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Fitness Sharing Particle Swarm Optimization Approach to FACTS Installation for Transmission System Loadability Enhancement

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Abstract – Proper installation of Flexible AC Transmission Systems (FACTS) devices in existing transmission networks can enable power systems to accommodate more power transfer with less network expansion cost. The problem to maximize transmission system loadability by determining optimal locations and settings for installations of two types of FACTS devices, namely static var compensator (SVC) and thyristor controlled series compensator (TCSC), is formulated as a mixed discrete-continuous nonlinear optimization problem (MDCP). For solving the MDCP, in the paper, the proposed method with fitness sharing technique involved in the updating process of the particle swarm optimization (PSO) algorithm, can diversify the particles over the search regions as much as possible, making it possible to achieve the optimal solution with a big probability. The modified IEEE-14 bus network and a practical power system are used to validate the proposed method.

Keywords: FACTS, Fitness sharing, MDCP, PSO, Security limits, System loadability

1. Introduction

Facing constantly increasing power transactions and electric demands, due to the right-of-way and environmental issues, some parts of the transmission network should be reinforced by temporary measures or advanced technology to avoid building new substations or more transmission lines. FACTS devices, such as TCSC, SVC, and unified power flow controller (UPFC), can be used to balance the transmission line flows and improve voltages security such that system loadability can be enhanced with less system loss. Effective methods for locating FACTS devices are becoming increasingly essential to cope with the transmission service requests of utilities and competitive power markets [1]. Maximum system loadability can be simulated by increasing the system load until the equipments or network constraints, such as thermal ratings, voltage security limits or instability, are reached. The problem to maximize transmission system loadability by determining the optimal locations and settings for SVC and TCSC installations can be formulated as an MDCP [2-5]. However, due to the huge search space of the MDCP for a practical system, the computational burden will be high.

Aiming at various objectives, different methods have been proposed to optimally determine the installation of various types of FACTS devices or best controls for the installed FACTS devices in transmission networks. In [6] and [7], to improve the system security and loadability, the continuation power flow (CPF) method was used to determine the controls of the installed FACTS devices. While in [8] and [9], linear programming and mixed integer linear programming based optimal power flow (OPF) methods, were used to determine the settings of the installed FACTS devices and load shedding to relieve the problems of overload and irregular voltages once outages occur in pool and hybrid electricity markets. Based on voltage stability margin (VSM), the method proposed in [10] was used to determine the best locations, size and control modes for SVC and TCSC installations. Under a competitive environment, in [11], for reactive power devices installation, a tangent vector based loss sensitivity analysis was performed to indicate which buses are most necessary for reactive compensation. With the TCSC and UPFC installations and based on specific generation pattern, in [12] and [13], a sensitivity-based repetitive linear iterative approach (SRLIA) optimization algorithm was used to improve control performance and enhance real-time loadability.

To reduce computing burden, in [14], the MDCP was solved by using a two steps approach, in which the locations suitable for SVC and TCSC installations were first investigated by analytical approaches such as eigenvector, tangent vector and real power flow performance index (PI) sensitivity factor, and then, a PSO-based OPF method was applied to determine the settings of the SVC and TCSC installations. While in [15], a crude model was proposed to fast estimate the rough solutions of the MDCP for a set of candidate locations, and then the accurate solutions for a smaller set of candidates selected based on ordinal optimization theory [4] were obtained with the correct method. The best solution in the selected set was taken as the good enough solution for recommendation.

Due to the nonlinear, nonconvex or even discrete inherence of planning problems like the MDCP, in general,

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traditional Newton type optimization methods have difficulties to achieve the global optimum. Alternatively, evolutionary algorithms (EAs) are able to account for this purpose in system planning areas [16]. In [17-23], related applications of the evolutionary techniques, such as genetic, hybrid tabu search, simulated annealing and PSO algorithms, were indentified with high efficiency to achieve the optimal solution.

