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Performance Evaluation of Mho and Quadrilateral Characteristic Relays on UPFC Incorporated Transmission Line

Nidhi Chauhan[1], M. Tripathy[2] and R. P. Maheshwari[3]

*[1,2,3]Department of Electrical Engineering,
Indian Institute of Technology Roorkee,
Roorkee-247 667, Uttarakhand (India)*

Abstract

The paper presents the errors in the estimation of impedance seen by mho relay due to the presence of UPFC in transmission line. These errors occur due to rapid change in the compensation parameters such as shunt reactive current and series voltage injection into the transmission line. The study presents the cause of under reach/ over reach of mho relay in this case. This error in impedance calculation results in mal operation of the relay for the faults like single line to ground fault specifically. Effect of fault location, fault resistance has also been investigated. Performance of quadrilateral characteristic relay under such scenario is also evaluated. The study suggests the supremacy of quadrilateral relay over mho relay during high resistance fault on UPFC compensated transmission lines. The paper also presents the need of adaptive measures of generating tripping boundaries to improve distance relaying scheme for FACTS compensated transmission line protection. The complete simulation including UPFC structure modeling, mho and quadrilateral relays setting has been carried out with PSCAD software tool.

Keywords: Unified Power Flow Controller (UPFC), Line to Ground fault (LG), Static Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), PSCAD/ EMTDC.

1. Introduction

FACTS technology has emerged as a sophisticated and reliable state of art providing with the flexibility to enhance power flow, maintain voltage stability etc., all at utilities choice. Thus in this era of incessant electricity demand, restricted right of ways and soaring prices, FACTS devices have helped in utilizing the transmission corridors to its fullest capacity. Unified Power Flow Controller (UPFC) is a versatile FACTS device, capable of regulating all the power flow parameters i.e. voltage, impedance and load angle, simultaneously and selectively [1]. UPFC via its controlling parameters like injected series voltage and reactive shunt current respond to the changes in the power system configuration rapidly, as desired. However, its adverse effects are faced by protection utilities where the distance relay operation for transmission line protection gets inadvertently affected owing to its dependence on power frequency voltage and current signals at the relay point, getting distorted in the presence of UPFC [2, 3]. The relay compares this apparent impedance calculated in the presence of UPFC, along with its impedance setting. Thus resulting in erroneous results for tripping decisions.

Different relay characteristics like mho and quadrilateral are used for protecting high voltage long and medium transmission lines in different scenarios. Till date all the theoretical performance evaluation of distance relay in presence of UPFC incorporated transmission line has been done using mho relay only [4, 5, 6]. Work in [7] presents synchrophasors assisted adaptive reach setting method of distance relay in presence of FACTS devices. Quadrilateral relay possesses flexible operating characteristic and encloses the desired fault region. The present paper discusses the theoretical analysis simply to illustrate the influence of UPFC incorporation, its location effect and effect of fault resistance during LG fault on both mho relay and quadrilateral relay establishing comparative overview.

2. Transmission Line Modeling With UPFC

System consisting of two terminal *230 kV, 50 Hz, 200 km* long transmission line with *100 MVA* short-circuit levels is simulated with load angle of *20 degree* with PSCAD/ EMTDC software tool. Positive sequence impedance of line is *(0.3624e-4+j0.5031e-4) ohm/m and* zero sequence impedance is *(0.37958e-3+j0.13277e-2) ohm/m*. Simulation is done using step size of 0.05ms. Fault duration is 0.2 s, fault resistance varies from 0 to 60 ohms. UPFC constitutes two back-to-back GTO based *six-pulse* voltage source converters (VSC) connected via a dc link with capacitance of *500µF*. A three phase *230 kV/ 20 kV Y/Δ* transformer is used to connect one VSC i.e. the STATCOM, in shunt with the transmission line. The other VSC i.e. the SSSC, is connected in series with the line with the help of three single phase series transformers of rating *20 kV/60 kV Y/Y* as shown in *Fig. 1.* The series converter of UPFC does the major function by injecting controllable series voltage into the line with varying magnitude (*0 to 15 % of line voltage*) and phase-angle (*0 to 360 degree*). The line current interacts with this voltage to provide real and reactive power flow control. The shunt converter generally provides for the real power demand of the series converter along with voltage support if desirable and also regulates the dc link voltage.*160 MVA* UPFC is connected at *mid-point* of the transmission line.

