Optimal Allocation of Multiple Unified Power Flow Controllers Using Particle Swarm Optimization

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Abstract

This paper proposes a new methodology to find the optimal locations and parameter settings of multiple unified power flow controllers (UPFC), using particle swarm optimization (PSO) in combination with a modified power flow method. The objective function aims at minimizing the generation cost of the network's generators ensuring the maximum possible profit for the electric power producer. The solution methodology consists of two phases. First, a new and simple way to model the UPFC is proposed. This model allows for the easy determination of the optimal settings for all UPFCs given their location and requires very small modifications to the standard optimal power flow algorithms. This new UPFC representation is combined with the standard PSO to determine the optimal location of each UPFC. The efficiency and accuracy of the proposed methodology is tested on a 39 bus power system and a 118 bus power system by comparing its results with those of the exhaustive search.

1 Introduction

Flexible alternating current (ac) transmission systems (FACTS) use power electronic based controllers to increase controllability and enhance power transfer capability of electric power systems [1]–[3]. Among all FACTS, the most versatile is the unified power flow controller (UPFC) [2], [4]. The UPFC is capable of controlling the voltage magnitude of a bus and the complex power flow at the other end of a transmission line connected to that bus [4]. Thus, by using the UPFC, the transmission system operator can improve voltage stability and minimize generation costs and transmission line congestion.

If one wishes to determine the best way to achieve generation cost minimization using one or more UPFCs, then the problem of optimal UPFC location and settings arises, which is also called optimal UPFC allocation problem. Because of the very large number of possible solutions, the majority of the proposed solution techniques involve approximate heuristic optimization methods, including genetic algorithm [5], and particle swarm optimization (PSO) [6]. However, most of the papers on the subject use the above methods to concurrently determine both UPFC location and parameter settings, which makes the solution of the optimization problem a more difficult, time consuming and less reliable process.

This paper proposes a new method for the optimal allocation of multiple UPFCs, which is based on a new power flow model for UPFCs. This new model leads to a modified power flow method capable of solving power systems with multiple UPFCs. The main advantage of the proposed power flow method is that it can be very easily integrated within already existing optimal power flow (OPF) models and software packages without UPFCs, such as MATPOWER [7], which is a widely accepted, worldwide used, state of the art, open access, software tool for power flow, OPF, and other very important power system operation and planning functions. Based on the proposed modified power flow method, this paper develops a particle swarm optimization method, which finds only the optimal locations of multiple UPFCs, since, as soon as the optimal UPFC locations are found, then the optimal UPFC settings for the given locations can be easily found from a slightly modified optimal power flow algorithm. The most important advantages of the proposed methodology are the following:

1. Easy to develop, since the proposed modified power flow model can be very easily integrated within existing power flow and optimal power flow packages that do not model UPFCs.
2. Fast to execute and leading to solutions closer to the global optimum, since only the optimal UPFC locations are the unknown design variables, in comparison with existing UPFC allocation methods that have four additional unknown design variables per UPFC (the UPFC parameters settings).
3. The running time is reduced further, since the proposed UPFC OPF model is symmetrical. When the proposed UPFC OPF model is considered between bus k and bus m, it can represent two different ways of installation: UPFC shunt branch at bus k and UPFC shunt branch at bus m. This allows these two different ways of installation to be tested by running only one OPF. Additionally, these two different ways of installation lead to different internal UPFC parameters for each way of installation. Because of that, reaching the operation limits of a UPFC can be often avoided, because one of the two different UPFC ways of installation may achieve the

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desired optimal state with none of the four UPFC parameters exceeding the operation limits.

The objective function aims at minimizing the generation cost of electric power. The effectiveness of the proposed method is validated by comparing it with an exhaustive search approach on a 39 bus power system and a 118 bus power system, since the exhaustive search always leads to the global minimum. Furthermore, for the 39 bus power system the optimal set of PSO parameters is determined through trial and error. This process leads to the best possible result the PSO can produce for the 39 bus power system, disregarding the running time.

The structure of the paper is as follows. In Section 2, the problem formulation is presented. In Section 3, the UPFC model, the PSO algorithm and the proposed solution methodology are described. The results of the exhaustive search method with the results of the proposed method, using different sets of parameters for PSO, on a 39 bus power system and a 118 bus power system are presented in Section 3. Conclusions are drawn in Section 4.

