Real Power Transmission Loss Minimization and Bus Voltage Improvement Using UPFC

Bhaskar Gaur, Ravi Ucheniya, and Amit Saraswat

Abstract A shunt–series type of flexible AC transmission system named as Unified Power Flow Controller (UPFC) has an ability to manage real as well as reactive power in the power system network in a simultaneous manner. In this paper, a simulation model of UPFC is tested for the IEEE 14 bus standard test system on the DIgSILENT power factory software. Moreover, an optimum reactive power dispatch problem in presence of UPFC has been solved to reduce the real power loss in transmission lines. The proposed UPFC-based ORPD problem has been solved using the interior point method. The proposed approach is simulated under different loading conditions of the network. A comparative analysis of the obtained simulation results for each loading condition shows the effectiveness of UPFC for real power losses reduction.

Keywords Optimal reactive power dispatch · UPFC · IEEE 14 bus system · Real power loss minimization · DIgSILENT power factory

1 Introduction

Some of the challenges in a modern power system are being overcome by flexible AC transmission system (FACTS) [1]. These challenges are becoming more complex with increasing power demand. Proper management of reactive power in the network is one of them. Due to improper management of reactive power in the network, voltage instability, and real power losses are increasing day by day. Similar to traditional reactive power sources [2], FACTS devices are also capable of compensating reactive power in networks. In this paper, a series–shunt type of FACTS device, namely Unified Power Flow Controller (UPFC) [3, 4], has been used to reduce the total active

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power loss in transmission lines. Optimal reactive power dispatch (ORPD) is a traditional and well-known optimization framework, by which the active transmission power loss is minimized, and hence the profile of all bus voltages is also improved [2, 5]. The structure of UPFC is an extraordinary combination of shunt and series elements. Due to which, it can regulate various transmission parameters such as line impedance, node bus voltage as well as angle. It can be able control both real as well as reactive power flow in the transmission line and improve the performance of the grid [1, 6]. In this paper, the performance of an UPFC connected in IEEE 14 bus test system [7] is investigated on the DIgSILENT power factory software simulation platform [8].

2 Mathematical Modeling of UPFC

UPFC has dual-voltage sources such as series and shunt voltage sources; therefore, it is capable of adjusting the flow of complex power in a transmission network. In UPFC, the series voltage source plays a vital role in controlling the complex transmission line power flow. The connection diagram of an UPFC to the given transmission network is presented in Fig. 1. Furthermore, according to the requirement of the series voltage source, the required amount of active power is supplied by the shunt source of voltage in the power network [9]. The static model of UPFC connected between the two buses is presented in Fig. 2.

The expression for injected voltage of UPFC is presented as follow:

$$V_{inj} = V_{sh} + V_{se} \tag{1}$$

$$V_{inj} = [\,V_{sh}\,(\cos\delta_{sh} + j\,\sin\delta_{sh})\,] + [\,V_{se}(\cos\delta_{se} + j\,\sin\delta_{se})\,] \tag{2}$$

where, V_{se} and δ_{se} are series injected controllable voltage magnitude and phase angle, respectively. V_{sh} and δ_{sh} are shunt injected an adjustable voltage magnitude and its phase angle, respectively. Moreover, the reactance of UPFC series and shunt coupling transformer denotes by X_{se} and X_{sh} respectively.

