

Optimal Placement and Parameter Settings of Unified Power Flow Controller Device using a Perturbed Particle Swarm Optimization

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Abstract -- This paper presents the application of a perturbed particle swarm optimization (PPSO) technique to find optimal location and parameter setting of unified power flow controller (UPFC) for enhancing power system security under single line contingencies. A contingency analysis is first outlined to identify the most severe line outage contingencies, considering lines overload and bus voltage limit violations as a performance index. Then, the proposed algorithm is applied to find out the optimal location and parameter setting of UPFC under the determined contingency scenario. Simulations are performed on IEEE 14 bus system. The results indicate that PPSO is a powerful optimization technique and enhance the convergence of the standard PSO. Installing UPFC in the optimal location determined by the proposed approach can significantly enhance the security of power system by eliminating or minimizing the number of overloaded lines and the bus voltage limit violations.

Index Terms--Power system security, optimal placement, FACTS, UPFC, Perturbed particle swarm optimization.

I. INTRODUCTION

NOWADAYS, actual power systems are facing new challenges due to deregulation and restructuring of the electricity markets. The secure operation of power system has become an important and critical issue. Security constraints such as thermal limits of transmission lines and bus voltage limits must be satisfied under all system operation conditions. Commonly, Power systems are planned and operated based on the N-1 security criterion, which implies that the system should remain secure under all important first contingencies [1]. Hence, in order to be able to obtain a high operational efficiency and networks security, large interconnected systems have been built. In this context, one possible solution to improve the system operation was the use of FACTS technologies [2]. FACTS devices can reduce the flows of heavily loaded lines, maintain the bus voltages at desired levels, and improve the stability of the power network. Among them, The Unified Power Flow Controller (UPFC) is a device that can simultaneously control the voltage magnitudes at the sending end and the active and reactive power flows at the receiving end bus [3].

However, to achieve such functionality of UPFC, it is highly important to determine the optimal location of this device in the power system with the appropriate parameter setting. Since UPFC can be installed in different locations, its effectiveness will be different. Therefore, we will face the problem of where we should install UPFC. For this reason, some performance indices must be satisfied. The factors that

can be considered in the selection of the optimal installation and parameter setting of UPFC may be the stability margin improvement, the power transmission capacity increasing, and the power blackout prevention, etc.

The placement of UPFCs is a very complex problem, even under the consideration of steady-state conditions only (neglecting dynamic controls). An optimal UPFC placement must incorporate not only each possible system topology (line outages, load profiles, etc.) but must also consider the entire range of possible control settings which may themselves be dependent on system topology [4]. In the last decade, new algorithms have been developed for the optimal power flow incorporating with UPFC device as well as for the optimal placement of UPFC. Some of them are sensitivity-based approach which has been developed for finding suitable placement of UPFC [5], an evolutionary-programming-based load flow algorithm for systems containing unified power flow controllers [6], a genetic algorithm which proposed for solving the optimal location problem of UPFC [7], and a particle swarm optimization (PSO) for optimal location of FACTS devices [8].

This paper proposes employing a new modified particle swarm optimization to find out the optimal location and parameter setting of UPFC device for enhancing system security under single line contingencies through eliminating or minimizing the overloaded lines and the bus voltage limit violations.

The organization of this paper is as follows: Section II defines the problem that must be solved. The UPFC model and the problem formulation are described. Section III describes the proposed particle swarm algorithm used to achieve the optimization problem. Section IV describes the results of the simulations conducted using the proposed approach, while Section V presents the conclusions of this work.

II. PROBLEM FORMULATION

A. UPFC power flow model

The UPFC (unified power flow controller) is a FACTS device able to control simultaneously active power flows, reactive power flows, and voltage magnitude at the UPFC terminals [3]. The UPFC consists of two switching converters operated from a common DC link, as shown in Fig. 1. These converters are connected to the power system via coupling transformers. One converter is connected in shunt to the sending end node while the second converter is connected in series between the sending and receiving end nodes. The series converter performs the main function of the UPFC by injecting an AC voltage with controllable

magnitude and phase angle in series with the transmission line. The UPFC cannot generate or absorb active power and as such the active power in the two converters must balance when active power loss is neglected. This is achieved via the DC link. The converters, however, may generate or absorb reactive power. The shunt converter can generate or absorb controllable reactive power and provide independent shunt reactive compensation for the line. UPFC can then regulate active and reactive power simultaneously. In principle, a UPFC can perform voltage support, power flow control and dynamic stability improvement in one and the same device [9]. The UPFC equivalent circuit shown in Fig. 2 is used to derive the steady-state model.

