Scientia Iranica D (2015) 22(6), 2432–2446

Sharif University of Technology
Scientia Iranica
Transactions D: Computer Science & Engineering and Electrical Engineering
www.scientiairanica.com

Multi-objective optimal location of Optimal Unified Power Flow Controller (OUPFC) through a fuzzy interactive method

A. Lashkar Ara[a,*], M. Shabani[a] and S.A. Nabavi Niaki[b]

a. *Department of Electrical Engineering, Dezful Branch, Islamic Azad University, Dezful, P.O. Box 313, Iran.*
b. *Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON M5 S 3G4, Canada.*

Received 24 June 2014; received in revised form 28 March 2015; accepted 16 June 2015

KEYWORDS
OUPFC;
UPFC;
FACTS;
Optimal location;
Multi-objective;
Fuzzy interactive method.

Abstract. This paper presents a fuzzy interactive approach to find the optimal location of Optimal Unified Power Flow Controller (OUPFC) device as a multi-objective optimization problem. The problem formulation is based on Optimal Power Flow (OPF) problem while the metric function and weighting method are added to ensure the collaboration among objective functions. The objective functions are the total fuel cost, power losses, and system loadability with and without the minimum cost of OUPFC installation. The proposed algorithm is implemented on IEEE 14- and 118-bus systems. The solution procedure uses nonlinear programming with discontinuous derivatives (DNLP) to solve the optimal location and settings of OUPFC device to enable power system dispatcher to improve the power system operation. The optimization problem is modeled in General Algebraic Modelling System (GAMS) software using CONOPT solver. Furthermore, the results obtained by OUPFC are compared with those of the Unified Power Flow Controller (UPFC) device. The OUPFC is outperformed by UPFC in the power system operation from the economic and technical point of view.

1. Introduction

The optimum operation of an interconnected power system involves dispatcher concerns such as optimal choice and allocation of Flexible AC Transmission Systems (FACTS) devices as power flow controllers. Optimal Unified Power Flow Controller (OUPFC) is a member of FACTS controllers that can provide the necessary functional flexibility for optimal power flow control through phase angle control. It is composed of a conventional Phase Shifting Transformer (PST) and a scale-down Unified Power Flow Controller (UPFC). The steady-state model of OUPFC and its operational characteristics are introduced in [1].

The multi-objective OPF problem considering FACTS devices is addressed in many technical literature. In [2], the best location of PSTs has been determined by genetic algorithm to reduce the flows in heavily loaded lines resulting in increased system loadability and reduced generation costs. The best optimal location of FACTS devices, in order to reduce the generation costs along with the device's cost using real power flow performance index, has been reported [3]. A hybrid tabu search and simulated annealing has been proposed to minimize the generator fuel cost in OPF control with multi-type FACTS devices [4]. The optimal location of FACTS devices has been found using the Particle Swarm Optimization (PSO) technique for considering system loadability and installation cost [5].

*. *Corresponding author. Tel.: +98-641-6260051; Fax: +98-641-6260890*
E-mail addresses: Lashkarara@iust.ac.ir (A. Lashkar Ara); nabavi.niaki@utoronto.ca (S.A. Nabavi Niaki)

In [6], the multi-objective optimal location of PST, UPFC, and OUPFC has been considered using the ε-constraint method. The contingency-based optimal location of UPFC and OUPFC has been investigated under a single-line contingency [7].

Several different methods have been widely applied for solving various power system problems such as optimal location and OPF problems. These methods can be divided into two main categories:

(i) Mathematical methods that include nonlinear programming [8], quadratic programming [9,10], linear programming [11,12], Newton-based techniques [13,14], sequential unconstrained minimization [15], interior point [16,17], and minimum cut algorithm [18],

(ii) Intelligent methods that include Evolutionary Programming (EP) [19], Genetic Algorithm (GA) [20-22], Differential Evolution (DE) [23], Artificial Neural Network (ANN) [24], Simulated Annealing (SA) [25,26], Artificial Bee Colony algorithm (ABC) [27], PSO [28], harmony search algorithm [29], and gravitational search algorithm [30].

Although some of the mathematical methods have excellent convergence characteristics, some drawbacks of these methods are [31]:

- The solution converges to a local optimum instead of a global optimum, depending on the selected initial values;
- Each technique is suitable for a specific kind of optimization problem based on the mathematical nature of the objectives and/or constraints;
- Some theoretical assumptions, such as convexity, differentiability, and continuity, are built into these methods which may not be suitable for the OPF problem;
- They are not able to interact with the decision-maker through optimization process.

In addition, the intelligent methods have been successfully used to solve the optimization problems in which global solutions are more preferred than local ones, or when the problem has non-differentiable regions. But these methods have some drawbacks, too, such as:

- These methods require significantly large computations and are not efficient enough for real-time systems that need to quickly change the system;
- Implementation of these methods is difficult;
- They generate a Pareto solution set; the decision-maker must select the best compromise solution through Pareto solutions by a decision-making approach;
- They are stochastic and cannot strictly figure on solutions optimally;
- They are not able to interact with the decision-maker through optimization process.

In order to handle the mentioned problems, the fuzzy optimization approach is used to solve the multi-objective optimization problems. The objective functions and constraints are considered as modified constraints in terms of their fuzzy membership functions. The model is constructed by definition of sets of membership functions for each constraint and objective function. Therefore, the main purpose of a fuzzy optimization problem is to maximize all membership functions at the same time. This is usually done using a formulation similar to the min–max formulation for the multi-objective optimization [32]. Consequently, fuzzy optimization lends itself to multi-objective optimization where additional objective functions are modeled as constraints. Moreover, the conflicting degree among objectives and the designer's preferences are nearly neglected in many fuzzy multi-objective optimization models; however, they are still an ongoing research topic.

In this paper, an interactive fuzzy multi-objective optimization method, incorporated in the metric function and weighting method, is proposed to enable the operator to interact with the algorithm through optimization process in contrast to other multi-objective methods.

To the best of our knowledge, no research work has been developed to locate and allocate the OUPFC device through the fuzzy interactive multi-objective optimization. The main contribution of this paper is to find the optimal location of OUPFC based on OPF problem incorporated in the metric function and weighting method as the multi-objective optimization problem. The objective functions are classified into four categories:

(i) The total fuel cost;

(ii) Active power losses;

(iii) System loadability;

(iv) Installation cost of the FACTS device.

The optimal location and settings of OUPFC are determined on the IEEE 14-, and 118-bus test systems to optimize these objective functions simultaneously. The optimization problem is modeled as a nonlinear programming with discontinuous derivatives (DNLP) problem in General Algebraic Modeling System (GAMS) software and solved using CONOPT solver [33]. Furthermore, in order to highlight the performance and applicability of the OUPFC, its results are compared with those of UPFC.

