Field Experience with Enhanced Hybrid Single Phase Tripping and Reclosing

Charles Henville, Hongbo Apollo Zhang, and Mukesh Nagpal

***Abstract* - This paper describes field experience with application of an enhanced hybrid single phase tripping and reclosing (SPTR) system for medium length extra high voltage (EHV) transmission lines. The concept of enhanced hybrid SPTR is an adaptation of conventional hybrid SPTR that has been applied to intermediate length 500 kV lines where the secondary arc may or may not self-extinguish within a reasonable length of time. BC Hydro has applied the enhanced hybrid SPTR scheme on six 500 kV transmission lines, for two summer lightning seasons, and experienced the benefit of more successful automatic reclosing than previously.**

***Keywords*: Single phase tripping and reclosing, Hybrid single phase tripping and reclosing, Secondary arc extinction detection, Field experience with secondary arcs.**

I. Introduction

THIS paper describes field experience with application of an enhanced hybrid (EH) single phase tripping and reclosing system for medium length extra high voltage (EHV) transmission lines. The conventional hybrid scheme of single phase tripping and reclosing involves delayed tripping of two unfaulted phases to ensure extinction of the secondary arc current supplied by them to the previously faulted and subsequently isolated phase. This scheme may be applied in cases for medium length transmission lines for which the secondary arc may or may not self-extinguish quickly enough to ensure successful reclose of the faulted phase.

BC Hydro has successfully applied an enhancement to the hybrid scheme, by checking the status of the secondary arc. If the arc self-extinguishes quickly enough, the faulted phase may be reclosed successfully without first tripping the two unfaulted phases. If the arc does not self-extinguish quickly enough, the conventional hybrid tripping of the two unfaulted phases proceeds as normal to remove the driving voltage for the secondary arc. Thus the enhancement of the hybrid scheme will provide the benefits of the pure single phase tripping and reclosing scheme when the secondary arc goes out promptly, without the need to trip the two unfaulted phases in all cases.

C. F. Henville is with Henville Consulting Inc. email c.henville@ieee.org
M. Nagpal is with BC Hydro email Mukesh.nagpal@bchydro.com
H. A. Zhang is with BC Hydro, email Apollo.Zhang@bchydro.com

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II. Background

A. Conventional Hybrid SPTR

Conventional hybrid SPTR has been described in [1]. The scheme may be applied in those transmission lines where there is a possibility that the secondary arc may not self-extinguish in time to allow successful high speed single phase reclosing. One advantage of this scheme is that it ensures successful reclosing in cases where the secondary arc does not self extinguish quickly enough for successful reclosure of the open phase. Another advantage is that power transfer is maintained for a short period after the faulted phase is tripped; so the impact on system stability is less than sudden tripping of all three phases.

It is noted that there are other methods of forcing the secondary arc to extinguish quickly. For instance, by use of a high speed grounding switch [1] or neutral grounding reactor [2]. These methods are often applied where there is negligible probability of the arc self-extinguishing quickly enough. A key consideration in deciding to apply these methods is whether the value of system reliability benefits (from successful single phase tripping and reclosing) exceeds the additional cost and complexity of applying them.

The disadvantage of conventional hybrid SPTR is that it always trips the line three phases, whether or not such tripping is necessary. The speed of extinguishing the secondary arc is highly dependent on the length of line, since the amount of inter phase capacitance is directly proportional to the line length. For 500 kV lines, of length greater than about 150 km, the secondary arc is unlikely to self-extinguish quickly enough for successful reclosing. For such long lines, BC Hydro usually applies shunt reactors together with neutral reactors to reduce the duration of the secondary arc. For lines shorter than about 80 km, the secondary arc will normally extinguish itself quickly enough to allow successful single phase reclosing.

Weather (particularly wind speed) is also a critical factor; so for lines between 80 and 150 km, in some cases the arc may self-extinguish quickly enough to allow successful SPTR and in other cases not. BC Hydro has observed varying reclosing success on six of its 500 kV lines, shown in Fig. 1. It can be seen that these lines are three pairs of parallel lines. During lightning storms, lightning strikes may cause single line to ground faults on both lines in a pair, within a few minutes of each other. Successful high speed automatic reclosing is very important to maintain the integrity of these transmission paths. Although conventional hybrid SPTR could be applied to these lines to improve the success rate of reclosing, the short period of three phase opening of the line would increase the exposure of pairs of these lines to simultaneous three phase open conditions which would interrupt the complete path.

