Mapping Based Technique for Distance Relays Setting in Presence of IPFC

Iraj Ahmadi  Non-member  (Tarbiat Modares University)
Ali Yazdian Varjani  Non-member  (Tarbiat Modares University)
Mojtaba Khederzadeh  Non-member  (Power and Water University of Technology)

Keywords: apparent impedance trajectory, distance relay, interline power flow controller, mapping based setting

Flexible AC Transmission System (FACTS) devices have been used to increase power transfer capability and to allow operation on the limits of long transmission lines.

The Interline Power Flow Controller (IPFC), consisting of several series converters, is a new device within the FACTS family which injects series voltage of variable magnitude and phase angle on related transmission lines. IPFC ability to solve power system congestion management problems and total active power loss minimization at the same time make it attractive to use in new power systems. Although FACTS devices like Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) introduce great benefits in power system operation and control, they cause some problems especially in power network protection systems operation, so the operation of distance relays, as the backup or in some cases as the main protective devices of EHV lines, are severely affected by FACTS devices.

A few solutions have been suggested to mitigate impacts of various FACTS devices on transmission systems protection, but the impact of IPFC on transmission systems protection has not yet been addressed. In this paper, along with analytical formulation of IPFC impacts on distance relays, a new technique for distance relay setting in presence of IPFC has been presented. The proposed technique employs active and reactive power injected by series converters to adjust first zone boundaries of distance relay by mapping so that the new boundary has the most overlap with impedance region.

Simulation results of a four bus system, including a two-converter IPFC, depicted in Fig. 1, have been used to study impacts of IPFC on distance relay seen impedance and to show the efficiency of the proposed technique.

It is shown for different injected series voltage of IPFC converters, distance relay seen impedance area may shifts up, down, right or left. Also it is shown presence of IPFC on fault loop not only affects on protective relays of the faulted lines, but also on adjacent lines protective relays.

As a solution VT relocation was also considered and it has been shown that VT relocation is not a total solution to overcome the problem.

As the main solution a new technique for distance relay setting in presence of IPFC has been presented. The technique uses active and reactive power injected by series converters to move and map distance relays tripping characteristic on impedance region of the line. The technique needs offline calculations, so it does not increase relays computational burden significantly. The efficiency of the proposed technique on a four bus model system has been shown by simulation and discussed for different types of fault. It has been shown the relay with mapped tripping characteristic behaves better than conventional relay characteristic. Except slightly over-reaches, no other mal-operation was observed for relay with mapped characteristic.

Fig. 1. Power system comprising two converters IPFC
Mapping Based Technique for Distance Relays Setting in Presence of IPFC

Iraj Ahmadi* Non-member
Ali Yazdian Varjani† Non-member
Mojtaba Khederzadeh** Non-member

In this paper, a new technique is proposed for distance relays setting in presence of Interline Power Flow Controller (IPFC). IPFC presence in power network impacts on conventional protection systems, particularly distance relays. The main impact of IPFC on distance relays is to deviate impedance region seen by distance relays from relays tripping characteristic. The proposed technique employs active and reactive power injected by series converter to adjust distance relay first zone boundaries by mapping so that the new boundary has the most overlap with impedance region. Since the technique needs off-line calculations, it does not impose significant computational burden on the relay during the fault. The efficiency of the proposed technique is shown by simulation results of a four bus system containing a two-converter IPFC.

Keywords: apparent impedance trajectory, distance relay, interline power flow controller, mapping based setting

1. Introduction

Flexible AC Transmission System (FACTS) devices have been used to increase power transfer capability and to allow operation on the limits of long transmission lines (1). Although FACTS devices like Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) introduce great benefits in power system operation and control, they cause some problems especially in power network protection systems operation. The operation of distance relays, as the backup or in some cases as the main protective devices of EHV lines, are severely affected by FACTS devices (2).

