Enhancement of Total Transfer Capability Using SVC and TCSC

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Abstract-- In this paper, Particle Swarm Optimization (PSO) algorithm and Guaranteed Convergence PSO (GCPSO) are proposed to determine the allocation of Thyristor Controlled Series Compensator (TCSC) and Static Var Compensator (SVC) for maximizing the Total Transfer Capability (TTC) between source and sink area by considering voltage limits and thermal limits in a power system. The optimization is made on two parameters: the location and size of devices. Also, to have a comparison, Genetic Algorithm (GA) is applied to deal with the problem. Simulation results show that standard PSO failed to solve the problem but GA and GCPSO algorithms converge to similar optimal solutions.

Key-Words -- TTC, particle swarm optimization, guaranteed convergence PSO, genetic algorithm, SVC and TCSC.

1 Introduction

Total Transfer Capability (TTC) is the largest value of electric power that can be transferred over the interconnected transmission network in a reliable manner without violation of specified constraints. Flexible AC Transmission System (FACTS) devices such as TCSC and SVC could help system to increase power transfer capacity. TCSC provides a series compensation which consists of a series capacitor bank shunted by thyristors that can change its apparent reactance smoothly and rapidly. SVC is a shunt compensation component whose output is adjusted to exchange capacitive or inductive current. Different mathematical methods and algorithms have been developed for calculating TTC where can be found in [1]-[5].

It is found that flexible AC transmission system (FACTS) devices are good choices to improve TTC in power systems. Various heuristic approaches have been adopted by researches including genetic algorithm, tabu search and evolutionary programming [6]-[9] to enhance TTC by placing the FACTS devices.

Particle swarm optimization (PSO) algorithm as an evolutionary computation technique has been proven to be very effective for static and dynamic optimization problems.

In view of this, in this paper, the PSO algorithm is used to enhance TTC by placing TCSC and SVC. The obtained results show that the original version of PSO algorithm (introduced by Kennedy and Eberhart [10]) may converge prematurely without finding a local extremum. To solve the problem, the guaranteed convergence PSO (GCPSO) is applied. Furthermore, due to many good features of GA techniques, GA is applied to solve the problem, and the results obtained by GCPSO and GA are compared.

2 Problem Formulation

The ability of interconnected transmission networks to reliably transfer electric power may be limited by voltage level limits, transmission line thermal limit, generation limit, voltage stability limit and transient stability limit [11]. For the TTC calculations, one area is considered as the source area and the other considered as the sink area where TTC is a directional quantity from the source to the sink.

In this paper, TTC is calculated by considering the above mentioned limitation except the transient stability limit. Also, the scenario that is used for TTC calculation is Load / Generation method (LG) so that the loads in the sink area are increased and the source area will compensate for this increase by

increasing its generation. The mathematical formulation of TTC can be expressed as follows:
Maximize λ
Subject to :

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |Vi||Vj|(GijCos\delta ij + BijSin\delta ij) = 0 \quad (1)$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} |Vi||Vj|(GijSin\delta ij + BijCos\delta ij) = 0 \quad (2)$$

$$|Vi|_{\min} \le |Vi| \le |Vi|_{\max} \quad (3)$$

$$S_{ij} \le S_{ij\max} \quad (4)$$

where λ is scalar parameter representing the increase in bus load or generation, $\lambda = 0$ corresponds to no transfer (base case) and $\lambda = \lambda_{\max}$ corresponds to the maximal transfer. P_{Gi}, Q_{Gi} are real and reactive power generation at bus i, P_{Di}, Q_{Di} are real and reactive power demand at bus i, n is the bus number, $|V_i|, |V_j|$ are voltage magnitude at bus i and j, δij is voltage angle difference between bus i and bus j, $|V_i|_{\min}, |V_i|_{\max}$ are lower and upper limits of voltage magnitude at bus i, S_{ij} is apparent power flow in line i and j and $S_{ij\max}$ is thermal limit of line i and j.

P_{Gi} and P_{Di}, Q_{Di} in the equations (1) and (2) are reformulated as follows:

$$P_{Gi} = P_{Gi}^{0}(1 + \lambda k_{Gi}) \quad (5)$$

$$P_{Di} = P_{Di}^{0}(1 + \lambda k_{Di}) \quad (6)$$

$$Q_{Di} = Q_{Di}^{0}(1 + \lambda k_{Qi}) \quad (7)$$

where P_{Gi}^{0} is original real power generation at bus i which is in source area, P_{Di}^{0}, Q_{Di}^{0} are original real and reactive load demand at bus i which is in sink area and k_{Gi}, k_{Di} are constants used to specify the change rate in generation and load as λ varies.