This paper is organized as follows. The modeling of FACTS controllers are studied in details in Section 2. Section 3 contains the problem formulation of OPF incorporated in the FACTS device, including variables, objective functions, and constraints. The multi-objective optimization problem is presented in Section 4. The simulation results and the optimal settings and the best location of OUPFC and UPFC are reported in Section 5.

2. Modeling of FACTS devices

2.1. Modeling of OUPFC [1]

The OUPFC is comprised of a PST and a UPFC, as shown in Figure 1. The power injection model of the OUPFC is shown in Figure 2 where:

$$P_{ss} = - b_s k V_i V_j \sin(\theta_i - \theta_j + \sigma) - b_s r V_i V_j \sin(\theta_i - \theta_j + \rho), \tag{1}$$

$$\begin{aligned} Q_{ss} = &- b_s V_i^2 (k^2 + r^2) - 2 b_s k r V_i^2 \cos(\sigma - \rho) \\ &- 2 b_s k V_i^2 \cos(\sigma) - 2 b_s r V_i^2 \cos(\rho) \\ &+ b_s k V_i V_j \cos(\theta_i - \theta_j + \sigma) \\ &+ b_s r V_i V_j \cos(\theta_i - \theta_j + \rho), \end{aligned} \tag{2}$$

$$P_{sr} = -P_{ss}, \tag{3}$$

$$Q_{sr} = b_s k V_i V_j \cos(\theta_i - \theta_j + \sigma) + b_s r V_i V_j \cos(\theta_i - \theta_j + \rho), \tag{4}$$

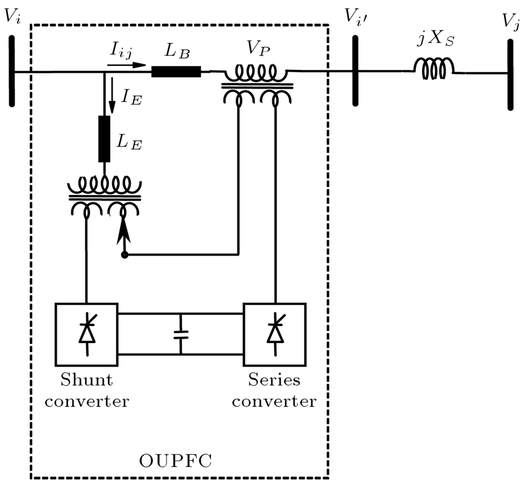

Figure 1. Per-phase schematic diagram of OUPFC.

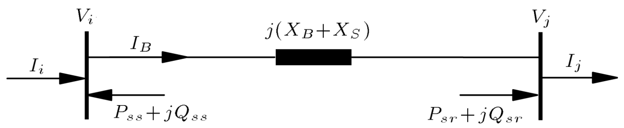

Figure 2. The power injection model of FACTS devices.

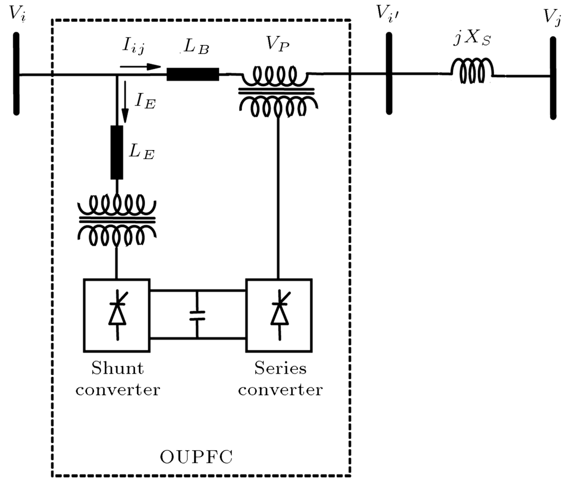

Figure 3. Basic schematic diagram of UPFC.

where k is the transfer ratio of PST; σ is the PST phase angle; r is the radius of the UPFC operating region; ρ is the UPFC phase angle; b_s is $1/(X_S + X_B)$ where X_S is the transmission line reactance; and X_B is the series transformer leakage reactance.

2.2. Modeling of UPFC

The basic schematic of the UPFC is shown in Figure 3. The power injection model of the UPFC is same as the OUPFC of Figure 2 where:

$$P_{ss} = -b_s r V_i V_j \sin(\theta_i - \theta_j + \gamma), \tag{5}$$

$$Q_{ss} = - b_s r V_i^2 (r + 2\cos(\gamma)) + b_s r V_i V_j \cos(\theta_i - \theta_j + \gamma), \tag{6}$$

$$P_{sr} = -P_{ss}, \tag{7}$$

$$Q_{sr} = +b_s r V_i V_j \cos(\theta_i - \theta_j + \gamma), \tag{8}$$

where r is radius of the UPFC operating region; and γ is the UPFC phase angle [34].

3. Problem formulation

The problem formulation is based on a multi-objective OPF problem to make trade-off between objective functions and optimize four objective functions simultaneously while satisfying several equality and inequality constraints. The objective functions and constraints are explained in the following.

3.1. Objective functions

The objective functions are dependent on the system requirements and on the system operator concerns. Therefore, the objective functions of this paper are the total fuel cost, active power losses, system loadability, and installation cost of the FACTS device.

3.1.1. Total fuel cost

The quadratic fuel cost functions are used to minimize the total operating cost as the objective function. The objective function of the total fuel cost can be formulated as follows [35]:

$$F_1(P_i) = \sum_{i=1}^{NG} C_i(P_{Gi}) = \sum_{i=1}^{NG} \alpha_{0i} + \alpha_{1i} P_{Gi} + \alpha_{2i} P_{Gi}^2 \ (\$/\mathrm{h}), \tag{9}$$

where P_{Gi} is generator active power output at bus i; α_{0i}, α_{1i}, and α_{2i} are cost coefficients of unit i; and NG is number of generators.

3.1.2. Active power losses

Loss minimization is very important in the power system operation and tends to reduce the reactive power flow in the power system. It can be expressed as follows [36]:

$$F_2(V, \theta) = \sum_{i=1}^{n} \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\alpha_{ij} + \theta_j - \theta_i), \tag{10}$$

where V_i and θ_i are voltage magnitude and angle of bus i; Y_{ij} and α_{ij} are the elements of admittance matrix magnitude and angle in row i and column j, respectively; and n is number of buses.

