Development of Adaptive Distance Relay for STATCOM Connected Transmission Line

Sham M V, Chethan K S and K P Vittal, *Member, IEEE*

Department of Electrical and Electronics Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore, India

***Abstract*—Flexible AC Transmission System (FACTS) devices are inserted into power grids in series, in shunt, and in some cases, both in shunt and series for the improved power transmission capability. They also improve the controllability, stability and power quality of the power system. Static Synchronous Compensator (STATCOM) is a shunt type FACTS device connected at the midpoint of the transmission line to maintain the voltage at desired level by injecting/absorbing the reactive power. These devices have fast dynamic response time, which overlap with the response time of the line protection distance relays. This interaction affects the performance of distance protection relay during line faults. In this paper the design and development of a new adaptive distance relaying scheme to mitigate the adverse effects of the STATCOM is presented. A ±100MVA 48 pulse STATCOM with associated control system, connected at the midpoint of a typical 400KV transmission system is selected for simulation. The line faults of different types at various locations of the line are simulated using EMTDC/PSCAD® and the performance of newly developed adaptive distance protection scheme has been evaluated and efficacy of the proposed scheme is illustrated.**

***Index Terms*—48 pulse STATCOM, Adaptive distance relay, EMTDC/PSCAD, Voltage Source Converter (VSC)**

I. Introduction

THE ability of FACTS devices to control the line impedance and the nodal voltage magnitudes and phase angles at both the sending and the receiving ends of key transmission lines, with almost no delay, has significantly increased the transmission capabilities of the network while considerably enhancing the security of the system. [1-2]. There are variety of FACTS devices developed in recent years. They are classified according to their respective topologies such as series, shunt and/or combination of both. The Shunt compensating devices are used for increasing the power transfer capability of a line [3]. The STATCOM is a shunt-connected reactive-power compensation device that is capable of generating and/or absorbing reactive power. The placement of the STATCOM device depends on the application for which it is installed. Particularly to meet the purpose of increasing the power transfer capability of long transmission lines, the midpoint sitting is the best location for shunt connected STATCOM. This is simply because, each side of the FACTS device addresses only half the line impedance and not the full line impedance as in the case of the transmission line end sitting [4]. For this reason the STATCOM connected at the midpoint of transmission line is considered for simulation studies in this paper. With the inclusion of FACTS controllers, transmission systems undergo rapid variations / changes in line impedance, power angle, load currents, and also the transients introduced at the fault occurrence [5]. Therefore, it is essential to study the effect of FACTS devices on the performance of the distance relay, which is used as the main protective gear for long distance power transmission lines.

Numbers of researchers have reported work on the effect of shunt compensation including FACTS Controllers on the performance of distance protection relays. The Authors in [5] have presented the analytical results based on steady-state model of STATCOM. Study revealed the under reaching phenomenon of the impedance distance relays. In [6], a detailed model of STATCOM is proposed and, the analytical results based on symmetrical component transformation for all types of fault are presented. It is shown that conventional distance relays are prone to malfunction, in the form of over-reaching or under-reaching in the presence of STATCOM. The work in [7-8] has presented the experimental results showing the channel aided distance protection schemes perform better than the stand alone schemes, in the presence of shunt FACTS devices.

In the present work an adaptive distance relay scheme to prevent the malfunction of the relay in the presence of STATCOM is developed. This scheme requires three phase STATCOM currents in addition to the three phase voltages and currents at the relaying location for the accurate calculation of the apparent impedance. The communication link is assumed to be accomplished through a dedicated high speed fibre optic channel between relay and STATCOM locations. In order to demonstrate the effectiveness of the scheme, a two source power system including STATCOM at the mid-point and a distance relay installed at the sending end, is selected. All the components of power system, STATCOM and associated control systems are modelled using PSCAD/EMTDC. The new adaptive relay program is developed in MATLAB® environment. All types of faults at

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various locations of the line are created and the performance of the newly developed scheme is presented with the help of impedance trajectories plotted over a mho relay characteristics.

