

Transmission Line Single-Pole Tripping: Field Experience in the Western Transmission Area of Mexico

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Abstract—In this paper, we describe the effects of single-pole tripping (SPT) and single-pole reclosing on power system transient stability. We discuss the application requirements for SPT schemes, describe SPT schemes applied in Mexico, and provide statistical data on SPT scheme operation. Based on an example of the Western Transmission Network of Mexico, we describe the power system studies required to implement SPT schemes. Finally, we present and discuss protection scheme operation for an actual fault.

I. INTRODUCTION

Today, many utilities use transmission line single-pole tripping (SPT) and single-pole reclosing (SPR) to enhance power system stability and reliability. The national Mexican utility, Comisión Federal de Electricidad (CFE), has successfully applied SPT schemes in transmission lines for more than 20 years. As of today, CFE has 174 SPT schemes on 400 kV lines (83.7 percent of all the lines) and 231 SPT schemes on 230 kV lines (48 percent of all the lines). CFE continues to implement SPT schemes on existing transmission lines.

Applying SPT schemes requires detailed power system studies. Critical clearing time information obtained from power system stability studies defines maximum allowable SPR times. Secondary arc extinction studies provide information to determine minimum SPR times. Transient overvoltage studies provide information on the maximum expected values of transient overvoltages caused by line-switching operations.

This paper describes SPT schemes applied in Mexico and provides data on SPT scheme operation. The paper also describes the power system studies required to implement SPT schemes. Finally, we present and discuss an actual case of protection scheme operation.

II. SPT IMPROVES POWER SYSTEM TRANSIENT STABILITY

Modern power systems typically have reduced redundancy and operate close to their security limits. In many power systems, tripping and reclosing all three phases for a single-phase-to-ground fault may cause the system to lose synchronism under certain operating conditions. Three-pole

tripping (TPT) and three-pole reclosing (TPR) are necessary for multiphase faults. However, for single-phase-to-ground faults (the most frequent fault type), it is possible to trip and reclose the faulted phase and keep the two healthy phases connected.

SPT schemes trip only the faulted phase for single-phase-to-ground faults. The line continues transmitting power over the two healthy phases during the single-pole open (SPO) condition. This power transfer reduces the chance of the system losing synchronism. Many publications describe the advantages of SPT in transmission and distribution systems [1] [2].

When a single-phase-to-ground fault occurs, the relays identify the faulted phase and trip the corresponding breaker pole. The open-pole period should be long enough for the secondary arc caused by the coupling with the unfaulted phases to extinguish. After this time interval, the automatic reclosing scheme closes the open breaker pole. If the fault persists, the scheme trips all three phases and recloses again or blocks reclosing. For all faults involving more than one phase, the scheme typically trips all three phases. Automatic reclosing for multiphase faults is optional and varies with each application.

We can use the simple power system shown in Fig. 1 (a generator connected by a power line to an infinite bus) to illustrate TPT and SPT effects on transient stability. The equal-area criterion of transient stability [3] is applicable to this lossless two-machine system. Equation (1) gives the generator electrical output power (P_E).

$$P_E = \frac{E_G E_B}{X} \sin \delta \quad (1)$$

where:

E_G is the voltage behind the generator transient reactance.

E_B is the infinite bus voltage.

X is the series reactance between the generator and infinite bus (for normal conditions, X is sum of the line reactance and the generator reactance).

δ is the angle by which the generator voltage leads the infinite bus voltage.

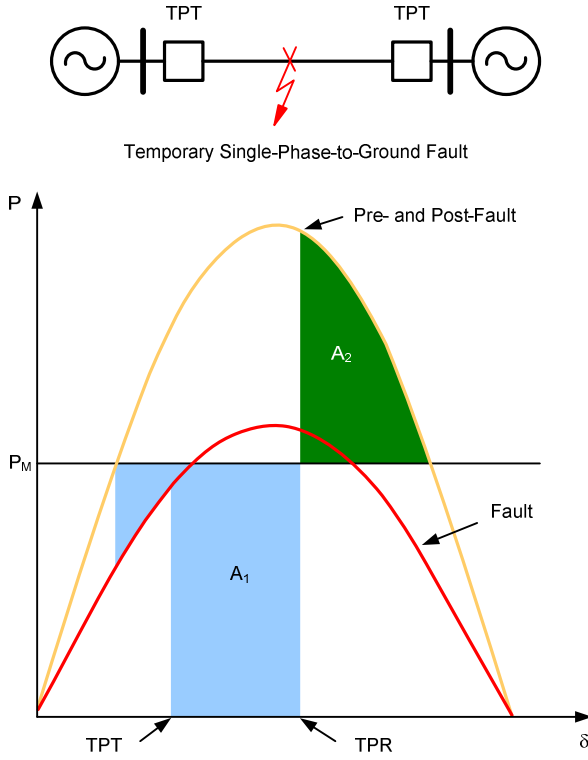


Fig. 1. TPT completely interrupts power flow through the faulted line, which increases the acceleration area and may cause the system to lose synchronism.

Under normal operating conditions, the mechanical power (P_M) supplied to the generator equals its electrical output power (P_E). In Fig. 1, the power angle curve resulting from (1) for normal conditions is labeled *pre- and post-fault*.

A single-phase-to-ground fault on the line reduces the system power transfer capability by increasing the series reactance X [3]. The resulting power angle curve is labeled *fault* in Fig. 1. During the fault condition, $P_M > P_E$, the generator accelerates and δ increases. When protection operates and the breakers open all three poles, the transfer power is zero. Angle δ continues to increase during the line-open period. Area A_1 in Fig. 1 represents the kinetic energy stored in the generator rotor during the period when $P_M > P_E$.

When the breakers reclose, the system recovers the prefault transfer capability. Now $P_E > P_M$ and the generator decelerates, but δ continues increasing because the generator speed is greater than the synchronous speed. The angle increases up to a value for which Area A_2 (which represents the kinetic energy drawn from the generator rotor during the period when $P_E > P_M$) equals Area A_1 . For Fig. 1, the power system loses synchronism because $A_1 > A_2$.

Fig. 2 shows the effects of SPT and SPR for the same single-phase-to-ground fault. When protection operates and the breakers open only the pole corresponding to the faulted phase, the transfer power does not fall to zero but to a value given by the curve labeled *SPO* in Fig. 2. As a result, the accelerating Area A_1 is smaller than that for TPT, and Area A_2 equals Area A_1 , so the system is stable.