3.1.3. System loadability

The power system operator usually prefers some further loading margins to decrease the risk of load variations, particularly in weak connections of the network. Therefore, the objective function of the system loadability can approximately remedy the maximum loading limits of the transmission lines and the dynamic power oscillations of the system that can be described as [37,38]:

$$F_3 = \rho(x, u), \tag{11}$$

and ρ can be obtained by assuming constant power factor at each load in both real and reactive power balance equations as follows:

$$P_G - \rho P_D = f_p(x, u), \tag{12}$$

$$Q_G - \rho Q_D = f_q(x, u), \tag{13}$$

where P_G and Q_G are the vectors of generators real and reactive power, respectively; P_D and Q_D are the vectors of loads real and reactive power, respectively; f_p and f_q are the vectors of real and reactive power flow equations, respectively; and x and u are sets of dependent and control variables, respectively.

3.1.4. FACTS investment cost

Since the installation of FACTS device is an investment issue, it interests the operator to decrease the total operating cost including its cost while the other objectives are considered. Therefore, the cost of FACTS installation is minimized in the multi-objective optimization framework. It can be mathematically formulated as follows:

$$F_4 = \frac{C_{\mathrm{FACTS}}}{8760 \times 5} \ (\$/\mathrm{h}), \tag{14}$$

where C_{FACTS} is the cost of FACTS installation in US\$. The OUPFC and UPFC cost functions are taken [6,39] as follows:

$$C_{\mathrm{OUPFC}} = [(12 \times S_{\mathrm{PST}}) + ((0.0003 S_{\mathrm{UPFC}}^2 - 0.2691 S_{\mathrm{UPFC}} + 188.22) \times S_{\mathrm{UPFC}})] \times 1000, \tag{15}$$

$$C_{\mathrm{UPFC}} = (0.0003 S_{\mathrm{UPFC}}^2 - 0.2691 S_{\mathrm{UPFC}} + 188.22) \times S_{\mathrm{UPFC}} \times 1000, \tag{16}$$

where S_{FACTS} is the operating range of FACTS devices in MVA. In this paper, a five-year period is assumed to usefully apply FACTS devices.

3.2. Constraints

The constraints of OPF problem can be divided into two categories: equality and inequality constraints.

3.2.1. Equality constraints

The equality constraints include active and reactive power balance equations for each bus as follows [35]:

$$P_{Gi} + P_{\mathrm{FACTS}i} = P_{Di} + \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\alpha_{ij} + \theta_j - \theta_i) \quad \forall i \in 1, 2, \cdots, n, \tag{17}$$

$$Q_{Gi} + Q_{\mathrm{FACTS}i} = Q_{Di} + \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\alpha_{ij} + \theta_j - \theta_i) \quad \forall i \in 1, 2, \cdots, n, \tag{18}$$

where P_{Gi} and Q_{Gi} are the generator active and reactive power at bus-i, respectively; P_{Di} and Q_{Di} are the load active and reactive power at bus-i, respectively; $P_{\mathrm{FACTS}i}$ and $Q_{\mathrm{FACTS}i}$ are the injected active and reactive powers by the FACTS device, respectively.

3.2.2. Inequality constraints

Inequality constraints represent the following limits on the active and reactive output power of generators, bus voltages, transmission lines loadings, and FACTS operational parameters [31].

a. The generators active and reactive output power is restricted by its lower and upper limits as follows:

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max} \qquad \forall i \in NG, \tag{19}$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \qquad \forall i \in NG. \tag{20}$$

b. Voltage magnitude of the buses is limited in the region defined by the operator in the following form:

$$\left|V_i^{\min}\right| \leq |V_i| \leq |V_i^{\max}| \qquad \forall i \in n. \tag{21}$$

c. The apparent power flow of transmission line l is lower than its maximum value, i.e.:

$$|S_l| \leq |S_l^{\max}| \qquad \forall l \in 1, 2, \cdots, NL. \tag{22}$$

d. The FACTS parameters are bounded as follows [1,34]:

$$\left.\begin{array}{l} r^{\min} \leq r \leq r^{\max} \\ \rho^{\min} \leq \rho \leq \rho^{\max} \\ \sigma^{\min} \leq \sigma \leq \sigma^{\max} \end{array}\right\} \quad \text{for OUPFC,} \tag{23}$$

$$\left.\begin{array}{l} r^{\min} \leq r \leq r^{\max} \\ \gamma^{\min} \leq \gamma \leq \gamma^{\max} \end{array}\right\} \quad \text{for UPFC.} \tag{24}$$

4. Interactive fuzzy multi-objective optimization algorithm

Generally, the multi-objective optimization problem attempts to find feasible solutions to optimize a vector of objective functions $F(x) = \{F_1(x), F_2(x), \cdots, F_n(x)\}$ while the constraints are satisfied. The problem can be formulated as follows:

minimize or maximize:

$$F(x) = \{F_1(x), F_2(x), \cdots, F_n(x)\},$$

subject to:

$$h_i(x) = 0, \qquad i = 1, 2, \cdots, I,$$

$$g_j(x) \leq 0, \qquad j = 1, 2, \cdots, J,$$

$$X_k^u \geq X_k \geq X_k^l \qquad k = 1, 2, \cdots, k, \tag{25}$$

where $F(x)$ is a vector of objective functions which can be minimized or maximized simultaneously; $h_i(x)$ and $g_j(x)$ are equality and inequality constraints, respectively; X_k^u and X_K^l are upper and lower bounds of variables, respectively. It is noted that the problem should be modeled as the fuzzy optimization framework. Therefore, the process of fuzzy implementation is explained in the following.

Table 1. Computed payoff table by single objective optimization for each function.

	F_1	F_2	F_3	F_4
$(\min F_1, F_2, F_3, F_4)$	$F_1^*(x_1^*)$	$F_2(x_1^*)$	$F_3(x_1^*)$	$F_4(x_1^*)$
$(F_1, \min F_2, F_3, F_4)$	$F_1(x_2^*)$	$F_2^*(x_2^*)$	$F_3(x_2^*)$	$F_4(x_2^*)$
$(F_1, F_2, \max F_3, F_4)$	$F_1(x_3^*)$	$F_2(x_3^*)$	$F_3^*(x_3^*)$	$F_4(x_3^*)$
$(F_1, F_2, F_3, \min F_4)$	$F_1(x_4^*)$	$F_2(x_4^*)$	$F_3(x_4^*)$	$F_4^*(x_4^*)$

4.1. Single objective optimization

The search space of multi-objective optimization is usually well defined by single objective optimization. Therefore, each objective function is optimized while the corresponding values of other objective functions are calculated at the optimal point. Consequently, the payoff table is constructed as shown in Table 1.

In order to normalize each objective function, its maximum and minimum values are directly obtained from the payoff table as follows:

$$m_i = F_i^*(x_i^*) \qquad i = 1, 2, 3, 4,$$

$$M_i = \max_{j=1,2,3,4} \{F_i(X_j^*)\} \qquad i = 1, 2, 4,$$

$$M_i = \min_{j=1,2,4} \{F_i(X_j^*)\} \qquad i = 3, \tag{26}$$

where x_i^* is the optimal solution of ith objective function as the Pareto optimal solution; m_i and M_i are the best and worst values of ith objective function, respectively.