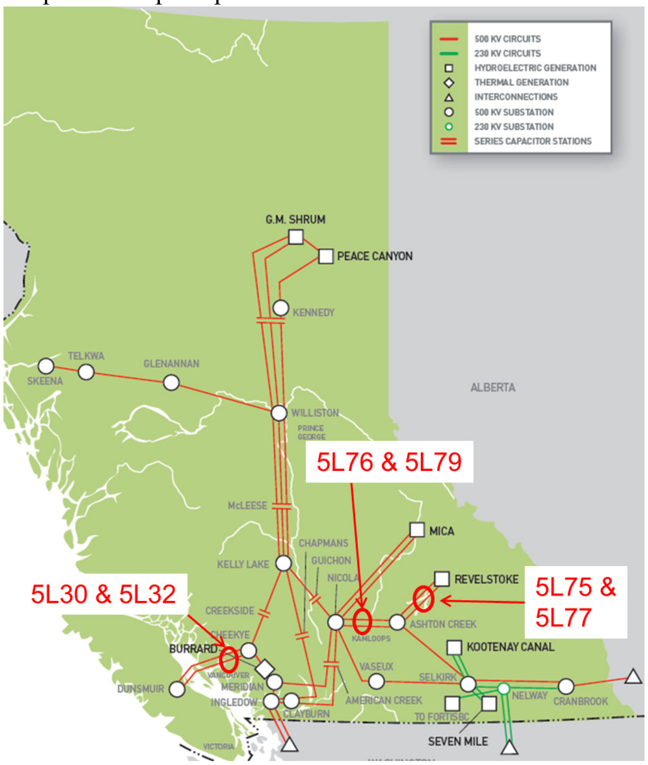

Fig. 1 Six medium length 500 kV transmission lines with EH logic

C. Secondary Arc Extinction Detection (SAED)

A considerable amount of research has previously been accomplished to determine when the secondary arc has been successfully extinguished [3-10]. The technique used for the application for the BC Hydro EH scheme is based on checking the magnitude and angle of the fundamental frequency voltage phasor on the faulted phase during the open pole interval. This technique has been described in [3, 4]. The principle is based on the fact that when the secondary arc is present, the angle of the voltage on the faulted phase lags the angle of the sum of the two unfaulted phase voltages by about 90 degrees. The secondary arc also depresses the voltage on the faulted phase to a value lower than it would be when the arc is extinguished. When the magnitude of the faulted phase voltage phasor (i.e. the recovery voltage on the faulted phase) exceeds a certain value, and the angle with respect to the two unfaulted phase voltages lies within certain limits, the secondary arc is determined to have been extinguished. Existing computer based protective relays on the six lines of interest could readily be configured to include this logic.

BC Hydro used records captured from relays of currents and voltages from several single phase trip events to determine whether the selected SAED logic would be reliable. The EH logic was implemented on existing (spare) relays which were injected with the captured records to test the logic [11].

D. Enhanced Hybrid SPTR Scheme

The EH scheme incorporates the advantages of the conventional hybrid scheme (by ensuring the secondary arc is extinguished) and eliminates the disadvantage of possible unnecessary three phase tripping when the secondary arc extinguishes itself early enough). Fig. 2 shows a simplified EH flow chart and logic diagram. It can be seen that as soon as a single phase trip signal is issued, two timers start. The reclose timer will determine when a reclose attempt should be made (as long as the secondary arc has been extinguished for a sufficient length of time). The one phase open check timer limits the maximum length of time a single phase could remain open if the secondary arc is not promptly extinguished. If the single phase timer completes its time, and the deionization timer has not yet expired, a three phase trip will be initiated, and the three phase reclose timer will be started.

