SINGLE-POLE SWITCHING ON BPA'S 500 KV SYSTEM

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ABSTRACT

The stability of a power system during fault interruption and reclosing is improved through the use of single-pole switching (SPS). Successful high-speed reclosing with SPS depends on rapid extinction of the secondary arc current. The Bonneville Power Administration (BPA) has incorporated four distinct methods of secondary arc extinction for SPS among 26 lines on its 500-kV network. This paper describes these arc extinction methods and the special considerations which have been given to power system equipment and configurations for the application of SPS.

INTRODUCTION

The Bonneville Power Administration (BPA) operates an extensive high-voltage and extra-high-voltage (EHV) transmission grid in the Pacific Northwest region of the United States. The primary voltage levels are 115, 230 and 500 kV. Approximately 97 percent of the faults which occur on the 500 kV network involve only one phase and are referred to as single-line-to ground (SLG) faults. Since the majority of these SLG faults are temporary in nature, the line can usually be restored to service by high-speed reclosure after any residual or secondary arcing at the fault location is extinguished.

The most common method of fault interruption and reclosure for SLG faults is three-pole switching. In this method all three phases are immediately cleared after fault detection and reclosed following a short "dead time". The secondary arcing which follows fault interruption is normally extinguished rapidly during three-pole switching, allowing the high-speed reclosure. Restoring all phases of a line to service as quickly as possible is beneficial to system stability. However, interrupting all three phases of a line creates an additional system disturbance beyond that caused by the original fault.

The method of clearing and high-speed reclosing only the faulted phase of a line is referred to as single-pole switching (SPS). The primary benefit of SPS is enhanced stability which is achieved by minimizing the system disturbance created during fault clearing and reclosing. By maintaining a path for power to flow on the unfaulted phases during the critical time following a fault, significant benefits in preventing instability and load loss are realized. A secondary but important benefit of SPS is the large reduction in switching surges which are normally generated during high-speed reclosing. This is because the most severe switching surges tend to occur during high-speed reclosure of unfaulted phases.

An SPS operation is successful if the faulted phase is reclosed without a second fault occurring. The secondary arc must therefore be extinguished and the arc path must have recovered its dielectric strength prior to reclosing. Thus a critical problem of applying SPS to a line is insuring successful secondary arc extinction. This paper describes BPA's experience in SPS including the methods used for secondary arc extinction and the special considerations given to line configurations and power system equipment.

SINGLE-POLE SWITCHING AT BPA

The first SPS installation at BPA was in 1973 where a four-reactor scheme was used for secondary arc extinction on a 229 km line [1]. Since then BPA has been committed to utilizing the benefits of SPS throughout its EHV network by applying it to nearly every 500 kV line energized in the past ten years. Presently BPA uses SPS on 26 lines at 500 kV and one at 230 kV. By 1993, SPS will be in operation on 33 of BPA's 500 kV lines.

BPA has also taken a leading role in the application of secondary arc extinction methods. Typically in the power industry successful SPS is accomplished using either natural secondary arc extinction or four-reactor schemes. However at BPA, four distinct methods of secondary arc extinction have been in successful operation for years. The two additional methods are "hybrid" switching and "high-speed ground switches" (HSGS). Table I lists the 26 lines using SPS on the BPA 500 kV system along with their method of secondary arc extinction. The length of each line and special line characteristics are also noted in Table I.