4.2. Developing the interactive constraint

One of the most important features of a fuzzy multi-objective optimization is presentation of candidate solutions in an interactive process. The general idea of interactive methods is to determine a good compromise solution integrating preferences of the operator. The operator's preferences can be consistently represented in the optimization model using the interactive process, although the objective functions naturally conflict with each other. In this paper, the interactive process is implemented by the metric function as defined by the following equation [40]:

$$d(x) = \sqrt[\rho]{\sum_{i=1}^{n} \left| \frac{M_i - F_i(X)}{M_i - m_i} \right|}, \tag{27}$$

where ρ belongs to the interval $[1, +\infty)$ and usually equals to 2; X is the vector of single objective solutions; the metric function is minimized to evaluate the optimum X using the common min-max method as follows:

$$F(X) = \min_x \max_i \left| \frac{M_i - F_i(X)}{M_i - m_i} \right|. \tag{28}$$

The importance degree of each objective function defined by the operator can be incorporated in the metric function as additional constraints in the optimization problem:

$$w_i \left| \frac{M_i - F_i(X)}{M_i - m_i} \right| \leq \varepsilon, \tag{29}$$

related to minimizing the ith objective function,

$$w_j \left| \frac{F_j(X) - M_j}{m_j - M_j} \right| \leq \varepsilon, \tag{30}$$

and to maximizing the jth objective function, and

$$\sum_{i=1}^{n} w_i = 1, \tag{31}$$

where w_i is the importance degree of the ith objective function and ε is the allowable degree of deviation from the optimal solution obtained by the single objective optimization.

The ideal value of the deviation degree is equal to 0. Therefore, the additional constraints, as equality constraints in the optimization problem, are equal to each other, i.e.:

$$\underset{i=1,2,4}{w_i} \left| \frac{M_i - F_i(x)}{M_i - m_i} \right| = \underset{j=3}{w_j} \left| \frac{F_j(x) - M_j}{m_j - M_j} \right|, \tag{32}$$

and:

$$\sum_{i=1}^{4} w_i = 1.$$

The collaboration among objective functions and the importance degree of each objective function are considered by adding these equality constraints into the multi-objective optimization problem. Furthermore, the relative deviations of each objective function from its optimal value can be minimized.

4.3. Constituting membership functions

The main idea is to simultaneously optimize objective functions and constraints in the fuzzy optimization [41]. To implement this idea, the multi-objective optimization problem can be converted into a single-objective optimization by the fuzzy optimization strategy. Therefore, the objective functions and constraints are reformulated by using fuzzy membership functions to reflect the satisfaction degree of a given solution. The first step is a fuzzification process of the objective functions and the constraints. This procedure converts the objective functions $F_i(x)$ and constraints $g_j(x)$ into pseudogoals $\mu_{F_i}(x)$ and $\mu_{g_j}(x)$, respectively.

The membership functions for F_1, F_2, and F_4 are provided by linear monotonically decreasing function when these objectives are in between their maximum and minimum values obtained by Eq. (26). In other words, the degree of satisfaction decreases while these objectives increase from m_i to M_i ($i = 1, 2, 4$). The mathematical formulation is expressed as follows [40]:

$$\mu_{\tilde{F}_i} = \begin{cases} 1 & F_i(x) \leq m_i \\ \frac{M_i - F_i(x)}{M_i - m_i} & m_i < F_i(x) < M_i, \\ 0 & F_i(x) \geq M_i \end{cases} \qquad i=1,2,4. \tag{33}$$

Similarly, the membership function of F_3 is determined by an increasing function when it is in the range between M_3 and m_3. These membership functions can be written as:

$$\mu_{\tilde{F}_i} = \begin{cases} 0 & F_i(x) \leq M_i \\ \frac{F_i(x) - M_i}{m_i - M_i} & M_i < F_i(x) < m_i, \\ 1 & F_i(x) \geq m_i \end{cases} \qquad i = 3. \tag{34}$$

In the conventional OPF, from other viewpoints, the equality and inequality constraints can be categorized into hard and soft constraints [42]. The hard constraints comprise the active and reactive power balance equations, output power of generators, bus voltages, and FACTS operational parameters. Because of technical and physical limitations, violations of these limits are not justifiable in any power system. On the other hand, the limits for the transmission line flows are soft constraints. The word "soft" signifies that the constraint is not absolutely enforced. Small violations of these limits sometimes can be acceptable, for example, when occurring especial conditions such as line over loaded or contingency. Normal and emergency limits are two usual limits for each constraint of the transmission line flows. The operators desire to operate the system in optimum performance within normal limits while small violations of the normal limits are allowed. However, the emergency limits can never be violated and are considered as hard limits. These practical considerations of constraint limits are not satisfactorily formulated in a conventional OPF.

Soft constraints on membership functions are made based on the desired lowest limit (b_j) and the highest limit ($b_j + d_j$) as normal and emergency limits of the transmissions line flows. The membership functions of inequality constraints are characterized by trapezoidal functions as follows [40]:

$$\mu_{\tilde{g}_j} = \begin{cases} 1 & g_j(x) \leq b_j \\ \frac{[(b_j + d_j) - g_j(x)]}{d_j} & b_j \leq g_j(x) \leq b_j + d_j \\ 0 & g_j(x) \geq b_j + d_j \end{cases} \tag{35}$$

4.4. Fuzzy multi-objective optimization modeling

After the fuzzification process, membership of the optimal function can be found by the aggregation of all the pseudo-goals and constraints. In the computation of fuzzy maximum function, the degree of satisfaction for fuzzy functions and fuzzy constraints can be represented by a membership variable λ. The membership variable λ is defined as the minimum of all the membership functions of the fuzzy functions and fuzzy constraints. This procedure can be formulated through the following equations [41]:

$$\lambda = \mu_D(x) = \min\{\mu_{F_1}(x), \cdots, \mu_{F_4}(x), \mu_{g_1}(x), \cdots, \mu_{g_n}(x)\}. \tag{36}$$

Using operator maximum, the optimal solution is computed as:

$$\max_{\lambda\in[0,1]} \lambda = \max_{\lambda\in[0,1]} \min\{\mu_{F_1}(x), \cdots, \mu_{F_4}(x), \mu_{g_1}(x), \cdots, \mu_{g_n}(x)\}. \tag{37}$$

