21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

**CIGRE US National Committee**
**2013 Grid of the Future Symposium**

# Utilizing Single Phase Operation Scheme on Untransposed 765kV lines for a Stability-Limited Plant

**Qun Qiu, David Ball, Jeffery Cavote**
**American Electric Power**
**USA**

## SUMMARY

One of the benefits of the Single Phase Operation (SPO) is to improve power system reliability performance by only switching out the faulty phase for a single-phase-to-ground fault. AEP utilizes Single Phase Operation for a stability limited plant to maximize the availability and output of the plant by avoiding pre-contingency curtailments and full load plant trip, even for multiple sequential faults. In addition to maintaining generator unit angle stability during system faults, the challenges such as secondary arc extinguishing and system imbalance due to untransposed lines need to be addressed. The purpose of this paper is to discuss a complicated protective scheme to achieve the above goals with a combination of the line Single Phase Operation, reactor cross-phase tripping, Quick Reactor Switching (QRS) and unit Fast Valving (FV) special protection system. Special controls are developed to address the type of unusual series of sequential faults and provide coordination between the plant and transmission line protection equipment. A Breaker Operation Limiter (BOL) function and a CT flashover protection function have been incorporated in the line circuit breaker control relays to limit the number of fault operations. Finally, the loss of signal delay timer on the power line carrier logic for the Permissive Overreaching Transfer Trip (POTT) scheme to improve relay security for external faults is discussed.

## KEYWORDS

Single Phase Operation, stability, single-phase-to-ground (SLG) fault, secondary arc extinction, Fast Valving.

qqiu@aep.com

## I. Introduction

Single Phase Operation (SPO) (or Single Phase Switching) has been used for more than half a century. One of the benefits of the SPO is to improve power system reliability performance by switching (opening and reclosing) only the faulty phase breakers (as opposed to 3-phase switching) for a single-phase-to-ground (SLG) fault. American Electric Power applied Single Phase Operation to two 765kV transmission lines associated with a generating plant to maintain or improve system stability and the availability of the plant, and possibly to reduce the torsional impact on the generator rotors during circuit reclosing.

The stability-limited plant has a capacity of 2640MVA, consisting of two 1320MW generators. Figure 1 shows the two 765kV outlets, R–J and R–S, connecting the plant to AEP System. Stability studies show that, if one of the outlets is out of service while the plant output is above 2100MW, the plant may lose synchronism with the AEP system, hence special control schemes are required to enhance the voltage and stability performance of the plant while maximizing the plant's availability and its output. These special controls include Single Pole Operation (Single Pole Tripping – SPT and High Speed Reclosing – HSP), Reactor Cross-Phase Tripping, Quick Reactor Switching (QRS) on R – S line (reactor RB2), Fast Valving (FV), etc. These controls are implemented via the dual-primary line protection systems, as well as single-pole breaker failure relays.

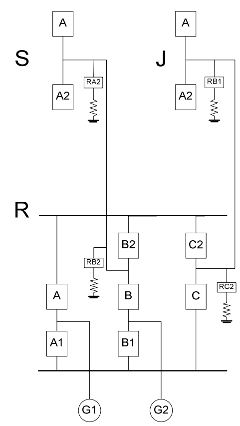


**Figure 1 Simplified System Configuration**

## II. Secondary Arc Extinction Requirements

During the single-phase switching, the phase which is opened at both ends to clear a line-to-ground fault is inductively and capacitively coupled to the remaining healthy load-carrying phases energized at normal system voltage. As shown in Figure 2, the secondary arc current continues to flow in the original primary arc channel of the line short circuit current after opening of the corresponding line circuit breakers on the faulted phase. The coupling, if not compensated, can maintain the secondary arc in the path and prevent successful high speed reclosing. To ensure successful SPO for a 0.5 second reclosing time, the secondary arc current should be in the low 30s and the rate of rise of the recovery voltage, following the secondary arc extinction, should not exceed 10 kV/ms.