Impacts of Static Var Compensators (SVC) and Static Compensators (STATCOM) on distance relays over/under reaches and on detection of faulted phases have been studied in Ref. (3), where use of communication based protection schemes have been suggested to overcome the problems. In Ref. (4), it has been shown that setting value of distance relay in presence of UPFC is bigger than the case with no UPFC, but no setting approach or impact of UPFC controlling mode on relay setting has been discussed. The problems of transmission lines protection systems raised by employing UPFC have been presented analytically in Ref. (5), without presenting any setting approach to mitigate the case. Impacts of different operating mode of STATCOM and SSSC working individually and in combination as a UPFC on distance relay have been studied in Ref. (6), and the effect of STATCOM settings and fault location on distance relay seen impedance have been discussed. Also it has been shown that by subtracting the zero sequence voltage of SSSC from relay voltage, improvement on distance relay performance can be achieved through shifting impedance trajectory to the relay tripping boundary.

The Interline Power Flow Controller (IPFC), consisting of several series converters, is a new device within the FACTS family which injects series voltage of variable magnitude and phase angle on related transmission lines (6). IPFC ability to solve power system congestion management problems and total active power loss minimization at the same time has been studied in Ref. (8). An intelligent adaptive controller for IPFC is designed in Ref. (9) to improve the transient stability performance of power systems. In Ref. (10) a novel power injection model of IPFC to be used in power flow analysis has been developed and the power flow control capability of IPFC has been exhibited. Impact of various configurations of New York Power Authority (NYPA)'s Convertible Source Converter (CSC) on voltage, small signal and transient stability studies were presented in Ref. (11), where it is shown all CSC configurations, including IPFC configuration, improve the voltage stability margin of the system. Although impacts of IPFC on power system control and management have been addressed by researchers, its impacts on other equipments, especially on protection systems, are yet to be studied.

A few solutions have been suggested to mitigate the impact of various FACTS devices on transmission systems protection, but the impacts of IPFC on transmission systems protection has not yet been addressed. It can be anticipated that like other FACTS controllers, especially SSSC, IPFC affects protection systems, but the main differences are as follows: (a) active power injection by IPFC series converters and (b) effect of second line converter operating conditions on the seen impedance of faulted line relay.

In this paper, along with analytical formulation of IPFC impacts on distance relays, a new technique for distance relay

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* Department of Electrical Engineering, Tarbiat Modares University
† Tehran, Iran
** Department of Electrical Engineering, Power and Water University of Technology
Teheran, Iran

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setting in presence of IPFC has been presented. The proposed technique employs active and reactive power injected by series converters to adjust first zone tripping boundaries of distance relay by mapping so that the new boundary covers the whole impedance region seen by the relay. Since the technique negates off-line calculations, relay computational burden is not increased significantly. Simulation results of a four bus system have been used to show the efficiency of the proposed technique.

2. Analytical Study of IPFC Impact on Distance Relays

In its general form, IPFC comprises a number of SSSC, which are linked together at their DC terminals. Each series converter injects a series voltage with controllable magnitude and phase to its own transmission line. In this scheme, in addition to providing series reactive compensation, any converter can be controlled to supply active power to the common DC link. Thus, the overall surplus power made available from the underutilized lines, can be used by other lines for active power compensation.

A power system including a two-converter IPFC, with a fault at point F of line LAB, is depicted in Fig. 1. IPFC installed at bus A comprises two converters, Con.B and Con.C, injecting series voltages V_SEB and V_SEC to lines LAB and LAC respectively. Converter Con.B is arbitrarily selected to be the prime converter whose injected voltage vector can be selected freely in a circular area and as a result, the active and reactive power of line LAB can be set freely at their reference values P_{B ref} and Q_{B ref} respectively. Since converter Con.C should supply active power demand of converter Con.B, only one component of V_SEC (active or reactive component) can be controlled freely to set active or reactive power of line LAC at its reference value (here reactive power of line LAC is set at Q_{C ref}).

