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Analysis of Over/Under-reaching of Distance Relay on Transmission Line in Presence of UPFC

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ABSTRACT

Due to presence of Flexible Alternative Current Transmission System (FACTS) devices such as Unified Power Flow Controller (UPFC) on transmission line, the measured impedance by the distance relay become lower or higher than the actual line impedance. In this study the influence value of UPFC and System conditions parameters on distance protection is investigated. First the comprehensive equation of impedance seen by the relay in presence of UPFC are derived and then, the accurate percentages of over-reaching or under-reaching corresponding to the variation of the UPFC parameters (voltage magnitude, phase angle) and locations are calculated. The studies also include the different power angles of networks and two types of faults. The analytical results are confirmed by the simulation in PSCAD/EMTDC software environment. For correct performance of distance protection a relaying adaptive scheme is required to cope with the problems of over/under-reaching.

Key words: Distance relay, protection, UPFC, over-reaching, under-reaching

INTRODUCTION

Transmission lines are usually protected by distance relaying techniques. The principle of these techniques is based on measured impedance at the fundamental frequency between the relay point and the fault location. There are different factors affecting the impedance seen by the distance relays (Sissoko *et al*., 2007). An important one of these factors is presence of FACTS devices in transmission lines which have been investigated in recent years in order to enhance the flexibility and controllability of high voltage transmission systems (Arzani *et al*., 2008).

The UPFC is a member of the FACTS family with very attractive features. It consists of a series and a shunt converter connected by a common dc link capacitor can simultaneously perform the function of transmission line real/reactive power flow control. The shunt part of the UPFC controls the UPFC bus voltage/shunt reactive power and the dc link capacitor voltage. The series part of the UPFC controls the transmission line real/reactive power flows by injecting a series voltage with adjustable magnitude and phase angle (Hingorani and Gyugyi, 1999; Papic *et al*., 1997; Gyugyi, 1992). The interaction between the series injected voltage and the transmission line current leads to exchange real and reactive power between the series converter and the transmission line. Under steady state conditions, the real power demand of the series converter is supplied by the shunt converter. During transient conditions, the series converter real power demand is supplied by the dc link capacitor. Because of the presence of FACTS controllers in a fault loop, the voltage and current waveforms at the relay point will be affected in both the steady state and the transient state (Gyugyi, 1992; Khederzadeh, 2002, 2008).

Alternatively, due to the interaction of the UPFC with the transmission system, the transient supper imposed on power frequency voltage and current waveforms (especially under faults) can be significantly different from those systems uncompensated and it yields in quick changes in systems parameters such as line impedance and power angle. Thus, it extremely important and necessary to investigate the impact of the UPFC on the impedance-based distance protection relay, which is the main protective device at EHV and HV levels.

The basic principle of distance protection involves the division of the voltage at the relaying point by the measured current. The apparent impedance so calculated is compared with the reach point impedance. If the measured impedance is less than the reach point impedance, it is assumed that a fault exists on the line between the relay and the reach point. This type of relaying is available for both phase and ground fault protection. The characteristics can be described using an R-X diagram. They provide primary and backup facilities by their three zone elements. In the presence of FACTS devices, the conventional distance characteristic such as Mho and Quadrilateral are greatly subjected to mal-operation in the form of Over-Reaching (OR) or Under-Reaching (UR). In an OR state, distance relay will act incorrectly and due to extension of relay reaching the external faults are seen as internal fault by the relay. Therefore, the conventional characteristics cannot be useful in the presence of FACTS devices (Kazemi *et al.*, 2008). Thus, setting for conventional distance relays must be readjusted to avoid OR/UR operation under the worst case scenarios.

Some papers have studied the effect of shunt devices. Albasri *et al.* (2007) and Sidhu *et al.* (2005) the adverse effect of the only midpoint shunt FACTS devices (Static Var Compensator: SVC and STATic COMpensator: STATCOM) on the performance of distance relay are evaluated. El-Arroudi *et al.* (2002) the impacts of STATCOM on distance relay for normal operating condition as well as for different fault under load angle variations are studied. Zhou *et al.* (2006) and Jamali *et al.* (2009) analytical and simulation results of employing the UPFC, on distance protection are considered. Zhou *et al.* (2006) have investigated only the effects of fault location and voltage magnitude of shunt part of the UPFC but the influence of the load angle variation on the impedance seen by the relay has not considered. The impacts of the following factors for a double circuits transmission line are studied in Jamali *et al.* (2009): fault location, setting parameters of UPFC (phase angle and voltage magnitude) and ground fault resistance, whereas the loading condition are kept constant and its effect on distance relay operation has not studied.

In this study, the three most important and applicable states of UPFC and system parameters are investigated. These states are as follows:

- UPFC location
- Voltage magnitude of UPFC
- Phase angle of UPFC
- Load angle variation

For comprehensive evaluation, the impacts of these states are presented in four case studies. The apparent impedance measured by distance relay in presence of the UPFC is expressed by mathematical equations and the results confirmed by the simulation in PSCAD/EMTDC software environment. It can be seen how much a distance relay is affected in presence of the UPFC at the transmission line.

The OR/UR percentages of distance relay in four case studies are depicted in a bar diagram. Based on obtained percentage of OR/UR, the adaptive schemes of the relay can be designed for reliable performance of distance protection.