This paper is organized as follows. First, detailed modelling of a ±100MVA STATCOM using a 48 pulse voltage source inverter is discussed. Also the harmonic analysis of the output voltage is presented in section II. In Section III modelling of STATCOM controller is given. In section IV the effect of STATCOM on the performance of distance relay for various types of faults on either side of the STATCOM is presented. The new adaptive distance scheme developed to mitigate the effect of midpoint STATCOM is described analytically and the performance of adaptive scheme is evaluated for different faults at various locations through simulations and the results are presented in section V. Conclusion is presented in section VI.

I. MODELING OF ±100 MVA 48 PULSE STATCOM

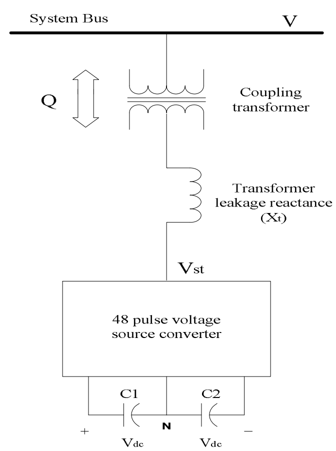

Fig. 1. Single line diagram of STATCOM connected to a power system

The basic voltage-sourced converter scheme for reactive power generation is shown in Fig. 1. From a dc input voltage source, provided by the charged capacitor, the STATCOM produces a set of controllable three-phase output voltages with the frequency of the ac power system. Each output voltage is in phase with, and coupled to the corresponding ac system voltage via leakage inductance of the coupling transformer. By varying the amplitude of the output voltages produced, the reactive power exchange between the converter and the ac system can be controlled [1].

Fig. 2 shows the block diagram of harmonically neutralized 48 pulse voltage source converter modeled in EMTDC/PSCAD. It consists of four 3-phase, three level inverters and four phase-shifting transformers (PST). The voltage generated by the inverter is applied to the secondary winding of respective phase-shifting transformer connected in either star (Y) or delta (D) configuration. The four transformer primary windings are connected in series. The converter pulse patterns are phase shifted so that the four fundamental voltage components sum up in phase on the primary side. Each transformer is rated for 25 MVA to produce a total output of 100 MVA [9-10]. Each three phase PST is developed by using three 3-winding single phase transformers.