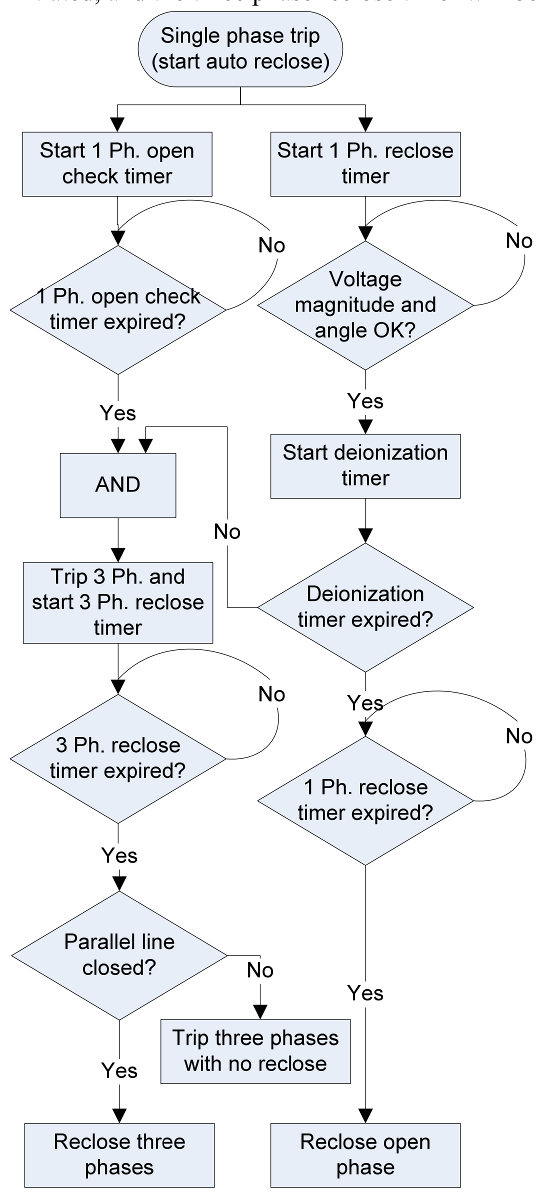

Fig. 2 Simplified EH Process Diagram

It may be noted that the single phase reclose time is fixed, and not shortened, even if the secondary arc self-extinguishes promptly, and the deionization timer completes well before the single phase reclose time expires. Thus the reclose time is not adapted by the SAED. BC Hydro chose not to try to shorten (or adapt) the reclose time since the one second open interval was considered acceptable. This avoids any additional complexity. In this respect, the EH scheme differs significantly from several adaptive SPTR schemes described in the literature [5-10]

III. Determination of Settings for SAED Voltage Magnitude and Angle Checks

Settings of SAED voltage magnitude and angle detectors for BC Hydro's 500 kV transmission lines were determined from observation of faulted phase voltages of several faults during the secondary arc, and after the arc was extinguished. The observations were supplemented with EMTP studies of the lines under various load conditions [11]. It was discovered that line length, loading, and transposition could significantly affect both the magnitude and angle of voltage on the faulted phase after the secondary arc extinguished. Under heaviest loading, simulations showed that the magnitude of the recovery voltage on the open phase with no fault could be as low as 42 kV, though under lighter loading cases it was normally closer to 50 kV for a fully transposed line. From observation of the magnitude of the secondary arc voltage during actual faults, it was determined that (for BC Hydro 500 kV lines) the voltage (filtered, fundamental frequency) was limited to somewhat less than 25 kV (depending of course, on the length of the arc). It was decided to choose threshold values of magnitude 30 kV, which is about 70% of the lowest recovery voltage. It was also observed that due to temporary lengthening of the fault arc, the voltage on the faulted phase could momentarily approach or even exceed 30 kV in some cases – see Fig. 3. The 30 kV measurement was chosen to be made on the 10 cycle average magnitude of the voltage. After the secondary arc extinguished, it was observed from the recorded data of several faults [11] that the angle of the voltage could range from about 0 degrees from the angle of the sum of the unfaulted phases to as much as 17 degrees from the angle of the sum of the unfaulted phases. However, an angle of +/- 45 degrees from the angle of the sum of the voltages on the two unfaulted phases was chosen as the range of angles for which the arc would be considered as extinguished to account for additional phase angle shift from imperfect line transposition. Fig. 3 shows the faulted phase voltage magnitude (without applying 10 cycle running averaging) and angle, on a typical single phase to ground fault and trip.

