Analysis and Evaluation of the Impacts of FACTS Devices on the Transmission Line Protection

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1 Introduction

We know from the fundamentals of power system that, transmission lines carries bulk power from far generating stations to the local distribution substation. Hence transmission line protection plays an important role in reliability and security of the power system. Over-current protection is very appealing and attractive because of its inherent simplicity; however reach of the over current relay depends on type of fault as well source impedance which are variable may lead to mal-operate in long transmission lines [1]. As EHV lines are the part of interconnecting grid, any mal- operation is not tolerable and any mal-operation may jeopardize the stability and security of the grid [1]. This led to the search of a relaying principle whose reach is not dependent on the type of fault current and its magnitude but depends on the ratio of voltage and current measured at relay location [1]. This is nothing but impedance based protection system called distance protection which can work effectively and accurately for transmission line protection. This protection technique works effectively in the conventional power system but in modern power system, performance parameters of the transmission lines can be controlled by reactive power compensating devices [2]. Transmission lines with compensating devices may leads to mal-operate the distance relay and may affect the security of the grid [3].

With the application of power electronic devices and controllers, it's made possible to control the power flow dynamically by controlling the levels of compensation. This led to the Flexible AC Transmission technology (FACTS) [4, 5] and commissioning of these FACTS device to improve the power transfer capability, stability and controllability is being carried in most of the grid transmission lines around the globe as well in India [3]. Due to the presence of these FACTS devices in transmission lines,

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Sanjeevikumar et al. (eds.), *Advances in Renewable Energy and Electric Vehicles*,
Lecture Notes in Electrical Engineering 767,
https://doi.org/10.1007/978-981-16-1642-6_3

may affect the proper functioning of distance relay which may lead to under reach and over reach problems [6]. During some worst cases, mal- operation of relay may leads to series of tripping and finally the system black-outs [7, 8]. From the view of security of the grid system, it's very much needed to investigate the new attributes of compensated transmission lines. Analytical calculation of apparent impedances seen by the relay in presence of midpoint TCSC and midpoint STATCOM during both ground faults and phase faults are performed by resolving sequence impedance networks, effect of shunt current in case of shunt compensation and series voltage in case of series compensation are analyzed by obtained equations. Using GPS synchronized measurements [9], measured current/voltage signal at the FACTS location, is transmitted with negligible communication delay by using fiber optic communication link offers a fast and quick intelligent relaying to react adaptively to the effects of FACTS compensation during faults [10, 11]. Based on the obtained analytical equations and GPS synchronized measurement a novel algorithm can be derived for adaptive relaying [12]. To perform the analysis, a modified IEEE-9 bus system is built and a conventional relaying is implemented using PSCAD/EMTDC [13]. STATCOM and TCSC is modeled and placed in mid-point to investigate its impacts on protection [14, 15].

2 Apparent Impedance Calculation

2.1 In Presence of STATCOM at the Midpoint

Let STATCOM be located at the midpoint of line whose impedance $Z_L = 1$ p.u. and a fault occurs at 'n' distance from the relay as shown in the Fig. 1