A. 48 Pulse Voltage Source Converter (VSC)

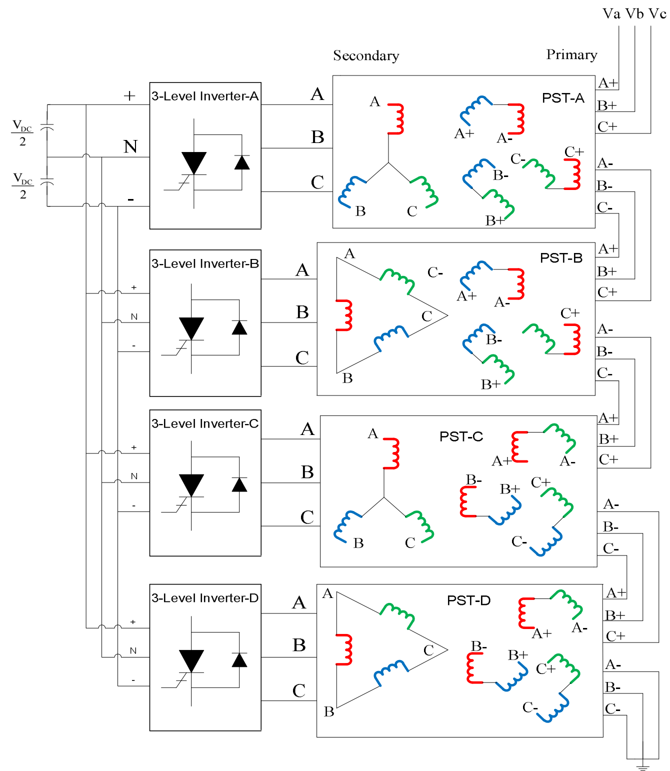

Fig. 2. Block diagram of 48 pulse voltage source converter

The three windings of each single phase transformer are shown in same color. The internal windings of the PSTs are connected as shown in the Fig. 2 to obtain required phase shifts as shown in Table 1. The primary windings of phase shifting transformers are connected in series to neutralize the harmonics and to increase the voltage level of fundamental voltage. Fig.3 shows the primary and secondary voltage waveforms of all four phase shifting transformers. The figure sub-windows on the left hand side shows the line to line output voltages of respective three level neutral point clamped inverters, whose output is connected to secondary windings of corresponding phase shifting transformers. The figure sub-windows on the right hand side show the line to line output voltage of respective phase shifting transformers.

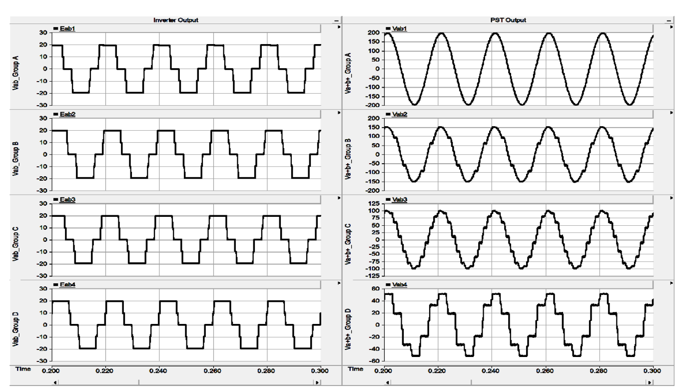

Fig. 3. Secondary and primary voltage waveforms of PST

Table. 1 Phase shift obtained by each PST

PST	Transformer Secondary	Phase shift Obtained in	Total phase shift in

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	connection	degrees	degrees
A	Star	+7.5	+7.5
B	Delta	+7.5	+37.5
C	Star	-7.5	-7.5
D	Delta	-7.5	+22.5

B. *Three Level Inverter used in VSC*

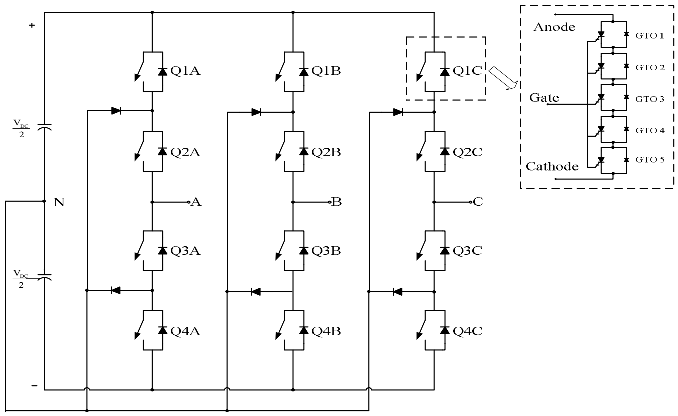

Fig. 4. Neutral point clamped (NPC) three level inverter

The neutral point clamped (NPC) inverter consists of four switches and two neutral point clamped diodes in each leg to produce a three level voltages at each phase. The two 3000μF capacitors connected in series are pre-charged to 9650 volts. When STATCOM is operating at ±100 MVA, the peak current flowing through each switch is around 1500 amperes. The forward blocking voltage across each switch is Vdc/2 i.e. 9650 volts. The voltage across the capacitor terminals varies depending upon the controller action and magnitude of the ac system voltage. During transient conditions such as close in faults, capacitor voltage may increase up to 1.5 times the rated voltage and also peak current flowing through each switch may increase up to twice the rated current. To meet these requirements, each switch is realized by connecting five gate turn off thyristors (GTO) with rating of 4.5 KV, 3 KA in series as shown in Fig. 4.