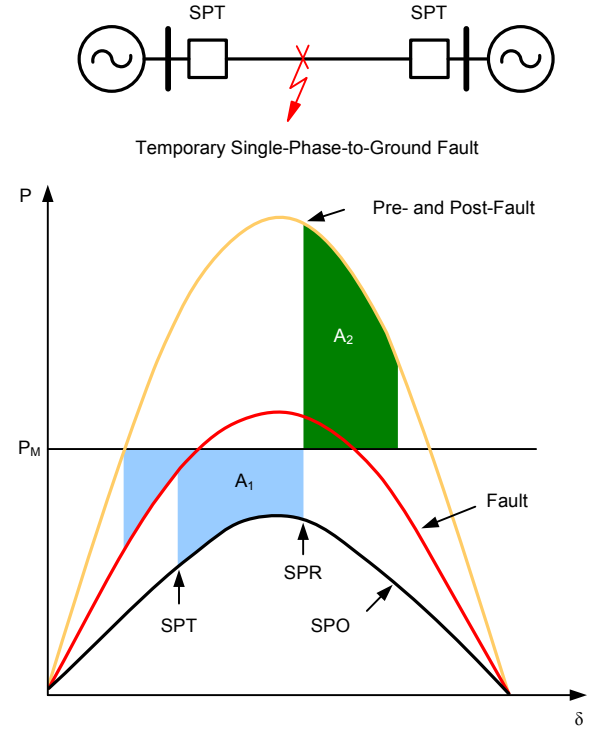


Fig. 2. SPT allows power to flow through the faulted line during the SPO period, which reduces the acceleration area and enhances transient stability.

Fig. 3 shows the sequence network interconnection for an SPO condition in the system presented in Fig. 2. The system series reactance X results from the series connection of the positive-sequence reactance with the parallel combination of negative- and zero-sequence reactances.

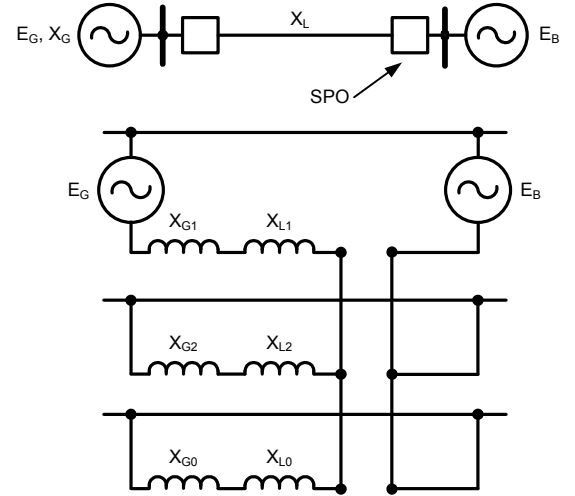


Fig. 3. Symmetrical component network interconnection for an SPO condition in a transmission line connecting a generator with an infinite bus.

III. APPLICATION CONSIDERATIONS

A. Scheme Requirements

An SPT scheme requires breakers with independent pole operation. Extra-high-voltage breakers typically have independent contact-operating mechanisms because of the large contact separation required to provide insulation. These breakers are suitable for SPT schemes at no additional cost. Lower-voltage breakers typically have three-pole operation. The version of these breakers with independent pole operation is more expensive than the version with three-pole operation. Some utilities that apply TPT for all fault types use breakers with independent pole operation to avoid the contingency of a breaker failing to open all three poles for a three-phase fault [4]. Using these breakers together with redundant relaying systems and redundant trip coils practically ensures the opening of at least two poles, which improves transient stability.

Breakers with independent pole operation require pole discrepancy logic that verifies all of the breaker poles are in the same position during normal operation [1]. This logic can reside in protective relays or breaker control devices. It is easy to implement using the logic programming abilities of modern relays. The logic trips all three breaker poles when the breaker remains with one or two poles open for longer than a settable time. In SPT schemes, the pole discrepancy timer must be set longer than the maximum duration of a normal SPO condition.

An SPT scheme requires relays with the ability to detect the faulted phases and issue SPT signals. Most modern microprocessor-based relays provide the faulted phase identification algorithms and tripping outputs required for SPT schemes at no additional cost. The main additional cost related to relays in an SPT scheme as compared with a TPT scheme is that of the wiring to the relays.

The secondary arc extinction process may require a bank of four shunt reactors, including three reactors connected between the phases and a neutral point and a fourth reactor connected between this neutral point and ground. The phase reactors may also serve to compensate the normal line-charging current for voltage control.

B. Faulted Phase Identification

Several methods provide faulted phase identification. Some relays compare the angle between the negative- and zero-sequence currents to identify the faulted phase. Furthermore, these relays distinguish single-phase-to-ground faults from phase-to-phase-to-ground faults by comparing the fault-resistance values estimated for all fault loops with the impedance measured for each phase-to-phase fault loop [5]. Finally, these relays use single-phase undervoltage elements to identify the faulted phase for ground faults that produce very low current at the relay. Also, the high-speed elements of some relays use incremental quantities for fast faulted phase identification [6].

Phase-segregated, current-only schemes provide inherent faulted phase identification, which functions well even for evolving, intercircuit, and cross-country faults. One relay uses

the outputs of phase differential elements to identify faulted phases. For low-current faults, the sequence-component differential elements of the relay apply the methods described in the previous paragraph for faulted phase identification. Sequence-component differential elements use the differential current rather than the terminal currents for faulted phase identification, which improves performance.

For the best selectivity, the faulted phase identification elements should be more sensitive than the fault detection elements. If the fault detection elements are more sensitive, the relay may trip the incorrect phase or all three phases when trying to clear a low-current, single-phase-to-ground fault.

C. Effects of the SPO Condition on Relays

The open-phase condition following an SPT on a transmission line creates unbalances that can affect relays. The protection elements must be designed to be immune to the unbalance effects or desensitized or blocked during the SPO period.

Reference [7] provides current and voltage values for an open-phase condition on one of two parallel lines in a two-source power system. When the relay receives voltage information from line-side voltage transformers (VTs), the voltage measured on the open-phase condition falls to zero. Furthermore, the shunt reactors and line capacitance cause transient damped oscillations in the open-phase voltage [1] [8]. These conditions may affect relay operation.

The relays on the line with the open-phase condition can determine that the phase is open. The protection scheme can use this information to modify the protection elements and scheme logic, thereby preventing any misoperations caused by the unbalanced currents. However, the relays at other locations typically do not have information about the open-phase condition. Therefore, users should desensitize these relays to prevent misoperations, unless the relays are immune to the unbalance caused by the open phase.

1) Distance Elements

When using line-side VTs, we should block the phase distance elements associated with the open phase during the SPO condition because the phase-to-phase voltages suffer magnitude and phase angle changes. For example, when the A-phase is open, we block the AB and CA phase distance elements.

The ground distance element associated with the open-phase condition should also be blocked because it may have no voltage signal but still have zero-sequence operating current. Depending on the polarization type, the unbalance may also affect the ground distance elements on the unfaulted phases. For example, in cross-polarized mho elements, when the A-phase opens, the phase angle of the polarizing voltage for the BG and CG ground distance elements shifts similarly to the effect of a blown fuse on the A-phase VT. Hence, these elements may misoperate. Reference [7] includes an example where the polarizing voltage for the AG mho element shifts ± 30 degrees and reduces its magnitude for an open B- or C-phase.

The open phase has little effect on the positive-sequence voltage angle [7]. Positive-sequence voltage-polarized mho elements are the preferred choice for SPT schemes.

Ground quadrilateral distance elements generally use zero- and/or negative-sequence currents for polarization [9]. The unbalanced phase currents created by the open phase may affect the performance of ground quadrilateral distance elements. The traditional solution is to block these elements during the SPO period following an SPT. The high-speed quadrilateral element described in [10] replaces the sequence-component currents with the fault loop incremental current during the SPO period. This element remains operational during the SPO period.

