Implementation of Fast Adaptive Single-Phase Reclosing Based on Measurement of Harmonic Content in the Real-Time Digital Simulator (RTDS)

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***Abstract*— This paper presents the implementation of a fast adaptive single-phase reclosing scheme based on the measurement of voltage harmonic content. The main objective of this scheme is to ensure the application of single-phase reclosing after the transient fault extinction or perform automatic blocking maneuver and three-phase tripping for permanent faults. The transmission system represented was based on an actual 500 kV Brazilian system and the tests were made with Real-Time Digital Simulator (RTDS). The protection scheme was implemented with a commercial relay and a measurement equipment, as well as in RTDS hardware. The proposed adaptive protection reduced typical dead-time and ensured successful reclosing only after arc extinction, enhancing system reliability.**

Keywords: Single-phase fault, Adaptive reclosing, Harmonic content, Real-time digital simulator (RTDS).

I. Introduction

Most disturbances in power systems occurs in transmission lines, the majority of which are transient and involves just one phase. When a fault occurs the protection system must operate and quickly eliminate the fault to maintain system stability and restore power supply.

For transient single-phase faults it is more advantageous to use single-phase opening/reclosing, since during the maneuver the other phases continue to transmit energy, enabling a power flow around 54% of the total power in single circuits and up to 75% in lines with double circuits [1]. This maneuver improves system stability and reliability as well as reduces torsional impacts on the turbogenerators rotors [2]. Besides, transient overvoltages due to three-phase reclosing are much more severe than the ones generated during single-phase reclosing [3].

The success of this maneuver depends basically on the secondary arc extinction. In traditional single-phase auto reclosing (SPAR) scheme the dead time is set to a high value, varying from 500 ms to 1 s, supposing the arc will extinguish within this period. In some cases this fixed time can be quite large, resulting in excessive time to reconnect the opened phase, or it can also be too short and the reclosing can be performed on an existing transient fault or on a permanent fault.

SPAR's alternative forms are being studied, mainly to ensure faster and successful reclosing and these are called adaptive SPAR. The main objective is the estimation of the arc extinction instant and the discrimination between transient and permanent faults. Adaptive reclosing offers advantages over the traditional technique: increases the chances of a successful reclosing, improves stability and reduces the impact of permanent fault [4].

In this paper an adaptive SPAR scheme based on the voltage harmonic content present in the opened phase terminal is described and tested in real time simulator. This approach has been investigated by several researchers as in [5 - 9].

Initially, the proposed protection scheme is implemented using an electrical meter and afterwards, using RTDS library, a fast harmonic content filter meter is implemented. The voltage harmonic content identifies the fault extinction and also its characteristics, transient or permanent. If no important harmonic content is observed when the phase is tripped it means that the fault is not transient but rather it has a high probability of being a permanent fault, indicating that the automatic reclosing must be blocked.

Simulation results of the proposed scheme are presented in the paper.

II. Proposed Scheme

The proposed scheme is implemented through the interaction between the protective relay and the harmonic content meter. The operating philosophy is based on the following assumptions:

- For permanent fault, the scheme blocks the automatic reclosing and generates transmission line breaker's three-phase opening;

- For transient fault, it detects the moment of the secondary arc extinction and after one cycle it recloses the phase.

The flowchart in Figure 1 presents the proposed scheme. The solution for single-phase reclosing is presented, however similar process can be proposed for the three-phase maneuver when transient faults involve more than one phase. In this paper only single-phase maneuver is considered.

The proposed scheme has been divided into two algorithms. Firstly, with the income relay signal the algorithm starts to check whether the fault is permanent for a fixed time of 450 ms when using SEL-735 meter and 150 ms when using the harmonic filter. This period was defined to prevent operation during the initial transient, allowing the arc plasma stabilization. For the meter a higher testing period was

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necessary due to the equipment's sampling window. Once this time has elapsed, the secondary arc current extinction detection algorithm was enabled.

