Leveraging Existing Relays to Improve Single Phase Auto-Reclosing

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Abstract—Single-phase auto-reclosing (SPAR) is used in power systems worldwide. However, many SPAR methods do not present a practical approach for field implementation. Although manufacturers have embedded SPAR functions into their commercial relays, the closed solutions make not trivial the application of new functions/methods. Thus, in this paper, a practical approach is proposed to leverage existing relays structure aiming to improve SPAR applications. A simple and effective phasor-based single-phase auto-reclosing scheme for non-compensated transmission lines is embedded in a commercially available relay equipped with a free-form programming logic. Field recordings of single-line-to-ground (SLG) faults followed by single-phase opening of transmission lines are used in a playback test procedure for validation. The results attest the effectiveness of the implemented SPAR method, as well as the feasibility of the proposed practical approach for real-world applications.

Index Terms—Secondary Arc Extinction; Single-Phase Auto-reclosing; Transmission Lines; Phasor Measurements; Practical Approach.

I. INTRODUCTION

The electricity sector has become increasingly competitive worldwide, requiring system efficiency and quality of service provided by utilities. However, power systems are subject to unexpected events, such as faults in transmission lines, which can cause the energy supply interruption and degrade the efficiency and quality of these services. Protecting transmission lines implies safeguarding system equipment and maintaining the continuous and economical supply of electricity. In this context, single-phase auto-reclosing (SPAR) of transmission lines is noteworthy because more than 80% of faults on power systems are single-line-to-ground (SLG) faults [1].

Single-phase auto-reclosing benefits and technical aspects have been widely discussed in the literature. Its main advantages lie in eliminating faults by isolating only the faulted phase, keeping part of the energy supply through the healthy phases [2]. SPAR has evolved during the years. Initially, it mainly consisted in only opening the faulted phase and reclosing it after a fixed dead time regardless the possibility of a permanent fault which could lead to an unsuccessful reclosing and cause damage to power system apparatus [3]. Then, secondary arc extinction detection methods have been proposed to avoid reclosing onto fault and provide a faster reclosing by adapting the line dead time. Thus, adaptive single-phase auto-reclosing (ASPAR) has emerged [4].

Several SPAR and ASPAR methods have been proposed in the literature [5]. Those methods can be divided into different categories, depending on the used techniques as well as its application for compensated or non-compensated lines [6]. The methods are based on harmonic signature [7], artificial neural networks [8], adaptive linear neural [9], convolutional neural network [10], wavelet transform [11], Kalman-filter [12] etc. However, most of those methods do not present a practical approach for field implementation, what may limit their application in the field.

In this paper, a practical approach is proposed to leverage existing relays structure in order to improve SPAR applications. A phasor-based single-phase auto-reclosing scheme for non-compensated transmission lines is embedded in a commercially available relay equipped with a free-form programming logic. As a result, the relay on-off signals and phasor estimations are used to implement and execute the user-defined SPAR/ASPAR logic, which is dynamically applied to the monitored signals allowing their application in the field. The implemented programming code is provided in the paper. A playback test procedure is carried out through a relay test set system and the events generated by the relay are analyzed. Field records from the Brazilian power grid are used and the obtained results reveal the effectiveness of the single-phase auto-reclosing scheme for all case studies, as well as the feasibility of its implementation in commercial available relay, providing a significant improvement in the system’s performance as a whole.

II. EXISTING RELAY AND FREE-FORM PROGRAMMING FOR SPAR/ASPAR IMPLEMENTATION

Due to their benefits and advantages, SPAR and ASPAR have been topics of interest to manufacturers, researchers and utilities worldwide [13], [14], [15]. Some manufacturers have embedded SPAR and ASPAR functionalities into their commercial relays, including the secondary arc extinction...
there detection. However, these relays usually do not permit user-defined logic implementations and the application of new functions/methods is not trivial for users. This problem is exacerbated when dealing with theoretical based and sophisticated methods with complex approaches for field implementation.