2 Problem Formulation

The following assumptions are considered for the proposed problem:

- The loads of the power system are represented as constant real and reactive power.
- The power system is balanced.
- A UPFC can only be installed at the sending end or the receiving end of a transmission line.
- When a UPFC is installed at bus *k* that is the sending end or receiving end of a transmission line *k*–*l*, a new bus *m* is created between the UPFC and the transmission line to simplify the analysis. This is shown in Fig. 1.
- The UPFC can be installed at bus *k* of transmission line *k*–*l*, as is shown in Fig. 1. If the UPFC shunt branch is connected with bus *k* (Fig. 1), then the UPFC can regulate the voltage magnitude of bus *k* ($V_k=V_{k\_reg}$), the active power flow from bus *m* to bus *k* ($P_{mk}=P_{mk\_reg}$), and the reactive power flow from bus *m* to bus *k* ($Q_{mk}=Q_{mk\_reg}$). Alternatively, the UPFC shunt branch may also be connected with bus *m*, in which case the UPFC can regulate the voltage magnitude of bus *m* ($V_m=V_{m\_reg}$), the active power flow from bus *k* to bus *m* ($P_{km}=P_{km\_reg}$), and the reactive power flow from bus *k* to bus *m* ($Q_{km}=Q_{km\_reg}$).

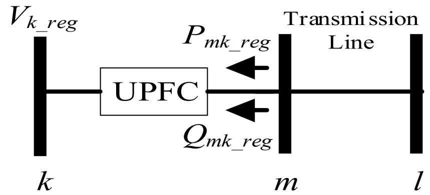

Fig. 1 UPFC installed at bus *k* of transmission line *k*–*l* and the UPFC shunt branch connected with bus *k*. The new bus *m* was created for convenience.

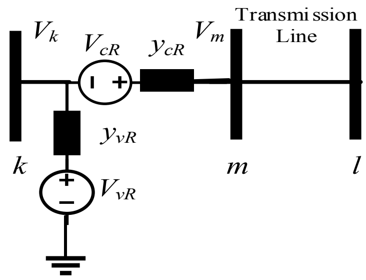

Fig. 2 Equivalent circuit of UPFC installed at bus *k* of transmission line *k*–*l* and the UPFC shunt branch connected with bus *k* (shown in Fig. 1). The new bus *m* is also shown.

The UPFC equivalent circuit, shown in Fig. 2, contains a series controlled voltage source with magnitude V_{cR} and angle δ_{cR} connected in series with a complex admittance $y_{cR} = jb_{cR}$. It also contains a shunt controlled voltage source with magnitude V_{vR} and angle δ_{vR} connected in series with a complex admittance $y_{vR} = jb_{vR}$.

2.1 Objective Function

The objective is to minimize the function *f*(*x*), which represents the sum of the generation costs (€/h) of each generator in the power system:

$$f(x) = \sum_{i=1}^{N_g} (a_{g_i} + b_{g_i} \cdot P_{g_i} + c_{g_i} \cdot {P_{g_i}}^2) \tag{1}$$

where N_g is the number of generators of the power system, P_{g_i} is the real power produced by generator i and a_{g_i}, b_{g_i}, c_{g_i} are given cost coefficients for each generator.

2.2 Constraints

The proposed optimization model is subject to the following constraints:

$$P_{G_i} - P_{D_i} = \sum_{i \neq j} P_{ij} \tag{2}$$

$$Q_{G_i} - Q_{D_i} = \sum_{i \neq j} Q_{ij} \tag{3}$$

$$P_{g_i}^{min} \leq P_{g_i} \leq P_{g_i}^{max} \tag{4}$$

$$Q_{g_i}^{min} \leq Q_{g_i} \leq Q_{g_i}^{max} \tag{5}$$

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{6}$$

$$\delta_i^{min} \leq \delta_i \leq \delta_i^{max} \tag{7}$$

$$-S_{ij}^{max} \leq S_{ij} \leq S_{ij}^{max} \tag{8}$$

$$0{,}001\, pu \leq V_{cR} \leq 0{,}6\, pu \tag{9}$$

$$-180^o \leq \delta_{cR} \leq 180^o \tag{10}$$

$$0{,}9\, pu \leq V_{vR} \leq 1{,}1\, pu \tag{11}$$

$$-180^o \leq \delta_{vR} \leq 180^o \tag{12}$$

$$P_{km} + P_{mk} = 0 \quad (13)$$

$$\begin{aligned} P_{km} = &-V_k \cdot V_m \cdot b_{cR} \cdot sin(\delta_k - \delta_m) \\ &+V_k \cdot V_{cR} \cdot b_{cR} \cdot sin(\delta_k - \delta_{cR}) \\ &-V_k \cdot V_{vR} \cdot b_{vR} \cdot sin(\delta_k - \delta_{vR}) \end{aligned} \quad (14)$$

