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Optimal allocation of multi-type FACTS controllers for optimal power flow using hybrid PSO/SA

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Abstract

In this paper, the new hybrid algorithm based on hybrid particle swarm optimization (hybrid-PSO), and Simulated Annealing (SA) is developed. Hybrid PSO/SA is proposed to determine the optimal allocation of multi-type flexible AC transmission system (FACTS) controllers for solving the optimal power flow (OPF) in power systems. The aim of this proposal is to merge their advantages for improving the step over performance from the local area of search space. The objective function is to maximize the power transfer capability without violating system constraints in electrical power system. The particular optimal allocation includes optimal types, locations, and parameter settings. Four types of FACTS controllers consist of thyristor-controlled series capacitor (TCSC), thyristor-controlled phase shifter (TCPS), static var compensator (SVC), and unified power flow controller (UPFC). Test result on IEEE 30-bus system indicates that optimally placed OPF with FACTS controllers by the hybrid PSO/SA provides effective the higher power transfer capability more than those from EP, conventional PSO, and hybrid-PSO.

Keywords: FACTS controller, optimal power flow, evolutionary programming, particle swarm optimization, simulated annealing

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1. Introduction

Nowadays, the electrical power systems become complicated systems due to many reasons, for example, they cover large areas of several power systems which have different characteristics. Many solutions can be used to improve the efficiency of these systems, but one of the most important objective functions is to enhance total transfer capability (TTC) in the power systems. TTC is defined as an amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of a set of defined pre- and post-contingency system conditions [1]. The general solution to enhance TTC is to adjust and determine suitable parameters of each power system, then calculate TTC. The alternative solution to enhance TTC is to use Flexible AC Transmission System (FACTS) controller [2]. FACTS controllers are power electronics based system and other static equipment that have the capability of controlling various electrical parameters in transmission networks [3]. These parameters can be adjusted to provide adaptability conditions of transmission network [4]. There are many types of FACTS controllers such as thyristor-controlled series capacitor (TCSC), static var compensator (SVC), thyristor-controlled phase shifter (TCPS), and unified power flow controller (UPFC) [5]. These FACTS controllers have been proved to be used for enhancing system controllability resulted in total transfer capability (TTC) enhancement and minimizing power losses in transmission networks [6]. The maximum performance of using FACTS controllers to increase TTC and to minimize system losses should be obtained by choosing suitable types, locations, and parameter settings [7]. Advantages of FACTS controller include lower cost of installations and operations, operating with none pollution, and providing flexible control of the existing transmission system [8].

In addition, the well-known solution to reach maximize the beneficial of TTC and FACTS controller is to use modern heuristic methods. Modern heuristic methods can provides optimal parameters for OPF and FACTS controllers which are in feasible search spaces. These parameters can be used for general operating in power system without violating system constraints. There have been proves that the modern heuristics optimization techniques such as evolutionary programming (EP) [9], tabu search (TS), genetic algorithm (GA) [10], particle swarm optimization (PSO) [11] and other recently heuristic methods are successfully implemented to solve complex problems efficiently and effectively [12].

Some researches present about hybrid method. Narimani et al. [13] presented a new hybrid algorithm based on the PSO and shuffle frog leaping algorithms (SFLA) for solving the OPF in power systems. However, these modern heuristic methods and other hybrid methods have their limitations. The main

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limitation is to stuck in local search spaces which provide the local answer values. It has been proved that by carefully controlling the rate of cooling of the temperature, SA can push the main algorithm to step over the local search spaces and find the global answer values [14]. In [15], the GA-based classifier using the GA with k-length chromosome is developed to classify 2-class data. The experimental results show that the proposed GA-based method gives comparable performance to the KNN, Decision Tree and Naïve Bayes approaches in terms of accuracy.

Therefore, in this paper, the new hybrid PSO/SA is developed. The aims of merging hybrid PSO [16] and SA are to solve those limitations and merge the ability of SA to hybrid PSO. The proposed hybrid PSO/SA is used to determine locations, and parameter settings of four types of FACTS controller (TCSC, TCPS, SVC, and UPFC) to conduct TTC enhancement. The IEEE 30-bus system is used as the test systems. Test results are compared with those from EP, conventional PSO, and hybrid PSO [16].