$$(nI_{s0}Z_{L0} + nI_{sh0}Z_{L0} - 0.5I_{sh0}Z_{L0} + R_f I_{f0});$$

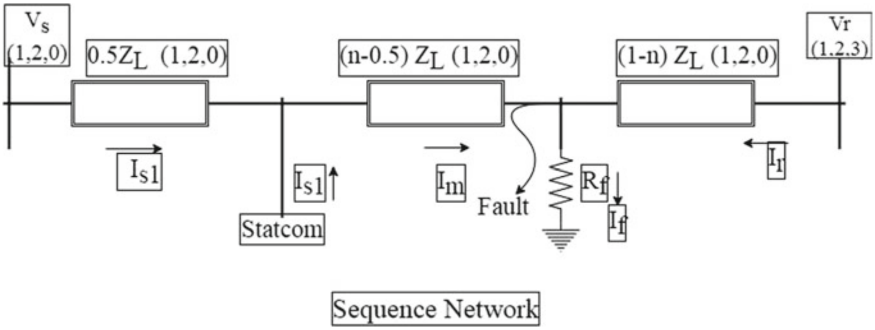


Fig. 1 Sequence network with STATCOM

Referring to Fig. 1, we have the following

$Z_{ss} = 0.5\, Z_L$ [Impedance from sending end to STATCOM];
$Z_{\mathrm{SF}} = n - 0.5 Z_L$ [Impedance from statcom to till fault];
$Z_{\mathrm{FR}} = (1 - n) Z_L$ [Impedance from fault to receiving end].

During Ground Fault: An L-G fault occur just after STATCOM (n > 0.5 p.u)

Positive negative and zero sequence components of voltages are expressed as,

$$\begin{aligned}
V_{s1} &= 0.5\, I_{s1} Z_{L1} + I_{m1}(n - 0.5) Z_{L1} + R_f I_f \\
V_{s2} &= 0.5\, I_{s2} Z_{L1} + I_{m2}(n - 0.5) Z_{L1} + R_f I_{f2} \\
V_{s0} &= 0.5\, I_{s0} Z_{L0} + I_{m0}(n - 0.5) Z_{L0} + R_f I_{f0}
\end{aligned}$$

In transmission line $Z_{L1} = Z_{L2}$.
Also,

$$\begin{aligned}
& I_{m1} = I_{s1} + I_{sh1};\ I_{m2} = I_{s2} + I_{sh2};\ \text{and} \\
& I_{m0} = I_{s0} + I_{sh0};
\end{aligned}$$

Sending end voltage/relay measuring voltage is given by,

$$\begin{aligned}
V_s = {} & V_{s0} + V_{s1} + V_{s2}; \\
V_s = {} & \left(n I_{s1} Z_{L1} + n I_{sh1} Z_{L1} - 0.5 I_{sh1} Z_{L1} + R_f I_{f1}\right) \\
& + \left(n I_{s2} Z_{L1} + n I_{sh2} Z_{L1} - 0.5 I_{sh2} Z_{L1} + R_f I_{f2}\right) \\
& + \left(n I_{s0} Z_{L0} + n I_{sh0} Z_{L0} - 0.5 I_{sh0} Z_{L0} + R_f I_{f0}\right);
\end{aligned}$$

Add and subtract $(n I_{S0} Z_{L1})$, $(n I_{Sh0} Z_{L1})$, and $(0.5 I_{S0} Z_{L1})$, we get,

$$V_s = n I_s Z_{L1} + (n - 0.5)(Z_{L0-} Z_{L1})(I_{sh} + I_{Sh0}) + n I_{s0}(Z_{L0} - Z_{L1}) + \left(R_f I_{fa}\right)$$

Ignoring I_{sh0}, and making $R_f = 0$ as there will be no neutral to ground current in delta connected side of the transformer connected in the STATCOM assembly.

We have,

$$V_s = n I_s Z_{L1} + (n - 0.5)(Z_{L0} - Z_{L1})(I_{sh}) + n I_{s0}(Z_{L0} - Z_{L1})$$

$$Z_{\mathrm{app}} = \frac{V_{\mathrm{relay}}}{I_{\mathrm{relay}}};\ V_{\mathrm{relay}} = V_S;\ I_{\mathrm{relay}} = I_S + K I_{S0};\ Z_{\mathrm{app}} = \frac{V_s}{I_s + k\, I_{s0}};$$

Finally we have

$$Z_{\mathrm{app}} = n Z_{L1} + \frac{(n - 0.5) I_{sh} Z_{L1}}{I_s + k\, I_{s0}}$$

where $K = \frac{Z_{L0} - Z_{L1}}{Z_{L1}}$; ‘$K$’ is the residual current compensation factor. By observing above equation we can infer that, the error introduced in the apparent impedance due to shunt compensation is given by

$$Z_{\text{error}} = \frac{(n - 0.5) I_{sh} Z_{L1}}{I_s + K I_{S0}};$$

Actually, nZ_{L1} represents line impedance up to fault point.