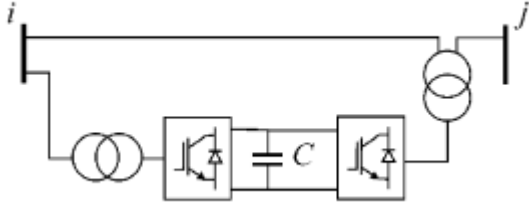


Fig. 1. Schematic representation of UPFC

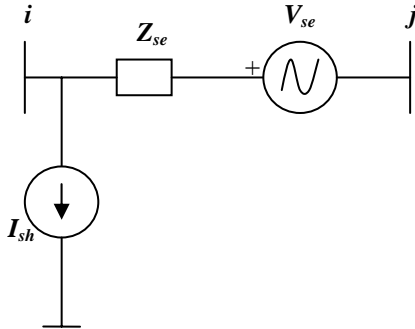


Fig. 2. Equivalent circuit of UPFC

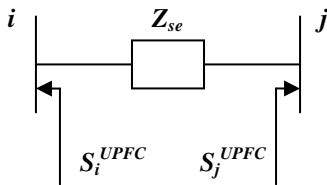


Fig. 3. Power injection model of UPFC

The UPFC model can be incorporated to the power flow equations by including the impedances of the converters transformers Z_{se} and Z_{sh} into the bus admittance matrix and adding the UPFC injection powers at buses i and j . Based on the equivalent circuit shown in Fig. 2, its model in terms of power injection, as it is shown in Fig. 3, can be written as the following equations:

$$S_i^{UPFC} = V_i \left(\frac{V_{se}}{Z_{se}} \right)^* - V_i I_{sh}^* \quad (1)$$

$$S_j^{UPFC} = -V_j \left(\frac{V_{se}}{Z_{se}} \right)^* \quad (2)$$

where

$$I_{sh} = I_p - jI_q \quad (3)$$

Then, modeled with this complex power injection model, the associated control variables are the series voltage and the shunt injected current of the device:

$$x_{UPFC} = [V_{se}, \delta_{se}, I_q] \quad (4)$$

V_{se} denotes the magnitude of the voltage injected in series with the transmission line through the series transformer. δ_{se} is the phase angle of this voltage. I_q is the shunt reactive current of UPFC. The UPFC parameters V_{se} , δ_{se} and I_q are chosen within a range due to physical and economic limitations. The current I_p represents the active power demanded by the series converter at the common DC link and supplied or absorbed by the shunt converter.

With these control variables it is possible to calculate the complex power injected S_i^{UPFC} and S_j^{UPFC} by the UPFC:

$$S_i^{UPFC} = P_i^{UPFC} + jQ_i^{UPFC} \quad (5)$$

$$S_j^{UPFC} = P_j^{UPFC} + jQ_j^{UPFC} \quad (6)$$

Based on the complex expressions above and assuming lossless converter $P_{sh} = P_{se}$, the active and reactive power injections associated to the UPFC are:

$$P_i^{UPFC} = -G_{se} V_{se}^2 + 2G_{se} V_i V_{se} \cos(\delta_i - \delta_{se}) - V_j V_{se} (G_{se} \cos(\delta_j - \delta_{se}) - B_{se} \sin(\delta_j - \delta_{se})) \quad (7)$$

$$Q_i^{UPFC} = V_i V_{se} (G_{se} \sin(\delta_i - \delta_{se}) - B_{se} \cos(\delta_i - \delta_{se})) - V_i I_q \quad (8)$$

$$P_j^{UPFC} = -V_j V_{se} (G_{se} \cos(\delta_j - \delta_{se}) + B_{se} \sin(\delta_j - \delta_{se})) \quad (9)$$

$$Q_j^{UPFC} = -V_j V_{se} (G_{se} \sin(\delta_j - \delta_{se}) - B_{se} \cos(\delta_j - \delta_{se})) \quad (10)$$

where:

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

Then, the power flow Newton–Raphson algorithm is expressed by the following relationship:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H_{new} & M_{new} \\ N_{new} & L_{new} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (12)$$

where the new error vectors are

$$\Delta P_i = P_i^{spec} + P_i^{UPFC} - P_i^{calc} \quad (13)$$

$$\Delta Q_i = Q_i^{spec} + Q_i^{UPFC} - Q_i^{calc} \quad (14)$$

P_i^{spec} and Q_i^{spec} are the classical specified powers, P_i^{UPFC} and Q_i^{UPFC} are the power injection associated to the UPFC device, and P_i^{calc} and Q_i^{calc} are computed using the power flow equations.

And, the Jacobian matrix is modified to introduce new power injections that are functions of the bus voltages:

$$H_{new} = H + \frac{\partial P^{UPFC}}{\partial \delta}; \quad M_{new} = M + \frac{\partial P^{UPFC}}{\partial V} \quad (15)$$

$$N_{new} = N + \frac{\partial Q^{UPFC}}{\partial \delta}; \quad L_{new} = L + \frac{\partial Q^{UPFC}}{\partial V} \quad (16)$$

H, M, N, L are the classic sub-Jacobian $\frac{\partial P}{\partial \delta}, \frac{\partial P}{\partial V}, \frac{\partial Q}{\partial \delta}$, and $\frac{\partial Q}{\partial V}$ respectively.

B. Contingency analysis procedure

A contingency is considered to be the outage of a generator, transformer or transmission line. The system may become unstable and enters an insecure state when a contingency event is occurred. Contingency analysis is one of the most important functions performed in power systems to establish appropriate preventive and/or corrective actions for each contingency. In this paper, we focus our attention only on the single line outage contingencies. For each line outage contingency in the system, we determine the all overloaded lines and the buses which have voltage limit violations, and then we rank the lines in the system according to the severity of the contingency. In other words, according to the number of the thermal and voltage limits violations the severities of contingencies are ranked, when the line outage contingency occurs. After determining the most critical contingency scenarios, the proposed method technique is applied to find out the optimal location and parameter setting of UPFC. Installing UPFC in the optimized location with the optimized parameter setting will eliminate or minimize the overloaded lines and the bus voltage limit violations under these critical contingencies according to the objective function described in next subsection.

C. UPFC objective function

To determine the optimal power flow setting for the UPFC, it is necessary to define an objective function that measures the “goodness” of a particular setting. In this paper, the main objective is to determine the optimal parameter setting and location of the UPFC in the network for enhancing the system security level. This enhancement can be achieved through eliminating or minimizing overloaded lines and bus voltage limit violations under the most severe single line contingencies. Therefore, we consider the following technical objective function [1,10], which provides simultaneously, the active and reactive power flow control setting with minimum overloading and the best voltage security.

$$PI = \sum_{l=1}^{nl} w_l \left(\frac{S_l}{S_{lmax}} \right)^2 + \sum_{i=1}^{nb} w_v \left(\frac{V_i - V_{iref}}{V_{iref}} \right)^2 \quad (17)$$

w_l and w_v represent two weights and are determined in order to have the same index value for 10% voltage difference and for 100% branch loading.

D. System constraints

(a) Equality constraints:

The equality constraints are the power flow equations, which are given in general form as follows:

$$P_{Gi} - P_{Di} - P_i(\delta, V) = 0 \quad (18)$$

$$Q_{Gi} - Q_{Di} - Q_i(\delta, V) = 0 \quad (19)$$

(b) Inequality constraints:

The inequality constraints represent the system operating limits:

$$\text{UPFC injected voltage limits : } 0 \leq V_{se} \leq V_{se \max} \quad (20)$$

$$\text{UPFC reactive current limits : } -I_{q \min} \leq I_q \leq I_{q \max} \quad (21)$$

$$\text{reactive power limits : } Q_{G \min} \leq Q_g \leq Q_{g \max} \quad (22)$$

$$\text{bus voltage limits : } V_{i \min} \leq V_i \leq V_{i \max} \quad (23)$$

$$\text{line power flow limit : } S_l \leq S_{l \max} \quad (24)$$

III. OPTIMIZATION METHOD

A. Overview of Particle Swarm Optimization

Particle Swarm Optimization (PSO), which has gained rapid popularity as an efficient optimization technique, is relatively a recent heuristic introduced by Eberhart and Kennedy [11]. It is based on the analogy of swarm of birds and school of fish. In PSO, each individual called particle makes his decision using his own experience together with other individuals' experience. PSO has a flexible and well-balanced mechanism to enhance and adapt the global and local exploration and exploitation abilities within a short calculation time. The main advantages of PSO algorithm are summarized as: simple concept, easy implementation, robustness to control parameters, and computational efficiency when compared with mathematical algorithm and other heuristic optimization techniques [12]. In PSO, two different definitions are used: the individual best and the global best. As a particle moves through the search space, it compares its fitness value at the current position to the best fitness value it has ever attained previously. The best position that is associated with the best fitness encountered so far is called the individual best or pbest. The global best, or gbest, is the best position among all of the individual's best positions achieved so far.

Using the gbest and the pbest, the i th particle velocity is updated according to the following equation:

$$v_i^{k+1} = w v_i^k + c_1 r_1 (pbest_i - s_i^k) + c_2 r_2 (gbest - s_i^k) \quad (25)$$

Where r_1, r_2 are random numbers; c_1, c_2 and w are the parameters of the PSO.

Based on the updated velocities, each particle changes its position according to the equation:

$$s_i^{k+1} = s_i^k + v_i^{k+1} \quad (26)$$

The following weighting function is usually utilized [13,14]:

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} \times iter \quad (27)$$

B. Perturbed Particle Updating Strategy

In PSO, the swarm converges rapidly within the intermediate vicinity of the gbest. However, such a high convergence speed often results in: (1) the lost of diversity and (2) premature convergence if the gbest corresponds to a local optima. This motivates the development of PPSO-a perturbed particle swarm optimization algorithm based on the perturbed gbest updating strategy, which is based on the concept of possibility measure [15,16] to model the lack of information about the true optimality of the gbest. In contrast to conventional approaches, the gbest in PPSO is denoted as "possibly" at gbest (pgbest) instead of a crisp location. Consequently, the calculation of particle velocity can be rewritten as

$$pgbest = N(gbest, \sigma) \quad (28)$$

$$v_i^{k+1} = wv_i^k + c_1r_1(pbest_i - s_i^k) + c_2r_2(pgbest - s_i^k) \quad (29)$$

From (28), it can be observed that the pgbest is characterized by a normal distribution $N(gbest, \sigma)$ where σ represents the degree of uncertainty about the optimality of the gbest. In order to account for the information received over time that reduces uncertainty about the gbest position, σ is modeled as some non-increasing function of the number of cycles. For simplicity, σ is defined using a linear model [16]:

$$\sigma = \sigma_{\max} - \frac{iter - 1}{\max it} (\sigma_{\max} - \sigma_{\min}) \quad (30)$$

where σ_{\max} and σ_{\min} are manually set parameters.

The perturbed global best updating strategy (28) should be distinguished from conventional mutation operator which applies a random perturbation to the particles. The function of pgbest is to encourage the particles to explore a region beyond that defined by the search trajectory. By considering the uncertainty associated with each gbest as a function of time, pgbest provides a simple and efficient exploration at the early stage when σ is large and encourages local fine-tuning at the latter stage when σ is small. Subsequently, this approach helps to reduce the likelihood of premature convergence and guides the search toward the promising search area.

C. The perturbed Particle Swarm Algorithm

The step by step implementation of the PPSO algorithm can be described as follows:

Step 1: Initialize power flow data and PSO related parameter such as the size of population (N), the maximum number of iteration or generation (maxit), the number of variables to be optimized.

Step 2: Randomly generate the initial population of N individuals in the feasible space satisfying the UPFC constraints considering the variables that should be optimized (i.e., the location and the parameter setting of UPFC). The candidate locations are in the range $[1, nl]$, nl is the number of lines in the system.