THE UPFC MODELING

As shown in Fig. 1, a combination of STATCOM (convertor 1) and a Synchronized Static Series Compensator: SSSC (convertor 2) which are interconnected via a common DC storage capacitor (DC link), to allow bidirectional flow of real power between the SSSC output and the STATCOM output. The UPFC is controlled to provide simultaneous real and reactive series line compensation without an external electric power supply. The UPFC is able to control the transmission line voltage, impedance and angle (v-i-a) or, alternatively, the real and reactive power flow in the transmission line (Hingorani and Gyugyi, 1999; Dash *et al.*, 2000a, b; Johns *et al.*, 1999; Sahoo *et al.*, 2010; Mailah *et al.*, 2008). The second converter, SSSC, injects a variable voltage, in the form of variable magnitude and phase angle. It is represented by the impedance Z_{se} and the voltage source $ke^{j\theta}V_{l1}$.

These converters are operating independently from the reactive power point of view, but the required active power of converter 2 and the losses of both converters, is provided via the converter 1 (Jamali *et al.*, 2006).

The major control functions of a UPFC are: (1) active power regulation; (2) reactive power regulation and (iii) voltage regulation. These control functions are mainly considered under steady-state operation of the power system.

The operation of UPFC during a fault via its control functions is an important issue that affects the protective relay behavior.

In Fig. 2, the shunt and series source models are shown and according to Fig. 2 V_{12} is obtained as $V_{12} = V_{l1}(1+ke^{j\theta})$ where $0 \le k \le k_{max}$ and $0 \le \theta \le 2\pi$. The shunt current I_{sh} is obtained as:

$$I_{sh} = \frac{V_{sh} - V_{l1}}{Z_{sh}} \tag{1}$$

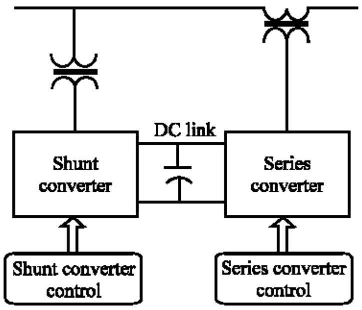


Fig. 1: Circuit arrangement of UPFC

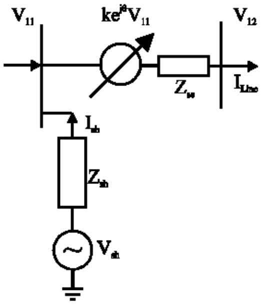


Fig. 2: Equivalent voltage representation of UPFC

where, V_{sh} is the shunt converter voltage controlled by the UPFC and Z_{sh} is shunt impedance. In a three phase UPFC, suitable expression for the constraint equation would be:

$$\mathrm{Real}\{V_{sh}I_{sh}^{*} + V_{se}I_{line}^{*}\} = 0 \tag{2}$$

Figure 2 shows the simplified model that dose not represent, the dc link and the internal controls.

APPARENT IMPEDANCE ANALYSIS

Distance protection determines the fault impedance from the measured short-circuit voltage and current at the relay point. The measured fault impedance is then compared with the known line impedance. If the measured fault impedance is smaller than the set line impedance, an internal fault is detected and a trip command issued to the circuit breaker.

This section presents the mathematical analysis of the effect of the compensation on the apparent impedance seen by the relay. The impedance calculations are derived for the midpoint compensation and the beginning compensation of the transmission line with UPFC. Figure 3 shows the schematic diagram of compensated line for considering distance protection.

For the analysis of the operation of a distance relay in the presence of UPFC as shown in Fig. 3, the relay is installed on the bus A. The apparent impedance calculation is based on symmetrical component transformation using power frequency component of voltage and current signals measured at the relay point (Zhou *et al.*, 2006).

Two hypothetical places of fault (F_A and F_B in Fig. 3) are investigated as follows:

The fault between relay and UPFC: In the transmission system when the fault occurs before UPFC (or without UPFC) for different type of fault (e.g., F_A in Fig. 3), the apparent impedance of distance relay can be calculated using the conventional equations (Ziegler, 2006).

The UPFC between relay and fault: In this situation the UPFC is at the fault path (e.g., F_B in Fig. 3). The apparent impedance seen by the relay is calculated for phase to ground fault and phase to phase fault in sections A and B, respectively.

When the UPFC is installed at midpoint of the line, the positive sequence voltage at the relay point, as shown in Fig. 4, is obtained by Eq. 3. Similarly negative and zero sequences will be calculated (Zhou *et al.*, 2006).

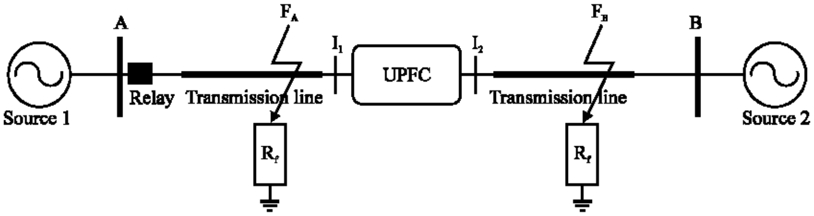


Fig. 3: Sample network used for simulation

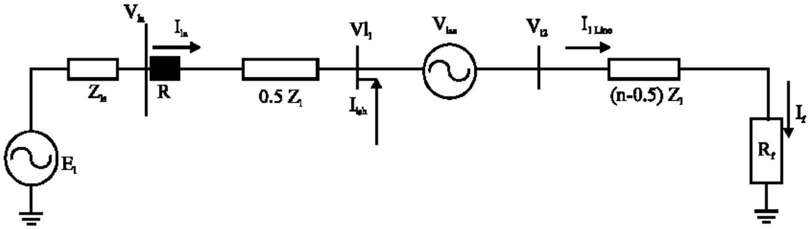


Fig. 4: The positive sequence network of the system from the relay point to fault (UPFC at middle point)

