AN ADAPTIVE STRATEGY FOR THREE ZONE OPERATION OF NUMERICAL DISTANCE RELAY WITH SHUNT FACTS, BASED ON PMU

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Abstract: *Modern energy transmission systems suffer from great voltage dropping due to enormous loads. Therefore appropriate schemes should be devised to regulate the voltage. FACTS devices such as Static Synchronous Compensator (STATCOM) are often used for this purpose. However, STATCOM at mid-point of transmission line may leads to deteriorate of distance relay operation, resulting in inaccurate estimation of faults locations i.e. over-reach or under reach for different cases. This paper proposed a new three zone algorithm that utilizes synchronized phasors measurement (SPM) to enhance the operation of distance protection in many aspects. The proposed method is tested for 230 kV system simulated in EMTDC/ PSCAD with Bergeron model of transmission line. The results prevailed for adaptive approach scheme are more accurate, victor and robust in equivalence with usable transmission line distance protection with STATCOM.*

Key words: *Adaptive algorithm, Phasors measurement unit, PSCAD/EMTDC, STATCOM, Power system protection*

1. Introduction

Power systems protection is considered as the first line of defence against power system disturbances such as faults. Hence, fast, accurate and reliable operation of the power system protection is vital to power system security and stability [1]. Studies of previous large disturbances and blackouts show that protective relay mal-operation either caused or aggravated the situation. As a result, it is very important to study the performance of the protection systems for different operating conditions and system configurations [2]. While the use of FACTS Controllers in power system improved the power transfer capability, and enhanced power system controllability and stability, among the basic concerns of implementing the FACTS Controllers are rapid changes in line impedance, power angle, load currents, and the transients introduced by the fault occurrence and the associated control action [3]. Protection of EHV and HV transmission line distance relay is widely used, due to its easy operating principle and ability to work independently under most critical circumstances. Due to presence of FACTS devices, transmission line may leads to deteriorate of distance relay operation, resulting in inaccurate estimation of faults location i.e. over-reach or under-reach for different cases. The improper working of distance relay leads to incorrect tripping and it not only diminishes the reliability and security of system but also can initiate the cascade tripping and blackouts [4].

Many papers reported the inaccurate estimation of faults location of distance relay in presence of shunt FACTS devices on the line [5]-[9]. The comparing effect of SVC and STATCOM on distance relay tripping characteristic varies with level of compensation, type of shunt devices used, and the installation point of shunt device [5]. The shunt compensation devices are mostly installed at mid-point of line to increase the power transfer and stability of power system. The operation of impedance protection relay with the STATCOM at mid-point of transmission line, distance relay mal-operate to locate the fault point in first zone of protection [6], [7]. The main problem arises when fault occur after the midpoint. In this case the shunt FACTS always comes in fault loop and considerably participates in fault current. This adversely affects distance relay apparent impedance measurement and it under-reaches or over-reaches depending on inductive or capacitive compensation. When fault occur before the mid-point, shunt FACTS does not come in fault loop and its participation in the fault current is negligible [8], [9].

In the presence of STATCOM, the Conventional distance relay characteristics are greatly subjected to mal-operation in the form of under-reaching and overreaching the fault point. Therefore the conventional characteristic cannot be utilized satisfactorily in the presence of STATCOM. To overcome the problems associated with the shunt compensation, several solution have been reported [10]-[15]. Fuzzy based approach, authors has used to overcome the problems related to shunt FACTS devices [10]-[12]. Author have used channel aided communication methodology using pilot directional comparison schemes but it take long time to send the trip decision at relaying bus giving rise to delay for trip decision[13], [14]. To increase the zone setting to the characteristics obtained for maximum point for compensation given by STATCOM but not depicted any equation by author for midpoint STATCOM [15].

The advancement in Global Positioning System (GPS) for synchronized measurement and fiber-optic data communication technology has given birth to Wide Area Measurement system (WAMs). Modern high speed communication transmission rates of the order of 274.2 Mbps or 155.5 Mb/s, respectively [16, 17]. GPS provides time synchronization of the order of 1 u sec, which is 0.018 for a 50 Hz power system and 0.0216 for a 60 Hz power system. Synchronization error can be practically eliminated if the same time stamped samples of two terminals are processed together at one relaying location [18], [19]. These advantages motivate us to use this new advance technology of data communication system for protection of transmission line. Adaptive current differential protection scheme[18]., author have used the basis of PMU technology to transfer the instantaneous sampled data from other end of line to relaying end line, instead in this work we are using above communication technology for data transfer over half of line length which reduces the investment cost.

In this work, the impact of STATCOM is investigated analytically by applying accurate modeling concepts which is missing in most of the literature, and then the analytical results are verified by detailed simulations with different cases. The analysis and simulation results help to understand errors associated with distance protection of transmission line when STATCOM is present. The main aim of this paper is to propose a new approach to mitigate the error due to STATCOM on three zones distance protection of transmission line. To meet this goal, first distance relay behaviour is analyzed using the sequence components with STATCOM connected at mid-point of line. A procedure to adaptively set the mho distance relay three zone reach is proposed in this paper.

