Distance protection in the presence of unified power flow controller

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Abstract

The presence of an important flexible AC transmission systems (FACTS) device like unified power flow controller (UPFC) can drastically affect the performance of a distance relay in a two-terminal system connected by a double-circuit transmission line. The control characteristics of the UPFC, its location on the transmission system and the fault resistance, especially the high ones make this problem more severe and complicated. The fault location with respect to the UPFC position also greatly influences the trip boundaries of the distance relay. The paper presents apparent impedance calculations for relaying of a double-circuit transmission system with varying UPFC parameters and location. The study reveals the adaptive nature of the protection scheme that necessitates the use of an artificial neural network (ANN) based procedure for the generation of trip boundaries during fault conditions. © 2000 Elsevier Science S.A. All rights reserved.

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1. Introduction

The rapid development of power electronics has made it possible to use high power electronic equipment for transmission systems. The concept of flexible AC transmission systems (FACTS) \[1\] envisages the use of solid state power converter technology for controlling the active and reactive power flow in the transmission line. The unified power flow controller (UPFC) \[2\] is the most versatile of the FACTS elements envisaged so far. The UPFC comprises of two voltage source converters connected by a capacitor charged to a DC voltage. One converter termed as the series voltage source converter injects a voltage of variable magnitude and phase angle which effectively modulates the reactance of the line, thereby altering the power flow of the line. The shunt converter, on the other hand, exchanges real power with the series branch drawn from the generating source as well as losses. If the power balance between the two converters is not maintained, the capacitor can not remain at a constant voltage.

Although the UPFC \[3,4\] improves the power flow in the transmission line, its presence imposes a number of problems including distance protection. The apparent impedance seen by a distance relay is influenced greatly \[5\] by the location and parameters of UPFC besides the fault resistance magnitude of the arc in case of a ground fault. If the impedance seen by a relay is lower or higher than the actual line impedance, the distance relay either overreaches or underreaches. Thus an adaptive relay setting of the distance protection is required to cope up with the problems of overreach or underreach.

Adaptive reach settings of the distance relays for faults involving high arc resistance have been researched \[6–13\] for sometime now. Methods for on-line corrections of the trip boundaries are presented in references \[8–10\]. This paper presents the apparent impedance calculation procedure along with detailed simulation results for distance relaying schemes in which the power transmission line has an UPFC. The variations of the UPFC parameters and the locations are found to influence the apparent impedance measurements and trip boundaries to a great extent.

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2. Apparent impedance calculations

A double-circuit transmission line fed from both ends with varying UPFC location (either at the relay point or midpoint) subjected to a single line to ground fault as shown in Fig. 1 is considered. The UPFC is modeled by two voltage sources as shown in Fig. 2. The unified power flow controller is a recently proposed FACTS device that is capable of directing power flow through a desired route resulting in an increase in the usable capacity of the transmission lines. The UPFC consists of two AC/DC converters, one connected in series with the transmission line with a series transformer and the other connected in parallel with the line through a shunt transformer. The series and shunt converters are connected together through a DC capacitor, which also acts as an energy storage device. The series converter introduces a voltage source of variable magnitude and phase angle, while the shunt converter provides the real power balance between the series converter and the power system. The real power losses are also supplied by the shunt converter, which also maintains the DC bus voltage at a desired value. For apparent impedance calculations, the UPFC model equations hold good for the a-phase are

\[ V_{ap} = C_p V_{ap}' \]  
\[ \text{where } C_p = 1/(1 + \gamma e^{j\theta}), \gamma = \frac{E_{se}}{|V_{ap}|} \]

The magnitude of \( E_{se} \) can be controlled by varying the dc voltage and firing angle of the series voltage source converter and \( \theta \) varies from 0 to 2\( \pi \) radians. The shunt current is obtained as

\[ I_{ah} = (V_{ap} - E_{ah})/Z_{sh} \]
\[ E_{sh} = V_{ap}/C_{sh} \]  
\[ (3) \]

Where \( E_{sh} \) = shunt converter voltage, \( C_{sh} \) = voltage ratio \((V_{ap}/E_{ah})\) and \( Z_{sh} \) is its impedance. Assume \( E_{ap} \) as the equivalent voltage source of the a-phase at the terminal P. Let the relation between bus voltage at P and \( E_{ap} \) be

\[ V_{ap} = h e^{-\delta} E_{ap} \]  
\[ (4) \]

Where \( h \) is the amplitude ratio \((V_{ap}/E_{ap})\) and \( \delta \) is the angle between the source voltage and bus voltage at P. The apparent impedance as seen by the phase to ground relay for both line to ground and double line to ground faults are derived in the following sections.

