Electrical Power and Energy Systems 55 (2014) 531–541

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Solution of multiple UPFC placement problems using Gravitational Search Algorithm

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ARTICLE INFO

Article history:
Received 17 August 2012
Received in revised form 11 August 2013
Accepted 12 October 2013

Keywords:
GSA
UPFC
Optimal placement of multiple UPFC
OPF
Cost minimization
Loss minimization

ABSTRACT

Optimal power flow is one of the key tasks to be performed in the complicated operation and planning of a power system. The Unified Power Flow Controller (UPFC) is a powerful power electronics device capable of providing complex control of power systems. In this paper, Gravitational Search Algorithm (GSA) is applied to solve optimal power flow problem in the presence of multiple UPFC devices. The performance of GSA is compared for accuracy and convergence characteristics with heuristic search techniques like Biogeography-Based Optimization (BBO), Stud Genetic Algorithm (StudGA), Genetic Algorithm (GA), Ant Colony Optimization (ACO), Probability-Based Incremental Learning (PBIL), on the different cases of standard test systems and real life power system. The tabulated results reveal that GSA has a great capability in handling power system planning and operational problems and to provide good quality solution quickly. The effort of optimal placement of multiple UPFC devices in power system cannot be commonly found in technical literature.

1. Introduction

The secured level of stability and flexibility is now a matter of profound and challenging concern in deregulated power system operation and planning. With the increase in power demand the complexity of the electric power supply industry also increases and to maintain continuous and steady supply, power system undergoes through tremendously rapid changes in terms of demand and generation patterns and trading activities that have great impacts on the system stability [1]. It requires an opening of unexplored potential of transmission system to maintain the synchronism between this fluctuating power demand and supply. But the transmission loss and costs are major hurdles of power transmission network expansion [8]. The Flexible AC Transmission System (FACTS) controllers may play a great role in this context as these controllers have the potential to direct the power in the desired path and hence regulate the active and reactive power flows of the network and maintain desired voltage levels at the regulated buses. Such controllers thus have the potential to operate the system in a secured and economic way [1].

The development of Flexible AC Transmission (FACTS) controllers has been initiated by Electric Power Research Institute (EPRI) in which power flow is dynamically controlled by various power electronic devices. Among a variety of FACTS devices, Unified Power Flow Controller (UPFC) is the most versatile one. The concept of UPFC has been established by Gyugyi for the first time [2]. In principle, UPFC may be used in power systems for several purposes, such as shunt compensation, series compensation and phase shifting [4]. Besides, UPFC can simultaneously provide active and reactive power control or voltage control [5,16]. Without violating the operating limits the UPFC regulates all three key power system variables simultaneously or any combination of them.

The benefits of UPFC placement on the system performance have been investigated by several authors [2,4,5]. But due to the high cost of UPFC devices there is practically a very serious concern regarding their optimal locations. The optimization occurring in a competitive environment comprises in particular cost minimization including different aspects of the procurement and the minimization of power losses. In the last few years a number of landmark publications have appeared in the open literature to find suitable location of UPFC devices [6,15,23]. But very few could be found dealing with the placement problem of multiple FACTS devices.

This paper presents a heuristic method based on Gravitational Search Algorithm (GSA) [9] to find optimal number and location of UPFC devices considering generation cost and power system losses. The proposed UPFC placement algorithm has been tested on several test and real life power systems and some of the results are produced in this paper to establish the computational ability and robustness of the method.

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http://dx.doi.org/10.1016/j.ijepes.2013.10.008

2. Unified Power Flow Controller (UPFC) modeling

The basic operating principles of UPFC are already established in open literature. A schematic representation of voltage source converter-based UPFC is shown in Fig. 1.

The UPFC consists of two self-commutating converters connected by a common DC capacitor, which is connected to the ac system through series and shunt coupling transformers. The dc capacitor provides a dc voltage support for the converter operation and functions as an energy storage element. One converter is connected in shunt to the sending end node *k*. The second converter is connected in series between sending-end node *k* and receiving-end node m. The active power injected into the *PV* bus *k* has the same value as the active power extracted in the *PQ* bus *m*, since UPFC and coupling transformers are assumed to be lossless [6]. The shunt converter is capable of generating or absorbing the real power demanded by series converter at the dc terminals. The independently controlled shunt reactive compensation can be used to maintain the shunt voltage stability.

The equivalent circuit of UPFC is shown in Fig. 2.

It consists of two ideal voltage sources represented by V_{sh} and V_{se}. The shunt voltage source V_{sh} is represented as: $V_{sh} = V_{sh}\angle\theta_{sh}$ and the series voltage source V_{se} is represented as: $V_{se} = V_{se}\angle\theta_{se}$, where V_{sh}, V_{se} are controllable magnitudes in the ranges of $(V_{sh,min} \leqslant V_{sh} \leqslant V_{sh,max})$ and $(V_{se,min} \leqslant V_{se} \leqslant V_{se,max})$ and θ_{sh}, θ_{se} are controllable angles in the ranges of $(0 \leqslant \theta_{sh} \leqslant 2\pi)$ and $(0 \leqslant \theta_{se} \leqslant 2\pi)$ respectively.

