Variation of UPFC controllable parameters during power swing and their impacts on distance relay

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Abstract: Unified power flow controller (UPFC) has impact on the performance of distance relay during power swing. Generally, power system’s parameters oscillate during power swing and since UPFC operation depends on some of these parameters (bus voltage, active and reactive power), the UPFC injects oscillated series voltage and draws oscillated shunt current. These oscillating series voltage and shunt current influence distance relays, as the impedance seen by a distance relay during power swing changes in UPFC-compensated lines. This study shows how and why series voltage and shunt current change during power swing. Moreover, the admittance swing characteristic is proposed in this study and effects of series and shunt branches of UPFC on the admittance seen by a distance relay during power swing have been examined.

1 Introduction

Generally, it is necessary to evaluate the impacts of flexible AC transmission systems (FACTS) devices on distance relays in different conditions of power system (steady state, fault, transient and power swing). Since FACTS devices lead to variations of line current and bus voltage, they affect the performance of a distance relay during different conditions [1–5].

Unified power flow controller (UPFC) is a widely known FACTS device used to control the power flow of a transmission line and to improve the system stability. In lines with UPFC, a conventional distance relay is influenced in the form of over-reaching or under-reaching the fault point during a short-circuit event [6, 7]. Many publications are devoted to the evaluation of the performance of distance relay applied for protection of a line compensated by FACTS devices. In [8, 9], the impacts of UPFC on distance relays are discussed and an adaptive protection scheme based on phase component approach and an adaptive protection scheme using artificial neural network are proposed, respectively. In [10], it is demonstrated that static VAR compensator (SVC) and static synchronous compensator (STATCOM) cause mal-operation of the distance relay in calculating the impedance, faulty-phase detection and also delays in operation. In [11], an adaptive scheme is proposed for protection of transmission line with SVC to mitigate the mal-operation of distance relay. Reference [12] presents a new algorithm based on synchronised measurement for adaptive setting of distance relay in transmission line compensated by STATCOM. In [13], the impacts of different modes of thyristor controlled series compensation (TCSC) on distance relay are analysed. In [14], a new method is proposed based on post-fault data for fault analysis in compensated line by TCSC. A method based on average of voltage and current and according to superimposed current in TCSC-compensated line is proposed in [15]. In [16–19], the effects of series compensations on the performance of the distance relay are examined.

In spite of extensive research on the impacts of FACTS devices in the performance of distance relay during a fault, limited works report their impacts during a power swing. For example, three methods for power swing detection, impedance decrease, swing centre voltage and power derivative are studied in [20] for fixed capacitor compensated lines. A method based on negative sequence component is proposed in [21] to discriminate the power swing from a fault in a fixed capacitor compensated line. In [22], the impacts of UPFC on the power swing impedance characteristics are examined, i.e. the variations of the radius and the centre point of circular characteristic are studied. It is shown that parameters of transmission line (ABCD) would change in the presence of UPFC. On the basis of the definitions of these parameters and the steady-state model of UPFC, new parameters (A'B'C'D') are extracted containing the data of UPFC.

In this paper, the behaviour and performance of UPFC is examined during power swing by analysing the variations of UPFC controllable parameters (series voltage and shunt current). The variations of these parameters are formulated in this paper and it is demonstrated that consideration of these parameters as constant values leads to invalid results (will be explained next) during power swing. Another contribution of this paper is proposing admittance swing characteristic to make analysis easier. Since it is possible to analyse series and shunt branches impacts individually in admittance plane, this plane has been selected and power swing admittance characteristic is proposed in this paper. Finally, the impacts of variations of controllable parameters of UPFC on admittance seen by distance relay are investigated in this paper.

Different cases are defined in simulation section to examine the performance of UPFC in different ways. Two different power systems are used in simulation section. The first one is two-machine equivalent system and the second one three-machine power system. According to these two power systems, five cases (Case 1, Case 2, Case 3, Case 4 and Case 5) are defined. The first four cases (Cases 1–4) analyse the performance of UPFC in two-machine equivalent system in different conditions (phasor model of UPFC and power swing in steady-state condition, phasor model of UPFC and power swing is simulated by phase modulation, phasor model of UPFC and power swing is simulated by amplitude modulation, detailed model of UPFC and power swing is simulated by phase modulation). The last case (Case 5) analyses the performance of UPFC in three-machine power system, in which detailed model of UPFC is used and power swing is simulated by triggering and clearing a fault in power system.

2 Power swing admittance characteristic

Nowadays, most distance relays monitor the apparent impedance and make decision based on this parameter. However, our reason for utilisation of admittance in UPFC-compensated line is only to simplify the analysis. The admittance plot is more convenient in UPFC-compensated line because it is possible to separate and so analyses the impact of series and shunt part of UPFC on admittance trajectory.
It is easier to study the effect of power swing on distance relay by considering two-machine equivalent system as shown in Fig. 1a. $E_A$ and $Z_A$ represent an equivalent network on the left-hand side of the transmission line and $E_B$ and $Z_B$ on the right-hand side. $V_i$ leads $V_f$ by the angle $\delta_i$ and $V_f$ is considered as reference. Therefore, admittance seen by the distance relay (in uncompensated line) is (1)

$$\frac{Y_{UN}}{V_{relay}} = \frac{|V_i| |Z_{\delta} - |V_f| |Z_0|}{|V_i| |Z_{\delta}|} Y_{Line} = (1 - (|k_i| L - \delta_i)) \cdot \frac{1}{|Y_{Line}|}$$

where $(|V_i|/|V_f|) = k_i$. On the basis of (1) we have:

(A) Each different ratio of $k_i$ gives a different locus, but all are circles. The same centre of all circles is $(\text{real}(Y_{Line}l), \text{imag}(Y_{Line}l))$ and their radii are $k_i \cdot |Y_{Line}|$. To demonstrate these conclusions, consider division of (1) by $Y_{Line}$ which results in (2)

$$\frac{Y_{UN}}{Y_{Line}} = 1 - k_i \cos \delta_i + j k_i \sin \delta_i = X_i + j Y_i$$

It is obvious the relationship between $X_i$ and $Y_i$ is (3)

$$(X_i - 1)^2 + Y_i^2 = k_i^2$$

By changing $0 \leq \delta_i \leq 2 \pi$, locus of (3) will be a circle with centre in (1, 0) and radius equal to $k_i$. Multiplication of each side of (2) by $Y_{Line}$ gives the locus of $Y_{UN}$. So, the amplitude of every point on circle is multiplied by the $|Y_{Line}|$ and its angle is added to $\angle Y_{Line}$. Finally, the locus of $Y_{UN}$ will be a circle with constant centre in $(\text{real}(Y_{Line}l), \text{imag}(Y_{Line}l))$ and radius equal to $k_i \cdot |Y_{Line}|$. For example, three of these circular characteristics (in terms of $k_i = 0.4, 1, 2.5$) are shown in Fig. 2a.

(B) If the phase difference $(\delta_i)$ is constant and the magnitude ratio $(k_i)$ varies, then the locus of admittance seen by relay is a straight line which is resulted from multiplying a constant complex (CC) value by $Y_{Line}$, which is described in (4)

$$Y_{UN} = (1 - (k_i \cos \delta_i + j k_i \sin \delta_i)) Y_{Line} = CC Y_{Line}$$

For example, four of these straight lines (in terms of $\delta_i = 45^\circ, 135^\circ, 225^\circ, 315^\circ$) are shown in Fig. 2a.

(C) Admittance characteristic of transmission line is straight line which is obtained by inverse of line impedance characteristic. This characteristic is also shown in Fig. 2a.

(D) Different zones of a distance relay will be straight lines perpendicular to admittance characteristic of transmission line. Admittance characteristics of all three zones are shown in Fig. 2a.

To sum up, all four kinds of characteristics mentioned in (A), (B), (C) and (D) sections can be shown in one figure (Fig. 2a). Fig. 2 is also provided to compare the impedance-based and admittance-based swing characteristics. In Fig. 2, there are four sub-figures which are dually inverted of each other in impedance and admittance planes. Figs. 2a and b show the general admittance-based swing characteristic and impedance-based swing characteristic, respectively. Three different zones of distance relay, swing loci of impedance/admittance for four constant values $\delta_i = 45^\circ, 135^\circ, 225^\circ, 315^\circ$, swing loci of impedance/admittance for three constant values $k_i = 0.4, 1, 2.5$. The principle use of these curves is that their interactions with impedance/admittance trajectory serve to make the values of $\delta_i$ and $k_i$ on these curves.

In Fig. 2, sub-figures (c) and (d) show an example of the impedance/admittance trajectory during power swing both for uncompensated ($Z_{UN}/Y_{UN}$) and compensated condition ($Z_{Y}/Y_{Y}$). For instance just consider the uncompensated ones, when $k_i = 1$, impedance/admittance starts from $\delta_i = 45^\circ$ in its first swing, reaches zone 3 and continues going inside of zone 3 and then reaches till maximum $\delta_i = 77^\circ$ and then comes backs and this process continues until it reaches an equilibrium point. Therefore, it is possible to analyse the performance of power system during power swing by both planes (impedance and admittance). However, impacts of series and shunt parts of UPFC on seen admittance are analysable separately, so it is more practical to use admittance plane.

### 3 Admittance seen by distance relay during power swing in UPFC-compensated line

In this section, the admittance seen by a distance relay during power swing is examined. Mathematical equations of voltage and current at relay point are extracted and admittance is calculated based on these two parameters. Moreover, the calculated admittance is analysed to obtain the range of admittance seen by distance relay during power swing when UPFC operates accurately (i.e. in controllable region).

Consider the compensated equivalent system as shown in Fig. 1b. According to this figure, two new parameters, series voltage ($V_{se}$) and shunt current ($I_{sh}$), enter power system as a result of UPFC performance. In this condition, the relay current ($I_{relay}$) is

$$I_{relay} = I_{se} + I_{sh}$$

where $I_{se}$ and $I_{sh}$ are currents of series and shunt branches, respectively. Series current is (6)

$$I_{se} = \frac{|V_f| |Z_{Line}|}{|Z_{Line}|} \left(1 - \frac{V_i}{|V_f|} \right) = \frac{|V_f| |Z_{Line}| + |V_f| |Z_{Line}| \rho_i - |V_f| |Z_{Line}|}{Z_{Line}}$$

where $Z_{Line}$ is the impedance of transmission line, $\rho_i$ is angle $V_{se}$ with respect to reference ($V_f$) and voltage at Bus 2 is $V_f = |V_f| |Z_{Line}|$. The shunt branch of UPFC has two major tasks. The first one is supporting demanded active power for series branch and the second one is injecting/absorbing reactive power at Bus 1. Therefore, the shunt current drawn by shunt branch consists of two parts: one part ($I_{sh}^{\text{upc}}$) is drawn to provide demanded active power for series branch to keep power flow of Bus 2 at its reference value and the other part ($I_{sh}^{\text{upf}}$) is drawn because of reactive power compensation for shunt branch to keep the amplitude of bus.
Admittance-based swing characteristic, impedance-based swing characteristic, example of the admittance trajectory, example of the impedance trajectory