TABLE I. SECONDARY ARC EXTINCTION ON BPA 500 KV LINES

Line Name	Length km (mi)	S.C. *	Arc Extinction Method
Ashe-Hanford	28 (17)	R	Natural
John Day-Big Eddy 1	30 (19)		Natural
John Day-Big Eddy 2	30 (19)		Natural
Vantage-Hanford	38 (24)		Natural
LoMo-Little Goose 1	39 (24)		Natural
LoMo-Little Goose 2	39 (24)		Natural
Hatwai-Dworshak	46 (28)		Natural
Lower Granite-Hatwai	53 (33)		Natural
L. Goose-L. Granite 1	53 (33)		Natural
L. Goose-L. Granite 2	53 (33)		Natural
Lower Monumental-Ashe	64 (40)	R	Natural
Taft-Hot Springs	87 (54)		Natural
Raver-Paul	112 (69)		Natural
Buckley-Slatt	84 (52)	R,D	Hybrid
Big Eddy-Ostrander	115 (71)		Hybrid
Ashe-Slatt	116 (72)	R,D	Hybrid
Grand Coulee-Hanford	154 (96)		Hybrid
Hanford-John Day	157 (97)		Hybrid
Buckley-Marion	160 (99)	R,D	Hybrid
Taft-Bell	155 (96)	R	4-Reactor
Buckley-Summer Lake	253 (157)	R	4-Reactor
Broadview-Garrison 1	362 (225)	R,P	4-Reactor
Broadview-Garrison 2	362 (225)	R,P	4-Reactor
Dworshak-Taft	146 (90)		HSGS
Garrison-Taft 1	257 (159)	R,D	HSGS
Garrison-Taft 2	257 (159)	R,D	HSGS

* S.C. Special Characteristics:
R Reduced insulation line design
D Double-circuit line
P Partial double-circuit and single-circuit line

A number of important factors have contributed to the success of SPS applications at BPA. Along with excellence in relay application and testing, BPA is well known for extensive staged system testing and measurement. This has allowed thorough testing of SPS methods and equipment prior to broad system application. Another factor is BPA's commitment to simulation of EHV methods and equipment applications using the Electromagnetic Transients Program (EMTP). This type of analysis has been instrumental in the development and application of nearly all aspects of SPS at BPA.

SECONDARY ARC EXTINCTION

The three critical elements in secondary arc extinction are the secondary arc current, the arc recovery voltage and the time allowed for extinction to occur. The secondary arc current is primarily caused by capacitive coupling from the energized phases into the faulted phase and increases linearly with line length. The arc recovery voltage is the voltage which appears on the open phase at the fault location after the secondary arc is extinguished. This voltage, which is characterized by both a steady-state magnitude and a rate-of-rise, is largely independent of line length. The arc recovery voltage is a function of the ratio of phase-to-phase and phase-to-ground capacitances but is dramatically altered by the presence of line-connected shunt reactors. In the power industry the typical times allowed for secondary arc extinction range from 0.5 to 1.5 seconds.

It is important to note that the transmission line design determines the coupling between the energized phases and the faulted phase. This coupling produces the secondary arc current and recovery voltage. Prior to 1980 the major portion of the BPA 500 kV network consisted of lines with conductor-to-steel clearances of 351 cm (138 in). This design produces secondary arc currents of about 0.17 A/km (0.27 A/mi) and arc recovery voltages of about 43 kV. Since 1980, however, nearly all of BPA's new 500 kV lines have used a "reduced insulation" design [2] which incorporates conductor-to-steel clearances of 254 cm (100 in). This new design results in secondary arc currents of about 0.24 A/km (0.38 A/mi) and arc recovery voltages of about 54 kV. The impact of this line design change on SPS is not only higher secondary arc currents and recovery voltages but also shorter strike distances for secondary arc reignitions. Thus BPA has had significant challenges in broadly applying reliable SPS at the 500 kV level. In Table I the eleven SPS lines which have this reduced insulation design are noted.

Analysis, field testing and operational experience at BPA combine to determine if the secondary arc current and recovery voltage magnitudes require a special arc extinction method for successful SPS. The particular methods used for secondary arc extinction on BPA lines are described below.

Natural Arc Extinction

The simplest method of arc extinction for SPS involves opening only the faulted phase and reclosing after a pre-determined dead time with no special equipment to assist in arc extinction. If the secondary arc current and recovery voltage are sufficiently small, the secondary arc will tend to self-extinguish through cooling and elongation. Other factors such as wind and humidity can influence this action. Since the recovery voltage is nearly constant for a particular line design, the probability of successful natural arc extinction is mainly a function of line length.

At BPA most short lines use natural arc extinction for SPS with dead times ranging from 0.5 to 0.75 seconds. Table I lists the 13 lines which use this method. It is interesting to note that the longest line using natural arc extinction is 112 km while a considerably shorter line of 84 km does not. The effects of the reduced insulation design and double-ciruit configuration of the 84 km line required special arc extinction methods.