The harmonic analysis of the output voltage is performed using the total harmonic distortion (THD) calculator block available in the EMTDC/PSCAD. Harmonic spectrum is shown in Fig. 5. It can be seen from the figure that, the dominant harmonics present in output voltage are 47^{th} and 49^{th} has a magnitude of 1.92% and 1.78% respectively, with respect to fundamental. THD of the output voltage waveform produced by the STATCOM under no load condition is found to be around 2.72%.

The line to line ac output voltage is given by [11]

$$v_{ab_{48}}(t) = 8 \sum_{n=1}^{\infty} v_{ab_n} \sin(n\omega t + 18.75^o n + 11.25^o i)$$
$$\forall n = 48r \pm 1,\ r = 0,1,2,\ldots \qquad (1)$$

Where,
i = 1 for positive sequence harmonics.
i = -1 for negative sequence harmonics.

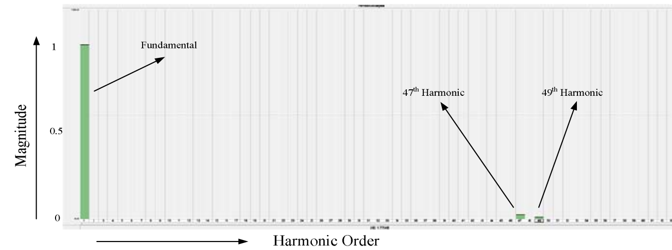

Fig. 5. Harmonic spectrum of STATCOM output voltage

II. STATCOM CONTROLLER

A Decoupled reactive current control technique [11] is used to implement the STATCOM controller and is shown in the Fig. 6. The objective of the controller is to regulate the mid-point voltage of the transmission line. The operation of the STATCOM controller is described as follows.

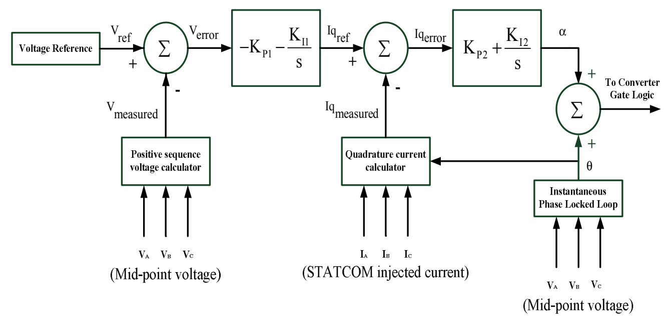

Fig. 6. Block diagram of STATCOM controller

The positive sequence voltage at mid-point calculated using equation (2) is compared with the reference input and the resultant error is given to the voltage PI-controller. This PI - controller is tuned to produce the required quadrature current reference (Iq_{ref}). Controller output is limited between ±1 p.u. The quadrature current (Iq) injected by STATCOM at mid-point is calculated using the equation (3) in per unit with the 100MVA and 400KV as base MVA and base voltage respectively. The angle θ is obtained from the instantaneous phase locked loop [12] . The calculated quadrature current (Iq) is compared with the reference (Iq_{ref}) and the resultant error required control angle (α) to vary the DC capacitor voltage which in turn controls the reactive power flow between STATCOM and ac system to regulate the ac system voltage. The current PI controller output is limited between $\pm 5^o$ to limit the over current during power system disturbances. The proportional and integral gains are, K_{PV}=12 and K_{IV}=1000 for voltage PI controller and K_{PI}=30 and K_{II}=200 for current PI controller respectively.

$$\begin{bmatrix} V_1 \\ V_2 \\ V_0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \qquad (2)$$

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$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (3)$$