Admittance seen by distance relay during power swing in UPFC-compensated line is (9)

\[ Y_{\text{sh}} = |V_{\text{sh}}| \cdot \angle \theta_{\text{sh}} \]

Admittance seen by distance relay is obtained by \( I_{\text{relay}}/V_{\text{relay}} \) which gives (8)

\[ Y = \frac{I_{\text{relay}}}{V_{\text{relay}}} = \frac{I_s + I_{\text{sh}}}{|V| \cdot |Z| \cdot \delta_i} \]

Therefore, based on (5)–(8), admittance seen by distance relay during power swing in UPFC-compensated line is (9)

\[ Y = Y^{\text{UN}} + Y^{\text{SE}} + Y^{\text{SH}} \]

\[ Y^{\text{UN}} = Y_{\text{Line}} - Y_{\text{Line}} \left( \frac{|V|}{|V|} \cdot \angle \theta - \delta_i \right) \]

\[ Y^{\text{SE}} = Y_{\text{Line}} \left( \frac{|V|}{|V|} \cdot \angle (\rho - \delta_i) \right) \]

\[ Y^{\text{SH}} = \frac{|V|}{|V|} \cdot \angle (\theta_{\text{sh}} - \delta_i) \]

where series voltage is \( V_{\text{se}} = |V_{\text{se}}| \cdot \angle \rho \) and shunt current is \( I_{\text{sh}} = |I_{\text{sh}}| \cdot \angle \theta_{\text{sh}} \). According to (9) and compared to (1), the admittance seen by a distance relay during power swing in compensated lines includes three parts, where one part is the same as uncompensated line \( (Y^{\text{UN}}) \) and the other two parts are resulted from compensating performance of series \( (Y^{\text{SE}}) \) and shunt \( (Y^{\text{SH}}) \) branches of UPFC during power swing.

To analyse admittance seen by distance relay during power swing in UPFC-compensated line, it is better to examine each part individually.

**Part1 \( Y^{\text{UN}} \):** Let it first be assumed that both the injected series voltage \( V_{\text{se}} \) and the shunt current \( I_{\text{sh}} \) are zero. Then, the admittance is similar to (1) described by circles with radius \( k_r \cdot |Y_{\text{Line}}| \) around the centre defined by \( \text{real}(Y_{\text{Line}}), \text{imag}(Y_{\text{Line}}) \) in \( G, B \) plane.

**Part2 \( Y^{\text{SE}} \):** Assume now that \( V_{\text{se}} \neq 0 \) and \( I_{\text{sh}} = 0 \). It follows from (9) that the admittance seen in this condition changes from its uncompensated value as function of magnitude \( (|Y_{\text{Line}}| \cdot |V_{\text{se}}|)/|V| \) and angle \( (\rho - \delta_i - \theta_{\text{Line}}) \), where \( \theta_{\text{Line}} \) is the angle of the line impedance. Since this angle is an unrestricted variable, the boundary of admittance region for this condition is obtained from a complete rotation of phasor with maximum magnitude \( r_i \) \( [r_i \text{ is defined in (10)] \). This region is a circle with a centre defined by \( Y^{\text{UN}} \) and the radius of \( r_i \)

\[ \left( \frac{\text{real}(Y(\delta_i, \rho) - Y^{\text{UN}}(\delta_i))}{|\text{imag}(Y(\delta_i, \rho) - Y^{\text{UN}}(\delta_i))|} \right)^2 = r_i^2 \]

**Part3 \( Y^{\text{SH}} \):** Assume now that \( V_{\text{se}} = 0 \) and \( I_{\text{sh}} \neq 0 \). The same explanation can be made in this condition, with the admittance seen in this condition changing from its uncompensated value as function of magnitude \( (|I_{\text{sh}}|/|V|) \) and angle of \( (\theta_{\text{sh}} - \delta_i) \). In this condition, admittance will be inside of circular region with a centre defined by \( Y^{\text{UN}} \) and the radius of \( r_s \) \( [r_s \text{ is defined in (11)] \). This region can be described by (11)

\[ \left( \frac{\text{real}(Y(\delta_i, \theta_{\text{sh}}) - Y^{\text{UN}}(\delta_i))}{|\text{imag}(Y(\delta_i, \theta_{\text{sh}}) - Y^{\text{UN}}(\delta_i))|} \right)^2 = r_s^2 \]

**TOTAL \( Y \):** Now suppose that \( V_{\text{se}} \neq 0 \) and \( I_{\text{sh}} \neq 0 \). The admittance in this condition will be the accumulation of previous two circular regions creating a larger circular region with a centre defined by \( Y^{\text{UN}} \) and the radius of \( r_s \). This region is
During power swing, by controlling and end of transmission line are equal (uncompensated position. While UPFC operates inside controllable change during time based on UPFC control aims (keep active and shunt current are not CC values and change during power swing. Where compensated line is related to series voltage and shunt current, it is seen by distance relay in UPFC-compensated line deviates from its uncompensated characteristic. However, by entering new complex values (complex series voltage and complex shunt current) in admittance formulation, the admittance seen by distance relay in UPFC-compensated line deviates from its uncompensated characteristic. While UPFC operates inside controllable region, admittance seen by distance relay is inside a circular region with centre on uncompensated line admittance (Y UN) and radius maximum of (r s). The boundary of this region depends on rating of UPFC.