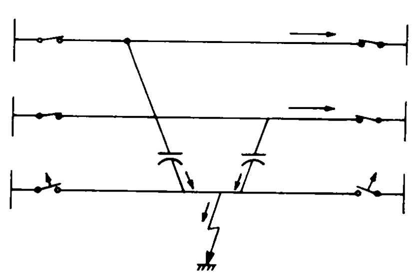

**Figure 2 Secondary Arc Path during Single Phase Operation**

Special 4-legged line reactors were installed at both ends of the two 765kV lines to provide phase-to-phase compensation of the capacitances between the faulted and sound phases, as well as compensation of phase-to-ground capacitances. This results in the reduction of the secondary arc current, thereby reducing arc extinction time and ensuring successful high speed line reclosing. The addition of neutral reactors also affects the rate of rise and the steady state values of the recovery voltage across the arc path, after the arc interruption.

Figure 3 shows simplified circuit diagrams of the reactor schemes used to reduce secondary arc current on the 765 kV outlets. In normal conditions, each line has two special 4-legged reactor banks. The configuration of one bank, called simple 4-legged reactor bank, remains unchanged during the single phase switching. The other bank, called modified 4-legged reactor bank, and the position of the reactor switches change during single phase switching, depending on the faulted phase. The change in the reactor switch position is needed to compensate for the unbalanced nature of AEP 765 kV lines since they are not transposed along their length. [1][2][3] The mechanism to switch open opposite phase reactor for a SLG fault on one of the outer phases is called cross-phase reactor switching, which is integrated into the line protection logic to ensure that a secondary arc current is reduced to a level for a successful high-speed reclose following a SLG fault.

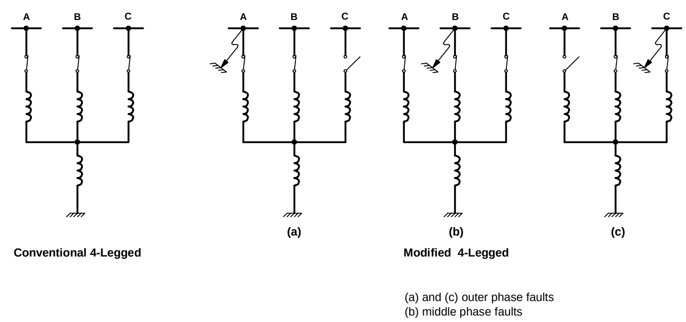


**Figure 3 Conventional 4-Legged Reactor vs. Modified 4-Legged Reactor**

## III. Single Phase Operation Implementation [5]

AEP 765kV line protection standards require three sets of protective relays (two primary systems – PS1 & PS2 and one backup system – BS1) to protect its critical EHV systems. Due to the unique stability issues associated with the plant, the three sets of relays use three different schemes on the two 765kV outlets: PS1 uses a Directional Carrier Blocking (DCB) scheme with stepped distance protection scheme as backup; PS2 utilizes a POTT (Permissive Overreaching Transfer Trip) scheme with stepped distance protection scheme as backup; In both PS1 and PS2 relays, three forward looking zones and one reverse looking zone are enabled for both phase and ground distance protections, while BS1 is used as a pure stepped distance backup.

Single Pole Tripping is implemented on both J and S lines at R. With SPT, only the faulty phase breakers will be switched out for a single-phase-to-ground fault, but if a subsequent single phase-to-ground fault occurs within 5 seconds of a successful reclose, all three phases will trip since three-pole trip is enabled for 5 seconds after a reclose. Other conditions listed below will also enable the three-pole trip:

- Phase Distance Zone 2 operates
- Phase Distance Zone 3 operates
- Ground Distance Zone 2 operates
- Ground Distance Zone 3 operates
- Ground Time Overcurrent operates
- 129 select switch turn on three-pole trip
- Trip while pole open timer is timing

Single pole trip also requires line reactor breaker to perform the following cross-phase reactor switching for the untransposed line:

- For phase 1-g faults, the single pole tripping relays will trip phase three of reactor breaker (1 pole)
- For phase 2-g faults, no reactor switches are tripped
- For phase 3-g faults, the single pole tripping relays will trip phase one of reactor breaker (1-pole)
- If another single phase fault occurs within 5 seconds of a previous single phase fault or the line breakers reclose into the fault, the line reactor breaker switching will be blocked

In general, the automatic sequences of operation for single line-to-ground (SLG) faults on R-station 765 kV lines are shown in Table 1. Reactor breaker will close in 35 cycles after being tripped by the single pole tripping relays. In case of unsuccessful reclosing or permanent faults, a three-phase trip will initiate in 33 cycles.