During Phase Fault: An L-L fault occur just after STATCOM (n > 0.5 p.u)

Through similar approach as described above, apparent impedance seen by the relay is given by

$$Z_{\text{app}} = nZ_{L1} + \frac{(n - 0.5) I_{sh} Z_{L1}}{I_{S1}}$$

During L-L fault there will be no zero sequence component and hence it is neglected.

2.2 *In Presence of TCSC at the Midpoint*

Let $Z_L = 1$ p.u and a fault is imposed at ‘n’ distance from relay (Fig. 2).

With a similar approach, after calculation using sequence network reduction for an LG/LL fault, we get in general

$$Z_{\text{app}} = nZ_{L1} + \frac{V_T}{I_{\text{relay}}};$$

where $I_{\text{relay}} = I_s + K I_{S0}$; in case of LL fault, we should ignore we should ignore I_{S0}.

As in shunt compensation, series compensation also affects relay operation and likely to mal-operate.

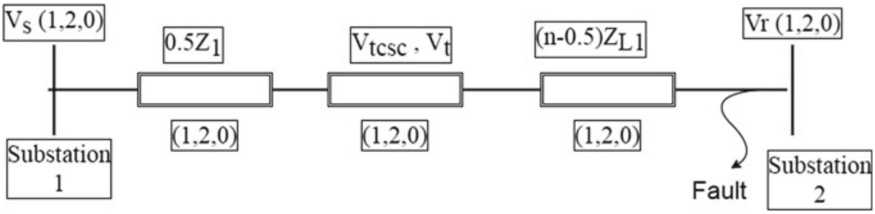


Fig. 2 Sequence network with TCSC

3 Under-Reach and Over-Reach Effects

Case 1: During Shunt compensation with STATCOM:

- When injected current is +Ve, i.e. Ish is inductive (+Ve), during which STATCOM is injecting capacitive reactive power into the system which increases the Zapp, hence relay suffers under-reach problem. i.e. apparent impedance trajectory falls outside the zone of protection during fault.
- When injected current is −Ve, i.e. Ish is −Ve, during which statcom draws capacitive reactive power from the system which decreases the Zapp, hence relay suffers over-reach problem. Apparent impedance trajectory falls within the zone of protection even though fault occurs outside the zone.

Case 2: During series compensation with TCSC:

Due to the series voltage injected, in presence of series compensation, relay suffers over reach problem.

Thus, analytically by sequence network reduction method, we have proved in presence of FACTS device in transmission line, causes relay to suffer overreach and under reach problems. So an adaptive novel algorithm is required to mitigate the problems.

4 Modeling of Test System

4.1 Modeling of Study System

IEEE-9 bus system is modeled in PSCAD and power flows are checked. FACTS device is placed in mid-point of the line which connects two weak buses.

4.2 Modelling of STATCOM and TCSC

A twelve pulse STATCOM using PI controller which regulates the weak bus voltage is modeled in PSCAD/EMTDC. Using the power flows obtained for the test system, the KVAR ratings of the STATCOM is decided so that the voltages at the weak buses are maintained at 1 p.u. The constants of the PI controller are obtained from nyquist plot plotted for the control system in PSIM platform where the system is found stable.

For different firing angles, PSCAD model of TCSC is simulated with 20% fixed compensation inserted at the mid of the line connecting the weak buses.

5 Simulation Results

The PSCAD/EMTDC model of WSCC 9 bus system is rigged up in PSCAD/EMTDC and after looking into power flows, Bus-8 found to have less voltage of 0.79 p.u and at the midpoint of the line connecting Bus-7 and Bus-8, FACTS device is inserted and Simulated with insertion of various faults at different distances to evaluate the performance of the relay for zone-1 operation. Results are summarized as follows.