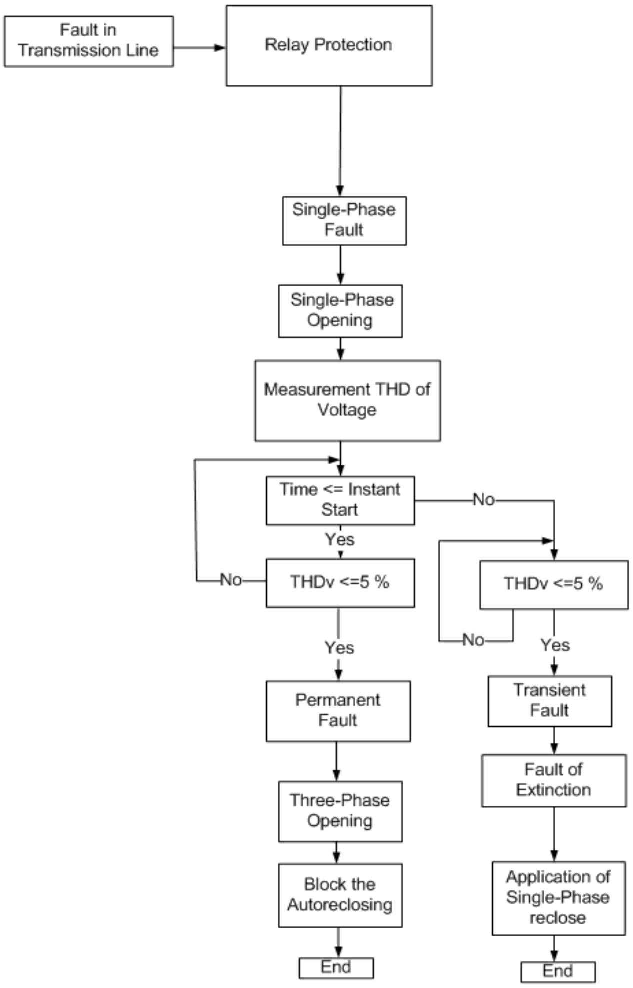

Fig 1. Flowchart of the proposed scheme.

The measurement of the opened phase voltage harmonic content is recommended by [5 - 9] to be done in both ends of the transmission line, however, in the performed simulations only one terminal information was used. As both line terminals have distance relays the use of both sides can enhance reliability in the proposed scheme. This has not been tested in the present research.

III. UTILIZED EQUIPMENT

In this study the following equipment were used:

a) Real-Time Digital Simulator (RTDS). The RTDS is a device developed for real-time studies of electromagnetic transient phenomena in electric power systems. One of its features is the application of closed-loop tests. Thus, control and protection devices are connected to RTDS to simulate on-site tests in electrical power systems. The RTDS is composed of hardware and software. The test system was modeled in this simulator as well as the proposed scheme.

b) To guarantee the protection of the proposed system SEL-421 relay was used. This equipment is a high speed transmission line distance protection relay with single-phase and three-phase opening/reclosing with synchronism check, breaker status monitoring, breaker failure protection, series compensation and logical protection. The relay has extensive measurement and data logging, it also has a feature known as SELOGIC that enables the execution of control equations for easy and flexible implementation of protection and control schemes.

c) To perform the voltage harmonic content measurement in the terminals of the opened phase SEL-735 meter was used. The meter has extensive measurement and data logging, it also has SELOGIC that enables the execution of control equations for easy and flexible deployment of automation schemes using the measurements. Such equipment is regulated by IEC 61000-4-7. One of the most important aspects of this standard is to define the time window to be used to sample the waveform before applying the Fourier transform. As the measuring instrument operates in both 50 Hz and 60 Hz, the window width is set to 10 cycles for 50 Hz systems and 12 cycles for 60 Hz systems. In either cases the window width is 200 ms, which results in a frequency resolution at the output of the Fourier transform of 5 Hz for both systems (50 and 60 Hz).

d) Harmonic content measuring equipment are built according to IEC 61000-4-7. The longer the duration of the sampling window, the better is the accuracy in the frequency domain. However, the lower is the accuracy of the harmonic content in the time domain. As the proposed scheme is based on voltage harmonic measurement, this long window may cause undesired operation. In order to avoid such problems it is proposed the use of a harmonic filter prepared by [10] making some simple adjustments. In [10] the filter extracted the second, fourth and fifth harmonic, and in the present study it was modified to extract third, fifth and seventh harmonic. The filter used is a cosine filter and the representative block diagram is shown in Figure 2. For more information see [10].

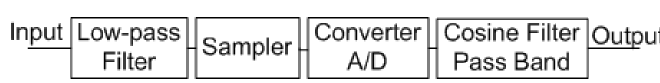

Fig 2. Block diagram of filter elaborate in RTDS.