However, in early stages of PSO procedure, the phenomenon of stagnation might occur and could lead to prematurely converged solutions. Also, if the diversity of the particles descends too fast during evolutional process, it may lead to a high possibility to achieve a local optimum [24]. The previous measures proposed to improve the performance of PSO, were classified into four categories in [25]. They are population topology [26-29], hybridization with auxiliary operations [30-32], adaptive PSO [33-35], and diversity maintenance [36, 37]. In the category of diversifying the population of PSO, the advances also include Pareto-based multi-objective PSO [38], guaranteed convergence PSO (GCPSO) [24] and fitness-distance-ratio based PSO [39]. As mentioned in [16], the technique of niche (or speciation) was originally used in genetic algorithms for approaching multiple optimums. Among the niche methods, fitness sharing [38] is well known and has successful experiences in practical applications. The criterion is to define a "niche radius", with which the fitness of similar particles is reduced and the population deserves more diversity over the search space.

In order for the proposed PSO-based solution method to achieve the global optimum of the MDCP with high probability, in the paper, the concept of fitness sharing is adopted. With the proposed fitness sharing scheme involved in the PSO procedure, in solving the MDCP, the personal best of each particle is applied to measure the diversity between the other particles during evolutional process. The fitness sharing of a particle with bigger diversity is upgraded and the personal best of the particle with the best fitness sharing is then taken as the global best to guide the swarm into the next generation. Compared with the test results derived from applying the traditional PSO-based method to solve the MDCP, the performance of the proposed method was validated with higher ability to achieve the optimal solution.

The rests of the paper are organized as: Section 2 presents the detailed formulation of the MDCP to maximize transmission system loadability with optimal SVC and TCSC installations. The fitness sharing PSO-based solution method proposed is introduced in Section 3 and, followed by Section 4, the performance of the proposed method is validated with detailed studies in the modified IEEE-14 bus system and the simplified Taiwan power transmission network. The study is simply concluded in the final section.

2. Problem Formulation

An SVC can be installed at a PQ bus to control bus voltage by providing reactive power and a TCSC can be installed on a transmission line to coordinate the network flow by regulating the line reactance.

Assuming bus i to be a PQ bus and letting Q_{ci} be a regulable reactive power provided by the SVC installation at the bus, the settings are limited within: $-\overline{Q}_c \le Q_{ci} \le \overline{Q}_c$. The equivalent injection at bus i with an SVC installation is shown in Fig. 1 and the real and reactive power balance equations are expressed as:

$$\sum_{\forall j} P_{ij,c} + P_{Dio} + \lambda \Delta P_{Di} = 0 \tag{1}$$

$$\sum_{\forall j} Q_{ij,c} + Q_{Dio} - Q_{ci} + \lambda \Delta Q_{Di} = 0 \tag{2}$$

While bus i is assumed to be a PV bus, the real and reactive power balance equations are expressed as:

$$\sum_{\forall j} P_{ij,c} - P_{Gio} - P_{Gi} + P_{Dio} + \lambda \Delta P_{Di} = 0 \tag{3}$$

$$\sum_{\forall j} Q_{ij,c} - Q_{Gio} - Q_{Gi} + Q_{Dio} + \lambda \Delta Q_{Di} = 0 \tag{4}$$

where $P_{ij,c}$ and $Q_{ij,c}$ are real and reactive line flows on line i-j including the effects of the TCSC installations in the network, $-P_{Gio} + P_{Dio}$ and $-Q_{Gio} + Q_{Dio}$ are the base real and reactive injections at the bus, ΔP_{Di} and ΔQ_{Di} are the loading level for the load at the bus to increase, and P_{Gi} and Q_{Gi} are the additional real and reactive power generations for providing increased system load.

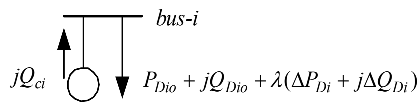

Fig. 1. A PQ bus with an SVC installation

As shown in Fig. 2, let $x_{ij,c}$ be the reactance provided by the TCSC installation on transmission line i-j. It is set to be regulated in compensation levels [-0.8, 0.2] and thus the settings are limited within: $-0.8x_{ij} \le -x_{ij,c} \le 0.2x_{ij}$, where x_{ij} being the reactance of line i-j. Then, the real and reactive power line flows in (1) to (4) can be expressed as:

$$P_{ij,c} = V_i^2 g_{ij}^{'} - V_i V_j (g_{ij}^{'} \cos\theta_{ij} + b_{ij}^{'} \sin\theta_{ij}) \tag{5}$$

$$Q_{ij,c} = -V_i^2 (b_{ij}^{'} + b_{sh}) - V_i V_j (g_{ij}^{'} \sin\theta_{ij} - b_{ij}^{'} \cos\theta_{ij}) \tag{6}$$

where $g_{ij}^{'} = \dfrac{r_{ij}}{r_{ij}^2 + (x_{ij} + x_{ij,c})^2}$ and $b_{ij}^{'} = \dfrac{-(x_{ij} + x_{ij,c})}{r_{ij}^2 + (x_{ij} + x_{ij,c})^2}$.