$$\begin{aligned} Q_{km} = &-(b_{vR} + b_{cR}) \cdot V_k^2 \\ &+V_k \cdot V_m \cdot b_{cR} \cdot cos(\delta_k - \delta_m) \\ &-V_k \cdot V_{cR} \cdot b_{cR} \cdot cos(\delta_k - \delta_{cR}) \\ &+V_k \cdot V_{vR} \cdot b_{vR} \cdot cos(\delta_k - \delta_{vR}) \end{aligned} \quad (15)$$

$$\begin{aligned} Q_{mk} = &-b_{cR} \cdot V_m^2 + V_m \cdot V_k \cdot b_{cR} \cdot cos(\delta_m - \delta_k) \\ &+V_m \cdot V_{cR} \cdot b_{cR} \cdot cos(\delta_m - \delta_{cR}) \end{aligned} \quad (16)$$

$$\begin{aligned} P_{mk} = &-V_k \cdot V_m \cdot b_{cR} \cdot sin(\delta_k - \delta_m) \\ &+V_k \cdot V_{cR} \cdot b_{cR} \cdot sin(\delta_k - \delta_{cR}) \\ &-V_k \cdot V_{vR} \cdot b_{vR} \cdot sin(\delta_k - \delta_{vR}) \end{aligned} \quad (17)$$

$$\begin{aligned} Q_{km} = &-b_{cR} \cdot V_m^2 + V_m \cdot V_k \cdot b_{cR} \cdot cos(\delta_m - \delta_k) \\ &+V_m \cdot V_{cR} \cdot b_{cR} \cdot cos(\delta_m - \delta_{cR}) \end{aligned} \quad (18)$$

$$\begin{aligned} Q_{mk} = &-(b_{vR} + b_{cR}) \cdot V_k^2 \\ &+V_k \cdot V_m \cdot b_{cR} \cdot cos(\delta_k - \delta_m) \\ &-V_k \cdot V_{cR} \cdot b_{cR} \cdot cos(\delta_k - \delta_{cR}) \\ &+V_k \cdot V_{vR} \cdot b_{vR} \cdot cos(\delta_k - \delta_{vR}) \end{aligned} \quad (19)$$

Equations (2) and (3) represent the active and reactive power balance at bus *i*, respectively. P_{G_i} is the active power generated at bus i and P_{D_i} is the active power absorbed at bus i. Q_{G_i} is the reactive power generated at bus i and Q_{D_i} is the reactive power absorbed at bus i. The minimum active power $P_{g_i}^{min}$ and the maximum active power $P_{g_i}^{max}$ that each generator g_i can provide are given by (4). The minimum reactive power $Q_{g_i}^{min}$ and the maximum reactive power $Q_{g_i}^{max}$ that each generator g_i can provide are given by (5). According to (6), the voltage magnitude of each bus *i* has to be within its minimum limit (V_i^{min}) and its maximum limit (V_i^{max}). According to (7), the voltage angle of each bus *i* has to be within its minimum limit (δ_i^{min}) and its maximum limit (δ_i^{max}). According to (8), the apparent power of each transmission line *i*–*j* has to be within its minimum limit ($-S_{ij}^{max}$) and its maximum limit (S_{ij}^{max}). The maximum and minimum voltage magnitude and voltage angle of the two internal controlled voltage sources of every UPFC are given by (9)–(12). The fact that the UPFC installed between buses *k* and *m* exchanges no real power with the power system is given by (13).

If the UPFC shunt branch is connected to bus *k* of transmission line *k*–*l*, the rest of the state equations of the UPFC are given by (14)–(16). If the UPFC shunt branch is connected to bus *k* of transmission line *k*–*l*, and if the two complex voltages (V_k, δ_k, V_m, δ_m) and two complex power flows (P_{km}, Q_{km}, P_{mk}, Q_{mk}) at the two terminals *k* and *m* of a UPFC are known, then the four UPFC parameters (V_{cR}, δ_{cR}, V_{vR}, δ_{vR}) are determined through the use of (13)–(16).