The filter has as output the fundamental component, and the third, fifth and seventh harmonics [11], being these the most significant during the transient fault (arc faults) [5]. After the filtering, the calculation of the total harmonic distortion is implemented as in equation 1:

$$\text{THD} = \frac{\sqrt{\text{Ch3}^2+\text{Ch5}^2+\text{Ch7}^2}}{\text{Ch1}} \qquad (1)$$

Where:

- THD – Total Harmonic Distortion
- Ch1 – Fundamental Component
- Ch3 – 3rd Harmonic
- Ch5 – 5th Harmonic
- Ch7 – 7th Harmonic

IV. Analyzed System

The transmission system used is based on a Brazilian 500 kV transmission system. Such system is composed of generating unit, step-up transformer and a shunt compensated 350-km balanced transmission line. The 60-Hz line parameters are shown in Table I.

TABLE I
TRANSMISSION LINE PARAMETERS.

Sequence	Series (Ω/km)	Shunt (μS/km)
Positive/Negative	0.0161 + j 0.2739	j 6.0417
Zero	0.4352 + j 1.4427	j 3.5227

Shunt compensation reactors, with 70% compensation level and quality factor of 400, are installed at both line ends. A neutral reactor can be designed to minimize capacitive coupling, which will reduce secondary arc current [12]. In the present study the neutral reactor was specified to adjust the secondary arc current to two values: 15 and 60 Arms.

It was also studied a case with a short line (70 km) without reactors banks that also had a secondary arc current of 15 Arms.

The neutral reactor data are presented in Table II.

TABLE II
NEUTRAL REACTORS DATA.

Test	Resistance (Ω)	Reactance (Ω)
15 Arms	-	-
15 Arms Compensated	1.946	414.7
60 Arms	1.1788	79.17

V. The Single-phase Fault Model

RTDS arc model was used to represent the transient fault. There are important researches ongoing aiming the establishment of robust arc model, such as [13]. In the present study the arc characteristics are modeled as in (2):

$$\frac{dg}{dt} = \frac{1}{T}(G - g) \qquad (2)$$

Where g is the time varying arc conductance, G is the stationary arc conductance and T is a time constant. T is calculated in each half cycle as it depends on the current peak value in the previous half cycle and the arc length, as shown in equation 3:

$$T = \alpha\frac{I_{mx}}{l} \qquad (3)$$

For primary arcs, α is fixed at 28.5 μs. For secondary arcs T is computed according to:

$$T = \beta\frac{\sqrt{I_{mx}}}{l} \qquad (4)$$

β is fixed at 2.51 ms. The following settings shown in Table III were used for each test. These values were defined to have 1 s arc duration.

TABLE III
RTDS ARC MODEL DATA

Test	Primary arc length (m)	Secondary arc length increase (m/s)
15 Arms	4	43
15 Arms compensated	4	60
60 Arms	4	80

VI. Performed Tests

Transient and permanent single-phase faults were applied to test the proposed scheme. The simulation consisted of applying a fault in the open-ended line. Both SEL-735 meter and RTDS developed THD filter were used.

Distance protection relay SEL-421 identified the faulted phase and sent the tripping phase order. Permanent faults were modeled through a 1 Ω resistance. The protection bits were defined as:

- 52AA1 - Bit that represents phase A breaker;
- 52AB1 - Bit that represents phase B breaker;
- 52AC1 - Bit that represents phase C breaker;
- OUT101 - Bit that represents phase A trip;
- OUT102 - Bit that represents phase B trip;
- OUT103 - Bit that represents phase C trip;
- OUT104 - Bit that represents faulted phase reclosing;
- IN107 - Bit that represents the pulse generated by reclosing for low THD value – SEL-735 meter;
- IN106 - Bit that represents the pulse generated by blocking for low THD value – SEL-735 meter;
- IN104 - Bit that represents the pulse generated by reclosing for low THD value - filter implemented in the RTDS (RTDS Filter);
- IN105 - Bit that represents the pulse generated by blocking for low THD value – RTDS filter.

A. Tests using the SEL-735 meter

The fault was applied in the middle of the line. The test results for 60 Arms arc current are presented in Fig. 3-6 and the main results obtained for the other tests are summarized in Table IV.

TABLE IV
TESTS PERFORMED USING SEL-735 METER.

