Analysis and Simulation of STATCOM based SSR controller on the First Zone operation of Digital Distance Relay with Remedy

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Abstract—**The adoption of compensation in series may cause to some problems in power system transmission lines like SSR (Subsynchronous Resonance). The damping of SSR is achieved by the injection of shunt current into the transmission line with static synchronous compensator (STATCOM) based on the information of Subsynchronous component (SSC) of current extracted from the study system. The use of STATCOM based SSR controller at centre of transmission line badly affects the operation of Distance relay. This research article addresses the prime issues that are concerns the problems of distance protection due to mid-point connected STATCOM based SSR controller in the transmission line. A novel algorithm is proposed to solve the associate problems with distance protection using the synchrophasors measurement. The power system is modelled as Bergeron model of transmission line using PSCAD software. The obtained simulation results show that the proposed adaptive setting scheme is more reliable and robust in comparison with existing distance protection schemes.**

Index Terms—**Adaptive distance relay, Current control, Distance protection, STATCOM, SSR**

I. INTRODUCTION

The adoption of series capacitor compensation in transmission line is used to enhance the capability of power transfer capability HV and EHV lines, sharing of load among parallel lines and improves the system stability. Moreover, the placing of compensation in series to the line may results to new problems like SSR and oscillations shaft. Series capacitors may produce oscillations due to SSR with any small disturbance or fault when the system natural frequency coincides with complement of torsional modes of turbine-generator shaft [1- 4].

The rapid growth in power electronics leads to the advancement of FACTs devices like SSSC, TCSC and STATCOM. With reference to recent literature, many solutions and methods have been proposed by the so-called authors to mitigate the issue of SSR with the reference to FACTS controllers [5-9]. Regardless of the solution, the major difficulty is that how quick and precise assessment of components (subsynchronous) from the study system.

The addition of FACTS devices in power system leads to new problems in the protection of transmission line. These devices are the most frequently adopted in power systems due to its fast response time, line impedance, load currents and system power angle are also changed rapidly. Therefore, it is highly recommended for a protection engineers to investigate these changes in power system. The Distance relays are the most frequently utilized for protection of power system lines because of its simple operation and capacity to work independently under adverse situations. Due to the insertion of FACTS, distance relay might not work satisfactorily and is not able to protect transmission line. The unacceptable operation of relay causes to false tripping and also reduces the reliability of system, further initiates the cascade trippings and blackouts [11, 12].

The false operation of distance relay with STATCOM is addressed in Ref [10-12]. The above cited reference completely explains the consequences of STATCOM on distance relay. Due to the existence of STATCOM at midway of line, the mho distance relay may over-reaches or under-reaches to locate the fault point in the first zone of protection [11]. The STATCOM will not be responsible in fault loop if the fault occurs prior to the mid-point and its contribution in the fault current is zero. The foremost problem arises if the fault occurs after the midpoint only. For this the STATCOM compulsory comes in the fault loop and also contributes towards fault current.

The prime idea of this research article is to mitigate the problems of SSR with STATCOM and its effect on distance protections of transmission line without losing its security. To improve the performance of distance protection, first the behaviour of distance relay is analysed through the help of sequence components with STATCOM placed at midway of transmission line. The impedance due to STATCOM compensated the calculated impedance due to fault at relay point. The error produced by the calculated compensated impedance in the measurement of actual impedance can be nullified at relay point using proposed algorithm with the support of synchronized measurement.

This research article is framed as follows: Section II introduced the study system model i.e., Study system model with STATCOM based SSR controller. In Section III, the subsynchronous component controller is given for assessing the subsynchronous component of current and voltage. Section IV gives the mathematical analysis of distance protection scheme with STATCOM based SSR controller at centre of transmission line. Moreover Section V explains the complete idea of synchronized measurement based adaptive mho relay setting. In section VI, simulation results of SSR mitigation and transmission line distance protection scheme with adaptive mho relay setting in presence of STATCOM are described. Section VII concludes the paper.