If the UPFC shunt branch is connected to the new bus *m* created between bus *k* and bus *l,* the rest of the state equations of the UPFC are given by (17)–(19). If the UPFC shunt branch is connected to bus *m*, and if the two complex voltages (V_k, δ_k, V_m, δ_m) and two complex power flows (P_{km}, Q_{km}, P_{mk}, Q_{mk}) at the two terminals *k* and *m* of a UPFC are known, then the four UPFC parameters (V_{cR}, δ_{cR}, V_{vR}, δ_{vR}) are determined through the use of (13) and (17)–(19).

3 Solution Methodology

Given the number *N* of UPFCs that are available for installation, the location and the four internal settings of each UPFC must be determined.

Suppose a combination of locations for the *N* UPFCs is given. The optimal settings of each UPFC for this location combination can be found as follows:

Step 1: Assuming the location for a certain UPFC is between bus *k* and bus *m,* where *m* is the new bus created upon the UPFC's installation, one can replace this UPFC with two generators, one at bus *k* and one at bus *m*. Of course, the generator at bus *k* must always generate or absorb the real power the generator at bus *m* absorbs or generates, because due to (13) the UPFC does not exchange real power with the rest of the power system. Thus, bus *k* and bus *m* are transformed to PV buses, unless one of them is the slack bus. If that is the case, the slack bus will remain the slack bus, while the other bus will be a PV bus. A constraint is also placed on the two PV buses.

Step 2: Applying the methodology of Step 1 to each UPFC, the power system with multiple UPFCs will become a power system without UPFCs, but having an additional number of constraints equal to the number of UPFCs. The resulting power system can be solved by the typical OPF algorithm.

Step 3: After the OPF problem is solved, for the UPFC between buses *k* and *m*, the optimal values (that minimize the generation cost) for V_{k_opt}, δ_{k_opt}, V_{m_opt}, δ_{m_opt}, P_{km_opt}, Q_{km_opt}, P_{mk_opt}, Q_{mk_opt} are known. Next, the optimal values (that minimize the generation cost) for the four UPFC parameters (V_{cR_opt}, δ_{cR_opt}, V_{vR_opt}, δ_{vR_opt}) can be calculated by solving the system of non-linear equations (13)–(16) in case the UPFC shunt branch is connected to bus *k*, or the system of non-linear equations (13) and (17)–(19) in case the UPFC shunt branch is connected to bus *m*. Thus, due to the fact that the UPFC is not symmetrical and has two ways of installation, two sets of the parameters (V_{cR_opt}, δ_{cR_opt}, V_{vR_opt}, δ_{vR_opt}) can lead to the same optimal values V_{k_opt}, δ_{k_opt}, V_{m_opt}, δ_{m_opt}, P_{km_opt}, Q_{km_opt}, P_{mk_opt}, Q_{mk_opt}. The set that satisfies the operational limit of the UPFC is chosen.

Step 4: The methodology of Step 3 is applied to each UPFC to calculate its controlled internal voltages.

Essentially, for OPF, the UPFC of Fig. 1 is replaced by the two generators shown in Fig. 3.

In this paper, the optimal locations of the *N* UPFCs will be determined by PSO. PSO has a predetermined number of iterations N_t and a swarm of a predetermined number of particles N_p.

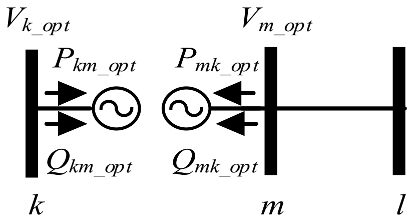

Fig. 3 Equivalent circuit for the OPF of the UPFC of Fig. 1.

To use PSO, N_p particles are created. At each iteration *t*, each particle *i* is a row vector $x_i(t)$ with *N* elements, each one of which is a real number in the interval [1, N_{br}+1], where N_{br} is the number of the branches of the power system. The *N* real numbers of each vector all belong in the proper interval and are randomly and uniformly selected upon the creation of the particles. Each row vector element corresponds to one of the *N* UPFCs.