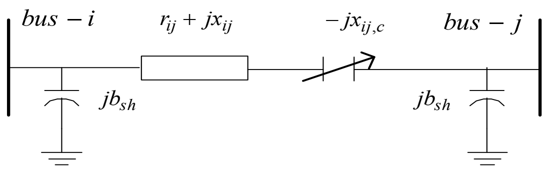

Fig. 2. Branch with a TCSC installation and the equivalent injection model

Depending on the generation dispatch policy, P_{Gi} and Q_{Gi} are the additional real and reactive power generation at bus *i* when system load is increased. System operation constraints are expressed as:

$$\underline{h} \le h(x,v) \le \overline{h} \quad (7)$$

Eq. (7) includes the bus voltage limits: $\underline{V}_i \le V_i \le \overline{V}_i$, generator output limits: $0 \le P_{Gio} + P_{Gi} \le \overline{P}_{Gi}$ and $\underline{Q}_{Gi} \le Q_{Gio} + Q_{Gi} \le \overline{Q}_{Gi}$, line thermal ratings: $|S_{ij}| = \sqrt{P_{ij,c}^2 + Q_{ij,c}^2} \le \overline{S}_{ij}$, and the SVC and TCSC operation limits. System state vector $x = [V \ \theta]^{\mathrm{T}}$ includes the bus voltage magnitudes and phase angles. Control variables vector $v = [P_G \ \ C_f \ \ V_a \ \ \lambda]^{\mathrm{T}}$, in which P_G includes the real power generations, C_f includes the locations and settings for SVC and TCSC installations, V_a includes the settings of the automatic voltage regulators, on load tap changing (OLTC) transformers and shunt capacitors (SC), and λ is the loading factor.

The MDCP is formulated below:

$$\begin{aligned} &Max \quad \lambda \\ &s.t. \quad g(x,v) = 0 \\ &\qquad \underline{h} \le h(x,v) \le \overline{h} \\ &\qquad \underline{v} \le v \le \overline{v} \end{aligned} \quad (8)$$

where functional vector $g(x,v) = 0$ representing (1) to (4). After solving the problem, the maximum additional system loading, $\lambda^* \sum P_{Dio}$, can be obtained.

3. Proposed Methodology

A PSO-based solution method can be used to solve the MDCP directly. In the solution process, all discrete variables, including the locations for SVC and TCSC installations, are treated as continuous variables first and changed to nearest discrete values upon convergence. Particles' positions and velocities in a traditional PSO algorithm can be updated with the following equations [22]:

$$X_i(k+1) = X_i(k) + V_i(k+1) \quad (9)$$

$$\begin{aligned} v_{i,j}(k+1) = wv_{i,j}(k) &+ c_1 r_{1,j}(pbest_{i,j} - x_{i,j}(k)) \\ &+ c_2 r_{2,j}(gbest_j - x_{i,j}(k)) \end{aligned} \quad (10)$$

$X_i(k)$ and $V_i(k)$ represent the position and velocity of particle *i* at iteration *k*. $x_{i,j}$ is the *j*th entry of $X_i(k)$. With the existing control devices simply fixed at the settings under the base state, in particle *i*, $X_i(k) = [P_G^i \ \ C_f^i \ \ \lambda_i]^{\mathrm{T}}$ includes all generations, locations and setting for SVC and TCSC installations, and loading factor. $v_{i,j}$ is the *j*th entry of V_i, $0.9 \le w \le 0.2$ is an inertia weight to determine how much the previous particles' velocities are preserved, c_1 and c_2 are two positive acceleration constants, as set to 2 in the algorithm, $r_{1,j}$ and $r_{2,j}$ are random numbers sampled with uniform distribution $U(0, 1)$, and $pbest_i$ and $gbest$ are the personal best position of particle *i* and the best position in the entire swarm, respectively.