Finally, the interactive fuzzy multi-objective optimization is modeled as follows [40]:

$$\begin{aligned}
&\text{maximize: } \lambda,\\
&\text{subject to:}\\
&\lambda \le \mu_{\tilde{F}_i}(x) \qquad i = 1, 2, 3, 4,\\
&\lambda \le \mu_{\tilde{g}_i}(x) \qquad i = 1, 2, \cdots, n,\\
&\underset{i=1,2,4}{w_i}\left|\frac{M_i - F_i(x)}{M_i - m_i}\right| = \underset{j=3}{w_j}\left|\frac{F_j(x) - M_j}{m_j - M_j}\right|,\\
&\sum_{i=1}^{4} w_i = 1,\\
&0 \le \lambda \le 1,\\
&X_k^u \ge X_k \ge X_k^l.
\end{aligned} \tag{38}$$

5. Case studies

The proposed method is applied to the IEEE 14-, and 118-bus test systems to verify its effectiveness to optimally locate OUPFC and UPFC devices. It is implemented in GAMS and modeled as a DNLP problem. The optimization problem is solved using CONOPT solver [33]. Data on the IEEE test systems are taken from [43]. Parameters and limits of the OUPFC and UPFC devices are given in Appendix A.

The CONOPT is used to solve static and dynamic large-scale nonlinearly constrained optimization problems. The GAMS/CONOPT solver is the link between the GAMS and CONOPT to solve the problem. It has a fast method for finding a first feasible solution that is particularly well suited for models with few degrees of freedom. It can also be used to solve square systems of equations without an objective function corresponding to the constrained nonlinear system model form [33].

The proposed algorithm is done for the optimum allocation of FACTS devices through individual optimization and various combinations of objective functions in IEEE 14- 118-bus test systems which can be expressed by the following frames:

Case 1: Minimizing total fuel cost and active power losses, simultaneously;

Case 2: Minimizing total fuel cost and maximizing system loadability at the same time;

Case 3: Minimizing active power losses and maximizing system loadability, concurrently;

Case 4: Minimizing total fuel cost, active power losses and maximizing system loadability, simultaneously.

In all cases, when the OPF problem is composed of the total fuel cost and FACTS investment cost as the objective functions, these functions are added together and become one objective, therefore take one weight in whole algorithm.

5.1. IEEE 14-bus test system

The single-objective and multi-objective optimization problems are performed on IEEE 14-bus test system considering the total fuel cost, active power losses, and the system loadability as objective functions. The results of the single-objective optimization are shown in Table 2 with and without minimization of the investment cost of OUPFC and UPFC devices. In the case without minimization of the investment cost, two devices have a similar performance with different sizes while the OUPFC investment cost is less than that of UPFC as much as 80%, 78%, and 81% for optimization of the total fuel cost, active power losses, and the system loadability, respectively. In the case with minimization of the investment cost, OUPFC has better performance than UPFC with 71.1% less investment cost for minimizing the total fuel cost and the investment cost, simultaneously. Also, the UPFC improves investment 2% more than OUPFC to minimize active power losses while the investment cost of UPFC is 92.8% more than that of OUPFC. The results show that utilizing both UPFC and OUPFC enhances system loadability objective function almost equally, but with 75.1% reduction in investment cost of OUPFC compared to that of UPFC.

Using fuzzy optimization method in solving different combinations of stated objectives, the multi-objective optimization results with the same weighting coefficients are tabulated in Table 3. The simulation results indicate better performance of OUPFC compared

Table 2. Single objective optimization results in IEEE 14-bus system.

Objective function	Parameters	Without FACTS	UPFC without investment cost	OUPFC without investment cost	UPFC with investment cost	OUPFC with investment cost
F_1	Total fuel cost (\$/h)	17278.80	17218.71	17218.71	17266.03	17252.75
	$\sum P_{\text{loss}}$ (MW)	1.712	0.9028	0.9028	1.538	1.3573
	$\sum Q_{\text{loss}}$ (MVAr)	14.281	11.3422	11.3422	13.7061	12.7804
	Loadability index	1	1	1	1	1.00
	Investment cost (\$/h)	-	236.89	47.42	42.36	12.0
	FACTS size (MVA)	-	59.92	56.92	10.00	26.31
	FACTS location	-	Line 1-5	Line 1-5	Line 3-2	Line 4-2
	FACTS settings	-	$r = 0.135$ $\gamma^\circ = 77.1$	$r = 0.131$ $\gamma^\circ = -180$, $\sigma^\circ = 13.06$	$r = 0.02$ $\gamma^\circ = 85.15$	$r = 0.04$ $\gamma^\circ = 92.04$, $\sigma^\circ = 1.02$
F_2	λ	-	-	-	0.835	0.783
	$\sum P_{\text{loss}}$ (MW)	1.128	0.759	0.759	0.859	0.878
	Total fuel cost (\$/h)	18186.61	18379.88	18379.88	18835.776	18884.398
	$\sum Q_{\text{loss}}$ (MVAr)	12.268	10.515	10.515	11.789	11.827
	Loadability index	1	1	1	1	1
	Investment cost (\$/h)	-	224.70	49.27	53.776	3.861
	FACTS size (MVA)	-	56.58	56.65	12.74	11.435
	FACTS location	-	Line 4-2	Line 4-2	Line 13-6	Line 13-6
	FACTS settings	-	$r = 0.105$ $\gamma^\circ = 72.77$	$r = 0.103$ $\gamma^\circ = 111.5$, $\sigma^\circ = 3.94$	$r = 0.02$ $\gamma^\circ = 67.757$	$r = 0.016$ $\gamma^\circ = 90.84$, $\sigma^\circ = 0.007$
F_3	λ	-	-	-	0.995	0.952
	Loadability index	1	1.57	1.57	1.557	1.559
	Total fuel cost (\$/h)	17992.81	30700.10	30700.10	30700.100	30700.100
	$\sum P_{\text{loss}}$ (MW)	2.273	4.2433	4.33	6.679	6.101
	$\sum Q_{\text{loss}}$ (MVAr)	13.245	21.0981	21.539	30.287	28.189
	Investment cost (\$/h)	-	353.59	66.08	23.478	5.837
	FACTS size (MVA)	-	93.48	76.22	5.507	14.855
	FACTS location	-	Line 2-3	Line 2-3	Line 14-13	Line 3-2
	FACTS settings	-	$r = 0.105$ $\gamma^\circ = 72.77$	$r = 0.15$ $\gamma^\circ = 88.08$ $\sigma^\circ = -0.96$	$r = 0.105$ $\gamma^\circ = 72.77$	$r = 0.03$ $\gamma^\circ = 90.46$, $\sigma^\circ = 0.209$

to that of UPFC with lower investment cost. According to Case 1, by placing OUPFC and minimizing its investment cost, the total fuel cost increases about 1.1% and active power losses decrease about 16% compared to that of UPFC, while without minimization of investment cost, both OUPFC and UPFC give the same result. In Case 2, OUPFC improves system loadability in both modes of with and without minimizing investment cost, i.e. increasing system loadability, but increases the total fuel cost slightly. Also in Cases 3 and 4, OUPFC has greater impact in reducing active power losses and improving all objective functions with lower investment cost compared to that of UPFC.