4 Variations of series voltage and shunt current during power swing

Since the admittance seen by a distance relay in UPFC-compensated line is related to series voltage and shunt current, it is necessary to analyse the variations of these parameters during power swing. When a power swing occurs in a line which is compensated by UPFC, the compensation parameters (V se, I sh) change during time based on UPFC control aims (keep active and reactive power at their references). Therefore, series voltage and shunt current are not CC values and change during power swing.

Consider the compensated equivalent system as shown in Fig. 1b with transmission line with impedance Z Line = R + jX. The complex power at Bus 2 (which is controlled by UPFC) is (13)

\[ S_2 = V_2^* J_2 \]

where S 2 is the complex power, V 2 is the voltage phasor and I 2 is the current phasor at Bus 2. Since the line currents at the beginning and end of transmission line are equal (I 2 = I 1), the complex power at Bus 2 is calculated as (14)

\[ S_2 = V_2^* \left( V_1^* - V_1 \right) = \frac{|V_2^*|}{Z_{\text{line}}} \sqrt{V_2^* - V_2} \left| V_2^* \right| \angle \delta_2 - \left| V_1^* \right| \angle 0 \]

On the basis of (14) and by separating the real and imaginary parts, (15) is extracted

\[ \text{real}(S Z_{\text{line}}') = |V_2^*|^2 - |V_1|^2 |V_2 \text{cos}(\delta_2) - |V_1| \sin(\delta_2) \]

\[ \text{imag}(S Z_{\text{line}}') = - |V_1| |V_2| \sin(\delta_2) \]

Since the control aim of UPFC is to keep the active and reactive powers at their reference values (S r = P ref + jQ ref) and according to (15), identity \( \sin^2(\delta_2) + \cos^2(\delta_2) = 1 \) and by some mathematical simplifications we have (16)

\[ a_1 X^2 + b_1 X + c_1 = 0 \]

\[ a_1 = 1 \]

\[ b_1 = - |V_1|^2 - 4 |V_2| \text{imag}(S Z_{\text{line}}') \]

\[ c_1 = \text{real}(S Z_{\text{line}}')^2 + \text{imag}(S Z_{\text{line}}')^2 \]

Therefore, the desired amplitude and phase angle of V 2 (for reaching the desired power flow) are (17) and (18)

\[ |V_2| = \sqrt{\frac{-b_1 \pm \sqrt{b_1^2 - 4a_1c_1}}{2a_1}} \]

\[ \delta_2 = \sin^{-1}\left(\frac{\text{imag}(S Z_{\text{line}}')}{|V_2|^2}\right) \]

According to (17), there are two values for |V 2 | based on being + or in - equation. Selection between these two signs is related to achievement of the control objectives of UPFC. Hence, in order to achieve the desired power flow (P ref and Q ref) at the compensated bus (Bus 2), the amplitude and phase of V 2 have to satisfy (17) and (18), respectively. On the basis of principle of UPFC, phasor of V 2 is provided by adding series voltage to V 1 as (19)

\[ |V_2| \angle \delta_2 = |V_1| \angle \delta_1 + |V_{\text{se}}| \angle \rho' \]

When a power swing occurs, V 2 changes during power swing and consequently V se should change during time [based on (19)] to keep V 2 constant. It is worthy of note that it is assumed changes are inside the controllable region of UPFC, so it can compensate all changes due to power swing. Therefore, the series voltage is controlled voltage source during power swing with amplitude (20) and angle (21)

\[ |V_{\text{se}}(t)| = \sqrt{(|V_2| \cos \delta_2 - |V_1(t)| \cos \delta_1(t))^2 + (|V_2| \sin \delta_2 - |V_1(t)| \sin \delta_1(t))^2} \]

\[ \rho'(t) = \tan^{-1}\left(\frac{|V_2| \sin \delta_2 - |V_1(t)| \sin \delta_1(t)}{|V_2| \cos \delta_2 - |V_1(t)| \cos \delta_1(t)}\right) \]
where \( V_{se}(t) \), \( \rho'(t) \), \( W_1(t) \) and \( \delta(t) \) are time-variant parameters during power swing and \( V_{sh}(t) \) and \( \delta_{sh} \) are time-invariant during power swing.

Shunt current during power swing drawn by the shunt branch of UPFC consists of two parts \( I_{sh}(t) = I_{sh}^{(1)}(t) + I_{sh}^{(2)}(t) \), where \( I_{sh}^{(1)}(t) \) is in-phase with \( V_1 \) to provide demanded active power in series branch, as described by (22)

\[
I_{sh}^{(1)}(t) = \frac{P_{ref}(t) - P_{ref}(t)}{|V_1(t)|} \angle \delta(t) \tag{22}
\]

where \( P_{ref}(t) = |V_{se}(t)| \cdot |I_{sh}(t)| \cos(\rho' - \angle I_{sh}) \) is needed active power in series branch which is assumed equal to \( P_{ref}(t) \). The other part of shunt current \( I_{sh}^{(2)}(t) \) is perpendicular to \( V_1 \) and keeps \( V_{sh}(t) \) constant by reactive power compensation \( (Q_{ref}(t)) \)

\[
I_{sh}^{(2)}(t) = \frac{Q_{ref}(t)}{|V_{sh}(t)|} \angle (\delta(t) \pm 90^\circ) \tag{23}
\]

where \( \pm \) depends on shunt current mode (+ is related to injection of reactive power and - is related to absorbing reactive power). On the basis of (22) and (23), shunt current drawn by UPFC is also time-variant parameter during power swing.