II. STUDY SYSTEM WITH STATCOM BASED SSR CONTROLLER

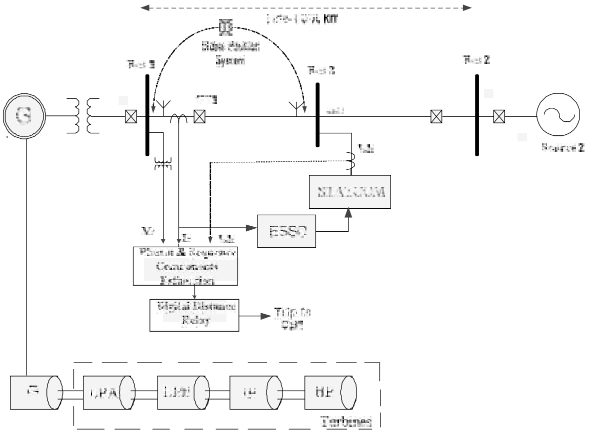

Figure 1. Study system model with STATCOM.

The study system model for this research work consists of two generators connected through single transmission line with different types of faults, location of fault and for different loading conditions [12]. Figure 1 shows the one line diagram of system under consideration and is modelled in PSCAD as a Bergeron model using the transmission line structural data. Appendix A determines the tower configuration of transmission line, parameters of conductor and source data. Figure1 illustrates the location of relay which is at bus A. The STATCOM is placed at midway of the transmission line-1to mitigate the SSR. An assumption is made that a GPS based synchronized measurement is existing on STATCOM bus and relaying bus. The data transmission is obtained with the help of an optical fiber. Therefore, the compensated current data of instantaneous time stamped is accessible at relaying bus with no delay. The generated voltage and grid current are denoted by v_s and i respectively. The injected current by STATCOM is denoted by I_{sh} [7, 8].

III. SUB-SYNCHRONOUS COMPONENT CONTROLLER

The analytical procedure for seperating the components (voltage and current) of subsynchronous frequency from the measured signals explained as follows:

When the rotor of generator oscillates around its rated speed, the terminal voltage in synchronous *dq* rotating reference frame is given by

$$v_s^{dq}(t) = v_{s,sub}^{(dq)}(t) + v_{s,f}^{dq}(t) + v_{s,sup}^{(dq)}(t) \quad (1)$$

The subscripts "f", "sup" and "sub" denote the fundamental, super and sub-synchronous frequency components of voltage. For frequencies above the fundamental, the network offers a little positive damping, and hence the component of this frequency is not considered in the proposed work. If the rotor of generator oscillates with angular frequencyω_m the base frequency is denoted byω_0. The dq$_m$represents another set of co-ordinate systems which rotates with synchronous voltage vector, equation (1) can be written as

$$v_s^{dq}(t) = v_{s,f}^{dq}(t) + v_{s,sub}^{(dq_m)}(t)e^{-j\omega_m t} \quad (2)$$

The rearrangement of equation (2) results the extraction of sub-synchronous component of voltage, so that $v_{s,f}^{dq}$ and $v_{s,sub}^{(dq_m)}$components are decoupled and are given to a low-pass filter, the expression of subsynchronous component (ESSC) controller is given as

$$v_{s,f}^{dq}(t) = H_f(p)[v_s^{dq}(t) - v_{s,sub}^{(dq_m)}(t)e^{-j(\omega_m t)}] \quad (3)$$

$$i_f^{dq}(t) = H_f(p)[i^{dq}(t) - i_{sub}^{(dq_m)}(t)e^{-j(\omega_m t)}] \quad (4)$$

$$v_{s,sub}^{dq_m}(t) = H_{sub}(p)[v_s^{dq}(t)e^{j(\omega_m t)} - v_{s,f}^{dq}(t)e^{j(\omega_m t)}] \quad (5)$$

$$i_{sub}^{dq_m}(t) = H_{sub}(p)[i^{dq}(t)e^{j(\omega_m t)} - i_f^{dq}(t)e^{j(\omega_m t)}] \quad (6)$$

WhereH$_{sub}$(p)and H$_f$(p) represents the low pass filter (LPF) transfer function for subsynchronous and fundamental component, respectively. By writing the equation (3) in synchronous dq-frame as

$$v_{s,sub}^{dq}(t) = H_{sub}(p + j\omega_m)[v_s^{dq}(t) - v_{s,f}^{dq}(t)] \quad (7)$$

In same way the current can be written as

$$i_{s,sub}^{dq}(t) = H_{sub}(p + j\omega_m)[i_s^{dq}(t) - i_{s,f}^{dq}(t)] \quad (8)$$

Solving equation (3) and (7) results the fundamental and the subsynchronous components of voltage. Similarly, by solving equations (4) and (8) results the subsynchronous and the fundamental components from the measured current.