2) Directional Overcurrent Elements

Unbalanced voltages and currents caused by the open phase affect the performance of zero- and negative-sequence directional elements. Unbalanced voltages have the greatest effect when the relay receives line-side voltage signals. To prevent misoperation, we should set the relay to block zero- and negative-sequence directional elements during the SPO period.

The open phase has a minimal effect on the phase overcurrent elements. However, the unbalance affects the performance and may call for settings adjustments of negative- and zero-sequence overcurrent elements. Reference [7], for example, compares the per-unit negative- and zero-sequence quantities measured by a relay on one of two parallel lines in a two-source power system for an open-phase condition on the parallel line and a resistive ground fault (without open phases) on the protected line.

Reference [7] shows that the measured current magnitude for internal faults may be less than the measured current magnitude for an open-phase condition on the parallel line. We can raise the pickup current of negative- or zero-sequence overcurrent elements to prevent operation during an SPO condition. However, raising the pickup current also reduces the sensitivity of the element for detecting high-impedance faults. A better solution is to coordinate the time delay of overcurrent elements with the maximum duration of a normal SPO condition.

3) Differential Elements

Phase differential elements function well during the SPO period but do not operate for low-current faults. For TPT applications, negative- and zero-sequence differential elements supplement the phase differential elements to provide additional sensitivity. However, the negative- and zero-sequence differential elements lose sensitivity for ground faults occurring during the SPO period in SPT applications [11].

D. Power Swing Blocking During the SPO Period in SPT Schemes

In SPT applications, negative-sequence current flows during the SPO period. Many SPT schemes inhibit power swing blocking (PSB) during this period to prevent misoperation of the negative-sequence elements used to detect unbalanced faults.

Some modern relays can detect power swings even if an SPO condition exists. These relays use the angle between the negative- and zero-sequence currents to detect single-phase-to-ground faults occurring during the SPO period. For example, when the PSB logic detects a power swing while the A-phase is open, it blocks only the BG, CG, and BC distance elements. If a B-phase-to-ground fault or a C-phase-to-ground fault occurs, the logic based on the sequence-current angle measurement unblocks the BG or CG distance element. If a B-to-C-phase fault or B-to-C-phase-to-ground fault occurs, phase fault detection logic unblocks the BC element.

IV. SPT APPLICATIONS IN MEXICO

A. SPT Schemes in Operation in Mexico

CFE has successfully applied SPT schemes in transmission lines for more than 20 years. As of today, CFE has 174 SPT schemes on 400 kV lines (83.7 percent of the lines) and 231 SPT schemes on 230 kV lines (48 percent of the lines). Table I shows the SPT schemes currently in operation on 400 kV and 230 kV transmission lines in Mexico. CFE continues to implement SPT schemes in existing transmission lines and in all new lines.

TABLE I
CFE TRANSMISSION LINES WITH SPT SCHEMES

CFE Area	400 kV			230 kV		
	Lines	SPT Schemes	%	Lines	SPT Schemes	%
Baja California	n/a	n/a	n/a	49	8	16.3
Northwestern	5	5	100	72	72	100
Northern	5	5	100	59	53	89.8
Northeastern	39	21	53.8	37	1	2.7
Eastern	52	41	78.8	33	16	48.5
Central	43	39	90.7	79	13	16.5
Western	52	51	98	103	19	18.4
Southeastern	12	12	100	20	20	100
Peninsular	n/a	n/a	n/a	29	29	100
Total	208	174	83.7	481	231	48

B. Typical Scheme Operation Logic

CFE typically applies the following SPT and SPR sequences:

- Temporary single-phase-to-ground faults
 - Trip the faulted phase pole of the breakers at both line ends.
 - Reclose the breaker at the line end having the weakest source first, which minimizes the impact to the power system of reclosing onto a permanent fault.
 - After a time delay, reclose the breaker at the line end having the strongest source.
- Permanent single-phase-to-ground faults
 - Trip the faulted phase pole of the breakers at both line ends.
 - Reclose the breaker at the line end having the weakest source first.
 - Because the fault did not clear, trip all three poles of this breaker, block its reclosing, and send a direct transfer trip signal to the remote-end breaker.
 - Trip the other two poles of the remote-end breaker upon receipt of the transfer trip signal, and block its reclosing.
- Multiphase faults
 - Trip all three poles of the breakers at both line ends.
 - Block breaker reclosing.
- Single-phase-to-ground fault occurring during the reclosing logic reset time
 - Trip all three breaker poles at both line ends.
 - Block breaker reclosing.
- Breaker tripping more than one pole for a single-phase-to-ground fault
 - Block breaker reclosing using supervisory logic to detect that more than one pole is open.
 - If the breaker remains with two poles open, the pole discrepancy logic operates to trip the pole that remains closed.
- Breaker reclosing failure (caused by a breaker failure or blocking condition)
 - Because the breaker remains with one pole open, the pole discrepancy logic operates to trip the other two poles.
 - The line remains fed from one end.

Fig. 4 shows a typical time chart for the SPT scheme of a line having a permissive overreaching transfer trip (POTT) directional comparison protection scheme. To create this chart, we assume a permanent single-phase-to-ground fault occurs at the line end with the strongest source.

The upper part of Fig. 4 is the time chart for the scheme at the line end with the weakest source. The local relay trips and sends a transfer trip signal to the remote line end. The relay initiates breaker tripping upon receipt of the permissive tripping signal from the remote end. The POTT scheme operating time is $t_r + t_c$. The breaker opens one pole and clears the fault in a time equal to $t_r + t_c + t_b$. When the reclosing timer expires, the breaker recloses the open pole onto the fault. The local relay operates again and sends a transfer trip signal to the remote end, which causes the remaining two poles of the remote breaker to open. The echo logic of the remote-end scheme sends the transfer trip signal back to the local end, which causes all three poles of the local breaker to open.

The lower part of Fig. 4 is the time chart for the scheme at the line end with the strongest source. The reclosing time delay of this scheme is set to a value that allows the scheme at the other line end to clear the permanent fault, plus a security time delay (t_s). For temporary single-phase-to-ground faults, this scheme successfully recloses the breaker open pole after the reclosing timer expires.

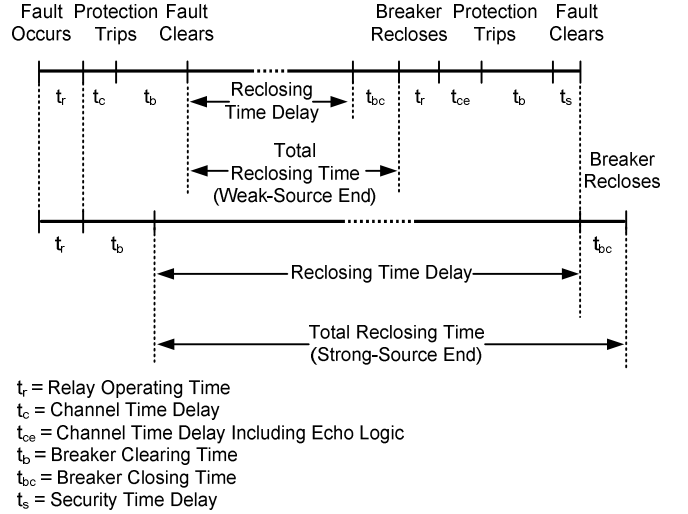


Fig. 4. Typical time chart of an SPT scheme.