The paper is organized as follows. First a brief description of the system model and STATCOM control scheme is given in section 2. Section 3 provides an analytical procedure for STATCOM is present at mid-point of line, using symmetrical analysis method. Consequently, in Section 4, the idea of adaptive mho rely setting using PMU is described. Section 5 explains the adaptive distance protection algorithm for three zones in PSCAD software for study system. In section 6, simulation results for three zones obtained for adaptive setting for distance protection scheme of transmission line in presence of STATCOM are presented. Section 7 concludes the paper.

2. STATCOM and power system model

2.1 Study System Modeling

A power system model with the facility to vary the system strength, types of fault and their location, load flow and direction of load is used to study so that all possible flow can be simulated. The inaccurate estimation of fault locations due to STATCOM on distance protection is studied. Fig 1 show the single line diagram of STATCOM with power system model is shown. The distance relay is located at station A, on line 1. The STATCOM installed is at the mid-point of the transmission line 1. It is presumed that PMU is available on STATCOM bus and relaying bus. Also high speed optical fiber data communication is usable for data transmission. Therefore STATCOM control is available at relaying bus without delay. Bergeron model is used to model all the three phase transmission line in PSCAD/EMTDC using given data in Appendix A. It is based on the distributed LC parameter and travelling wave line model, with lumped resistance. It represents the L and C elements of PI section in distributed manner. This model is suitable for studies where the fundamental frequency load flow and relay studies is most important [20].

2.2 Modeling and Performance of STATCOM

The FACTS controller is connected to the transmission system via an interfacing transformer as shown in fig.1. For the dynamic simulation study, 12 pulse STATCOM is considered. The power rating of STATCOM controller is selected such that it can regulate the mid-point voltage at 1p.u. and provide sufficient compensation for all conditions of loading and system strength. To accurately model the STATCOM controllers used in transmission system, a three phase balanced firing scheme is adopted. This implies that all the three phases are fixed at the same angle but 120 degree apart. Four filters have been provided in the FACTS controllers to limit the effects of system resonance and the harmonics [2], [3]. A slope of 3% is employed in the STATCOM. Thus the resulting per unit current is multiplied by 0.003 to calculate the ΔV and then added to the measured voltage to capture the actual voltage of the STATCOM.

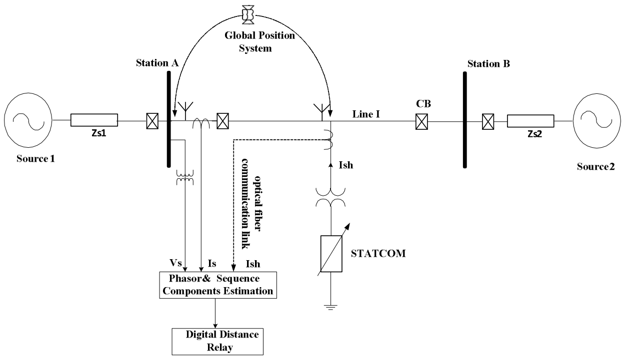

Fig. 1. Single line diagram of study system model

Measured reactive power and root mean square (RMS) voltage p.u. is given as the input. The measured reactive power is divided with the rated reactive power of the circuit. This output is divided with the measured RMS voltage p.u. After allowing a drop of about 3% the output of this block is summed up again with the measured RMS voltage. This summed output is passed through filters. The reference voltage in p.u, is summed with the output signal of the filters. This is given as input to the PI controller. PI controller is used as a voltage regulator. The gain of the PI controller is set based in the step response performance to step 10% change in reference voltage with overshoot of not more than 15% and rise time less than 16.667 milliseconds having settling time not more than 50 milliseconds [8]. Fig.2 illustrates the performance of STATCOM with 100 MVAR reactive power reference.

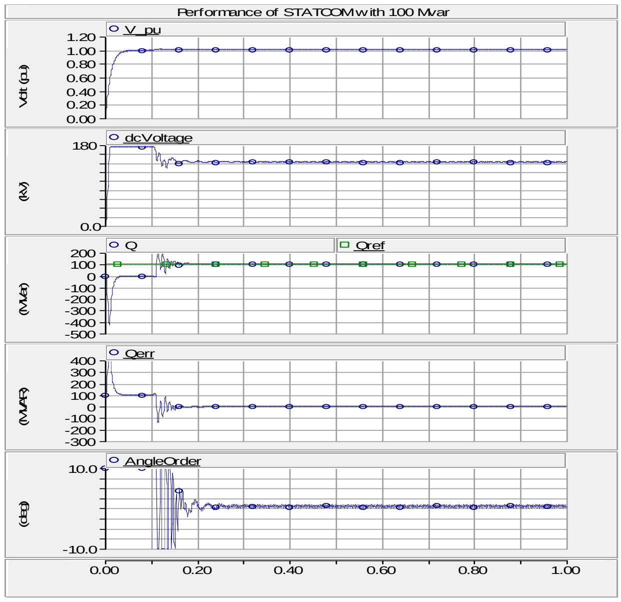

Fig. 2. Performance of STATCOM with 100 MVAR

3. Analysis of STATCOM impact on the measured impedance by distance relay

In this section, the expression for apparent impedance is derived when STATCOM is connected at mid-point of transmission line. To make the accurate adaptive distance relay setting, the digital distance relay is present at bus A which takes the voltage and current samples from instrument transformer. The symmetrical components of voltage and current are used to calculate apparent impedance. The voltage and current samples are pre-processed to calculate phasors (fundamental only) using Fast Fourier Transform (FFT) which has the ability to filter out dc decaying components and other harmonics and inter-harmonic components presents in the signal [5].