Type of Fault	Fault application location (%)	15 Arms	15 Arms Compensated	60 Arms
Permanent Fault	50	312.5	306.25	293.75
Transient Fault	50	337.5	248	215

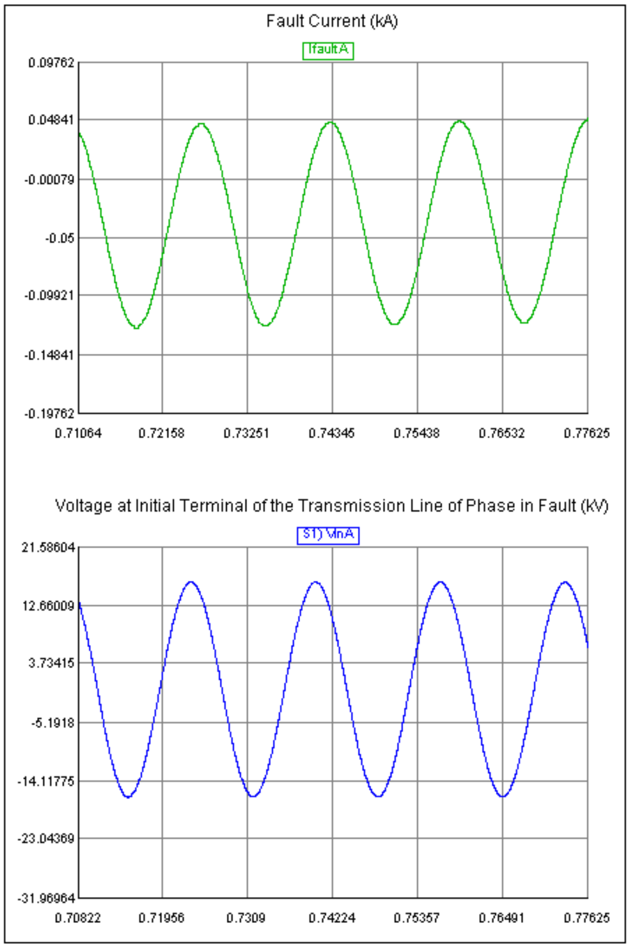

Fig 3. Fault current and opened phase voltage in TL sending end for permanent fault using the meter SEL-735.

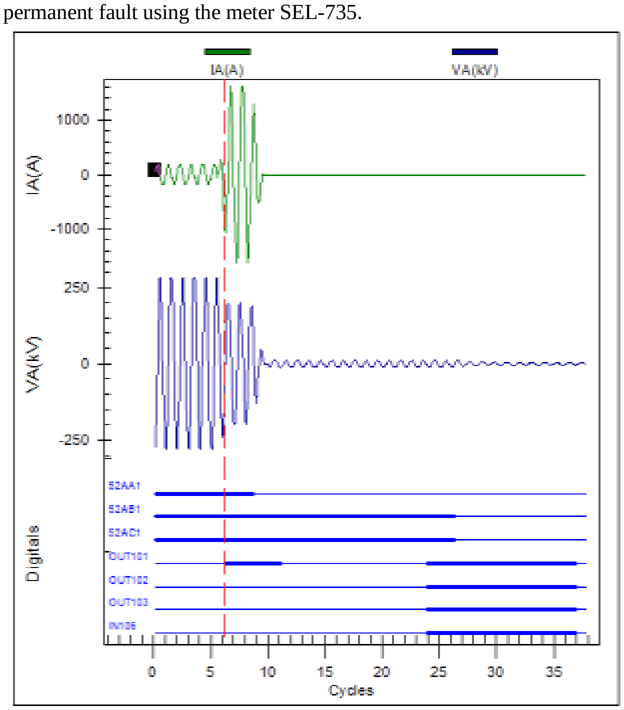

Fig 4. Relay oscillography for permanent single-phase fault using SEL-735 meter.

1) Permanent Fault

Figures 3 and 4 present the results for the proposed method for a permanent fault. The relay recognizes the fault and generates single-phase tripping. However the fault was permanent and the voltage waveform of the faulted phase (Figure 3) is purely sinusoidal after the tripping transient. As a result, the harmonic distortion of this voltage is very low, generating a blocking pulse (IN106, Figure 4). The single-phase reclosing is blocked and three-phase opening is initiated due to fault permanent. Detection (IN106) takes around 300 ms after single phase tripping.

