Mitigation of Adverse Effects of Midpoint Shunt- FACTS Compensated Transmission Lines on Distance Protection Schemes

Fadhel A. Albasri, *Student Member, IEEE,* T.S. Sidhu, *Fellow, IEEE,* Rajiv K. Varma, *Member, IEEE*

Abstract— This paper presents practical solutions to mitigate the adverse effects on distance protection schemes when they are used to protect transmission networks that are compensated by shunt connected Flexible AC Transmission System (FACTS) Controllers/devices. Two types of shunt-FACTS devices, Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM), are considered and designed to regulate the midpoint voltage of the transmission line. The mitigation techniques are implemented in commercial relays and tested using Real Time Digital Simulator (RTDS). The results show the effectiveness of the proposed modifications to the channel aided distance protection schemes under various faults and varying operating conditions.

***Index Terms*—Power system protection, FACTS, Distance protection relay, Distance channel-aided schemes, Shunt compensation, SVC, STATCOM, Real Time Digital Simulation.**

I. Introduction

Distance protection relays have been widely applied as the primary protection in high voltage transmission lines due to their simple operating principle and capability to work independently under most circumstances [1]. The basic operation principle of distance relay is based on the fact that the line impedance is fairly constant with respect to the line length. However, the implementation of FACTS Controllers in power system transmission for enhancing the power system controllability and stability have introduced new power system issues in the field of power system protection that must be considered and analyzed [2]. Some of the concerns include the rapid changes in line impedance and the transients introduced by the fault occurrence and the associated control action of the FACTS Controllers. The presence of the FACTS devices in the faulted loop introduces changes to the line parameters seen by the distance relay. The effect of FACTS device would affect both the steady state and transient trajectory of the apparent impedance seen by distance relays due to the fast response time of FACTS Controllers with respect to that of the protective devices. Therefore, it important to study how distance relays would perform when protecting transmission lines equipped with FACTS Controllers.

The impact of FACTS devices on distance protection varies depending on the type of FACTS device used, the application for which it is applied and the location of the FACTS device in the power system. The effect of different types of FACTS devices on distance protection of transmission lines has been reported [3]-[12] and most of the work is based on the performance evaluation of stand-alone distance protection. In addition, few of them had proposed solutions to the highlighted issues such as [4]. However, the authors have not come across any reported work on mitigation of the impact of midpoint shunt FACTS compensated transmission lines on distance protection.

The focus of this paper is to present mitigations to some of the issues that have been reported in [11] and [12] on the impact of SVC and STATCOM on distance protection schemes when protecting transmission lines with midpoint shunt-FACTS compensation. It also explores to find a suitable channel-aided scheme for the application of midpoint shunt compensated lines and present any required modification to improve the overall performance of the existing distance protection schemes such as the Permissive Under-reach Transfer Trip (PUTT), the Permissive Over-reach Transfer Trip (POTT), Directional Comparison Blocking (DCB) and the Directional Comparison Unblocking (DCUB) Schemes. The mitigation techniques are implemented using numerical commercial relays and tested using Real Time Digital Simulator (RTDS) [13]. The shunt-FACTS devices are designed to regulate the midpoint voltage of the transmission line at 1 p.u. in order improve the power transfer capability of the transmission line [12].

The paper is organized as follows. First, a brief description of the system model and the testing setup is given in Section II. Section III summarizes the issues encountered in distance protection schemes for shunt-FACTS midpoint compensated transmission line. In section IV, the required mitigation methods to overcome the problems of shunt-FACTS compensated lines on distance schemes are presented. Finally, the conclusion is presented in Section VII.

All the authors are presently with the Department of Electrical and Computer Engineering, at the University Of Western Ontario, London, Ontario, Canada.

1-4244-1298-6/07/$25.00 ©2007 IEEE.

II. Real Time Digital Simulation (RTDS) Study

This section present the study system and the testing setup used to study and mitigate the adverse impact of midpoint shunt-FACTS compensated transmission lines on the performance of the distance protection schemes.

A. Study System and Testing Setup

The single line diagram of the study system is shown in Fig. 1. All the elements that are shown in Fig. 1 are modeled in RSCAD/RTDS except the relays which represent the commercial numerical distance relays. The FACTS control systems is also modeled in the RTDS. The SVC or STATCOM is installed at the midpoint of line I. The commercial distance relays are located at each line terminal of line I. The system data are shown in the Appendix.

The distance relays are connected to the RTDS through the inputs and outputs interfaces of the RSCAD. Relays receive the three phase currents and voltages at the corresponding bus from the RTDS test system via the RTDS analogue output interface (AO). The trip signal from the each relay is fed back to the RTDS via the Digital input interface (DI) of the RTDS to trip the corresponding circuit breaker modeled in the RTDS. In addition, other internal elements in the relays, such as status of the asserted zones and the carrier signals (permissive/blocking), were also fed into the RTDS via the digital interface in order to monitor these signals in real time along with the other signals such as the voltages, currents; circuit breakers status and the relay operating time in the RTDS simulation environment.

All faults are applied for duration of 500ms (30 cycles) and the fault is cleared by the operation of the line circuit breakers. The operating delay of the circuit breakers modeled in the RTDS is set for 3 cycles (50 ms). The relay is declared as failed to operate if the commercial relay fails to give a trip signal within the maximum fault duration (500ms). A Mho characteristic is used for the three zones of the distance relay. The forward reach of the instantaneous Zone 1 and zone 2 are set at 80% and 120%, respectively. The time delay of Zone 2 is set at 20 power cycles (60 Hz). The reverse looking Zone 3 is set at 50% for the Blocking scheme and 25% for other schemes.