2. Materials and methods

2.1 Problem formulation

In this section, TTC problem is formulated as an optimal power flow problem. TTC value can be transferred from generators in source buses to load buses in power systems subjected to real and reactive power generations limits, voltage limits, line flow limits, and FACTS controllers operating limits. The objective function is formulated as maximization of TTC and deduction of power losses represented by (1). Maximizing

$$F = \sum_{i=1}^{ND\_SNK} P_{Di} + \sum_{i=1}^{ND\_SNK} P_{Lossi} - \sum_{i=1}^{NG} P_{Gi} \quad (1)$$

$$P_{Gi} - P_{Di} + \sum_{k=1}^{m(i)} P_{Pi}\left(\alpha_{Pk}\right) + \sum_{k=1}^{n(i)} P_{Ui}\left(V_{Uk}, \alpha_{Uk}\right) - \sum_{j=1}^{N} V_i V_j Y_{ij}\left(X_S\right)\cos\left(\theta_{ij}\left(X_S\right) - \delta_i + \delta_j\right) = 0 \quad (2)$$

$$Q_{Gi} - Q_{Di} + \sum_{k=1}^{m(i)} Q_{Pi}\left(\alpha_{Pk}\right) + \sum_{k=1}^{n(i)} Q_{Ui}\left(V_{Uk}, \alpha_{Uk}\right) + Q_{Vi} + \sum_{j=1}^{N} V_i V_j Y_{ij}\left(X_S\right)\sin\left(\theta_{ij}\left(X_S\right) - \delta_i + \delta_j\right) = 0 \quad (3)$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad \forall i \in NG \quad (4)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \qquad \forall i \in NG \quad (5)$$

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad \forall i \in N \quad (6)$$

$$\left|S_{Li}\right| \le S_{Li}^{\max} \qquad \forall i \in NL \quad (7)$$

$$VCPI_i \le 1 \qquad \forall i \in N \quad (8)$$

$$\left|\delta_{ij}\right| \le \delta_{ij}^{\text{crit}} \qquad \forall i \in NL \quad (9)$$

$$X_{Si}^{\min} \le X_{Si} \le X_{Si}^{\max} \quad (10)$$

$$\alpha_{Pi}^{\min} \le \alpha_{Pi} \le \alpha_{Pi}^{\max} \quad (11)$$

$$V_{Ui}^{\min} \le V_{Ui} \le V_{Ui}^{\max} \quad (12)$$

$$\alpha_{Ui}^{\min} \le \alpha_{Ui} \le \alpha_{Ui}^{\max} \quad (13)$$

$$Q_{Vi}^{\min} \le Q_{Vi} \le Q_{Vi}^{\max} \quad (14)$$

$$0 < location_k \le N \text{ or } NL \quad (15)$$

F objective function,

$P_{Gi}^{\min}, P_{Gi}^{\max}$ lower and upper limits of real power generation at bus i,

$Q_{Gi}^{\min}, Q_{Gi}^{\max}$ lower and upper limits of reactive power generation at bus *i*,

$V_i^{\min}, V_i^{\max}$ lower and upper limits of voltage magnitude at bus *i*,

$S_{Li}^{\max}$ *i*th line or transformer loading limit,

$\delta_{ij}^{\text{crit}}$ critical angle difference between bus *i* and *j*,

$X_{Si}^{\min}, X_{Si}^{\max}$ lower and upper limits of TCSC at line *i*,

$\alpha_{Pi}^{\min}, \alpha_{Pi}^{\max}$ lower and upper limits of TCPS at line *i*,

$V_{Ui}^{\min}, V_{Ui}^{\max}$ lower and upper voltage limits of UPFC at line *i*

$\alpha_{Ui}^{\min}, \alpha_{Ui}^{\max}$ lower and upper angle limits of UPFC at line *i*,

$Q_{Vi}^{\min}, Q_{Vi}^{\max}$ lower and upper limits of SVC at bus *i*,

N, *NL* number of buses and branches,

NG number of generator buses,

ND_SNK number of load buses in a sink area,

$n_{CFk}^{\max}$ maximum allowable component of FACTS type *k*,

V_i, V_j voltage magnitudes at bus *i* and *j*,

δ_i, δ_j voltage angles of bus *i* and *j*,

P_{G1}, Q_{G1} real and reactive power generations at slack bus,

P_{Gi}, Q_{Gi} real and reactive power generations at bus *i*,

P_{Di}, Q_{Di} real and reactive loads at bus *i*,

P_{Lossi} power loss at bus *i*,

$P_{Pi(\alpha Pk)}$ injected real power of TCPS at bus *i*,

$Q_{Pi(\alpha Pk)}$ injected reactive power of TCPS at bus *i*,

$P_{Ui(VUk,\alpha Uk)}$ injected real power of UPFC at bus *i*,

$Q_{Ui(VUk,\alpha Uk)}$ injected reactive power of UPFC at bus *i*,

$Y_{ij(XS)}$, $\theta_{ij(XS)}$ magnitude and angle of the *ij*th element in bus admittance matrix with TCSC included,