For each particle, the integer part of its j^{th} element is the branch number of the j^{th} UPFC, and the decimal part of its j^{th} element determines whether the j^{th} UPFC will installed at the sending end or the receiving end of the branch. If the decimal part belongs to the interval [0, 0.5), then the UPFC is installed at the sending end. Otherwise, it is installed at the receiving end. Because of that, each particle's row vector $x_i(t)$ is in fact a combination of locations for the *N* UPFCs. The optimal settings of the *N* UPFCs are easily determined through the Step 3 of the methodology presented at the beginning of this section. Finally, each particle's combination of *N* UPFC locations, along with the optimal settings of the *N* UPFCs corresponds to an objective function value.

For each iteration *t*, the following process is repeated:

- For each particle *i*, the objective function value that corresponds to its row vector $x_i(t)$ is calculated.
- If the row vector corresponds to the lowest objective function value for particle *i* so far, then it is stored in the row vector $pbest_i(t)$.
- If the row vector corresponds to the lowest objective function for all particles so far, then it is stored in the row vector $gbest(t)$.
- Then, $x_i(t)$ is updated through equations (20)–(22).

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{20}$$

$$\begin{aligned} v_i(t+1) &= w(t) \cdot v_i(t) \\ &+c_1 \cdot r_1 \cdot [pbest_i(t) - x_i(t)] \\ &+c_2 \cdot r_2 \cdot [gbest(t) - x_i(t)] \end{aligned} \tag{21}$$

$$w(t) = w_{initial} + (w_{final} - w_{initial}) \cdot \frac{(t-1)}{(t_{max}-1)} \tag{22}$$

  where r_1, r_2 are random numbers uniformly distributed in [0, 1].

- *i* is then increased by 1 and if it exceeds N_p, then it is set equal to 1 and *t* is increased by 1. If *t* exceeds N_t, then PSO returns the value $gbest(t)$.

This way, the optimal combination of UPFC locations is approximately found by PSO and the optimal settings for each UPFC are found using the Step 3 of the methodology presented at the beginning of this section. The results of PSO depend on the values of the following six parameters that are involved in its execution: number of iterations: N_t; number of particles: N_p; first acceleration coefficient: c_1; second acceleration coefficient: c_2; initial inertial coefficient: $w_{initial}$; and final inertial coefficient: w_{final}.

4 Results and Discussion

The proposed PSO algorithm in tested on the 39 bus power system [8] and a 118 bus power system [9]. For the considered loading scenarios, without UPFC, the total hourly generation cost, computed by OPF, is 33.491,2 €/h for the 39 bus power system and 103.728 €/h for the 118 bus power system. This cost will be compared with the respective cost when UPFCs are installed to evaluate the generation cost reduction that can be achieved thanks to the UPFCs.

All tests were performed on a PC with an Intel Core i7 CPU at 2.50 GHz and 16 GB of RAM.

4.1 Allocation of Two UPFCs in the 39 Bus Power System

If two UPFCs are allocated into the 39 bus power system, then the optimal solution of the exhaustive search method is that the first UPFC is located at bus 2 of the transmission line 2–25, the second UPFC is located at bus 4 of the transmission line 4–5 and the total hourly generation cost, computed by OPF, is 33.479,20 €/h, which means that the installation of two UPFCs reduces the generation cost by 0,04%. The exhaustive search method requires 390,82 s to compute the optimal solution.

In regards to PSO, the following parameter values were initially used for 20 trials: number of iterations: $N_t = 30$; number of particles: $N_p = 30$; first acceleration coefficient: $c_1 = 2$; second acceleration coefficient: $c_2 = 2$; initial inertial coefficient: $w_{initial} = 0{,}9$; and final inertial coefficient: $w_{final} = 0{,}4$.

The average computation time of each PSO trial was 84,78 s. Out of 20 trials of PSO, 11 of them were able to locate the global minimum generation cost of 33.479,2 €/h. As a result, the success rate was 55%. The mean minimum generation cost of the 20 trials of PSO was 33.479,76. The results of the 20 trials are presented in Fig. 4. The convergence of a successful trial of PSO, that located the global minimum generation cost of 33.479,20 €/h is presented in Fig. 5.