The traditional PSO-based algorithm for solving the MDCP is presented below:

1. Set iteration and particle numbers.
2. Narrow down the control variable adjustment ranges and generate a swarm.
3. A load flow computation is conducted for each particle *i*, denoted as $X_i(k) = [P_G^i \ \ C_f^i \ \ \lambda_i]^{\mathrm{T}}$. If no load flow solution exists in the swarm, return to step 2. Otherwise, set $pbest_i$ and fitness f_i for particle *i*. For particle *i* with a converged load flow solution, $f_i = \lambda_i/(1 + pen\_i)$, and for particle *i* without a load flow solution, $f_i = -10$, where *pen_i* is a penalty that is proportional to the severity of security constraint violation and λ_i is the personal current loading factor. Restore the control variable adjustment range to the traditional problem. Set *Ite_num* = 1 and go to step 4.
4. *gbest* = the *pbest* of the particle with maximum fitness. Update the particles using (9) and (10). For each particle, the discrete variables (locations for SVC and TCSC installations) are rounded to the nearest discrete values.
5. Execute load flow analysis for each particle and check the security constraints. Update particle fitness ($f_i = \lambda_i/(1 + pen\_i)$). If *Ite_num* is lower than the iteration number set, *Ite_num* = *Ite_num*+1 and go to step 4, otherwise, go to step 6.
6. Record the SVC and TCSC installation locations, settings, generation outputs and the loading factor value obtained.

On the other hand, to increase the chance to achieve the optimal solution of solving the MDCP, in the proposed PSO-based solution method, the fitness sharing scheme proposed is composed into the traditional PSO process such that the particles can be diversified over the search regions as much as possible during evolutional process. The proposed fitness sharing scheme is used to distribute a population of particles along a set of resources and, as particle i is sharing resources with other particles, its fitness f_i is degraded proportional to the number and closeness to particles that surround it. If a maximum solution is the objective of the problem, the fitness sharing of particle i is defined as:

$$f_{S_i} = f_i \Big/ \sum_{k=1}^{NP} sh_i^k \qquad (11)$$

A bigger fitness sharing represents that particle i is distant from the swarm. Whereas, if the target is to achieve a minimum objective, the fitness sharing is defined as:

$$f_{S_i} = f_i \cdot \sum_{k=1}^{NP} sh_i^k \qquad (12)$$

where sh_i^k denoting the sharing factor that measures the similarity from particles i to k by a distance function d_i^k. When the particle is averagely more distant from other particles, a smaller sharing factor takes place. In the paper, they are given as:

$$sh_i^k = \begin{cases} 1-(d_i^k/\sigma)^2 & \text{if } d_i^k < \sigma \\ 0 & \text{Otherwise} \end{cases} \qquad (13)$$

and

$$d_i^k = \sum_j \left(\frac{pbest_{i,j} - x_{k,j}}{x_j^{\max} - x_j^{\min}} \right)^2 \qquad (14)$$

where σ being the distance set for the particles to remain distant from each other and j indexing the variables in the particles.

In the proposed method, except the process of step 4 of the traditional PSO solution algorithm presented above, the other steps are also used without change in the solution algorithm. While in step 4 of the proposed solution algorithm, a particle with the best fitness sharing will instead take the position to guide the swarm into the next generation. And, accordingly, due to that the objective of the MDCP is to maximize the loading factor, with the fitness sharing of each particle calculated by (11), (13) and (14), the *gbest* in step 4 of the proposed solution algorithm is determined as follows:

gbest = the *pbest* of the particle with the best fitness sharing (15)

The setting of σ is determined on a basis of system case-by-case; in the study, with a certain number of simulations, the effects of various σ values to achieve the optimal solution are carefully inspected for the test systems.

4. Test Results and Discussions

4.1 IEEE-14 bus system

The base-case load flow of the test system depicted in Fig. 3 is shown in Table 1. It can be found in Fig. 3 that most of the system demand is concentrated in the upper area of the network while all generators are located at the lower area. The system loadability under without any reinforcement is found to be $\lambda^* \sum P_{Dio} = 0.42$ p.u. at $\lambda^* = 0.18$. It can be seen in Table 1 that, under without any reinforcement, the voltage security problem at bus 14 will impede the amount of the power transferred from the lower to the upper areas. It can also be seen in Table 2 that, when system operating at the loadability under without any reinforcement, due to short of mechanisms to effectively coordinate network power flow, only line 1-5 is sufficiently utilized.