Based on a literature review regarding SPAR/ASPAR methods that could be cost-effective in terms of simplicity and performance, the method proposed in [16] is remarkable. It is a phasor-based single-phase auto-reclosing scheme for non-compensated transmission lines, which analyses the line side voltage phasors in the modal domain to safely and quickly identify the presence and the extinction of the secondary arc in the line. The method requires only voltage phasors at one line terminal, it has a low computational burden, it is simpler than most existing SPAR techniques and it can be easily implemented in readily available IEDs, such that no additional hardware or equipment is required. Unlike other methods, it is independent of line parameters, line length, line transposition, fault location, fault resistance, and system loading, being quite promising for field applications. Moreover, it is much faster than existing phasor-based SPAR methods and even faster than sophisticated or higher burden methods to detect the secondary arc extinction or re-ignition. Table I shows a qualitative comparison with other SPAR techniques regarding the time delay to detected the arc extinction or re-ignition for non-compensated lines.

Aiming to leverage existing relays structure for SPAR implementation and practical application, a commercial relay equipped with free programming module, which is characterized by open access programming environment, was used [23]. By using this environment, it is possible to access digital and analog variables from the relay. Additionally, by means of control elements from available equations, it is possible to customize the relay operation and create additional functions, such as SPAR/ASPAR. In this way, through direct access of digital variables and voltage phasors estimated by the relay, the mentioned single-phase auto-reclosing method could be implemented and executed in the same processing time as the relay’s native protection functions, resulting in realistic operation times.

### III. IMPLEMENTED PHASOR-BASED SPAR SCHEME

In this section, the basics on the mentioned phasor-based single-phase auto-reclosing scheme is presented for better understanding. Additionally, implementation details are addressed and the implemented programming code is provided.

#### A. Basics on the Phasor-Based SPAR Scheme

In [16], aiming to determine the secondary arc extinction time, the Clarke’s matrix is applied to the line side voltage phasors, yielding:

\[
\hat{V}_0 = \frac{1}{3} \left( \hat{V}_a + \hat{V}_b + \hat{V}_c \right)
\]

(1)

and

\[
\hat{V}_a = \frac{1}{3} \left( 2\hat{V}_a - \hat{V}_b - \hat{V}_c \right).
\]

(2)

After the single-phase opening due to a single-line-to-ground fault at phase A, ideally \( |\hat{V}_a| \ll |\hat{V}_b + \hat{V}_c| \). In this situation, while the fault persists in the line, it can be shown that:

\[
\frac{\hat{V}_a}{\hat{V}_a} \approx 1.
\]

(3)

After the secondary arc extinction, the phase-to-ground voltage at the opened line phase recovers and its value can be approximated by [24]:

\[
\hat{V}_a = K \left( \hat{V}_b + \hat{V}_c \right)
\]

(4)

where

\[
K = \frac{C_m}{C_a + 2C_m},
\]

(5)

being \( C_m \) the capacitance between the line phases and \( C_a \) the capacitance between each phase and the earth. Substituting (4) in (1) and (2), it can be shown that the following equality is valid after the fault extinction:

\[
\frac{\hat{V}_0}{\hat{V}_a} = \frac{1 + K}{1 - 2K}.
\]

(6)

The absolute value for the ratio \( \frac{V_0}{V_a} \) is defined in (7), which will always be greater than 1 after the fault extinction because \( 0 < K < 0.5 \), according to (5).

\[
R = \left| \frac{V_0}{V_a} \right|.
\]

(7)

This simple relation derived in the modal domain is used for secondary arc extinction detection and SPAR. According to (3) and (6), if \( R \) is close to one, then the fault persists on the line. Conversely, if \( R \) is greater than one, then the fault has been extinguished. However, these statements are valid for the ideal situation where \( |\hat{V}_a| \ll |\hat{V}_b + \hat{V}_c| \). Then, instead of comparing \( R \) to 1, \( R \) is compared to a threshold \( \lambda \) that safely indicate the presence, extinction or re-ignition of the fault. Here, a fixed value for \( \lambda \) was used \( (\lambda = 1.28) \) for all

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<table>
<thead>
<tr>
<th>Approach</th>
<th>Arc event</th>
<th>Time delay (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Mean</td>
</tr>
<tr>
<td>[16]</td>
<td>Extinction</td>
<td>0.43</td>
</tr>
<tr>
<td>[17]</td>
<td>Extinction</td>
<td>0.31</td>
</tr>
<tr>
<td>[18]</td>
<td>Extinction</td>
<td>1.20</td>
</tr>
<tr>
<td>[19]</td>
<td>Extinction</td>
<td>2.70</td>
</tr>
<tr>
<td>[20]</td>
<td>Extinction</td>
<td>0.70</td>
</tr>
</tbody>
</table>

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**TABLE I**

**TIME DELAY FOR ARC EXTINCTION/RE-IGNITION DETECTION [16].**
case studies, which was set based on the parameters from 219 lines from the Brazilian power grid, being 102 lines rated 230 kV and 117 rated 500 kV. By using the lines capacitances, the minimum value for $R$, obtained by (7), lies around 1.343. Then, $\lambda$ was conservatively set as 95% of that value. A deeper discussion concerning the value for $\lambda$ can be found in [16].