Using the above PSO parameter values as a starting point, an attempt through trial and error was made to determine the parameter values that lead to the highest possible success rate. Each parameter combination was used for 20 trials. The results of the various trials are presented in Tables 1–3. After determining the optimal value for a parameter, that value is kept constant and used in future trials (where another parameter is varied). The optimal values are highlighted with bold in each Table. The highest possible success rate was 85% using the following optimal parameter values: number of iterations: $N_t = 60$; number of particles: $N_p = 40$; first acceleration coefficient: $c_1 = 2$; second acceleration coefficient: $c_2 = 2$; initial inertial coefficient: $w_{initial} = 0{,}9$, and final inertial coefficient: $w_{final} = 0{,}4$.

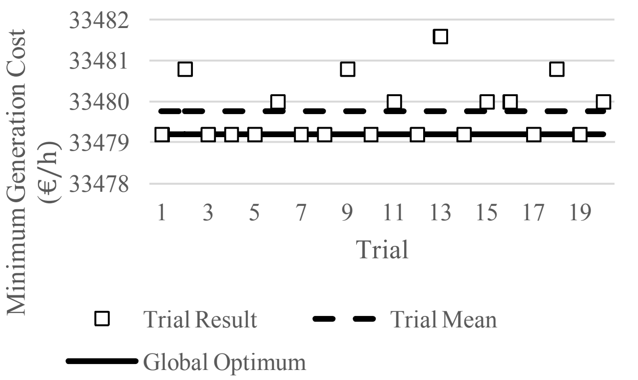

Fig. 4 Results of 20 trials of PSO for the 39 bus system with 30 iterations and 30 particles.

Fig. 5 The convergence of a successful trial of PSO for the 39 bus system, which located the global minimum generation cost of 33.479,2 €/h.

Table 1 PSO results as a function of N_t for the 39 bus system

N_t	Minimum generation cost (€/h)			Success rate (%)
	Mean	Min	Max	
20	33.479,81	33.479,20	33.481,60	50
30	33.479,76	33.479,20	33.481,60	55
40	33.479,74	33.479,20	33.480,80	60
50	33.479,40	33.479,20	33.480,00	75
60	**33.479,36**	**33.479,20**	**33.480,00**	**80**
70	33.479,36	33.479,20	33.480,00	80
80	33.479,36	33.479,20	33.480,00	80

Table 2 PSO results as a function of N_p for the 39 bus system

N_p	Minimum generation cost (€/h)			Success rate (%)
	Mean	Min	Max	
10	33.480,11	33.479,20	33.481,60	45
20	33.479,78	33.479,20	33.481,60	70
30	33.479,36	33.479,20	33.480,00	80
40	**33.479,32**	**33.479,20**	**33.480,00**	**85**
50	33.479,32	33.479,20	33.480,00	85
60	33.479,32	33.479,20	33.480,00	85
70	33.479,32	33.479,20	33.480,00	85

Table 3 PSO results as a function of c_2 for the 39 bus system

c_2	Minimum generation cost (€/h)			Success rate (%)
	Mean	Min	Max	
1,7	33.479,40	33.479,20	33.480,00	75
1,8	33.479,36	33.479,20	33.480,00	80
1,9	33.479,32	33.479,20	33.480,00	85
2,0	**33.479,32**	**33.479,20**	**33.480,00**	**85**
2,1	33.479,32	33.479,20	33.480,00	85
2,2	33.479,36	33.479,20	33.480,00	80
2,3	33.479,40	33.479,20	33.480,00	75

As can be seen from Table 3, for the case of the highest possible success rate (85%), the mean generation cost of the 20 trials of PSO was 33.479,32 €/h, which is practically identical to the cost of the optimal solution (33.479,20 €/h) found by exhaustive search. The running time of one PSO trial was 248,94 s for the above optimal parameter values.

4.2 Allocation of Three UPFCs in the 118 Bus Power System

If three UPFCs are allocated into the 118 bus power system, then the optimal solution of the exhaustive search method is that the first UPFC is located at bus 26 of the transmission line 26–30, the second UPFC is located at bus 65 of the transmission line 38–65, the third UPFC is located at bus 4 of the transmission line 4–5 and the total hourly generation cost, computed by OPF, is 103.544 €/h, which means that the installation of three UPFCs reduces the generation cost by 0,18%. The exhaustive search method requires 1.083.811,55 s to compute the optimal solution.

