Impact of UPFC on Power Swing Characteristic and Distance Relay Behavior

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***Abstract*—This paper analyzes the distance relay performance during power swing conditions for an uncompensated and compensated transmission line with a unified power-flow controller (UPFC). UPFC can control voltage and power flow of the transmission line independently; hence, it has an impact on the apparent impedance seen by the distance relay. To analyze the case, the apparent impedance seen by the distance relay during a power swing is extracted, and the results are synopsized graphically. The impact of UPFC on different transmission-line parameters from an impedance point of view is investigated. Moreover, the impact of different operation modes of UPFC and their reference values on the apparent impedance seen by concentric mho circles as a power swing detection method are also evaluated by detailed simulations.**

***Index Terms*—Distance relay, power swing, static compensator (STATCOM), static synchronous series compensator (SSSC), unified power-flow controller (UPFC).**

I. INTRODUCTION

THESE DAYS, more than ever, advanced power-electronic equipment technologies or flexible ac transmission systems (FACTS) are paramount for more efficient utilization and control of existing transmission networks. The new generation of FACTS controllers with self-commutated voltage-source converters (VSCs) are similar to an ideal rotating synchronous machine with instantaneous response, no inertia, controllable amplitude, and phase angle [1]–[3]. They do not significantly alter the existing line impedance, but they can internally generate or absorb reactive power. Furthermore, some devices, such as a unified power-flow controller (UPFC) can exchange real power with the ac system. However, the reaction of FACTS controllers during different system conditions, such as faults or power swings, has an adverse effect on the operation of distance relays as the positive-sequence impedance measured by traditional distance relays is no longer an indicator of the distance to a fault [4], [5].

UPFC consists of series and shunt VSCs with a common dc link. The function of the shunt converter is to supply or absorb the real power demanded by the series converter at the common dc link. Moreover, it can also generate or absorb controllable reactive power for voltage regulation. The function of the series converter is to supply or absorb the required reactive power locally. It also exchanges active power as a consequence of the controllable injection ac voltage in series with the transmission line via a series transformer [1], [2]. Therefore, a UPFC can regulate the bus voltage and active/reactive power independently and simultaneously lead to uncertain apparent impedance measuring by the distance relay during a fault or even power swings.

The impact of UPFC on the operation of protective relays is analyzed in the literature. In [6], the effect of UPFC on distance relay is simulated for different fault locations. In [7], the distance relay tripping characteristic in the presence of UPFC is obtained and a modified distance protection scheme is proposed. The work in [8], evaluates a distance relay performance in a compensated line with UPFC for different fault conditions. In [9], the impact of series and shunt compensating parts of a UPFC on the distance relay is analyzed individually and collectively. In [5] and [10], the impacts of VSC-based multiline FACTS controllers and STATCOM modeling on the distance relay are investigated analytically and by detailed simulations for different fault conditions, respectively.

Although many researchers considered the distance relay performance for different fault types with various FACTS devices, very few publications are available considering the distance relay performance for a compensated line during a power swing condition. In [11], it is shown that the impedance seen by distance relays at the sending and receiving end terminals of the transmission line are circles during power swings. The authors in [12] simulated and compared the performance of two power swing detection algorithms with and without series capacitors.

The aim of this paper is to analyze the impedance seen by a distance relay during power swing conditions in a compensated line with UPFC using analytical and simulation methods. The main contributions of the paper are as follows.

- An analytical comparison between an uncompensated and compensated line with UPFC during a power swing condition is presented analytically by extracting apparent impedance equations and graphically by impedance diagrams.
- The impact of UPFC on the line constants (ABCD) from an impedance point of view is analyzed. The UPFC practical constraint to provide the active power needed by the series converter by using a shunt converter via a common dc link is also considered.
- The impedance locus corresponding to a new π-model of a UPFC-embedded line during the power swing condition is presented.

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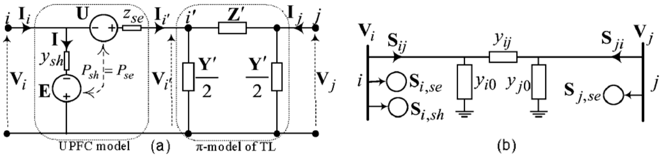

Fig. 1. (a) Equivalent UPFC-embedded line where $\mathbf{A} = \mathbf{D} = (\mathbf{Y}'\mathbf{Z}'/(2) + 1), \mathbf{B} = \mathbf{Z}'$, and $\mathbf{C} = \mathbf{Y}'(\mathbf{Y}'\mathbf{Z}'/(4) + 1)$. (b) Equivalent power injection p-model.

- The impedance seen by the distance relay during a power swing utilizing full detailed modeling of the UPFC-embedded line is simulated. The impact of the dynamic response of UPFC, reference values of the controllers, and operation modes of UPFC on the impedance locus are also investigated.
- The impact of different operation modes of a UPFC and their reference values on the concentric characteristic scheme are considered [13]. The elapsed time required by the impedance locus to traverse between two impedance characteristics is evaluated for different conditions.

The apparent impedance analysis during the power swing is described in Section II. The sample system is presented in Section III. The simulation results and discussions are presented in Section IV. This paper concludes in Section V.