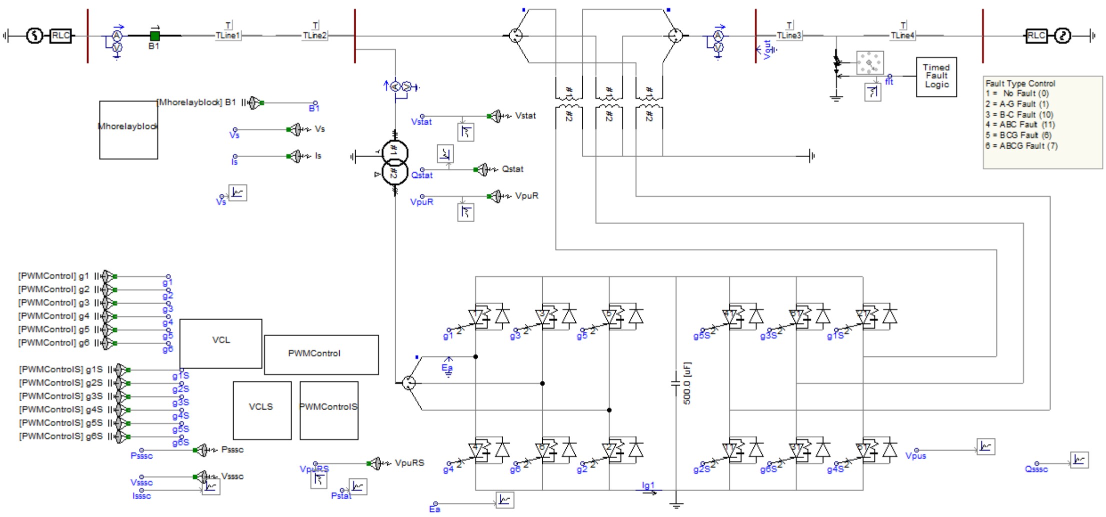


Fig. 1 Model of transmission line with UPFC simulated in PSCAD

UPFC controller’s modeling for both STATCOM and SSSC has been used as presented in [8, 9]. It employs PWM control strategy to generate the firing pulse of converter valves to respond to desired reference settings of voltage and current. Automatic voltage control and automatic power flow modes of UPFC are its most practical operational modes and the rapidly changing reactive shunt current and variable series voltage during these modes presents UPFC as a major source or sink of impedance to the rest of the power system. The effect of UPFC on distance protection of transmission lines during LG fault is analytically presented by the equations below:

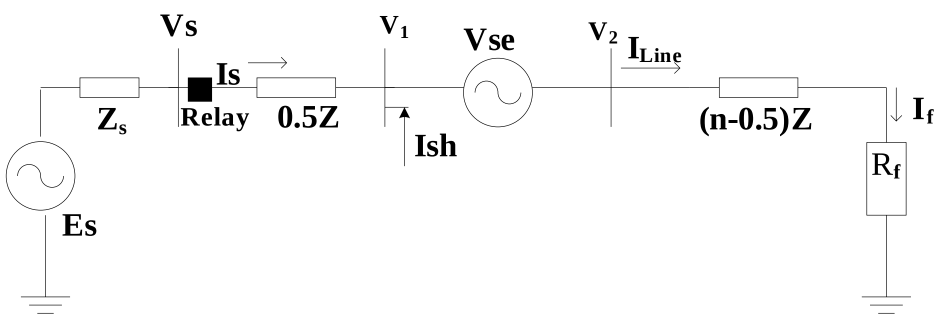


Fig. 2: The single line network of the system from the relay end to the fault end (known as fault loop) when UPFC is at mid-point

The apparent impedance seen by the relay when fault occurs after UPFC is given as:

$$Z = \text{——} \quad n \quad + \text{——} \, (n-0.5) \quad + \text{——} + \text{——} + \quad . \qquad (1)$$

where,

$$I_{relay} = I_s + \frac{Z_0 - Z_1}{Z_1} I_{s0}. \quad (2)$$

When only STATCOM is present then apparent impedance seen by relay is given as,

$$Z = \frac{V_s}{I_{relay}} = nZ_1 + \frac{I_{sh}}{I_{relay}} (n\text{-}0.5) Z_1. \quad (3)$$