To assure the subsynchronous current component to zero, the subsynchronous voltage component of bus is injected by SSSC in the proposed control strategy. The Laplace domain of SSCC (sub-synchronous component controller) can be written as

$$V_{SSSC_{sub}}^{(dq_m)*}(s) = v_{s,sub}^{dq_m}(s) + (R + j(\omega_0 - \omega_m)(L_T + L''))i_{sub}^{(dq_m)}(s) + (K_p + \frac{K_i}{s})[i_{sub}^{(dq_m)}(s) - i_{sub}^{(dq_m)*}(s)] \quad (9)$$

$$I_{STAT_{sub}}^{(dq_m)*}(s) = i_{sub}^{dq_m}(s) + \frac{v_{s,sub}^{(dq_m)}(s)}{(R + j(\omega_0 - \omega_m)(L_T + L''))} + [(v_{s,sub}^{(dq_m)}(s) - v_{s,sub}^{(dq_m)*}(s)) \Big/ (K_p + \frac{K_i}{s})] \quad (10)$$

Figure2 illustrates the block diagram of SSCC. First three-phase currents and voltages which are measured from the line are converted in to αβ plane and then to dq-cordinate system with the help of θ_f(angle of transformation) obtained from PLL (phase locked loop). The resultant of the estimation block is the fundamental and

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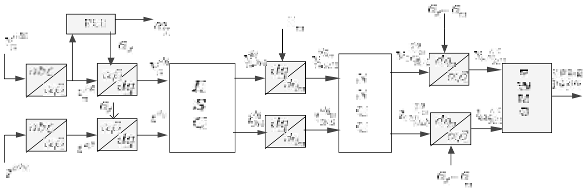

Figure2. Complete control diagram of SSCC

subsynchronous component of current and voltage in dq-frame of reference. The component of subsynchronous quantity is further transformed into dq$_m$-frame of systems using θ_m (transform angle), obtained by integrating oscillating frequencyω_m. The resultant quantities are then given to the SSCC. The output quantities of SSCC are again transformed into αβ-plane in and then to abc in natural reference frame and further given to the PWM pulse generator for switching the three phase 48 pulse voltage source converter.

IV.REALIZATION OF APPARENT IMPEDANCE WITH MID-POINT STATCOM BASED SSR CONTROLLER

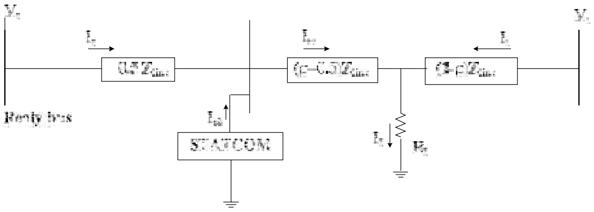

Figure 3. Simplified circuit of study with STATCOM during fault.

The apparent impedance expression is realized with STATCOM based SSR controller at centre of transmission line is realized, which is the basic step for calculating the adaptive distance relay setting. The digital distance relay is placed at bus A usually extracts the current and voltage samples and further the current and voltage in symmetrical components are utilized for calculating the apparent impedance. Generally Fast Fourier Transform (FFT) is used to calculate phasors (fundamental only) from voltage and current samples [15]. Fig.3 shows the simplified circuit of study system for line-1.