To illustrate flexibility and interactive properties of the proposed algorithm, Case 4 is investigated considering various weighting factors of objective functions. In Table 4, it is assumed that the weighting factor of the total fuel cost objective function is increased while the other weighting factors are decreased through four steps. Consequently, the total fuel cost

Table 3. Multi-objective optimization results in IEEE 14-bus system.

Objective function	Parameters	Without FACTS	UPFC without investment cost	OUPFC without investment cost	UPFC with investment cost	OUPFC with investment cost
Case 1	λ	0.712	0.771	0.771	0.751	0.928
	Total fuel cost ($/h)	17540.137	17257.807	17257.807	17236.078	17428.629
	$\sum P_{\text{loss}}$ (MW)	1.296	0.881	0.881	1.056	0.887
	$\sum Q_{\text{loss}}$ (MVAr)	12.665	11.172	11.172	11.860	11.216
	Loadability index	1	1	1	1	1
	Investment cost ($/h)	-	220.934	48.358	128.351	42.564
	FACTS size (MVA)	-	55.554	55.597	31.214	56.159
	FACTS location	-	Line 5-1	Line 5-1	Line 5-1	Line 5-1
	FACTS settings	-	$r = 0.126$ $\gamma^\circ = 75.191$	$r = 0.15$ $\gamma^\circ = 51.7$ $\sigma^\circ = -3.5$	$r = 0.071$ $\gamma^\circ = 73.21$	$r = 0.122$ $\gamma^\circ = 94.8$ $\sigma^\circ = 0.04$
Case 2	λ	0.528	0.533	0.529	0.529	0.527
	Total fuel cost ($/h)	23609.059	23515.023	23563.741	23601.625	23607.898
	Loadability index	1.294	1.296	1.298	1.294	1.297
	$\sum P_{\text{loss}}$ (MW)	4.127	2.477	2.539	4.029	3.331
	$\sum Q_{\text{loss}}$ (MVAr)	22.327	16.030	16.080	22.160	19.005
	Investment cost ($/h)	-	323.250	62.597	13.176	31.229
	FACTS size (MVA)	-	84.466	72.151	3.080	35.792
	FACTS location	-	Line 5-1	Line 5-1	Line 14-9	Line 5-1
	FACTS settings	-	$r = 0.189$ $\gamma^\circ = 81.271$	$r = 0.15$ $\gamma^\circ = 96.9$ $\sigma^\circ = 0.06$	$r = 0.01$ $\gamma^\circ = 65.85$	$r = 0.15$ $\gamma^\circ = 122.1$ $\sigma^\circ = 3.75$
Case 3	λ	0.589	0.669	0.588	0.570	0.583
	$\sum P_{\text{loss}}$ (MW)	3.485	2.877	2.585	3.442	2.290
	Loadability index	1.328	1.363	1.320	1.317	1.330
	Total fuel cost ($/h)	25833.821	25293.534	24348.723	25662.438	25794.512
	$\sum Q_{\text{loss}}$ (MVAr)	19.266	18.034	16.260	19.310	15.362
	Investment cost ($/h)	-	352.765	62.153	73.332	28.225
	FACTS size (MVA)	-	93.230	71.634	17.495	44.632
	FACTS location	-	Line 5-1	Line 5-1	Line 3-2	Line 3-2
	FACTS settings	-	$r = 0.207$ $\gamma^\circ = 82.515$	$r = 0.15$ $\gamma^\circ = 96.6$ $\sigma^\circ = 0.06$	$r = 0.035$ $\gamma^\circ = -180.0$	$r = 0.09$ $\gamma^\circ = 90.53$ $\sigma^\circ = 0.26$
Case 4	λ	0.528	0.529	0.528	0.528	0.533
	Total fuel cost ($/h)	23615.607	23590.860	23575.906	23618.122	23636.588
	$\sum P_{\text{loss}}$ (MW)	3.836	3.352	2.830	3.356	2.810
	Loadability index	1.294	1.296	1.298	1.296	1.300
	$\sum Q_{\text{loss}}$ (MVAr)	21.095	19.437	17.696	19.341	17.186
	Investment cost ($/h)	-	291.164	51.767	177.095	33.859
	FACTS size (MVA)	-	75.158	59.552	43.825	49.620
	FACTS location	-	Line 2-1	Line 5-1	Line 2-1	Line 5-1
	FACTS settings	-	$r = 0.048$ $\gamma^\circ = 93.64$	$r = 0.15$ $\gamma^\circ = 122.2$ $\sigma^\circ = 3.76$	$r = 0.028$ $\gamma^\circ = 89.19$	$r = 0.10$ $\gamma^\circ = 94.7$ $\sigma^\circ = 2.36$

Table 4. Interactive results in Case 4 of IEEE 14-bus system.