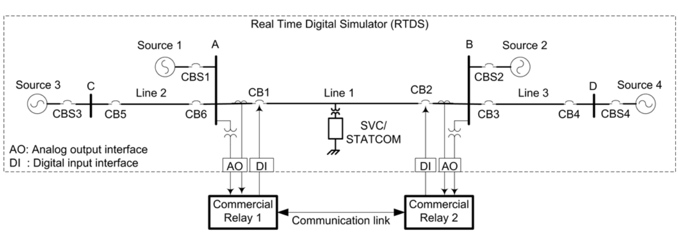


Fig. 1. Single line diagram of the study system

B. SVC and STATCOM Model

The shunt FACTS devices (SVC and STATCOM) are operated in voltage control mode to maintain the voltage at their point of connection at 1 per unit voltage during normal operating conditions. The SVC and the STATCOM power rating is selected based on the load flow studies such that the mid-point voltage is regulated at 1 per unit. The two shunt-FACTS devices are modeled with 12-pulse and a current droop of 3% is employed in the controller characteristic. The FACTS Controllers are connected to the transmission system via an interfacing transformer as shown in Fig. 1. Some necessary filters have been incorporated in the FACTS controllers to limit the effects of system resonance and other harmonics [14]. A proportional-integral (PI) controller is used as a voltage regulator and their parameters are tuned based on a 10% step response in the reference voltage. The PI parameters are tuned such that they give reasonable control performance for both the weak and strong system conditions in order to make sure that the FACTS controllers perform best for the two tested system configurations (weak and the strong) [11]-[12].

III. Impact of Shunt-FACTS on Distance Protection

In this section, the issues encountered when protecting a shunt-FACTS compensated transmission line using distance protection, are highlighted. The performances are evaluated for both stand-alone and five channel-aided schemes based on more than 3600 test cases in which the following are considered: different types of faults (LG, LL and 3PH), different pre-fault loading condition (20 and 40 degrees), two power directions (forward and reverse), different fault locations (internal and external faults), three communication channel delays (0, 0.5 and 1 cycle), two system strength conditions (strong and weak systems) for both STATCOM and SVC compensated systems. The following are the summary of the issues that have been observed for both stand-alone and channel-aided schemes [12]. The results are shown in Table I, II and III for non-pilot and five channel- aided schemes. The relay trip status is indicated as “I”, “II”, “C”, “X” when the relay tripped on Zone 1, Zone 2, channel-assisted trip, and no trip conditions, respectively.

A. Under-reach Effect

The performance of the commercial Relay 1 for different protection schemes is shown in Table I under different internal fault types. The performance of the relay is shown for two internal faults locations in the line section beyond the location of the FACTS device. The status of Relay 2 operation is not shown as it operated on Zone 1 for all the cases shown in Table I. The results shows the impact of the presence of the SVC and the STATCOM shunt compensation in the faulted loop of relay 1, which results in high under-reach effect manifested by no relay operation for most internal LG faults and some LL faults under both strong and weak system conditions. The results also demonstrate the higher under-reach impact of the STATCOM compared to that of the SVC compensated system which resulted in more cases of no relay operations for the STATCOM conditions compared to that of SVC compensated system. This can be attributed to the nature of the STATCOM V-I characteristics compared to that of the SVC [11].

In addition, the shunt-FACTS caused either short time pickup or no pickup of the distance elements even for internal faults within zone 1 reach. This led to the failure of the relay to trip. Unlike the non-pilot scheme, which would fail to trip if the zone 1 element did not pickup or if the zone 2 element picked up for a time shorter than its settable time delay, the channel-aided schemes performed better under such conditions. As a result, the overall performance of the channel-aided schemes is much improved compared to that of the stand-alone distance protection. Among the five channel-aided schemes, the Direct Underreach Transfer Trip (DUTT) performed well as compared to the other schemes for the internal faults because the remote end relay (relay 2) tripped correctly on zone 1 and hence initiated direct transfer trip to relay 1. However, it is not common in practice to use this scheme due to its low security in comparison to the other channel-aided schemes. Furthermore, the performance of both the DUTT and PUTT would be affected for faults involving high fault resistance since they utilize the under-reaching zone 1 element for the carrier signal.

In a bid to overcome the under-reach effect, the reach of Zone 2 is extended from 120% to 150% of the protected line for the schemes that utilize the overreaching elements for keying. However, this did not resolve all the relay failure problems to trip for internal faults, particularly for LG faults [12].

B. Over-reach Effect:

Relay over-reaching is observed only for STATCOM compensated weak system during 3-phase faults at high pre-fault loading condition (40 and 60 deg.) in the reverse direction (from Bus "B" to Bus "A"). There was no case of relay over-reaching condition observed for the SVC regardless of the system strength, pre-fault loading and fault conditions. Table II shows the relay 1 performance for external faults when the system is highly loaded with pre-fault power flowing in the reverse power direction at 40 deg load angle. As there is no problem of directionality, all the schemes show similar performance for external faults. The main concern is the over-reach effect of the STATCOM, which causes relay 1 to trip on zone 1 for 3-phase fault at the adjacent line regardless of the type of protection scheme implemented. Relay 1 takes about 40 ms (2.4 cycles) to overtrip on zone, which is faster than the fault clearing time of the primary protection of the adjacent line (considering CB operating time of 3 cycles). The over-reaching of Zone 1 beyond the remote end terminal would lead to relay mal-operation regardless of the protection scheme used. Relay 2 did not operate because the fault occurred behind its forward zones. Although an overreach condition was also noted for internal faults, as shown in Table I (the row elements marked next to I** during the reverse pre-fault power flow in the weak system condition), it is not of a concern as the protection is required to operate for all internal faults.