$$V_{1a} = I_{1a} 0.5 Z_1 + V_{1se} + I_{1Line}(n - 0.5) Z_1 + R_f I_{1f} \tag{3}$$

$$V_{2a} = I_{2a} 0.5 Z_1 + V_{2se} + I_{2Line}(n - 0.5) Z_1 + R_f I_{2f} \tag{4}$$

$$V_{0a} = I_{0a} 0.5 Z_1 + V_{0se} + I_{0Line}(n - 0.5) Z_0 + R_f I_{0f} \tag{5}$$

$$I_{1Line} = I_{1a} + I_{1sh} \tag{6}$$

$$I_{2Line} = I_{2a} + I_{2sh} \tag{7}$$

$$I_{0Line} = I_{0a} + I_{0sh} \tag{8}$$

Where:

V_{1a}, V_{2a}, V_{0a} : The sequence phase voltages at the relay location
V_{1se}, V_{2se}, V_{0se} : The series sequence phase voltages injected by UPFC
I_{1a}, I_{2a}, I_{0a} : The sequence phase currents at the relay location
I_{1Line}, I_{2Line}, I_{0Line} : The sequence phase currents in the line
I_{1f}, I_{2f}, I_{0f} : The sequence phase currents of the fault
I_{1sh}, I_{2sh}, I_{0sh} : The shunt sequence phase currents injected by UPFC
Z_1, Z_0 : The sequence impedance of the transmission line
E_1 : The positive sequence of the voltage source
Z_{1s}, Z_{2s}, Z_{0s} : The sequence of the source impedance

n : Per unit distance of a fault from the relay location. n can be varied in range between $0.5 \le n \le 1$, because the fault location is beyond the UPFC
L : The length of the transmission line
n×L : Fault location

First the phase to ground fault is considered. When an L-G fault occurs on the right side of the UPFC and the fault location is n×L from the relay point, the positive, negative and zero sequence circuits of the study case (Fig. 3) during the fault are shown in Fig. 5.

The measured impedance at the relaying point for a phase to ground fault at the transmission line system can be calculated by the following Eq. 9 (Ziegler, 2006):

$$Z_R = \frac{V_a}{I_a - \frac{Z_0 - Z_1}{Z_0} I_{a0}} = \frac{V_a}{I_{realy}} \tag{9}$$

V_a is the voltage at the relay point, according to the sequence circuits shown in Fig. 5.

From Eq. 3-5, it can be derived as:

$$V_a = nI_a + nI_{0a}(Z_0 - Z_1) + I_{sh}(n - 0.5)Z_1 + (n - 0.5)I_{0sh}(Z_0 - Z_1) + V_{se} + R_f I_f \tag{10}$$

Where:

$$V_a = V_{1a} + V_{2a} + V_{0a} \tag{11}$$

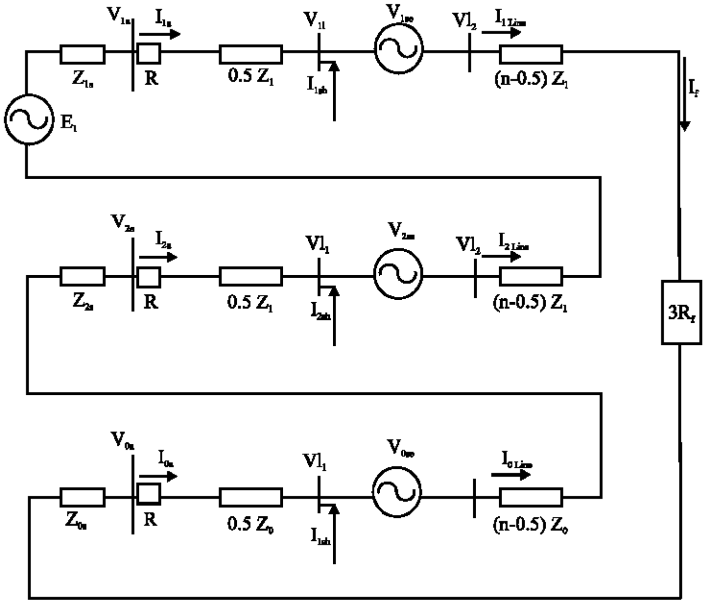


Fig. 5: Sequence circuits for a single phase-to-ground faults

$$I_a = I_{1a} + I_{2a} + I_{0a} \tag{12}$$

$$I_{sh} = I_{1sh} + I_{2sh} + I_{0sh} \tag{13}$$

$$V = V_{1se} + V_{2se} + V_{0se} \tag{14}$$

By substituting Eq. 10 into 9 and after simplifying, the apparent impedance seen by the relay can be obtained by the following equation:

$$Z_R = nZ_1 + \frac{I_{sh}}{I_{relay}}(n-0.5)Z_1 + \frac{I_{0sh}}{I_{relay}}(n-0.5)(Z_0 - Z_1) + \frac{V_{se}}{I_{realy}} + \frac{I_f}{I_{relay}}R_f \tag{15}$$

In equation 15 I_{0sh} is assumed zero, because in practice one side of the shunt transformer is often based on a delta connection.