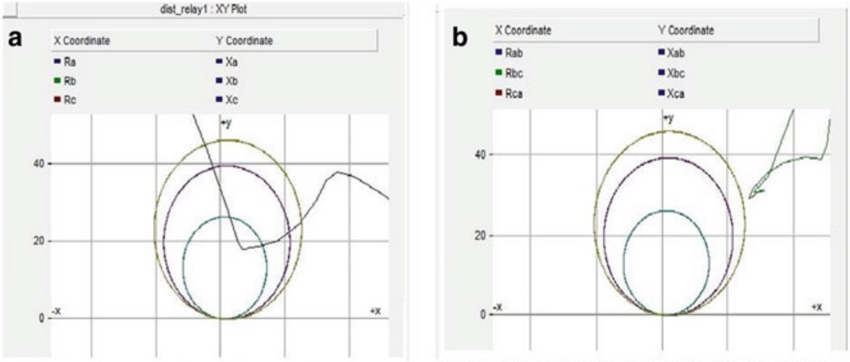
- From Fig. 3a, it is cleared that, relay is operating absolutely fine and the apparent impedance trajectory is falling inside the zone-1 when fault is injected within zone-1 only.
- From Fig. 3b, when a fault occurs within zone-1, but relay suffers under reach problem, apparent impedance trajectory falls beyond zone-1.
- From Fig. 3c, when a fault is inserted at zone-3, still the apparent impedance trajectory falls very near to zone-1 suffering overreach effect.
- Similarly, from Fig. 3d, apparent impedance trajectory falling in zone-2 when a fault is imposed at zone-3 suffering overreach problem in presence of TCSC.
- In Fig. 3e. when Phase-a to Ground fault is applied (A-G) fault, a trip signal is initiated and fault current(Ia) peak can be noted during fault and after trip signal, current become zero.

Thus distance relay will prone to have errors in presence of shunt and series compensation which is verified both analytically and practically by simulation.

6 Adaptive Relay Setting Flow Chart

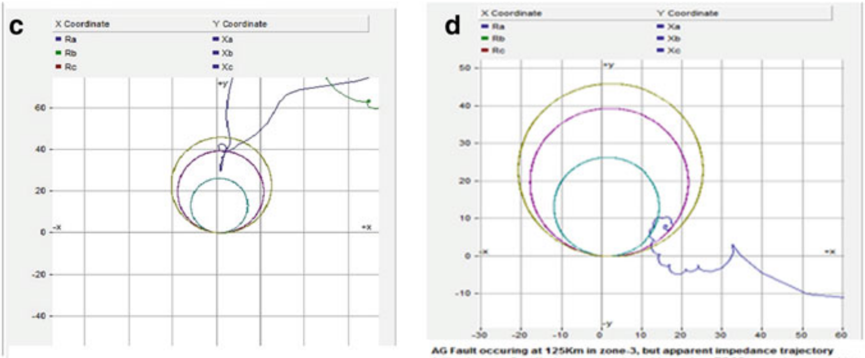
- With changing system condition, a relay has to adapt to the new conditions without incurring any errors and for the same we have to design a new adaptive relay setting.
- After understanding the impacts of the compensation on distance protection, the other objective is to obtain an adaptive relay algorithm flow chart by taking the feedbacks of shunt current I_{sh} by STATCOM and series injected Voltage (Vt) by TCSC.

  Using PMU's at both relaying bus as well at the FACTS bus, the phasor estimations are done at both the buses for voltage and current samples and communicated to the relay without any delay.
- A relay algorithm flow chart is presented in the Fig. 4 through phasor estimation by PMU's at both relay bus and FACTS bus, a new setting zone is determined without any communication delay and accordingly new mho circle for the new zone is plotted. A new trip law is given to the relay to mitigate the errors. This mean the synchronized measurements(sequence components using Fourier Transforms) from phasor measurement units (PMU) i.e. samples of current and voltage magnitudes and phasors at relay bus as well at the FACTS bus without any