A. Apparent Impedance seen for Line to Ground Fault

With mid-point STATCOM and fault occur after the STATCOM in the line, the sequence voltage at relaying bus is expressed as follows:

$$V_{s1} = I_{m1}(\rho - 0.5)Z_{line1} + 0.5I_{s1}Z_{line1} + R_f I_{f1} \quad (11)$$

$$V_{s2} = I_{m2}(\rho - 0.5)Z_{line2} + 0.5I_{s2}Z_{line1} + R_f I_{f2} \quad (12)$$

$$[\text{Since } Z_{line2} = Z_{line1}]$$

$$V_{s0} = 0.5I_{s0}Z_{line0} + I_{m1}(\rho - 0.5)Z_{line0} + R_f I_{f0} \quad (13)$$

$$I_{m1} = I_{sh1} + I_{s1} \quad (14)$$

$$I_{m2} = I_{sh2} + I_{s2} \quad (15)$$

$$I_{m0} = I_{sh0} + I_{s0} \quad (16)$$

Where suffix,1, 0 and 2 represents positive, zero and negative sequence components. ρ is per unit distance of fault from relying bus.

V_{sa} can be obtained from sequence components as:

$$V_{sa} = V_{s1} + V_{s2} + V_{s0} \quad (17)$$

Substituting equation (11) to (16) in equation (17)

$$V_{sa} = \rho I_{sh1}Z_{line1} + \rho I_{s1}Z_{line1} - 0.5Z_{line1}I_{sh1} + R_f I_{f1}$$
$$\rho I_{s2}Z_{line1} + \rho I_{sh2}Z_{line1} - 0.5Z_{line1}I_{sh2} + R_f I_{f2}$$
$$\rho I_{s0}Z_{line1} + \rho I_{sh0}Z_{line1} - 0.5Z_{line1}I_{sh0} + R_f I_{f0} \quad (18)$$

Equation (18), represents the phase-a voltage at relying bus. Normalization of this equation will give the voltage (V_{sa}) in terms of line current (I_{fa}). For that, add and subtract ($\rho\, I_{s0}Z_{line1}$), ($\rho\, I_{sh0}Z_{line1}$), ($0.5\, I_{s0}Z_{line1}$) in equation (18) and after solving,

$$V_{sa} = \rho I_{sa}Z_{line1} + [(\rho - 0.5)(Z_{line0} - Z_{line1})(I_{sha} + I_{sho}) + \rho I_{s0}(Z_{line0} - Z_{line1})] + R_f I_{fa} \quad (19)$$

Considering R_f=0, the last term of equation (19) can be removed and zero sequence current of the STATCOM (I_{sh0}) as shown in (19) can be removed.

$$V_{sa} = \rho I_{sa}Z_{line1} + [(\rho - 0.5)(Z_{line0} - Z_{line1})I_{sha} + \rho I_{s0}(Z_{line0} - Z_{line1}) \quad (20)$$

$$Z_{app} = \frac{V_{sa}}{I_{sa} + mI_{s0}} \quad (21)$$

where, compensation factor i.e. $m = \frac{Z_{line0} - Z_{line1}}{Z_{line1}}$

Substituting the value of V_{sa} in (21) and after simplification we get,

$$Z_{app} = \rho Z_{line1} + \frac{(\rho - 0.5)I_{sha}Z_{line1}}{I_{sa} + mI_{s0}} \quad (22)$$

From equation (22), it is seen that in absence of STATCOM on the line (I_{sha}=0), calculated apparent impedance by the distance relay is only the function of Z_{line1} and the per unit distance (ρ) of fault point from relaying bus.

B. Apparent Impedance seen for LLL fault

the apparent impedance seen by the distance relay for LLL fault with R_f =0 can also be calculated in the same way

$$Z_{app} = \rho Z_{line1} + \frac{(\rho - 0.5)I_{sh}Z_{line1}}{I_s} \quad (23)$$

V.ADAPTIVE DIGITAL DISTANCE PROTECTION WITH MID-POINT STATCOM

Adaptive Protection scheme allows adjustments to various functionalities of protection in order to make them more recognizable to existing power system conditions [16-18]. To take prompt decision of trip or no trip for fault in the first zone of protection, compare obtained apparent impedance with distance relay first zone setting (Z_{set}) of relay. By considering the apparent impedance calculated in (22) to be equal to distance relay setting (80% of line)

$$Z_{app} = Z_{set} = 0.8Z_{line1} \tag{24}$$

Comparing equation (22) and (24), we get

$$0.8Z_{line1} = \rho Z_{line1} + \frac{(\rho - 0.5)I_{sh}Z_{line1}}{I_s + mI_{s0}} \tag{25}$$