2.1 Apparent Impedance Analysis

Operation of distance relays are based on apparent impedance measurement at the relay installation point. Apparent impedance calculation is based on symmetrical component transformation, using power frequency components of voltage and current signals measured at the relay installation point. In this section the impact of IPFC on conventional distance relay is shown by apparent impedance analysis. A Single Line to Ground (SLG) fault at point F of line LAB in Fig. 1 is considered. Fault resistance is supposed to be R_f. IPFC converters model consists of a voltage source behind the impedance of coupling transformer. Fault location distance from relay R_{AB} is p*L, where L is the length of line LAB and p is per-unit distance (0 ≤ p ≤ 1).

The equivalent circuit of faulted system is depicted in Fig. 2. Regarding Fig. 2, the apparent impedance seen by the relay R_{AB} for a single line to ground fault is:

\[
Z_{R_{AB}} = pZ_{L_{AB}} + Z_{SEC} + \frac{3R_t - K_{OAB}C_{OAB}Z_{SEC} - CV_Fs e^{j\beta_S}}{C_{I_{slab}} + 2C_{I_{lab}} + C_{OAB}(1 + K_{OAB})} \]  \hspace{1cm} \text{(1)}

Where Z_{L_{AB}}, Z_{SEC} and R_t are positive sequence impedance of line L_{AB}, converter Con.B coupling transformer impedance and fault resistance respectively in ohms.

Other parameters of Eq. (1) are defined in appendix A. Equation (1) shows the impedance seen by distance relay is not equal to value which the distance relay is set to measure i.e. pZ_{1LAB}, even if the fault resistance is regarded zero.

To study IPFC operation impact on distance relay, the series voltages of two converters should be selected in a manner that exchanged active powers are balanced. Thus the following equation set should be solved.

\[
\begin{align*}
    h_t & = Z_{L_{LAB}}(I_{L_{LAB}} + I_{L_{sec}}) + (V_{p-seb} + jV_{q-seb}) \\
    & - (Z_{L_{LAB}} + Z_{SEC})I_{L_{sec}} - h_b = 0 \\
    h_t & = Z_{L_{LAC}}(I_{L_{LAC}} + I_{L_{sec}}) - (Z_{L_{LAC}} + Z_{SEC})I_{L_{LAB}} - h_c \\
    & - Re\{(V_{p-sec} + jV_{q-sec})I_{L_{LAB}}\} + jQ_{sec} \\
    I_{L_{sec}} & = 0
\end{align*}
\]  \hspace{1cm} \text{(2)}

Where the superscript * denotes conjugate operator and V_p-seb and V_q-seb: Active and reactive component of V_{SEC}. Q_{sec}: Reactive power injected by converter Con.C, I_{L_{LAB}}, I_{L_{LAC}}: Currents flowing lines L_{LAB} and L_{LAC}. Z_{L_{LAB}}, Z_{L_{LAC}} and Z_{L_{LAC}}: Positive sequence impedance of lines L_{LAB}, L_{LAC} and L_{LAC} respectively, h_t, h_b and h_c: Per unit voltages of buses T, B and C respectively based on bus A phase to ground voltage.
To show the difference between relay seen impedance and its characteristic, the impedance region seen by distance relay \( R_{AB} \) is derived for different operating conditions of converter \( \text{Con}B \) and depicted in Fig. 3. Here, the impedance region is the area created by \( p \) ranging from 0 to 0.8 and \( R_f \) within 0 to 50 ohms.

Table 1 shows the magnitudes of active and reactive component of arbitrary selected \( \text{VSEB} \) and calculated \( \text{VSEC} \) in per unit, based on system phase to ground voltage. Transmission lines data are presented in appendix B.

In Fig. 3 distance relay impedance region without IPFC is depicted too. As it can be seen, for different injected series voltage of IPFC converters, distance relay seen impedance area may shift up, down, right or left. Among these shifts left shift has the most serious effect, because it causes all length of the line to be left unprotected for low resistance faults. The next worst shift is down shift, since it causes faults in the first part of the line that produce higher fault currents, not to be sensed by the relay. Also down shift could cause losing the selectivity in the form of forward zone over-reach.