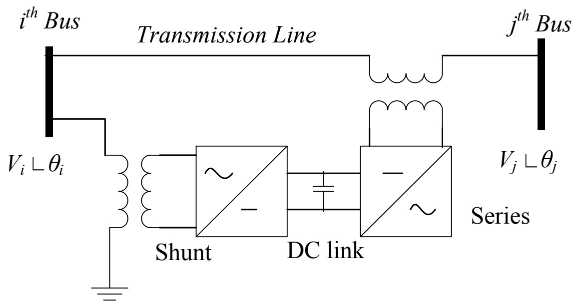

Fig. 1 Connection diagram of UPFC to the network

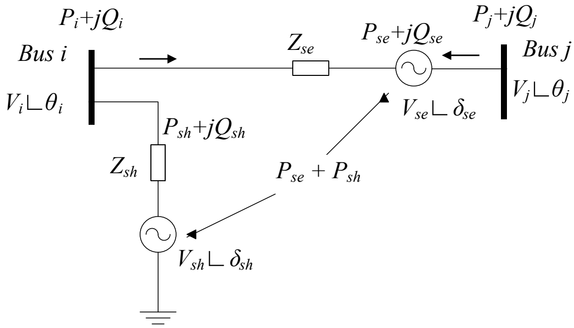

Fig. 2 A static model of UPFC

The conductance and susceptance for shunt and series coupling transformer for UPFC may be denoted by G_{sh}, B_{sh}, G_{se} and B_{se}, respectively. For a static model of UPFC, the power injections at i^{th} buses are mathematically expressed as follow [9, 10]:

$$\begin{aligned} P_i = G_{ii}V_i^2 + V_j\,V_i\,[G_{ij}\cos(\theta_j-\theta_i) - B_{ij}\sin(\theta_j-\theta_i)] \\ +V_i\,V_{se}\,[G_{ij}\cos(\theta_i-\delta_{se}) - B_{ij}\sin(\theta_{se}-\delta_i)] \\ +V_i\,V_{sh}\,[G_{sh}\cos(\theta_i-\delta_{sh}) - B_{sh}\sin(\theta_{sh}-\delta_i)] \end{aligned} \quad (3)$$

$$\begin{aligned} Q_i = -B_{ii}\,V_i^2 + V_jV_i\,[G_{ij}\sin(\theta_i-\theta_j) - B_{ij}\cos(\theta_i-\theta_j)] \\ +V_{se}V_i\,[\,G_{ij}\sin(\theta_i-\delta_{se}) - B_{ij}\cos(\theta_i-\delta_{se})] \\ +V_{sh}V_i\,[G_{sh}\sin(\theta_i-\delta_{sh}) - B_{sh}\cos(\theta_i-\delta_{sh})] \end{aligned} \quad (4)$$

where as the power injections at j^{th} buses are mathematically expressed as follow:

$$\begin{aligned} P_j = G_{jj}V_j^2 + V_{se}V_j\,[-B_{jj}\sin\,(\delta_{se}-\theta_j) + G_{jj}\cos\,(\delta_{se}-\theta_j)] \\ +V_j\,V_i\,[-B_{ij}\sin\,(\theta_j-\theta_i) + G_{ji}\cos\,(\theta_j-\theta_i)\,] \end{aligned} \quad (5)$$

$$\begin{aligned} Q_j = -B_{jj}\,V_j^2 - V_j\,V_{se}\,[\,B_{jj}\cos\,(\theta_j-\delta_{se}) - G_{jj}\sin\,(\theta_j-\delta_{se})] \\ -V_j\,V_i\,\,[\,B_{ji}\cos\,(\theta_j-\theta_i) - G_{ji}\sin\,(\theta_j-\theta_i)\,] \end{aligned} \quad (6)$$

Also, the real and reactive power injected by series and shunt converters are as follows:

$$\begin{aligned} P_{se} = G_{jj}V_{se}^2 + V_jV_{se}\,[\,G_{jj}\cos\,(\delta_{se}-\theta_j) + B_{jj}\sin\,(\delta_{se}-\theta_j)\,] \\ +V_iV_{se}\,[B_{ij}\sin\,(\delta_{se}-\theta_i) + G_{ij}\cos\,(\delta_{se}-\theta_i)\,] \end{aligned} \quad (7)$$

$$\begin{aligned} Q_{se} = -\,B_{jj}V_{se}^2 - V_jV_{se}\,[\,-G_{jj}\sin\,(\delta_{se}-\theta_m) + B_{jj}\cos\,(\delta_{se}-\theta_j)] \\ -V_iV_{se}\,[\,B_{ij}\cos\,(\delta_{se}-\theta_i) - G_{ij}\sin\,(\delta_{se}-\theta_i)\,] \end{aligned} \quad (8)$$

$$P_{sh} = -\,G_{sh} V_{sh}^2 \;+ V_{sh}\; V_i\;[\,G_{sh}\cos\left(\delta_{sh} - \theta_i\right) + B_{sh}\sin\left(\delta_{sh} - \theta_i\right)] \tag{9}$$

$$Q_{sh} = G_{sh} V_{sh}^2 \;+ V_{sh}\; V_i\;[G_{sh}\cos\left(\delta_{sh} - \theta_i\right) - B_{sh}\cos\left(\delta_{sh} - \theta_i\right)] \tag{10}$$