**Table 1 Single Phase Operation Sequence of Events**

| Sequence of Events | Time (~Cycles) |
|---|---|
| 1. Single line-to-ground fault initiates | t1 |
| 2. Breaker poles of the faulted phase opens | t1 + 3 |
| 3. Proper reactor switch opens | t1 + 3 |
| 4. Line breaker poles reclose | t1 + 30 |
| 5. If line breaker poles reclose unsuccessfully, open three phases | t1 + 33 |
| 6. Reactor switch recloses | t1 + 35 |

As descripted in Section II, both reactor banks are necessary to ensure successful single phase reclosing. However, single phase switching should be maintained if a 4-legged reactor bank at a terminal of the R-J or R-S 765 kV line is taken out of service for voltage control, maintenance or repair.

It should be noted, however, that under heavy line loading conditions and for specific fault locations, successful single phase reclosing after a line-to-ground fault may be compromised if a 4-legged reactor bank is out of service. To reduce this possibility, the outage of a 4-legged reactor bank must be minimized. Therefore, whenever when a SPO is initiated, the line relays issue a three-phase close signal to switch the reactor bank back in service, which helps reduce the secondary arc current during the line SPO. It is recommended to schedule the reactor bank outage when the line loading is not heavy, otherwise, the plant output can be curtailed if necessary.

## IV. Special Protection Scheme to Maintain Unit Stability [6]

In addition to the SPO, Fast Valving is required to maintain the plant stability under some disturbance scenarios. FV allows the plant to generate its rated MW capability without risking transient instability for specified transmission disturbance events when both units are on line. Both units use FV operation when a triggering event occurs. Stability studies indicate that when the R-J line opens three-phase or a single phase opening occurs on one R-station line when the other is out of service, and R-plant generation is high, FV operation is effective to maintain unit stability. However, if steam generator pressure or throttle pressure is above a limiting threshold value, the unit power relief valves may operate during the next FV event, and a unit must be tripped.

FV of both R-plant units is initiated by the 765kV line relays at R-765kV Station whenever plant generation exceeds 2100 MW and any of the following three transmission disturbance events occurs:

1. Multi-Phase fault or line current/MVA on R–J 765kV falls below 450A/600MVA
2. Single-phase fault of R–J 765kV when R–S 765kV is out of service
3. Single-phase fault of R–S 765kV when R–J 765kV is out of service

Figure 4 shows the fast valving initiation logic implemented in the line relays. The plant turbine control logic monitors the FV initiation signal, boiler pressures and the number of FV operations during a 3-minute window to determine if a FV can be completed.