If line-connected shunt reactors are in service, the secondary arc current is not appreciably affected but the rate-of-rise of arc recovery voltage is normally reduced significantly. This helps extinguish an arc more rapidly and could even allow natural arc extinction to be used on a line which would otherwise be too long. However, since the reactor could be out of service for voltage control or maintenance, BPA does not rely on this recovery voltage effect in determining the arc extinction method to be used.

Hybrid Switching

Through system stability simulations at BPA, it became apparent that most of the benefits of SPS result from having the two unfaulted phases in service immediately following fault interruption and through part of the first system "swing". This was the basis for BPA's development of hybrid switching, which is so named because it is a combination of single-pole and three-pole switching [3]. When a SLG fault occurs, the faulted phase is cleared while the unfaulted phases remain energized, like a typical SPS operation. However, after a dead time of about 0.8 seconds, the two unfaulted phases are tripped to extinguish the secondary arc. Approximately 1.2 seconds after the initial fault, all three phases are reclosed. The tripping and reclosing times used for hybrid switching are based on stability studies.

Hybrid switching, which was first put into operation at BPA in 1985, is currently used on the six lines listed in Table I. This method is now applied at BPA to lines which are too long for natural arc extinction and do not have another readily available means to extinguish the secondary arc. Since there is no cost for arc extinction equipment, hybrid switching has proven to be a very economical method of gaining most of the benefits of SPS.

Stability studies show that hybrid switching is about 80 percent as effective as standard SPS in maintaining system stability following a fault. The secondary benefit of switching surge reduction is lost, however, due to the high-speed, 3-pole reclose operation. BPA will generally not use hybrid switching for interties with one or two lines. This is to avoid potential out-of-step conditions which could develop during the 3-pole open time if one intertie line is already out of service. For these lines standard SPS may be the only type of switching acceptable, requiring secondary arc extinction equipment such as that described below.

Four-Reactor Scheme

The configuration of three line-connected shunt reactors which incorporates a reactor to ground at the neutral point is called a four-reactor scheme. This is the oldest and most common method of secondary arc extinction for long lines. BPA has used this method of secondary arc extinction when shunt reactors were already planned for a new line. Therefore the costs of the four-reactor scheme have been limited to the costs of the neutral reactor, associated surge arrester, and a higher insulation level for the neutral of each phase reactor. However, the need for a higher neutral insulation level on the phase reactors has made retrofitting a standard shunt reactor bank with a neutral reactor impractical. The four lines which utilize four-reactor schemes are listed in Table I. BPA lines at 500 kV are nearly always transposed or well-balanced. This makes the application of four-reactor schemes a relatively simple matter since the optimum neutral reactor impedance is the same for each phase of the line.

A neutral reactor with the proper impedance will reduce the capacitively-coupled secondary arc current and arc recovery voltage to low levels and thus insure successful extinction. Determining the proper neutral reactor impedance is normally a matter of straight-forward calculation for single-circuit lines [4]. However, for the lines shown in Figure 1, the process was more complicated. These lines are 362 km long and are a combination single-circuit and double-circuit configurations. The neutral reactor sizing was performed by steady-state parametric studies using the EMTP. Figure 2 is a typical study result which shows how the secondary arc current and recovery voltage change with neutral reactor impedance for an SPS operation. As shown in Figure 1, a neutral reactor size of 700 ohms was chosen for the four-reactor schemes on these lines.