$$0.8 = \rho + (\rho - 0.5)\frac{I_{sh}}{I_s + mI_{s0}} \tag{26}$$

Let ρ = (μ + 0.5), substituting in (26)

$$0.8 = (\mu + 0.5) + \mu\frac{I_{sh}}{I_s + mI_{s0}} \tag{27}$$

$$\mu\left(1 + \frac{I_{sh}}{I_s + mI_{s0}}\right) = 0.3 \tag{28}$$

$$\mu = \frac{0.3}{\left(1 + \frac{I_{sh}}{I_s + mI_{s0}}\right)} \tag{29}$$

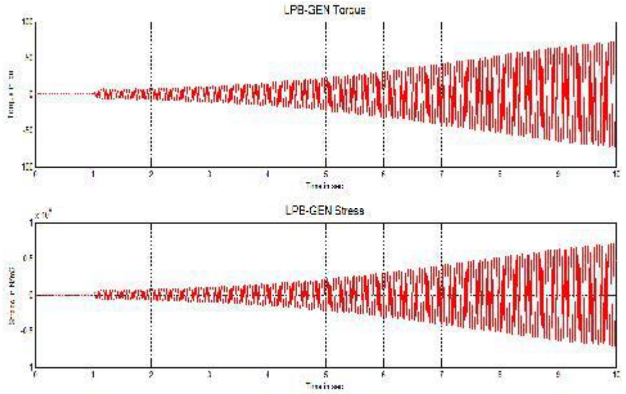

Figure 5. Simulated Turbine-Generator shaft Torque, Stress between LPB-GEN of Study system model without SSC based STATCOM.

Putting μ = (μ + 0.5) in (29) we get,

$$\rho = 0.5 + \frac{0.3}{\left(1 + \frac{I_{sh}}{I_s + mI_{s0}}\right)} \tag{30}$$

Hence to get the new setting, multiply equation (30) with Z_{line1}.

$$Z_{setnew} = \rho\, Z_{line1} \tag{31}$$

Multiplying equation (30) with (Z_{line1}) and substituting in (31), we get

$$Z_{setnew} = \left(0.5 + \frac{0.3}{\left(1 + \frac{I_{sh}}{I_s + mI_{s0}}\right)}\right)Z_{line1} \tag{32}$$

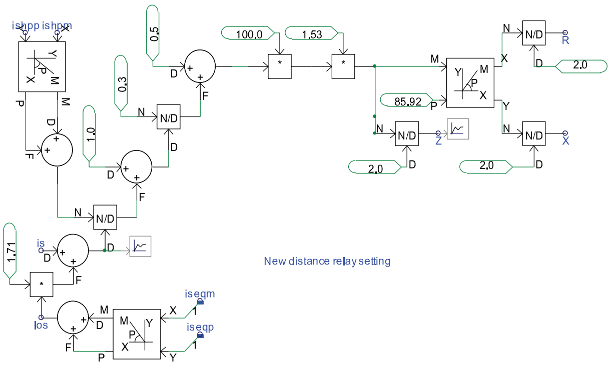

Figure 4. Simplified circuit of study system with STATCOM during fault.

From mentioning above equation, some important information is remarked as:

(i) If the injected current of STATCOM is capacitive, that is I_{sh} is positive and there is an increase in adaptive zone where as for inductive (I_{sh}) is negative and there is decrease in adaptive zone.

(ii) Depending on the compensation level the proposed adaptive distance protection setting will automatically adjusts the first zone reach.

(iii) With the nature of injected voltage the adaptive distance protection primary zone setting formula adjusted adaptively.

(iv) Injected current of STATCOM will also affect the calculation of apparent impedance with fault after STATCOM.

The location of STSATCOM also affects the calculation of apparent impedance. Modelling of Adaptive distance protection is shown in Figure 4.

