Effect of SSSC-based SSR controller on the performance of distance relay and adaptive approach using synchronized measurement

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ABSTRACT

The use of series compensation in transmission line with capacitors may results the new problems like torsional oscillations in shaft sections of turbine-generator due to subsynchronous resonance (SSR), when system frequency matches with any one of torsional mode frequency of shaft system during fault or disturbances occurs in the transmission line. The subsynchronous current due to SSR during fault also affects the reach of a distance protection system. The diminution of SSR is enhanced by series voltage injection in to the power transmission line with static synchronous series compensator (SSSC) from the knowledge of subsynchronous components, extracted from the system. The use of SSSC in transmission line reduces the subsynchronous oscillations but it adversely affects the distance protection system leads to imprecise assessment of fault location i.e. over or under-reach. This paper investigates the SSR mitigation in presence of SSSC and its effect on distance protection scheme. A new approach is proposed for mitigating the problems associated with distance protection by using the synchrophasor measurement. The entire study of simulation is investigated by using a 48-pulseSSSC carried out with Bergeron model of transmission line in PSCAD. The simulation results represents that the suggested adaptive scheme is truthful, reliable and secure with change in compensation level of SSSC.

Key words- Adaptive distance relay, Distance relay, Phasor measurement unit (PMU), SSR, SSSC, voltage source converter (VSC).

1. INTRODUCTION

Series capacitor compensation is most widely used from past decades in transmission lines to partially cancel out a part of reactance of line impedance to improve the ability of transmitted power, load sharing between parallel lines and enhance the stability limits of long

transmission lines [1, 2]. Nevertheless, the incorporation of series compensation in the line can produce oscillations in the shaft system with the frequency which is usually less than the system frequency i.e. subsynchronous resonance (SSR), completely damages the entire shaft system. If the complement frequency (system frequency – resonant frequency) of the system coincides with any of the mode frequency of the T-G shaft system, the oscillations are drastically excited with fault or disturbance in the series compensated transmission line [3, 4].The production of subsynchronous current due to SSR might badly affect the reach of the distance protection scheme. The increase in the level of series compensation, the effect becomes more worsen. Subharmonics of lower frequency can affect the relay reach as more as compared to higher subharmonics [5].

With the advent of power electronic devices with digital control, new development in Flexible AC transmission devices (FACTS) like TCSC- thyristor controlled series capacitor, SSSC and STATCOM-statics synchronous series compensator are achieved and the research in this area is most attractive at present days [6]. With reference to recent literature, variety of research works has been proposed by the researchers to bypass the issue of SSR using FACTS devices [7]. Regardless of solution, the major complexity is that, how fast the control strategy precisely mitigates the subsynchronous oscillations from the transmission line and further an appropriate protection system should also be designed to avoid turbine shaft damage due to SSR [8].The problem of SSR can be mitigated by series compensation which consists of passive components and SSSC. Ref [9], [10] addresses the damping of SSR using PI controller based SSSC. The injection of voltage of subsynchronous frequency component in series with current of subsynchronous component to damp out SSR is proposed in [11]. In ref. [12-14] the mitigation of SSR is achieved by using FACTS devices with fractional-order PI controller in the control circuit. However, proper control strategy with fast response and robust performance is mandatory and it should be further investigated.

The insertion of devices in power system, such as FACTS leads to new issues in the area of transmission line protection. These devices are most frequently used in power systems because of its fast response time, line impedance, load currents and system power angle are also changed rapidly. Therefore, it is highly significant for a protection engineer to consider and investigate these types of changes in power system. The distance protection relays are most frequently used because of its ease in operating principle and potential to work autonomously under adverse situations for primary protection in high voltage (HV) lines [15,

16]. Due to the existence of FACTS controllers, the distance relay scheme may not operate correctly and will not able to protect the transmission line. The inappropriate functioning of distance relay causes false tripping and diminishes the consistency and system security but can also instigate the blackouts [17-20].

The variation in distance protection is depends on the type of FACTS device which is used for particular application and its position in the power system. The effect on distance protection of transmission lines with different types of FACTS controllers have been reported in [17-21]. The STATCOM and SVC have an effect on the distance relays with regard to phase selection, measurement of impedance and time of operation, may cause over or under-reach [17-19]. The action of the voltage source converter (VSC) based STATCOM on multiline, increase the resistance to reactance ratio of line, which leads to the impedance relay under-reaching, but no counter measures were not found for zone protection [19], [20].The work made in [21] provides a fruitful contribution towards the calculation of apparent impedance of distance relay for series devices, viz., TCSC, and SSSC; though, it did not considered the procedure for computing the apparent impedance in case of transmission line consists of series and shunt FACTS controllers. Ref [22-24] addresses the associated problems of shunt/series compensation on distance protection of transmission lines with remedies. The work in [25] made useful techniques about mitigation of shunt FACTS on relay were implemented in real time digital simulator and suggested modifications to the channel aided distance protection scheme. The phasor measurement unit (PMU) provides variety of applications that uses synchrophasors measurements for functional decision-making. Several applications of these are includes security assessment, state estimation, adaptive relaying, control, etc. [26-28]. The work in [29] outline the problems associated with conventional distance protection and proposed the steady state based modified quadrilateral distance relay. But the fixed setting will not work for transient conditions and varying injection of SSSC which is one of the major concern. Similar work is reposted in work [30], but the solution is for severe fault conditions and steady state characteristics. The work presented in [31] give the solution based on digital protection technique utilizing the apparent impedance trip characteristics with SSSC in steady state analysis and the trip boundaries have been considered as new relaying scheme. But the problems associated with the distance based protection remains same and need improvement in its characteristics based on the value of SSSC injection. The active power based protection scheme is presented as a potential solution for SSSC compensated transmission line with no

suggestion or mitigation of distance based scheme which in require more emphasis to provide the solution for improvement in distance based protection scheme.

The main objective of this research paper is to mitigate the issues of subsynchronous resonance with SSSC and its effect on distance protection of transmission line without sacrificing its security. To improve the performance of distance protection without losing its security, first the behaviour of distance relay is analysed through the help of sequence components with SSSC placed at middle of transmission line. The insertion of SSSC adds corresponding impedance in the fault loop, based on the voltage injected by SSSC. The impedance due to SSSC compensates 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. Simulations are made to prove the robustness of the algorithm by comparing the proposed algorithm with the traditional algorithms.

The organization of this research article is given as: Section 2 introduces the study system model with subsynchronous component based SSSC. The estimation of subsynchronous component of current and voltage which is useful to know the value of series injected voltage in to the line using SSSC by means of subsynchronous component controller is presented in Section 3. Section 4 describes the mathematical analysis of distance protection scheme with SSSC placed at middle of transmission line to mitigate SSR and this analysis is useful to resolve the errors present in distance protection with SSSC. Moreover, the section 5 explains the complete idea of synchronized measurement based adaptive mho relay setting. In section 6, simulation results of SSR mitigation and transmission line distance protection scheme with adaptive mho relay setting in presence of SSSC are described. Finally the conclusion of proposed research work is given in section 7.

2. SYSTEMMODEL WITH SSR (SSSC) CONTROLLER

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 [18, 19]. 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

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bus A. Subsynchronous component based SSSC is connected at middle of the transmission line-1to mitigate SSR. An assumption is made that a GPS based synchronized measurement is existing on SSSC 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 [26-28].