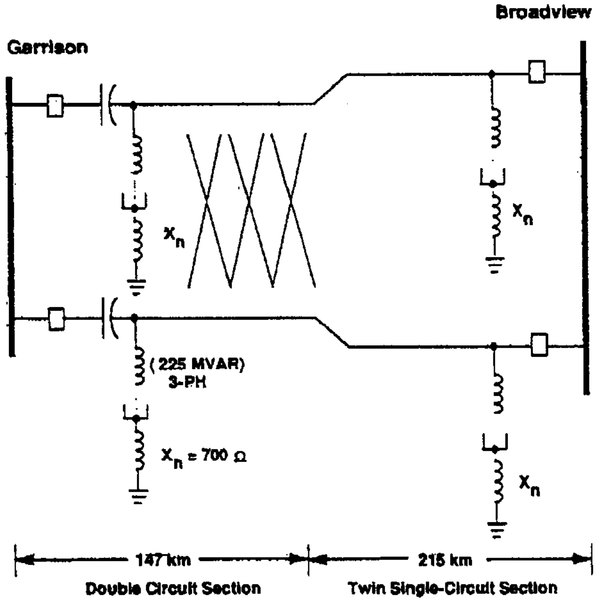

Figure 1. Partial single-circuit and double-circuit 500-kV lines using single-pole switching and four-reactor schemes.

To provide operational flexibility in voltage control, BPA generally uses load-break switches or circuit breakers on shunt reactor banks. Two BPA lines with four-reactor schemes use a breaker for high-speed reactor insertion during SPS. If the reactor bank is initially out of service for voltage control, the breaker is closed approximately 0.1 seconds after the start of an SPS operation. This insures proper secondary arc extinction prior to reclosing at 0.5 to 0.75 seconds. After the SPS operation the reactor bank remains in service and is deenergized at the operator's discretion. Figure 3 is a diagram of a three-terminal line which uses high-speed reactor insertion.

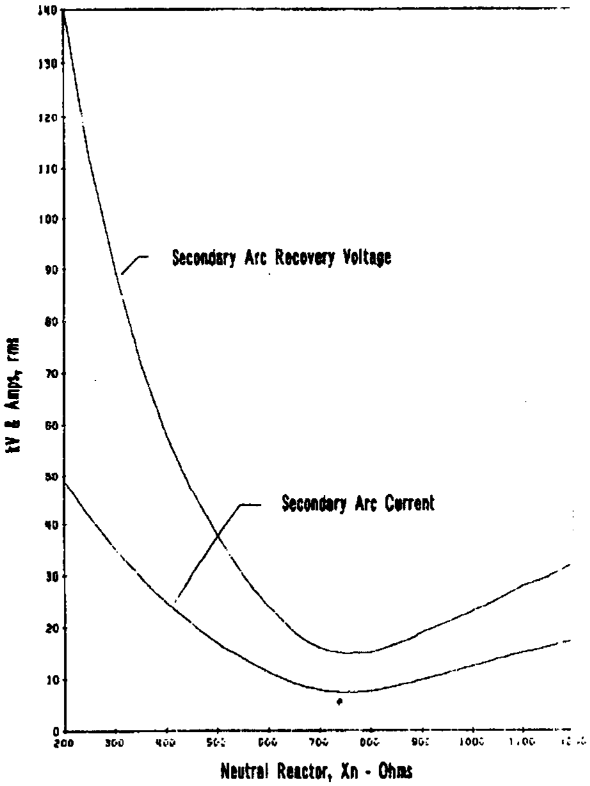

Figure 2. Parametric study of neutral reactor sizing for the lines in Figure 1.

High-Speed Ground Switches (HSGS)

The concept of secondary arc extinction using HSGS was field tested at BPA in 1979 [5] and put into operation on three lines in 1985. An application of HSGS on double-circuit lines is shown in Figure 4. Because of the effects of reduced insulation and double-circuit design, it was determined that HSGS would provide the most reliable method of arc extinction for these critical lines. In a typical operation, breakers at each end of the line on the faulted phases interrupt the SLG fault. HSGS at each end close approximately 0.1 second later and remain closed for about 0.3 seconds. The line is reclosed approximately 0.7 seconds from the initial fault, after relays have insured that the HSGS are open.

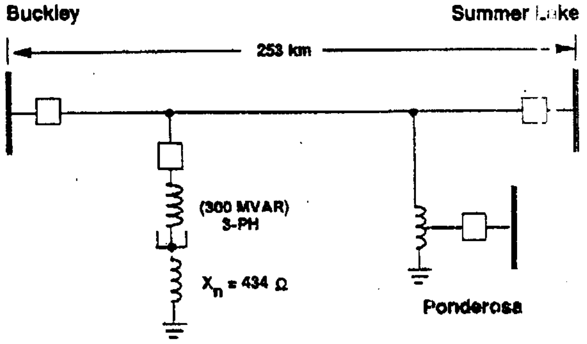

Figure 3. Three-terminal Buckley-Ponderosa-Summer Lake line with four-reactor scheme and transformer termination.