Fig. 3 shows that the faulted phase voltage exhibits two clearly different magnitudes and angles after the primary arc clears. While the secondary arc exists, the magnitude of the voltage varies wildly, but generally stays below 50 kV. During this phase, the angle of the voltage phasor leads the angle of the sum of the two unfaulted phases by about 90 degrees. After the secondary arc is extinguished, the magnitude of the voltage on the open phase rises to 50 kV and the angle decreases to be approximately equal to the angle of the sum of the voltages of the two unfaulted phases.

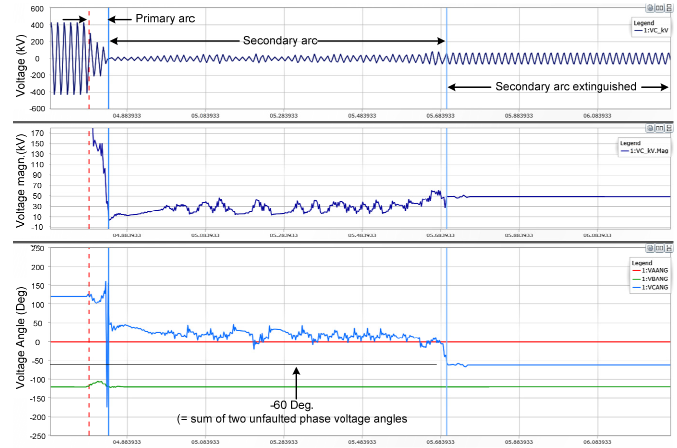

Fig. 3 Faulted phase voltage magnitude and angle

Simulations showed that for untransposed lines, the angle of the open phase voltage was not the same (with respect to unfaulted phases) for all phases. For instance, in the case of a flat untransposed construction, the recovery voltage on the outside phases, tilted significantly toward the center phase voltage; so the angle settings selected as +/- 45 degrees to accommodate untransposed lines.

IV. EH Scheme Performance

The scheme has worked as expected several times during the two lightning seasons for which it has been operational.

For instance, In July of 2016 a lightning strike caused a single phase trip of Circuit 5L77. In this case, the secondary arc did not extinguish in time. The EH scheme issued a three phase trip, and a subsequent automatic reclosure that successfully restored the transmission capability.

Fig. 4 illustrates the performance of the EH scheme during the single phase trip of 5L77. When the timer expired after the maximum allowable time for extinction of the secondary arc and de-ionization time, a three phase trip command was issued. The magnitude OK check was briefly asserted at the instant of the single phase trip, but this was only due to slow reset of the voltage detector (measuring 10 cycle average voltage) together with instantaneous assertion of the single phase open status. The angle OK check never asserted. After the three phase reclose dead time expired, a successful three phase reclose occurred. The three phase reclose is not shown in Fig. 4, because the oscillographic record was not long enough. However, the sequence of events recorder in the relay recorded a successful three phase reclose.

Only two weeks after the successful three phase trip and reclose of this circuit, another lightning strike caused a single line to ground fault occurred on the same circuit. This time, the secondary arc did self-extinguish soon enough to ensure a successful reclose. The secondary arc detection logic declared that the secondary arc was extinguished, and the reclose occurred after approximately one second. Fig. 5 shows the currents and voltages recorded during the event, and declaration of secondary arc extinguishment. It can be seen that the secondary arc was extinguished quite promptly in this case. The automatic reclose was also allowed relatively early, but the fixed single phase open duration caused the reclose to be initiated one second after the single phase was opened.