C. Effect of Shunt-FACTS Transients

The shunt-FACTS Controller will not only affect the steady state impedance seen by the relay, manifested as an under and/or over reaching effect, but also the transient trajectory of the impedance seen by the distance relay. The transient effect is found to cause either delayed pickup of the impedance elements of the relay or cause a series of pickup and dropout of the relay impedance elements, both of which may lead to relay delayed operation. The relay trip time is affected for both the Zone 1 and Zone 2 asserted tripping. A delayed tripping of about 6 to 8 cycles is observed for Zone 1 asserted trips, which is absolutely unacceptable for zone 1 operation. One case of relay delayed tripping for Zone 1 is indicated as "I*" in Table 1 at which relay 1 took 114ms to trip during LL fault at 65%, which is within zone 1 reach. Similarly, a delayed tripping on Zone 2 is also observed and some cases take more than 9 cycles of additional delay compared to the settable Zone 2 time (20 cycles). This is due to the initial sequence of pickup and dropout of Zone 2 element during external fault. Failure of the permissive schemes can also result from the short time pickup of Zone 2 (as a result of FACTS transient effect) and then dropout before a permissive signal is received from a remote end relay (particularly for communication links with long delays).

TABLE I
COMMERCIAL RELAY PERFORMANCE FOR INTERNAL FAULTS

System Condition	Fault Location	FACTS Device	Fault Type	Power Flow Direction at 40 deg. Load angle											
				Forward						Reverse					
				NON-PILOT	DUTT	PUTT	POTT	DCB	DCUB	NON-PILOT	DUTT	PUTT	POTT	DCB	DCUB
STRONG SYSTEM	65 (%)	SVC	LG	x	C	C	C	C	C	x	C	C	C	C	C
			LL	I	I	I	I	I	I	I	I	I	I	I	I
			3PH	I	I	I	I	I	I	I	I	I	I	I	I
		STAT	LG	x	C	C	C	C	C	x	C	C	C	C	C
			LL	II	C	C	C	C	C	I	I	I	I	I	I
			3PH	I	I	I	I	I	I	I	I	I	I	I	I
	95 (%)	SVC	LG	x	C	x	x	x	x	x	C	x	x	x	x
			LL	II	C	C	C	C	C	II	C	C	C	C	C
			3PH	II	C	C	C	C	C	II	C	C	C	C	C
		STAT	LG	x	C	x	x	x	x	x	C	x	x	x	x
			LL	x	C	x	x	x	x	x	C	x	x	C	x
			3PH	x	C	C	C	C	C	x	C	C	C	C	C
WEAK SYSTEM	65 (%)	SVC	LG	x	C	x	x	x	x	x	C	x	x	x	x
			LL	I	I	I	I	I	I	I	I	I	I	I	I
			3PH	I	I	I	I	I	I	I	I	I	I	I	I
		STAT	LG	x	C	x	x	x	x	x	C	C	x	x	x
			LL	II	C	C	C	C	C	I*	C	C	C	C	C
			3PH	I	I	I	I	I	I	I	I	I	I	I	I
	95 (%)	SVC	LG	x	C	x	x	x	x	x	C	x	x	x	x
			LL	x	C	C	C	C	C	II	C	C	C	C	C
			3PH	II	C	C	C	C	C	II	C	C	C	C	C
		STAT	LG	x	C	x	x	x	x	x	C	x	x	x	x
			LL	x	C	x	x	x	x	x	C	x	x	x	x
			3PH	x	C	C	C	C	C	I**	I	I	I	I	I

TABLE II
RELAY 1 PERFORMANCE FOR EXTERNAL FAULT (40 DEG REVERSE POWER)

Fault Location	System	FACTS Device	Fault Type	Protection Scheme					
				NON-PILOT	DUTT	PUTT	POTT	DCB	DCUB
100%	STRONG	SVC	LG	x	x	x	x	x	x
			LL	II	II	II	II	II	II
			3PH	II	II	II	II	II	II
		STAT	LG	x	x	x	x	x	x
			LL	x	x	x	x	x	x
			3PH	x	x	x	x	x	x
105%	WEAK	SVC	LG	x	x	x	x	x	x
			LL	II	II	II	II	II	II
			3PH	x	x	x	x	x	x
		STAT	LG	x	x	x	x	x	x
			LL	x	x	x	x	x	x
			3PH	I	I	I	I	I	I

D. Other Issues

Incorrect phase selection is also observed for unsymmetrical faults. In these cases, the commercial relays indicate different fault type compared to the applied fault type. This mostly occurs when shunt-FACTS Controller is present in the fault loop and during high pre-fault loading condition. However, no case of incorrect phase selection is observed for relay 2 for faults located between midpoint of line 1 to the terminal of bus “B”. This may result from the balanced three-phase firing technique employed in the voltage controllers of the shunt FACTS devices in which control system acts on a dc voltage equivalent of the measured three-phase voltage. Correct phase selection is necessary for applications such as single pole tripping to improve system stability.

The presence of shunt-FACTS would also contribute in increasing the error in the measured apparent impedance for fault involving high fault resistance [12]. This would result in no relay operation of relay 2 for fault located within the second section of the compensated line (i.e. between the line midpoint to Bus “B”). This would mostly affect the performance of the schemes that utilize the under-reach elements for the carrier signal such as the DUTT and PUTT schemes. Table III shows relay 1 and relay 2 operating status for high resistance LG faults at 60% of the compensated line from relay 1 for the weak system condition. It shows that relay 2 trips correctly on Zone 1 for no shunt FACTS connected case when fault resistance is varied from 0 to 50Ω. Similarly, it trips on Zone 1 for the lower fault resistance faults for both the SVC and STATCOM compensated systems. On the other hand, the relay tips on Zone 2 for the 50Ω fault resistance in the SVC compensated system and does not trip for similar fault resistance in case of STATCOM compensated system. This would impact the performance of the channel-aided schemes, particularly those using the under-reaching zone elements for the communication channel keying.