Step 3: For each individual i in the population, the objective function given by (17) is evaluated after running load flow.

Step 4: Compare particle's fitness evaluation with its pbest. If current value is better than pbest, then let pbest be the current value.

Step 5: Identify the particle in the neighborhood with the best success so far, and assign its index to the variable gbest.

Step 6: Create a new population by changing the velocity and position of the particle according to (26) and (29) using (28).

Step 7: Stop the process and print the best individual (optimal location and optimal parameter setting of UPFC) if the stopping criterion is satisfied, else go back to Step 3.

IV. SIMULATION RESULTS AND DISCUSSION

Matlab programming codes for PSO and modified power flow algorithm to include UPFC are developed and incorporated together for the simulation purposes in this work. The suggested algorithm is applied to the IEEE 14-bus test system [13]. The system consists of five synchronous machines, three of which are synchronous compensators used only for reactive power support, 14 buses, 20 transmission lines, and 11 loads totaling 259 MW and 81.3 Mvar.

A. Contingency Analysis

Contingency analysis and ranking process was carried out. For each single line outage contingency, we determine the overloaded lines (OLL) and voltage limit violation buses (VVB). Loading of the lines up to their thermal limits is considered to be the threshold or the criterion for determining the overloaded lines, and the range $[0.90-1.10]$ p.u. for bus voltage limits is considered to be the threshold or the criterion for determining the buses which have voltage limit violations. Secondly, we rank the tripped lines according to the severity of the contingency, in other words, according to OLL and VVB results. The contingency analysis and ranking process was performed in case of heavy load (20% over the initial load) instead of initial load in order to obtain violations (at initial or light load there are no violations even for line outages). The results showed that the most severe contingencies were the outages of lines (1-2), (2-3), and (1-5). For the (1-2) line outage, there is no solution for the initial load level (load flow routine diverges).

B. Optimal location and parameter setting of UPFC

The following variables are considered as the optimization variables:

(a) The location of UPFC in the network is considered as the first variable to be optimized, and the location candidates for this variable can be any line in the network;

(b) The series voltage source magnitude (V_{se}) of the UPFC is considered as the second variable to be optimized, and the working range for this variable is $[0.001, 0.2]$.

(c) The series voltage source phase angle (δ_{se}) of the UPFC is considered as the third variable to be optimized, and the working range for this variable is $[0, 2\pi]$

(d) The shunt reactive current (I_q) of the UPFC is considered as the fourth variable to be optimized, and the working range for this variable is $[-0.15, 0.15]$.

These variables are optimized to enhance the security of power system under single line contingencies through eliminating or minimizing the line overloads and the bus voltage limit violations using the objective function given by (17).

PSO is one among techniques which are probabilistic and stochastic search techniques, there are no standard values for their parameter and the adopted values were found to give the best performance in most cases as it is stated in the

literature. The parameters of the PSO are set as follows: $c_1=c_2=1$; $N=30$; $\text{maxit}=70$; The data for the UPFC are taken from [17].

Table 1 shows the optimal locations and optimal parameter setting of UPFC obtained by applying PPSO for peak load (150%) and line 2-3 outage. The line 2-3 outage is the severest feasible contingency scenario considered here.

TABLE I

Optimal location and setting of UPFC obtained by PPSO

case	location	V_{se}	δ_{se}	I_q
Line 2-3 outage	17	0.069	341	0.139
Peak load 150%	14	0.074	352	0.15

Fig. 4 shows the power flow distribution obtained for the 2-3 line outage case with and without UPFC installed in the optimal location. After using UPFC in the optimized location obtained, the power flow distributions are significantly reduced in most lines. We only choose this case as a sample of the results we have obtained, because this is the severest feasible contingency scenario and also because of the limited space of this paper. Fig. 5 shows voltage distribution for the system with UPFC installed in the optimized location with the optimized parameter setting obtained when line 2-3 is outage. After using UPFC all of voltages are enhanced.

We note that in case of this contingency scenario, although with the help of using UPFC in the optimized location with the optimized parameter setting did not result in eliminating all of the overloaded lines. Also, the bus 3 voltage limit violation is not eliminated.