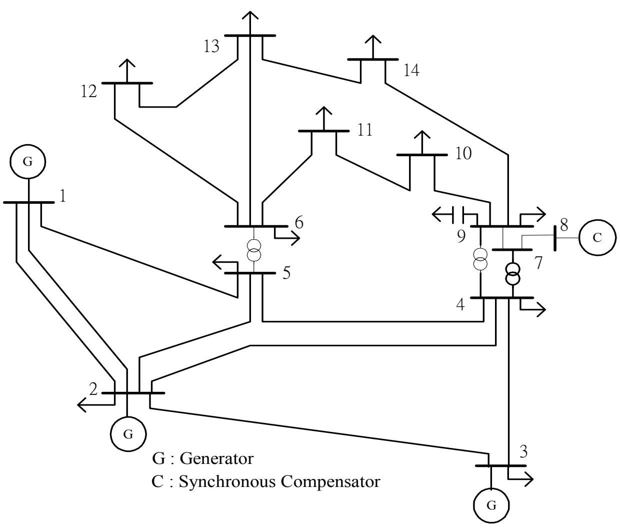

Fig. 3. Modified IEEE-14 bus system

The system loadability enhancement study in the 14-bus network is managed under the normal state. Both the traditional PSO and the proposed fitness sharing PSO solution algorithms can be used to solve the MDCP to determine the best locations and settings for two SVC and two TCSC installations. The optimal SVC and TCSC installations obtained are shown in Table 3. As found that the system loadability, $\lambda^* \sum P_{Dio} = 1.31$ p.u. at $\lambda^* = 0.55$, resulted from the optimal SVC and TCSC installations is much larger than that at $\lambda^* = 0.18$ under without any reinforcement. With the TCSC installations on lines 2-5 and 3-4 in the lower area, the network flow can be properly coordinated by regulating the line reactances such that more power can be transferred from the lower to the upper areas. And, with the reactive powers provided by the SVC installations at buses 4 and 6, the low voltage problem at bus 14 under without reinforcement can be relieved. Therefore, it can be found from Tables 1 and 2 that, with the reinforcement, voltage security is effectively improved and most transmission lines are utilized sufficiently, especially, besides line 1-5, lines 2-4, 3-4 and 5-6 are also utilized up to their limits.

Table 1. Load flows at base-case, and at $\lambda^* = 0.18$ without and at $\lambda^* = 0.55$ with reinforcement

	Base Case					Without			With		
Bus	Vol.	P_G	Q_G	P_L	Q_L	Vol.	P_G	P_L	Vol.	P_G	P_L
1	1.080	0.168	0.788	-	-	1.080	0.522	-	1.080	0.156	-
2	1.045	0.521	-0.706	-	0.127	1.045	0.637	-	1.045	1.645	-
3	1.070	1.735	0.281	0.942	0.190	1.070	1.693	1.108	1.070	1.991	1.461
4	1.030	-	-	0.478	-0.039	1.023	-	0.562	1.020	-	0.742
5	1.031	-	-	0.076	0.016	1.023	-	0.089	1.024	-	0.118
6	0.991	-	-	0.112	0.075	0.974	-	0.132	1.024	-	0.174
7	1.034	-	-	-	-	1.025	-	-	1.026	-	-
8	1.090	-	0.345	-	-	1.090	-	-	1.090	-	-
9	1.003	-	-	0.295	0.166	0.988	-	0.347	0.992	-	0.458
10	0.994	-	-	0.090	0.058	0.977	-	0.106	0.985	-	0.140
11	0.989	-	-	0.035	0.018	0.971	-	0.041	0.999	-	0.054
12	0.977	-	-	0.061	0.016	0.957	-	0.072	0.999	-	0.095
13	0.974	-	-	0.135	0.058	0.953	-	0.159	0.991	-	0.209
14	0.971	-	-	0.149	0.050	0.950	-	0.175	0.961	-	0.231
Sum	-	2.424	0.708	2.373	0.735	-	2.852	2.791	-	3.792	3.682