The measured impedance at the relaying point for a phase to phase fault at the transmission line system can be calculated by the following equation (Ziegler, 2006).

$$Z_R = \frac{V_{a1} - V_{a2}}{I_{a1} - I_{a2}} = \frac{V_b - V_c}{I_b - I_c} \tag{16}$$

Where:

V_b, V_c : Phase voltages

I_b, I_c : Phase currents

Z_R : Measured impedance by the relay

This equation is obtained according to the sequence circuits as shown in Fig. 6.

If the phase to phase fault in the presence of UPFC at the midpoint of transmission line occurs, by substituting Eq. 3 and 4 into 16 and after simplifying, equation of the apparent impedance by the relay will be derived as:

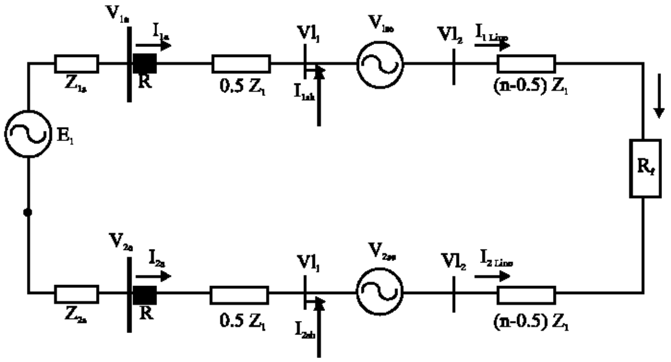


Fig. 6: Sequence circuits for a phase-to-phase faults

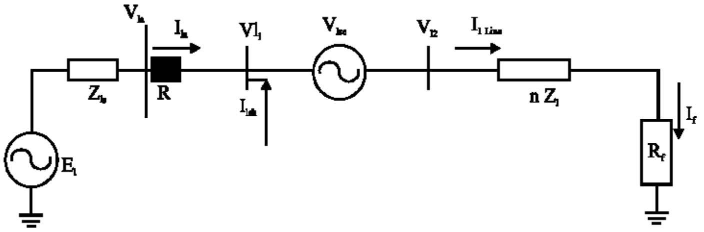


Fig. 7: The positive sequence network of the system from the relay point to fault (UPFC at the beginning of the line)

$$Z_R = nZ_1 + \frac{I_{bsh} - I_{csh}}{I_b - I_c}(n - 0.5)Z_1 + \frac{V_{bse} - V_{cse}}{I_b - I_c} + \frac{I_{bf} - I_{cf}}{I_b - I_c}R_f \tag{17}$$

From Eq. 15 and 17 it can be seen that a UPFC would affect the measured impedance at the relay point by two terms; one results from the shunt current I_{sh}, injected by the STATCOM (shunt compensator) and another is the impact of the series voltage V_{se}, injected by the SSSC. The last term of the apparent impedance is due to the fault resistance.

When the UPFC is installed at the beginning of the line as shown in Fig. 7, with same calculations for apparent impedance at the relay point, Eq. 15 and 17 are modified as Eq. 18 and 19, respectively.

The measured impedance in case of phase to ground faults is as follows:

$$Z_R = nZ_1 + \frac{I_{sh}}{I_{relay}}nZ_1 + \frac{I_{0sh}}{I_{relay}}n(Z_0 - Z_1) + \frac{V_{se}}{I_{realy}} + \frac{I_f}{I_{relay}}R_f \tag{18}$$

The measured impedance in case of phase to phase faults is as follows:

$$Z_R = nZ_1 + \frac{I_{bsh} - I_{csh}}{I_b - I_c}nZ_1 + \frac{V_{bse} - V_{cse}}{I_b - I_c} + \frac{I_{bf} - I_{cf}}{I_b - I_c}R_f \tag{19}$$

By comparison between pair Eq. 15, 18 and 17, 19, n-0.5 change to n that shows the UPFC is installed at the beginning of the line. The impedance calculated by Eq. 18 and 19 are greater than impedance calculated by Eq. 15 and 17. Thus, in the same conditions (k, θ, δ and R_f) the influence of the UPFC at the beginning of the line is higher than when the UPFC is installed at the midpoint of the line. The simulation in next section will be indicated same result.

SIMULATION RESULTS

A: performance evaluation: This section investigates the impact of the UPFC on the transmission line distance relay. If the apparent measured impedance by the relay can reflect the actual impedance between relaying point and fault point, the UPFC will have no effect on distance relay and the distance relay act correctly.

If the apparent measured impedance by the relay cannot reflect the actual impedance due to the presence of the UPFC, the distance relay will act incorrectly (Dash *et al.*, 2000a,b).

The sample system shown in Fig. 3 is used for the simulation. PSCAD/EMTDC is used to model a 230-kV transmission system that a UPFC is installed at the beginning and also in the middle of the transmission line. The 200-km 230-kV transmission line is terminated in the two sources with the two angle difference of 20 and 40°.

The compensation percent is such that the line voltage (any fault does not exist) is in the allowed range. The simulation time step length is 0.05 m sec.

The positive and negative sequence line impedances are 0.01787+j0.2538 and the zero sequence transmission line impedance is 0.181606+j0.66323.

In this study the first zone (Z_1) of the relay is set to detect faults on 85% of the protected line without any intentional time delay. A phase to ground fault is assumed to be occurred at a distance of 85% the line length from the relay point.