The voltage of generator and grid current is denoted by v_s and i and series voltage injected by SSSC is V_{se}. The mitigation of SSR with classical control is that, the generated voltage of fundamental frequency component by the fixed capacitor bank is to be neutralized by generating complementary component of voltage using series converter [9-13].
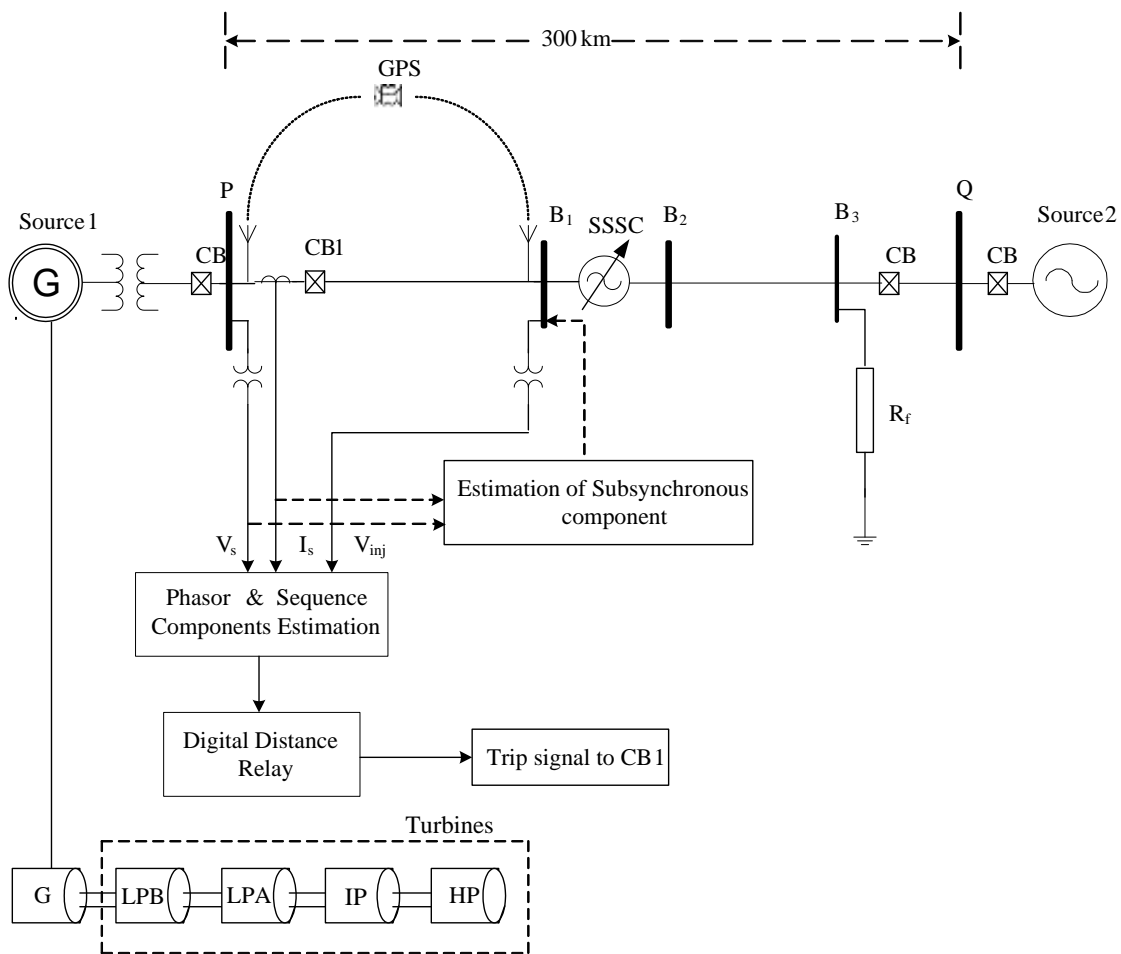
Figure 1.One-line diagram of study system including SSSC [24]

With the injection of series voltage by SSSC into the line, capacitive reactance offered by capacitor bank is nullified and also shifts the system electrical resonance, thus avoids the problem of SSR. The analytical procedure of extracting the components (voltage and current) of subsynchronous frequency from the measured signals explained as follows.

3. SUB-SYNCHRONOUS COMPONENT CONTROLLER

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

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

The subscripts "f", "sup" and "sub" denote the fundamental, super-synchronous and sub-synchronous frequency components of grid 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 frequency ω_m the base frequency is denoted by ω_0. The dq_m represents another set of co-ordinate systems which synchronously rotates with synchronous voltage vector, equation (1) can be written as

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

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 then a low-pass filter is applying on the resulting expression [2], the assessment of subsynchronous component (ESSC) controller is expressed as

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

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

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

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

Where $H_{sub}(p)$ 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

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

In same way the current can be written as

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

By solving equation (3) and (7), we can obtain the subsynchronous and the fundamental components from the measured voltage. Similarly, by solving equations (4) and (8) we can obtain the subsynchronous and the fundamental components from the measured current.

To assure the subsynchronous current component to be 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

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

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

whereR is the resistance,$L_T$is the leakage inductance and L" is thesubtransient inductance of system, transformer and generator. The current and voltage reference are $i_{sub}^{(dq_m)*}$, $v_{s,sub}^{(dq_m)*}$ while $K_p$and $K_i$is the is the proportional and integral gain of the PI-controller.
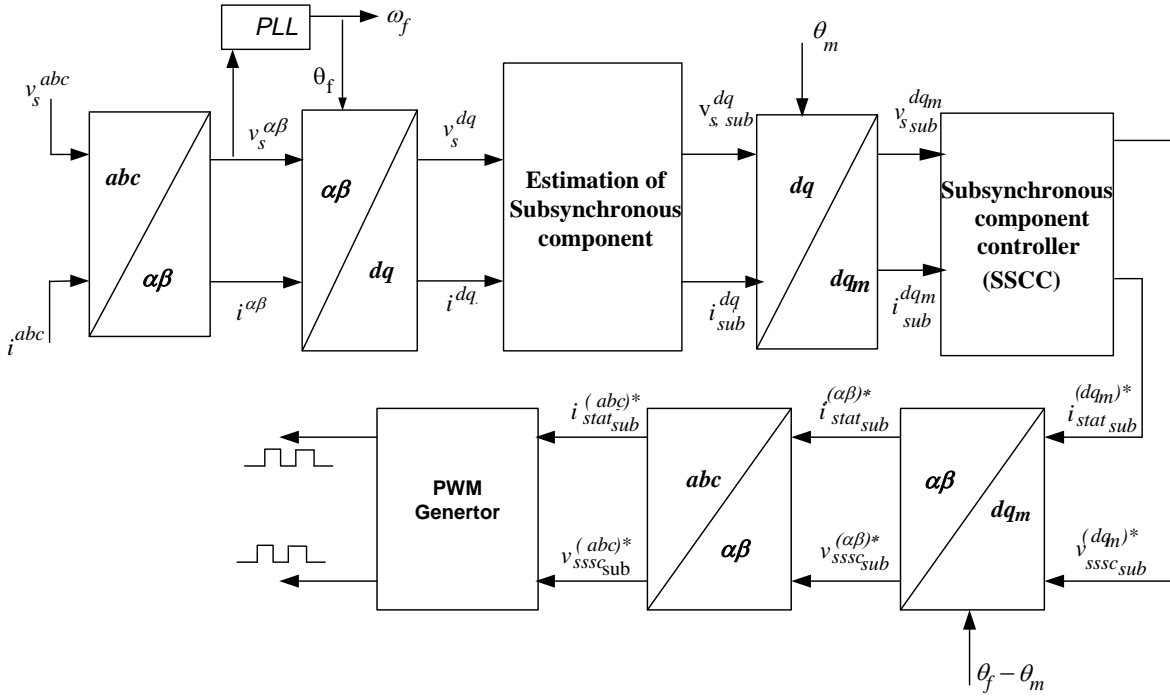

Figure 2. Complete block diagram of subsynchronous component controller

Figure2 illustrates the block diagram of the subsynchronous component controller. First the three-phase voltages and currents which are measured from the line are converted in to αβ plane and then to dq-cordinate system with the help of θf(angle of transformation) obtained from PLL (phase locked loop). The resultant of the estimation block is the subsynchronous and the fundamental component of current and voltage which are in the dq-frame of reference. The component of subsynchronous quantity is further transformed in to subsynchronousdq$_m$-frame of systems using θ$_m$ (transform angle), obtained by integrating oscillating frequencyω$_m$. The resultant quantities are then sent to the SSCC (subsynchronous

component controller). The output quantities of SSCC are again transformed into αβ-plane in stationary reference frame and then transformed into abc in natural reference frame and further given to the PWM pulse generator for switching the three phase 48 pulse voltage source converter [29].