In addition to shift, IPFC presence causes distance relay seen impedance to be rotated and resized in comparison with impedance region without IPFC. So presence of IPFC can cause distance relay \( R_{AB} \) to mal-operate in many aspects. To better show the impedance region deviation, curves around zero point have shown in a separate rectangle.

Presence of IPFC on fault loop (the path between relay installation point and fault point) not only affects on protective relays of the faulted lines, but also on adjacent lines protective relays. Fig. 4 shows distance relays \( R_{AC} \) and \( R_{AT} \) seen impedance when faults have occurred on line \( L_{AB} \). In this case, faults occurring within 1.19% of line \( L_{AB} \) length are sensed as forward zone fault by relay \( R_{AC} \). Comparing Figs. 4(a) and (3) shows distance relay \( R_{AC} \) misunderstanding backward faults as forward fault still remains. Also this solution will not influence on far end relays seen impedance. Fig. 5 shows distance relay \( R_{AC} \) seen impedance after VT relocation, when faults occurred on line \( L_{AB} \). In this case, voltages of the first row of Table 1 are again used. As it can be seen, relay \( R_{AC} \) senses behind faults as forward faults. In this case, faults occurring within 1.19% of line \( L_{AB} \) length are sensed as forward zone fault by relay \( R_{AC} \). Comparing Figs. 4(a) and (3) shows distance relay \( R_{AC} \) misunderstanding backward faults as forward faults is mitigated but not disappeared, so VT relocation is not a total solution to overcome problems raised by IPFC.

3. Proposed Setting Technique to Mitigate IPFC Impact on Distance Relays

Conventional distance relay setting is carried out based on apparent impedance seen by the relay in three phase fault conditions\(^{12}\). In presence of IPFC, because of difference between the impedance seen by distance relay and its tripping boundary, conventional setting method should be modified.

3.1 Conventional Setting Considerations

Figure 6 shows the equivalent sequence network of power system depicted in Fig. 1, for a three phase fault occurred at point F of
line $L_{AB}$.

In Fig. 6 $E_{th}$ and $Z_{th}$ are equivalent source and positive sequence impedance of network behind bus A. The apparent impedance seen by distance relay $R_{AB}$ can be expressed as follow:

$$Z_{R_{AB}} = pZ_{L_{AB}} + Z_{SEB} - \frac{V_{SEB}}{\Delta Z_{SC}}$$

$$= pZ_{L_{AB}} + Z_{SEB} + \Delta Z_{R} \quad \text{.......... (3)}$$

Equation (3) shows that in presence of IPFC and in three phase fault conditions, two additional terms i.e. $Z_{SEB}$ and $\Delta Z_{R}$, appear in distance relay seen impedance, where $Z_{SEB}$ is a constant value and $\Delta Z_{R}$ is a variable term. $\Delta Z_{R}$ is proportional to the injected voltage of series converter and reverse of short circuit currents. This variable term introduces variable shift in distance relay seen impedance area, so to overcome the problem it is necessary the relay to be aware of the value of this term. In other words, if $\Delta Z_{R}$ is known, it is possible to change distance relays tripping boundaries to mitigate IPFC impact on distance relay.

To formulate $\Delta Z_{R}$ the circular operating area of converter $Con_B$ is depicted in Fig. 7.

In Fig. 7 the circular arc $Q_{IPFC} = 0$ (dashed arc), whose center is located at the middle of the linkages line between voltage phasors $V_A$ and $E_B$, specifies the trajectory of the phasor $V_{SEB}$ in phase with respective line current. It means if the end point of the phasor $V_{SEB}$ stays on the mentioned arc the reactive power exchange of converter $Con_B$ is zero.