m(i) number of injected power from TCPS at bus *i*,

n(i) number of injected power from UPFC at bus *i*,

$|SLi|$ *i*th line or transformer loading,

$VCPI_i$ voltage collapse proximity indicator at bus *i*,

$|\delta_{ij}|$ angle difference between bus *i* and *j*,

X_{Si} reactance of TCSC at line *i*,

α_{Pi} phase shift angle of TCPS at line *i*,

V_{Ui}, α_{Ui} voltage magnitude and angle of UPFC at line *i*,

Q_{Vi} injected reactive power of SVC at bus i, and

$location_k$ integer value of line or bus location of FACTS type *k*.

In this paper, voltage collapse proximity indicator (VCPI), thermal line flow limit, and static angle stability constraint are used.

2.2 Proposed algorithm

In this paper, simulated annealing (SA) [17] is used to merge into hybrid-PSO [16] to enhance the ability of step over from the local value in multi-dimension search spaces. Major advantage of SA over other methods is an ability to avoid becoming trapped in local minima. Hybrid PSO/SA is an integrated approach between hybrid-PSO by using hybrid-PSO as a main algorithm and replacing general weighting value by SA value. The general flowchart of hybrid PSO/SA is shown in Fig. 1. The main components of the algorithm are briefly explained as follows:

Step 1: Generation of initial condition of each particle. The initialization of all parameters of each particle are usually random within the search space range. All parameters are set for each particle. The overall best particle is set to *Gbest* of PSO/SA.

Step 2: Cooling Schedule Procedure. The initial temperature is determined in equation (16). The temperature is cooled down by the temperature annealing function or cooling schedule in equation (17).

$$T_{0,m} = \frac{-(F_m^{\max} - F_m^{\min})}{\ln p_r} \quad (16)$$

$$T_{r,m} = \lambda^{(r-1)} \cdot T_{0,m} \quad (17)$$

$T_{0,m}$ is the initial temperature, $F_m^{\max}\, and\, F_m^{\min}$ are the objective value of the worst and the best particles, P_r is the probability of accepting the worst particle with respect to the best particle, $T_{r,m}$ is the annealing temperature after the *r*th reassignment, and λ_r is the rate of cooling, and iteration counter of reassignment strategy.

Step 3: Evaluation of searching point of each particle. The objective function value is calculated for each particle. If the value is better than the current *Pbest* of the particle, the *Pbest* value is replaced by the current value. If the best value of is better than the current *Gbest*, *Gbest* is replaced by the best value and the best value is stored.

Step 4: Modification of each search point. The current searching point of each particle is changed using conventional velocity equation of PSO in (18) [18].