4. APPARENT IMPEDANCE CALCULATION WITH MID-POINT SSSC

Figure 3 shows the dual fed transmission line in presence of SSSC at middle of the line and is subjected to line to ground (L-G) fault. When this fault occurs on the right hand side of SSSC at a distance ρ from the relay point, the sequence network (both positive and negative are same) of the study system during the fault is shown in Figure3.
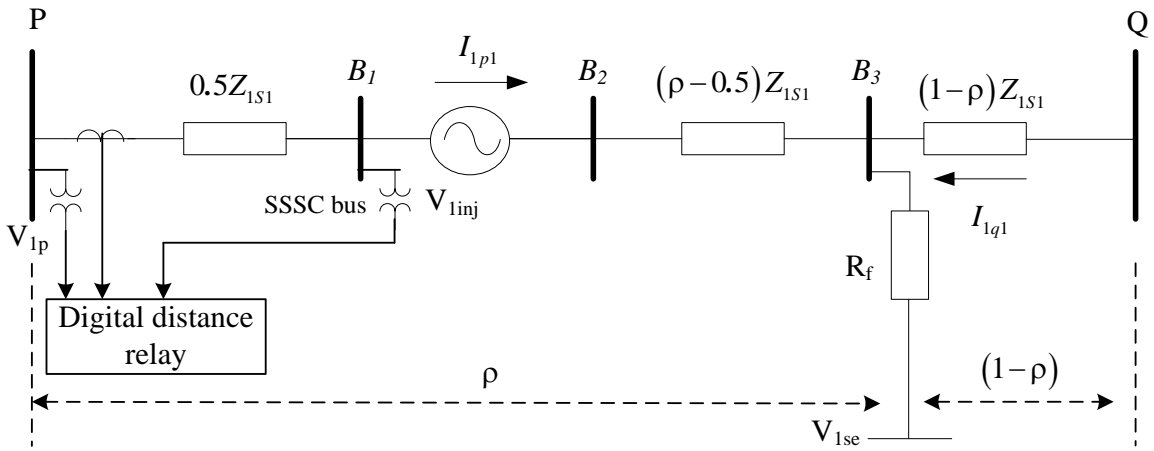
Figure 3. Simplified circuit diagram of study system in presence of SSSC during fault

This section gives the procedure for deriving the apparent impedance expression with SSSC at middle of transmission line. For making the distance relay setting to adaptive and accurate, place the distance relay (digital) at bus P uses the samples of current and voltage obtained with the help of instrument transformers. The apparent impedance is calculated with the use of symmetrical components of current and voltage. The pre-process of current and voltage samples are required to compute phasors of fundamental with FFT), has the capability to filter the decaying components of dc, inter-harmonic components and harmonics of other present in the signal [26-28].

By applying Kirchhoff's law to the Figure 3, the sequence voltage at the relay location P, for L-G fault after SSSC can be written as

$$V_{1p} = \rho Z_{1s1} I_{1p1} + V_{1inj} + \frac{R_f}{(1-\rho)}\left(I_{1p1} - Z_{1s1} + \frac{V_{1inj}}{Z_{1s1}}\right) \tag{11}$$

For negative sequence and zero sequence voltages are derived in the similar way;

$$V_{2p} = \rho Z_{1s1} I_{2p1} + V_{2inj} + \frac{R_f}{(1-\rho)}\left(I_{2p1} - Z_{2s1} + \frac{V_{2inj}}{Z_{1s1}}\right) \tag{12}$$

$$V_{0p} = \rho(Z_{0s1} I_{0p1}) + V_{0inj} + \frac{R_f}{(1-\rho)}\left(I_{0p1} - Z_{0s1} + \frac{V_{0inj}}{(1-\rho)(Z_{0s1}-Z_{0m})}\right) \tag{13}$$

The derivation of voltage at the relay bus is written as:

$$V_p = \rho Z_{1s1} I_{1p1} + \rho(Z_{0s1} - Z_{1s1})I_{0p1} + V_{inj} + \frac{R_f}{(1-\rho)}\left(I_{p1} - Z_{1s1} + \frac{V_{inj}}{Z_{1s1}} + V_{0inj}\left(\frac{1}{Z_{1s1}}\right)\right) \tag{14}$$

where:

$$V_{0p} + V_{1p} + V_{2p} = V_p$$

$$I_{0p1} + I_{1p1} + I_{2p1} = I_{p1}$$

$$V_{0inj} + V_{1inj} + V_{2inj} = V_{inj} \tag{15}$$

Where, V_P, I_{P1} are the phase voltage and current at relay location at bus P respectively,

V_{0P}, V_{1P}, V_{2P} and I_{0P1}, I_{1P1}, I_{2P1} are sequence phase voltages and current respectively.

I_{0q1}, I_{1q1}, I_{2q1} are sequence phase currents at bus Q.

V_{0se}, V_{1se}, V_{2se} are sequence phase voltages at fault location E; R_f is the fault resistance.

Z_{0s1}, Z_{1s1}, Z_{2s1} are sequence impedances of the transmission line and $Z_{1s1} = Z_{2s1}$.

$Z_0 S_1$, $Z_1 S_1$, $Z_2 S_1$, $Z_0 S_2$, $Z_1 S_2$, $Z_2 S_2$ are sequence impedance of source 1 and source 2 respectively. ρ is fault per unit distance from relay location.

The apparent impedance of distance relay without SSSC, for SLG fault, can be computed by using bellow equation:

$$Z = \frac{V_p}{I_{p1} + m I_{0p1}} = \frac{V_p}{I_{p1} + \left(\frac{Z_{0s1}-Z_{1s1}}{Z_{1s1}}\right)I_{0p1}} = \frac{V_p}{I_{Relay}} \tag{16}$$

where, m is compensation factor and is given by $\quad m = \frac{Z_{0s1} - Z_{1s1}}{Z_{1s1}}$

The seen apparent impedance of conventional distance relay with SSSC is written as

$$Z_{app} = \rho Z_{1s1} + \frac{R_f}{(1-\rho)I_{Relay}}\left(I_{p1} - Z_{1s1}\right) + \Delta Z \tag{17}$$

When there is no SSSC, ΔZ in (20) is zero and the apparent impedance is to be same as uncompensated lines, so ΔZ depends on the SSSC and equals;

$$\Delta Z = \frac{V_{inj}}{I_{Relay}} + \frac{R_f}{(1-\rho)I_{Relay}}\left(\frac{V_{inj}}{Z_{1s1}} + V_{0inj}\left(\frac{1}{Z_{1s1}}\right)\right) \tag{18}$$

It is clear in equation (18) that, the existence of SSSC in fault loop affects the computed impedance by relay, with a fault distance of 0.5 p.u from relay or in the absence of SSSC, the effect of it in impedance $Z = Z_{app}$ is only by R_f.

For a line to line (L-L) fault, the calculation of distance relay apparent impedance can be given by:

$$V_{1se} = \alpha V_{2se} \tag{19}$$

$$\text{Where:}\alpha = -0.5 + j0.886 \tag{20}$$

From equation (13), (14) and (23) we have obtained final equation of line to line fault with mid-point SSSC given by

$$Z_{app} = \rho Z_{1s1} + \frac{R_f}{(1-\rho)I_{Relay}}\left(I_{p1} - \alpha I_{2p1} - k_1\right) + \Delta Z \tag{21}$$

$$\Delta Z = \frac{V_{inj} - \alpha V_{2inj}}{I_{Relay}} + \frac{R_f}{(1-\rho)I_{Relay}}\left(\frac{V_{1inj} - \alpha V_{2inj}}{Z_{1s1}}\right) \tag{22}$$

In above equation R_f is the fault resistance between two phases. According to equation (21) for $R_f = 0$, SSSC is due to the positive and negative sequence voltage differences.

5. ADAPTIVE DISTANCE PROTECTION SCHEME WITH SSSC

The prime objective of the proposed research work is to design an adaptive algorithm for distance protection in presence of SSSC to mitigate SSR at mid-point of transmission line. The research objective is achieved by making necessary modifications in the calculation of apparent impedance formula, which is in equation (17). Equation (17) compares with relay setting (Z_{set}) of first zone to take the exact decision of no trip or trip during fault in the protected zone. The expression for a new distance relay setting is obtained with the data of series injected voltage (V_{inj}) at relaying bus P. Therefore, equate the calculated apparent impedance give in equation (17) to distance relay setting of which is 80% of line to be protected.

$$Z_{app} = Z_{set} = 0.8Z_{line1} = 0.8Z_{1s1} \tag{23}$$

Comparing equation (20) and (26), we get

$$0.8Z_{1s1} = \rho Z_{1s1} + \frac{R_f}{(1-\rho)I_{Relay}}\left(I_{p1} - Z_{1s1}\right) + \Delta Z \tag{24}$$

Considering R_f=0, the right half term of equation (24) can be eliminated by making changes equation (25) and is expressed as

$$0.8Z_{1s1} = \rho Z_{1s1} + \frac{V_{inj}}{I_{Relay}} \tag{25}$$

per unit distance (ρ) can be rewritten as in equation

$$\rho_1 = 0.8Z_{1S1} - \left(\frac{V_{inj}}{I_{Relay}Z_{1s1}}\right) \tag{26}$$

where, ρ is becomesρ_1 and noted as adaptive setting factor. After checking the calculated apparent impedance (Z_{app}) in existence of SSSC at middle of the line, then only the adaptive distance protection setting scheme will take the decision of trip. Therefore to obtain the new setting, equation (26) is multiplied withZ_{line1}.

$$Z_{setnew} = \rho Z_{1S1} = \rho_1 Z_{Line1} \tag{27}$$

Multiplying equation (26) with (Z_{line1}) and substituting in (27), we get

$$Z_{setnew} = \left[0.8 Z_{1S1} - \left(\frac{V_{inj}}{I_{Relay Z_{1S1}}} \right) \right] Z_{line1} \tag{28}$$

From equation (28), the fallowing points are addressed

(i) If SSSC injects capacitive compensation then adaptive zone is increased while for inductive compensation adaptive zone is decreased.