For a lossless converter, a real power provided by the shunt element (P_{sh}) is equal to a real power consumed by the series element (P_{se}). Therefore,

$$P_{sh} + P_{se} = 0 \tag{11}$$

UPFC can simultaneously inject real power as well as reactive power in a given network. Hence, the Jacobian matrix of power flow analysis has been modified. The modified Jacobian matrix is represented by (12). Here, ΔP_{kk} is the real power mismatch of both the series as well as shunt converters.

$$\begin{bmatrix} \Delta P_i \\ \Delta P_j \\ \Delta Q_i \\ \Delta Q_j \\ \Delta P_{ji} \\ \Delta Q_{ji} \\ \Delta P_{kk} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_i}{\partial \theta_i} & \frac{\partial P_i}{\partial \theta_j} & \frac{\partial P_i}{\partial V_i} & \frac{\partial P_i}{\partial V_j} & \frac{\partial P_i}{\partial \delta_{se}} & \frac{\partial P_i}{\partial V_{se}} & \frac{\partial P_i}{\partial \delta_{sh}} \\ \frac{\partial P_j}{\partial \theta_i} & \frac{\partial P_j}{\partial \theta_j} & \frac{\partial P_j}{\partial V_i} & \frac{\partial P_j}{\partial V_j} & \frac{\partial P_j}{\partial \delta_{se}} & \frac{\partial P_j}{\partial \delta_{se}} & 0 \\ \frac{\partial Q_i}{\partial \theta_i} & \frac{\partial Q_i}{\partial \theta_j} & \frac{\partial Q_i}{\partial V_i} & \frac{\partial Q_i}{\partial V_j} & \frac{\partial Q_i}{\partial \delta_{se}} & \frac{\partial Q_i}{\partial V_{se}} & \frac{\partial Q_i}{\partial \delta_{sh}} \\ \frac{\partial Q_j}{\partial \theta_i} & \frac{\partial Q_j}{\partial \theta_j} & \frac{\partial Q_j}{\partial V_i} & \frac{\partial Q_j}{\partial V_j} & \frac{\partial Q_j}{\partial \delta_{se}} & \frac{\partial Q_j}{\partial V_{se}} & 0 \\ \frac{\partial P_{ji}}{\partial \theta_i} & \frac{\partial P_{ji}}{\partial \theta_j} & \frac{\partial P_{ji}}{\partial V_i} & \frac{\partial P_{ji}}{\partial V_j} & \frac{\partial P_{ji}}{\partial \delta_{se}} & \frac{\partial P_{ji}}{\partial V_{se}} & 0 \\ \frac{\partial Q_{ji}}{\partial \theta_i} & \frac{\partial Q_{ji}}{\partial \theta_j} & \frac{\partial Q_{ji}}{\partial V_i} & \frac{\partial Q_{ji}}{\partial V_j} & \frac{\partial Q_{ji}}{\partial \delta_{se}} & \frac{\partial Q_{ji}}{\partial V_{se}} & 0 \\ \frac{\partial P_{kk}}{\partial \theta_i} & \frac{\partial P_{kk}}{\partial \theta_j} & \frac{\partial P_{kk}}{\partial V_i} & \frac{\partial P_{kk}}{\partial V_j} & \frac{\partial P_{kk}}{\partial \delta_{se}} & \frac{\partial P_{kk}}{\partial V_{se}} & \frac{\partial P_{kk}}{\partial \delta_{sh}} \end{bmatrix} \begin{bmatrix} \Delta \theta_i \\ \Delta \theta_j \\ \Delta V_i \\ \Delta V_j \\ \Delta \delta_{se} \\ \Delta V_{se} \\ \Delta \delta_{sh} \end{bmatrix} \tag{12}$$