The impact of the UPFC location and different system operational conditions (load angle) are evaluated. Here four cases are introduced as follow:

- **Case 1:** The UPFC is installed at the beginning of the line with the angle difference of 20°
- **Case 2:** The UPFC is installed at the beginning of the line with the angle difference of 40°
- **Case 3:** The UPFC is installed at the midpoint of the line with the angle difference of 20°
- **Case 4:** The UPFC is installed at the midpoint of the line with the angle difference of 40°

Case 1: The values of k and θ of the UPFC are varied between 0-0.5 and 0-270°, respectively. In this case the load angle is 20° and the fault resistance is assumed to be 25Ω for all cases. Table 1 shows the reach setting of mho distance relay for resistance and reactance values.

From Table 1, the relay in the case of θ = 0° and the variation of k between 0.1- 0.5 per unit is over-reached. When θ is assumed 90° with variation of k between 0.2-0.5, relay is over- reached too. Whereas at k = 0 the relay will be in the risk of over-reach. On other hand, at θ = 270° with changing k in the normal range of 0.2-0.5 per unit, the relay becomes under-reached whereas for k = 0 there is risk of under-reach.

Case 2: From Table 2, it can be seen when the load angle increase, the present of over-reaching at the different values of k and θ becomes greater. Therefore the distance relay over-reaching depends on power system condition.

Table 1: UPFC at the beginning of the line with δ = 20° and R_f = 25Ω

k θ	0.1	0.2	0.3	0.4	0.5
θ = 0°	30% (OR)	47.4% (OR)	56.3% (OR)	61% (OR)	65.5% (OR)
θ = 90°	(Risky OR)	10.1% (OR)	15.2% (OR)	20.22% (OR)	24.89% (OR)
θ = 270°	(Risky UR)	12.5% (UR)	18.1% (UR)	25% (UR)	27.2% (UR)

Table 2: UPFC at the beginning of the line with δ = 40° and R_f = 25Ω

k θ	0.1	0.2	0.3	0.4	0.5
θ = 0°	36% (OR)	52.3% (OR)	61.5% (OR)	68.7% OR)	70.1% (OR)
θ = 90°	17% (OR)	20.5% (OR)	27.3% (OR)	30.1% (OR)	32.7% (OR)
θ = 270°	(Risky UR)	(Risky UR)	10.2% (UR)	19.8% (UR)	23.1% (UR)

Table 3: UPFC at the midpoint of the line with δ = 20° and R_f = 25Ω

k θ	0.1	0.2	0.3	0.4	0.5
θ = 0°	13.1% (OR)	24.6% (OR)	31.5% (OR)	36.6% (OR)	40% (OR)
θ = 90°	(Risky OR)	11.3% (OR)	18.5% (OR)	24.7% (OR)	30.1% (OR)
θ = 270°	(Risky UR)	13% (UR)	21.5% (UR)	30.4% (UR)	35.5% (UR)

Table 4: UPFC at the midpoint of the line with δ = 40° and R_f = 25Ω

k θ	0.1	0.2	0.3	0.4	0.5
θ = 0°	20% (OR)	28.1% (OR)	41.5% (OR)	47.7% (OR)	49.8% (OR)
θ = 90°	14.1% (OR)	20.5% (OR)	26% (OR)	32.3% (OR)	38.1% (OR)
θ = 270°	(Risky UR)	(Risky UR)	12.1% (UR)	25.2% (UR)	28.9% (UR)

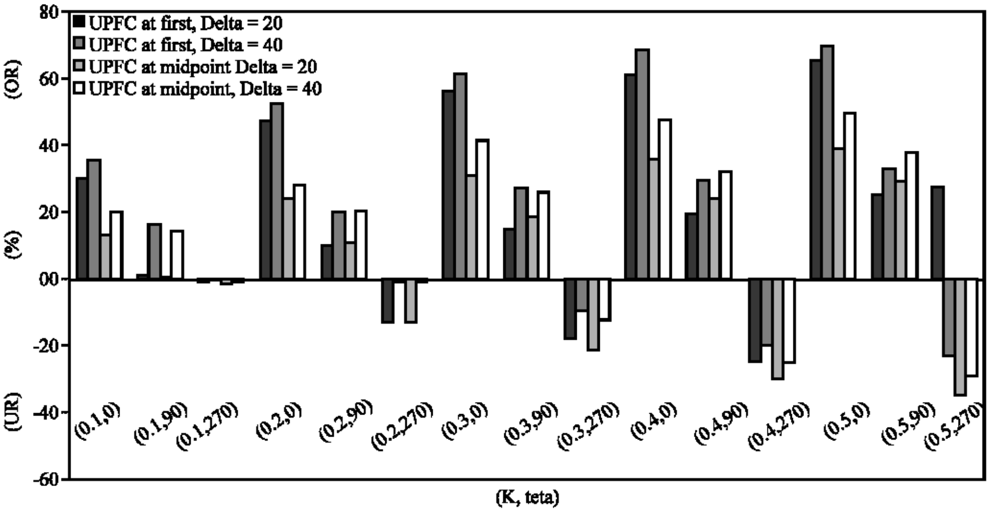


Fig. 8: The bar diagram of all calculated results related to four cases

Case 3: Table 3 shows the impact of location. In this case the UPFC is installed at the midpoint of the transmission line. The simulation results in compared to case 1, when the UPFC is located at the midpoint of line the percent of over-reaching decreased.