C. Field Operation Experience

Table II and Table III summarize the field operating record of the SPT schemes in Mexico.

The 400 kV schemes operated correctly for 303 single-phase-to-ground faults (97.4 percent of all faults):

- Tripped one pole and successfully reclosed for 204 temporary faults (65.6 percent).
- Tripped all three poles after SPT for 99 permanent faults (31.8 percent).

The 230 kV schemes operated correctly for 242 single-phase-to-ground faults (96 percent of all faults):

- Tripped one pole and successfully reclosed for 196 temporary faults (77.8 percent).
- Tripped all three poles after SPT for 46 permanent faults (18.2 percent).

TABLE II
SUMMARY OF 400 kV SPT SCHEME OPERATIONS

CFE Region	SLG Faults	Correct Operations				Scheme Failures
		Temporary Faults	Permanent Faults	Total	%	
Northwestern	15	12	2	14	93.3	1
Northern	5	3	2	5	100	0
Northeastern	21	13	8	21	100	0
Eastern	57	35	19	54	94.7	3
Central	45	37	8	45	100	0
Western	124	73	49	122	98.4	2
Southeastern	44	31	11	42	95.5	2
Total	311	204	99	303	97.4	8

TABLE III
SUMMARY OF 230 kV SPT SCHEME OPERATIONS

CFE Region	SLG Faults	Correct Operations				Scheme Failures
		Temporary Faults	Permanent Faults	Total	%	
Baja California	12	12	0	12	100	0
Northwestern	54	31	20	51	94.4	3
Northern	38	31	7	38	100	0
Northeastern	2	1	0	1	50.0	1
Eastern	34	29	4	33	97.0	1
Central	20	20	0	20	100	0
Western	14	10	2	12	85.7	2
Southeastern	50	41	8	49	98.0	1
Peninsular	28	21	5	26	92.8	2
Total	252	196	46	242	96.0	10

V. POWER SYSTEM STUDIES FOR SPT APPLICATION

Applying SPT schemes requires detailed power system studies. In this section, we present examples of these studies based on the 400 kV network of the CFE Lázaro Cárdenas Transmission Zone depicted in Fig. 5. This network connects with the rest of the Mexican Interconnected System at Buses MTA-400 and SMD-400. Fig. 5 also shows the bus voltages and line power flows for the base case, in which the network has a generation surplus smaller than 2,300 MW. Generating Unit LCP-U6 is out of service for this base case in order to keep the exported power under the value (2,300 MW) for which the automatic generator-shedding scheme is armed.

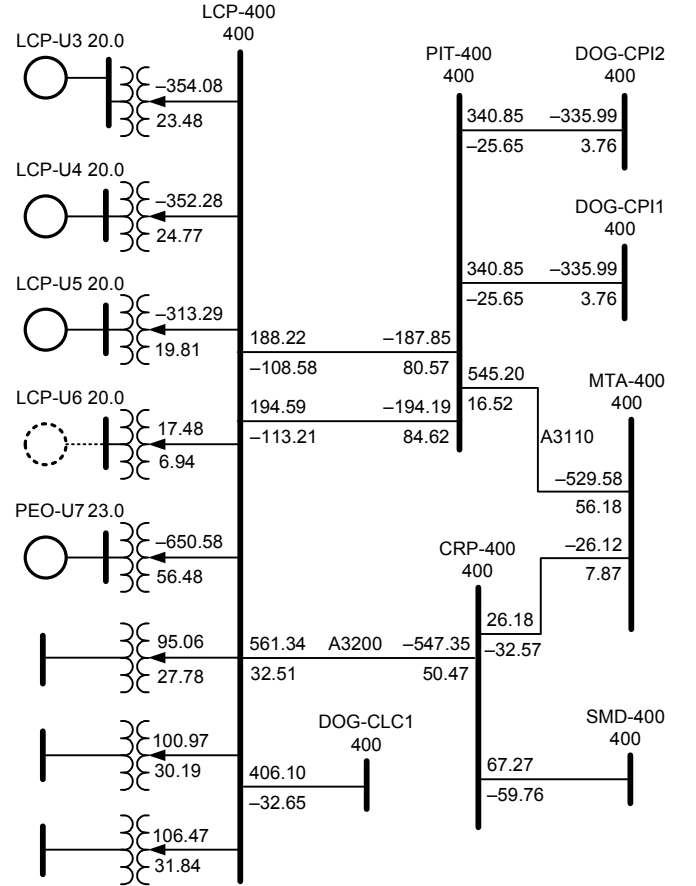


Fig. 5. Single-line diagram of the CFE Lázaro Cárdenas Transmission Zone.

A. Transient Stability Analysis

Power system transient stability studies allow evaluating the need for SPT. We can analyze the system stability for TPT, TPR, SPT, and SPR by applying single-phase-to-ground faults on different locations under different power system conditions and with different tripping and reclosing times. For example, Fig. 6 shows the time variation of the angles of Generators LCP-U3, LCP-U4, LCP-U5, and PEO-U7 (see Fig. 5) with respect to a generator of the Manuel Moreno Torres Hydroelectric Power Station, located far away from the Lázaro Cárdenas Transmission Zone.

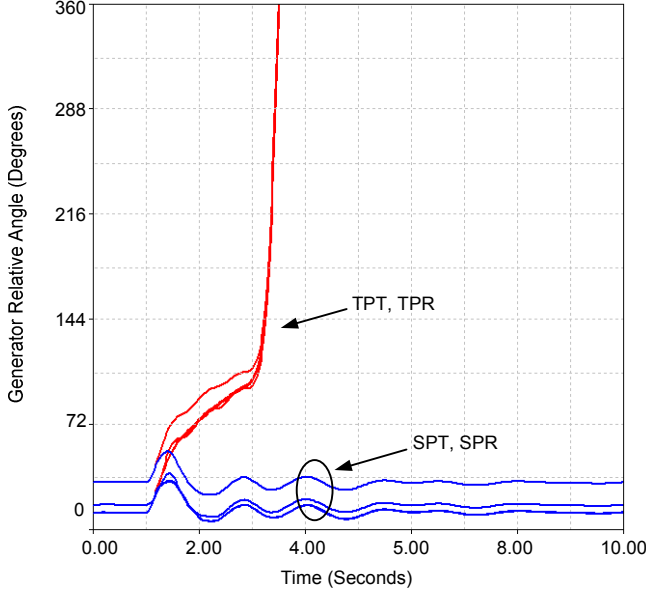


Fig. 6. Angle between generators of Plutarco Elías Calles Power Station and a generator external to the Lázaro Cárdenas Transmission Zone for a single-phase-to-ground fault on the CRP-A3200-LCP line. The blue traces are for SPT and SPR, and the red traces are for TPT and TPR.