Apparent impedance seen by relay in the absence of UPFC is given as,

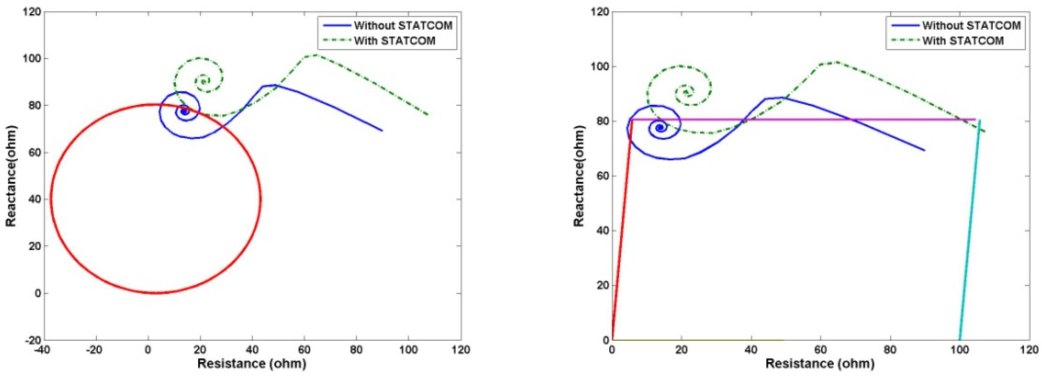
$$Z = \frac{V_s}{I_{relay}} = nZ_1 . \quad (4)$$

V_s and I_s are phase voltage and current at the relay point and I_{s0} is zero sequence phase current, Z_1 and Z_0 are positive sequence and zero sequence impedance of the transmission line, I_{sh} is shunt reactive current injected by UPFC (via STATCOM), V_{se} is series voltage injected by UPFC (via SSSC) and R_f and I_f are fault resistance and fault current respectively. Further, n is per-unit distance of a fault from the relay location.

3. Results and Discussions

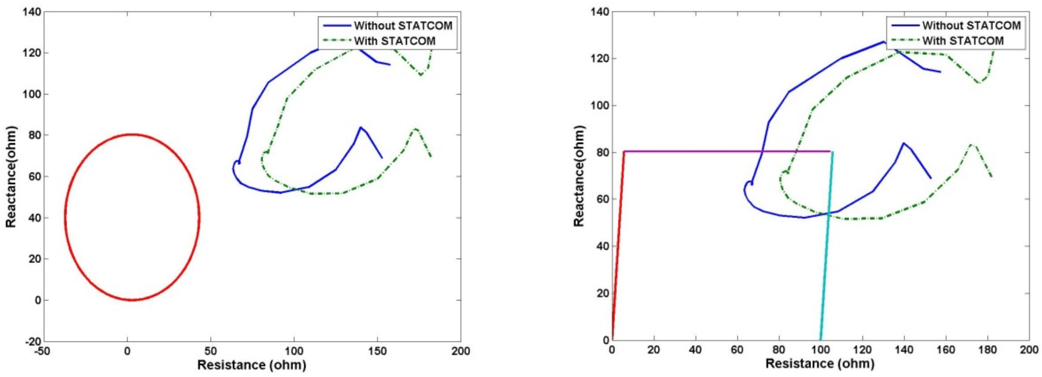
The mho and quadrilateral relays are set for first zone of protection i.e. 80% of positive sequence impedance [2], and their reach setting method is given in [10, 11]. Resistance and reactance is calculated assuming ideal CTs and CVTs at the relay end. The measured impedance trajectory is plotted on the R-X diagram along with ideal characteristics of mho and quadrilateral relays.

Case 1: Voltage regulation mode of UPFC (STATCOM only): When fault resistance is absent and fault loop includes STATCOM (fault location after STATCOM, at160 km), STATCOM regulates the connecting point voltage by injecting reactive current I_{sh} into the line *(Eq. 3)*. This leads to increase in apparent impedance, causing under-reaching of mho relay as shown in *Fig. 3(a)*. The quadrilateral relay on the other hand, is able to detect the fault under such condition (*Fig. 3(b)),* improving dependability of line protection. Magnitude of fault resistance involved in ground fault is always a matter of concern which varies from zero to several ohms. Mho relay is highly affected and mal-operates because of underreaching with increase in fault resistance *(Fig 4(a))*. It is seen that quadrilateral relay is able to enclose the fault region with high fault resistance and hence is more reliable than mho relay *(Fig. 4(b))*.



a. b.