TABLE III
EFFECT OF FAULT RESISTANCE ON RELAYS PERFORMANCE FOR LINE-GROUND FAULTS AT 60% OF LINE 1 (STAND-ALONE DISTANCE)

FACTS Device	Fault Resistance (Ω)	Power Flow Direction for 20 deg Load			
		Forward		Reverse	
		Relay 1	Relay 2	Relay 1	Relay 2
Not connected	0 to 50	I	I	I	I
SVC	0	x	I	x	I
	30	x	I	x	I
	50	x	II	x	II
STATCOM	0	x	I	x	I
	30	x	I	x	I
	50	x	x	x	x

IV. MITIGATION OF THE ADVERSE IMPACT ON PROTECTION SCHEMES

The mitigations of the problems that have been described section IV are explored in this section.

A. Mitigation of Over-reach Effect

The result presented in the previous section (Table II) shows that for the STATCOM compensated system, the relay trips incorrectly for external fault 3-phase faults on Zone 1 with minimum trip time of 39ms (2.4 cycles). This false relay operation can not be avoided because the trip time of relay 1 is shorter than the clearing time of the fault by the distance protection of the adjacent line (at line 3). This is because the distance protection of the adjacent line, at which the fault is located, would require around 4 cycles (sum of relay trip time and breaker operation time) to clear the fault. It is thus necessary to take some countermeasures to this problem. The following are some of the approaches that can be used to overcome this problem. These recommendations are not required for midpoint SVC compensated system as there is no problem of overreach condition.

1) Reducing Reach of Zone 1 Phase element:

The simplest approach to overcome the overreach problem of the STATCOM compensated system is by reducing the reach of zone 1. Since the problem of overreach is encountered for only 3-phase faults, only the reach of the distance phase element is required to be reduced. Based on this study, the minimum measured impedance seen by the relay for 3-phase external faults is 69.7% as a result of the overreach effect of the STATCOM. Therefore, reducing the reach of the phase element of zone 1 from 80% to 65% would overcome this problem. Table VI shows the result of relay 1 operation status for different setting of Zone 1 reach and for cases when the circuit breaker (CB3) is operating normally (indicated as enabled) and for a case when the breaker is not functioning (i.e. the breaker is not allowed to open the line to clear the fault, and indicated in the Table as disabled). The worst operating condition that causes the highest overreach is chosen (3-phase fault for the weak system at 60 deg of pre-fault reverse power flow) in the following testing. The result shows the over-trip problem is eliminated when the relay zone 1 reach is set at 65%.

In addition, further modification can be made to restrict the reach reduction to the conditions when an overreach is encountered such as during 3-phase faults at high reverse power flow and weak system. Therefore, an adaptive setting can be implemented to enable the reach reduction of the phase element of zone 1 whenever a 3-phase fault is detected during a reverse power direction. However, the concern here is that the phase selection is not secure at the local end as the relay sees the STATCOM in its faulted loop.

TABLE VI
RELAY 1 OPERATION STATUS FOR 3-PHASE FAULT WITH PRE-FAULT LOAD OF 60 DEG (REVERSE) FOR STATCOM COMPENSATED WEAK SYSTEM

Zone 1 Reach Setting	CB3 status	Fault Location in percentage of the line length					
		90	95	105	110	120	130
65%	Blocked	II	II	II	x	x	x
	Enabled	x	x	x	x	x	x
70%	Blocked	I	I	II	x	x	x
	Enabled	x	x	x	x	x	x
80%	Blocked	I	I	I	I	I	I
	Enabled	I	I	I	I	I	I

2) Delaying Phase element of Zone 1:

A second alternative approach to overcome the overtripping of Zone 1 is by introducing a delay time for the phase element of zone 1 in order to allow the protection of the adjacent line to clear the external 3-phase fault within the adjacent line before zone 1 element of the local relay picks up. As we have indicated before that the minimum trip time during overreaching condition is about 2.4 cycles, which is smaller than the response time of the protection of the adjacent line to clear the fault (1 cycle relay response + 3 cycles). Therefore, a time delay of 4 cycles can be selected to delay the pickup of zone 1 phase elements (Z1P) for the relays protecting the STATCOM compensated line. Table V shows the trip status of relay 1 operation for external 3-phase faults with different pickup time delay setting (T_d) for the Z1P element. It shows that the over-trip of Zone 1 for external fault has been avoided by introducing a time delay of 4 cycles.

While method 1 provide faster trip time for internal faults at an expense of a reduced reach coverage for phase distance elements of zone 1 (65% instead of 80%), this method provide the same coverage of 80% (normal Zone 1 reach) on the expense of slower trip time for 3-phase faults. This can be indicated in Table VI which shows the impact of the settable pickup time delay (T_d) of Zone 1 phase element on the relay trip time for internal 3-faults.

