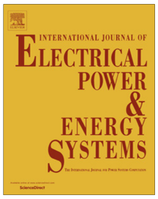
Electrical Power and Energy Systems 76 (2016) 69–81

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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



Optimal power flow with UPFC using security constrained self-adaptive differential evolutionary algorithm for restructured power system

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A R T I C L E   I N F O

Article history:
Received 1 May 2014
Received in revised form 15 September 2015
Accepted 29 September 2015
Available online 24 October 2015

Keywords:
Self-adaptive differential evolutionary algorithm
Unified power flow controller
Optimal power flow
Line losses
Security constraints
Tuning parameters

A B S T R A C T

The restructuring of the power industry begins with the 21st century and this restructuring of the power system requires a careful analysis because of the nature of the real-time operations. For the restructuring power system (RPS), the self-adaptive differential evolutionary (SADE) algorithm is proposed for enhancing and controlling the power flow using Unified Power Flow Controller (UPFC) under practical security constraints (SCs). The new formulas for the tuning parameters of Differential Evolutionary technique are designed in such a manner that they become automatically adaptive throughout the whole iteration. The UPFC is modeled considering losses of the both converters, transmission loss in UPFC and losses of the coupling transformers. The unique mathematical modeling of the cost function is developed considering practical SCs. The proposed algorithm and other evolutionary algorithms are applied on the IEEE standard and ill-conditioned test systems. With and without UPFC, the power flow and line losses are observed for the three sets of user-defined active and reactive power. The use of UPFC not only enhances the power flow but also reduces the total line losses. Comparing characteristics, convergence rate, success rate for all cases, the best performances are observed for the proposed Security Constraint SADE (SCSADE) algorithm.

Introduction

Recent electric supply industry is rapidly changing worldwide because of increasing load demand, scare natural resources and deregulated energy market [1]. For today's large power system, the secure operation of transmission system becomes an important and critical issue [1,2]. It is noticed that electric utilities are experiencing restructuring throughout the world. Since the 1980s, the power industries have been undergoing restructuring in many developed and developing countries over the world [1–3]. The previous monopolistic regulated public utilities are being replaced by restructured power system (RPS) to solve the problem such as capacity shortage, transmission congestion, and line losses. But, reforming the existing transmission systems or altering the present transmission lines are not practically, technically and economically feasible [4]. Hence, the change of transmission line is controlled considering environmental impact, health hazards of magnetic & electric fields and financial issues. In this situation, for secure and stable operation and controlling power flow, the use of Flexible Alternating-Current Transmission Systems (FACTS) is a cost effective, suitable option [2–4]. The FACTS devices are used in the transmission system for the retaining of power flow, low system loss, improved stability of contractual requirements by controlling the power flows in the network.

The Unified Power Flow Controller (UPFC), one of the FACTS devices, has both the advantages of Static Synchronous Series Compensator (SSSC) and Static Compensator (STATCOM) and most versatile applications in the frequent changing modern power systems or RPS [5–18]. Different algorithms and new devices are currently used for the restructuring of the power systems [5–18]. In the present restructured energy market, new modeling approaches for UPFC and UPFC controller design are being developed to uplift the power system performances [5–8]. The optimal locations of the UPFCs are important for the congestion management in RPS [9–12]. Recently, optimal parameter settings and allocation of UPFC are prime concern of the researchers to enhance the power transfer capacity in critical situation [13–15]. Different evolutionary techniques are now-a-days popularly applied on the UPFC to improve the power flow in the restructured electricity market [16–18]. Moreover, applying a suitable objective function for optimal power flow with practical limitations of the FACTS devices plays a very important role in the RPS.

Many new versions of DE algorithms are developed modifying the original DE [19–28]. Price and Storn [19] depicted that choosing of control parameters were not very difficult; whereas

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http://dx.doi.org/10.1016/j.ijepes.2015.09.025
0142-0615/

Gamperle et al. [20] explained that for better performances exact values of the control parameters could not be determined easily. Liu and Lampinen reported that the settings of the control parameters were very important to improve the convergence rate and reliability of the DE algorithm [21]. Introducing an auxiliary population and population set based method, a new DE algorithm was proposed by Ali and Town [22] where the weighting factor (F) was calculated automatically by a new developed rule. Based on the experimental results, Sun et al. [23] developed a combination of the DE algorithm and the estimation of distribution algorithm. In [24], both the learning strategy and parameter setting were gradually self-adapted according to the learning experience. Liu and Lampinen [25] developed a Fuzzy Adaptive Differential Evolution (FADE) to obtain better optimization. In [26], the voltage stability was improved by the adaptive tuning parameters of DE technique under practical security constrains. In [27,28], performance of self-adaptive differential evolution (SADE) was analyzed and compared.