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

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

(iv) Injected voltage will affect the calculation of apparent impedance with fault after SSSC.

(v) The location of SSSC also affects the calculation of apparent impedance.

6. TRANSIENT SIMULATION RESULTS

To investigate the effectiveness of the suggested adaptive distance protection, the system shown in Fig.1, is simulated using PSCAD/EMTDC software (Manitoba HVDC Research Centre, Winnipeg, Manitoba, Canada) [30]. A Symmetrical (LLL) fault is applied to the grid for 55% series compensation at 1 sec with 0.05 sec fault clearing time. Even though the fault is cleared, the torque and stress between the LPB and generator is very high due to SSR and are shown in Figure 4.There is an increase in torque and mechanical stress with a fast rate even though the fault is cleared and this completely damages the turbine shaft system. The injected voltage of SSSC in series with the line is decided by the firing angle of PWM generator, and is obtained from the subsynchronous component estimation control. The mitigation of SSR with the help of SSSC is shown in Figure 5 and the injected voltage of SSSC to mitigate SSR is shown in Figure 6. With the proper injection of series voltage into the line, the turbine-generator oscillations stress between LPB and Generator are reduced to a

low extent that will not harm to the shaft system. Load-flow analysis is used for calculating the magnitudes of generator voltage and load angles. A three level 48-pulse VSC is used for the design SSSC [29].
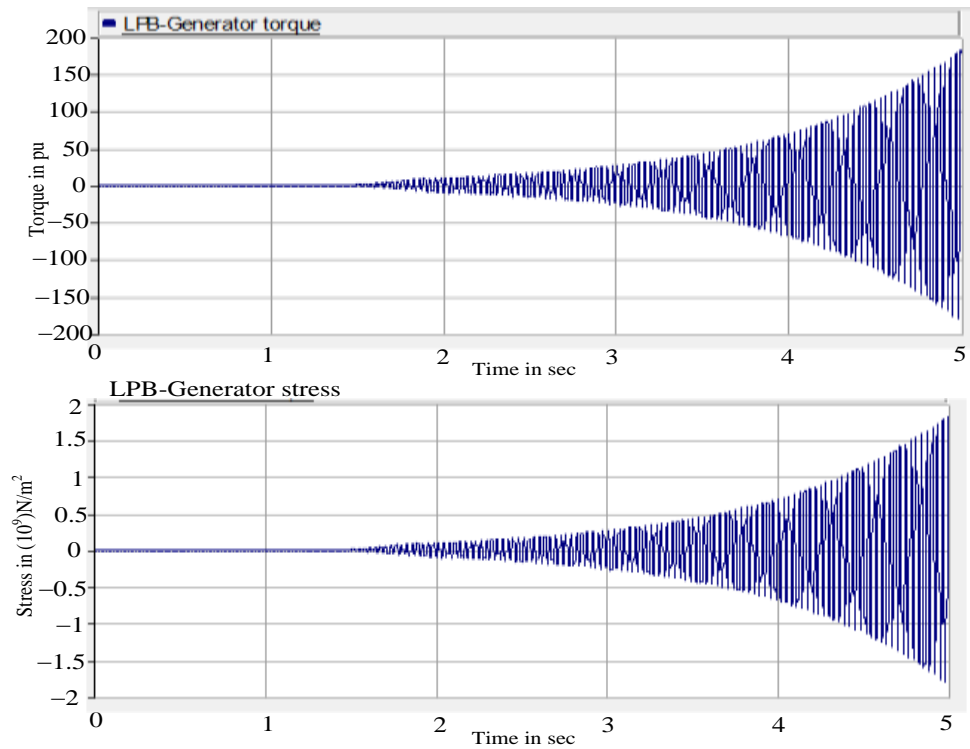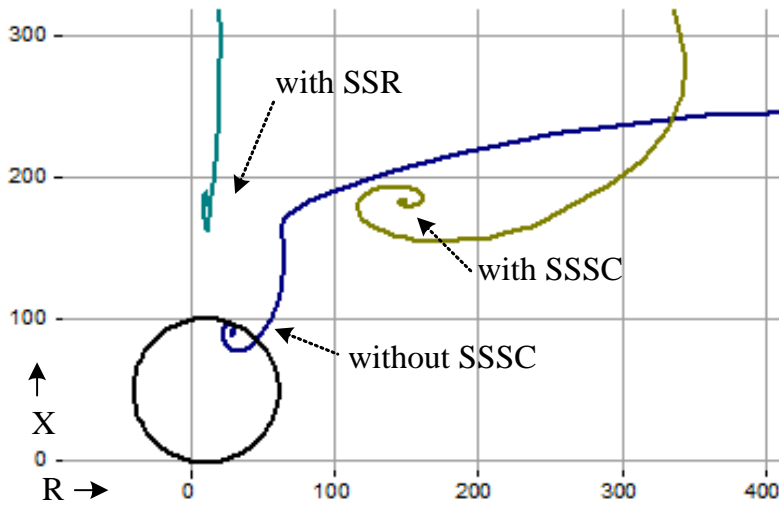

Figure 4. Simulated Turbine-Generator shaft Torque, Stress between LPB-GEN of Study system model without SSC based SSSC.
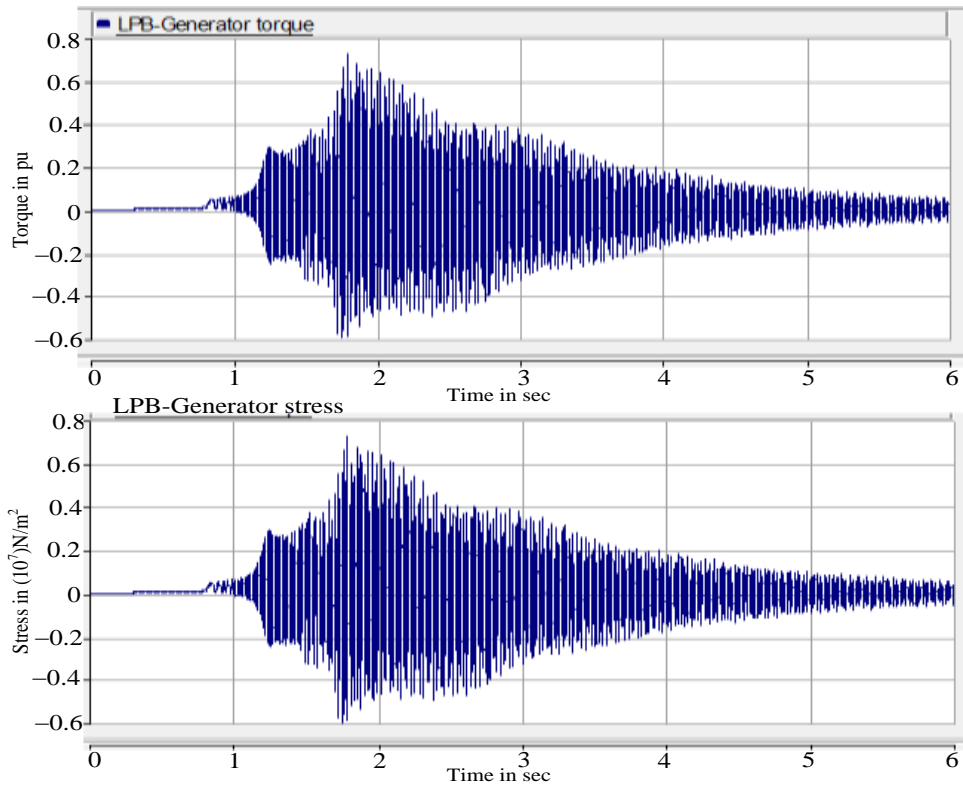
Figure 5. Simulated Turbine-Generator shaft Torque, Stress between LPB-GEN of Study system model with SSC based SSSC.
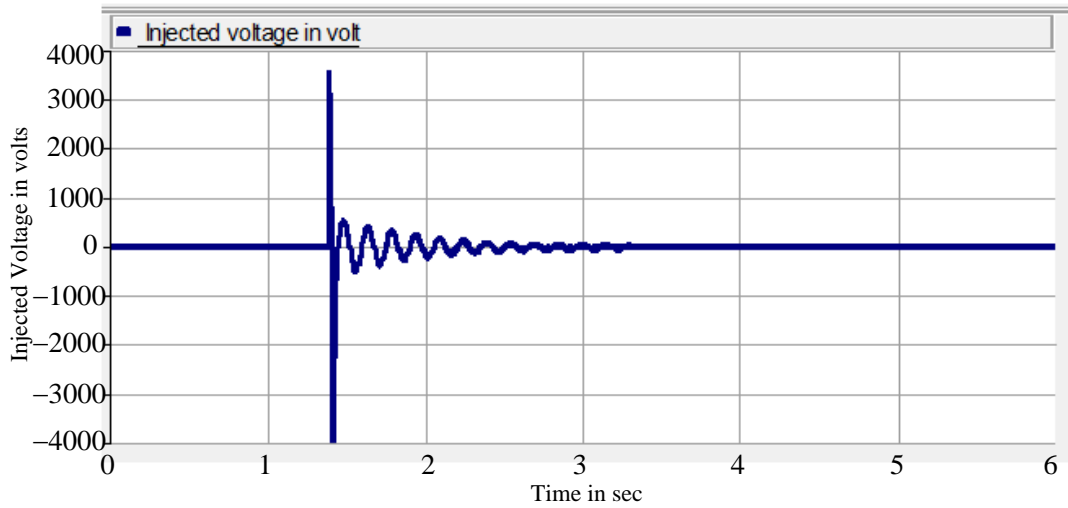