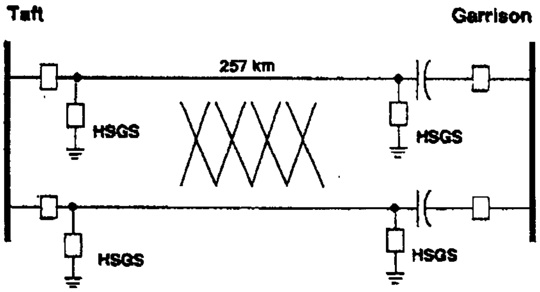

Figure 4. Double-circuit 500-kV lines utilizing high-speed ground switches (HSGS) for secondary arc extinction.

Figure 5 depicts the circuit conditions with both HSGS closed. The capacitively-coupled current from the energized phases, which was the most critical part of the secondary arc for all previous forms of extinction, is entirely shunted from the fault location by the closed HSGS. However, with the HSGS closed, large circulating currents are induced in the two closed paths formed by the secondary arc and the HSGS. This circulating current is created by magnetic coupling from the current in the unfaulted phases. The magnitude of this induced current is approximately proportional to the current in the unfaulted phases. As shown in Figure 5, the currents in the HSGS are nearly equal and thus the current in the secondary arc is close to zero. This is true regardless of the fault location. By grounding both ends of the line, the arc recovery voltage is also forced to a very low level. With virtually no current or recovery voltage present, the secondary arc extinguishes immediately [6]. It is necessary that HSGS are used at each end of the line to insure cancellation of arc current and a low recovery voltage.

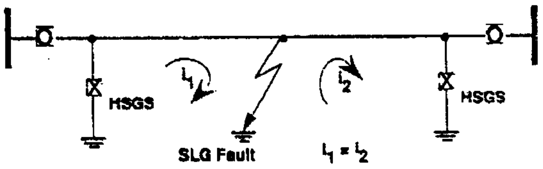

Figure 5. Faulted phase during SPS operation, with both HSGSs closed. The currents are induced by the load in the two energized phases.

The HSGS used at BPA are relatively simple devices which are capable of interrupting currents up to 600 A with recovery voltages up to 70 kV. The three lines which use HSGS are listed in Table I. Unfortunately, the relaying required for lines using HSGS is more complicated than for other types of SPS. This is because it is necessary to protect the system from potential faults by insuring that the line breakers and HSGS are never closed at the same time.

SPECIAL CONSIDERATIONS FOR SINGLE-POLE SWITCHING

Transformer-Terminated Lines

The term "transformer-terminated line" is used for the case where there is no breaker between the line and transformer, such as the three-terminal configuration of Figure 3. During fault clearing, dead time and reclosing operations, the transformer remains connected to the faulted phase. Since all sources of fault current must be interrupted to clear a fault, SPS is only considered for transformers without tertiary windings.

The feasibility of SPS on lines terminated in transformers was in doubt for a considerable time because of concern about ferroresonance. The strong capacitive coupling from the energized phases during SPS creates a classic circuit for ferroresonance with the faulted phase transformer. Extensive EMTP simulation, which was verified by field testing at BPA, showed that after secondary arc extinction and prior to reclosing, the transformer on the faulted phase does go into ferroresonant oscillations. However these oscillations do not create overvoltages and the short duration of the ferroresonance does not harm the transformer. Field testing also confirmed that the presence of a shunt reactor eliminated all ferroresonance.

BPA currently has three transformer-terminated lines in operation using SPS, including one two-terminal line and two three-terminal lines. Two of these lines have four-reactor schemes such as the one shown in Figure 3 and one line uses natural arc extinction with no shunt reactors. All three lines use autotransfomers with separate tanks for each phase.