In regards to PSO, the following parameter values were initially used for 20 trials: number of iterations: $N_t = 70$; number of particles: $N_p = 140$; first acceleration coefficient: $c_1 = 2$; second acceleration coefficient: $c_2 = 2$; initial inertial coefficient: $w_{initial} = 0{,}9$; and final inertial coefficient: $w_{final} = 0{,}4$.

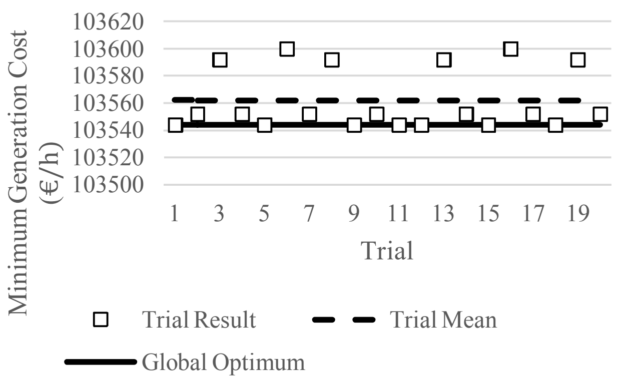

Fig. 6 Results of 20 trials of PSO for the 118 bus system with 30 iterations and 30 particles.

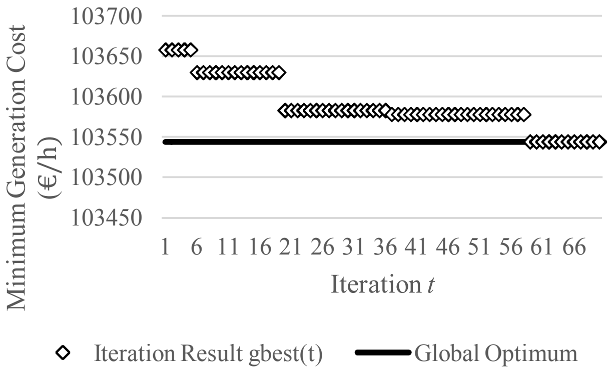

Fig. 7 The convergence of a successful trial of PSO for the 118 bus system, which located the global minimum generation cost of 103.544 €/h.

The average computation time of each PSO trial was 1252,15 s. Out of 20 trials of PSO, 7 of them were able to locate the global minimum generation cost of 103.544 €/h. As a result, the success rate of PSO was 35%. The mean minimum generation cost of the 20 trials of PSO was 103.562 €/h, which is practically identical to the cost of the optimal solution (103.544 €/h) found by exhaustive search. The results of the 20 trials are presented in Fig. 6. The convergence of a successful trial of PSO, which located the global minimum generation cost of 103.544 €/h is presented in Fig. 7.

5 Conclusion

The proposed methodology uses a very simple, yet very effective way to model UPFCs in steady-state power flow and optimal power flow studies. Through the use of this model and a slightly modified power flow algorithm the optimal parameters of multiple UPFCs can be readily calculated. A method based on PSO is proposed to compute the location of multiple UPFCs. The UPFC location results of the proposed PSO method are compared with the results of the exhaustive search method, which guarantees the finding of the global optimum solution.

The PSO method was tested on the 39 bus power system and a 118 bus power system. PSO found the global optimal solution with a success rate of 55% and 35%, respectively. It follows from the geometric distribution of probability theory, that the average number of PSO trials required to locate the optimal result is 1,82 (i.e., 1/0,55) and 2,86 (i.e. 1/0,35), respectively. The average number of trials required in both cases is very low and significant time is saved in comparison with the exhaustive search. Moreover, after modifying each PSO parameter separately and finding the value that lead to the best possible success rate, it was found that the maximum possible success rate of PSO for the 39 bus system is 85%.

The proposed approach has much greater reliability than approaches which use PSO to find both the optimal UPFC locations and their settings, since PSO is only used to find the optimal UPFC locations. Also, the easy way to implement the modelling of UPFC can be of great use to engineers not having access to higher end software. By utilizing this model, engineers are capable of analysing power systems containing multiple UPFCs by slightly changing the power flow algorithm of free, open access software, like MATPOWER.

The cost reduction per hour provided by UPFCs is not great. However, two facts should not be overlooked. First, the cost reduction is per hour and as such, the cost reduction becomes significant in the long term. Second, cost reduction is one of the many benefits the UPFC provides, since it can also improve power system stability and allow for voltage control.

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