To obtain Fig. 6, we simulated the following conditions:

- Opened the PIT-A3110-MTA line and two 230 kV lines (not shown in Fig. 5) to increase the power flow through the CRP-A3200-LCP line to 1,200 MW.
- Applied a single-phase-to-ground fault at the LCP end of the CRP-A3200-LCP line.
- Tripped the breakers at both line ends in 6 cycles. We simulated both SPT and TPT for comparison.
- Successfully reclosed the breakers at both line ends.

According to Fig. 6, the system is stable for SPT and SPR (blue traces), but it loses synchronism for TPT and TPR (red traces). Only three traces are visible for each condition because the angle curves for two of the generators are identical.

Once the need for SPT is defined, we should perform transient stability studies to determine the maximum allowable SPR times. For example, CFE performed these studies to evaluate the impact of adding a new generating unit (PEO-U7 in Fig. 5) to the Plutarco Elías Calles Power Plant.

The worst-case scenario considered for this study (see Fig. 5) is as follows:

- Opening the PIT-A3110-MTA line (first contingency) to increase the power flow through the CRP-A3200-LCP line.
- Applying a single-phase-to-ground fault at the LCP end of the CRP-A3200-LCP line (second contingency), which produces the maximum fault current value.
- Tripping the faulted phase at both line ends in 6 cycles.
- Successfully reclosing the open breaker pole at both line ends.

The simulations showed the system to be stable for SPR times of 0.6, 0.8, 1.0, 1.2, and 1.6 seconds. Fig. 7 shows the time variation of the angles of Generators LCP-U3, LCP-U4, LCP-U5, and PEO-U7 (see Fig. 5) and other nearby generators for a reclosing time of 1.6 seconds.

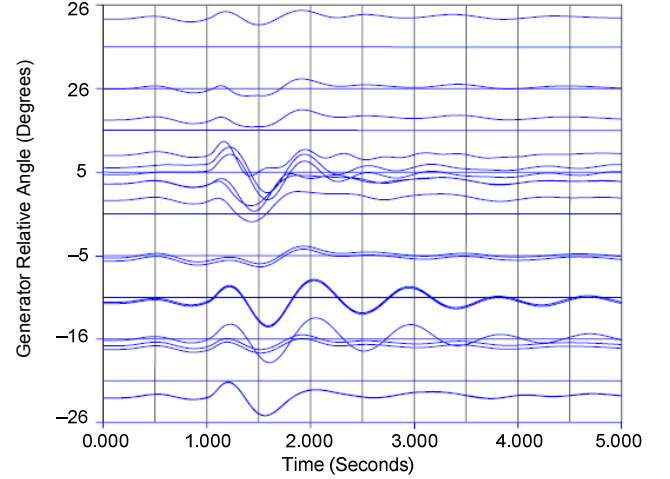


Fig. 7. Generator angles for a single-phase-to-ground fault at the LCP end of the CRP-A3200-LCP line, followed by SPT and successful reclosing in 1.6 seconds.

B. Secondary Arc Extinction Analysis

During the SPO period, capacitive and inductive coupling between the conductor of the open phase and the unfaulted phase conductors induces a voltage in the open phase conductor. This voltage sustains the secondary arc for a given time after the phase opening. The secondary arc should self-extinguish within 500 milliseconds if the arc current is no greater than 40 A in lines with shunt reactor compensation and no greater than 20 A in uncompensated lines [4].

Secondary arc extinction studies provide information to determine minimum SPR times. For example, CFE decided to move the shunt reactors of the CRP-A3200-LCP line from the LCP substation to the CRP substation. These reactors include three 25 MVA phase reactors and a neutral 795 Ω reactor. It was necessary to perform a secondary arc extinction study to evaluate the effect of the reactors in their new location and the possibility of operating the line without reactors during the reactor relocation process.

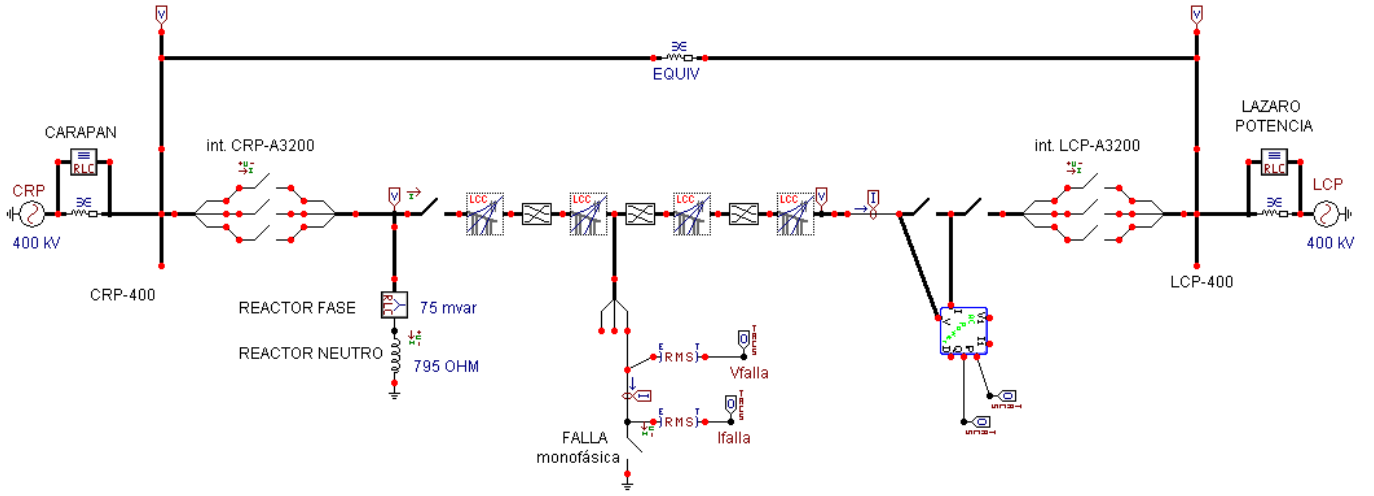


Fig. 8. Power system model for the secondary arc extinction study.

Fig. 8 shows the power system model used for this study. The CRP-A3200-LCP transposed line is 238 kilometers long and has two ACSR1113 conductors per phase in a horizontal configuration.

Table IV shows the root-mean-square (rms) secondary arc currents and recovery voltages for different fault locations and a power flow of 252 MW over the CRP-A3200-LCP line.

TABLE IV
RESULTS OF THE SECONDARY ARC EXTINCTION STUDY

Reactor Status	Fault Location	Secondary Arc Current (A)	Recovery Voltage (kV)
In Service	CRP Substation	17.5	42.5
	First Transposition	15.6	36.8
	Second Transposition	6.7	20.1
	Third Transposition	6.7	23.4
	LCP Substation	11.28	23.3
Out of Service	CRP Substation	26.2	41.4
	First Transposition	24.5	41.4
	Second Transposition	24.1	44.3
	Third Transposition	29.4	51.1
	LCP Substation	29.7	49.7

Table IV shows that the secondary arc current is always below 40 A with the reactors in service, which should result in the arc extinguishing in no more than 500 milliseconds. Table IV also shows that the secondary arc current is always above 20 A when the reactors are out of service, which makes

arc extinction difficult. We conclude that the reactors work well at the CRP substation, but we do not recommend operating the line without reactors. The SPR time should be above 500 milliseconds.