TABLE V
EFFECT OF T_D SETTING ON RESPONSE (60 DEG REVERSE, 3-PHASE FAULT)

Fault Location	**Pickup time delay setting for Zone 1 phase element (cycles)**			
	2	**2.5**	**3**	**4**
101 %	Zone 1	Zone 1	Zone 1	X
105 %	Zone 1	Zone 1	X	X
120 %	Zone 1	Zone 1	X	X
130 %	Zone 1	Zone 1	X	X

TABLE VI
RELAY RESPONSE TIME (IN MS) OF FOR INTERNAL 3-PHASE FAULTS WITHIN ZONE 1 REACH (BOTH RELAYS TRIPPED ON ZONE 1)

Fault Location		**55%**		**65%**		**75%**	
Relay		**R1**	**R2**	**R1**	**R2**	**R1**	**R2**
$\mathbf{T_d}$	**0 cycles**	22	20	24	18	26	16
	4 cycles	92	90	94	87	93	86

3) *Blocking Phase Element of Zone 1:*

The third approach to overcome the overtrip of Zone 1 is by restraining (blocking) the local zone 1 phase element using a blocking signal from the remote end relay when a reverse fault is detected at the remote end terminal by the reverse looking distance phase elements as shown in Fig. 2. In this figure, the phase and ground elements of Zone 1 are referred to as Z1P and Z1G respectively. Unlike the DCB scheme in which a received blocking signal restrains only the overreaching element (Zone 2), the blocking signal in this method is utilized for blocking the instantaneous under-reaching distance elements (Zone 1). As a result, Zone 1 phase elements (Z1P) need to be delayed by a short time delay (T_{Z1PU}) to allow time for any possible blocking signal to be transmitted over the communication channel. It is assumed that the maximum channel delay is 1 cycle and the remote end relay fault detection in the reverse direction would take 1 cycle. This would make a total of 2.5 cycles when considering an additional 0.5 cycle as safety margin. This means that any blocking signal would take a maximum of 2.5 cycles to reach the local relay over the communication link. On the other hand, the time that Zone 1 takes to over-trip for external faults during the overreach conditions is about 2.4 cycles. Therefore, the local relay might trip before it receives a blocking signal. Therefore, a short time delay (T_{Z1PU}) of 0.5 to 1 cycle would be reasonable to delay the phase element of Zone one. In addition, there is additional natural margin due to the fact that the reverse looking element of the remote end picks up faster than the local element for external fault.

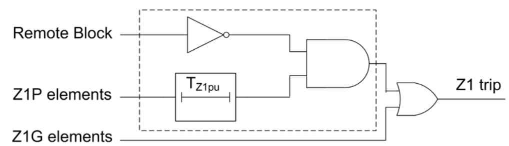
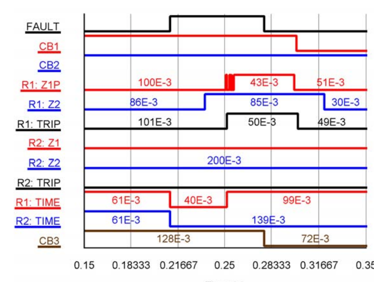
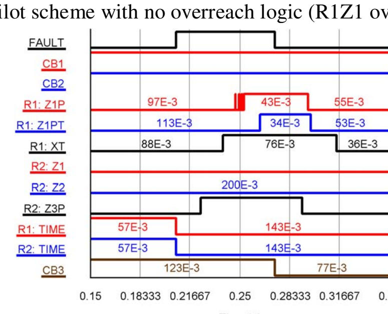


Fig. 2. Zone 1 blocking logic circuit.

Fig 3 shows the result for external 3-phase fault at 110% (i.e. at 10% of the adjacent line) for STATCOM compensated weak system during a pre-fault load of 60 deg in the reverse power direction. It shows the relay operations for two cases, one for the non-pilot distance protection and the other case when the blocking logic of Fig. 2 is utilized. The signal R1XT in Fig. 1 represents the received blocking signal at relay 1 from the remote end relay 2 and Z1PT represents the time delayed element of Z1P phase elements. A communication delay of 0.5 cycle is considered in this case and T_{Z1PU} is set at 0.5 cycles. The phase element of the reverse looking Zone 3 is used for sending the blocking signal. A dropout time delay of 1 cycle is used for carrier send signal to add additional security to make sure that the blocking signal does not dropout before the dropout of the remote Zone 1 in case of overreaching conditions. With this, the over-tripping of Zone 1 is restrained and blocked as shown in Fig. 3b.



(a) Non-pilot scheme with no overreach logic (R1Z1 over-tripped)



(b) With overreach blocking logic

Fig. 3. Relay operation for 3-Phase fault at 110% in a STATCOM compensated weak system

Although this method has successfully restrained the overreach of Zone 1 for other fault locations as shown in Table VI, it has the drawback of requiring an additional channel and would lead to the delay of relay operations for internal 3-phase faults as shown in Table VIII. The result in the Table shows the effect of selecting the pickup time delay setting of zone 1 (T_{Z1PU}) on the operating time for internal faults. On the other hand, however, the response time of this method is faster than that of method 2 as method 2 require additional coordination time delay to account for time of operation of the adjacent line circuit breaker (CB3).

TABLE VII
RELAY 1 PERFORMANCE FOR 3-PHASE FAULTS AT VARIOUS FAULT LOCATIONS

Fault Location	Relay 1 operation status	
	40 deg (reverse)	60 deg (reverse)
105%	x	x
110%	x	x
120%	x	x
130%	x	x
150%	x	x

TABLE VIII
EFFECT OF ZONE 1 PICKUP DELAY SETTING FOR 3-PH INTERNAL FAULT

Fault Location	Relay 1 operation Time (ms)		
	No delay	T_{Z1PU} = 0.5 cycle	T_{Z1PU} = 1 cycle
55%	25	33	40
75%	27	41	49

4) Choice of the Method:

The blocking method is better compared to the first two methods because it does not require reduction in zone 1 reach compared to method 1. In addition, it requires a lower coordination time delay requirement as compared to method 2. However, it requires an availability of additional channel when implemented with permissive schemes. It can be integrated with the DCB schemes and hence will not require any additional channel for such scheme. If for any reason, the channel is lost, this method will not work. Therefore, a combination between method 1 and 3 would be more secure option. This can be implemented by keeping method 3 as main whereas method 1 take effect once a loss of channel is detected as part of an adaptive setting.