The circular operating area of converter $Con_B$ is sectionized into four sub-areas by the linkages line between voltage phasors $V_A$ and $E_B$ and the circular arc $Q_{IPFC} = 0$. Phasor diagram of $V_{SEB}$ in each sub-area is shown in Fig. 7. In sub-areas 1 and 2 (Fig. 7(a)) where $V_{SEB}$ is denoted as $V_{SE1}$ and $V_{SE2}$ respectively, converter $Con_B$ injects active power, but in areas 3 and 4 (Fig. 7(b)) where $V_{SEB}$ is denoted as $V_{SE3}$ and $V_{SE4}$, converter $Con_B$ absorbs active power. Also in areas 2 and 3, converter $Con_B$ injects reactive power, but in areas 1 and 4 absorbs reactive power.

In Fig. 7(a) $I_1$ represents the line $L_{AB}$ current when converter $Con_B$ operates on sub-areas 1 or 2, also In Fig. 7(b) $I_2$ represents the line $L_{AB}$ current when converter $Con_B$ operates on sub-areas 3 or 4. According to Fig. 7, in each operating area $V_{SEB}$ can be decomposed into two components $V_p$ and $V_Q$ that are in phase and in quadrature with line current respectively. If line current passing through relay is selected as reference vector, in each sub-area $\Delta Z_{R}$ can be expressed as below.

$$\Delta Z_{R1} = \frac{-V_{P1} + jV_{Q1}}{|I|} = \frac{-P_1 + jQ_1}{|I| |V_{SC}| < (-90 - \theta_1)}$$

$$= \frac{-jP_1 + Q_1}{|I||I_{SC}| < (-90 - \theta_1)}$$

$$\Delta Z_{R2} = \frac{-V_{P2} + jV_{Q2}}{|I|} = \frac{-P_2 - jQ_2}{|I| |I_{SC}| < (-90 - \theta_1)}$$

$$= \frac{-jP_2 + Q_2}{|I||I_{SC}| < (-90 - \theta_1)}$$

$$\Delta Z_{R3} = \frac{-V_{P3} - jV_{Q3}}{|I|} = \frac{P_3 + jQ_3}{|I| |I_{SC}| < (-90 - \theta_1)}$$

$$= \frac{jP_3 + Q_3}{|I||I_{SC}| < (-90 - \theta_1)}$$

$$\Delta Z_{R4} = \frac{-V_{P4} + jV_{Q4}}{|I|} = \frac{P_4 - jQ_4}{|I| |I_{SC}| < (-90 - \theta_1)}$$

$$= \frac{jP_4 + Q_4}{|I||I_{SC}| < (-90 - \theta_1)} \quad \text{.......... (4)}$$

Where

$V_{P_i}, V_{Q_i}, i = 1, 2, 3, 4$: Active and reactive component of $V_{SEB}$ in sub-area $i$,

$\Delta Z_{R_i}, i = 1, 2, 3, 4$: Impedance term showing IPFC impact on distance relay,

$P_i, Q_i, i = 1, 2, 3, 4$: Converter $Con_B$ injected active and reactive power in sub-area $i$. 

---

Fig. 7. Phasor diagram of $V_{SEB}$ in four operating areas of IPFC.

(a) Operating areas 1 & 2

(b) Operating areas 3 & 4
Regarding converter active and reactive power and selecting power injection direction as positive direction, four parts of Eq. (4) can be summarized as follow:

\[
\Delta Z_R = \left( \frac{Q_C - jP_C}{|I| |I_{SC}|} \right) < \theta
\]
\[
= \frac{[Q_C \cos(\theta) + P_C \sin(\theta)] + j [Q_C \sin(\theta) - P_C \cos(\theta)]}{|I| |I_{SC}|} \tag{5}
\]