C. Analysis of Transient Overvoltages During Switching Operations

Transient overvoltage studies provide information on the maximum expected values of transient overvoltages caused by line-switching operations. For example, CFE conducted a study to determine the transient overvoltages resulting from breaker switching with the reactors relocated at the CRP substation. The study evaluates the effect of the breaker used to energize the line and the effect of the line lightning arresters, which have a discharge voltage of 360 kV. The line has two breakers (resulting from a breaker-and-a-half bus arrangement) at each end. The rated withstand impulse phase-to-ground voltage is 1,050 kV for all of the breakers. The breakers at the CRP substation (CRP-A3200 and CRP-A8200) and the bus-side breaker at the LCP substation (LCP-A3200) have a 200 Ω pre-insertion resistor. The middle breaker at the LCP substation (LCP-A8200) has no pre-insertion resistor.

The study simulated 500 breaker closes at random wave points at each line end for each case resulting from combinations of:

- Reactors at the CRP substation in service and out of service.
- Line with and without lightning arresters.
- Line energization with the bus-side and middle breaker at the CRP substation (to evaluate the pre-insertion resistor effect) and with one of the breakers at the LCP substation.

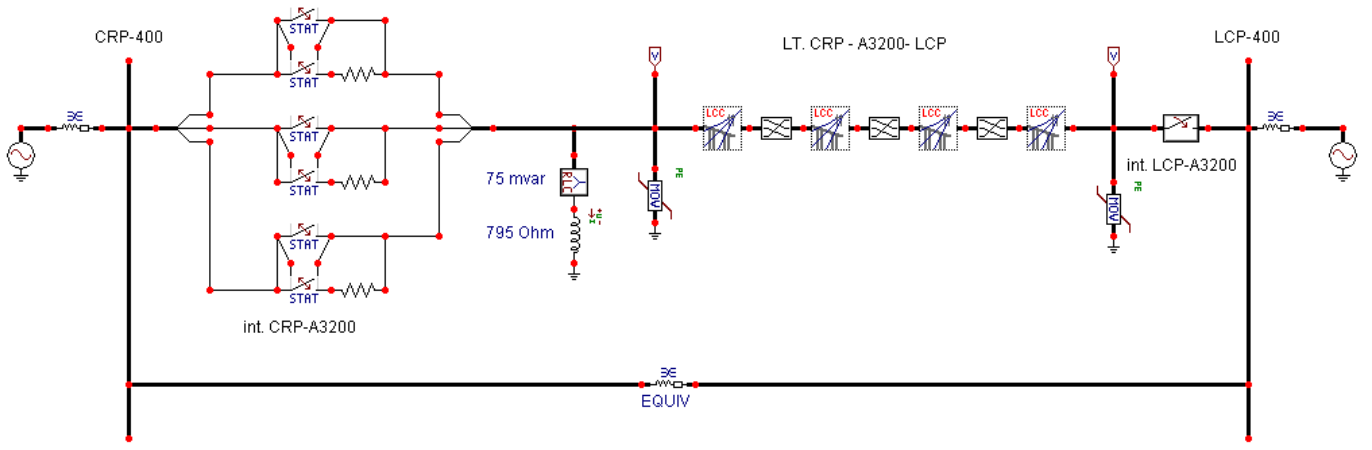


Fig. 9. Power system model for the transient overvoltage study.

Fig. 9 shows the power system model used for this study. Table V through Table VIII show the maximum rms pu values of the phase-to-ground transient overvoltages obtained in the study.

TABLE V
TRANSIENT OVERVOLTAGES AT THE LINE ENDS WITH THE REACTORS IN SERVICE AT THE CRP SUBSTATION AND WITHOUT LIGHTNING ARRESTERS

Breaker Used to Energize the Line	Maximum Voltages at CRP (pu)			Maximum Voltages at LCP (pu)		
	A-Phase	B-Phase	C-Phase	A-Phase	B-Phase	C-Phase
CRP-A3200	1.3	1.3	1.35	1.85	1.78	1.85
CRP-A8200	1.65	1.7	1.75	2.7	2.95	2.95
LCP-A3200	1.9	1.85	1.95	1.35	1.3	1.3

TABLE VI
TRANSIENT OVERVOLTAGES AT THE LINE ENDS WITH THE REACTORS OUT OF SERVICE AT THE CRP SUBSTATION AND WITHOUT LIGHTNING ARRESTERS

Breaker Used to Energize the Line	Maximum Voltages at CRP (pu)			Maximum Voltages at LCP (pu)		
	A-Phase	B-Phase	C-Phase	A-Phase	B-Phase	C-Phase
CRP-A3200	1.37	1.38	1.4	1.88	1.86	1.91
CRP-A8200	1.7	1.7	1.8	2.75	3.0	2.95
LCP-A3200	2.05	1.9	2.05	1.4	1.3	1.35

TABLE VII
TRANSIENT OVERVOLTAGES AT THE LINE ENDS WITH THE REACTORS IN SERVICE AT THE CRP SUBSTATION AND WITH LIGHTNING ARRESTERS

Breaker Used to Energize the Line	Maximum Voltages at CRP (pu)			Maximum Voltages at LCP (pu)		
	A-Phase	B-Phase	C-Phase	A-Phase	B-Phase	C-Phase
CRP-A3200	1.33	1.3	1.35	1.81	1.78	1.85
CRP-A8200	1.65	1.65	1.6	2.15	2.2	2.2
LCP-A3200	1.9	1.88	1.95	1.35	1.3	1.3

TABLE VIII
TRANSIENT OVERVOLTAGES AT THE LINE ENDS WITH THE REACTORS OUT OF SERVICE AT THE CRP SUBSTATION AND WITH LIGHTNING ARRESTERS

Breaker Used to Energize the Line	Maximum Voltages at CRP (pu)			Maximum Voltages at LCP (pu)		
	A-Phase	B-Phase	C-Phase	A-Phase	B-Phase	C-Phase
CRP-A3200	1.4	1.35	1.39	1.85	1.82	1.90
CRP-A8200	1.7	1.7	1.65	2.15	2.2	2.2
LCP-A3200	2.05	1.9	2.05	1.4	1.3	1.35

Table V through Table VIII show that the shunt reactors and lightning arresters limit transient overvoltages. The highest overvoltages occur when energizing the line with the CRP-A8200 breaker, which lacks a pre-insertion resistor. These voltages reach maximum values of 2.95 pu and 3 pu in some cases, which are close to the breaker withstand impulse voltage. Hence, we do not recommend energizing the line with the CRP-A8200 breaker.

VI. SCHEME OPERATION FOR AN ACTUAL FAULT

A C-phase-to-ground fault occurred on the LCP-A3200-CRP line on June 23, 2010. The line length is 238 kilometers. The fault location was 67.6 kilometers away from the LCP line end. The line protection is a redundant POTT directional comparison scheme. Fig. 10 shows the voltages and currents recorded at the LCP substation. Fig. 10 shows the fault on the C-phase, the SPO period following breaker tripping, and the successful sequential breaker reclosing.