B. Mitigation of Under-reach Effect

In this section, mitigation techniques will be presented to improve the performance of the standard distance channel-aided schemes for midpoint compensated shunt-FACTS compensated transmission system. The DUTT scheme will not be considered here as it performs well for the studied system with the exception of its limitation when fault involving fault resistance. In such fault condition, Zone 1 distance element might not pickup. Based on the performance of the five channel-aided schemes, the highest number of relay failure to clear the internal fault occurred for LG faults and then followed by LL faults as a result of the high under-reach effect of the shunt-FACTS midpoint compensation device. For such system, using a directional element such as negative sequence directional element, in conjunction with the overreaching Zone 2 element will improve the performance of distance based channel-aided schemes. The negative sequence directional element (NSDE) is selected, as it will work for all unsymmetrical faults and is immune to mutual impedance coupling in case of parallel lines. The performance of the POTT with weak-infeed logic (WIF), which is available in some types of commercial distance relays, will be evaluated first. Then the modification required to improve the WIF logic for lines with midpoint shunt-FACTS devices is introduced. The improvement in the relay performance when using the NSDE in the schemes utilizing overreaching element such as POTT, DCB and DUCB is subsequently examined. Furthermore, the PUTT performance can be also improved when the scheme is supplemented with the WIL or NSDE.

1) POTT Scheme with Weak Infeed Logic Feature:

POTT scheme, in some commercial distance relays, is supplemented with a weak-infeed logic to improve the scheme performance when a distance relay, at the weak terminal, does not see internal faults. This feature, when used, would improve the performance of the POTT scheme for midpoint shunt-FACTS compensated lines, in which one of the relays would not detect the fault. The basic principle of operation of a weak infeed logic is based on the fact that some of the phase voltages will depress for internal faults even if the relay does not detect the fault as a result of the small contribution of fault current from the weak-infeed source behind the relay. With such logic, the relay at the weak terminal issues a trip signal for its local breaker even if it does not detect the fault if the following conditions are satisfied:

- None of the relay reverse looking elements pickup.
- It receives a permissive signal from the remote end relay for a settable duration of time.
- An undervoltage is detected by any of its the phase elements. Some distance relay manufactures use also the residual overvoltage element in conjunction with the phase undervoltage elements for detecting possible fault condition.
- All the local poles of the local breaker are closed as it is of no use to issue a trip signal when a local breaker is already open. The condition of open breaker is taken care by the echo logic.

While the logic allows tripping of the local breaker (after some settable echo time delay, typically 2 to 3 cycles) when the above condition are met, it also echoes back the permissive signal to the remote relay. This will initiates a trip signal to its breaker once the echo signal is received. This logic would permit clearing of the fault from the two terminals of the line provided that it is acceptable to clear the fault after the echo time delay.

The same logic can be applied for midpoint shunt-FACTS compensated lines in which the relays experience high under-reach effect leading to the fault being not detected by one of the relays and hence result in failure to clear internal faults. The result of testing this scheme is shown in Table IX for LG and LL faults at the end of the line (95% from Bus “A”). It shows that an improvement is achieved as compared to the

POTT without WIF logic, specially for the weak system. However, the scheme would fail to trip when the voltage drop due to the fault is not higher than the settable undervoltage phase elements such as fault in strong system condition. As result, the relay 1 fails to trip for LL fault in the strong system condition as shown in the highlighted cells in Table IX. This problem does not show up in the weak system condition because the voltage drop due to the fault at the relay point is large as a result of the high source impedance behind the relay. This problem can be solved by modifying the weak-infeed logic as will be shown in the next subsection.

2) POTT Scheme with Modified Weak-Infeed Logic:

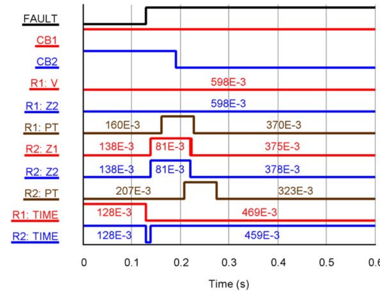
The standard weak-infeed logic would fail if the voltage reduction due to the fault is smaller than the threshold values of the undervoltage phase elements (UVP) and the zero-sequence overvoltage (ZSOV) elements, which would be possible in strong operating system condition of shunt-FACTS midpoint compensated system. Therefore, POTT scheme performance can be further enhanced by modifying the WIF logic to work with strong system conditions, as one of the relays would not operate in shunt-FACTS compensated strong systems. This can be achieved by adding another voltage element (negative sequence overvoltage element-NSOV) to detect non-ground faults (LL) at which both the zero-sequence and the phase elements would not detect the small voltage drop in strong system condition. Fig. 4 shows the performance of the POTT scheme with the standard WIF logic in (a) and the POTT with the modified WIF logic in (b) during a BC fault at 95% (from relay 1) for a STATCOM compensated strong system. The voltage elements are summed and represented by "V" in figure. This figure shows that the POTT with a standard WIF logic does not trip at relay 1 as the voltage elements (V) does not pickup. However, after adding the NSOV element, the relay tripped by the WIF logic as shown in 4b. With this modification, the relay trips correctly for all internal faults as shown in Table IX for both weak and strong system conditions.