It is noteworthy that the method proposed in [16] is based on the Clarke’s Matrix, which is applicable to ideal transposed lines. However, it has been shown that the method can be successfully applied to both actually transposed and non-transposed lines as well.

### B. Implementation

Fig. 1 shows the flowchart for the SPAR implementation, which can be easily adapted for ASPAR as well [16]. After a SLG fault takes place and the single-phase opening, the Clarke’s matrix is applied to the line side voltage phasors in order to obtain $V_\alpha$ and $V_\beta$. Then, $R$ is calculated and compared to $\lambda$. The steps that follow are addressed according to the following word-bits, which are initially de-asserted for all cases:

- $RLAMB = 1$ when $R > \lambda$, indicating the secondary arc extinction;
- $RLAMB = 0$ when $R \leq \lambda$, indicating the presence of the fault in the line;
- $TDEAD = 1$ after the line dead time ($T_{dead}$) elapses;
- $TDEION = 1$ when the time elapsed since the secondary arc extinction detection is longer than the arc deionization time ($T_d$);
- ESPAR = 1 to enable SPAR;
- BSPAR = 1 to block SPAR.

![Fig. 1. Phasor-Based SPAR flowchart [16].](Image)

Based on the flowchart in Fig. 1, the phasor-based SPAR scheme was embedded into the used relay, making use of the free programming module. The relay on-off signals and phasor estimation are used to implement and execute the SPAR logic. Table II shows the implemented programming code.