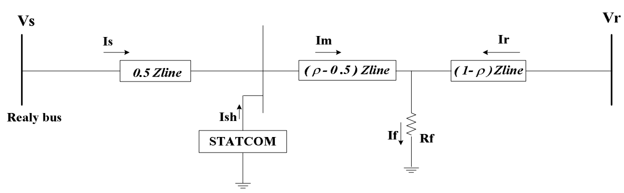

Fig. 3. Equivalent circuit of study system for fault on line-1 with STATCOM

Fig.3 shows the equivalent circuit of study system for line-1. The voltage drop in line is a function on line current from the relaying bus and remote-end bus current. The remote-end contribution cannot be measured at relying bus hence it is not considered in apparent impedance calculation. In the fallowing subsections expression for the apparent impedance seen by distance relay for Line to Ground (L-G) fault and phase to phase faults (L-L) are derived using sequence components of voltage and current at relying bus when STATCOM is present at mid-point of line-1.

3.1 Apparent impedance seen for L-G and L-L fault

When STATCOM is present at the mid-point of line and fault occur after the STATCOM, the sequence components of current and voltage at relaying bus is expressed as follows:

$$I_{m1} = I_{s1} + I_{sh1} \tag{1}$$

$$I_{m2} = I_{s2} + I_{sh2} \tag{2}$$

$$I_{m0} = I_{s0} + I_{sh0} \tag{3}$$

$$V_{s1} = 0.5 I_{s1} Z_{line1} + I_{m1}(\rho - 0.5) Z_{line1} + R_f I_{f1} \tag{4}$$

$$V_{s2} = 0.5 I_{s2} Z_{line1} + I_{m2}(\rho - 0.5) Z_{line1} + R_f I_{f2} \tag{5}$$

$$V_{s0} = 0.5 I_{s0} Z_{line0} + I_{m1}(\rho - 0.5) Z_{line0} + R_f I_{f0} \tag{6}$$

Where V_{s1},V_{s2}, V_{s0}, I_{s1}, I_{s2}, and I_{s0} are positive, negative and zero sequence components of voltage and current at relay bus respectively. Z_{line1}, Z_{line2} and Z_{line0} are positive, negative and zero sequence components of transmission line and $Z_{line2} = Z_{line1}$. I_{f1}, I_{f2} and I_{f0} are positive, negative and zero sequence component of fault current. I_{sh1}, I_{sh2} and I_{sh0} are positive, negative and zero sequence components of shunt injected current by STATCOM. ρ is per unit distance of fault from relying bus .

Now, phase-a voltage at relaying bus is V_{sa} which can be obtained from sequence components as:

$$V_{sa} = V_{s1} + V_{s2} + V_{s0} \tag{7}$$

$$V_{sa} = \rho I_{sa} Z_{line1} + [(\rho - 0.5)(Z_{line0} - Z_{line1})(I_{sha} + I_{sho}) + \rho I_{s0}(Z_{line0} - Z_{line1})] + R_f I_{fa} \tag{8}$$

Considering R_f =0, the last term of equation (8) can be eliminated and zero sequence current of the STATCOM (I_{sh0}) as shown in (8) can be eliminated due to the fact that there will be no zero sequence current injection because of delta connection at one side of the coupling transformer for the STATCOM.

After making these changes equation (9) can be rewritten as

$$V_{sa} = \rho I_{sa} Z_{line1} + [(\rho - 0.5)(Z_{line0} - Z_{line1}) I_{sha} + \rho I_{s0}(Z_{line0} - Z_{line1})] \tag{9}$$

The conventional line to ground element of distance relay measures apparent impedance for phase-a as

$$Z_{app} = \frac{V_{sa}}{I_{sa} + m I_{s0}} \tag{10}$$

Substituting the value of V_{sa} in (10) and after simplification we get,

$$Z_{app} = \rho Z_{line1} + \frac{(\rho - 0.5) I_{sha} Z_{line1}}{I_{sa} + m I_{s0}} \tag{11}$$

Similarly, the apparent impedance seen by the distance relay for L-L fault with R_f =0 can be calculated and the final equation after simplification is given,

$$Z_{app} = \rho Z_{line1} + \frac{(\rho - 0.5) I_{sh} Z_{line1}}{I_s} \tag{12}$$

From equation (11), it is observed that if STATCOM is not present on the line (I_{sha}=0), apparent impedance calculated by the distance relay is only the function of positive sequence impedance of the line (Z_{line1}) and the per unit distance (ρ) of fault point from relaying bus. When STATCOM is present on the mid-point of transmission line, apparent impedance expression have another factor with shunt injected current (I_{sha}) as the main contributing component. Because of this factor distance relay erroneously calculate the apparent impedance and mal-operate to locate the fault point.