3) PUTT Scheme with Weak Infeed Logic:

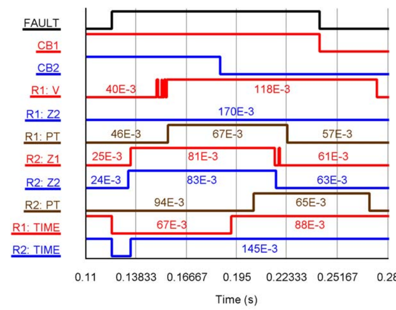
According to common practice, the WIF logic is only implemented with the POTT scheme. However, using the WIF logic with the PUTT schemes would improve its performance for midpoint shunt-FACTS compensated transmission lines. Fig 5 shows the advantages of using the WIF logic with the PUTT for shunt-FACTS midpoint compensated lines in which relay 1 does not trip for standard PUTT, whereas it trips when the WIF logic is integrated in the scheme.

4) Keying using Negative Sequence Directional Element:

The high under-reach effect and the transients of the shunt-FACTS midpoint compensation result in failure of the POTT scheme to clear the fault for LG and LL faults. This is because the overreaching Zone 2 under-reaches to the level that it either does not see the fault or picks up for short time and dropout before a permissive signal arrive from the remote end relay. Therefore, one effective way to overcome this is by using a negative sequence directional element in conjunction with the overreaching Zone 2 distance element for the carrier signal to key the scheme and initiate its operation. The same can be applied for DCB and DCUB. The results in Table IX show the improvement compared to schemes using only the overreaching zone 2 element for carrier signal. Some commercial relay manufacturers provide provision to add, as an option, some of the available functions in the relay to be used in the logic for keying the scheme.

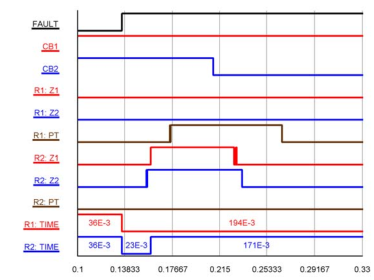


(a) POTT with standard WIF Logic

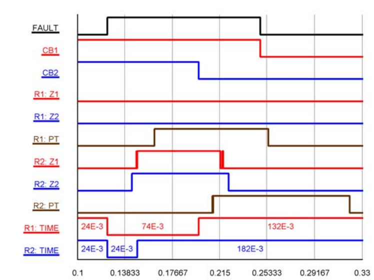


(b) POTT with modified WIF Logic

Fig. 4. POTT Scheme Performance for BC fault at 95% in a STATCOM compensated strong system.



(a) PUTT without WIF Logic



(b) PUTT with WIF Logic

Fig. 5. PUTT Scheme Performance for AG fault at 70% with 40Ω fault resistance for STATCOM compensated Strong system (40 deg forward).

Fig. 6 shows the performance of the POTT scheme when the forward negative sequence directional element (shown as FD in the figure) is used in conjunction with the overreaching zone 2 distance element for the carrier signaling. It can be seen from the figure that Z2 of R1 does not pickup whereas as the (Z2+FD) pickup, which implies that this relay would not operate if the NSDE element had not been implemented.

The performance of the suggested recommendations and mitigations for fault involving high fault resistance is shown in Table X. The overall performance of the schemes shows the superiority of using directional negative sequence element for carrier and/or qualifying signals compared to standard distance based channel aided schemes.

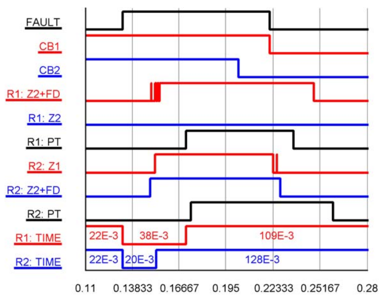


Fig. 6. POTT with NSD for AG fault at 95%, 40 deg (forward), 1 cycle channel delay in SVC compensated weak system.

TABLE IX
RELAY 1 TRIP STATUS FOR MITIGATED CHANNEL-AIDED SCHEMES

	System Condition	STRONG SYSTEM								WEAK SYSTEM							
	Fault Type	LG				LL				LG				LL			
	FACTS Device	SVC		STATCOM		SVC		STATCOM		SVC		STATCOM		SVC		STATCOM	
	Load Angle (deg.)	20	40	20	40	20	40	20	40	20	40	20	40	20	40	20	40
Protection Scheme	POTT with WIF Logic	C	C	C	C	C	C	x	x	C	C	C	C	C	C	C	C
	POTT with Modified WIF Logic	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
	PUTT with WIF Logic	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
	POTT with NSD Carrier	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
	DCB with NSD Carrier	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
	DCUB with NSD Carrier	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C

TABLE X
PERFORMANCE OF THE MITIGATED CHANNEL-AIDED SCHEMES FOR FAULTS WITH RESISTANCE (CHANNEL DELAY = 0.5 CYCLE)

Fault Location	Protection Scheme	Fault Resistance (Rf) = 40 Ohms								Fault Resistanc (Rf) = 50 Ohms							
		STRONG SYSTEM				WEAK SYSTEM				STRONG SYSTEM				WEAK SYSTEM			
		SVC		STATCOM		SVC		STATCOM		SVC		STATCOM		SVC		STATCOM	
		R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
60%	POTT with WIF Logic	C	C	C	I	C	I	X	X	C	C	C	C	C	C	X	X
	POTT with Modified WIF Logic	C	C	C	I	C	I	X	X	C	C	C	C	C	C	X	X
	PUTT with WIF Logic	X	II	C	I	C	I	X	X	X	II	X	II	X	II	X	X
	PUTT with NSD	X	II	C	I	C	I	X	X	X	II	X	II	X	II	X	X
	POTT with NSD Carrier	C	C	C	I	C	I	C	C	C	C	C	C	C	C	C	C
	POTT with Modified WIF + NSD	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
	DCB with NSD Carrier	C	C	C	I	C	I	C	C	C	C	C	C	C	C	C	C
	DCUB with NSD Carrier	C	C	C	I	C	I	C	C	C	C	C	C	C	C	C	C

V. CONCLUSION

In this paper, different mitigation methods for improving the performance of distance based protection schemes are proposed for midpoint shunt-FACTS compensated transmission lines. The mitigations are intended to overcome the issues such as the under and overreach impacts of SVC and STATCOM shunt compensated lines. The proposed methods of mitigation have been implemented in commercial relays and tested using RTDS. The results show the effectiveness of the mitigation methods for improving the distance channel-aided schemes for transmission line with midpoint shunt-FACTS devices.