Fig. 11 shows the C-phase voltage and current and some of the digital quantities recorded at the LCP substation. From Fig. 11, we conclude the following:

- The fault starts at 35.841 seconds.
- The high-speed ground distance elements Z1G (Zone 1) and Z2G (overreaching zone) operate at 35.849 seconds. Output FSC of the high-speed faulted phase selection logic also asserts at 35.849 seconds. The operating time of these elements is 8 milliseconds.

- The Z1G assertion initiates tripping of the C-phase pole of the local breaker (bits TRIP and SPT assert) at 35.849 seconds.
- The Z2G assertion causes the KEY bit to assert, which initiates transmission of the permissive tripping signal at 35.87 seconds.
- The local breaker clears the fault at 35.884 seconds. The total fault-clearing time is 43 milliseconds.
- Bits LOPHC and SPOC assert to declare the breaker SPO condition.
- The remote (CRP substation) breaker successfully recloses at 36.61 seconds (0.769 seconds after the fault inception). CRP is the line end with the weakest source.
- The local (LCP substation) breaker successfully recloses at 36.785 seconds (0.944 seconds after the fault inception).

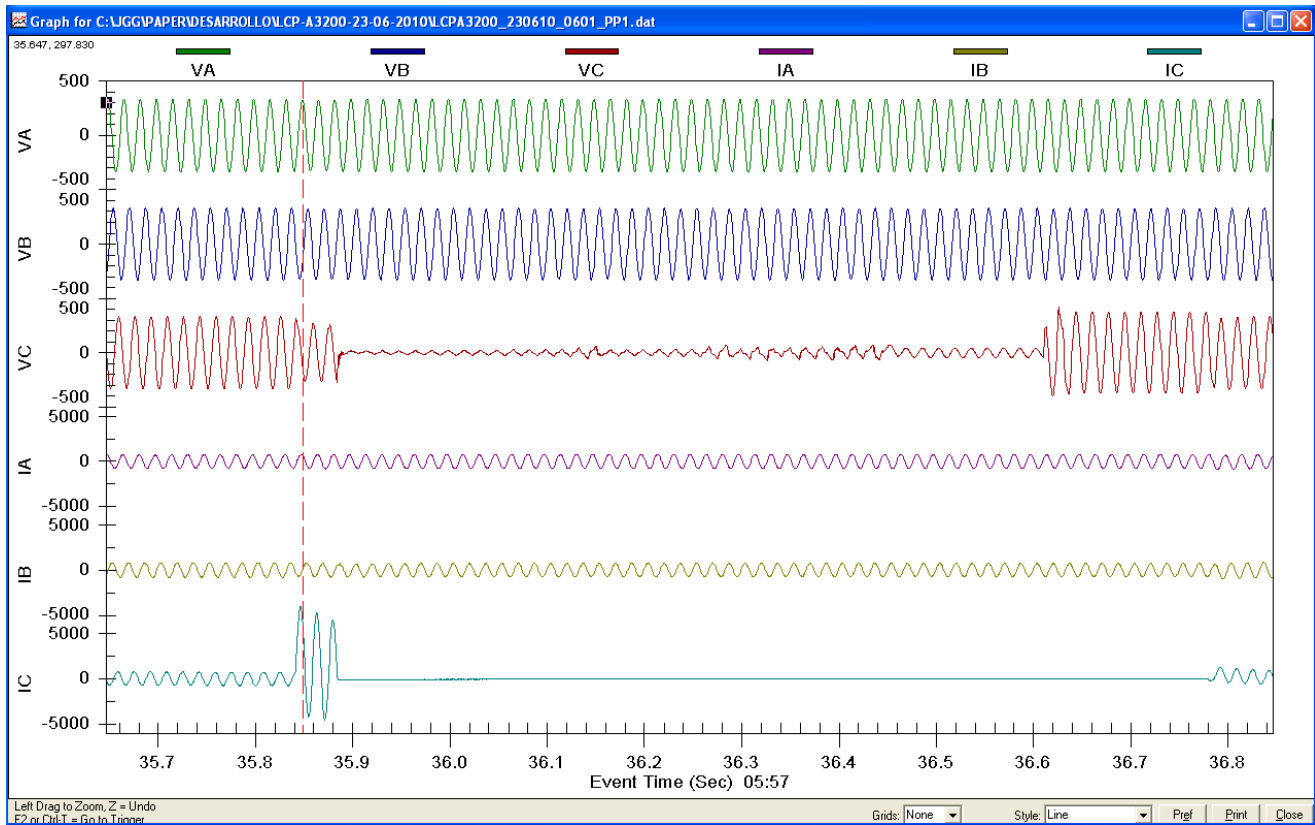


Fig. 10. Voltages and currents recorded at the LCP end of the LCP-A3200-CRP line.

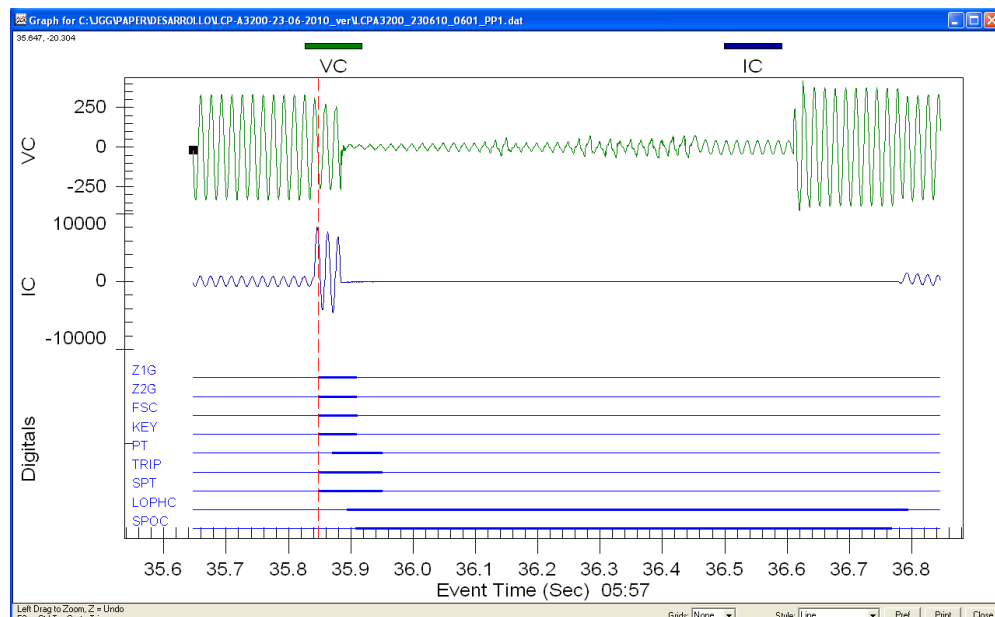


Fig. 11. C-phase analog quantities and some digital quantities recorded at the LCP end of the LCP-A3200-CRP line.