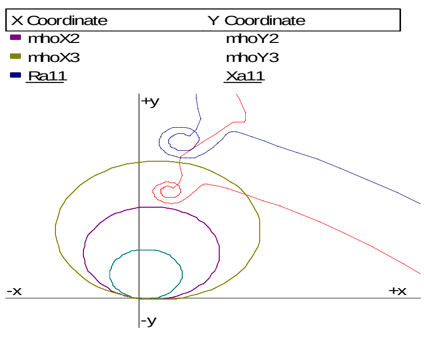

Fig. 4. Apparent impedance trajectory of L-G unit (legend: red = without STATCOM, blue = with STATCOM)

When shunt injected current is inductive, I_{sha} is negative, increasing the apparent impedance seen by relay causing under-reaching effect. When injected current is capacitive I_{sha} is positive and it decreased the calculated apparent impedance causing over-reaching effect. Similar effect in the apparent impedance calculation will occur for L-G fault in other phases. For an L-G fault occurred in Zone 3 from the relay. Fig.4 shows the apparent impedance calculated by L-G measuring unit, which shows that with and without STATCOM trajectory, the presence of STATCOM in the fault loop and its injected capacitive current, force the relay to under-reach. This is also due to the zero-sequence component of the injected current increases; this current has a direct impact on the apparent impedance.

3.2 Reactive power setting effect of STATCOM

Fig.5 shows the apparent impedance trajectory for variation of reactive power by STATCOM. For an L-G fault occurred at Zone 2 from the relay, when the STATCOM reactive power setting (Q_{ref}) are 100 and -100 MVAR respectively. As can be seen from fig 5, when STATCOM is connected at the mid-point of the transmission line and working in capacitive or inductive mode, the measured impedance seen by the relay is out of the zone 2 of line. This causes the mal-operation of the distance relay in the form of under-reaching and over-reaching respectively.

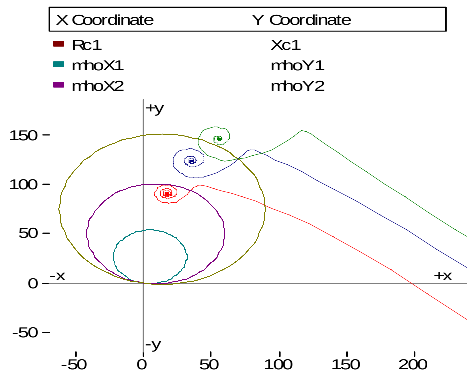

Fig. 5. Apparent impedance trajectory of L-G fault for different reactive power setting (Q_{ref}) (legend: blue = 0 MVAR, red = - 100 MVAR (inductive) , green = 100 MVAR (capacitive))

As fault resistance increases the deviation are more severe and distance relay mal-operate in both the cases to detect accurate fault location in the form of under-reaching and over-reaching.

4. Adaptive approach for distance relay with mid-point STATCOM

Adaptive Protection is a protection philosophy which permits and seeks to make adjustments to various protection functions in order to make them more attuned to prevailing power system conditions [4]. The protection algorithm which self tunes with the changing system conditions taking feed-back from various system parameters is said to be adaptive protection system. The main aim of this work is to make distance protection algorithm "adaptive" when STATCOM is present at mid-point of transmission line. Taking feedback of shunt injected current (I_{sh}) by STATCOM in distance protection algorithm to make it adaptive as observed from (11) and (12) and using synchronized measurement at relaying bus and STATCOM connecting point. Assuming time stamped GPS synchronized measurement at both terminal with high speed optical fiber data communication system which transfers information of (I_{sh}) at relay bus without any communication delay as shown in fig 1.

To achieve this aim, we have to modify the apparent impedance calculation formula derived in (11) or (12). Compare calculated apparent impedance with distance relay three zone setting(Z_{set}) of relay to make the decision of trip or no trip for fault in the zone of protection. As, the information of shunt injected current (I_{sh}) is available at relaying bus, the new distance relay setting expression is required which adaptively defines the setting. The line to be protected 100 km from station A to station B, the relay setting with three zones setting criteria, considering apparent impedance calculated in (11) to be equal to setting of first zone, second zone and third zone of distance relay which is 80%, 150% and 225% of the line to be protected respectively is express as follows.

$$Z_{1app} = Z_{set} = 0.8\ Z_{line1} \quad (13)$$

$$Z_{2app} = Z_{set} = 1.5\ Z_{line1} \quad (14)$$

$$Z_{3app} = Z_{set} = 2.25\ Z_{line1} \quad (15)$$

Comparing equation (11) and (13), we get

$$\rho = 0.5 + \frac{0.3}{\left(1+\frac{I_{sh}}{I_s+mI_{s0}}\right)} \quad (16)$$

Comparing equation (11) and (14), we get

$$\rho = 0.5 + \frac{1}{\left(1+\frac{I_{sh}}{I_s+mI_{S0}}\right)} \quad (17)$$

Comparing equation (11) and (15), we get

$$\rho = 0.5 + \frac{1.75}{\left(1+\frac{I_{sh}}{I_s+mI_{S0}}\right)} \quad (18)$$