### Table II: Implemented Code for SPAR

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>#VOLTAGES</td>
<td>PMV01 := VAYFR # VA_REAL</td>
<td>PMV02 := VAYFI # VA_imag</td>
<td>PMV03 := VBYFR # VB_REAL</td>
<td>PMV04 := VBYFI # VB_imag</td>
<td>PMV05 := VCYFR # VC_REAL</td>
<td>PMV06 := VCYFI # VC_imag</td>
</tr>
<tr>
<td>#CURRENTS</td>
<td>#CURRENTS MAGNITUDE (IA, IB AND IC)</td>
<td>PMV23 := SQRT((PMV17) + (PMV18) + (PMV19))</td>
<td>PMV24 := SQRT((PMV19) + (PMV20) + (PMV21))</td>
<td>PMV25 := SQRT((PMV21) + (PMV22) + (PMV23))</td>
<td>PMV26 := (PMV23 &lt; 0.050000) OR (PMV24 &lt; 0.050000) OR (PMV25 &lt; 0.050000)</td>
<td>PSV08 := (PSV07 OR PSV08) AND PSV09</td>
</tr>
<tr>
<td>#REGISTERS</td>
<td># CLARKE MATRIX - PHASE A TO GROUND FAULT</td>
<td>PMV10 := 1.000000 / 3.000000 * (PMV01 + PMV03 + PMV05)</td>
<td>PMV11 := 1.000000 / 3.000000 * (PMV02 + PMV04 + PMV06)</td>
<td>PMV12 := -1.000000 / 3.000000 * (PMV13 + PMV14 + PMV15)</td>
<td>PSV09 := (PMV23 &lt; 0.050000)</td>
<td>PSV09 := (PMV24 &lt; 0.050000)</td>
</tr>
<tr>
<td># COUNTER V VALUE THAT MAKES OUTPUT EQUAL TO 1</td>
<td># CURRENT RESET AT THE TIME COUNTER OUTPUT CHANGES TO 1</td>
<td>PMV13 := -1.000000 / 3.000000 * (PMV02 + PMV04 - PMV06)</td>
<td>PMV14 := SQRT((PMV10) + (PMV11) + (PMV12))</td>
<td>PMV15 := SQRT((PMV12) + (PMV13) + (PMV14))</td>
<td>PSV09 := (PMV24 &lt; 0.050000) OR (PMV25 &lt; 0.050000) OR (PMV26 &lt; 0.050000)</td>
<td>PSV09 := (PMV24 &lt; 0.050000) OR (PMV25 &lt; 0.050000) OR (PMV26 &lt; 0.050000)</td>
</tr>
<tr>
<td># ASSIGNMENT OF LOGICAL VARIABLE PSV01 TO ENTRY OF COUNTER PCN01</td>
<td># SQUARED WAVE SIGNAL 10101...</td>
<td>PCN01R := PCN02Q OR NOT PSV04</td>
<td>PCN02Q := 119.000000</td>
<td>PCN02Q := (PSV01 OR NOT PSV04) AND NOT PCN02Q</td>
<td>PCN01P := (NOT PSV01) AND R</td>
<td>PCN01R := PCN01Q OR (NOT PCN01Q)</td>
</tr>
<tr>
<td># CURRENT VALUE THAT MAKES OUTPUT EQUAL TO 1</td>
<td># CURRENT RESET AT THE TIME COUNTER OUTPUT CHANGES TO 1</td>
<td>PCN02Q := 119.000000</td>
<td>PCN01Q := (NOT PSV01) AND R</td>
<td>PCN01Q := (NOT PSV01) AND R</td>
<td>PCN02Q := 119.000000</td>
<td>PCN02Q := (PSV01 OR NOT PSV04) AND NOT PCN02Q</td>
</tr>
<tr>
<td># DEIONIZATION TIME COUNTER###</td>
<td># DEIONIZATION TIME COUNTER###</td>
<td>PCN01IN := PSV01</td>
<td>PCN01IN := (NOT PSV01) AND R</td>
<td>PCN01IN := PSV01</td>
<td>PCN01IN := (NOT PSV01) AND R</td>
<td>PCN01IN := PSV01</td>
</tr>
<tr>
<td># AND LAMBDA CALCULATION###</td>
<td># AND LAMBDA CALCULATION###</td>
<td>R := (PMV14 / PMV15)</td>
<td>R := (R &gt; 1.280000) AND PSV09</td>
<td>R := (R &gt; 1.280000) AND PSV09</td>
<td>R := (R &gt; 1.280000) AND PSV09</td>
<td>R := (R &gt; 1.280000) AND PSV09</td>
</tr>
<tr>
<td># R &gt; LAMBDA AND NOT LAMBDA</td>
<td># R &gt; LAMBDA AND NOT LAMBDA</td>
<td>R := (R &gt; 1.280000) AND PSV09</td>
<td>R := (R &gt; 1.280000) AND PSV09</td>
<td>R := (R &gt; 1.280000) AND PSV09</td>
<td>R := (R &gt; 1.280000) AND PSV09</td>
<td>R := (R &gt; 1.280000) AND PSV09</td>
</tr>
</tbody>
</table>
IV. Test Procedure

Aiming to evaluate the performance of this practical approach for SPAR of transmission lines, a playback test procedure is carried out through a relay test set and the events generated by the commercial relay are analyzed, as shown in Fig. 2. At first, field oscillographic recordings (in COMTRADE format) of SLG faults followed by single-phase opening of transmission lines are loaded and configured in the Doble F6150sv relay test set, which reproduces the field records by injecting the current and voltage signals into the analyzed programmable relay.

The results are obtained and evaluated through oscillographic analysis of the events generated by the relay. It is noteworthy that for the evaluated cases it was necessary to use only one relay test set, which feeds a single relay connected to only one of the transmission line terminals. By using this procedure, the implemented SPAR scheme is dynamically applied to the monitored signals as if it were installed in the field.

![Diagram of test procedure](Fig. 2. Test procedure.)

V. Results

Field recordings of SLG faults from 230 kV and 525 kV transmission lines from the Brazilian power grid are used to evaluate the proposed practical approach for SPAR. The lines lengths are 138 km and 208 km, respectively. The recordings also present the line single-phase opening, and some of them, the auto-reclosing attempt. Some of the reclosing maneuvers were carried out successfully and others were not. The unsuccessful reclosing usually occurs when the fault persists on the line. This situation could have been avoided by applying the method presented here.

Several oscillographic recordings were evaluated and some of them are presented in the following. For simplicity, only the voltage signal from the line side faulted phase is presented for each case. Additionally, the digital signals from the used relay are also presented, which correspond to the word-bits described in Fig. 1, as well as the control signals that correspond to the threshold $\lambda$ and the ratio $R$.