### 3.2 Proposed Setting Technique

If after any changes in each converter injected power, \( \Delta Z_R \) is calculated and fed to the relay, it is possible to change relay tripping characteristic to have the most overlap with impedance region. All parameters of Eq. (4) can be measured at relay installation point except \( I_{SC} \). Because of stochastic characteristic of fault current, it is not possible to use exact \( I_{SC} \) to calculate \( \Delta Z_R \) before fault occurrence. In this paper, regarding converter conditions, maximum or minimum values of fault currents extracted from load flow and fault studies have been used. After any changes in network configuration these values are calculated by computer simulation and fed to the relay. When impedance region shifts left (i.e. when the real part of the numerator of Eq. (5) is negative), all length of the line will be left unprotected for low resistance faults if tripping region of distance relay shifts less than impedance region. For the case of down shifting of impedance region (i.e. when the imaginary part of the numerator of Eq. (5) is negative), the problem also remains. To achieve the most overlap with impedance region and to leave no part of the line unprotected in these two cases, \( I_{SC-min} \) should be used in \( \Delta Z_R \) calculation. But in two other cases, if \( I_{SC-min} \) is used, the tripping region displacement may exceed impedance region displacement and cause some part of line remain unprotected. In this way, when impedance region shifts right or up, \( I_{SC-max} \) should be used in \( \Delta Z_R \) calculation.

As mentioned earlier, \( P_C \) and \( Q_C \) are the injected active and reactive power of converter respectively that can be calculated in each relay. Fig. 8 shows the block diagram of the procedure of these calculations for relays \( R_{AB} \) and \( R_{AC} \).

In this figure, \( P_{R_{AB}} \) and \( Q_{R_{AB}} \) are active and reactive power passing through relay \( R_{AB} \) respectively, also \( Q_{R_{AC}} \) is reactive power passing through relay \( R_{AC} \). These powers are measured internally within relays and then are subtracted from reference values to result pure active and reactive injecting power of each converter.

The flow chart of the procedure is shown in Fig. 9. The decision box (rhombus) in Fig. 9 ensures no changes in tripping boundaries during transient conditions when \( \Delta Z_R \) oscillates.

### 4. Simulation Results

To show the efficiency of proposed technique to mitigate IPFC impact on distance relays, different types of fault are simulated using PSCAD/EMTDC software and the results are presented. Some considerations about models used in simulations are mentioned below.

Transmission System Employing a Two Converter IPFC:

Power system depicted in Fig. 1 is used in simulations. System voltage is 230 kV. The angle difference of sources \( T \), \( B \), and \( C \) respect to bus \( A \) are +25°, −30° and −25° respectively. As mentioned earlier the impedance data of transmission lines are presented in appendix B. IPFC included in power system consists of two converters that are modeled as three phase voltage sources having maximum amplitude of 0.12 pu based on phase to ground voltage. Converter \( Con_B \) injecting \( V_{SEB} \) to line \( L_{AB} \) is arbitrarily selected to be the prime converter.
**IPFC Control:** The control system of IPFC can be divided into two parts, the control of prime converter and the control of secondary converter. Prime converter control strategy is to set active and reactive power of line \( L_{AB} \) on desired values. To achieve this goal, desired active and reactive power of line \( L_{AB} \) are compared with measured values and the errors are used to derive the magnitude and phase angle of series voltage source of prime converter. To control the secondary converter, it should be noticed that this converter should supply active power demand of prime converter, so the error signal obtained from comparison of injected active powers of two converters (prime and secondary converters) and the other error obtained from comparison of desired and measured reactive power of line \( L_{AC} \), are used to derive the magnitude and phase angle of series voltage source of secondary converter.

**Distance Relay:** Distance relay takes use of FFT algorithm with sampling rate of 128 samples per cycle to obtain phasors of voltage and current signals. The impedance protection region used for this simulation is based on a quadrilateral characteristic with a positive sequence voltage polarization.

### 4.1 IPFC Operation

**IPFC** is started to operate at \( t = 0.3 \text{ Sec} \) and by controlling it, active and reactive power of line \( L_{AB} \) is increased from 220 MW to 250 MW and from \(-64 \text{ Mvar} \) to \(-50 \text{ Mvar} \) respectively, also reactive power of line \( L_{AC} \) decreased from \(-66 \text{ Mvar} \) to \(-76 \text{ Mvar} \). Active and reactive power of lines \( L_{AB} \) and \( L_{AC} \) and injected active and reactive power of converter \( Con_B \) are depicted in Fig. 10.