Double-Circuit Lines

As shown in Table I BPA currently uses SPS on seven lines which are entirely or partially double-circuit. These lines are generally transposed, which helps reduce the influence of one circuit on the other. However, a number of special considerations have been required for most of these lines in applying and operating SPS.

For reliable secondary arc extinction with a four-reactor scheme, the neutral reactor sizing studies must go beyond the normal operating mode. The optimum neutral reactor impedance for a circuit must be chosen to also bring the secondary arc current and recovery voltage to sufficiently low levels with the second circuit energized or deenergized and either grounded or ungrounded. These conditions have an impact on the coupling to the faulted phase during SPS. On double-circuit lines which use HSGS, secondary arc extinction is not affected by the condition of the parallel circuit.

It is also important to consider abnormal faults when designing for SPS on double-circuit lines, particularly with four-reactor schemes. BPA has experienced several simultaneous SLG faults on its double-circuit lines. These have been lightning-caused faults where like phases (e.g. A-ph & A-ph) on each line have flashed over to the same tower. These faults have occurred both on lines using four-reactor schemes and lines using HSGS. In all cases the secondary arc extinction on each line was successful.

Series and Shunt Compensation

The location of series capacitors on a line using SPS is normally not a critical concern for secondary arc extinction. This is because the impedances associated with capacitive coupling and shunt reactors is large compared to the typical impedance of a series capacitor bank. However, for HSGS applications, series capacitance must be considered very carefully. If the capacitor is located between the HSGS, then the induced currents through the closed HSGS will not be equal and the net current in the secondary arc will not be zero. The resulting current in the secondary arc will depend on the fault location and will increase as the load current increases. Thus, for the lines in Figure 4, it is clear why the HSGS were placed on the line-side of the series capacitors.

The combination of series capacitors and shunt reactors can impact secondary arc extinction time both for SPS and three-pole switching. With modern metal-oxide protection on series capacitors, a SLG fault will normally not result in a capacitor bypass. Therefore, when the fault is interrupted by the line breakers, a trapped charge will remain on the series capacitor as shown in the circuit of Figure 6. If the fault is located such that the shunt reactor, series capacitor and fault are in series, an oscillation will develop to discharge the capacitor. The current from this L-C oscillation will add to the normal secondary arc current and will tend to extend the secondary arcing time. Simulations which model the arcing characteristics indicate that the energy in the L-C oscillation will usually be dissipated by the secondary arc within typical reclose times used on BPA lines.

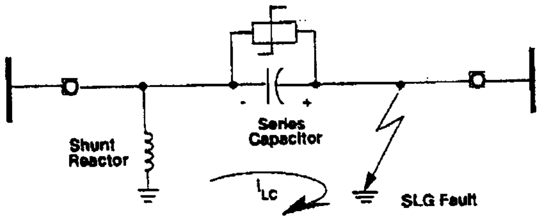

Figure 6. Shunt reactor and series capacitor combination which leads to longer secondary arcing times.

For hybrid switching, as well as three-pole switching, shunt reactors tend to increase secondary arcing times. After the three-pole trip the shunt reactor and line capacitance create an L-C oscillation on the unfaulted phases which is attenuated rather slowly. This oscillation will couple current into the faulted phase and can maintain the secondary arc for a period of time. The amount of resulting secondary arc current depends on the frequency of oscillation and the length of the line. Extension of secondary arcing by this phenomena has been demonstrated by BPA during field tests. A delay in reclose time may be required to insure successful arc extinction, particularly if the duration of the natural L-C oscillation can be extended by coupling from a parallel or double-circuit line.

CONCLUSIONS

BPA has long recognized the significant benefits to system stability that SPS provides. SPS is currently used at BPA on 26 lines at 500 kV and is planned for nearly all new lines on the EHV network. Through continuing innovation, four different methods of secondary arc extinction are in successful operation. Natural arc extinction is used on short lines, while long lines use hybrid switching, four-reactor schemes or HSGS. Hybrid switching, which is a modified form of SPS that eliminates the need for arc extinction equipment, provides most of the stability benefits of standard SPS. Special conditions and configurations which have provided challenges in implementing SPS on the BPA system include reduced insulation designs, double-circuits, transformer terminations, shunt reactors and series capacitors.

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