5 Simulation results

Variations of series voltage and shunt current during power swing and the impacts of these variations on admittance seen by a distance relay during steady state and power swing are examined in this section. Both fully detailed model of compensated power system (power system and UPFC) and its simple model are used in this section. The simple model is used at the first to illustrate the theoretical concept more clearly and then detailed model is used to validate the results.

To analyse UPFC performance in different conditions, five different cases are provided. The Case 1 is the assessment of UPFC (phasor model) performance in steady-state condition. The Case 2 is simulation of UPFC (phasor model) performance during power swing (sinusoidal changes of \( \delta \)) and the Case 3 consists in the simulation of UPFC (phasor model) performance during power swing (sinusoidal changes of \( |V_1(t)| \)). Case 4 examines the performance of detailed model of UPFC during power swing and Case 5 simulates three-machine power system with detailed model of UPFC.

5.1 UPFC performance during steady state (investigation by phasor model of UPFC)

Phasor model of UPFC-compensated power system (Fig. 1(b)) is programmed in MATLAB. This model is programmed based on (13)–(23) to model the basic performance of UPFC simply. Data of the power system is presented in the Appendix section. Generators are considered programmed ideal voltage source which has the options of phase and amplitude modulations. Distance relay is installed in Bus 1 and impedance is calculated by phasor of voltage over phasor of current.

5.1.1 Case 1: UPFC performance without power swing (steady-state condition): First, assume there is no power swing in power system (\( \delta = 45^\circ \)). Initially, \( P_{ref} = +0.707 \) pu and \( Q_{ref} = +0.2929 \) pu (these values are related to uncompensated condition). However, at \( t = 0.5 \) s, \( P_{ref} \) is changed to \( +0.72 \) pu and \( Q_{ref} \) is kept constant at \( 0.2929 \) pu. Moreover, since \( V_{sh}(t) \) is equal to its reference value during simulation, \( Q_{sh} \) is zero. Simulation results of this condition are tabulated in Table 1. According to Table 1, two columns are compared and some conclusions and their reasons can be summarised as:

- Since there is no power swing in this condition, amplitude and angle of \( V_1 \) are constant.
- To track new reference values for active and reactive powers flowing at Bus 2, UPFC forces \( V_1 \) to change (Its angle is increased and its amplitude is decreased compared with uncompensated condition). Voltages of both columns are shown in Fig. 4a.
- On the basis of calculated series voltage and current, series active power \( (P_{se}) \) is calculated by UPFC. This is \( -0.032 \) pu in compensated condition, which shows that direction of active power inside UPFC block is from series to shunt branch.
- Since amplitude of \( V_1 \) equals to reference value \( (V_{ref} = 1 \) pu), reactive power compensation of shunt branch \( (Q_{sh}) \) is zero, second part of shunt current \( (I_{sh}^{(2)}) \) is zero and just first part \( (I_{sh}^{(1)}) \) of shunt current is present. On the basis of (16), since \( P_{se} \) is zero, angle of shunt current \( \angle I_{sh}^{(1)} = -135 \) = 45° - 180°. Moreover, amplitude of shunt current \( (I_{sh}^{(1)}) \) increases to 0.032 because of increasing in active power in compensated column of Table 1.
- Active and reactive powers at Bus 2 equal reference values, as a result of meeting UPFC control aims.
- The active power at Bus 1 is the same as Bus 2 in both columns of Table 1, because shunt active power \( (P_{sh}) \) and series active power \( (P_{se}) \) are equal.
- The admittance seen by a distance relay changes when reference values of UPFC change. The impact of UPFC on admittance seen by distance relay when reference value of UPFC change is shown in Fig. 4b. According to this figure, uncompensated admittance \( (Y_{UN}) \) is \( 0.7075 - 0.2929 \) pu. However, the admittance in compensated condition \( (Y) \) changes to 0.72 – 0.2662 pu, which is the summation of series admittance \( (Y^{sh}) \), shunt admittance \( (Y^{sh}) \) and uncompensated admittance \( (Y^{UN}) \).
5.2 UPFC performance during power swing (investigation by phasor model of UPFC)

Generally, power swing is created when two generators or groups of generators are fluctuating with respect to each other. So, the resultant signal in this condition is superposition of two signals with different frequencies as (24)

\[ y(t) = A_a \cos(\omega_a t + \phi_a) + A_b \cos(\omega_b t + \phi_b) \]  

