent and non-permanent faults and optimize the dead time for protection operation. In the case of permanent fault the algorithm blocks automatic reclosing and trips the sound phases. Many different simulation studies for different cases were performed. The outcome of this study indicates that secondary arc harmonic signature analysis together with SPAR technique can be used as an attractive means of achieving a fast adaptative autoreclosure scheme.

Field tests produced with specific characteristics were used as if they represent secondary arc in an actual transmission system, not including the system response contribution to the secondary arc formation. The authors are aware of the approximations, but it is not expected that the proposed method will give different results in actual transmission systems.

VI. Acknowledgment

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