2) Transient Fault

Figures 5 and 6 present the results for the proposed method for transient fault. The relay recognizes the fault and generates single-phase tripping. As the fault is transient, the voltage waveform of the faulted phase (Figure 5) is quite distorted. As a result, harmonic distortion rate remains high until the extinction of the fault. The detection of the fault extinction is made, generating the reclosing pulse (IN107, Figure 6). The single-phase reclosing is applied and the system returns to normal operation. The detection of the fault extinction takes around 215 ms after its occurrence. In Table IV the summary of the performed tests is presented.

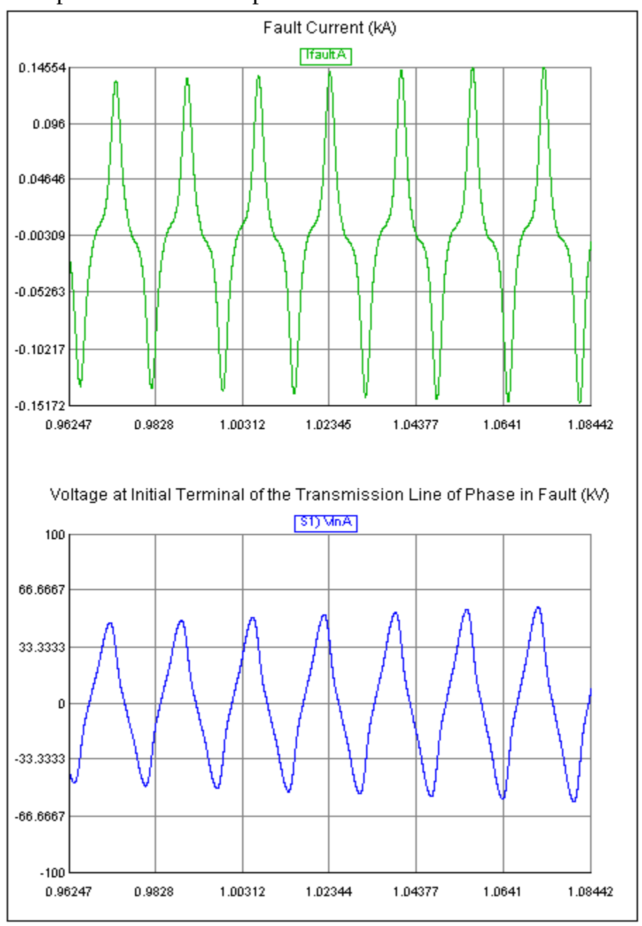

Fig 5. Fault current and opened phase voltage in TL sending end for transient fault using the meter SEL-735.

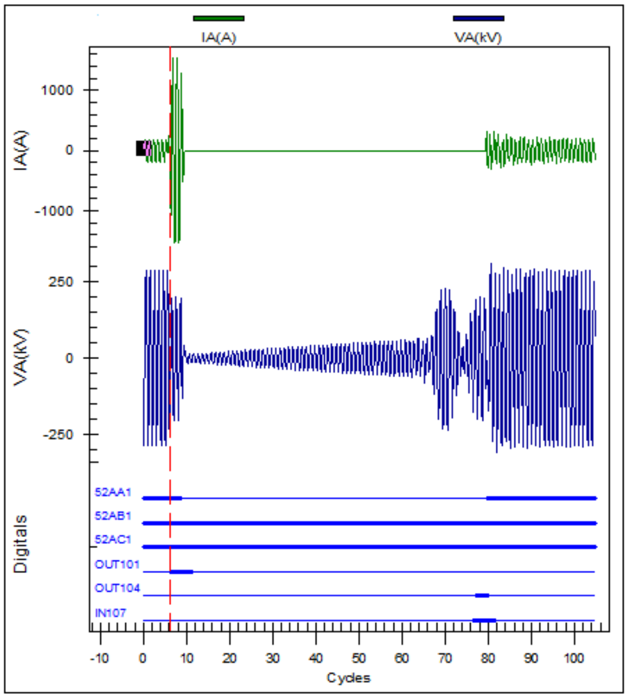

Fig 6. Relay oscillography for transient single-phase fault using SEL-735 meter.

In both tests performed the proposed adaptive protection scheme had a good performance, both for permanent fault and for transient fault. Nevertheless, the time response, although lower than regular pre-set dead-time and more reliable, can still be reduced. In order to enhance the method, specifically to speed up the recognition process of permanent faults and the application of safe single-phase reclosing, the fast THD filter was used.