### 4.2 Fault Studies

To show the impact of IPFC on distance relay \( R_{AB} \) and the efficiency of proposed technique to mitigate this impact, different types of fault are simulated. For each fault type, two different fault locations, one near to the converter installing point (at 3.33% of line length from the relay installation point) and the other at the end of zone 1 of distance relay (at 80% of line length from the relay installation point) are considered. The real and imaginary parts of \( \Delta Z_R \) are negative, considering converter \( Con_B \) power exchanges depicted in Fig. 10(c), so the tripping region of distance relay \( R_{AB} \) should be shifted left and down simultaneously. Apparent impedance trajectory for all cases accompanied by ideal and post movement quad characteristics of distance relay is shown in Figures below. For more clarity, the final impedance area is zoomed in a separate rectangle.

**Three phase fault:** For three phase fault conditions apparent impedance trajectories are shown in Fig. 11. As it can be realized from Fig. 11, if distance relay characteristic does not move, relay will not sense three phase faults occurred on all length of the line but after relay characteristic movement, the impedance trajectory falls into the relay quad boundary. Since in most cases, three phase faults produce highest fault currents, relay mal-operation could expose system stability to risk, so relay correct operation in this case, achieved by proposed method, is very important. Fig. 11(b) shows distance relay with modified characteristic over-reaches (line \( H_m \)) too. The reason is, during the fault \( P_c \) and \( Q_c \) of the convertor are not the pre-fault values (used to calculate \( \Delta Z_R \)), so the displacement of impedance region is bigger than the calculated value. Nevertheless the over-reach of the modified characteristic relay is less than the case with normal characteristic (line \( H_n \)) and limited to 6.7% of line length.

**Single Phase-to-Ground Fault:** In this case the apparent impedance trajectories are shown in Fig. 12. Like the three phase fault case, here again distance relays characteristic should be moved and mapped on impedance region of the line to sense fault correctly. In this case, the over-reach of modified characteristic distance relay is about 28% of line length. Although this is a high over-reach situation, it is less than the case with normal characteristic.

**Two phase fault:** For two phase fault conditions apparent impedance trajectories are shown in Fig. 13. Like the other cases, distance relays characteristic should be moved and mapped on impedance region of the line to sense faults correctly. In this case, the over-reach of modified characteristic distance relay is limited on 4% of line length. Table 2 shows the summary of results for all types of faults.
5. Conclusion

In this paper, impacts of IPFC on distance relays have been analytically formulated and shown by simulation. It was shown that in presence of IPFC and regarding converters operating conditions, distance relay will face problems such as over-reach, not sensing faults occurred near relay installation point and not sensing low resistance faults at all length of the line. As a solution VT relocation was also considered and it has been shown that VT relocation is not a total solution to overcome the problem. As the main solution a new technique for distance relay setting in presence of IPFC has been presented. The technique uses active and reactive power injected by series converters to move and map distance relays tripping characteristic on impedance region of the line. The technique needs offline calculations, so it does not increase relays computational burden significantly. The efficiency of the proposed technique on a four bus model system has been shown by simulation and discussed for different types of faults. It has been shown the relay with mapped tripping characteristic behaves better than conventional relay characteristic. Except slightly over-reaches, no other mal-operation was observed for relay with mapped characteristic.

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Appendix

1. Lines and Sources Impedance Data

The parameters used in Eq. (2) are defined as below:

\[
E_T = h_1e^{j\delta} \quad \text{(A1)}
\]

\[
E_B = h_0e^{j\delta_0} \quad \text{(A2)}
\]

\[
E_C = h_2e^{j\delta} \quad \text{(A3)}
\]

\[
V_{EB} = r_0e^{j\rho} \quad \text{(A4)}
\]

\[
V_{EC} = r_0e^{j\rho} \quad \text{(A5)}
\]

\[
K_{0AB} = \frac{Z_{0AB} - Z_{1AB}}{Z_{1AB}} \quad \text{(A6)}
\]