Objective functions (Case 4)	$w_i(w_1, w_2, w_3)$	λ	Total fuel cost ($/h)	$\sum P_{\text{loss}}$ (MW)	Loadability index	$\sum Q_{\text{loss}}$ (MVAr)	Investment cost ($/h)	FACTS size (MVA)	FACTS location	FACTS settings
Without FACTS	(0.333,0.333,0.333)	0.528	23615.607	3.836	1.294	21.095	-	-	-	-
	(0.6,0.2,0.2)	0.233	20711.066	5.527	1.130	31.772	-	-	-	-
	(0.7,0.15,0.15)	0.079	19926.515	6.407	1.044	34.729	-	-	-	-
	(* 0.8,0.1,0.1)	0.055	19923.887	6.545	1.031	36.031	-	-	-	-
UPFC without investment cost	(0.333,0.333,0.333)	0.529	23590.860	3.352	1.296	19.437	291.164	75.158		$r=0.04$ $\gamma^\circ=93.64$
	(0.6,0.2,0.2)	0.272	20518.203	4.580	1.152	24.933	574.640	165.749		$r=0.11$ $\gamma^\circ=118.5$
	(0.7,0.15,0.15)	0.189	19590.702	4.975	1.106	25.475	545.663	155.594	Line 2-1	$r=0.10$ $\gamma^\circ=34.03$
	(* 0.8,0.1,0.1)	0.112	18747.465	5.346	1.062	27.060	612.092	179.175		$r=0.13$ $\gamma^\circ=56.70$
OUPFC without investment cost	(0.333,0.333,0.333)	0.528	23575.906	2.830	1.298	17.696	51.767	59.552		$r=0.15$ $\gamma^\circ=122.1$ $\sigma^\circ=3.75$
	(0.6,0.2,0.2)	0.272	20488.562	3.892	1.154	24.601	63.330	79.077		$r=0.133$ $\gamma^\circ=152.9$ $\sigma^\circ=-3.1$
	(0.7,0.15,0.15)	0.190	19558.092	4.232	1.107	25.542	65.578	75.628	Line 5-1	$r=0.15$ $\gamma^\circ=180.0$ $\sigma^\circ=-1.5$
	(* 0.8,0.1,0.1)	0.113	18713.055	4.551	1.064	27.586	66.960	91.038		$r=0.117$ $\gamma^\circ=180.0$ $\sigma^\circ=-5.7$
UPFC with investment cost	(0.333,0.333,0.333)	0.528	23618.122	3.356	1.296	19.341	177.095	43.825		$r=0.03$ $\gamma^\circ=89.19$
	(0.6,0.2,0.2)	0.266	20466.682	4.608	1.149	27.959	213.730	53.601		$r=0.04$ $\gamma^\circ=180.0$
	(0.7,0.15,0.15)	0.181	19514.161	5.013	1.102	28.544	217.933	54.739	Line 2-1	$r=0.04$ $\gamma^\circ=-104.9$
	(* 0.8,0.1,0.1)	0.094	18572.258	5.430	1.053	29.348	308.041	80.026		$r=0.06$ $\gamma^\circ=-86.82$
OUPFC with investment cost	(0.333,0.333,0.333)	0.533	23636.58	2.810	1.300	17.186	33.859	49.620		$r=0.102$ $\gamma^\circ=94.7$ $\sigma^\circ=2.36$
	(0.6,0.2,0.2)	0.277	20546.94	3.871	1.156	23.420	15.908	50.635		$r=0.102$ $\gamma^\circ=180.0$ $\sigma^\circ=8.27$
	(0.7,0.15,0.15)	0.194	19599.89	4.217	1.109	24.861	25.601	81.497	Line 5-1	$r=0.01$ $\gamma^\circ=180.0$ $\sigma^\circ=12.3$
	(* 0.8,0.1,0.1)	0.115	18736.02	4.543	1.065	24.561	34.584	110.096		$r=0.01$ $\gamma^\circ=180.0$ $\sigma^\circ=15.9$

function approaches its ideal solution value and two other functions are kept out of their ideal solution values.

5.2. IEEE 118-bus test system

The IEEE 118-bus test system is used to examine the performance capability of the proposed algorithm in locating UPFC and OUPFC, individually, in order to improve objective functions. Single- and multi-objective optimization results are shown in Tables 5 and 6, respectively. Although UPFC has better performances compared to OUPFC in some cases, the OUPFC investment cost is low compared to that of UPFC.

Table 5. Single objective optimization results in IEEE 118-bus system.

Objective function	Parameters	Without FACTS	UPFC without investment cost	OUPFC without investment cost	UPFC with investment cost	OUPFC with investment cost
F_1	Total fuel cost ($/h)	129660.997	129345.89	129378.1	129629.85	129656.15
	$\sum P_{\text{loss}}$ (MW)	74.408	70.479	71.075	76.755	77.287
	$\sum Q_{\text{loss}}$ (MVAr)	507.25	480.66	465.114	504.036	506.91
	Loadability index	1	1	1	1	1
	Investment cost ($/h)	-	668.46	170.141	42.36	3.97
	FACTS size (MVA)	-	200.00	200.00	10.00	12.64
	FACTS location	-	Line 75-69	Line 27-25	Line 27-25	Line 49-48
	FACTS settings	-	$r = 0.256$ $\gamma^\circ = 81.21$	$r = 0.15$ $\gamma^\circ = 123.9$ $\sigma^\circ = 17.24$	$r = 0.02$ $\gamma^\circ = 61.20$	$r = 0.01$ $\gamma^\circ = -46.1$ $\sigma^\circ = -0.33$
F_2	λ	-	-	-	0.998	0.999
	$\sum P_{\text{loss}}$ (MW)	9.2476	7.8019	7.9387	9.065	9.255
	Total fuel cost ($/h)	166390.358	166554.07	166482.14	166257.53	166381.267
	$\sum Q_{\text{loss}}$ (MVAr)	69.38	64.07	64.580	68.69	63.510
	Loadability index	1	1	1	1	1
	Investment cost ($/h)	-	489.77	406.72	42.635	1.746
	FACTS size (MVA)	-	136.59	101.19	10.065	5.078
	FACTS location	-	Line 96-80	Line 96-80	Line 43-34	Line 49-48
	FACTS settings	-	$r = 0.238$ $\gamma^\circ = 76.37$	$r = 0.15$ $\gamma^\circ = 102.45$ $\sigma^\circ = 6.29$	$r = 0.02$ $\gamma^\circ = 81.20$	$r = 0.017$ $\gamma^\circ = -9.95$ $\sigma^\circ = -0.016$
F_3	λ	-	-	-	0.914	0.872
	Loadability index	2.039	2.28	2.28	2.053	2.116
	Total fuel cost ($/h)	348899.979	417113.21	417113.21	351906.276	361074.973
	$\sum P_{\text{loss}}$ (MW)	198.577	275.547	275.767	211.28	215.844
	$\sum Q_{\text{loss}}$ (MVAr)	1141.87	1542.681	1543.39	1215.03	1254.67
	Investment cost ($/h)	-	668.46	170.141	76.679	11.370
	FACTS size (MVA)	-	200.00	200.00	18.314	36.192
	FACTS location	-	Line 75-69	Line 75-69	Line 80-77	Line 118-75
	FACTS settings	-	$r = 0.267$ $\gamma^\circ = 52.92$	$r = 0.15$ $\gamma^\circ = 117.65$ $\sigma^\circ = 13.92$	$r = 0.02$ $\gamma^\circ = 180.0$	$r = 0.01$ $\gamma^\circ = 40.03$ $\sigma^\circ = 0.83$

6. Conclusions

Power system optimization is one of the most important off-line tools in the field of operation, planning, and control of power systems. This paper made an attempt to find the optimal location of OUPFC and UPFC devices to simultaneously optimize total fuel cost, power losses, and system loadability as a multi-objective optimization problem to enable power system dispatcher to operate the power system reliably and economically. The multi-objective optimization problem was performed by a fuzzy interactive approach. The fuzzy method is preferable to common methods of multi-objective optimization since it is able to interact with the decision-maker through the optimization process. The proposed algorithm was implemented in GAMS software and solved using CONOPT solver as a DNLP problem. Simulations were performed on IEEE 14-, and 118-bus test systems. Simulation results show that OUPFC is more capable of improving the

Table 6. Multi-objective optimization results in IEEE 118-bus system.