The adaptive distance protection with this new setting will check the calculated apparent impedance (Z_{app}) and take the trip decision when STATCOM is present at mid-point of transmission line. Hence to get the new setting, multiply equation (16) with Z_{line1}

$$Z_{setnew} = \rho \, Z_{line1} \quad (19)$$

Multiplying equation (16) with (Z_{line1}) and substituting in (19), we get first zone setting

$$Z_{1setnew} = \left(0.5 + \frac{0.3}{\left(1+\frac{I_{sh}}{I_S+mI_{S0}}\right)}\right) Z_{line1} \quad (20)$$

Multiplying equation (17) with (Z_{line1}) and substituting in (19), we get second zone setting

$$Z_{2setnew} = \left(0.5 + \frac{1}{\left(1+\frac{I_{sh}}{I_S+mI_{S0}}\right)}\right) Z_{line1} \quad (21)$$

Multiplying equation (18) with (Z_{line1}) and substituting in (19), we get third zone setting

$$Z_{3setnew} = \left(0.5 + \frac{1.75}{\left(1+\frac{I_{sh}}{I_S+mI_{S0}}\right)}\right) Z_{line1} \quad (22)$$

From mentioning equation (20), (21) and (22), some important information is remarked as: The installation point of STATCOM affects the apparent impedance calculation. STATCOM injected current have dominant effect in apparent impedance calculation for fault after STATCOM. The adaptive distance protection three zone setting formula adaptively adjusted with nature of STATCOM injected current. The adaptive distance protection setting will automatically adjust the three zone reach, depending on the level of compensation. If STATCOM injects capacitive current (I_{sh}) is positive and adaptive zone increased while if current is inductive (I_{sh}) is negative and adaptive zone is decreased.

5. Algorithm of adaptive distance protection

Fig.6 shows the algorithm of adaptive distance protection setting equation derived in (20-22) in PSCAD software. The new adaptive setting is obtained with actual study system parameter. Three zones setting obtained dynamically using the adaptive setting factor. The adaptive distance relay adaptively sets the three zone setting using equation (20-22) utilizing the information of shunt injected current and compares estimated the apparent impedance using equation (10) as soon as there is any change in the STATCOM compensation level it modifies the setting parameter to adapt with new compensation level and when fault will on the line the relay compares the measured apparent impedance with this setting to issues signal for circuit breaker to clear faults

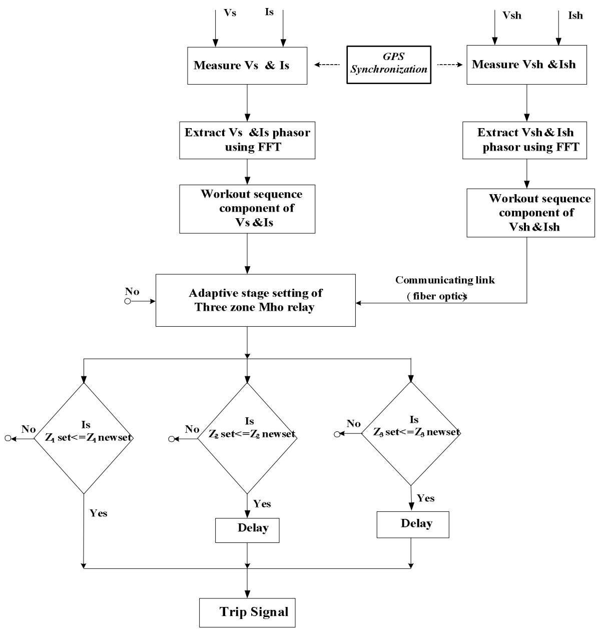

Fig. 6. Algorithm of three zones adaptive distance protection

6. Simulation results

To judge the performance of the proposed adaptive distance protection, study system shown in fig.1, is modelled in PSCAD software [20]. The 12-

pulse dynamic model of STATCOM is designed and control system is tuned to regulate the mid-point voltage to 1 per unit. But to calculate various adaptive zone settings of distance relay, control over the reactive power injection is set between $\pm$ 100 MVAR. The STATCOM connected at mid-point is connected at 0.1 sec into the system. When, STATCOM absorbs inductive reactive power, the mid-point voltage decreases, from normal operating voltage without STATCOM. This results decrease in relaying bus voltage due to this apparent impedance seen by distance relay decreases causing over-reaching.

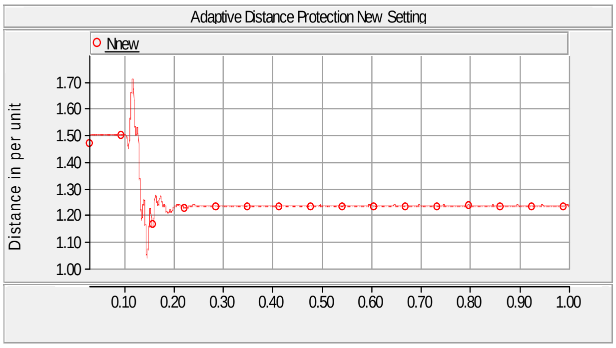

Fig. 7. Adaptive mho relay second zone setting factor ρ with STATCOM supplying inductive reactive power of 100 MVAR into the system with forward power flow

From adaptive distance relay simulation for second zone with STATCOM absorbing inductive reactive power of 100 MVAR, the setting factor ρ is shown in fig.7 for forward power flow (consider, from station A to station B).