\[
Z_T = Z_{ST} + Z_{TFA} \quad \text{(A7)}
\]

\[
Z_C = Z_{SC} + Z_{SEC} + Z_{DAC} \quad \text{(A8)}
\]

\[
Z_{dA} = Z_{dA} + Z_{SEP} + pZ_{dAB} \quad \text{(A9)}
\]

\[
Z_{tB} = Z_{tB} + (1 - p)Z_{tAB} \quad \text{(A10)}
\]

\[
Z_{tAB} = \frac{Z_{tA} + Z_{tB}}{Z_{tA} + Z_{tB}} \quad \text{(A11)}
\]

\[
K_{ih} = \frac{Z_{ih} + Z_{ih}}{Z_{1A} + Z_{1B}} \quad \text{(A12)}
\]

\[
C_V = \frac{(Z_{1A} + Z_{1B})(2Z_{1AB} + Z_{1AB} + 3R_f)}{Z_{1B}K_{ih} + Z_{1A}h_0e^{j\rho}} \quad \text{(A13)}
\]
2. Lines and Sources Impedance Data
The transmission system used in simulation has the following data.

<table>
<thead>
<tr>
<th>Component</th>
<th>Data</th>
<th>$Z_2$ (Ω)</th>
<th>$Z_3$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line $L_{AB}$</td>
<td>12.696 + 75.752 * i</td>
<td>53.429 + 154.521 * i</td>
<td></td>
</tr>
<tr>
<td>Line $L_{AC}$</td>
<td>10.157 + 60.602 * i</td>
<td>42.743 + 123.617 * i</td>
<td></td>
</tr>
<tr>
<td>Line $L_{BC}$</td>
<td>10.157 + 60.602 * i</td>
<td>42.743 + 123.617 * i</td>
<td></td>
</tr>
</tbody>
</table>

app. Table 1. Lines and sources impedance data

<table>
<thead>
<tr>
<th>Component</th>
<th>Data</th>
<th>$Z_2$ (Ω)</th>
<th>$Z_3$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source T</td>
<td>4.629 + 9.252 * i</td>
<td>1.307 + 7.046 * i</td>
<td></td>
</tr>
<tr>
<td>Source B</td>
<td>5.824 + 15.351 * i</td>
<td>1.978 + 11.611 * i</td>
<td></td>
</tr>
<tr>
<td>Source C</td>
<td>3.402 + 9.123 * i</td>
<td>1.134 + 6.106 * i</td>
<td></td>
</tr>
<tr>
<td>Coupling Transformers</td>
<td>3 * i</td>
<td>3 * i</td>
<td></td>
</tr>
</tbody>
</table>

app. Table 2. Sources and coupling transformers impedance data

Iraj Ahmadi (Non-member) was born in Iran. He obtained his B.Sc. degree in Electronic Engineering from Amir Kabir University of Technology (Tehran Polytechnic) in 1996 and M.Sc. degree in Electrical Engineering from K.N. Toosi University of Technology in 1999, Tehran, Iran, respectively. Presently he is a Ph.D. student in Tarbiat Modares University, Tehran, Iran.

Ali Yazdian-Varjani (Non-member) was born in Iran. He obtained B.Sc. degree in Electrical Engineering from Sharif University of Technology and M.Sc. and Ph.D. degrees in Electrical Engineering from the University of Wollongong, Australia. Dr. Yazdian is presently an assistant professor at the Department of Electrical Engineering at Tarbiat Modares University, Tehran, Iran. His research interests include power quality, power system protection and digital signal processing.

Mojtaba Khederzadeh (Non-member) received B.Sc. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, in 1980, M.Sc. degree in electrical engineering from Tehran University, Tehran, in 1990, and Ph.D. degree in electrical engineering from Sharif University of Technology in 1996. Currently, he is an Associate Professor and Director of Power System Protection and Control Researches in the Department of Electrical Engineering of Power and Water University of Technology, Tehran, Iran. His research interests include power system protection, control and monitoring; and power system dynamics.