Thus the under-reaching percent becomes greater.

Case 4: In this case the UPFC location is same as case 3 but the load angle is increased to be 40°. The results Table 4 confirms the impact of load angle increasing on the distance relay maloperation due to greater over-reach percent.

For the better comparison of the distance relay over/under-reaching percentage, the calculated results in four above cases are depicted in a bar diagram as shown in Fig. 8. The positive and negative percentages, indicate the values of OR and UR, respectively.

This diagram shows that the maximum percentage of OR in case2 and the maximum percentage of UR in case3, are occurred. Due to the change of the UPFC location, from the middle of the transmission line to beginning of it, the similar results are obtained (i.e., increasing of over-reaching).

The measured impedance by the distance relay in normal state of the transmission line (without UPFC) is equal to nZ_1. With respect to the Eq. 15, 17, 18 and 19, when the load angle increase or the UPFC location change, from midpoint to beginning of the line, the impedance seen by the distance relay becomes smaller than nZ_1, therefore the percentage of OR increase that it confirmed by simulation results.

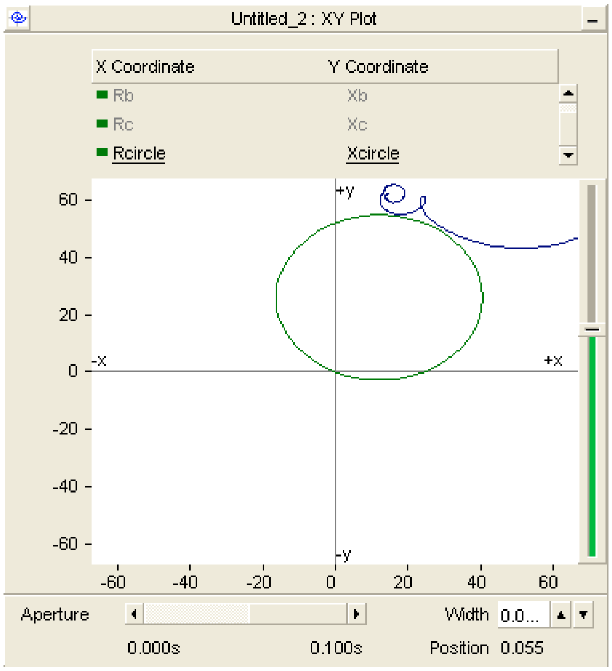


Fig. 9: Impedance trajectory in the absence of UPFC

Impedance trajectory characteristics: The impedance characteristics can be described using the R-X diagram. Following a disturbance the distance relay at different locations will observe different swing characteristics in the R-X plane and if a swing trajectory enters zone 1, then it is considered as Severe enough to cause system instability and the relay will trip.

By keeping the fault resistance, the same impedance trajectories can be generated when the location of the UPFC is varied along the line and a single line to ground fault is occurred under different power angle. The location of the UPFC is assumed to be at the beginning and midpoint of the line.

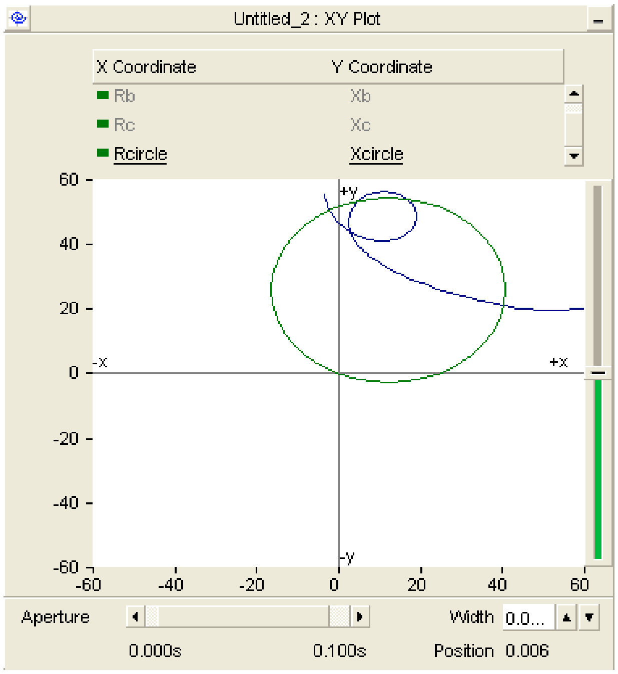
Figure 9 depicts the impedance characteristic in the absence of the UPFC for phase to ground fault at 90% length of the line. Figure 9 clearly shows that the distance relay does not see the fault at zone 1, because 85% length of line is protected.

The UPFC exchanges active and reactive power by regulating the series injected voltage. For considering effect of the UPFC location and power angle, four cases are studied as fallows:

A : UPFC is installed at the beginning of the line, $\delta = 20°$
B : UPFC is installed at the beginning of the line, $\delta = 40°$
C : UPFC is installed at the midpoint of the line, $\delta = 20°$
D : UPFC is installed at the midpoint of the line, $\delta = 40°$

In all above cases k and θ are assumed to be 0.3 and 0°, respectively.