2.1. Line to ground fault

2.1.1. UPFC at the relaying point

A two terminal model with equivalent generating sources, source impedances and a double circuit line is shown in Fig. 3. The UPFC is placed on circuit G at
Fig. 4. (a) Positive sequence network; (b) zero-sequence network of the faulted power system.

the relay point R. A single-line-to ground fault is considered on the circuit at the point F as shown in Fig. 3.

The prefault a-phase currents $I_{a\text{ldg}}$ and $I_{a\text{ldg}}^\prime$ are given by,

$$I_{a\text{ldg}} = I_{a\text{ldg}} - I_{a\text{sh}}$$

$$I_{a\text{ldg}}^\prime = I_{a\text{sh}} + I_{a\text{ldh}} + e^{\jmath \delta} V_{a\text{p}} / Z_1$$

(5)

Again

$$I_{a\text{ld}} = I_{a\text{ldg}} + I_{a\text{ldh}} = (E_{a\text{p}} - V_{a\text{p}}) / Z_{a\text{sp}}$$

$$I_{a\text{ldg}}^\prime = (V_{a\text{p}'} - V_{a\text{fd}}) / Z_{a\text{pf}}$$

(6)

Where $Z_1$ is the positive sequence impedance of each circuit, $V_{a\text{fd}}$ is the a-phase voltage at the fault point, $Z_{a\text{pf}}$ is the positive sequence impedance of the line between the bus P and F. From the above we get

$$V_{a\text{p}} = C_{a\text{pf}} I_{a\text{of}}$$

(7)

where $C_{a\text{pf}} = -(3R_f + Z_s) /

\begin{align*}
&\left(1/\left(1/e^{-\jmath \delta} - 1\right)\right)Z_{a\text{pf}} / 2Z_{a\text{sp}}) \\
&+ \left(1/C_p - 1\right)Z_{a\text{pf}} / 2Z_1 \\
&+ \left(1/C_{a\text{sh}} - 1\right)Z_{a\text{pf}} / 2Z_{a\text{sh}} - 1/C_p
\end{align*}$

(8)

and $Z_s = Z_s' + Z_1 + Z_{a\text{sh}}$ (refer Eqs. (11) and (12))

$I_{a\text{of}}$ being zero sequence component of fault current.

Fig. 5. UPFC placed at the midpoint of circuit G.

Fig. 6. (a) Double line to ground fault; (b) its sequence network.
Further \( I_{\text{aldg}}' \) and \( I_{\text{ash}} \) are rewritten as

\[
I_{\text{aldg}}' = C_{\text{ldd}}I_{\text{of}}, \quad I_{\text{ash}} = C_{\text{sh}}I_{\text{of}}
\]

Where \( C_{\text{ldd}} = \left( \frac{C_p}{C_p - (3R_s + Z_S)} \right)/Z_{\text{tpf}} \) and

\[
C_{\text{sh}} = C_p(1 - 1/C_{\text{sh}})/Z_{\text{sh}}
\]

The magnitudes of \( Z'_{0}, \ Z'_{1} (Z'_{2} = Z'_{1}) \) are obtained from the equivalent sequence diagrams as shown in Fig. 4.
Fig. 7. Trip characteristic without UPFC for LG fault.

\[
Z_i' = \frac{n(1 - n)Z_i}{2} + \frac{(Z_{1sp} + \frac{nZ_i}{2})(Z_{1sq} + \frac{(1 - n)Z_i}{2})}{Z_{1sp} + Z_{1sq} + \frac{Z_i}{2}} \tag{11}
\]

\[
Z_0 = \frac{(Z_{osp} + n\frac{Z_{0m} + Z_0}{2})(Z_{osq} + \frac{(1 - n)(Z_{om} + Z_0)}{2})}{Z_{osp} + Z_{osq} + \frac{Z_{om} + Z_0}{2}} + n(1 - n)\frac{(Z_0 - Z_{om})}{2} \tag{12}
\]

Where \(Z_{1sp}, Z_{1sq}, Z_{osp}, Z_{osq}\) = positive and zero sequence impedances of the sources at the terminals P and Q, respectively. \(Z_{om}\) = zero sequence mutual impedance between circuit G and circuit H. \(n\) = per unit distance of the fault point F from the relaying point R.