(24)

where \( A_a \) and \( A_b \) are amplitudes, \( \omega_a \) and \( \omega_b \) are angular frequencies and \( \phi_a \) and \( \phi_b \) are phase angles of two sinusoidal signals \( a \) and \( b \). On the basis of trigonometric identity, adding these two sinusoidal signals results in (25)

\[ y(t) = A_m \cos(\omega_a t + \phi_m) \]

\[ A_m = \sqrt{A_a^2 + A_b^2 + 2A_aA_b\cos((\omega_a - \omega_b)t + \phi_a - \phi_b)} \]

\[ \phi_m = \arctan \left( \frac{A_a \sin(\omega_a t + \phi_a) - A_b \sin(\omega_b t + \phi_b)}{A_a \cos(\omega_a t + \phi_a) - A_b \cos(\omega_b t + \phi_b)} \right) \]

(25)

It is clear from (25) that the effect of this type of superposition is to modulate both the amplitude and phase of the signal during power swing. Therefore, it is necessary to consider both amplitude and phase of signal as modulated signals. So, both amplitude and phase modulation are included in this section. However, in order to analyse the results conveniently, amplitude modulation and phase modulation are examined separately (Case 2 and Case 3). It is worth noting that combination of both of them will also be examined in Case 5 (three-machine power system).

5.2.1 Case 2: UPFC (phasor model) performance during power swing (sinusoidal change of \( \delta \)): This case is programmed to examine the phase modulation during power swing. In this step of analysis, sinusoidal variation of \( \delta \) is considered. To simulate the power swing phenomenon, displacement angle of \( V_1 \) is considered as (26)

\[ \delta_i(t) = \delta_i^0 + k \sin(2\pi f_{\text{slip}} t) \]  

(26)

Three different time intervals with different conditions are programmed for this case. Initially, power system is in uncompensated condition and there is no power swing in power system during \( 0 \leq t < 0.5 \text{ s} \); next, reference values of UPFC changes at \( t = 0.5 \text{ s} \) (\( P_{\text{ref}} \) increases to 0.72 pu) and so power system is compensated during \( 0.5 \leq t < 1 \text{ s} \); and finally power swing is created in compensated power system at \( t = 1 \text{ s} \) [variation \( \delta_i \) is based on (26)] and so power system is in compensated and in power swing condition during \( 1 \leq t < 3 \text{ s} \).

Variation of displacement angle \( \delta_i(t) \) in this case is shown in Fig. 5a, which its power swing condition is based on (26) where \( k = 0.22, \delta_i^0 = 45^\circ \) and \( f_{\text{slip}} = 0.5 \text{ Hz} \). Here, \( k \) is selected 0.22 to enforce UPFC operates inside region of its performance. On the basis of control aim of UPFC, this device should provide time-varying series voltage and shunt current to compensate variation of power in transmission line. Amplitude and phase of both series voltage and shunt current are shown in Fig. 5b.

According to Fig. 5, \( V_{\text{se}} \) and \( I_{\text{sh}} \) change during time because \( \delta_i \) changes during power swing. Variation of these parameters can be explained based on (20) and (21). Fig. 5b completely demonstrates that considering constants \( V_{\text{se}} \) and \( I_{\text{sh}} \) during power swing is not correct and it is necessary to be considered as time-variant parameters in analysis.

Fig. 5c shows active and reactive at Bus 1 and Bus 2 in Case 2. According to this figure, UPFC can cancel variations in active and reactive powers at Bus 2 and keep them constant at their reference during power swing (\( 1 < t < 3 \text{ s} \)). Since series active power \( (P_s) \) is considered equal to shunt active power \( (P_{\text{sh}}) \), active power at Bus 1 equals to active power at Bus 2. However, reactive power at Bus 1 is different from Bus 2 and changes during power swing.

Admittance analysis can easily validate the impacts of UPFC on admittance seen by a distance relay during power swing. Comparison between admittance in uncompensated and UPFC-compensated line is shown in Fig. 5d [only the admittance of first line (\( 1 < t < 1.5 \text{ s} \)) is shown in this figure]. According to this figure, uncompensated admittance (\( Y_{\text{UN}} \)) moves on uncompensated admittance swing characteristic (\( K = 1 \)) during power swing. However, admittance in compensated line (\( Y \)) moves in a different way because\( Y = Y_{\text{UN}} + Y_{\text{SH}} \). Moreover, since \( Y_{\text{SH}} \) and active power at Bus 1 are constant during power swing, the real part of admittance is constant (0.72 pu). These results demonstrate that UPFC changes admittance trajectory during power swing and that change is related to variation of series voltage and shunt current during power swing.

In [22], the impacts of UPFC on the power swing blocking characteristics are examined and it is shown that centre and radius of impedance trajectory change in compensated line. However, there is an impractical hypothesis in analysis part of this paper which series voltage and shunt current are considered constant (steady-state model of UPFC is considered during power swing). To compare [22] with our paper, both of them are simulated for the same condition (reference values of UPFC are equal to uncompensated condition and power swing is started at \( t = 1 \text{ s} \)) and their results are shown in Fig. 6.

The simulation result of our paper is shown in Fig. 6a. According to Fig. 6a, uncompensated trajectory (\( Y_{\text{UN}} \)) moves on uncompensated characteristic (\( k_1 = 1 \)) and also compensated trajectory (\( Y \)) is inside the defined area [combination of different circle with radius \( r \) based on (12)]. These results validate that the proposed idea in our paper that we need an area for showing the variation of swing trajectory during power swing in compensated line. On the other hand, the proposed method in [22] is simulated \( (V_{\text{se}} \text{ and } I_{\text{sh}} \text{ are considered constant values: } V_{\text{se}} = 0.172 \pm 40^\circ \text{ and } I_{\text{sh}} = 0.028 \pm 54.8^\circ \) and its result is shown in Fig. 6b. According to Fig. 6b, Moravej et al. [22] just provide new circular swing characteristic for compensated condition. Although the uncompensated trajectory (\( Y_{\text{UN}} \)) moves on uncompensated characteristic, the compensated trajectory (\( Z \)) does not move on compensated characteristic and cuts it only in one point. Therefore, we can conclude that considering constant value for \( V_{\text{se}} \text{ and } I_{\text{sh}} \) leads to wrong results.