3. UPFC power flow equations

Based on the equivalent circuit shown in Fig. 2, the active and reactive power equations are:

at node *k*:

$$P_k = V_k^2 G_{kk} + V_k V_m (G_{km} \cos(\theta_k - \theta_m) + B_{km} \sin(\theta_k - \theta_m)) + V_k V_{se}(G_{km} \cos(\theta_k - \theta_{se}) + B_{km} \sin(\theta_k - \theta_{se})) + V_k V_{sh}(G_{sh} \cos(\theta_k - \theta_{sh}) + B_{sh} \sin(\theta_k - \theta_{sh})) \quad (1)$$

$$Q_k = -V_k^2 B_{kk} + V_k V_m (G_{km} \sin(\theta_k - \theta_m) - B_{km} \cos(\theta_k - \theta_m)) + V_k V_{se}(G_{km} \sin(\theta_k - \theta_{se}) - B_{km} \cos(\theta_k - \theta_{se})) + V_k V_{sh}(G_{sh} \sin(\theta_k - \theta_{sh}) - B_{sh} \cos(\theta_k - \theta_{sh})) \quad (2)$$

At node *m*:

$$P_m = V_m^2 G_{mm} + V_m V_k (G_{mk} \cos(\theta_m - \theta_k) + B_{mk} \sin(\theta_m - \theta_k)) + V_m V_{se}(G_{mm} \cos(\theta_m - \theta_{se}) + B_{mm} \sin(\theta_m - \theta_{se})) \quad (3)$$

$$Q_m = -V_m^2 B_{mm} + V_m V_k (G_{mk} \sin(\theta_m - \theta_k) - B_{mk} \cos(\theta_m - \theta_k)) + V_m V_{se}(G_{mm} \sin(\theta_m - \theta_{se}) - B_{mm} \cos(\theta_m - \theta_{se})) \quad (4)$$

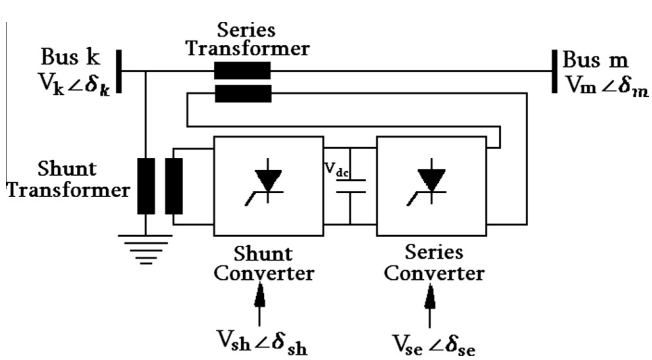

Fig. 1. UPFC model.

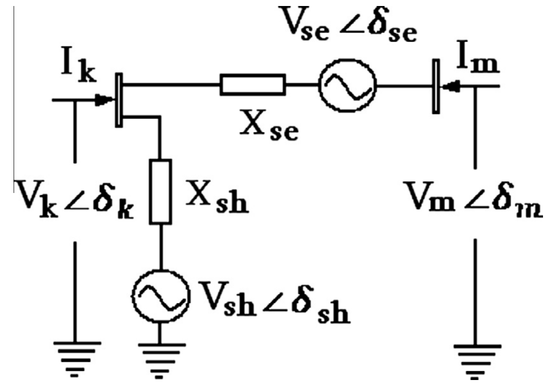

Fig. 2. Equivalent circuit of UPFC.

Series converter:

$$P_{se} = V_{se}^2 G_{mm} + V_{se} V_k (G_{km} \cos(\theta_{se} - \theta_k) + B_{km} \sin(\theta_{se} - \theta_k)) + V_{se} V_m (G_{mm} \cos(\theta_{se} - \theta_m) + B_{mm} \sin(\theta_{se} - \theta_m)) \quad (5)$$

$$Q_{se} = -V_{se}^2 B_{mm} + V_{se} V_k (G_{km} \sin(\theta_{se} - \theta_k) - B_{km} \cos(\theta_{se} - \theta_k)) + V_{se} V_m (G_{mm} \sin(\theta_{se} - \theta_m) - B_{mm} \cos(\theta_{se} - \theta_m)) \quad (6)$$

Shunt converter:

$$P_{sh} = -V_{sh}^2 G_{sh} + V_{sh} V_k (G_{sh} \cos(\theta_{sh} - \theta_k) + B_{sh} \sin(\theta_{sh} - \theta_k)) \quad (7)$$

$$Q_{sh} = V_{sh}^2 B_{sh} + V_{sh} V_k (G_{sh} \sin(\theta_{sh} - \theta_k) - B_{sh} \cos(\theta_{sh} - \theta_k)) \quad (8)$$

where

$$Y_{kk} = G_{kk} + jB_{kk} = Z_{se}^{-1} + Z_{sh}^{-1} \quad (9)$$

$$Y_{mm} = G_{mm} + jB_{mm} = Z_{se}^{-1} \quad (10)$$

$$Y_{km} = Y_{mk} = G_{km} + jB_{km} = -Z_{se}^{-1} \quad (11)$$

$$Y_{sh} = G_{sh} + jB_{sh} = -Z_{sh}^{-1} \quad (12)$$

On account of constant DC link voltage, active power supplied to the shunt converter, P_{sh}, must be equal to the active power demanded by the series converter, P_{se} [7], i.e.,

$$P_{sh} + P_{se} = 0 \quad (13)$$

A number of research publications have dealt with the handling of UPFC equations in the power flow problem. Nabavi and Iravani proposed a way to handle UPFC with power flow algorithms by connecting the UPFC in the transmission line where sending end is transformed into a *PV* bus and receiving end is transformed into *PQ* bus [6]. The active and reactive power loads in the *PQ* bus and the voltage magnitude at the *PV* bus are set at the values to be controlled by UPFC. The UPFC parameters are computed after the load flow converged [13].

4. Formulation of the UPFC placement problem

By optimal power flow [3,22] we mean an operating condition in which the power flow in an electrical system occurs to optimize one or more objectives while satisfying the specified operating limits of the system. In this paper the objective functions to be optimized [8] are: (i) minimization of the operating cost,

(ii) minimization of transmission loss

Here the objective functions: (i) operating cost is given by the fuel cost of the thermal generators,