3 Problem Formulation

In this paper, minimizing the total real power loss has been considered as an objective function. The mathematical expression of the objective function has adopted from [2] and is presented as follows:

$$f = \min(P_{loss}) \tag{13}$$

where

$$P_{loss} = \sum_{k=1}^{N_{TL}} G_k (V_i^2 + V_j^2 - 2 V_i V_j \cos\theta_{ij}) \tag{14}$$

The above objective function is minimized while satisfying the following equality constraints (15)–(16) as well as inequality constraints (17)–(25):

$$P_{gen,i} - P_{load,i} = \sum_{j=1}^{N_B} |Y_{ij}|\,|V_j|\,|V_i|\,\cos\,(\delta_i - \delta_j - \theta_{ij}) \tag{15}$$

$$Q_{gen,i} - Q_{load,i} = \sum_{j=1}^{N_B} |Y_{ij}|\,|V_j|\,|V_i|\,\sin\,(\delta_i - \delta_j - \theta_{ij}) \tag{16}$$

$$P_{Gen,i}^{\min} \le P_{Gen,i} \le P_{Gen,i}^{\max}\ \mathrm{i} \in \mathrm{N}_{PV} \tag{17}$$

$$Q_{Gen,i}^{\min} \le Q_{Gen,i} \le Q_{Gen,i}^{\max}\ \mathrm{i} \in N_{PV} \tag{18}$$

$$V_{Gen,i}^{\min} \le V_{Gen,i} \le V_{Gen,i}^{\max}\ \mathrm{i} \in \mathrm{N}_{PV} \tag{19}$$

$$T_j^{\min} \le T_j \le T_j^{\max}\ \mathrm{j} \in N_T \tag{20}$$

$$q_{cap,i}^{\min} \le q_{cap,i} \le q_{cap,i}^{\max}\ \mathrm{i} \in \mathrm{N}_{cap} \tag{21}$$

$$S_{TL,i} \le S_{TL,i}^{\max}\ \mathrm{i} \in \mathrm{N}_{TL} \tag{22}$$

$$V_L^{\min} \le V_L \le V_L^{\max}\ \mathrm{L} \in \mathrm{N}_{PQ} \tag{23}$$

$$V_{sh}^{\min} \le V_{sh} \le V_{sh}^{\max} \quad ; \quad \delta_{sh}^{\min} \le \delta_{sh} \le \delta_{sh}^{\max} \tag{24}$$

$$V_{se}^{\min} \le V_{se} \le V_{se}^{\max} \quad ; \quad \delta_{se}^{\min} \le \delta_{se} \le \delta_{se}^{\max} \tag{25}$$

4 Solution Methodology

In this paper, an IEEE 14 bus test system is considered to analyze the performance of UPFC. The single-line diagram of the UPFC-connected standard test system is presented in Fig. 3. A detailed description of standard test systems (such as branch data, bus data, and generator data) has been adopted from [7]. The permissible limits of all control and state variables are also adopted from [7]. In the present simulations, it is assumed that an UPFC has been connected between buses 9 and 14 [11] as shown in Fig. 3. It is also assumed that this is an optimum location for the UPFC which has been adopted as in line with [11]. The weakest line in the network for UPFC is identified based on (a) voltage collapse point indicators (VCPI) and (b) line stability indices such as a line index (LQP) [11]. The simulations includes the interior point solution method [9] for ORPD problem in the presence of an UPFC as presented in subsequent section.