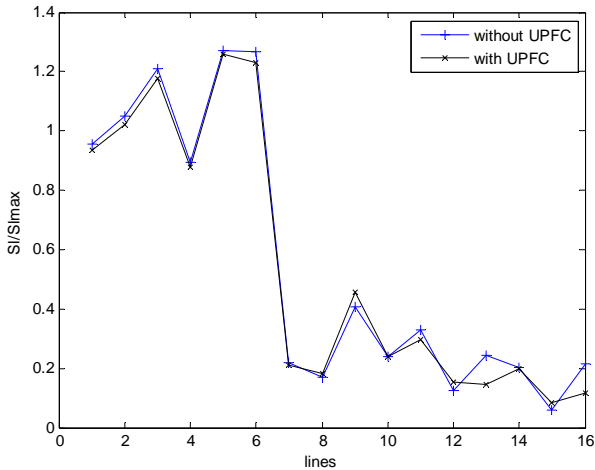


Fig. 4. Power flow distribution when line 2-3 is outage

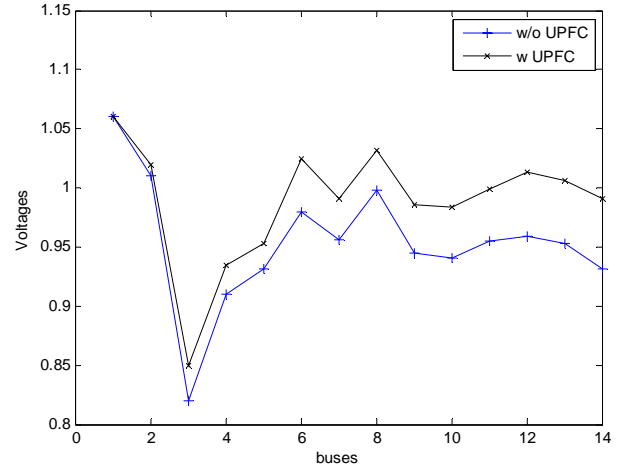


Fig. 5. Voltage profile when line 2-3 is outage

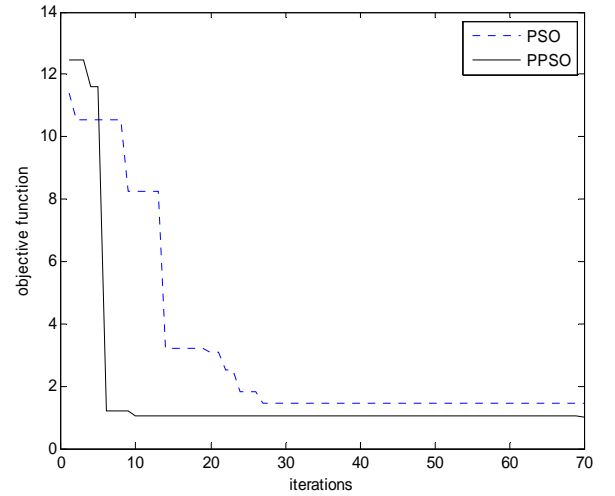


Fig. 6. Convergence characteristics of PPSO and standard PSO when line 2-3 is outage

Finally, Fig. 6 shows the convergence characteristics of the objective function by PPSO compared to standard PSO technique when line 2-3 is outage. PPSO is able to achieve good results consistently with fast performance. It finds the smallest value of the objective function compared with PSO in the studied cases which was the purpose of the perturbation introduced to gbest.

V. CONCLUSION

In this paper, the effectiveness of the optimal location of UPFC for enhancing the security of power systems under single line contingencies has been investigated. Determinations of the severest contingency scenarios were performed based on the contingency selection and ranking process. A modified version of PSO technique, namely: Perturbed PSO has been successfully applied to the problem under consideration. Maximization of power system security is considered as the optimization criterion. The performance of PPSO is compared with that of the standard PSO. Through a case study conducted using an IEEE 14-bus system, the obtained results show the proposed technique has good features and that the proposed algorithm is an effective and practical method for the allocation of UPFCs in large power systems. Finally, our results show that using UPFC in the optimal location with the optimal parameter

settings can significantly improve the security of power systems under single line contingencies.

VI. REFERENCES

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