II. APPARENT IMPEDANCE ANALYSIS DURING THE POWER SWING

In this section, a general equation for sending and receiving end impedances seen by the relays during the power swing is extracted based on the line constants (ABCD), UPFC components, and the sending/receiving terminals voltage. As shown in Fig. 1(a), UPFC is inserted at the beginning of the line. The apparent impedance seen by the relay is analyzed at buses $i'(\mathbf{Z}_{i'})$ and $i(\mathbf{Z}_i)$ for uncompensated and compensated lines, respectively.

A. Transmission Line Without a Compensator

The sending power at bus i' is $\mathbf{V}_{i'}\,\mathbf{I}_{i'}^*$, whereas $\mathbf{V}_{i'}$ and $\mathbf{I}_{i'}$ are related by the line constants matrix. Consequently, the sending end apparent impedance seen by the distance relay at bus i' can be calculated by $\mathbf{Z}_{i'} = \mathbf{V}_{i'}^2/(\mathbf{V}_{i'}^*\mathbf{I}_{i'})$. Therefore, $\mathbf{Z}_{i'}$, in terms of line constants and terminal voltages, can be derived as [6]

$$\mathbf{Z}_{i'} = \frac{D.B}{D^2 - (V_j/V_{i'})^2}\angle(\overline{\theta_D - \theta_B}) - \frac{B(V_j/V_{i'})}{D^2 - (V_j/V_{i'})^2}\angle(\phi - \theta_B) \quad (1)$$

where ϕ is a function of the power angle $\theta_{ji'}$. Generally, in this paper, $A\angle\theta_A, B\angle\theta_B, C\angle\theta_C$, and $D\angle\theta_D$ are the line constants; $V_n\angle\theta_n$ and $\mathbf{I}_n$ stand for voltage and current at bus $n(n = i, i'$, and j); and the bold symbols are the complex values. More details regarding (1) are described in [6].

Similarly, the equation of the apparent impedance seen by the relay at the receiving end terminal (at bus j) can be derived.

When (1) is plotted on the R-X diagram, it is portrayed by a family of circles, as depicted in Fig. 2. The derivation of impedance circles based on power-angle variation between 0–360°, as shown in Fig. 2, has the following significant notes [6]:

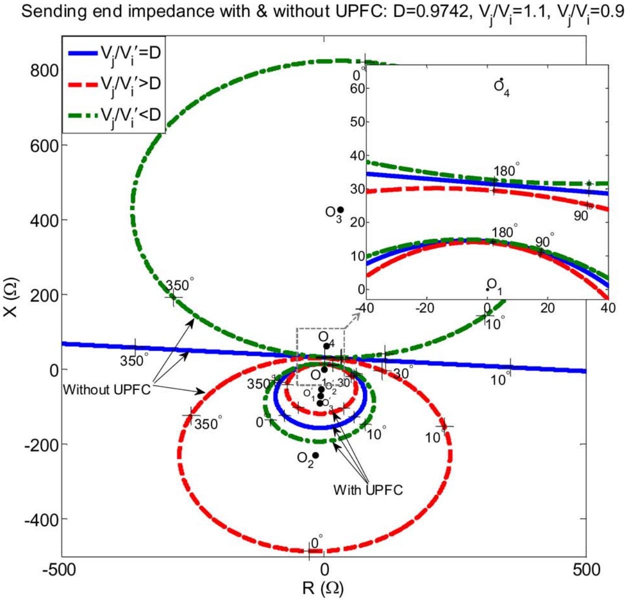

Fig. 2. Construction of the sending end impedance locus (with/without UPFC).

- In the case of $V_j/(V_{i'}) > D$ and $V_j/(V_{i'}) < D$, the centers of circular characteristics lie below and above the origin of the R-X diagram, for example, O_2 and O_3, respectively. In the case of $V_j/(V_{i'}) = D$, the circle radius is ∞ and it seems to be a straight line. In the case of a short circuit at the relay location and far end of the line, the impedance loci change from a circle to a point which coincide with origin O_1 and O_4, respectively. Therefore, the far end of the protected line is identified at O_4, whereas the origin O_1 can likewise be named near the end of the protected line.
- In Fig. 2, circles corresponding to $V_j/(V_{i'}) = 1\pm$ 0.1 p.u. are plotted. Prior to system disturbances, in normal system operation, the power angle $\theta_{ji'}$ is relatively small (between 0°–30°). At this moment, the direction of the power flow is from bus i' to the line at the relay location. In the power swing condition, terminal voltages will have drifted apart by several degrees. Therefore, the sending impedance seen by the relay has moved around circular characteristics from the normal position (small power angle) toward the trip zone of the relay. In Fig. 2, it can be seen that by increasing the power angle, as it exceeds 90°, the resulting impedances have smaller values. The recovery of the system to normal operation causes the impedance to retrace the path (between 0°–90°) until the system operates at a new power angle. It is worth noting that the out-of-step circumstance develops the circular characteristic of the impedance locus. For opposite direction of power flow, a similar analysis can be performed.

B. Transmission Line With UPFC

Fig. 1(a) represents an equivalent UPFC-embedded line. The UPFC is inserted between buses i and i' in the line. The config-