*MVA base = 100MVA

Table 2. Line flows at $\lambda^* = 0.18$ without FACTS and at $\lambda^* = 0.55$ with FACTS installation

Lines	Without FACTS	With FACTS	Limit
1-2/2-1	0.578/0.616	0.711/0.744	0.80
1-5/5-1	0.397/0.400	0.397/0.400	0.40
2-3/3-2	0.152/0.111	0.347/0.327	0.74
2-4/4-2	0.444/0.433	0.560/0.544	0.56
2-5/5-2	0.400/0.392	0.560/0.583	0.60
3-4/4-3	0.541/0.522	0.800/0.762	0.80
4-5/5-4	0.203/0.206	0.179/0.178	0.42
4-7/7-4	0.376/0.377	0.473/0.476	0.56
4-9/9-4	0.223/0.216	0.274/0.267	0.40
5-6/6-5	0.507/0.483	0.639/0.639	0.64
6-11/11-6	0.049/0.049	0.123/0.120	0.40
6-12/12-6	0.089/0.087	0.127/0.124	0.40
6-13/13-6	0.198/0.194	0.295/0.285	0.40
7-8/8-7	0.377/0.401	0.376/0.399	0.47
7-9/9-7	0.514/0.496	0.577/0.557	0.74
9-10/10-9	0.142/0.140	0.1181/0.1174	0.40
9-14/14-9	0.159/0.153	0.1708/0.1655	0.30
10-11/11-10	0.031/0.031	0.0650/0.0659	0.30
12-13/13-12	0.013/0.013	0.0281/0.0279	0.30
13-14/14-13	0.041/0.041	0.0861/0.0835	0.30

Table 3. Optimal SVC and TCSC installation Results

λ^*	SVC		TCSC	
	Bus	p.u.	Line	Level
0.55	4	0.026	2-5	-0.136
	6	0.437	3-4	-0.707

To take the stochastic nature of PSO into account, with particle and iteration numbers set to 30 and 1000 respectively, the proposed method with $\sigma = 5$ is performed for 100 trials of solving the MDCP. The solution results of the 100 trails are analyzed and shown in Fig. 4. As seen that the minimum, average, and maximum system loadabilities in the 100 trails at values of λ^* are 0.40, 0.52, and 0.55 respectively. On the other hand, using the same iteration and particle numbers, the traditional PSO method is also performed for 100 trials of solving the MDCP and the minimum, average and maximum λ^* values obtained are 0.22, 0.50, and 0.55 respectively. Obviously, the minimum system loadability resulted from the SVC and TCSC installations obtained with the proposed method is much larger than that obtained from the traditional PSO method, due to the premature phenomenon that lowers the efficiency of the traditional PSO to achieve the optimal solution. Also, the average loadability of the 100 trails obtained from the traditional PSO is also found to be less than that obtained from the proposed method. In this scene, the performance of the proposed method is validated to be better than the traditional PSO method.

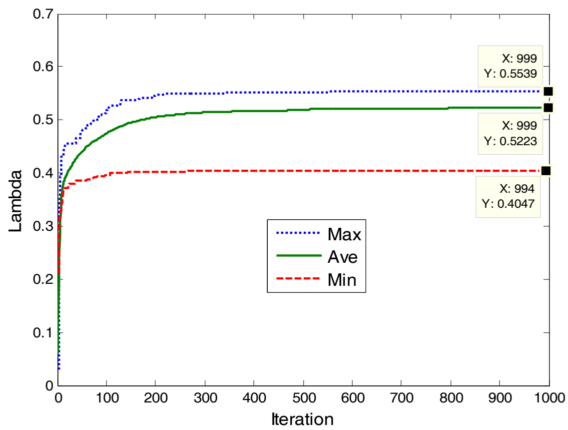

Fig. 4. Performance analysis of solutions in the 100 trials

With the same iteration and particle numbers, for each σ set to 1, 5, 10, 15 and 20 respectively, the proposed method is performed to solve the MDCP for 100 trials. As a result, the optimal solution numbers found in the respective 100 trials are 7, 32, 26, 21 and 14 for each σ set to 1, 5, 10, 15 and 20, respectively. On the other hand, the optimal solution number found in the results from the 100 trials of solving the MDCP by using the traditional PSO method is 24. Therefore, the proposed method with $\sigma = 5$, as can help derive the biggest optimal solution number, is identified with the best efficiency in solving the MDCP.