VI. SIMULATION RESULTS AND DISCUSSIONS

To test the efficiency of the suggested controller to diminish SSR, the study system model with SATCOM is simulated in Mat lab-Simulink environment. With 55% compensation, a symmetrical (LLL) fault is initiated at 1sec for duration of 0.05 sec to the grid. Due to the SSR, the oscillations are increased between the various sections of the turbine-generator shaft after the clearance of fault. Figure 5 illustrates LPB - Generator torque and stress. Even though the fault is clear the mechanical stress and torque of LPB-Generator are amplifies with a faster rate because of SSR which is avoidable.

The STATCOM injects the shunt current into the line in accordance with the triggering pulse produced by the PWM generator. The control of firing angle for STATCOM is designed based on the knowledge of Subsynchronous component controller. Figure6 illustrates the SSR mitigation with shunt injected current supplied by STATCOM. The magnitude of current injected in to the line with STATCOM is shown in Figure 7.

To investigate the effectiveness of the suggested adaptive distance protection scheme with STATCOM shown in Figure 1 is simulated in PSCAD software. If the STATCOM takes reactive power (inductive), the mid-point voltage decreases as compared to nominal operating voltage in absence of STATCOM. This leads to relay bus voltage to reduce and further there is a decrease in seen impedance (apparent) by distance relay causes to over-reach. The ρ (setting factor) for adaptive distance relay with STATCOM taking reactive power of 100 MVAR (inductive) for forward power flow is shown in Figure 8.

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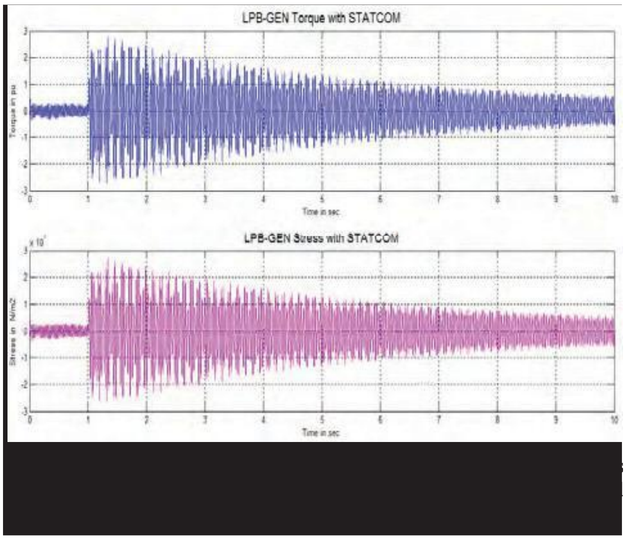

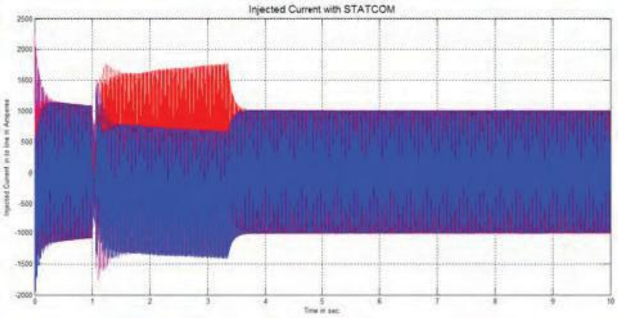

Figure 7. Injected Current in to the line to mitigate SSR oscillations with SSC based STATCOM

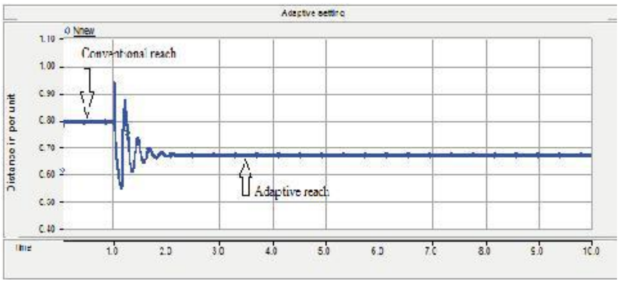

Figure 8. Adaptive Distance Protection Setting factor ρ with reactive power of 100 MVAR (inductive) of STATCOM.

If the STATCOM enters into the system at 1.05 sec and taking reactive power of 100 MVAR (inductive) for this the setting factor ρ is is reduced adaptively to 0.7671 per unit distance and it takes 40 milliseconds to acquire new adaptive setting which is shown in Figure 9.