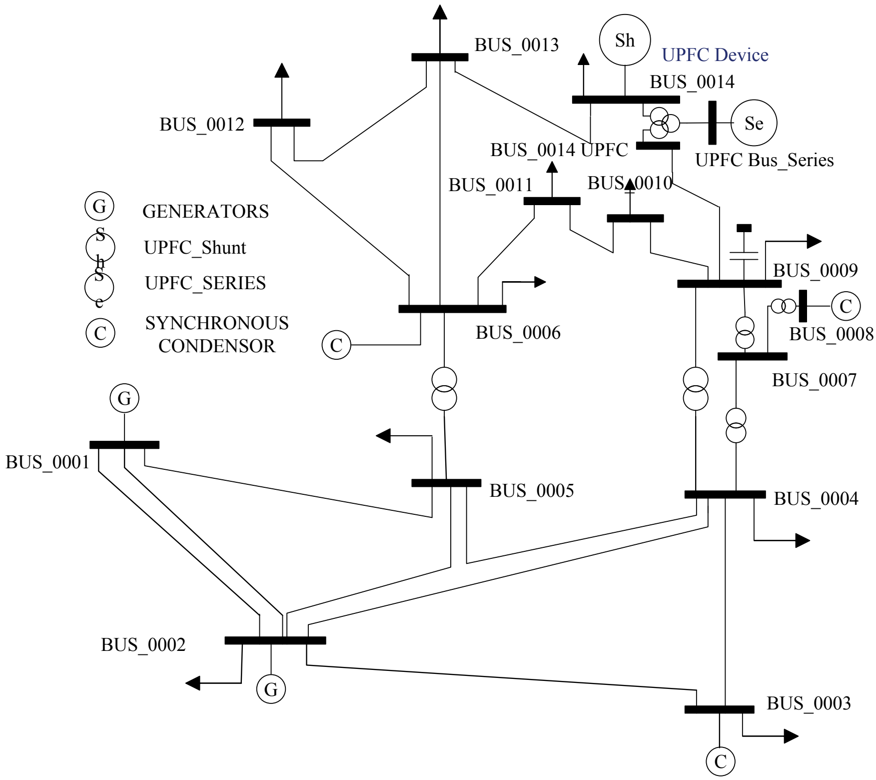

Fig. 3 Single-line diagram of IEEE 14 bus system

5 Simulation Results

The UPFC-based modified ORPD problem has been tested on a standard IEEE 14 bus test system and simulated the system under heavy loading conditions. For this, a total of ten loading conditions have been created and solved the modified ORPD problem using the interior point method. The entire simulation work is divided into two cases; the first is modified ORPD with UPFC and the second is without UPFC. Comparative analysis of simulation results has been performed. A comparative analysis based on real power losses for each loading condition is depicted in Fig. 4. It shows the effectiveness of the UPFC for a significant reduction in its real power transmission loss. Furthermore, the comparison of the voltage profile for two extreme situations such as base loading condition and extreme loading condition is presented in Fig. 5. The optimal setting of the control variables under each loading condition is presented in Table 1.

