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Modelling of Optimal Unified Power Flow Controller (OUPFC) for optimal steady-state performance of power systems

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ABSTRACT

In this paper a hybrid configuration of a FACTS controller called Optimal Unified Power Flow Controller (OUPFC) which is composed of a mechanical phase shifting transformer augmented with a small scale Unified Power Flow Controller (UPFC) is introduced. The steady-state model of OUPFC is developed as a power injection model. This model is used to develop an Optimal Power Flow (OPF) algorithm including OUPFC to find the optimum number, location, and settings of OUPFCs to minimize the total fuel cost and power losses. Simulation results are presented for the IEEE 14-, 30-, and 118-bus systems. The optimization method is numerically solved using Matlab and General Algebraic Modelling System (GAMS) software environments. The results demonstrate the effectiveness of the proposed approach to solve the optimal location and settings of OUPFCs incorporated in OPF problem and improve the power system operation. Furthermore, the ability of OUPFC to optimize the objective functions is compared to that of PST and UPFC.

1. Introduction

FACTS controllers are introduced to the power system to enhance the security, capacity and flexibility of power transmission systems. FACTS solutions enable power grid to increase existing transmission network capacity while maintaining or improving the operating margins necessary for grid stability.

The Unified Power Flow Controller (UPFC) is one of the most interesting and potentially most versatile classes of FACTS device which its concept was proposed by Gyugyi in 1992 [1]. The UPFC is capable of providing active and reactive power control and voltage magnitude control and it regulates all the three variables simultaneously [2,3]. Phase shifting transformer (PST) is also an effective power flow controller which its ability to control power flow in a power system has long been recognized [4]. The PST includes an exciting transformer, injecting transformer and a set of mechanical switches that change the turn ratio of transformer. The operation and configuration of PST is very similar to that of UPFC [5]. Since the high-power UPFC is an expensive device comparing to the other FACTS controller, a combination of UPFC and conventional PST [3,6], named Optimal Unified Power Flow Controller (OUPFC), can be used as a more cost effective device in comparison with a standalone UPFC. Since investment issue is the main concern regarding the installation of FACTS controllers, it is necessary for any new installation of FACTS to be allocated in the power system. This requires an off-line simulation with different candidate FACTS devices location to assess power system operation improvement. Optimal Power Flow (OPF) is a power full simulation tool that can be used for this assessment studies. The OPF problem aims to achieve an optimal solution of a specific power system objective function, such as fuel cost, by adjusting the power system control variables, while satisfying a set of operational and physical constraints [7]. Incorporating FACTS devices in OPF provides a valuable decision making tool for the optimal investment.

Many evolutionary algorithms such as simulated annealing (SA) [8], evolutionary programming (EP) [9], differential evolution (DE) [10,11], genetic algorithm (GA) [12–14] and particle swarm optimization (PSO) [15–17] have been employed to optimize problems in power systems that refers to the minimization (or maximization) of an objective function in the presence of randomness in the optimization process. A drawback of these algorithms is that a solution is judged better only in comparison to currently known other solutions whereby these algorithms actually have no reasonable way to test whether a solution is, even local, optimal [18]. Therefore, in this paper, a mathematical optimization method is

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performed to solve the optimal location and settings of OUPFCs using General Algebraic Modelling System (GAMS) [19]. In the current application, GAMS solves the optimal model, and Matlab is used to feed parameters to the GAMS routine.

To the best of our knowledge, no research work has been developed on the modelling of OUPFC and its application to optimal operation of power systems. The main contribution of this paper is the modelling of OUPFC as a voltage-controlled variable load as well as investigation of its capability to control active and reactive power flow in a transmission line in the $\{Q_r, P\}$ plane. The main advantage of the developed model is that there is no need to change the Jacobian matrix elements which is common in the existing approaches [20,21]. Furthermore, the effect of single and multiple OUPFCs is investigated in IEEE 14-, 30-, and 118-bus test systems and the best location of OUPFCs is selected to minimize the total fuel cost and power losses as objective functions while satisfying the power system constraints. In order to highlight the ability of OUPFC, the results are compared to PST and UPFC from an economical and technical point of view.

The paper is organized as follows. Section 2 describes the basic operating principles of OUPFC. Section 3 explains the model of OUPFC. In Section 4, the regions of OUPFC operation are illustrated. Section 5 presents the formulation of OPF with OUPFC, including the optimal location. Section 6 contains simulation results followed by conclusions.

2. The basic operating principles of OUPFC

The OUPFC is constructed from a PST and a UPFC linked by two triple winding transformers (Fig. 1). The PST which is connected to secondary windings of exciting and injecting transformers injects a voltage with a fixed phase to the transmission line controlled by mechanical or static switches. The injected voltage changes transmission angle depending on system conditions. The UPFC connected to a tertiary winding of exciting and injecting transformer consists of two voltage source converters. The back-to-back converters are operated from a common dc link provided by a dc storage capacitor. The series converter injects a voltage with controllable magnitude and phase angle in series with the line via an injecting transformer [3,6].