Figure 6. Injected Voltage in to the line to mitigate SSR with SSSC.

Figure 7. First zone trajectories of distance relay without SSSC, with SSR and with SSSC

First zone trajectories of distance relay under normal operation without SSSC represented by blue line shown in Figure 7. With SSR the operating point is out of the zone (under-reach) shown by the dark green line. The operating point with SSSC also shifts to out of the zone (under-reach) shown by the green line. Figure 7 describes the affect of SSR and existence of SSSC on distance protection.

To estimate the adaptive first zone settings of distance rely, control over the setting value of SSSC i.e. V_{Ref} is set between ± 0.1 p.u. The SSSC is connected at mid-point and it comes into the system at 1.05 sec. The voltage at mid-point is decreases with the absorption of Inductive reactive power by SSSC as compared to the usual working voltage without SSSC. This results the reduction in relaying bus voltage and further a decrease in seen apparent impedance of distance relay causing over-reach. The simulation result of Adaptive distance relay with SSSC setting value $V_{ref} = -0.1$ p.u., the setting factor ρ_1 is illustrated in Figure8 for power flow in forward from P to Q. When SSSC is connected at 1.05 sec into the system and absorbs reactive power of inductive, the setting factor ρ_1 is decreased adaptively and it settles to 0.7671 per unit distance value by taking 13 milliseconds to get a new first zone adaptive setting. This new adaptive setting factor is used to define dynamic mho distance relay reach as shown in Figure9. It is observed that for SSSC setting value $V_{ref} = -0.1$ p.u., a reduction in adaptive relay reach which is represented in dark green colour as compared to relay reach of conventional represented by red colour.
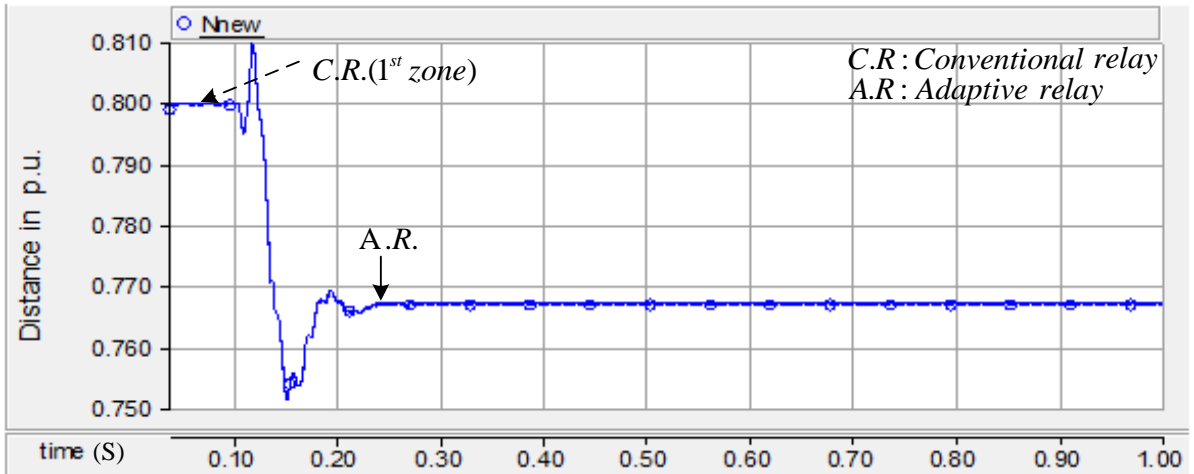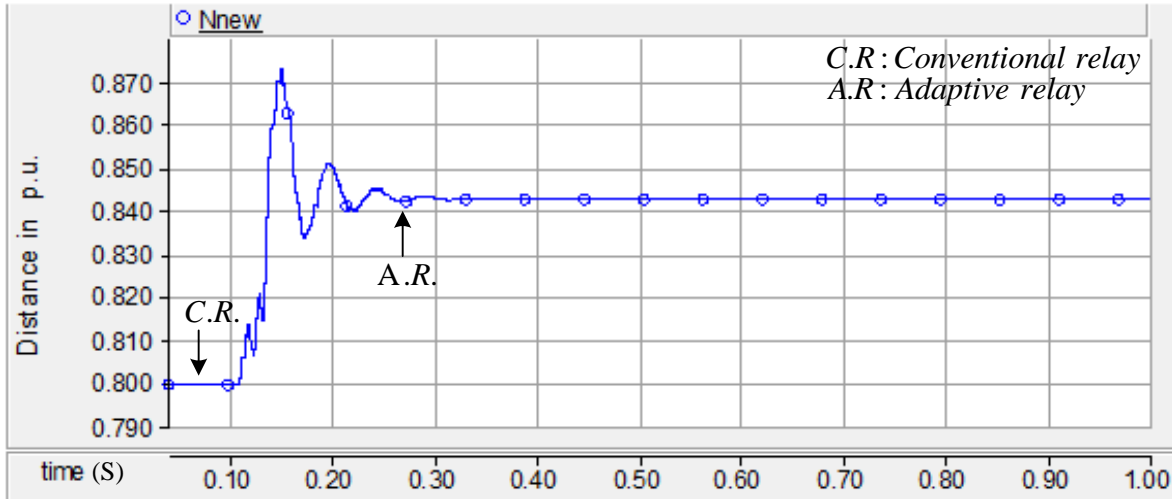
Figure 8. Adaptive distance setting factor ρ_1 with SSSC setting value $V_{ref} = -0.1$ p.u., with power flow from P to Q
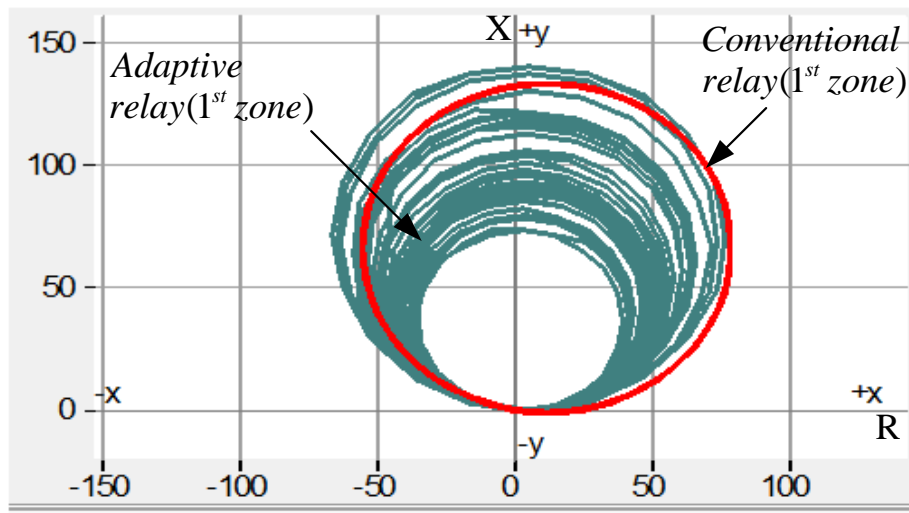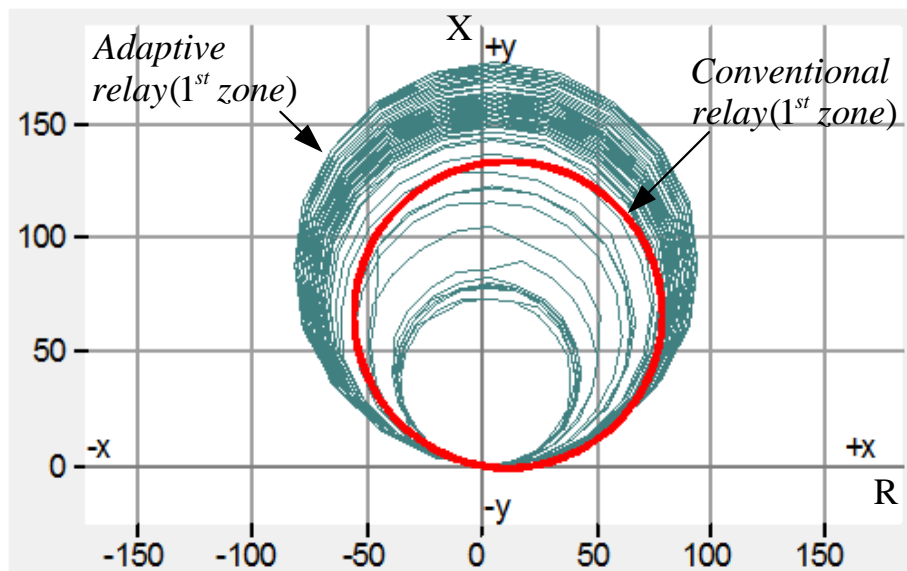