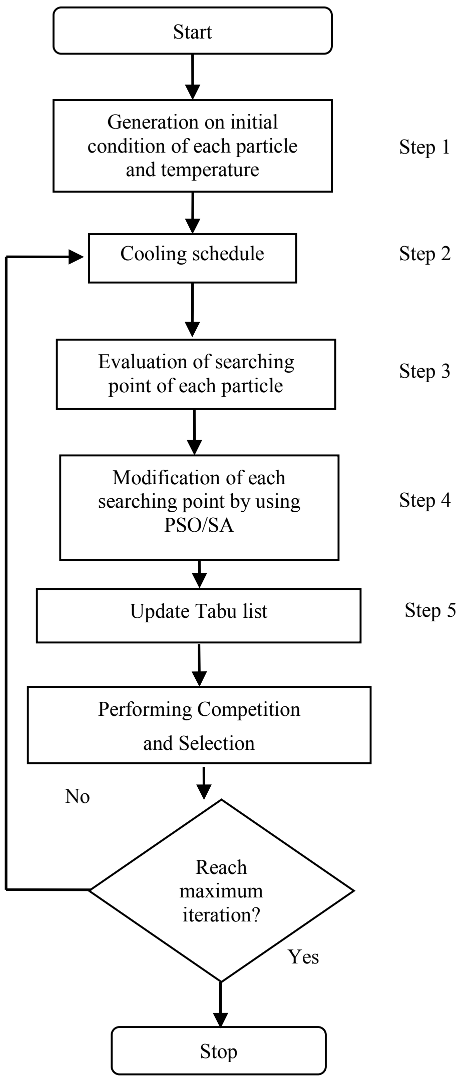

Figure 1 General flowchart of hybrid PSO/SA

$$v_i^{k+1} = w \times v_i^k + c_1 \times rand_1 \times (p_{besti} - s_i^k) + c_2 \times rand_2 \times (g_{best} - s_i^k) \quad (18)$$

Where, v_i^k is the velocity of particle ith at iterations, w s the weight function, c_1 and c_2 are the weighting coefficients both equal to 2, $rand_1$ and $rand_2$ are the random number between 0 and 1, s_i^k is the current positions of particle ith at iteration k, p_{best_i} is the best position of particle ith up to the current iteration, and g_{best} is the best overall position found by the particles up to the current iteration. Weight function is given by (19):

$$w = w_{\min} + \left(w_{\max} - w_{\min}\right) \times T_{r,m} \quad (19)$$

Where, $w_{\max}$ is initial weight equal to 0.9, $w_{\min}$ is final weight equal to 0.4, $iter_{\max}$ is maximum iteration number, and $iter$ is current iteration number.

Step 5: Tabulist. This is well known as meta-heuristic method. Tabulist stores movement of solution and deny backtracking to previous movement in its list [19, 20].

Step 6: Competition and selection. This utilization technique is a tournament scheme, which can be computed by using general competition and selection method of EP.

Step 7: Checking the exit condition. The current iteration number reaches the pre-determined maximum iteration number, then exits. Otherwise the process proceeds to step 2.

Hybrid PSO/SA is used to determine the optimal allocation of multi-type FACTS controllers to

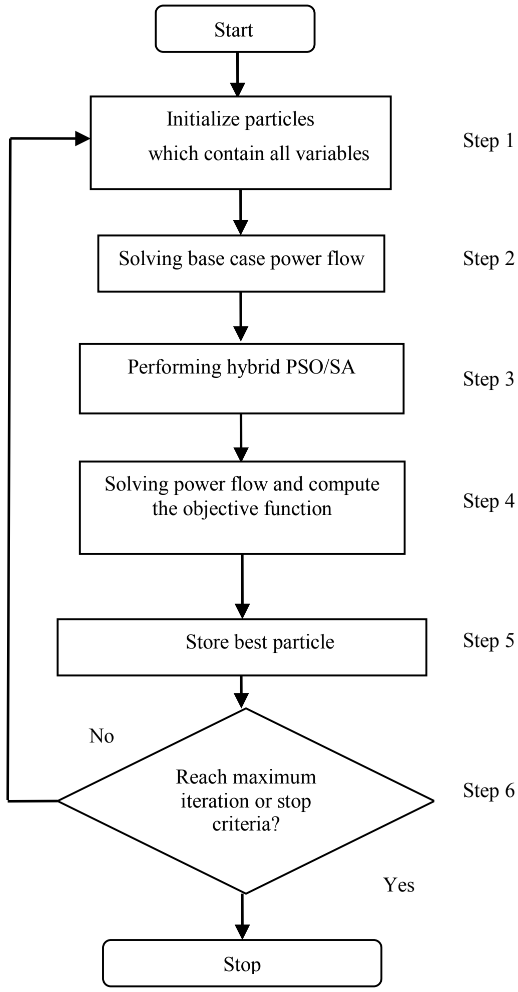

Figure 2 General flowchart of Proposed Algorithm

maximize the objective function. The proposed method is shown in Figure 2.