Objective function	Parameters	Without FACTS	UPFC without investment cost	OUPFC without investment cost	UPFC with investment cost	OUPFC with investment cost
Case 1	λ	0.783	0.815	0.807	0.832	0.795
	Total fuel cost ($/h)	137628.342	136167.20	136521.570	135115.161	137140.359
	$\sum P_{\text{loss}}$ (MW)	24.033	20.543	21.328	20.641	23.473
	$\sum Q_{\text{loss}}$ (MVAr)	159.278	154.002	158.010	160.255	166.209
	Loadability index	1	1	1	1	1
	Investment cost ($/h)	-	668.462	169.706	668.462	42.564
	FACTS size (MVA)	-	200.00	199.649	200.00	33.614
	FACTS location	-	Line 25-27	Line 89-90	Line 25-27	Line 71-70
	FACTS settings	-	$r = 0.336$ $\gamma^\circ = 84.184$	$r = 0.15$ $\gamma^\circ = 97.86$ $\sigma^\circ = 7.91$	$r = 0.328$ $\gamma^\circ = 84.675$	$r = 0.018$ $\gamma^\circ = 132.9$ $\sigma^\circ = 0.007$
Case 2	λ	0.544	0.561	0.561	0.561	0.560
	Total fuel cost ($/h)	229721.811	255699.838	255724.476	256029.644	256412.833
	Loadability index	1.565	1.720	1.720	1.721	1.719
	$\sum P_{\text{loss}}$ (MW)	123.94	117.226	117.794	123.378	138.693
	$\sum Q_{\text{loss}}$ (MVAr)	771.634	716.075	718.571	740.122	792.658
	Investment cost ($/h)	-	668.462	150.120	29.555	3.351
	FACTS size (MVA)	-	200.00	175.819	6.946	8.668
	FACTS location	-	Line 69-75	Line 75-69	Line 69-75	Line 69-75
	FACTS settings	-	$r = 0.225$ $\gamma^\circ = 66.99$	$r = 0.15$ $\gamma^\circ = 111.4$ $\sigma^\circ = 0.19$	$r = 0.01$ $\gamma^\circ = 55.26$	$r = 0.03$ $\gamma^\circ = 1.76$ $\sigma^\circ = -0.907$
Case 3	λ	0.692	0.687	0.686	0.689	0.689
	$\sum P_{\text{loss}}$ (MW)	67.554	92.513	92.798	66.897	66.971
	Loadability index	1.719	1.879	1.878	1.715	1.721
	Total fuel cost ($/h)	288049.622	317130.493	317002.857	292525.263	293478.742
	$\sum Q_{\text{loss}}$ (MVAr)	373.173	546.476	546.982	390.622	392.800
	Investment cost ($/h)	-	668.462	170.141	48.245	84.639
	FACTS size (MVA)	-	200.00	200.00	11.411	118.283
	FACTS location	-	Line 75-69	Line 75-69	Line 49-42	Line 95-94
	FACTS settings	-	$r = 0.259$ $\gamma^\circ = 64.99$	$r = 0.15$ $\gamma^\circ = 116.1$ $\sigma^\circ = 0.23$	$r = 0.036$ $\gamma^\circ = 180.0$	$r = 0.112$ $\gamma^\circ = 26.52$ $\sigma^\circ = -4.15$
Case 4	λ	0.549	0.548	0.547	0.548	0.546
	Total fuel cost ($/h)	228558.945	228264.058	228227.40	228797.072	228620.300
	$\sum P_{\text{loss}}$ (MW)	94.679	89.718	90.190	89.668	96.007
	Loadability index	1.570	1.569	1.569	1.569	1.569
	$\sum Q_{\text{loss}}$ (MVAr)	597.684	552.788	554.097	551.055	594.677
	Investment cost ($/h)	-	668.462	170.141	41.719	3.120
	FACTS size (MVA)	-	200.00	200.00	9.846	9.930
	FACTS location	-	Line 30-26	Line 30-26	Line 30-26	Line 87-86
	FACTS settings	-	$r = 0.181$ $\gamma^\circ = 80.418$	$r = 0.15$ $\gamma^\circ = 102$ $\sigma^\circ = 6.08$	$r = 0.01$ $\gamma^\circ = 65.104$	$r = 0.01$ $\gamma^\circ = -31.68$ $\sigma^\circ = -1.6$

dispatcher's ability to effectively operate power systems compared to UPFC, while the cost of OUPFC is less than the one of UPFC.

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Appendix A

OUPFC data

$$-20^\circ \leq \sigma \leq 20^\circ, \qquad 0 \leq r \leq 0.15,$$

$$-\pi \leq \rho \leq \pi, \qquad X_B = 0.007 \text{ p.u.};$$

$$X_E = 0.001 \text{ p.u.}; \qquad S_{\text{base}} = 100 \quad \text{MVA}.$$

UPFC data

$$0 \leq r \leq 1 \qquad X_B = 0.007 \text{ p.u.};$$

$$X_E = 0.001 \text{ p.u.}; \qquad -\pi \leq \gamma \leq \pi,$$

$$S_{\text{base}} = 100 \text{ MVA}.$$

Biographies

Afshin Lashkar Ara (M'11-SM'15) was born in Tehran, Iran, in 1973. He received his BSc degree in Electrical Engineering from the Islamic Azad University, Dezful Branch, Dezful, Iran, in 1995. He received his MSc degree in Electrical Engineering from University of Mazandaran, Babol, Iran, in 2001. He received his PhD degree in Electrical Engineering from Iran University of Science and Technology (IUST), Tehran, Iran, in 2011. He is currently a faculty member in Islamic Azad University, Dezful Branch, Dezful, Iran, as well as a senior member of IEEE Power and Energy Society (IEEE-PES). His current research interests include analysis, operation, and control of power systems and FACTS controllers.

Meisam Shabani was born in Ahwaz, Iran, in 1984. He received his BSc and MSc degrees in Electrical Engineering from the Islamic Azad University, Dezful branch, Dezful, Iran, in 2007 and 2011, respectively. His research interests are in power system analysis, fuzzy systems, stability and control, and FACTS devices.

Seyed Ali Nabavi Niaki (M'92-SM'04) received the BSc and MSc degrees in Electrical Engineering from Amirkabir University of Technology, Tehran, Iran, in 1987 and 1990, respectively, and the PhD degree in Electrical Engineering from the University of Toronto, Toronto, ON, Canada, in 1996. He joined University of Mazandaran, Babol, Iran, in 1996, as a faculty member. Currently, he is in his sabbatical leave in the University of Toronto, ON, Canada. His current research interests include analysis, operation, and control of power systems and FACTS controllers.