The restructuring of the electric power industry has involved paradigm shifts in the real-time control activities of the smart grids. The optimal power flow (OPF) has been the most significant technique for controlling and maintaining the power flow with existing transmission and operational constraints. In this paper, new unique security constrained SADE (SCSADE) algorithm is developed and the UPFC is so modeled that it can control and enhance the power flow under practical security constraints. Losses of the UPFC are also considered. The weighting factor (F) and crossover rate (C_γ) of the SCSADE algorithm are made adaptive with the RPS problem. The SCSADE algorithm is applied on both ill-conditioned and standard test systems for three sets of power flows. The performances of the algorithm in the context of RPS are compared with other evolutionary techniques such as Real Coded Genetic Algorithm (RCGA), Ordinary Differential Evolution (ODE) and General Particle Swarm Optimization (GPSO).

UPFC model and cost function

UPFC with coordination controller

The changing nature of the modern electricity supply industry is introducing many new topics and devices into power system operation related to trading in a deregulated, competitive market. For restructured Power System (RPS), the FACTS devices make an increasingly important role for flexible power flow operation with low loss under constraint situations. One of the most versatile FACTS devices is Unified Power Flow Controller which consists of two self-commuted Voltage Source Converters (VSCs) connected back to back through DC link capacitor [29]. The UPFC can be treated as a combination of Static Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC) working independently or simultaneously. The UPFC model with coordinated controller in the transmission line is shown in Fig. 1.

The notation mentioned in the above diagram is given below. where

P_i, P_j: Active power at bus i and j respectively.

Q_i, Q_j: Reactive power at bus i and j respectively.

I_i, I_j: Injected current at bus i and j respectively.

V_i, V_j: Voltage magnitude at bus i and j respectively.

θ_i, θ_j: Power angle at bus i and j respectively.

P_{CR}, Q_{CR}: Active and reactive power of the series converter respectively.

P_{VR}, Q_{VR}: Active and reactive power of the shunt converter respectively.

V_{CR}, V_{VR}: Voltage magnitude of series and shunt converter respectively.

δ_{CR}, δ_{VR}: Phase angle of series and shunt converter respectively.

I_{CR}, I_{VR}: Current flow for the series and shunt converter respectively.

Z_{CR}, Z_{VR}: Impedance of series and shunt converter respectively.

VSI: Voltage Source Inverter.

The UPFC can control voltage magnitude, phase angle, impedance without violating security limits and operating limits. In other words, it is capable to control all three variables such as voltage magnitude, active and reactive power flow simultaneously or any combination of them. In the traditional UPFC model, shunt converter is coupled through a shunt transformer. The UPFC bus voltage, shunt reactive power and capacitor voltage at the DC link are controlled by the shunt converter. On the other hand, SSSC or series converter is inserted to the AC system through a series transformer. Controlling the injected voltage (V_{CR}) of the series converter, both active and reactive power can be independently/simultaneously controlled. Requirement of the complex power injection of the series converter is determined by the line current and series injected voltage. DC link draws power from the AC system through shunt converter and provides necessary injected active power of the series converter. Generally to maintain the voltage magnitude at the desired level in the AC system, the reactive power of the shunt converter can be used. The two converters can absorb or supply reactive power independently. If the losses of the coupling transformers and converters are neglected, the active power balance equation of the UPFC can be expressed as: $\vec{P}_{VR} + \vec{P}_{CR} = 0$. For fundamental steady-state analysis, the equivalent UPFC circuit model is given in Fig. 2.

Powers of the voltage source converters

The equivalent circuit consists of two synchronous voltage sources which are interlinked by the coordinated controller (see Fig. 1). The series voltage source converter (VSC) can be represented with an ideal series voltage (V_{CR}) in series with series reactance (X_{CR}). A fictitious voltage (V_i') is assumed before Z_{CR} and the model of the series connected VSC is shown in Fig. 3(a).

Both voltage source $\vec{V}_{VR}$ and $\vec{V}_{CR}$ are controllable in their corresponding voltage magnitudes and phase angles. r and γ are the magnitude in p.u. and phase angle of V_{CR} in radian respectively. Taking $\vec{V}_i$ as a reference voltage, the vector diagram of equivalent series VSC is shown in Fig. 3(b).

Here,

$$\alpha + \phi + \varphi = 90^\circ$$

$$\alpha + \phi = \gamma$$

$$\vec{V}_i' = \vec{V}_{CR} + \vec{V}_i \tag{1}$$

$\vec{V}_{CR}$ can be expressed as,

$$\vec{V}_{CR} = r\vec{V}_i e^{j\gamma} \tag{2}$$

where $0 \leqslant r \leqslant r_{\max}$

$-\pi \leqslant \gamma \leqslant \pi$

For practical case, there exist losses of power transmission in UPFC, switching losses of the two converters of UPFC and losses of the coupling transformers. The shunt converter supplies the active power required by the series converter and the total losses in the UPFC. The losses of the UPFC will be approximately equal