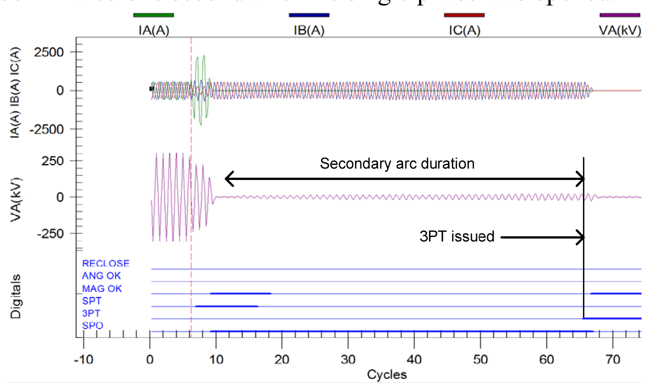

Fig. 4 5L77 Fault 25 July 2016, 3 phase trip allows successful reclose

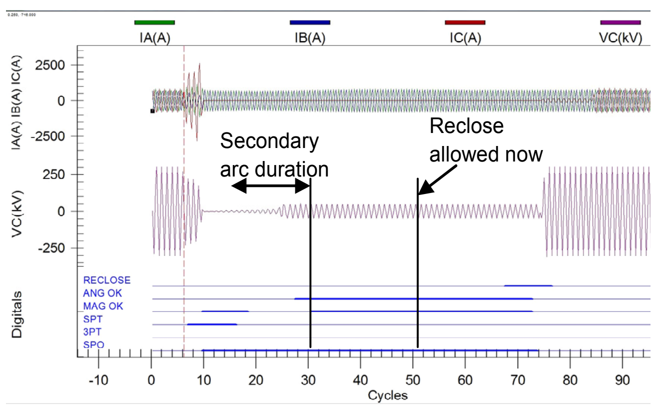

Fig. 5 ACK 5L77 7 Aug 2016 Successful SPTR

Fig. 6 shows a case where the secondary arc persisted for just too long to allow a successful reclose. Though the secondary logic is only applied at the lead line reclosing terminal, the relay record from that terminal was lost so the follow terminal relay record is used in this case to illustrate effectiveness of the EH logic. The EH logic de-ionization timer did not quite expire soon enough to allow a single phase reclose at the master terminal. The follow terminal had a reclose time set slightly longer than at the master terminal and managed to issue a reclose command (BK1CLS). However the three phase direct transfer trip from the master terminal with the EH logic arrived just 10 ms after the close signal was issued. The open phase tripped free at the same time as the two closed phases also tripped.

There have been two years of lightning season since the EH scheme has been deployed on the six medium length transmission lines. Table 1 shows the performance of the EH scheme with respect to line trips since the deployment. Note that in Table 1, AR means "automatic reclose", 1P and 3P indicate one or three phase trips.

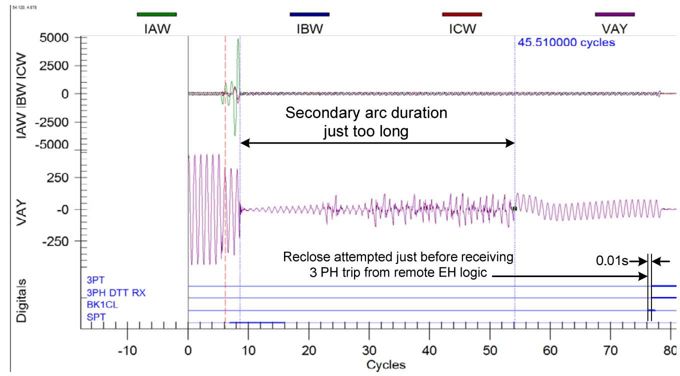

Fig. 6 ACK 5L76 Marginal case of secondary arc persists just too long

TABLE 1 PERFORMANCE OF EH SCHEME SINCE DEPLOYMENT

Line Name	Flt No.	1P	1P AR	3P trip	3P AR	EH Helped	Comments
5L30	1	1					AR switched off
	2			1	1		Multiphase fault
5L32	1	1	1				
5L75	1			1			No fault. Forced SPO due to SPT on adjacent line
	2	1	1				
	3	1	1				
	4			1	1		Multiphase fault
	5			1	1		Multiphase fault
5L76	1	1	1				
	2	1		1			
	3	1		1	1	1	
	4	1		1	1	1	
5L77	1						No fault on line. Trip due to testing
	2	1		1	1	1	
	3	1	1				
	4			1	1		Multiphase fault
	5			1	1		Multiphase fault
	6	1	1				
5L79	1	1	1				
	2	1	1				
	3	1		1	1	1	
	4	1	1				
	5			1	1		Multiphase fault
	6			1	1		Multiphase fault
	7	1	1				
Total trips	25	16	10	13	11	4	
Perc-ent	100 %	64 %	40 %	52 %	44 %	16%	