With capacitive reactive power injected by STATCOM, there is an increase in the mid-point voltage in comparison with usual operating voltage in absence of STATCOM. Further increase in voltage of relay bus also cause an increase in seen impedance (apparent) by distance relay leading to under-reach. The calculated adaptive relay setting factor for STATCOM supplying 100 MVAR (capacitive reactive power) into the system for forward power flow is shown in Figure 10. It is observed that the setting factor is 0.8 in absence of STATCOM. With the insertion of STATCOM at 1.1 seconds the setting factor is adaptively increased and settled to 0.8425 per unit in 25 milliseconds.

Figure 11 clearly shows the conventional mho relay and adaptive mho distance relay with different colours. With the injection of capacitive reactive power, there is an increase in adaptive mho relay reach as compared with conventional mho relay reach.

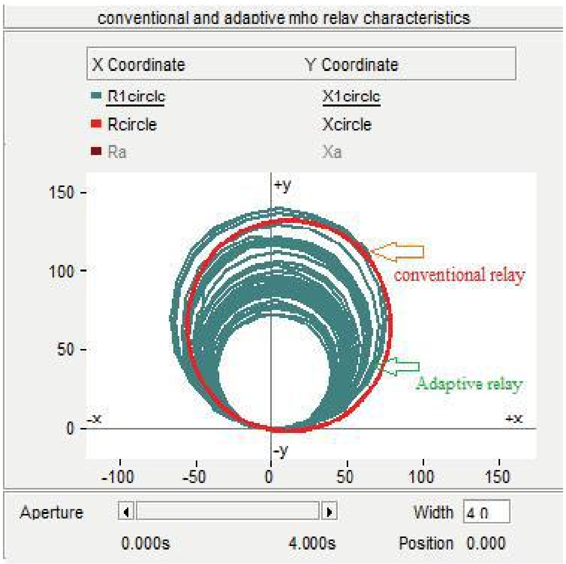

Figure 9. Characteristics of Adaptive Mho relay Distance Protection with STATCOM supplying reactive power of 100 MVAR (inductive)

The variation of adaptive setting factors obtained by varing the STATCOM reference reactive power injection (Q_{ref}) in step of 10 MVAR. The positive value represents the reactive power injection of capacitive and the negative value represents the reactive power of inductive. When STATCOM is in inactive mode the system neither injects nor absorbs any reactive power and the corresponding setting factor is 0.7998. For power flow A to B, the setting factor (adaptive) is 0.7671, 0.7998 and 0.8425 per unit distance for 100 MVAR inductive compensation level, 0 MVAR and 100MVAR capacitive respectively. Adaptive setting factor is 0.8575, 0.7998 and 0.7071 for compensation level of 100 MVAR capacitive, 0 MVAR and 100 MVAR inductive respectively for power flow B to A.

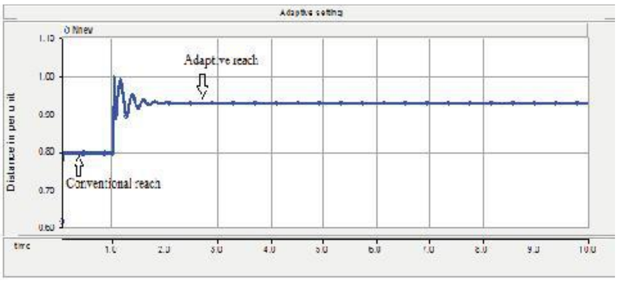

Figure 10. Adaptive Distance Protection Setting factor ρ with STATCOM supplying reactive power of 100 MVAR (capacitive).