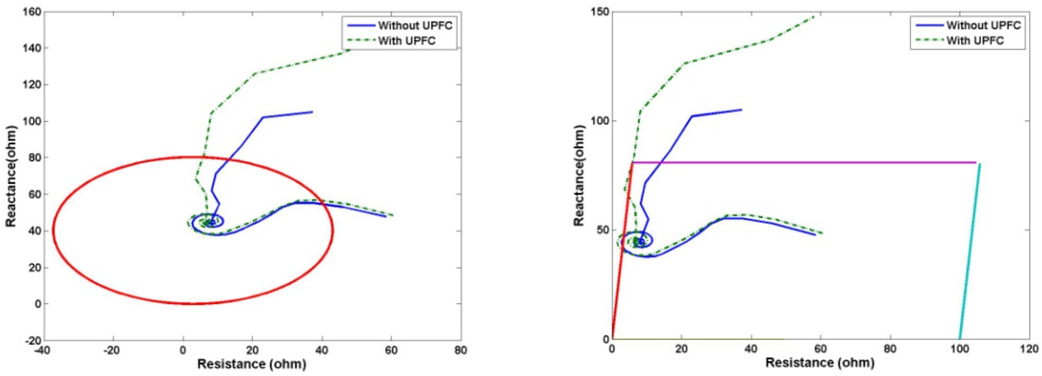
Fig. 3(a) and 3(b): Apparent impedance trajectory with mho and quadrilateral characteristics respectively, with and without STATCOM in absence of fault resistance



a. b.

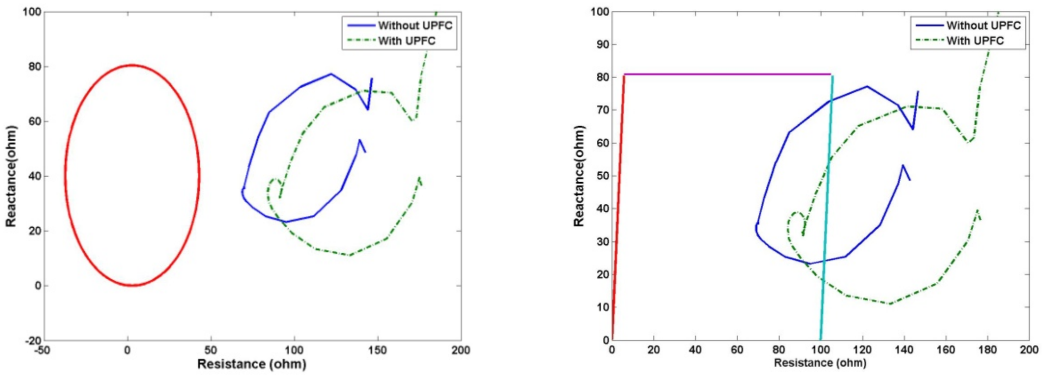
Fig. 4(a) and 4(b): Apparent impedance trajectory with mho and quadrilateral characteristics respectively, with and without STATCOM in presence of fault resistance

Case 2: Power flow mode of UPFC (Full UPFC with both SSSC and STATCOM): When fault loop excludes UPFC (fault location before UPFC, at 90 km) and fault resistance is zero *(Eq. 4),* then the apparent impedance trajectory seen by both the relays is approximately similar with or without UPFC *(Fig. 5(a) and 5(b))*. But the estimated impedance changes widely in the presence of fault resistance *(Fig. 6(a)),* causing mho relay to mal-operate. Hence, fault resistance becomes the major factor in relays' underreaching. To mitigate its effect quadrilateral relay if used, is proved to be highly effective *(Fig. 6(b)).*



a. b.

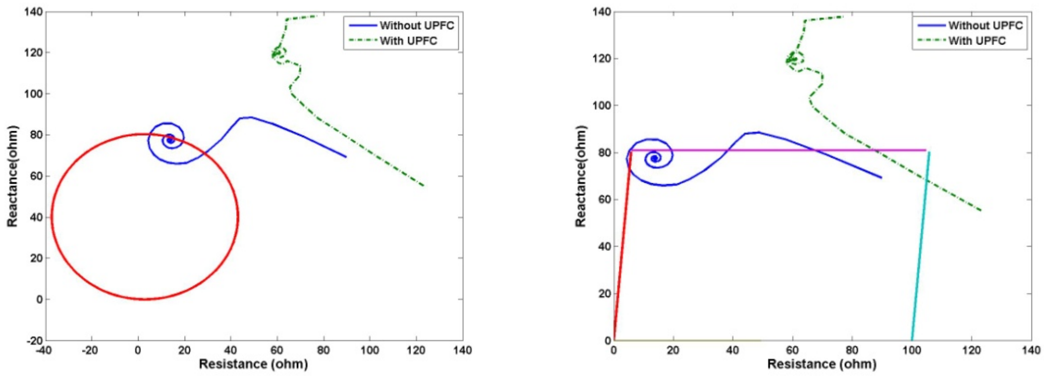
Fig. 5(a) and 5(b): Apparent impedance trajectory with mho and quadrilateral characteristics respectively, with and without UPFC when fault resistance is zero ohm and fault loop excludes UPFC



a. b.