The relay current \((I_{aR})\) and voltage \((V_{aR})\) of a-phase are obtained as

\[
I_{aR} = I_{aldg} + I_{ash} + I_{ap'f} + K_0I_{op'f} \tag{13}
\]

Where the a-phase fault current at P' (UPFC injection bus) is

\[
I_{ap'f} = I_{1ap'f} + I_{2ap'f} + I_{op'f}
\]

The suffixes 1, 2, and 0 pertain to the positive, negative and zero sequences, respectively, and the zero sequence compensation factor \(K_0 = (Z_0 - Z_i)/Z_i\).
Fig. 10. Trip characteristics for UPFC at relay point, \( \gamma = 0.5; \theta = 90^\circ \) (LG fault).

Fig. 11. Trip characteristics for UPFC at midpoint, \( \gamma = 0.5; \theta = 90^\circ \) (LG fault).

Fig. 12. Trip characteristics for UPFC at relay point, \( \gamma = 0.5, \theta = 270^\circ \) (LG fault).

V_aR = C_p(3R_I + I_{1apf}Z_{1pf} + I_{2apf}Z_{2pf} + I_{opf}Z_{opf})
+ I_{op}Z_{om} + I_{id}Z_{1pf}) \quad (14)

Substituting \( Z_{1pf} \) by \( nZ_1 \), the apparent impedance seen by a-phase to ground relay is obtained as

\[ Z_a = \frac{V_{aR}}{I_{aR}} = C_p(nZ_1 + \Delta Z) \quad (15) \]

where

\[ \Delta Z = \frac{3R_f + C_m nZ_{om} - nZ_l C_{ish}}{C_{idd} + C_{ish} + 2C_1 + C_0(1 + K_0)} \quad (16) \]

\[ C_m = \frac{nZ_{osq} - (1 - n)Z_{osp}}{2Z_{osp} + Z_0 + Z_{om} + 2Z_{osq}} \quad (17) \]

\[ C_0 = \frac{(2 - n)Z_{osp} + (1 - n)(Z_0 + Z_{om} + Z_{osp})}{2Z_{osp} + Z_0 + Z_{om} + 2Z_{osq}} \quad (18) \]

\[ C_1 = \frac{(2 - n)Z_{1sp} + (1 - n)(Z_1 + Z_{1sp})}{2Z_{1sp} + Z_1 + 2Z_{1sq}} \quad (19) \]

From Eq. (15) it can be observed that if the UPFC is placed at the relaying point on one of the circuits of the double circuit transmission line, the apparent impedance seen by the relay for a single-line-to-ground fault is influenced by the factor \( C_p \) of the UPFC. Also the incremental impedance \( \Delta Z \) is influenced by the resistance \( R_f \) in the fault path, zero sequence mutual impedance, UPFC shunt branch current, fault location and prefault system condition.

2.1.2. UPFC at the midpoint of one circuit

In the above configuration (Fig. 5) the fault can occur at \( F_1 \) on one of the line section that does not include the UPFC, while as the fault occurring at \( F_2 \) includes the UPFC and thus influences the apparent impedance seen by the relay. If the fault occurs at \( F_2 \), the apparent impedance \( Z_a \) seen by a-phase to ground relay is given by

\[ Z_a = \frac{Z_1}{2} + C_p(n - \frac{1}{2})Z_1 + \Delta Z' \quad (20) \]

where

\[ \Delta Z' = \frac{3R_f C_p + C_m \left(C_p(n - \frac{1}{2})Z_{om} + \frac{Z_{om}}{2} \right) - C_{ish}C_p(n - \frac{1}{2})Z_1}{C_{idd} + C_{ish} + 2C_1 + C_0(1 + K_0)} \quad (21) \]

Fig. 13. Trip characteristics for UPFC at midpoint, \( \gamma = 0.5; \theta = 270^\circ \) (LG fault).
Similarly for a fault at $F_1$ the value of $Z_a$ is
\[ Z_a = nZ_1 + \frac{3R_i + C_mZ_{0m}}{C_{idd} + C_{ish} + 2C_1 + C_{0}(1 + K_0)} \tag{22} \]