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VII. CONCLUSIONS

In this research article a robust subsynchronous component based STATCOM controller with adaptive setting scheme is proposed to mitigate the SSR and its effect on distance protection of transmission line. By injecting the current (shunt) into the line using STATCOM, the adverse effect of SSR on turbine-generator is reduced to a great extent. In order to diminish the effect of STATCOM at midway of transmission line on distance protection an adaptive setting scheme is proposed. For various compensation levels, the reported adaptive distance protection setting algorithm (first zone) gives required data for modifying the zone reach of mho distance relay. For lower level of compensation, the Adaptive distance protection setting factor is reduced and is increased for higher level of compensation. By comparing the conventional technique with proposed adaptive scheme, there is a noteworthy enlarges in the enclosed area by distance relay and the false operation of distance relay with SSSC has been overcome. Finally, the simulation result illustrates the robustness of the suggested distance relay setting, the zone is increased adaptively and gives very accurate relay trip decision.

APPENDIX

The study system parameter of IEEE first bench mark model, SSSC parameter and Bergeron model are given in Tables I-III [1, 3, 4, 15, 16].

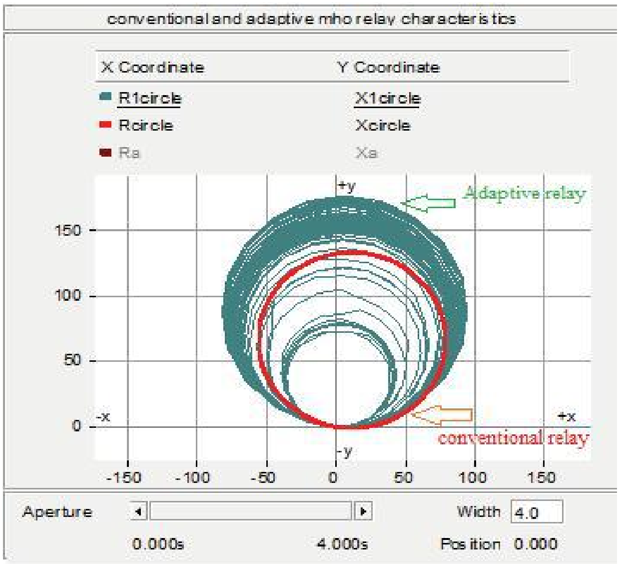


Figure 11. Characteristics of Adaptive Mho relay Distance Protection with STATCOM supplying reactive power of 100 MVAR (capacitive).

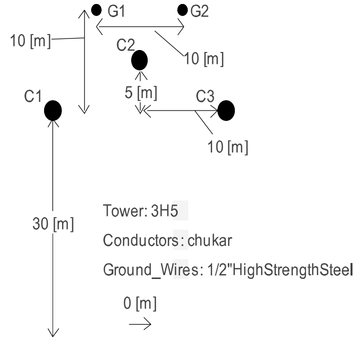
TABLE I
STUDY SYSTEM NETWORK PARAMETERS

Network resistance	R_L	0.0113 pu
Transformer reactance	X_T	0.142
Transformation ratio		22/539KV
Line reactance	X_L	0.50pu
Transmission line reactance	X_{sys}	0.08pu

TABLE II
SYNCHRONOUS MACHINE PARAMETERS

Reactance	Value [pu]	Time constant	Value [sec]
X_a	0.130	$T_{d0}^{'}$	4.3
X_d	1.79	$T_{d0}^{''}$	0.032
$X_d^{'}$	0.169	$T_{q0}^{'}$	0.85
$X_d^{''}$	0135	$T_{q0}^{''}$	0.05
X_q	1.71		
$X_q^{'}$	0.228		
$X_q^{''}$	0.200		

TABLE III
STUDY SYSTEM DATA OF FIG.1.

Study System Elements	Quantity
Equivalent Source (1-6)	Frequency of System = 60Hz Voltage of System = 230 KU $Z_1 = 25.9\angle 80°\ \Omega$ $Z_0 = 25.9\angle 80°\ \Omega$
Connecting Transformer = (Y/y/d) 3 winding	Impedance of Transformer = 0.1 p.u. Transformer ratio =230/11/11KV Rating of Transformer = 200 MVA
STATCOM rating	+/- 100 (inductive & capacitive)
Transmission Line (I-V)	Line length = 300 Km $Z_0 = 1.385\angle 74.68°\ \Omega/Km$ $Z_1 = 0.51\angle 85.92°\ \Omega/Km$
Fig A.1 shows the physical structure of the Bergeron model.	
Fig.A.1. Transmission Line in Bergeron model	

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