5.2.2 Case 3: UPFC (phasor model) performance during power swing (sinusoidal change of \( \psi \)) This case is

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Simulation results of Case 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>( P_{\text{ref}} = 0.707Q_{\text{ref}} = 0.2929 )</td>
</tr>
<tr>
<td>(uncompensated)</td>
<td>(compensated)</td>
</tr>
<tr>
<td>(</td>
<td>V</td>
</tr>
<tr>
<td>( \delta_i, \text{ deg} )</td>
<td>45</td>
</tr>
<tr>
<td>(</td>
<td>V</td>
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<tr>
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<td>45</td>
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<tr>
<td>(</td>
<td>V</td>
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<tr>
<td>( \rho, \text{ deg} )</td>
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</tr>
<tr>
<td>(</td>
<td>u</td>
</tr>
<tr>
<td>( \delta_{\text{sh}}, \text{ deg} )</td>
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</tr>
<tr>
<td>( P_{\text{se}} = P_{\text{sh}}, \text{ pu} )</td>
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<tr>
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<tr>
<td>( Q_s, \text{ pu} )</td>
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</tr>
<tr>
<td>( Y, \text{ pu} )</td>
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<tr>
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</tr>
<tr>
<td>( Y_{\text{SH}}, \text{ pu} )</td>
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</tbody>
</table>

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programmed to examine the amplitude modulation during power swing. So, sinusoidal variation of $|V_1|$ is considered based on (27)

$$|V_1|(t) = |V_1|^0 + k_v \sin(2\pi f_{\text{slip}} t)$$  \hspace{1cm} (27)

During $0 \leq t < 0.5$ s, power system is in uncompensated condition and there is no power swing in power system. At $t = 0.5$ s, active power reference of UPFC increases to 0.72 pu, and finally power swing is simulated based on (27) and is started at $t = 1$ s. Variation of $|V_1|$ in this case is shown in Fig. 7a, which is based on (27) where $k_v = -0.022$, $|V_1|^0 = 1$ and $f_{\text{slip}} = 0.5$ Hz. Amplitude and phase of both series voltage and shunt current in this case are shown in Fig. 7b which shows that UPFC provides time-varying series voltage and shunt current during power swing. Fig. 7c shows active and reactive at Bus 1 and Bus 2 in Case 3. According to this figure, UPFC can cancel variations in active and reactive powers at Bus 1 and Bus 2 in Case 3. According to this figure, uncompensated admittance $(Y_{\text{UN}})$ moves on uncompensated admittance swing characteristic ($\delta_1 = 45^\circ$) during power swing. However, admittance in compensated line $(Y)$ moves in a different way which demonstrates that UPFC changes admittance trajectory during power swing.

5.3 UPFC performance during power swing (investigation by detailed model of UPFC)

In this section, two cases (Case 4 and Case 5) are examined, in which detailed model of UPFC is utilised that is presented in demo of Simulink/MATLAB and models complete behaviour of UPFC. Detailed model of UPFC consists of two major parts: electrical and control parts.

i. Electrical part: Series and shunt converters in detailed model of UPFC use voltage-sourced converter (VSC) connected to the secondary side of a coupling transformer. The VSCs use gate turn-off thyristors to synthesise a square-wave voltage signal from a DC voltage source. Four three-level inverters are used to build a semi-sinusoidal voltage waveform which amplitude of each odd harmonic $(n)$ of a three-level inverter is
where $V_{dc}$ is the voltage of DC link and $\sigma$ is the conduction angle. Moreover, special interconnections of these phase-shifting transformers which provide phase shift of $\pm 7.5^\circ$ are used to neutralise harmonics contained in the square waves. By utilisation of these phase-shifting transformers and choosing the appropriate conduction angle for the three-level inverter, UPFC generates a 48-step voltage.

ii. Control part: Control of shunt branch regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. The control system consists of different parts. A phase-locked loop (PLL) which synchronises gate turn-off thyristor pulses to the system voltage. The output of the PLL is used to compute $d$ and $q$ components of voltage and current in measurement blocks. Two proportional–integral (PI) controllers are used for voltage regulator and current regulator. The output of the current regulator is angle which is phase shift of the inverter voltage with respect to the system voltage (for providing demanded active power by series branch). Finally, firing pulses generator which produces pulses for the four inverters.

Control of series branch is used to manage power flow. The series branch injects a voltage $V_{ac}$ in series with the transmission line. The control system of series branch consists of different parts. PLL which its task is synchronisation. The output of the PLL is used to compute $d$ and $q$ components of voltage and current in measurement blocks. The measured active and reactive powers are compared with reference values to produce errors. These errors are used by two PI regulators to produce the reference values of $d$ and $q$ components of $V_{ac}$ to be synthesised by the VSC. Finally, firing pulses generator which produces pulses for four inverters.