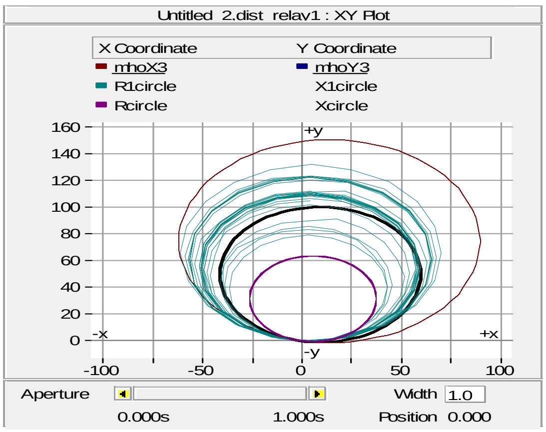

Fig. 8. Adaptive mho relay second zone characteristics with STATCOM supplying inductive reactive power of 100 MVAR into the system with forward power flow

It is observed that prior to the introduction of STATCOM, the shunt current (I_{sha}) is zero. The setting factor ρ value is 0.8 per unit distance. When STATCOM is connected at 0.1 sec into the system and absorbing inductive reactive power of 100 MVAR, the setting factor ρ is adaptively decreased and settled to 1.2353 per unit distance value taking 50 milliseconds to derive new adaptive setting for second zone. This adaptive setting factor is utilized to define mho distance relay reach dynamically as shown in fig.8. It is observed that for inductive reactive power injection, adaptive mho distance relay reach is reduced shown in green colour as compared to conventional setting shown in black colour.

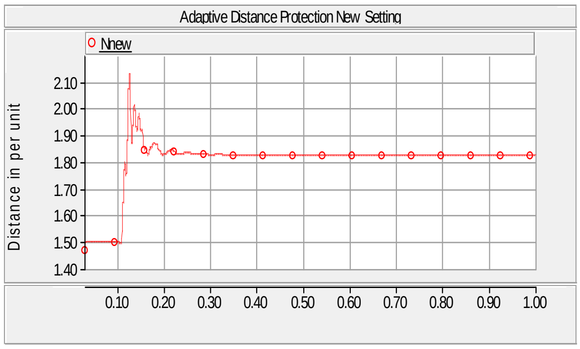

Fig. 9. Adaptive mho relay second zone setting factor ρ with STATCOM supplying capacitive reactive power of 100 MVAR into the system with forward power flow

When STATCOM is injecting capacitive reactive power into the system, the mid-point voltage increased as compared to normal operating voltage without STATCOM. Consequently there is increase in relaying bus voltage and the apparent impedance seen by distance relay increases causing under-reaching. The adaptive relay setting factor ρ obtained for STATCOM supplying capacitive reactive power of 100 MVAR into the system is shown in fig.9 for forward power flow. It is observed that in absence of STATCOM setting factor is 0.8 and with introduction of STATCOM at 0.1 seconds for this case, it adaptively increases and settles to 1.8263 per unit distance value taking 80 milliseconds to settle. Fig.10 shows the adaptive mho distance relay with green colour and conventional mho relay with black colour.

It is observed that for capacitive reactive power injection adaptive mho relay reach is increased in comparison with conventional mho relay reach. Similarly, results are obtained for second zone when STATCOM injecting inductive and capacitive

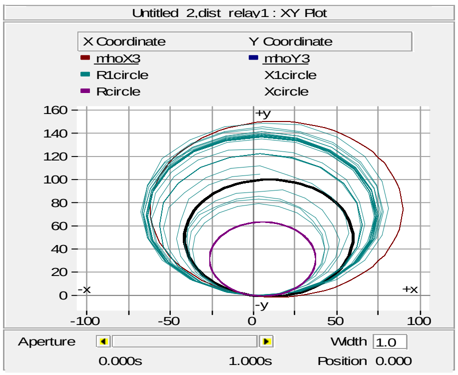

Fig. 10. Adaptive mho relay second zone characteristics with STATCOM supplying capacitive reactive power of 100 MVAR into the system with forward power flow

reactive power into the system for reverses power flow (consider, from station B to station A).

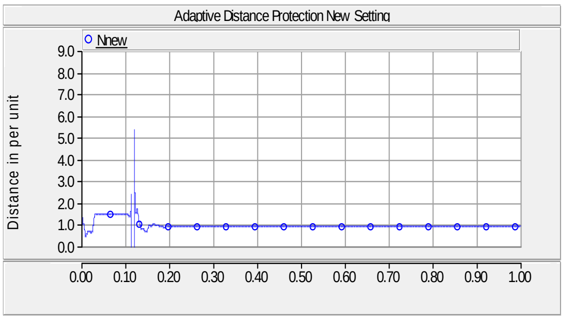

Fig. 11. Adaptive mho relay second zone setting factor ρ with STATCOM supplying inductive reactive power of 100 MVAR into the system with reverse power flow

Fig.11 shows adaptive distance protection setting factor with STATCOM absorbing inductive reactive power of 100 MVAR. Fig.12 shows characteristics of adaptive mho distance relay for above case with conventional mho relay reach.