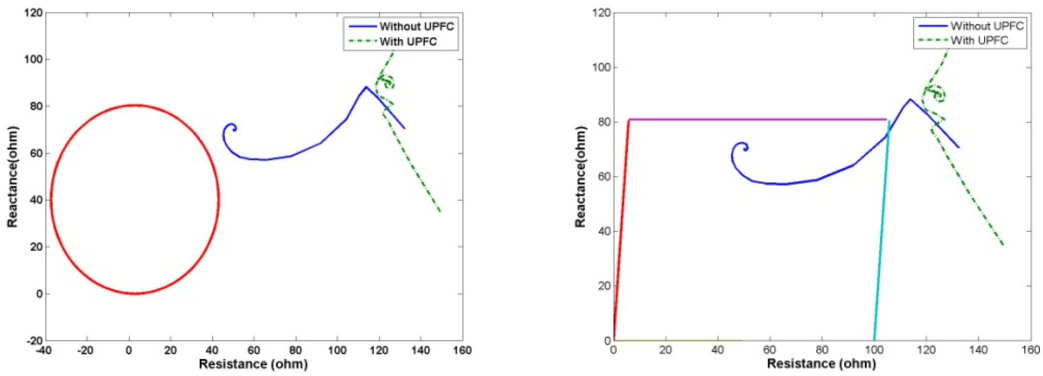
Fig. 6(a) and 6(b): Apparent impedance trajectory with mho and quadrilateral characteristics respectively, with and without UPFC in the presence of fault resistance when fault loop excludes UPFC

When fault loop includes UPFC (fault location at 160 km), the apparent impedance seen by the relay is then given by *Eq. 1*. Due to insertion of magnetizing branch of series transformer of the series converter of UPFC (i.e. SSSC), there is large amount of zero sequence voltage injection into the lines during the most commonly encountered LG fault. Thus, apparent impedance in presence of UPFC is tremendously large. Validation by PSCAD also gives the same results. From *Fig. 3(a)* and *Fig. 7(a)* it is observed that mho relay suffers huge underreaching effect when full UPFC is in operation as compared to the presence of STATCOM only. This also determines effect of the presence of SSSC only, which gives approximately same results as in the presence of UPFC. This due to the fact that the faulted circuit encounters the same series injected voltage via series transformer of SSSC as in UPFC. Hence, it is inferred that collective effect of both SSSC and STATCOM is quite detrimental for mho relay performance. Still quadrilateral relay seems workable in UPFC integrated transmission line, as seen from *Fig. 7(b).* If fault resistance is present and is too high, even quadrilateral relay under-reaches and fails to detect the fault in the presence of UPFC *(Fig. 8(b))*. Overreaching of relay occurs when there is capacitive voltage injection into the lines and is a difficult issue to deal with the conventional fixed operating relay characteristics like mho and quadrilateral.



a. b.

Fig. 7(a) and 7(b): Apparent impedance trajectory with mho and quadrilateral characteristics respectively, with and without UPFC when fault resistance is absent and fault loop includes UPFC



a. b.

Fig. 8(a) and 8(b): Apparent impedance trajectory with mho and quadrilateral characteristics respectively, with and without UPFC when fault resistance is present and fault loop includes UPFC

During phase to phase, double phase to ground and three phase fault, impact of UPFC remain same on the mho and quadrilateral relay performance as in single line to ground fault. The mho relay mal-operates and fails to detect fault during all such types of faults when faulted circuit includes the UPFC. The quadrilateral relay seems to be very effective and reliable during high resistance fault on UPFC incorporated transmission lines, relative to mho relay.

4. Conclusion

UPFC effects for all its mode of operation on distance relays has been investigated thoroughly. Transmission line protection when compensated with UPFC is difficult to achieve with the help of conventional relaying methods. Mho relay undergoes under-reaching and over-reaching problems as has been described. Therefore, the quadrilateral relay seems as a viable alternative to mho relay because of its flexible operating characteristics to cover fault region in the presence of high resistance fault on UPFC compensated transmission lines. But enormously high fault resistance causes relay underreaching and capacitive reactive power exchange via UPFC leading to relay over-reaching. In such case even the quadrilateral relay mal-operates. This invokes the need of going for adaptive trip boundaries generation methods which is able to accommodate the rapidly changing control parameters of UPFC, fault resistance, fault location, change in load angle etc. and correctly gives the tripping decision. Thus distance relaying scheme can further be improved and made reliable by adaptive methods during faults on compensated transmission lines.

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