In addition, with the same iteration number and for each particle number set to 10, 30, 50, 70 and 90 respectively, the optimal solution numbers in the respective 100 trails of solving the MDCP by the proposed method with $\sigma = 5$ and the traditional PSO method respectively, are shown in Fig. 5. It can be found that, as the particle number set bigger than 20, the optimal solution number in the 100 trials of solving the MDCP by the proposed method with σ set to 5 will be bigger than that derived with the traditional PSO method. Obviously, as particle number set to 30, the proposed method with $\sigma = 5$ will perform the best in the network reinforcement.

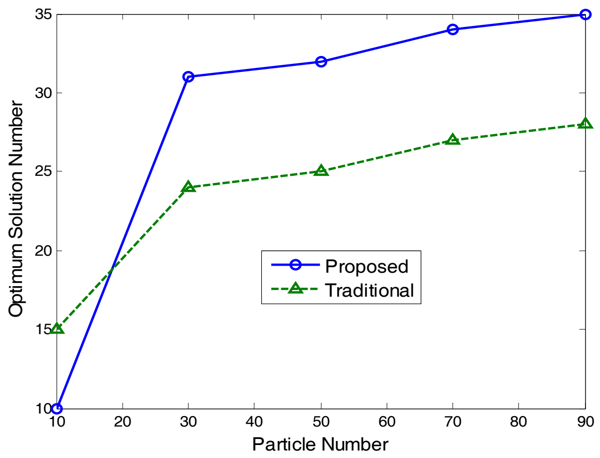

Fig. 5. Optimal solution numbers vs. particle numbers

4.2 Taiwan power system

The simplified Taipower 345 kV transmission network with 76 buses, including 50 PQ buses and 25 PV buses, and 113 transmission lines, is also used for testing. The network is divided into three areas: north, central and south areas. One line diagram of the central part of the studied EHV system is shown in Fig. 6. In the study, it is assumed that two nuclear units in the north area are out of service and certain contingencies are considered. The demand and supply of the system during peak-load hours are shown in Table 4. Demand in the north area is higher than those in the central and south areas. For most of the time, the north has to count on the support from the south. Before making reinforcement, the system loadability under each N-2 contingency was investigated and the most serious N-2 contingency scenario with the smallest system loadability at $\lambda^* = 0.0206$ is shown in Table 4, which is considered in the MDCP for loadability enhancement. Under the contingency considered, the performance of the proposed method applied to the MDCP to determine three SVC and three TCSC installations is studied below.

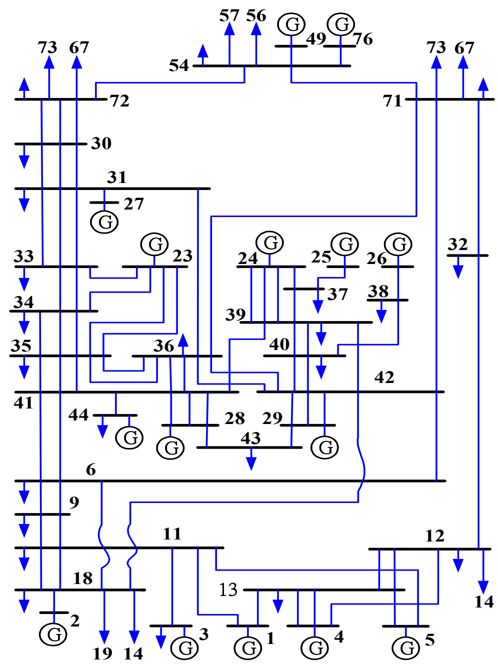

Fig. 6. Central part of Taipower network

Table 4. Supply and demand at different areas, and the studied contingency and loading factor

Area (Bus)	North (45-76)	Central (23-44)	South (1-22)	Total x100MW
Gen. Capacity	205.22	134.56	161.63	501.41
Generation	205.11	118.44	124.43	447.98
Demand	196.09	122.76	126.03	444.89
Contingency	Scenario			λ^*
N-2	36-41(CKT 1), 36-42(CKT 1)			0.0206