### 2.2. Double line to ground fault

In furthering the study on the effect of UPFC on apparent impedance, a double-line to ground fault (b-c-g) is initiated and the impedance seen by one of the ground elements (b phase to ground) is calculated. In the fault path besides $R_f$ another fault resistance $R_s$ is considered between phase to phase as shown in Fig. 6(a). The sequence network (Fig. 6(b)) for such a case is used to derive the seen impedance.

\[ I_{oaf} = \left[ \frac{Z_2' + R_s}{(Z_2' + R_s) + (Z_0' + R_s + 3R_f)} \right] I_{1af} \]
\[ I_{2af} = \left[ \frac{Z_0' + R_s + 3R_f}{(Z_2' + R_s) + (Z_0' + R_s + 3R_f)} \right] I_{1af} \tag{23} \]

Let $I_{1af} = CC_1 I_{0af}$ and $I_{2af} = CC_2 I_{0af}$

Hence $I_{1bf} = \alpha^2 CC_1 I_{0af}$, $I_{2bf} = \alpha CC_2 I_{0af}$, $I_{1cf} = \alpha CC_1 I_{0af}$, $I_{2cf} = \alpha^2 CC_2 I_{0af}$

where

\[ CC_1 = -\frac{(Z_2' + Z_0' + 2R_s + 3R_f)}{(Z_2' + R_s)} \]
\[ CC_2 = -\frac{(Z_0' + R_s + 3R_f)}{(Z_2' + R_s)(Z_0' + R_s + 3R_f)} \cdot CC_1 \tag{24} \]

and $\alpha$ is the 120° shift operator.

\[ 3I_{0f} = I_{0f} + I_{cf} = (2 - CC_1 + CC_2)I_{0af} \]
\[ V_{aaf} = \left( \frac{Z_1' + R_s}{(Z_1' + R_s) + (Z_0' + R_s + 3R_f)} \right) CC_1 I_{0af} = C_{aaf} I_{0af} \tag{25} \]
where

\[ C_{\text{afd}} = \left( Z_1 + R_s \right) + \frac{(Z_2 + R_s)(Z_0 + R_s + 3R_f)}{(Z_2 + R_s)(Z_0 + R_s + 3R_f)} C_1 \]

2.2.1. UPFC at relay location

Using Eqs. (1)–(6) and Eqs. (23)–(25) we can deduce the apparent impedance seen by the b phase to ground element in the case of b-c-g fault as

\[ Z_b = C_{\text{p}} n Z_1 + \frac{C_{\text{p}} (R_f (2 - (CC_2 + CC_3)) + C_m n Z_{0m} - \alpha C_{\text{sh}} n Z_1 + R_f (\alpha CC_2 + x^2 CC_1 + 1))}{C_{1dd} + \alpha C_{\text{sh}} + \alpha CC_2 C_2 + x^2 CC_1 C_1 + C_0 (1 + K_0)} \]  

(26)

2.2.2. UPFC at midpoint of one circuit

For faults beyond UPFC (b-c-g type) at F_2 in Fig. 5

\[ Z_b = \frac{Z_1}{2} + C_{\text{p}} \left( n - \frac{1}{2} \right) Z_1 \]

\[ + \Delta Z \left[ R_f C_{\text{p}} (2 - (CC_1 + CC_2)) \right] \]

\[ + C_m \left( C_{\text{p}} \left( n - \frac{1}{2} \right) Z_{0m} + \frac{Z_{0m}}{2} \right) \]  

(27)

3. Simulation results

The 200 km, 400 kV double-circuit transmission line considered for computer simulation has the following data:
Parameters for sources at P and Q are:

\[
Z_{u} = 0.1064 + j 0.8670 \ \Omega/km
\]

Zero sequence mutual impedance of line:

\[
Z_{u}^{0} = 0.1718 + j 0.6930 \ \Omega/km
\]

From the above results it can be seen that for the UPFC placed near the relaying point (Table 1) and \(\theta = 0^\circ\), the resistance and reactance seen by the relay; the real and imaginary parts of \(Z_{a}\), respectively, for values of \(\gamma\) varying from 0 to 0.5 and \(\theta\) at discrete angles of 0, 90, and 270°. The fault resistance \(R_{a}\) is assumed to be 5 Ω. The location of the UPFC is now changed to the midpoint of the transmission line of the circuit G. Table 2 exhibits the variations in \(R_{a}\) and \(X_{a}\) for different values of \(\gamma\) and \(\theta\).