A. Tests using the filter implemented in RTDS

The tests with the proposed filter were applied for different fault location, specifically at 5%, 25%, 50%, 75% and 98% of the line. The main test results are presented in Table V. In these cases a much faster response was obtained. An additional information presented is the harmonic content, not available with SEL meter.

1) Permanent Fault

Figures 7, 8 and 9 present the results for the calculation with THD filter for permanent fault. The proposed scheme detects properly the permanent fault in the beginning of the fault when THD (Figure 8) falls below a set value of 5%, generating a blocking pulse (IN105, Figure 9). It instantaneously blocks automatic reclosing and generates three-phase trip, as planned. The response with this filter is remarkably fast, detecting the fault in only 70 ms after the phase trip, and reducing the dead-time which was previously around 300 ms.

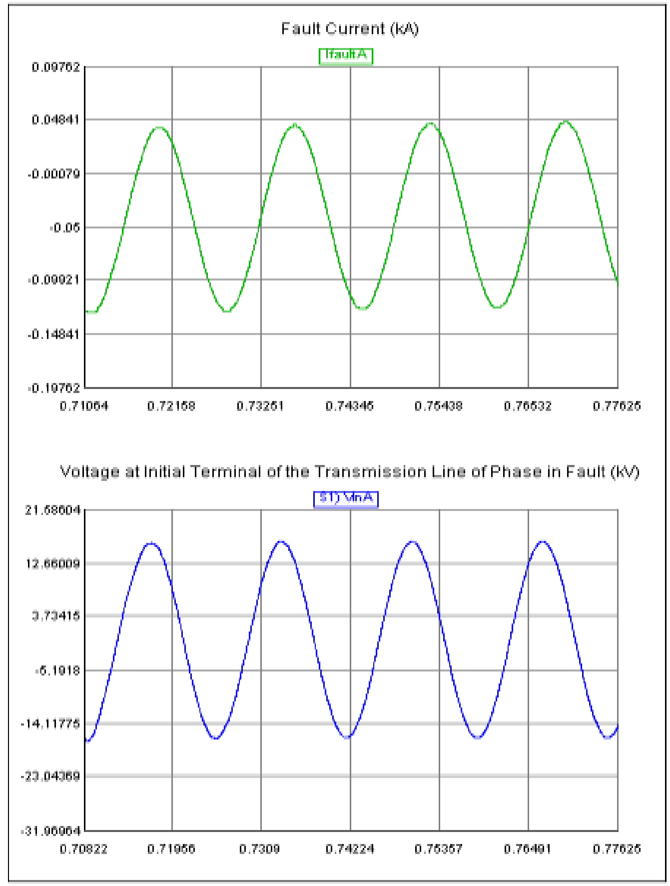

Fig 7. Fault current and opened phase voltage in TL sending end for permanent fault using RTDS filter.

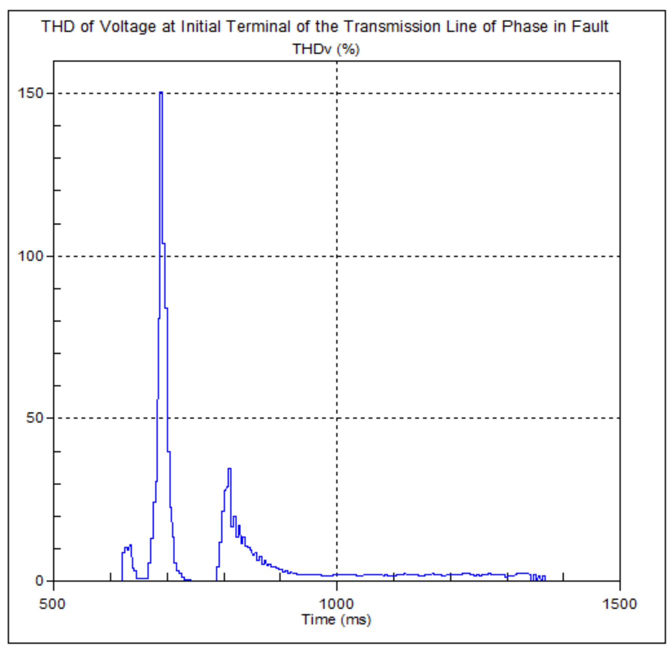

Fig 8. Voltage THD at TL sending end for permanent fault using RTDS filter.