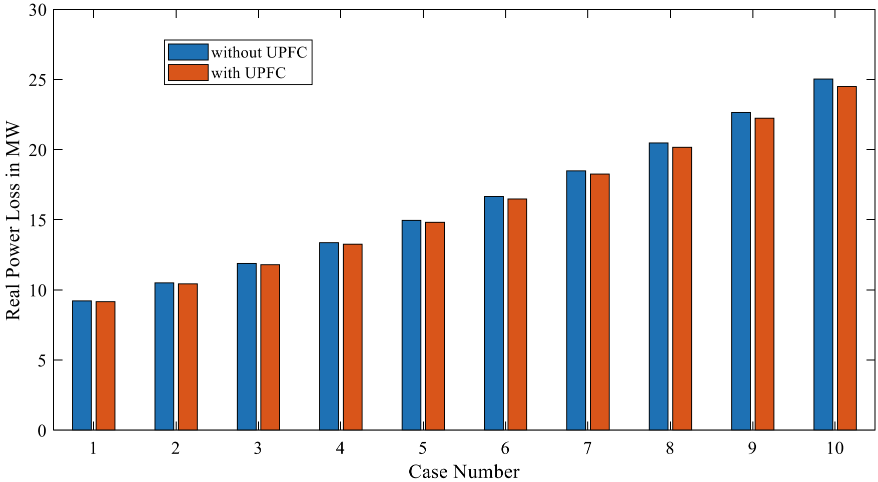

Fig. 4 Comparison of real power losses without and with UPFC device

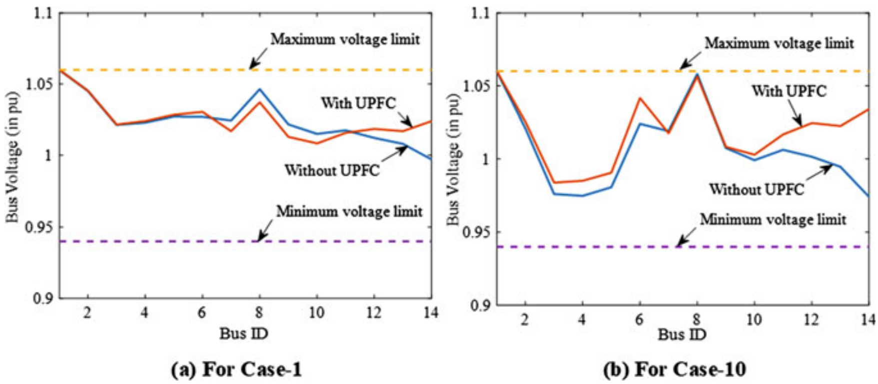

Fig. 5 The best voltage profiles obtained in case-1 and case-10

6 Conclusion

In this paper, the UPFC-based modified ORPD problem has been successfully solved by interior point method. A comparative analysis of the obtained simulation results gives a clear indication that the power loss in transmission network is effectively reduced by UPFC. Moreover, it is also observed that UPFC can provide controlled voltage support as well as it minimize the real power losses under the systems overloading conditions with no violation in any system constraint.

Table 1 Optimal settings of control variable considering UPFC for loss minimization

Optimal settings with UPFC					
Control variables	Case-1	Case-2	Case-3	Case-4	Case-5
V_1 (in pu)	1.0600	1.0600	1.0600	1.0600	1.0600
V_2 (in pu)	1.0453	1.0447	1.0441	1.0436	1.0428
V_3 (in pu)	1.0216	1.0196	1.0178	1.0160	1.0142
V_6 (in pu)	1.0305	1.0324	1.0333	1.0344	1.0354
V_8 (in pu)	1.0372	1.0407	1.0442	1.0470	1.0497
V_{sh} (in pu)	1.0240	1.0257	1.0265	1.0276	1.0286
V_{se} (in pu)	0.3537	0.3699	0.3915	0.4116	0.4364
$T_{4\text{-}7}$	1.0210	1.0170	1.0230	1.0240	1.0240
$T_{\text{-}9}$	0.9820	0.9780	0.9750	0.9710	0.9670
$T_{5\text{-}6}$	1.0020	0.9980	0.9940	0.9900	0.9850
$Q_{c\text{-}9}$ (in MVar)	14.0000	15.0000	15.5000	16.5000	17.0000
P_{se}, (in MW)	0.3695	0.4033	0.4452	0.4874	0.5372
P_{loss} (in MW)	9.1595	10.4299	11.7950	13.2548	14.8147
Control variables	Case-6	Case-7	Case-8	Case-9	Case-10
V_1 (in pu)	1.0600	1.0600	1.0600	1.0600	1.0600
V_2 (in pu)	1.0416	1.0394	1.0359	1.0310	1.0253
V_3 (in pu)	1.0121	1.0089	1.0030	0.9941	0.9836
V_6 (in pu)	1.0358	1.0368	1.0381	1.0399	1.0416
V_8 (in pu)	1.0518	1.0535	1.0550	1.0559	1.0564
V_{sh} (in pu)	1.0291	1.0301	1.0312	1.0326	1.0341
V_{se} (in pu)	0.4642	0.4962	0.5326	0.5774	0.6273
$T_{4\text{-}7}$	1.0230	1.0200	1.0130	1.0030	0.9910
$T_{4\text{-}9}$	0.9640	0.9600	0.9560	0.9500	0.9430
$T_{5\text{-}6}$	0.9800	0.9730	0.9640	0.9520	0.9390
$Q_{c\text{-}9}$ (in MVar)	17.5000	18.0000	18.5000	18.5000	18.5000
P_{se}, (in MW)	0.5938	0.6579	0.7306	0.8173	0.9150
P_{loss} (in MW)	16.4788	18.2552	20.1623	22.2354	24.4975

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