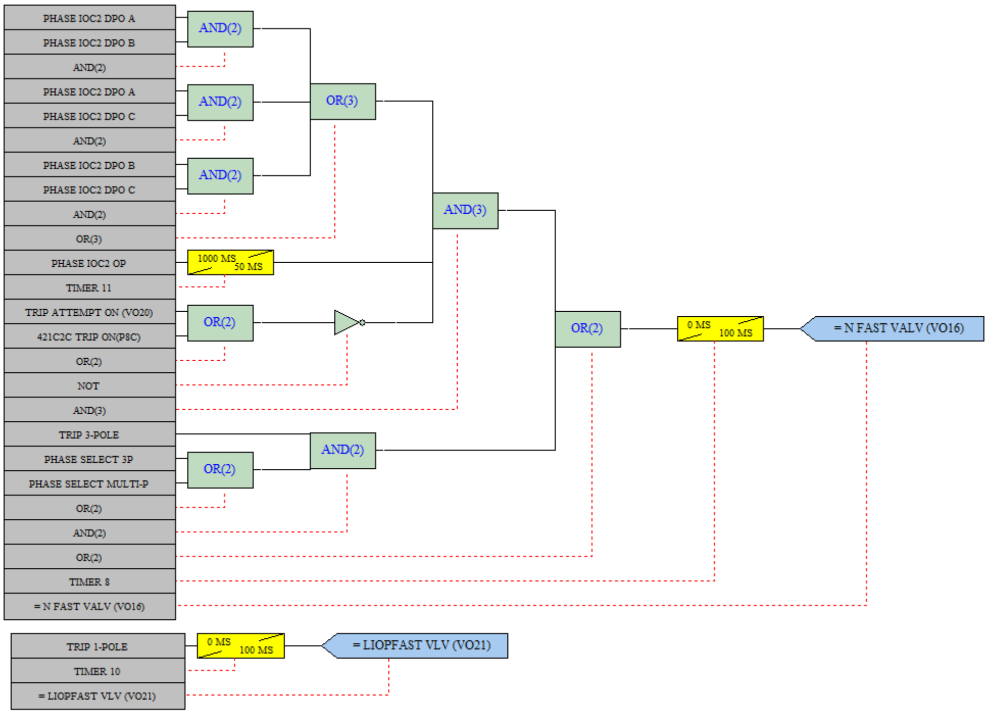


**Figure 4 Protective Relaying Fast Valving Logic**

In the event that no Fast Valving operation can be completed without lifting the boiler pressure relief valves on the R-plant units an Emergency Unit Trip will be performed instead of a Fast Valve operation. [7]

## V. Special Controls to Improve System Reliability

### *A. Quick Reactor Switching (QRS)*

For further improving the plant stability performance, the protective relaying systems on the R – J line will issue a trip to switch open the line reactor breaker RB2 on the other 765kV outlet once a Fast Valving signal is sent to the plant. This trip request initiated from R – J line relaying is called Quick Reactor Switching. Figure 5 shows the QRS initiation logic in the J line relays. By tripping the reactor on S line at R-Station, it boosts the 765kV voltage at the plant exit to help the unit stability during a disturbance. When a QRS is initiated, J line (C2C) relays at R station must open the RB2 reactor at $T_1$=0 and lock it out for 60 seconds (Timer 1). If the reactor was already open, there is no problem in tripping a tripped reactor. However, when the reactor was closed initially, only an S line (B2B) relay knows the pre-fault state of the reactor. Therefore, an S line relay will attempt a close at 60 sec (Timer 2) if the reactor was closed initially.

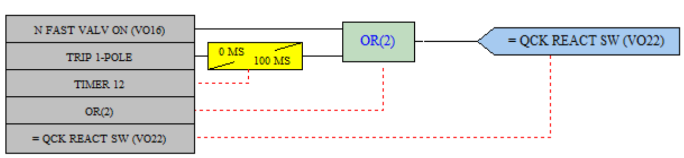


**Figure 5 Quick Reactor Switching Logic**

When multiple temporary faults occur during a short period time, C2C relays is subject to multiple QRS initiations, and its timer $T_1$ restarts from 0, while the timer $T_2$ on B2B is coasting along. The timers can get out of sync and the reactor RB2 will not get back to a close state. As shown in Figure 6, an 1-shot logic was developed to accept the first QRS event, and no more, until the C2C timer $T_2$ is completely finished with its timing, which enables the RB2 reactor closed after 60 seconds and makes it ready for the next event.

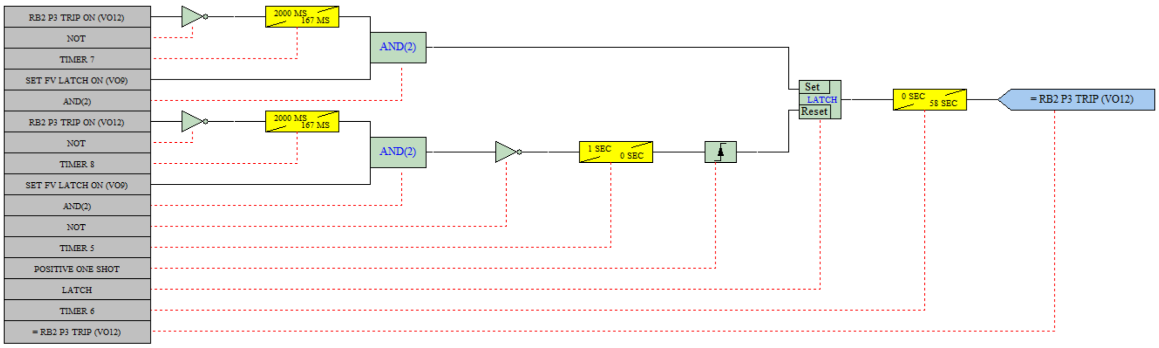


**Figure 6 1-shot Logic for Multiple QRS Events**

*B. Breaker Operation Limiter*

Breaker Operation Limiter (BOL) relays are used to limit 3 recloses in the initial 30 minutes period plus one reclose allowed per every additional 30 minutes period to a maximum of 3 after 3 periods of no operations. The BOL relays also provide CT ground flash over protection by operating associated lockout relays without time delay, so column CT faults to ground are isolated from all sources and automatic reclosing of adjacent transmission lines are prevented