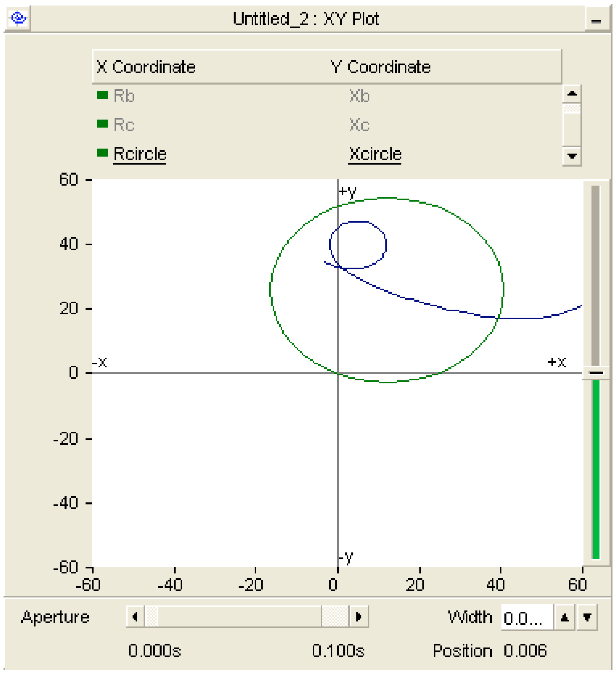
Figure 10 and 11 show the simulation of case A and case B, respectively. Comparison between Fig. 10 and 11 show the effect of the variation of power angle on the measured impedance, with the same parameters of UPFC. Here, the power angle takes the values 20 and 40°. It can be seen that, the greater load angle cause to the increasing of over-reaching percent.



X Coordinate	Y Coordinate
🟩 Rb	Xb
🟩 Rc	Xc
🟩 Rcircle	Xcircle

Width 0.0...
Position 0.006

Fig. 10: UPFC is installed at the beginning of line, δ = 20°, k = 0.3 and θ = 0°

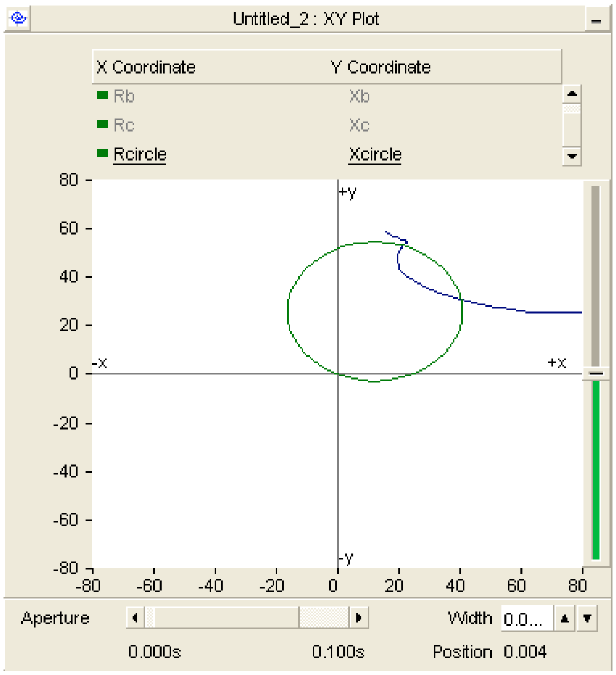


X Coordinate	Y Coordinate
🟩 Rb	Xb
🟩 Rc	Xc
🟩 Rcircle	Xcircle

Width 0.0...
Position 0.006

Fig. 11: UPFC is installed at the beginning of line, δ = 40°, k = 0.3 and θ = 0°

Figure 12 and 13 show the simulation of case C and case D, respectively. The comparison between these Figures and Fig. 10, 11 shows the effect of the UPFC location on the impedance

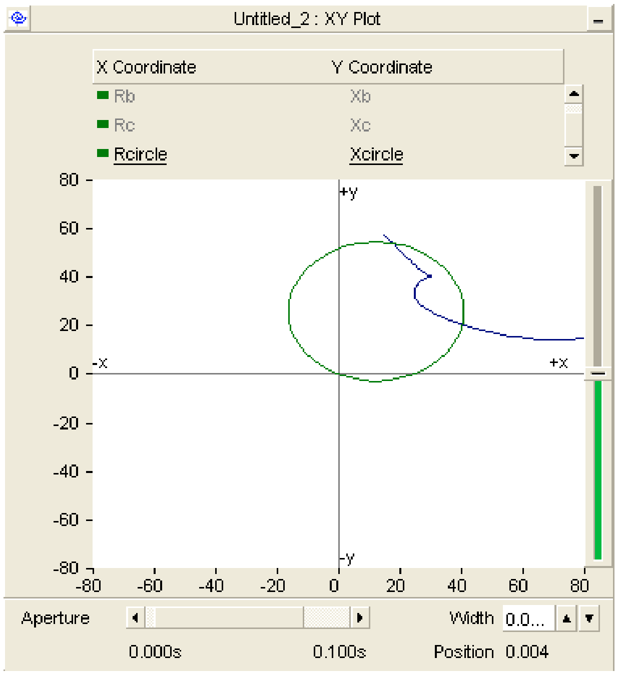

Untitled_2 : XY Plot

X Coordinate	Y Coordinate
Rb	Xb
Rc	Xc
Rcircle	Xcircle

Width 0.0...

Position 0.004

Fig. 12: UPFC is installed at the midpoint of line, δ = 20°, k = 0.3 and θ = 0°


Untitled_2 : XY Plot

X Coordinate	Y Coordinate
Rb	Xb
Rc	Xc
Rcircle	Xcircle

Width 0.0...