III. Effect of STATCOM on Distance Relay

To study the effect of STATCOM on the performance of the distance relay a model power system selected for simulation is as shown in Fig. 10. The power system consist of two 400 KV Thevinin equivalent sources E_s and E_r at the sending and receiving end respectively. Two sources are connected by a 200 kilometre length transmission line with a ±100MVA STATCOM at midpoint. The system parameters are given in the appendix. Several cases involving all types of faults at different locations of the transmission line have been simulated. The results are saved in the corresponding fault data files. These data files consisting of relaying quantities namely, three phase voltage and currents obtained from PSCAD/EMTDC are exported to the MATLAB. These signals are used as input for the distance relay model developed in MATLAB. A mimic filter is also implemented to remove the decaying dc component from the fault current signals [13] to improve the performance of the relay. A Mho relay characteristic is used for detection of faults. The relay is set to protect 80% of the line. Although several cases are simulated only two cases have been presented here. An AB fault at 50 kilometers from the relay location is simulated. In this case STATCOM is not present in the fault loop. Fig. 7 shows the apparent impedance trajectory seen by the relay. Impedance trajectory is super imposed on the relay characteristic for better visualization. It can be seen that the, impedance trajectories for line with STATCOM and without STATCOM converge to a same value. Thus, the performance of the distance relays will not be affected for the faults in which STATCOM is not present in the fault loop. An AB fault at 80% of the transmission line is simulated as another case. In this case STATCOM is present in the fault loop. From the impedance trajectory shown in the Fig.8 it can be observed that impedance seen by the relay is different for the line with STATCOM and line without STATCOM. Thus, the relay under reaches for faults with STATCOM present in the fault loop. Table 2 shows the apparent impedance measured for the different faults applied at the relay reach setting (80% of line) with and without STATCOM connected to the system. It can be seen that, impedance measured by normal distance protection scheme in the presence of STATCOM at mid-point of the transmission line is more than the actual impedance in all types of faults. Hence, the relay will under reach. It is also observed that the under reaching effect increases as the fault location moves farther from the relay location.

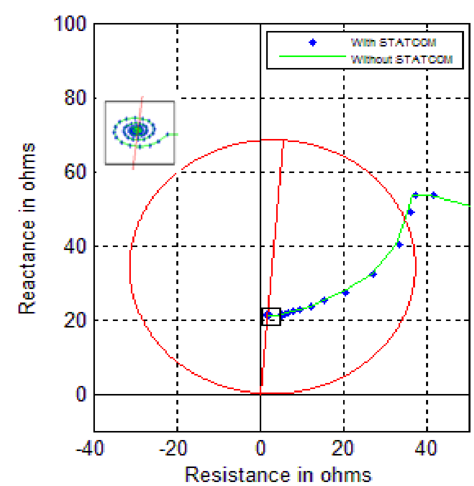

Fig. 7. Phase AB impedance trajectory during AB fault at 25% of the line

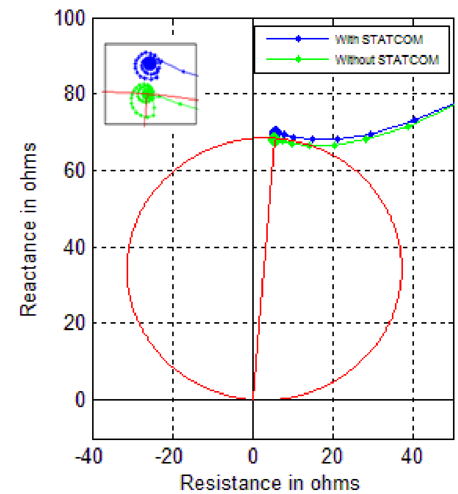

Fig. 8. Phase AB impedance trajectory during AB fault at 80% of the line

TABLE.2 Apparent impedance measured by the relay with and without STATCOM

Type of fault	Without STATCOM		With STATCOM	
	R in ohms	X in ohms	R in ohms	X in ohms
A-G	5.66	68.35	6.17	69.96
AB-G	5.68	68.39	6.28	70.02
AB	5.68	68.39	6.22	70.05
ABC	5.68	68.39	6.16	69.94

IV. Development of Adaptive Distance Protection Scheme

The relay will under reach in the presence of STATCOM only for the faults occurring beyond the midpoint of the line. This is shown with the help of simulation in the previous section. In this section an adaptive scheme is developed to mitigate the under reaching effect. Equivalent circuit diagram

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of the power system for faults appearing beyond 50% of the line from relay location can be written as shown in the Fig. 9.