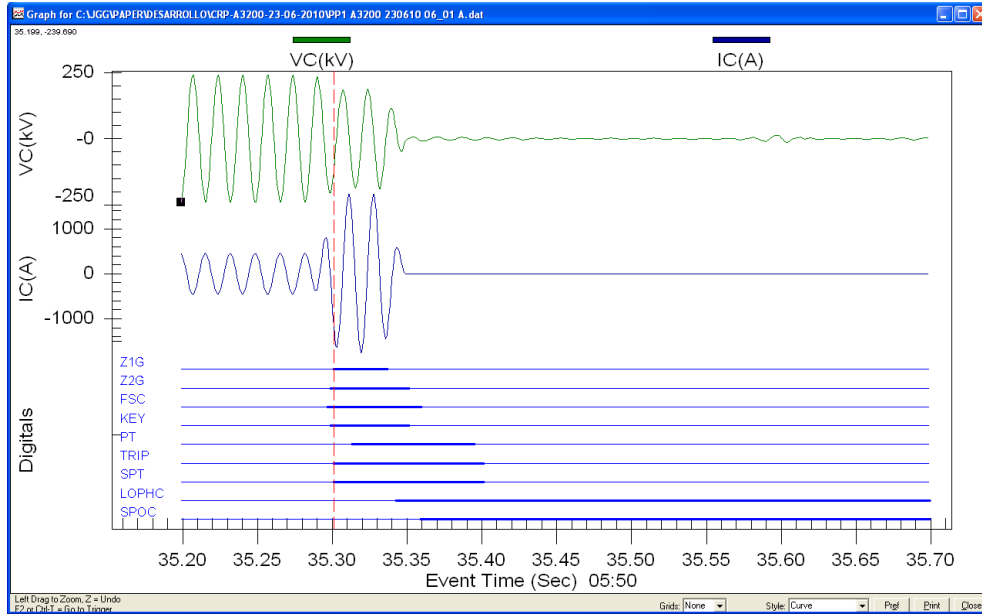


Fig. 12. First oscillogram recorded at the CRP end of the LCP-A3200-CRP line.

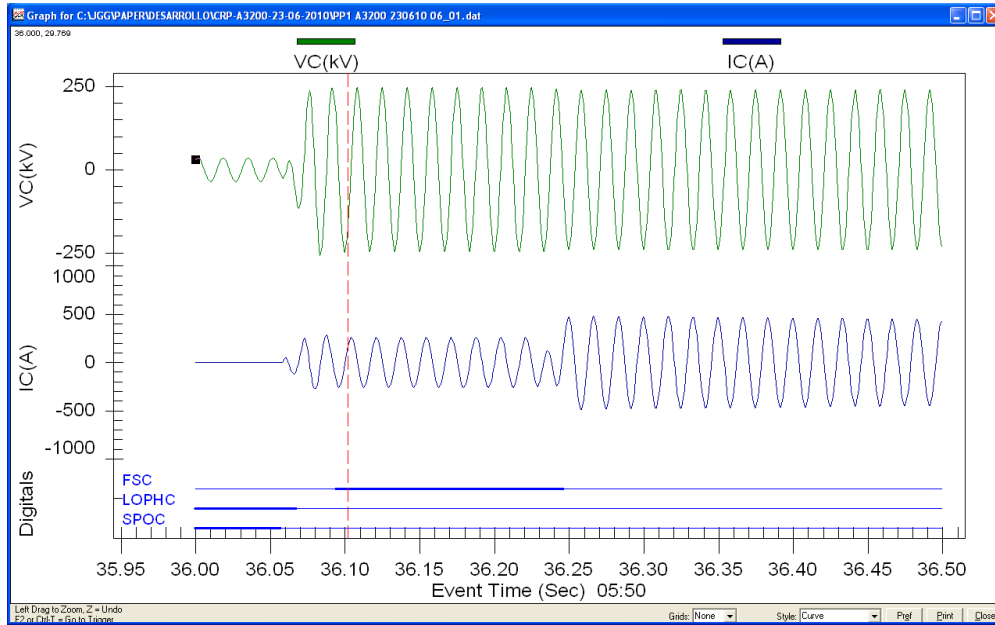


Fig. 13. Second oscillogram recorded at the CRP end of the LCP-A3200-CRP line.

Fig. 12 shows the first oscillogram recorded at the CRP substation. From Fig. 12, we conclude the following:

- The fault starts at 35.29 seconds. This time is slightly different from that of Fig. 11 because the relays are not time-synchronized.
- The high-speed elements, Z2G and FSC, operate at 35.299 seconds. Bit KEY asserts.
- The element Z1G (Zone 1) operates at 35.301 seconds.
- Bits TRIP and SPT assert at 35.301 seconds.
- The breaker clears the fault at 35.349 seconds. The total fault-clearing time is 58 milliseconds.
- Bits LOPHC and SPOC assert to declare the breaker SPO condition.

Fig. 13 shows the second oscillogram recorded at the CRP substation. From Fig. 13, we conclude the following:

- The local (CRP substation) breaker successfully recloses at 36.06 seconds (0.77 seconds after the fault inception).
- The remote (LCP substation) breaker successfully recloses at 36.235 seconds (0.945 seconds after the fault inception).

VII. CONCLUSIONS

From the results presented in this paper, we conclude:

- SPT and SPR improve power system stability by keeping two phases of the line connected during the SPO period.

- An SPT application requires breakers with independent pole operation and relays with faulted phase discrimination and SPT abilities. Modern relays provide these functions at no additional cost. Shunt reactors may also be necessary for secondary arc extinction.
- CFE has successfully applied SPT schemes in transmission lines for more than 20 years. As of today, CFE has 174 SPT schemes on 400 kV lines (83.7 percent of all the lines) and 231 SPT schemes on 230 kV lines (48 percent of all the lines). CFE continues to implement SPT schemes on existing transmission lines.
- In Mexico, SPT schemes have correctly operated for 97.4 percent of faults on 400 kV lines and for 96 percent of faults on 230 kV lines.
- Applying SPT schemes requires power system stability studies to determine maximum SPR times, secondary arc extinction studies to determine minimum SPR times, and transient overvoltage studies to determine maximum expected transient overvoltages caused by line-switching operations.

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IX. BIOGRAPHIES

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Héctor J. Altuve Ferrer received his BSEE in 1969 from the Central University of Las Villas, Santa Clara, Cuba, and his PhD in 1981 from Kiev Polytechnic Institute, Kiev, Ukraine. From 1969 until 1993, he served on the faculty of the Electrical Engineering School at the Central University of Las Villas. He served as a professor of the Graduate Doctoral Program in the Mechanical and Electrical Engineering School at the Autonomous University of Nuevo León, Monterrey, Mexico, from 1993 to 2000. From 1999 to 2000, he was the Schweitzer Visiting Professor at Washington State University's Department of Electrical Engineering. In January 2001, he joined Schweitzer Engineering Laboratories, Inc., where he is currently a distinguished engineer and director of technology for Latin America. He has authored and coauthored several books and more than 100 technical papers and holds four patents. His main research interests are in power system protection, control, and monitoring. He is an IEEE senior member.

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