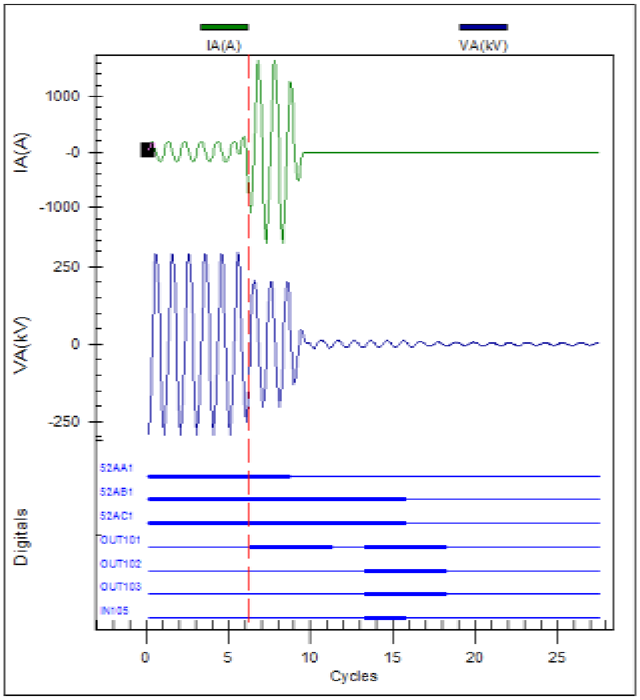

Fig 9. Relay oscillography for permanent single-phase fault using RTDS filter.

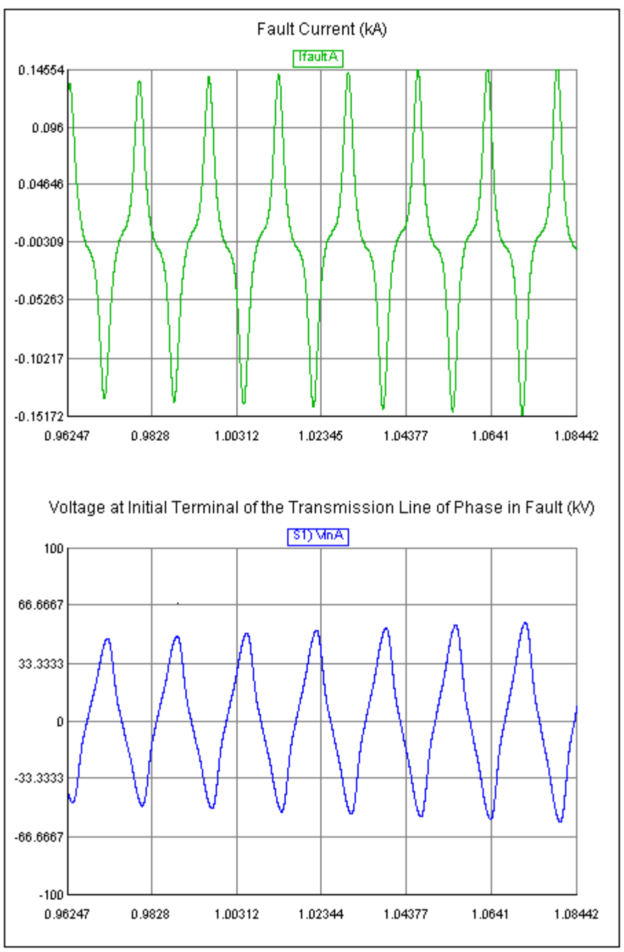

Fig 10. Fault current and opened phase voltage in TL sending end for transient fault using RTDS filter.

2) Transient Fault

Figures 10, 11 and 12 present the results for the proposed method for a transient fault generated by the RTDS arc model.

The proposed scheme detects the instant of the secondary arc current extinction, represented by the bit IN104. After extinction is detected, single-phase reclosing is initiated and the system returns to normal operation. The fault extinction recognition takes from 50 to 85 ms after the actual arc extinction.