From the results in Table 2 the seen reactance \(X_{a}\) with UPFC at midpoint of circuit G for \(\theta = 0^\circ\) and \(\gamma\) increased from 0.0 to 0.5 shows complex variation whereas the resistance decreases from 36.06 to 18.50 Ω. The apparent reactance for \(\theta = 90^\circ\) decreases from 21.70 to 13.77 Ω. Similar to earlier observation the UPFC influences the apparent impedance seen by one of the ground elements significantly even in the case of double line to ground fault, as expected.

4. Trip characteristics

4.1. Line to ground fault

The system operating conditions described by \(h\), \(\delta\), \(Z_{sp}\), and \(Z_{sq}\) are kept constant and the fault location in km on one of the circuit and fault resistance \(R_{f}\) (from 0 to 200 Ω) are varied to provide the trip characteristics of the parallel transmission systems with and without UPFC. Fig. 7 depicts the trip characteristic without the presence of UPFC for line to ground fault. However, if the UPFC is located at the midpoint, the trip characteristic exhibits two different trip boundaries, the upper one for faults between the midpoint and to 95% of the line length (\(R_{f}\) varying from 0 to 200 Ω). The lower characteristic is due to the fault location lying between the relaying point to the midpoint where the UPFC is located. Figs. 8–13 represent the trip boundaries for line to ground fault with the presence of UPFC either at relaying point or midpoint of circuit G for \(\theta\) values of 0, 90 and 270° keeping \(\gamma\) unchanged (\(\gamma = 0.5\)). In Fig. 8 it is observed that for \(\theta = 0^\circ\) and UPFC at relaying point the trip area is reduced significantly as both \(R_{a}\) and \(X_{a}\) values are decreased. With same system conditions with the UPFC at midpoint of circuit G (\(\theta = 0^\circ\)) the upper characteristic boundary shows complex variation in both \(X_{a}\) and \(R_{a}\) (Fig. 9). Though the range of \(X_{a}\) is increased in this case that of \(R_{a}\) is decreased signifi-
6. Conclusions

The presence of a FACTS device like UPFC on a double-circuit transmission line in a two-terminal system can substantially influence the apparent impedance seen by a distance relay. This phenomenon has been clearly demonstrated in this paper by varying the UPFC parameters, its location, fault resistance magnitude variations along with source impedance and other uncertainties for both line to ground and double line to ground faults. The ideal trip boundaries are derived clearly showing the influence of UPFC operating parameters. In real-time applications these boundaries need to be generated adaptively for issuing the necessary trip commands to the circuit breakers.

4.2. Double line to ground fault

With $R_s = 0.1\,\Omega$, $R_t$ varying from 0 to 200 $\Omega$, keeping system operating condition remaining same as earlier, the influence of UPFC to the seen impedance of $b$ phase to ground element for double line to ground fault ($b$-c-g) is examined in this section. Fig. 14 depicts the trip boundary for such a fault without the presence of UPFC. At $\theta = 0^\circ$, for UPFC at relaying point the trip area is reduced significantly (Fig. 15) whereas for UPFC at midpoint the trip boundary is not affected significantly (Fig. 16). Similar effects are observed for the case of $\theta = 90^\circ$ as shown in Figs. 17 and 18. At $\theta = 270^\circ$ the upper boundary is at higher level for both positions of UPFC (Figs. 19 and 20). These boundaries in Figs. 15–20 show the influence of UPFC parameters and position on the trip characteristics of a distance relay for double line to ground fault.

5. Discussions

From the results described in the preceding section, it can be observed that the trip boundaries of the relay are influenced significantly by the presence of the UPFC and its exact location. The parameters $\gamma$ and $\theta$ of UPFC make the total impedance seen by the relay small or large making it either an equivalent capacitance or inductance. The low or high magnitude of the earth fault resistance $R_t$ alters the trip area significantly. Thus to provide a suitable trip boundary for faults on a double-circuit line, the boundary needs to be manipulated adaptively with $\gamma$ and $\theta$ of the UPFC on the time. This adaptation can be carried out using a neural network whose weights will be changed with $\gamma$ and $\theta$.