It can be seen from Table 1 that of the total number of line trips since deployment, 64% of the trips were due to single line to ground faults. In 16% of the trips, if the EH scheme had not been deployed, the faulted line would probably not have reclosed successfully, and would have had to have been manually reclosed. Interestingly, it can also be seen that 7 of the 23 faults (30%) were multiphase faults. This shows that on these lines, typical fault characteristics for EHV circuits are not applicable. In typical cases, more than 90% of EHV faults are due to single line to ground faults.

Performance during the two years since the EH scheme has been deployed was consistent with historical records that showed during approximately 25% of the single line to ground faults on these six lines, the secondary arc did not self extinguish quickly enough to ensure successful single phase reclose. Fig. 7 shows an example of a fault on Circuit 5L79 which did not allow a successful reclose.

The fault shown in Fig. 7 is unusual because the secondary arc did self extinguish temporarily. Normally, when the secondary arc goes out, it does not start up again. However, in this case, the arc re-ignited about 16 cycles after it was extinguished. The reason for the re-ignition is not known. It can be seen that when the arc re-ignited the two measured criteria (faulted phase magnitude and angle) would both have reset before the deionization timer would have expired. Therefore if the EH scheme had been deployed for that fault a three phase trip would have been initiated, followed by a successful three phase auto reclose. Because the EH scheme was not yet deployed at that time, there was no successful automatic reclose.

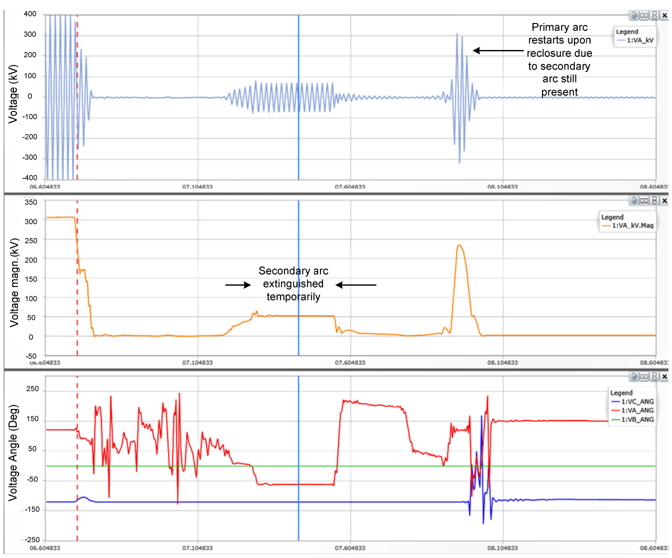

Fig. 7 Faulted phase voltage on 5L79 during a historical fault (before EH was deployed)

V. Conclusions

In transmission constraint corridors, single phase and automatic reclose protection schemes can be applied to improve transmission reliability. But if special secondary arc mitigation methods are not applied, the reliability of the scheme itself is often challenged due to a sustained secondary arc on medium length EHV lines. Reclose attempts in presence of secondary arc diminishes the system reliability instead of enhancing as well as subject sudden torque to generators connected to the line reclosing on to the fault. Medium length EVH lines are typically not equipped with the shunt reactors and therefore additional equipment required to hasten the secondary arc extinction is not often economically justified.

The conventional hybrid single phase trip and reclose scheme avoided additional equipment but had a drawback that required conversions of all single phase trips into three phase trips before a reclose attempt to ensure successful extinction of secondary arc. This paper, introduced an enhanced hybrid single phase trip and auto reclose scheme where additional logic is deployed to assess the status of the secondary arc. The logic is applied on six 500 kV transmission lines in BC Hydro and has been in service for two years. The result reported in this paper demonstrated that the introduced logic eliminated the drawback of conventional hybrid scheme i.e. the lines had successful single phase auto reclose when the secondary arc had extinguished and thereby avoided unnecessary three phase trips in those cases.

VI. Acknowledgment

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