3. Results and discussion

The IEEE 30-bus system was used as test systems. The IEEE 30-bus system consisted of 6 generating plants, 30 load buses, and 41 lines. Bus 1was set as swing bus. Base case TTC of IEEE 30-bus system equaled 164.30 MW. In the simulations, the reactance limit of TCSC in p.u. was $0 \le X_{si} \le 60\%$ of line reactance, phase shifting angle limit of TCPS was $-\frac{\pi}{4} \le X_{si} \le \frac{\pi}{4}$ radian, angle limit of UPFC was $-\pi \le \alpha_{Ui} \le \pi$ radian, voltage limit of UPFC was $0 \le V_{Ui} \le 0.1$ p.u., and reactive power injection limit of SVC was $0 \le Q_{Vi} \le 10$ MVAR. Loads were modeled as constant power factor loads. The population size of EP was set to 30. The particle group sizes of conventional PSO, hybrid-PSO, and hybrid PSO/SA were set to 30. The maximum iteration numbers of EP, conventional PSO, hybrid-PSO, and hybrid PSO/SA were set to 400.

From Table 1, TTC results from hybrid PSO/SA were higher than TTC from EP, conventional PSO and hybrid-PSO. The best, the average and the worst TTC obtained from hybrid PSO/SA were 371.06 MW, 288.30 MW, and 250.83 MW, respectively. In this test system, the standard deviation and average CPU time of hybrid PSO/SA are slightly high by comparing with hybrid PSO. This can indicate that hybrid PSO/SA can escape from local search space and converge to the better answer than other comparing methods. The allocation of multi-type FACTS controllers from hybrid PSO/SA was represented in Table 2.

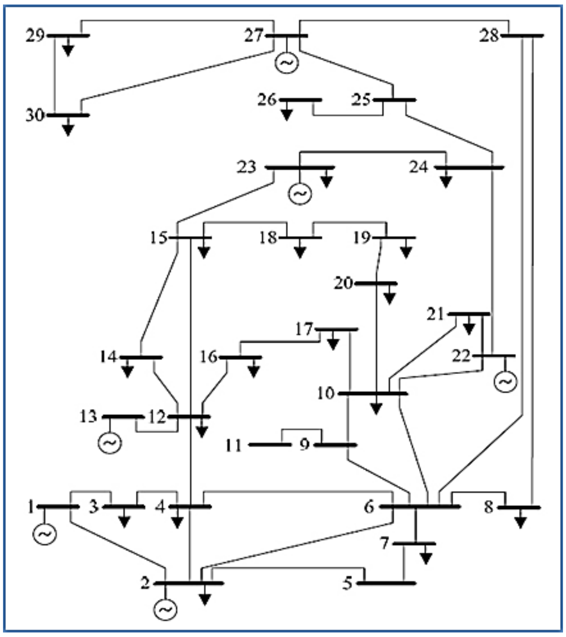

Figure 3 Diagram of IEEE 30-bus system

Table 1 TTC Results and CPU Time from EP, conventional PSO, hybrid-PSO, and hybrid PSO/SA on IEEE 30-bus system

Method / TTC (MW)	EP	conventional PSO	hybrid-PSO	hybrid PSO/SA
Best	224.61	228.65	361.52	371.06
Average	221.62	211.13	284.01	288.30
Worst	203.79	202.49	263.87	250.83
Standard deviation	10.73	7.80	21.52	27.58
Average CPU time (min)	6.47	2.17	8.86	10.77

Table 2 Optimal allocation of multi-type FACTS controllers from hybrid PSO/SA of IEEE 30-bus system

Type of FACTS Controller	**TCSC**	**TCPS**	**UPFC**		**SVC**
Parameter of FACTS Controller	X_s (p.u.)	α_p (rad)	α_u (rad)	V_u (p.u.)	Q_v (MVAR)
	0.0471	0.0255	-2.0153	0.0995	3.051
Location	Line 37	Line 8	Line 9		Bus 25

4. Conclusions

In this paper, hybrid PSO/SA was developed and used to determine the optimal allocations of multi-type FACTS controllers. The hybrid PSO/SA used the selection mechanism of EP and updating strategy based on TS to step over from the local solutions. Moreover, hybrid PSO/SA uses ability of TS and SA which is powerful performance for step over from local search spaces. In addition, hybrid PSO/SA can reach the convergence by mechanism of PSO. The hybrid PSO/SA resulted in the effectiveness to improve the searching for optimal location and the operating points of multi-type FACTS controllers. The overall results from the test systems indicated that the hybrid PSO/SA can effectively and successfully enhance the higher TTC more than those from EP, conventional PSO, and hybrid-PSO. Therefore, the installation of FACTS controllers with optimal allocation using hybrid PSO/SA are worthwhile and beneficial for the decision making and further expansion plans.

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