In Figs. 3, 4 and 5, temporary SLG faults in 230 kV and 525 kV transmission lines are presented. In each case, the fault occurs at instant $t_1$ and the transmission line faulted phase is opened at instant $t_2$. After $t_2$, $R$ approaches the unit value in all cases, indicating the presence of the secondary arc. The secondary arc is extincted at instant $t_3$. As a consequence, $R$ increases and becomes higher than $\lambda$. At that moment, $RLAMB = 1$, indicating the fault extinction. Then, a timer is started in order to wait for a safe de-ionization time ($Td$), which can be set according to the utility strategy. Here, $Td$ was set as two cycles. After $Td$ elapses, TDEION = 1, indicating that the single-phase auto-re-closing can be performed safely.

Just for the sake of illustration, it was considered that the line dead time is elapsed at instant $t_4$, in which TDEAD becomes 1. Thus, once the implemented SPAR scheme indicates that the secondary arc has been extinguished and the time considered for deionization has elapsed, as well as the line dead time, the line reclosing is enabled (ESPAR = 1) at $t_4$.

For the presented recordings, the actual reclosing maneuver was performed at $t_5$. However, the application of the implemented SPAR scheme would enable a significant and safe reduction in the system’s recomposition time, considering that the arc was extinguished at $t_3$.

![Graphs showing fault behavior](Fig. 3. Temporary single-line-to-ground fault recording, at phase B of a 230 kV transmission line, 208 km long, from the Brazilian power grid, with a fast secondary arc extinction followed by a successful autoreclosing. (a) $R$ behavior; (b) Line side faulted phase voltage; (c) SPAR scheme word-bits.)

Fig. 6 shows a temporary SLG fault at a 230 kV transmission line from the Brazilian power grid, which takes place at the instant $t_1$. In this case, the secondary arc lasts more than one second and its non-linearity effects can be observed at the faulted phase voltage behavior after the line opening at $t_2$. The arc is extincted at $t_4$. The magnitude of the faulted phase voltage clearly varies during the fault and reaches amplitudes similar to the recovery voltage, which takes place after the arc extinction. The faulted phase voltage makes $R$ oscillate above 1 during the fault. However, $R$ never reaches...
the threshold value set by $\lambda$ and the presence of the fault is correctly indicated. Additionally, considering that the line dead time elapses at $t_3$ ($T_{DEAD} = 1$), the SPAR would be blocked because the fault persisted on the line till that instant ($B_{SPAR} = 1$).

Fig. 7 shows a persistent SLG fault at a 525 kV transmission line from the Brazilian power grid. In this case, an unsuccessful reclosing attempt is observed. Here, the fault occurs at $t_1$ and the faulted phase is opened at $t_2$. After $t_2$, during the entire line dead time $R \approx 1$, indicating the presence of the fault along the recording ($R_{LAMB} = 0$). As in the previous cases, just for illustrating purposes, the dead time elapses at $t_3$, and $T_{DEAD} = 1$ at that moment. However, since the implemented SPAR scheme indicates the presence of the fault ($R_{LAMB} = 0$), the line reclosing is blocked ($B_{SPAR} = 1$) and a trip signal to open the line healthy phases would be sent. This would be a typical situation in which the application of this practical approach would avoid an unsuccessful reclosing and possible consequences for the system and its equipment.

VI. CONCLUSIONS

A practical approach for single-phase auto-reclosing of transmission lines, with secondary arc extinction detection function, was addressed in this work, leveraging an existing relay structure. The relay equipped with free programming module was used to embed a phasor-based SPAR scheme for non-compensated lines.

A playback test procedure was presented and by means of a relay test set. Field oscillographic recordings of single-line-to-ground faults followed by single-phase opening of 230 kV and 525 kV transmission lines from the Brazilian power grid were used for case studies. The results attest the efficiency and robustness of the embedded single-phase auto-reclosing method, which was easily implemented in a commercial relay without the need for additional equipment.

Based on the above and on the presented practical approach, it is expected that the benefits provided by single-phase auto-reclosing schemes be better exploited by utilities. Additionally to intrinsic advantages of SPAR/ASPAR, by using the presented approach and the embedded single-phase auto-reclosing method, other advantages are observed. For example, after the secondary arc extinction detection, it is possible to reclose the line and minimizing the time in which it is out of operation. Thus, it is possible to reduce the system restoration time and increase its reliability and availability. Moreover, by monitoring the secondary arc after opening the line faulted phase, reclosing onto fault is prevented, which could lead to an
unsuccessful reclosing and cause a great impact to the system and eventual damage to its equipment.

REFERENCES