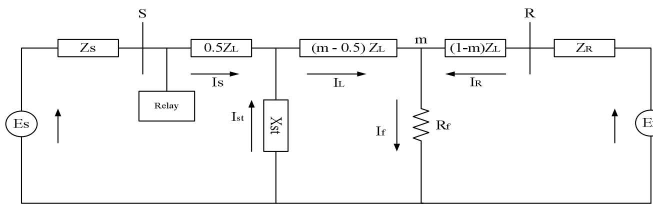

Fig. 9. Equivalent circuit diagram for faults beyond 50% of the line from relay location

Where,

E_S, E_R = Equivalent sending and receiving end voltages
Z_S, Z_R = Equivalent sending and receiving end impedances
I_S, I_R = Equivalent sending and receiving end currents
R_f = Fault resistance in ohms
I_f = fault current in amperes
X_{st} = STATCOM equivalent reactance
I_{st} = STATCOM injected current
m = Fault location in per unit
Z_L = Transmission line impedance in ohms
S, R = Sending and receiving end buses
V_S, V_R = Sending and receiving end bus voltages
Z_{relay} = Apparent impedance measured at relay point

From the Fig. 9, the voltage at sending end relay location is given by,

$$V_S = 0.5 Z_L I_S + (m - 0.5) Z_L I_L + I_f R_f \quad (4)$$

$$\text{but, } I_L = I_S + I_{st}$$

$$\text{and } I_f = I_S + I_{st} + I_R$$

$$\therefore V_S = m Z_L I_S + (m - 0.5) Z_L I_{st} + I_f R_f \quad (5)$$

And the apparent impedance seen by the relay can be calculated by writing,

$$Z_{relay} = \frac{V_S}{I_S}$$

$$Z_{relay} = m Z_L + (m - 0.5) Z_L \left(\frac{I_{st}}{I_S}\right) + R_f \left(\frac{I_f}{I_S}\right) \quad (6)$$

It can be seen from (6), that the apparent impedance measured by the relay is different from the actual impedance mZ_L. Therefore, the relay is prone to under reach its setting. The extent of reach problem depends upon the fault location and ratio of STATCOM current to sending end current and also on the fault resistance. For solid line to ground faults R_f=0, substituting this in equation (6) and after rearranging the terms, equation for computation of actual fault impedance can be written as

$$m Z_L = \frac{Z_{relay} + 0.5 Z_L C_{ratio}}{1 + C_{ratio}} \quad (7)$$

Where, $C_{ratio} = \frac{I_{st}}{I_S}$ is called the current ratio factor.

Equation (7) indicates that, if the time stamped three phase STATCOM currents made available to the relay, fault impedance can be calculated accurately. To achieve this, a dedicated communication channel between relay location and STATCOM location should be established. Communication channel is not modeled in this paper. But for simulation STATCOM currents obtained through simulations are directly used in the relay program. The block diagram of the adaptive distance scheme along with the power system is shown in the Fig. 10.

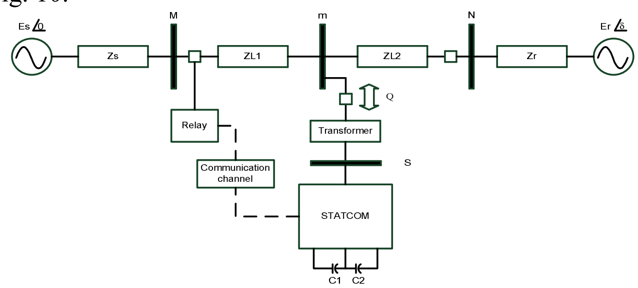

Fig. 10. Adaptive distance protection scheme

The current ratio factor (C_{ratio}) can be calculated by using equations (8) and (9), for phase to ground and phase to phase mho relay units respectively.

$$(C_{ratio})_x = \left[\frac{I_{st(x)} - I_{st(0)}}{I_x + k\, I_0}\right] \quad (8)$$