The operation of the OUPFC is summarized with reference to the phasor diagram shown in Fig. 1. The basic function of the shunt converter is to supply or absorb the real power demanded by the series converter at the common dc link to support the real power exchange resulting from the series voltage injection. In addition to the real power which is needed for series converter, the shunt converter can also generate or absorb controllable reactive power, if it is desired, and thereby provide independent shunt reactive compensation for the line. Furthermore, the shunt converter is also able to control the dc bus voltage.

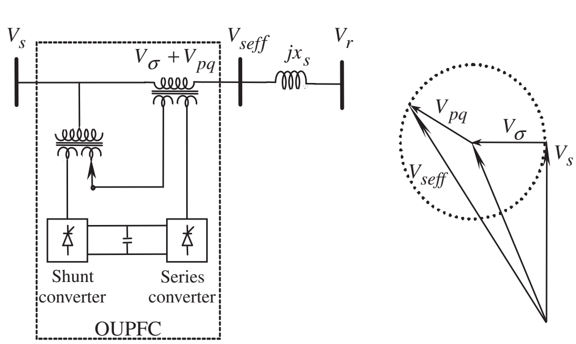

Fig. 1. Basic scheme and phasor diagram of OUPFC.

3. Modelling of OUPFC

A model of OUPFC is shown in Fig. 2. This model effectively demonstrates OUPFC behavior in steady state within a power system. According to this model, the current of exciting transformer is modeled as an ideal shunt current source:

$$\bar{I}_{sh} = (I_p + jI_q)e^{j\theta_s} \tag{1}$$

where I_p is the magnitude of current in phase with respect to $\overline{V}_s$ and I_q is the magnitude of current in quadrature with respect to $\overline{V}_s$.

The voltage $\overline{V}_{pq}$ is the injected voltage into the transmission line by UPFC as follows:

$$\overline{V}_{pq} = re^{j\rho}\overline{V}_s \tag{2}$$

where r is the radius of the UPFC operating region and ρ is the UPFC phase angle [21].

The voltage $\overline{V}_\sigma$ is the injected voltage into the transmission line by PST as below:

$$\overline{V}_\sigma = ke^{j\sigma}\overline{V}_s \tag{3}$$

where k is the transfer ratio of PST voltage injection with respect to exciting transformer and σ is the PST phase angle [5].

The reactance x_s is the total circuit reactance (the transmission line reactance plus the reactance of injecting transformer). The voltage source $\overline{V}_{inj}$ is the total injected voltage by PST and UPFC ($\overline{V}_{inj} = \overline{V}_\sigma + \overline{V}_{pq}$). The voltage $\overline{V}_{s_{eff}}$ is obtained by vectorially adding the total injected voltage $\overline{V}_{inj}$ to the sending-end voltage $\overline{V}_s$. The series injected current is:

$$\bar{I}_{se} = (\overline{V}_{s_{eff}} - \overline{V}_r)/jx_s \tag{4}$$

Assuming an ideal model for transformers and converters, the OUPFC does not exchange any real and reactive power with the system. Therefore

$$3\overline{V}_{inj}\bar{I}^*_{se} = 3\overline{V}_s\bar{I}^*_{sh} \tag{5}$$

Substituting $\bar{I}_{sh}$ from (1), $\overline{V}_{inj}$ from (2) and (3), and $\bar{I}_{se}$ from (4) into (5)

$$I_p = b_skV_r\sin(\delta+\sigma) + b_srV_r\sin(\delta+\rho) - b_skV_s\sin(\sigma) - b_srV_s \times \sin(\rho) \tag{6}$$

$$I_q = b_skV_r\cos(\delta+\sigma) + b_srV_r\cos(\delta+\rho) - b_skV_s\cos(\sigma) - b_srV_s\cos(\rho) - b_sV_s(r^2+k^2) - 2b_skrV_s\cos(\sigma-\rho) \tag{7}$$

where $\delta = \theta_s - \theta_r$ and $b_s = 1/x_s$.

The voltage source $\overline{V}_{inj}$ is replaced by the current source $\bar{I}_{inj} = -jb_s\overline{V}_{inj}$ in parallel with x_s. By changing the placement of current source $\bar{I}_{inj}$, the injected currents into sending and receiving ends can be determined as follows:

$$\bar{I}_{ss} = \bar{I}_{sh} + \bar{I}_{inj} \tag{8}$$

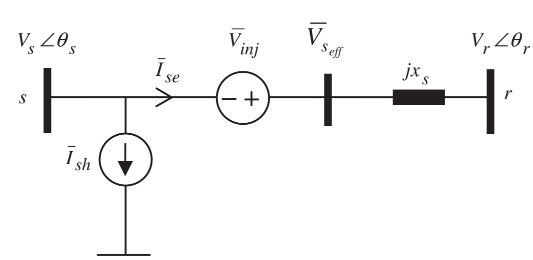

Fig. 2. The OUPFC model including series voltage and parallel current sources.