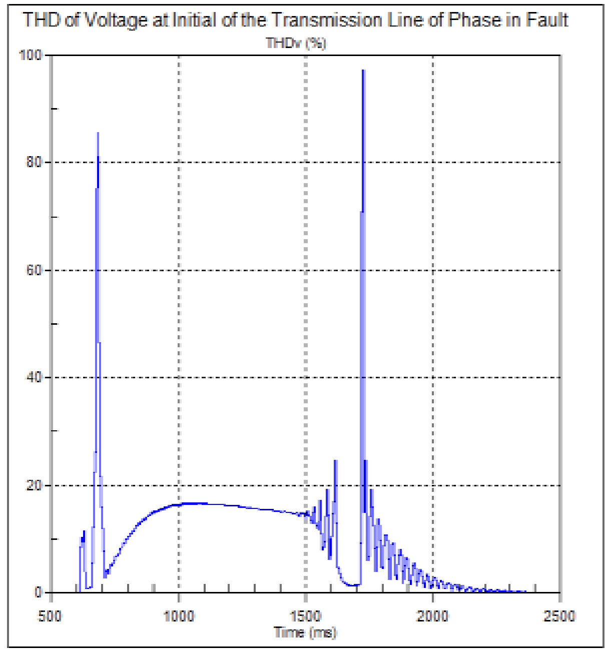

Fig 11. Voltage THD at TL sending end for transient fault using RTDS filter.

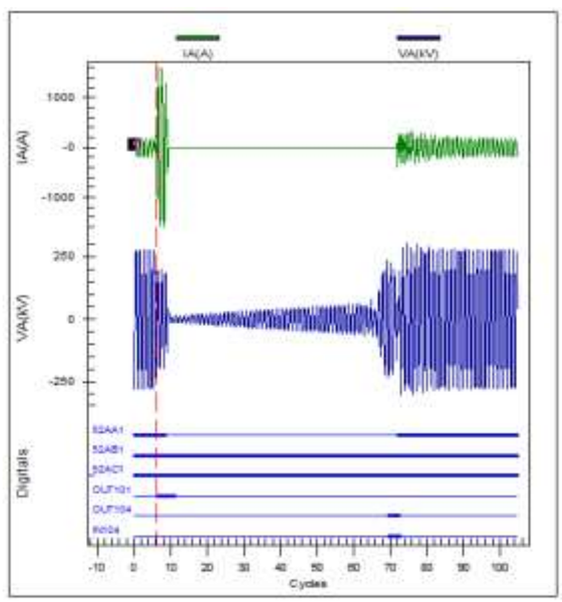

Fig 12. Relay oscillography for transient single-phase fault using RTDS filter

In the Table V the summary of the performed tests is presented. For permanent faults the time response was between 67 and 105 ms after tripping the faulted phase. For the transient fault cases, the time response occurred between 53 and 84 ms after the secondary arc extinction.

TABLE V
TESTS PERFORMED USING THE HARMONIC FILTER.

Type of Fault	Fault application location (%)	15 Arms	15 Arms Compensated	60 Arms
Permanent Fault	5	70.83	104.17	104.17
	25	70.83	66.67	68.75
	50	70.83	68.75	75.
	75	70.83	75.	77.08
	98	68.75	79.17	79.17
Transient Fault	5	53.16	62.62	66.69
	25	52.95	60.56	64.27
	50	52.91	59.16	64.23
	75	52.92	59.52	64.13
	98	52.57	59.42	63.16

VII. CONCLUSIONS

In the present study a scheme for fast adaptive single-phase auto reclosing based on measuring the opened phase voltage harmonic content was implemented in real time digital simulator (RTDS). The results presented were obtained with the proposed method generated using SEL-735 meter and THD filter implemented in RTDS.

With SEL-735 meter a good response was granted, both for permanent fault, when the scheme blocked the automatic reclosing and initiated three-phase tripping, as for transient fault, when the scheme detected arc extinction instant and applied the single-phase reclosing in a shorter time than the regular protection. However, the proposed scheme dead-time was not extremely small, as the harmonic content measuring equipment performs calculations using a 200 ms window according to IEC 61000-4-7.

On the other hand, the THD filter developed within RTDS, which has the main characteristic of performing calculations using a 16.67 ms window, was very fast and accurate.

It is worth mentioning that for a greater reliability of the proposed scheme the technique of tele-protection can be implemented, measuring the harmonic content in both line terminals.

In general, it is possible to perform the adaptive single-phase reclosing using a programmable relay and a power quality meter by measuring the voltage harmonic content in one line terminal.

The power quality meter operated properly, but the response was slow due to its steady-state harmonic monitoring design. It is suggested to implement the proposed adaptive SPAR in a fast measurement harmonic content filter as presented in the paper, what can be done in a programmable relay or even in a device specifically designed for this purpose.

It should be emphasized that adaptive SPAR can enhance system reliability by preventing reclosing on permanent faults and by restoring the system faster.

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