Where, x ε {A,B or C}

$$(C_{ratio})_{xy} = \left[\frac{I_{st(x)} - I_{st(y)}}{I_{(x)} - I_{(y)}}\right] \quad (9)$$

Where, x,y ε {A,B,C} and x≠y.
k = Zero sequence compensation factor of transmission line
$I_{st(x)}$ = STATCOM phase X current
I_x = Phase x current at relay location
I_0 = Zero sequence current at relay location
$I_{st(0)}$ = STATCOM zero sequence current

The relay will automatically adapt equations (8) & (9) for apparent impedance calculation as soon as the distance measured by the conventional distance relay exceeds 50% of the total line impedance.

A. Simulation results

Performance of the proposed adaptive distance relay scheme is evaluated by creating several fault scenarios. But the results of only two cases will be presented here. First, a phase A to ground fault is simulated at 80% of the line. The impedance trajectories for all the three cases i.e., relay without STATCOM, relay with STATCOM and adaptive relay are plotted on the mho characteristic as shown in Fig. 11 . It can be seen that, the apparent impedance seen by the conventional relay without STATCOM sees correct impedance to fault and performs as expected. But, for the STATCOM connected line impedance trajectory settles outside the mho characteristics therefore, conventional relay under reaches its setting and does not operate. Whereas, the apparent impedance seen by the adaptive scheme is almost same as the impedance seen by the conventional relay without STATCOM and therefore, the adaptive relay operates as expected and issues the trip signal. Similarly a phase to phase (AB) fault is applied at the reach setting of the relay and impedance trajectories for all the three cases have been presented in Fig.12. Once again, it can be

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verified from the figure that the conventional relay under reaches its setting where as the adaptive relay sees the exact fault impedance and operates as expected.

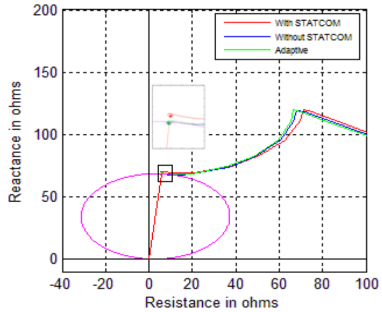

Fig. 11 Phase A impedance trajectory during A-G fault at 80% of the line

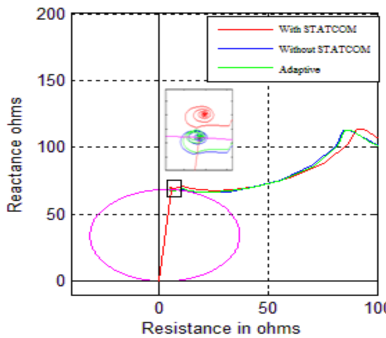

Fig. 12. Phase AB impedance trajectory during AB fault at 80% of the line

V. Conclusion

The performance of a distance relay deployed to protect a transmission system with STATCOM connected at mid point is studied. The study revealed that conventional stand alone distance relay cannot provide reliable protection in the presence of midpoint static compensator. Therefore, an adaptive distance protection scheme using three phase time stamped current signals of the STATCOM is developed and its performance is evaluated through simulations. It is found that the new adaptive distance protection scheme effectively mitigates the influence of STATCOM on distance relay operation.

Appendix

Table A1 : parameters of Simulated power system

Equivalent Voltage Sources	
Base Voltage	400 KV
3 phase short circuit level at base voltage	6500 MVA
X/R Ratio	8
Frequency	50 Hz
δ	Load angle (deg)
Transmission Line	
Resistance	0.03467 Ohms/KM
Series Reactance	0.42336 Ohms/KM
Line Length	200 KM
STATCOM	
Rated Power	± 100 MVA
Rated Voltage	138 KV
Number of Pulses	48
Capacitance	3000 μ F each
Capacitor Voltage	9.650 KV each
Coupling Transformer	
Nominal Power	100 MVA
Primary Voltage	138 KV
Secondary Voltage	400 KV
Positive Sequence Leakage Reactance	0.1 pu

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