*C. Enhance POTT Scheme Security*

AEP normally utilizes single phase coupling with a 10 watt guard and a 10 watt trip frequency. If an internal fault involves the coupled phase, there is a chance that the trip frequency won't get through. It is a recommended practice to allow the carrier set that sees a loss of signal to give trip permission to the relay for a 150 milliseconds window. If the relay sees a forward tripping condition, a trip occurs. On the other hand, it is too dangerous to allow a 150 ms window whenever the 10 watt signal disappears or falls below a S/N ratio.

Prior 2007, the power line carrier design did not account for a momentary loss of signal during an external line fault. As a result, the R–J 765-kV line tripped at R-Station for the five sequential external CT flashover faults. After the event, the loss of signal delay timer (20 ms) was added to the power line carrier loss-of-signal (i.e. loss of guard & low level) logic for the POTT scheme to improve relay security.

## VI. Conclusion

Since most of the 765kV line faults are single phase to ground faults, only switching out the faulty phase can avoid unnecessary FV for the 2640MW plant with only two 765 kV transmission outlets. The implementation of Single Phase Operation helps maintain stability of the plant during a number of operating conditions involving single line-to-ground faults. More specifically, the plant is expected to achieve the following three major benefits:

1) Although SPS (FV or Unit SPS trip) is still required to maintain the plant stability for three-phase faults or SLG faults with only one line in service, SPS operations can be avoided during temporary SLG faults on one of the two 765kV lines when both lines are in service, which is an improvement from the original design;
2) Plant shutdown can be avoided for temporary SLG faults on the only in-service line; and
3) Compared to a single phase switching, a three-phase switching at the exit of a large turbine generator results in a larger imbalance between the mechanical torque of a driving turbine and the electromagnetic torque of the driven generator, hence inducing higher transient electromagnetic torques and more torsional stresses in the turbine-generator shaft. By avoiding unnecessary three-phase switchings, the shaft system responds to lower torsional torques that might occur upon SPO following temporary SLG faults with both lines in service.

The protective scheme was implemented with a combination of the improved line Single Phase Operation, Quick Reactor Switching (QRS) and unit Fast Valving (FV) special protection system. To address the type of unusual series of sequential faults leading to the plant 2007 blackout event and provide coordination between the plant and transmission line protection equipment, a breaker operation limiter (BOL) function and a CT flashover protection function have been incorporated in the line circuit breaker control relays to limit the number of fault operations. The scheme presented in the paper can be applicable for those lines connecting a stability limited plants, and it can also be applied to those heavily-loaded lines where maintaining system integrity is critical. The combination of SPO and other special controls may greatly improve system reliability and provide economic benefit to asset owners. The SPO scheme can also be modified to facilitate Independent Phase Operation (IPO refers to the operating condition that a line would remain in service for certain period of time with two phases only following a sustained single-phase fault). Additional studies would be required on the impacts of IPO on system operations, protections, equipment, ground wire capability requirements and ground path.

## BIBLIOGRAPHY


[1] B. R. Shperling and "Single Phase Switching Parameters for Untransposed EHV Transmission Lines", IEEE Transactions on Power Apparatus and Systems, Mar/Apr. 79.

[2] A. J. F. Keri (Fakheri), T.C. Shuter, J.M. Schneider and C.H. Shih, "Single Phase Switching Tests on the AEP 765 kV System – Extinction Time for Large Secondary Arc Currents", IEEE Transactions on Power Apparatus and Systems, August 1983.

[3] B. R. Shperling, A. J. F. Keri (Fakheri), C.H.Shih, B.J.Ware "Analysis of Single-Phase Switching Field Tests on the AEP 765 kV System", IEEE Transactions on Power Apparatus and Systems, April 1981

[4] AEP EHV Operating Guidelines

[5] Q. Qiu, Rockport Protection Scheme, AEP Report, May, 2009

[6] Q. Qiu, et al, Rockport SPS Testing Procedures, AEP Report, March, 2009

[7] AEP Rockport Operating Guidelines