VI. APPENDIX

POWER SYSTEM ELEMENT	PARAMETERS
Transmission Lines (I, II & III)	Length= 300km; Z_1= 0.51 ∠85.92 ° Ω/km; *Z_0= 1.385 ∠74.68° Ω/km*
Equivalent Sources (1,2,3 & 4)	230kV, 60 Hz, $Z_{1=}$ 25.9 ∠80° Ω; *Z_0= 25.9 ∠80° Ω*
Coupling Transformer	*230/11/11kV, 200MVA, X_t=0.1pu*
SVC Rating	*110MVA/100MVA (Capacitive/Inductive)*
STATCOM Rating	±110MVA (Inductive & capacitive)

VII. REFERENCES

[1] Network Protection & Automation Guide, ALSTOM, third edition, 2002.
[2] M. Adamiak and R. Patterson, “Protection requirements for flexible AC transmission systems,” Proc. CIGRE, Paris, France, 1992.
[3] M. Khederzadeh, T. S. Sidhu, “Impact of TCSC on the Protection of Transmission Lines”, IEEE Transactions on Power Delivery, Volume 21, Issue 1, Jan 2006 Pages: 80 – 87.
[4] T. S. Sidhu, M. Khederzadeh, “TCSC impact on Communication-aided Distance Protection Schemes and its Mitigation”, IEE Proceedings on Generation, Transmission and Distribution, Vol. 152, Issue 5, Sep. 2006, Pages: 714-728.
[5] P. K. Dash, A. K. Pradhan, G. Panda and A. C. Liew, “Digital Protection of Power Transmission Lines in the Presence of Series Connected FACTS Devices”, IEEE Power Engineering Society Winter Meeting, 2000, Volume: 3, 23-27 Jan. 2000 Pages: 1967 - 1972
[6] W. Wang, Y. Xianggen, Y. Jiang, D. Xianzhong and C. Deshu, “The Impact of TCSC on Distance Protection Relay”, International Conference on Power System Technology, POWERCON '98. 1998, Volume: 1, 18-21 Aug. 1998, Pages: 382 – 388.
[7] P. K. Dash, A. K. Pardhan, G. Panda, “Distance Protection in the Presence of Unified Power Flow Controller”, Electric Power System Research, Vol. 54, 2000, Pages 189-198.
[8] Xiaoyae Zhoe, Haifeng Wang, R. K. Aggarwal, Phil Beaumont, “Performance Evaluation of a Distance Relay as Applied to a Transmission System with UPFC”, IEEE Transactions on Power Delivery, Vol. 21, Issue 3, July 2006 Pages: 1137 – 1147.
[9] S. Jamili, M. Khalantar, H. Shateri, “Effect of instrument transformers location on measured impedance by distance relay in presence of UPFC”, IEEE Power India Conference, April 10-12,2006, Pages: 6 pp.
[10] K. El-Arroudi, G. Joos, D. T. McGillis, “Operation of Impedance Protection Relays with the STATCOM”, IEEE Transactions on Power Delivery, Volume: 17, Issue: 2, April 2002, Pages: 381 – 387.
[11] T.S. Sidhu, R.K. Varma, P.K. Gangadharan, F.A. Albasri, G.R. Ortiz, “Performance of Distance Relays on Shunt—FACTS Compensated Transmission Lines”, IEEE Transactions on Power Delivery, Volume 20, Issue 3, July 2005 Pages: 1837 – 1845.
[12] F. A. Albasri, T.S. Sidhu, R.K. Varma, “Performance Comparison of Distance Protection Schemes for Shunt- FACTS Compensated Transmission Lines”, Accepted for publication in the IEEE Transactions on Power Delivery.
[13] Real-Time Digital Simulator (RTDS) User’s Manual Set, RTDS Technologies Inc., June 2001.
[14] R. M. Mathur and R. K. Varma, “Thyristor-Based FACTS Controllers for Electrical Transmission Systems”, Wiley-IEEE Press, Feb. 2002.

VIII. BIOGRAPHIES

Fadhel Abbas Albasri (S’94), received the B.Sc. and M.Sc. degrees in electrical engineering from the University of Bahrain, Bahrain, in 1992 and 1997, respectively. He is pursuing his PhD degree in Power System Protection at the University of Western Ontario, London, Ontario, Canada.

Tarlochan Singh Sidhu (SM’94-F’04) is Professor and Hydro One Chair in Power Systems Engineering, and Chair of the Department of Electrical and Computer Engineering at the University of Western Ontario, London, Ontario, Canada.

Rajiv K. Varma (M’96) did his B. Tech and Ph. D. from Indian Institute of Technology (IIT), Kanpur in 1980 and 1988, respectively. He was a faculty member at IIT Kanpur from 1989-2001. He subsequently moved to University of Western Ontario, London, Canada where he is an Associate Professor. His research interests are FACTS, Power System Stability and Wind Power Systems.