Figure 9. Conventional versus adaptive mho characteristics with SSSC setting value $V_{ref} = -0.1$ p.u., with power flow from P to Q

When SSSC setting value is $V_{ref} = 0.1$ p.u., there is an increase in voltage at mid-point as compared to voltage under usual operating condition without SSSC. Subsequently the relaying voltage of bus and the seen apparent impedance of distance relay also increase and leads to under-reach. The adaptive relay setting factor ρ_1 obtained for SSSC $V_{ref} = 0.1$ p.u. into the system is illustrated by Figure10 for flow of power in forward. The setting factor of relay is 0.8 without SSSC and is adaptively increases to 0.8425 per unit distance value with SSSC by taking 25 milliseconds to settle shown in Figure10.

Figure 10. Adaptive distance setting factor ρ_1 with SSSC setting value $V_{ref} = 0.1$ p.u., with power flow from P to Q

Figure 11. Conventional versus adaptive mho characteristics with SSSC setting value $V_{ref} = 0.1$ p.u., with power flow from P to Q

Figure11 shows the conventional relay reach represented by red colour and adaptive mho relay reach represented by black colour. It is seen that for SSSC setting value $V_{ref} = 0.1$ p.u., the reach of relay is increased adaptively as compared to conventional relay reach. In the same way, conclusion is drawn from Figures7-10 with the injection of capacitive and inductive reactive power by SSSC to make distance relay setting factor adaptive. The adaptive setting factor ρ requires a less time to settle (approximately one and half cycle) for $V_{ref} = - 0.1$ p.u., and around three cycle to get settle for $V_{ref} = 0.1$ p.u.. It is because of the use

of PI controller and is having its own settling time constant which is represented in modelling of SSSC in the paper.

Adaptive setting factor for SSSC reference value, V_{ref} = -0.1 p.u. for power flow in forward direction is 0.7671 p.u. distance and is less as compared to SSSC reference value, V_{ref} = 0.1 p.u in forward power flow is 0.8425 p.u distance. From Figures 9 and 11, the time taken to reach new adaptive setting is different because it depends on capacitive/inductive compensation mode, settling time of PI controller and interfacing transformer of SSSC.

Figure 12 shows the variation of adaptive setting factor with change in SSSC reference voltageV_{ref} in the step of 0.01 p. u. The capacitive reactive power injection is represented by positive value and the inductive reactive power absorption represented by negative value. When SSSC is in inactive mode the system neither injects nor absorbs any reactive power and the observed setting factor is 0.7956. This is due to the reactance of interfacing transformer which comes into circuit of 0.1 per unit. For flow of power in forward direction from P to Q, adaptive setting factor for first zone is 0.8425 and 0.7671 per unit distance for V_{ref} = 0.1 p.u., and V_{ref} = - 0.1 p.u., respectively as shown in Figure 12.
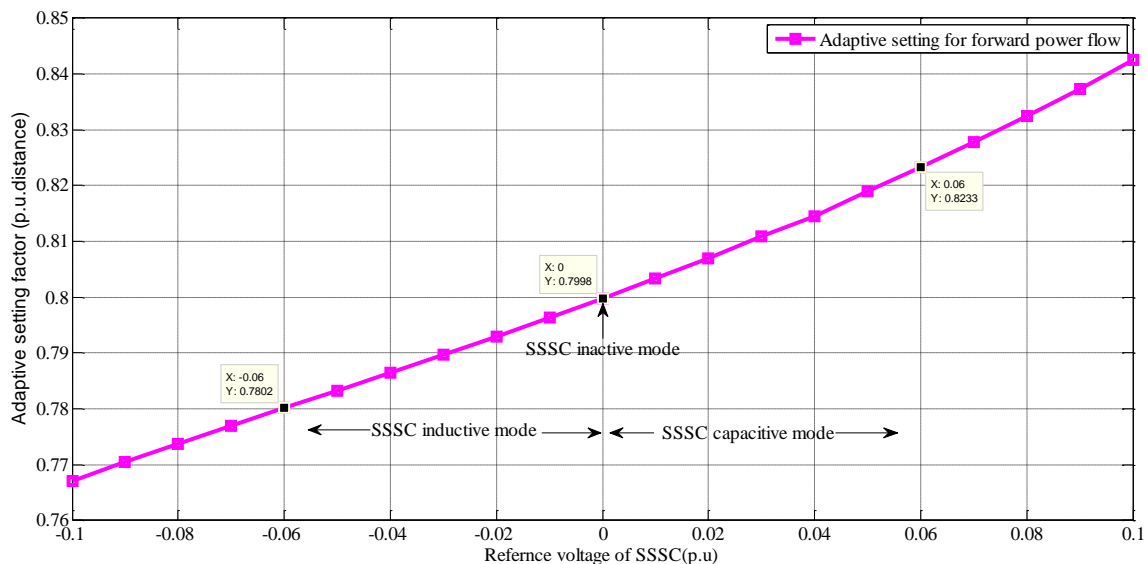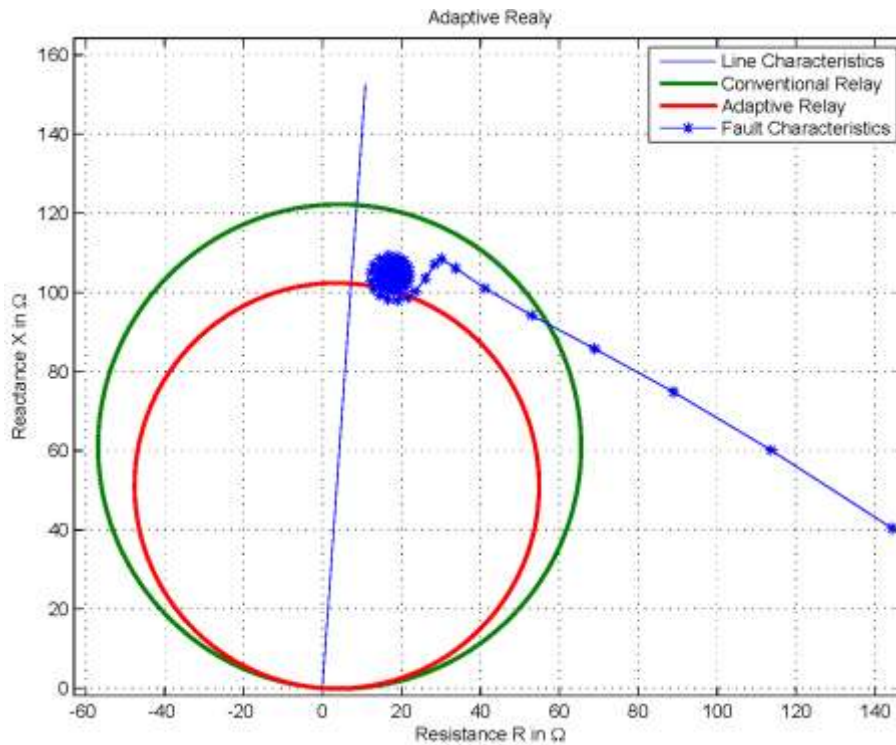