5.3.1 Case 4: Investigation in two-machine equivalent system: To validate the extracted conclusions by precise model of UPFC during power swing, detailed model of UPFC is allocated in two-machine equivalent system (simulated by Simulink of MATLAB). UPFC constructed by three-level, 48-pulse gate turn-off thyristor-based converters, one connected in shunt (is coupled to power system by transformer 200 MVA and 500 kV/30 kV) at bus Bus 1 and one connected in series (is coupled to power system by transformer 200 MVA and 25 kV/25 kV) between buses Bus 2 and Bus 3. Moreover, power swing is created by utilisation of programmed voltage-source block which has the facility of phase modulation. The same events as the previous simulation are also considered in this condition. First, power system is in uncompensated and steady state during $0 \leq t < 0.5$ s; second, reference values of UPFC changes at $t = 0.5$ s ($V_{ref}$ increases to 0.72 pu) and so compensated power system is in steady state during $0.5 \leq t < 1$ s; moreover finally, power swing is created at $t = 1$ s (variation $\delta_i$ is shown in Fig. 8a) and so power system is in compensated and power swing state during $1 \leq t < 3$ s. Series voltage, shunt current, active power and reactive power at Bus 1 and Bus 2 during whole of simulation are shown in Figs. 8b and c. In addition, the admittance seen by distance relay is also shown in Fig. 8d. First, by comparing the simulation results presented in Case 2 and Case 4, it is possible to conclude that the programmed phasor model is an accurate model. Second, voltage series and shunt current provided by UPFC should be modelled as time-varying parameters during power swing. Finally, the admittance seen by distance relay during power swing in compensated line is different from uncompensated condition. It is worth noting that the ripples in Fig. 8 are resulted from switching operation and control equipment in detailed model of UPFC.

5.3.2 Case 5: Investigation in three-machine power system: In the previous cases, ideal voltage sources with amplitude and phase modulation capability are utilised to help in understanding phenomena. However, it is not usually encountered in power systems. Controllers of synchronous generators affect the system response during power swings, so three-machine power system (is shown in Fig. 9a and its data is presented in [22]) is simulated in Simulink; which machines are modelled dynamically and governor and automatic voltage regulator (AVR) are considered for every machine. The compensated three-machine power system is simulated by sampling frequency 30.72 kHz and then measured voltage/current is pre-filtered by low-pass filter for
preventing aliasing phenomenon. To model distance relay, sampling rate of measured voltage and current are decreased by integer factor 16 and are sent to discrete Fourier transform to estimate their phasors for calculation of impedance. Detailed model of UPFC (the same configuration as Case 4) is installed at the left-end of transmission line $L_5$ to control the active and reactive powers at the Bus 2. The natural power flow (without UPFC) at Bus 2 is $P_2 = 9.32$ pu and $Q_2 = 0.66$ pu. ($V_{\text{base}} = 500$ kV and $S_{\text{base}} = 100$ MVA). The reference voltage of the shunt converter is kept constant at $V_{\text{ref}} = 0.9749$ pu. First, power system is in steady-states condition and UPFC is set to keep active and reactive powers at Bus 2 equal to their values in uncompensated condition. Next, at $t = 1$ s, UPFC increases active power to 10 pu. A three-phase fault is simulated at $t = 2$ s at line $L_4$ and is vanished after 0.07 s. This event causes a power swing and is observed by the distance relay. Series voltage, shunt current, active power and reactive power at Bus 1 and Bus 2, admittance trajectories for uncompensated and compensated conditions during whole of simulation are shown in Figs. 9b–d. According to simulation results, series voltage and shunt current of UPFC during power swing are not constant and change during time. Moreover, impedance trajectories shows that, uncompensated admittance trajectory ($Y_{\text{UN}}$) does not move exactly on uncompensated characteristic ($k_1 = |D| = 0.9741$ where $D$ is one of the parameters of $\pi$ model of transmission line) because amplitude of voltages changes during power swing. In addition, Fig. 9d shows that compensated admittance trajectory ($Y$) moves in a different way compared with $Y_{\text{UN}}$.

6 Conclusion

Both power swing and UPFC influence admittance seen by distance relay. Moreover, power swing has effects on UPFC performance so that the series voltage and shunt current provided by UPFC change during power swing. Finally, the admittance seen by a distance relay during power swing in compensated line by UPFC is different from an uncompensated line. In this paper, UPFC during power swing has been examined and it has been demonstrated how interaction of power swing and UPFC changes the admittance seen by distance relay during power swing.
7 References


8 Appendix

8.1 Data of two-machine equivalent system

\[ V_1 = 1.0 \angle 0^\circ, \]
\[ V_2 = 1.0 \angle 90^\circ, \]
\[ Z_A = 0.1 \angle 90^\circ, \]
\[ Z_B = 0.1 \angle 90^\circ, \]
\[ Z_{Line} = 1.0 \angle 90^\circ \]

Amplitude values are in per unit (\( \sqrt{3} V_{base} = 500 \text{kV}, \)
\( S_{base} = 100 \text{MVA} \)).

Fundamental frequency is 60 Hz.

Distance relay zones: Mho characteristic (zones 1–3) with radius 0.85 × |Z_{Line}|, 1.2 × |Z_{Line}| and 1.5 × |Z_{Line}|, respectively.

Fig. 9 Results of Case 5
(a) Three-machine power system, (b) Variation of series voltage and shunt current, (c) Active and reactive powers at Bus 1 and Bus 2, (d) Admittance seen by relay.