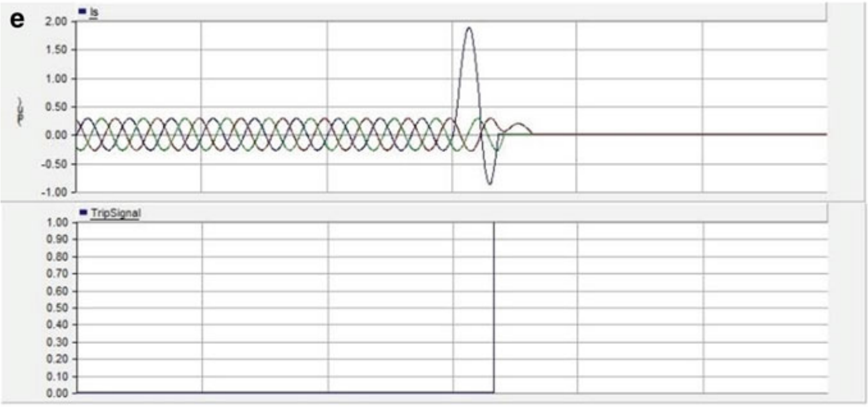
Apparent impedance trajectory falls within zone-1, when AG fault occurs at 60Km when the line is without STATCOM & TCSC

Apparent Impedance Trajectory Falls outside zone-1 and suffers under-reach in presence of Statcom when applied with B-C phase fault when Satcom operating in capcitive mode



Apparent Impedance Trajectory falls in Zone-2 when AG fault occurs at Zone-3 125Km suffering over reach problem when STATCOM is present with Qref=-100MVAR

AG Fault occuring at 125Km in zone-3, but apparent impedance trajectory falling in zone-2 suffering overreach problem when TCSC operating capacitive mode with α=170°



Current waveform and Trip signal Initiation by the relay during A-G fault applied within Zone-1 at 60Km from Relay Location

Fig. 3 **a** Impedance trajectory without STATCOM and TCSC (base case), **b** Under-reach effect in presence of STATCOM, **c** Over-reach effect in presence of STATCOM, **d** Over-reach effect in presence of TCSC, **e** Current waveform and trip signal initiation by the relay during A-G fault applied within Zone-1