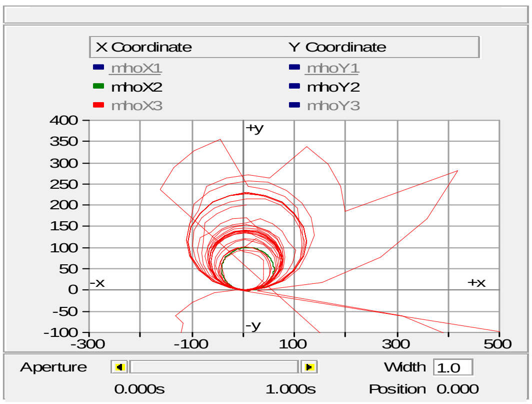

Fig. 12. Adaptive mho relay second zone characteristics with STATCOM supplying inductive reactive power of 100 MVAR into the system with reverse power flow

Fig.13 shows adaptive setting factor when STATCOM supplying capacitive reactive power of 100 MVAR into the system for reverses power flow. For above case Fig.14 shows the characteristics of adaptive mho distance relay with conventional mho relay. Similar conclusion is drawn from fig.11-14 for inductive and capacitive reactive power injection by STATCOM into the system for adaptive distance relay setting factor and adaptive distance mho relay characteristics.

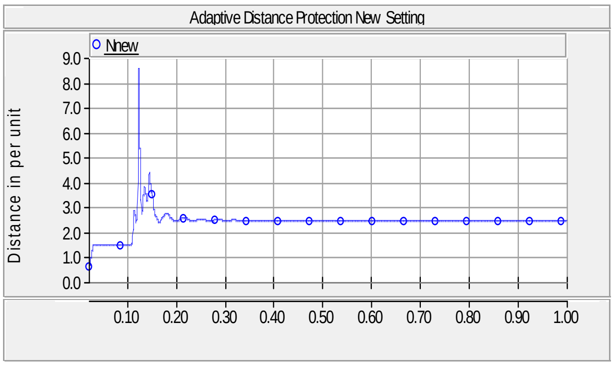

Fig. 13. Adaptive mho relay second zone setting factor ρ , with STATCOM supplying capacitive reactive power of 100 MVAR into the system with reverse power flow

It is observed that, the adaptive setting factor ρ takes very less time to get settle for inductive reactive power compensation as compare to get settle for capacitive reactive power compensation. It is due to the fact the PI controller is used which has its own settling time is constant as discussed in STATCOM modeling section.

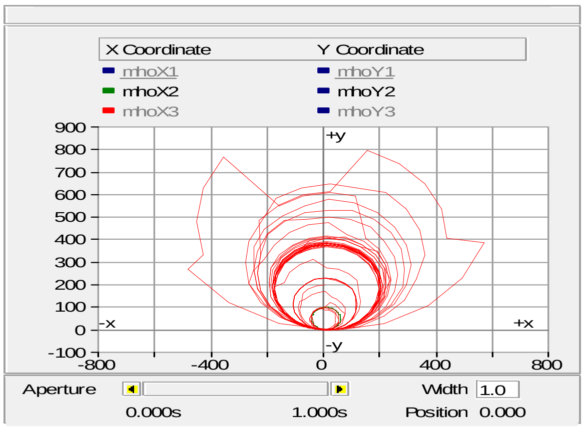

Fig. 14. Adaptive mho relay second zone characteristics with STATCOM supplying capacitive reactive power of 100 MVAR into the system with reverse power flow

Table I and II, shows the adaptive setting factors obtained by varying the value of STATCOM reactive power injection (Q_{ref}) reference in the step of 10 MVAR. The positive value shows capacitive reactive power injection and negative value shows inductive reactive power absorption.

Table I: Adaptive distance relay setting for three zones, forward power

Reactive power reference Value in MVAR	Adaptive setting factor ρ per unit distance		
	Forward Power		
	First Zone	Second Zone	Third Zone
100	0.8979	1.8263	2.8211
90	0.8875	1.7919	2.7608
80	0.8773	1.7578	2.7012
70	0.8670	1.7236	2.6414
60	0.8570	1.6900	2.5826
50	0.8471	1.6570	2.5248
40	0.8373	1.6243	2.4676
30	0.8277	1.5923	2.4116
20	0.8181	1.5604	2.3557
10	0.8086	1.5288	2.3004
0	0.7996	1.4987	2.2477
-10	0.7907	1.4691	2.1959
-20	0.7819	1.4399	2.1449
-30	0.7734	1.4116	2.0953
-40	0.7652	1.3840	2.0470
-50	0.7571	1.3572	2.0001
-60	0.7493	1.3312	1.9546
-70	0.7418	1.3060	1.9105
-80	0.7344	1.2815	1.8677
-90	0.7274	1.2580	1.8266
-100	0.7206	1.2353	1.7868

When STATCOM is present into the system neither injecting nor absorbing any reactive power the setting factor observed is 0.7996, 1.4987 and 2.2477 for forward first, second and third zones respectively, similarly 0.7989, 1.4966 and 2.2441 for reverse first, second and third zones respectively. This is because of reactance of coupling transformer comes into feature which is 0.1 per unit. For forward power flow, adaptive setting factor is 0.8979, 1.8263 and 2.8211 per unit distance for three zones compensation level of 100 MVAR capacitive, and for 100MVAR inductive compensation, adaptive setting factor is 0.7206, 1.2353 and 1.7868 per unit distance for three zones. For reverse power flow, adaptive setting factor is 1.0902, 2.4676 and 3.9430 for three zones compensation level of 100 MVAR capacitive, and for 100 MVAR inductive compensation, setting factor is 0.6268, 0.9229 and 1.2402 for three zones respectively.