Figure 12. Adaptive distance relay setting factor Vs Reference Voltage of SSSC setting value
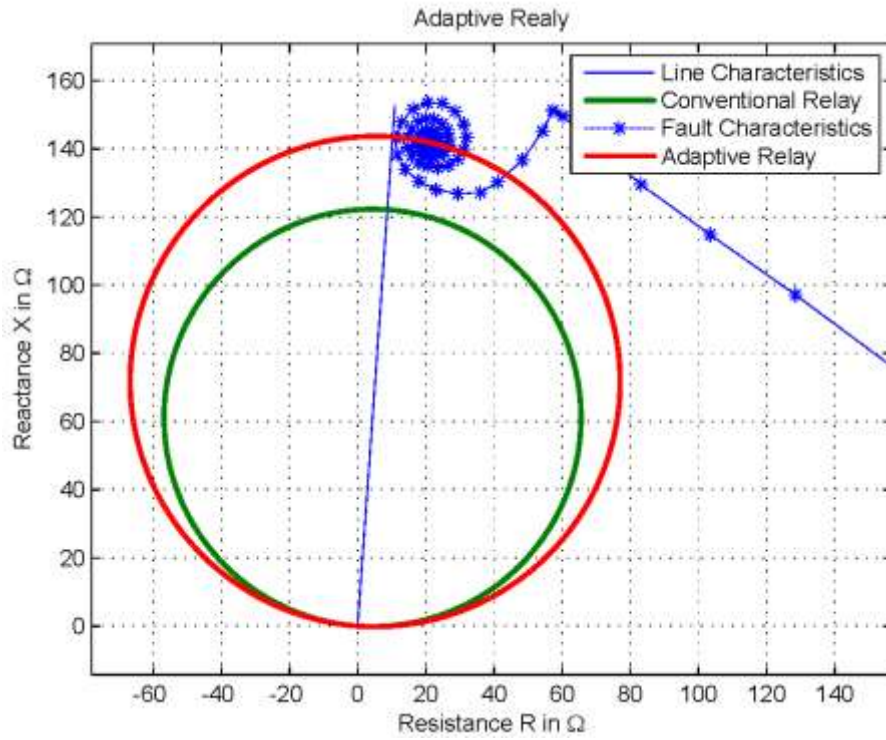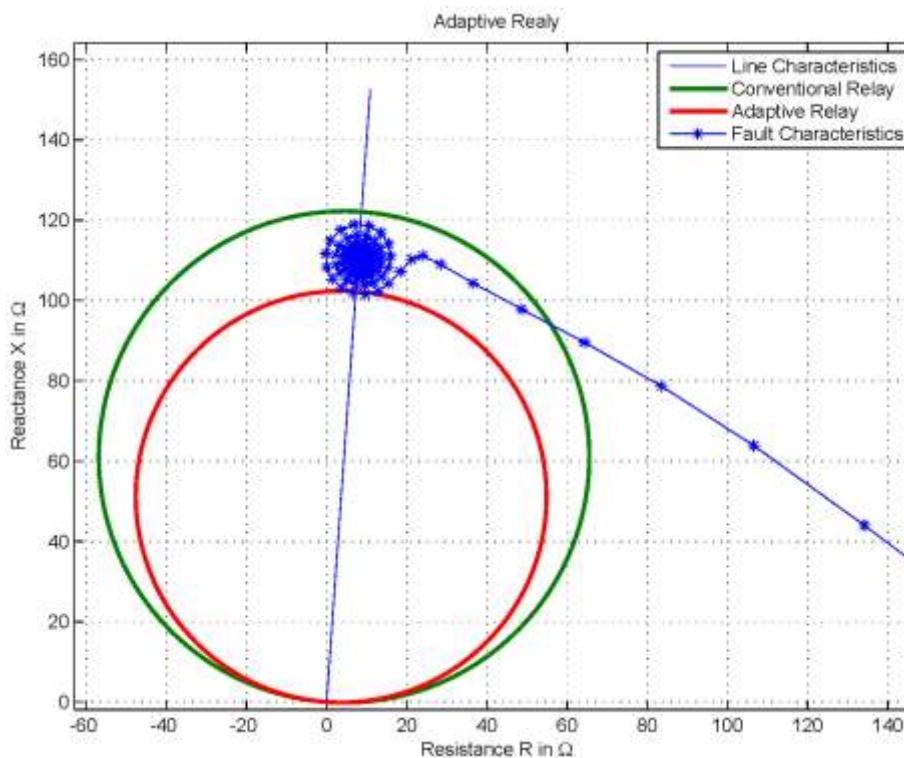
Figure 13. Ag fault at 80% of line length with SSSC (0.1) and 1 Ω fault resistance
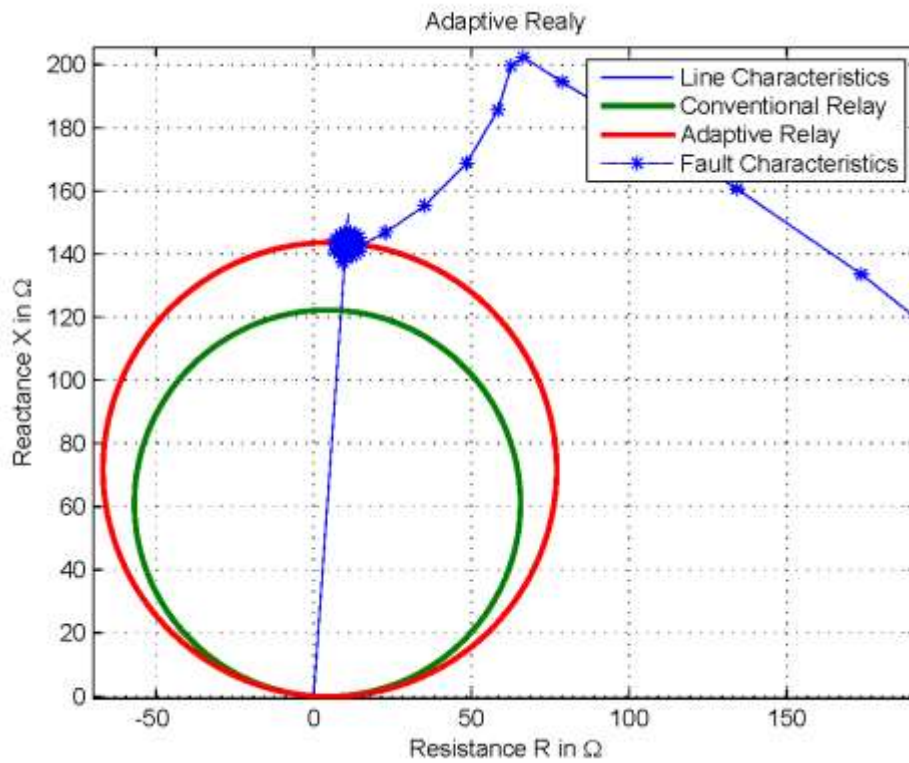
Figure 14. BCg fault at 80% of line length with SSSC (0.1) and zero fault resistance

Figure 15. Ag fault at 85% of line length with SSSC (-0.1) and 1Ω fault resistance

Figure 16. AB fault at 90% of line length with SSSC (-0.1) and Zero fault resistance

For different changing compensation mode and level, the adaptive relay settings have been calculated and stored in the relay lookup table. So, when the adaptive relay have the feedback from the compensation (V_{ijn}) the pre-calculated setting will used to detect and locate the fault point which make the relay adaptive. Theses settings stored in the lookup table is for

proposed system and for any other system, using the adaptive relay equation and other related parameters, the settings can be calculated to load into the relay lookup module. The adaptive relay response for the associated problem of underreach and overreach of conventional distance relay have been shown with the different fault conditions in the figure 13-16. Its highly important to check for the boundary conditions, like when fault is occurring near to the first zone of protection for underreach settings and ahead from first zone setting for overreach setting in different compensation mode.

Figure 13 shows the results for Ag fault at 80 % of line length with positive SSSC compensation (0.1) with 1 ohm fault resistance. The appropriate legends are shown in the figure for better understanding. It is observed that, the conventional relay underreach the fault trajectory and adaptive relay able to locate the fault in its first of protection. In simulation and numerical modelling of relay, it is assumed that, if 10 continues samples lies in the zone of protection than only relay will issue the trip decision, else no trip for both the relays. Similar observations are made in Figure 14 for BGg fault at 80% of line length and results are highly satisfactory.