*MVA base = 100MVA

Using the traditional PSO-based method with particle and iteration numbers set to 30 and 1000 respectively, the MDCP under the considered contingency are solved for 1000 trails. In the 1000 trails, it is found that there are only eight solutions with system loadabilities at values of λ^* larger than or equal to 0.0651, each of which is considered as a good enough solution and to be capable of the required loadability [15]. The SVC and TCSC installation results of a good enough solution with loadability at $\lambda^* = 0.0651$ are shown in Table 5. As seen that the SVC installations are at buses 36, 45 and 68 and the TCSC installations are on lines 12-32, 20-21 and 32-71. Obviously, the SVC installations are all located in the central-north area and the TCSC installations are all close to the central area. In this scene, it conceivable that, when transferring power from the south to the north areas, the voltage security around the central area can be maintained appropriately with the reactive powers provided by the SVC installations and the network flow can be coordinated effectively with the line reactances regulated by the TCSC installations properly.

Table 5. SVC and TCSC installation results of a good enough solution [15]

λ^*	SVC		TCSC	
	Bus	p.u.	Line	Level
0.0651	36	0.1108	12-32	-0.7966
	45	0.0565	20-21	-0.0104
	68	0.0939	32-71	-0.7954

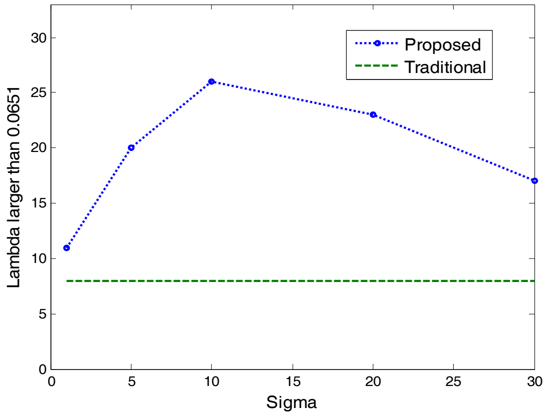

Fig. 7. Number of the solutions with λ^* larger than 0.0651 derived from the proposed and traditional PSO methods

With particle and iteration numbers set to 30 and 1000, the traditional PSO method and the proposed fitness sharing PSO method for each σ set to 1, 5, 10, 20 and 30, are performed for 1000 trials to solve the MDCP, respectively. In the respective 1000 trials, the numbers of the solutions with loadabilities at values of λ^* larger than 0.0651 derived from the proposed method for each σ and the traditional PSO method, are shown in Fig. 7, respectively. As found that the proposed method with $\sigma = 10$ can derive the biggest number, i.e. 26, of solutions with λ^* larger than 0.0651, in which $\lambda^* = 0.0694$ is the largest. The SVC and TCSC installations for deriving the system loadability at $\lambda^* = 0.0694$ are shown in Table 6. As seen that all SVC installations are located in the central-north areas and are utilized more sufficiently than the SVC installations shown in Table 5. The settings for the TCSC installations on lines 12-32 and 32-71 of both solutions are all similar with each other. While the compensation level of the TCSC installation on line 36-41 is set to 0.1953, the flow on the line can thus be reduced for more power to be transferred from the south to the north areas.

Table 6. The SVC and TCSC installations of the best solution in the 1000 trails by the proposed method

λ^*	SVC		TCSC	
	Bus	p.u.	Line	Level
0.0694	36	1.6957	12-32	-0.7991
	64	1.1548	32-71	-0.7976
	72	1.2005	36-41	0.1953

5. Conclusion

From a long-term economic development perspective, it is expectable that regional or integral electricity demands will increase or change constantly. Besides, in the deregulated power systems, due to open access to the transmission networks, various types and a large amount of power transactions would result in huge changing power flow. In this view, serious threats to power system security may occur. To improve the operational security while avoid network expansion by building new transmission lines, it is a good choice to properly install FACTS devices in existing networks such that more power transfer can be accommodated in the networks. In this paper, the problem to maximize the system loadability by determining the optimal locations and settings for SVC and TCSC installations is formulated as an MDCP and solved by using the proposed fitness sharing PSO-based method. From the numerical results, it is confirmed that, when solving the MDCP by the proposed method, with the fitness sharing scheme the particles can be as much diversified as possible, leading the PSO algorithm with a high efficiency to achieve the optimal solution.

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