Table II: Adaptive distance relay setting for three zones, reverse power

Reactive power reference Value in MVAR	Adaptive setting factor ρ per unit distance		
	Reverse Power		
	First Zone	Second Zone	Third Zone
100	1.0902	2.4676	3.9430
90	1.0573	2.3578	3.7511
80	1.0250	2.2501	3.5628
70	0.9930	2.1436	3.3763
60	0.9621	2.0404	3.1958
50	0.9323	1.9412	3.0222
40	0.9034	1.8448	2.8535
30	0.8758	1.7528	2.6924
20	0.8488	1.6629	2.5350
10	0.8228	1.5763	2.3835
0	0.7989	1.4966	2.2441
-10	0.7761	1.4205	2.1109
-20	0.7544	1.3481	1.9843
-30	0.7340	1.2803	1.8655
-40	0.7150	1.2169	1.7546
-50	0.6973	1.1579	1.6514
-60	0.6809	1.1030	1.5552
-70	0.6656	1.0522	1.4664
-80	0.6515	1.0053	1.3842
-90	0.6386	0.9622	1.3089
-100	0.6268	0.9229	1.2402

Results obtained from simulation show some important aspects noted are -Adaptive setting factor for 100 MVAR inductive reactive power absorption in forward power flow is 0.7671 per unit distance while is more than the setting factor in reverse power flow which is 0.7071 per unit distance. For 100 MVAR capacitive reactive power injections setting factor in forward power flow is 0.8425 per unit distance which is lesser than the reverse power flow 0.8575 per unit distance.

7. Conclusion

The major contribution of this research is the measured impedance at the relaying point in presence of STATCOM on a transmission line and representation of the relay characteristic impedance in presence of the STATCOM for L-G and L-L fault. An adaptive distance protection setting scheme is presented using the information of shunt injected current by STATCOM at mid-point of line. The adaptive distance protection three zone setting procedure gives absolutely necessary data to modify the zone reach of mho distance relay for different level of compensation. At lower level of compensation, adaptive distance protection setting factor is found to be lesser. At larger level of compensation adaptive distance protection setting factor is increased.

Comparing the adaptive scheme with the conventional technique, it is observed that, there is significant increase in the covered region by distance relay and the mal-operation of the distance relay with STATCOM has been overcome. The results show that, with the proposed setting the distance relay zones is adaptively increased and gives relay trip decision very accurately. The proposed scheme is new and simple to implement with the knowledge of transmission system and operating modes of STATCOM.

Appendix A

Study System Data of fig.1.

<table>
<tr><td>Elements of Study System</td><td>Parametric quantity</td></tr>
<tr><td>Equivalent Source (1-2)</td><td>System Voltage = 230 KV
System Frequency = 60Hz
$Z_1 = 25.9\angle 80°\ \Omega$
$Z_0 = 25.9\angle 80°\ \Omega$</td></tr>
<tr><td>Interfacing Transformer = 3 winding (Y/y/d)</td><td>Transformer ratio =230/11/11KV
Transformer rating = 200 MVA
Transformer Impedance = 0.1 p.u.</td></tr>
<tr><td>STATCOM rating</td><td>+/- 100 (capacitive & inductive)</td></tr>
<tr><td>Transmission Line</td><td>Line length = 300 Km
$Z_1 = 0.51\angle 85.92°\ \Omega/Km$
$Z_0 = 1.385\angle 74.68°\ \Omega/Km$</td></tr>
<tr><td>Fig A.1 shows the physical structure of the Bergeron model transmission line. By utilizing of transmission line in PSCAD/EMTDC with proper tower configuration and height of conductor and ground wire as shown in the fig.A.1</td><td>

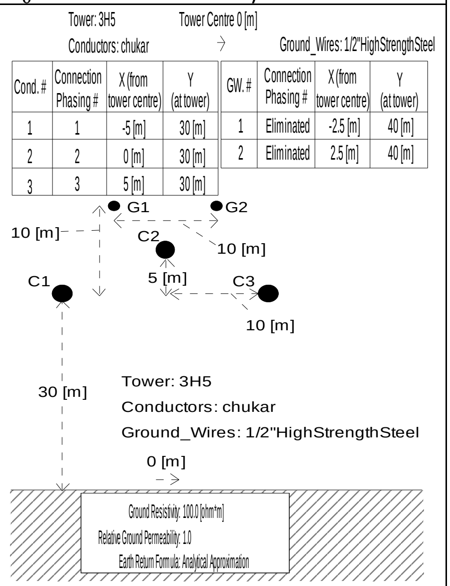

Fig.A.1.Physical Structure of Bergeron model Transmission Line</td></tr>
</table>

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