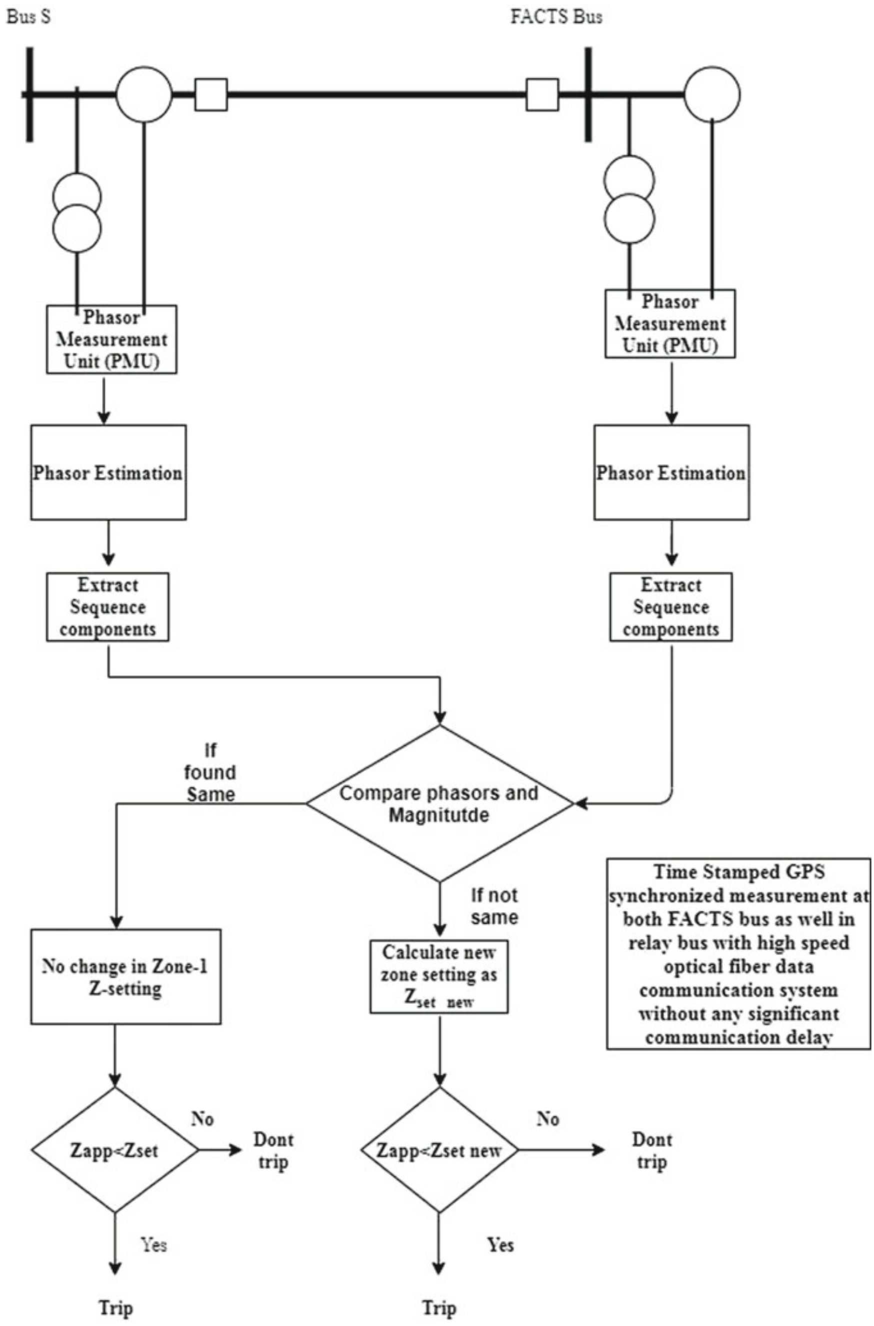


Fig. 4 Relay algorithm flow chart

communication delay, are extracted and apparent impedances are calculated and compared, if it is as per zone-1 setting, no changes in relay function but FACTS device is contributing reactive currents (may be during fault), then after comparison it will not be same, hence relay adapt by itself by changing to a new zone setting for zone-1 and hence avoiding the under reach and overreach effects. It is clearly depicted in Fig. 4.

7 Conclusion and Future Scope

A shunt/series compensated transmission line will prone to have under reach and overreach effects. It's been verified analytically step by step using sequence network methods during unsymmetrical faults (both ground and phase faults). This analysis depicted the under reach and overreach effects during presence of series and shunt compensations separately. The same analytical results are verified using PSCAD modelling and simulations. A WSCC 9 bus system is rigged up to see the power flows and bus-8 found critical with a voltage of 0.79 p.u. Hence a line connecting bus-7 and bus-8 is taken for the experimental verification, FACTS devices TCSC (for series compensation) and STATCOM placed at the midpoint of the weak line. In both cases without FACTS and with FACTS a mho relay characteristics are obtained and observed that it shown under reach and overreach effects. An algorithm flow chart to determine a new zone setting to compensate the errors due to the presence of FACTS device is proposed. It uses synchronized measurement principle using PMU's and communication without any delay using fiber optic communication link to calculate new zone setting so that relay act adaptively to the prevailing changes in the system due to interactions of the FACTS devices. But practical implementation and verification of the adaptive relay algorithm flow chart as a proof for mitigating the errors is the future work identified.

Acknowledgements This work is done during the Summer Faculty Fellowship-2019 at IIT Delhi. I would like to profusely thank Prof. B K Panigrahi Department of Electrical Engineering IIT Delhi for the opportunity and support.

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