Position 0.004

Fig. 13: UPFC is installed at the midpoint of line, δ = 40°, k = 0.3 and θ = 0°

trajectory. It can be seen that, when the UPFC is located at midpoint of transmission line, it leads to lower risk of over-reaching.

CONCLUSIONS

This study considered the effects of the UPFC on measured impedance by distance relay. Influence of the UPFC is investigated by mathematical analysis and the software simulation. The impact of the UPFC location, UPFC parameters (voltage magnitude and phase angle) and system condition (load angle) are studied. The related results are obtained for two types of phase to ground and phase to phase fault. Here, the fault resistance is assumed to be constant. The mathematical analysis and simulation results show that the severity of the relay over-reaching is increased with rising of load angle and voltage magnitude of the UPFC. It also indicates that percent of relay over-reaching is decreasing with higher value of the UPFC phase angle. When the UPFC is installed at the beginning of the line, the impedance seen by the distance relay is greater with compared to line midpoint location of the UPFC.

REFERENCES

Albasri, F.A., T. Sidhu and R.K. Varma, 2007. Performance comparison of distance protection schemes for shunt-FACTS compensated transmission lines. IEEE Trans. Power Delivery, 22: 2116-2125.

Arzani, A., M. Jazaeri and Y. Alinejad-Beromi, 2008. Available transfer capability enhancement using series FACTS devices in a designed multi-machine power system. Proceedings of the 43rd International Universities Power Engineering Conference, Sept. 1-4, Semnan University, pp: 1-6.

Dash, P.K., A.K. Pradhan, G. Panda and A.C. Liew, 2000a, b. Adaptive relay setting for flexible AC transmission systems (FACTS). IEEE Power Eng. Soc. Winter Meeting, 15: 38-43.

Dash, P.K., A.K. Pradhan, G. Panda and A.C. Liew, 2000a, b. Digital protection of power transmission lines in the presence of series connected FACTS device. Proceedings of the IEEE Power Engineering Society Winter Meeting, Jan 23-27, Regional Engineering College, Rourkela, pp: 1967-1972.

El-Arroudi, K., G. Joos and D.T. McGillis, 2002. Operation of impedance protection relays with the STATCOM. IEEE Trans. Power Delivery, 17: 381-387.

Gyugyi, L., 1992. Unified power flow control concept for flexible AC transmission systems. IEE Proc., 139: 323-331.

Hingorani, N.G. and L. Gyugyi, 1999. Understanding FACTS: Concepts and Technology of Flexible AC Transmission System. 1st Edn., IEEE Press, New York.

Jamali, S., M. Kalantar and H. Shateri, 2006. Effects of instrument transformers location on measured impedance by distance relay in presence of UPFC. Proceedings of the IEEE Power India Conference, April 10-12, New Delhi, pp: 6-6.

Jamali, S., A. Kazemi and H. Shateri, 2009. Effects of UPFC on measured impedance by distance relay in double-circuit lines. Proceedings of the IEEE Power and Energy Society General Meeting, July 26-30, Tehran, Iran, pp: 1-8.

Johns, A.T., A. Ter-Gazarian and D.F. Warne, 1999. Flexible ac Transmission Systems. Wiley-IEEE Press, Padstow.

Kazemi, A., S. Jamali and H. Shateri, 2008. Voltage inversion due to UPFC presence on second circuit of double circuit transmission line causing distance relay mal-operation. Proceedings of the IEEE Power Engineering Society Winter Meeting, June 30-July 2, Iran University of Science and Technology, Tehran, pp: 384-389.

Khederzadeh, M., 2002. The impact of FACTS devices on digital multifunctional protective relays. Transmission Distribution Conf. Exhibition IEEE PES, 3: 2043-2048.

Khederzadeh, M., 2008. UPFC operating characteristics impact on transmission line distance protection. Proceedings of the IEEE Power and Energy Society General Meeting- Conversion and Delivery of Electrical Energy in the 21st Century, July 20-24, Pittsburgh, PA., pp: 1-6.

Mailah, N.F., S.M. Bashi, N. Mariun and I. Aris, 2008. Simulation of a three-phase multilevel unified power flow controller UPFC. J. Applied Sci., 8: 503-509.

Papic, I., P. Zunko, D. Povh and M. Weinhold, 1997. Basic control of unified power flow controller. IEEE Trans. Power Syst., 12: 1734-1739.

Sahoo, A.K., S.S. Dash and T. Thyagarajan, 2010. Power flow study including FACTS devices. J. Applied Sci., 10: 1563-1571.

Sidhu, T., R.K. Varma, P. Gangadharan, F. Albasri and G. Ortiz, 2005. Performance of distance relays on shunt-FACTS compensated transmission lines. IEEE Trans. Power Delivery, 20: 1837-1845.

Sissoko, S.B., A.N. Abdalla, J. Zhang and S.J. Cheng, 2007. Graph partitioning applied to fault location in power transmission lines. J. Applied Sci., 7: 2327-2332.

Zhou, X., H. Wang, R.K. Aggarwal and P. Beaumont, 2006. Performance evaluation of a distance relay as applied to a transmission system with UPFC. IEEE Trans. Power Delivery, 21: 1137-1147.

Ziegler, G., 2006. Numerical Distance Protection Principles and Applications. Siemense Aktiengesellschaft, Wiley and Sons, Berlin, Germany, ISBN 3-89578-266-1.