Figure 14 shows the results for SSSC compensation (-0.1) for Ag fault at 85% of line length with zero resistance. The in this mode of SSSC compensation conventional relay detects the fault in its first zone and hence overreach the fault point. Whereas, adaptive relay not able to detect the fault as continues 10 samples are not lies in the first zone of protection and hence no detection of fault. Similarly, for AB fault at 90% of line length results is shown in Figure 16 and the adaptive relay not mal-operate for overreaching the fault.

7. CONCLUSIONS

In this research work an accurate subsynchronous component based on SSSC controller with adaptive setting scheme to mitigate the SSR and its effect on distance protection of transmission line is reported.With the injection of series voltage in to the line using SSSC the adverse effect of SSR on turbine-generator is reduced to a great extent. In order to mitigate the effect of SSSC at middle of transmission line on distance protection an adaptive setting scheme is proposed. To change the reach of relay for various levels of compensation (series) a method of adaptive distance protection first zone setting is proposed. Adaptive distance protection setting factor is decreased for lower level of compensation and is increased for larger level of compensation. By comparing the conventional technique with proposed

adaptive scheme, it is understand that, there is a noteworthy enlarge in the enclosed area by distance relay and the mal-operation of the distance relay in presence of SSSC has been overcome. The simulation results show the effectiveness of the proposed distance relay setting, the zone is increased adaptively and gives very accurate relay trip decision in presence of SSSC based SSR controller.

Appendix A

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

Table A.I Study System Network Parameters

Resistance of power network	R_L	0.0113 p.u.
Reactance of Transformer	X_T	0.142
Ratio of Transformation		22/539 kV
Reactance of line	X_L	0.50p.u.
Reactance of Transmission line	X_{sys}	0.08p.u.

Table A. II Parameters of Synchronous Machine

Reactance	Value [p.u.]	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 A. III Study System Shaft Parameters

Inertia	H [s^{-1}]	Shaft section	Spring constant [p.u. T/rad]
Generator	0.868495		
LPB turbine	0.884215	LPB-GEN	70.858
LPA turbine	0.858670	LPA-LPB	52.038
IP turbine	0.155589	IP-LPA	34.929

| HP turbine | 0.092897 | HP-IP | 19.303 |

Table A. IV SSSC parameters

Rated power of converters	P_{VSC}	12.86 MVA
Rated Voltage of converters	V_{VSC}	8 kV
DC-link Capacitor	C_{dc}	15 µF
Controller parameters		
Sampling frequency	f_s	1.4 kHz
Switching frequency	f_{sw}	660 Hz
PLL bandwidth	α_{PLL}	16.62 rad/sec
SSCC bandwidth	α_{cc}	9.96 rad/sec
DCVC bandwidth	α_{dc}	12.25 rad/sec

The parameters of SSSC are given in Table A. IV [9, 10].
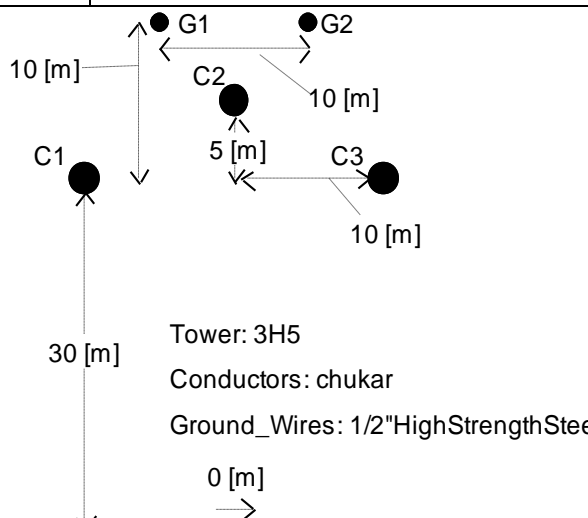
Table A. V Data of Study System shown in Fig.1.

Study System elements	**Parametric quantity**
Equivalent Source	Frequency of System = 60Hz $Z_0 = 25.9\angle 80°\Omega; Z_1 = 25.9\angle 80°\Omega$
Interfacing Transformer = 3 winding (Y/y/d)	Transformer ratio =539/11/11kV Transformer Impedance = 0.1 p.u.
Rating of SSSC	+/- 100 (inductive & capacitive)
Transmission Line (I)	Line length = 300 km $Z_1 = 0.51\angle 85.92°\Omega/Km$ $Z_0 = 1.385\angle 74.68°\Omega/Km$

Figure A.1.Physical Structure of Bergeron model Transmission Line

Figure.A.2. describes the algorithm of proposed Mho relay (Adaptive)for the protection of transmission line with SSSC. This is the modified version of the Mho relay (conventional) with the help of synchronized phasors measurement unit. The setting of Mho relay is made to protect80% of transmission line 1 and is located at bus P(sending-end). The distance relay at relay bus P measures line current (I_s) and phase voltage (V_s) by using a current transformer (CT) and potential transformer (PT), respectively. The SSSC is positioned 100 km from the generator (sending-end) of line 1 at coupling bus B_1, which measures injected voltage V_{inj} by SSSC. All measurements at bus $B_1$are transferred to bus P with the help of fiber-optic communication channel and are given to adaptive setting relay unit. In this unit, the equivalent impedance due to SSSC in the transmission line is computed and is a function of V_{inj} by SSSC. The communication channel consists of fiber-optic is simulated with the help of transmitter/receiver tools in PSCAD/EMTDC software.
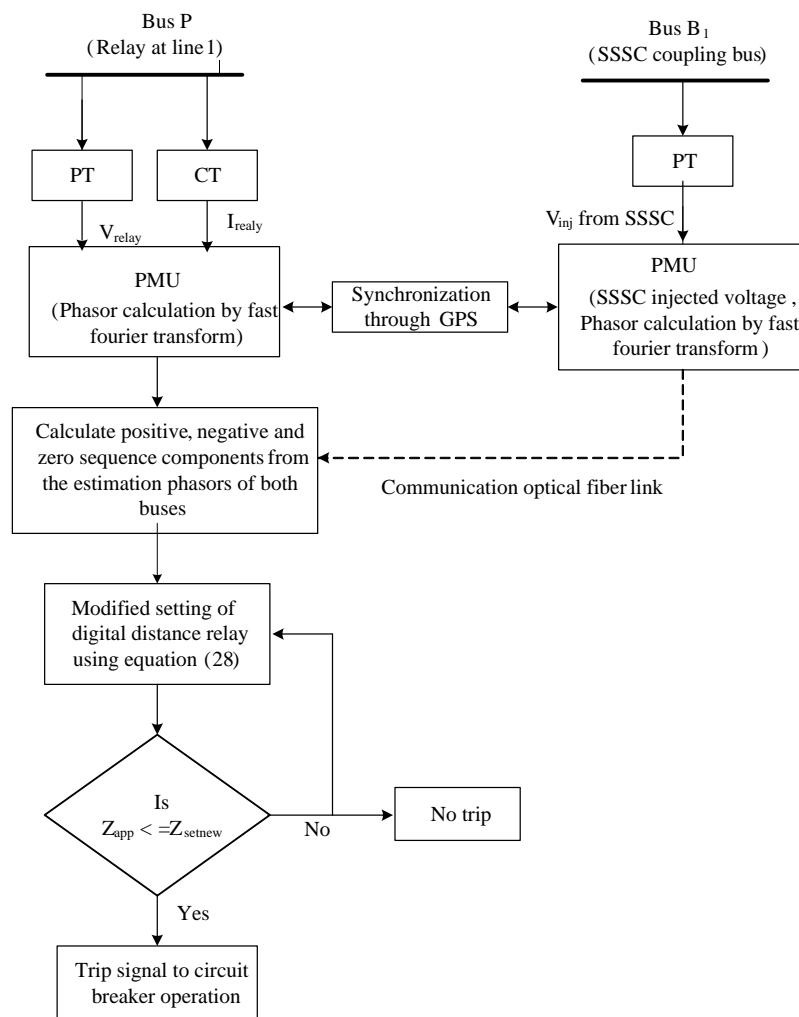
Suggested Adaptive Mho Relay Algorithm

Figure A. 2 Adaptive algorithm of digital distance relaying

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Fault impedance Z (R and X) is computed and is modified with the help of adaptive procedure at the point of relay using sequence and fundamental components of the fault current and voltage signal. The transient current and voltage can be decomposed into the fundamental quantity using Fast Fourier transform, and the zero and positive -sequence value of voltage and current are obtained with the help of sequence filter [23-24].The proposed adaptive Mho relay algorithm changes the parameter of setting to adaptive for new compensation level and the fault is on the line, the relay issue proper command to circuit breaker by comparing the measured apparent impedance with the modified setting to clear faults.

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