TTC level in each case (normal or contingency case) is calculated as follows:

$$TTC = \sum_{i \in Sink} P_{Di}(\lambda_{\max}) - \sum_{i \in Sink} P_{Di}^{0} \quad (8)$$

where $P_{Di}(\lambda_{\max})$ is the sum of loads in sink area when $\lambda = \lambda_{\max}$ and P_{Di}^{0} is the sum of loads in sink area when $\lambda = 0$.

3 Particle Swarm Optimization

Through cooperation and competition among heuristic methods, the population-based optimization approaches, such as GA and PSO, often can find very good solutions efficiently. GA is motivated by evolution as seen in nature. PSO is motivated from the simulation of social behavior. All of these optimization approaches update the population of individuals by applying some kinds of operators according to the fitness information obtained from the environment so that the individuals of the population can be expected to move towards better solution areas. A brief of explanation of PSO is given below:

3.1 Standard PSO

In PSO, each particle moves in the search space with a velocity according to its own previous best solution and its group's previous best solution [12]. The dimension of the search space can be any positive integer. Each particle updates its position and velocity with the following two equations:

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

where $X_i(t)$ and $V_i(t)$ are vectors representing the current position and velocity respectively.

$$V_{i,j}(t+1) = wV_{i,j}(t) + c_1 r_{1,j}(pb_{i,j} - X_{i,j}(t)) + c_2 r_{2,j}(gb_j - X_{i,j}(t)) \quad (10)$$

where $j \in 1,2,...,d$ represents particle dimension . $0 \le w < 1$ is an inertia weight determining how much of particle's previous velocity is preserved, c_1 and c_2 are two positive acceleration constants; and $r_{1,j}, r_{2,j}$ are two uniform random sequences sampled from $U(0,1)$, pb_i is the personal best position found by the i^{th} particle and gb is the best position found by the entire swarm so far.

Although, PSO has been proven to be very effective for static and dynamic optimization problems, but in some cases, it converges prematurely without finding a local optimum. Standard PSO may converge at the early stage due to the best particle moves based only on the inertia term since $X_i = pb_i = gb$ at the time step when it became the best. Later, its position may improve where $X_i = pb_i = gb$ holds again. Also, its position will worsen where it will be drawn back to $pb_i = gb$ by the social component. In this case, it is possible for the inertia weight to drive all velocities to zero before the swarms manage to reach a local extremum. When all the particles collapse with zero velocity on a given position in the search space, then the swarms have converged. Thus it is possible for the standard PSO to converge prematurely without finding a local extremum [13]-[14]. To solve this problem, the Guaranteed Convergence PSO (GCPSO) is introduced in [13].

3.2 Guaranteed Convergence PSO (GCPSO)

The GCPSO was introduced by Van den Bergh [13] to address the issue of premature convergence to solutions that are not guaranteed to be local extrema. The modifications to the standard PSO involve replacing the velocity update Equation (10) of only the best particle with the following equation:

$$V_{i,j}(t+1) = wV_{i,j}(t) - X_{i,j}(t) + pb_{i,j} + \rho(t)r_j \tag{11}$$

where r_j is a sequence of uniform random numbers sampled from U(-1,1) and $\rho(t)$ is a scaling factor determined using :

$$\rho(0) = 1.0$$

$$\rho(t+1) = \begin{cases} 2\rho(t) & if\,\#\,successes > s_c \\ 0.5\rho(t) & if\,\#\,failures > f_c \\ \rho(t) & otherwise \end{cases} \tag{12}$$

where s_c and f_c are tunable threshold parameters. Whenever the best particle improves its personal best position, the success count is incremented and the failure count is set to 0 and vice versa. The success and failure counters are both set to 0 whenever the best particle changes.

These modifications cause the best particle to perform a directed random search in a non-zero volume around its best position in the search space.

4 The Study System and Results

A 5-area-16-machine system is chosen as a study system. The study system is shown in Fig. 1, consisting of 16 machines and 68 buses. This is a modified reduced order model of the New England (NE) New York (NY) interconnected system. The first nine machines are the simple representation of the New England system generation. Machines 10 to 13 represent the New York power system. The last three machines are the dynamic equivalents of the three large neighboring areas interconnected to the New York power system. The 5 areas are shown in Fig. 2. The power transfers from area 2 to three other areas (areas 1, 3 and 5). Also the power transfers from area 5 to 4 and 4 to 3.

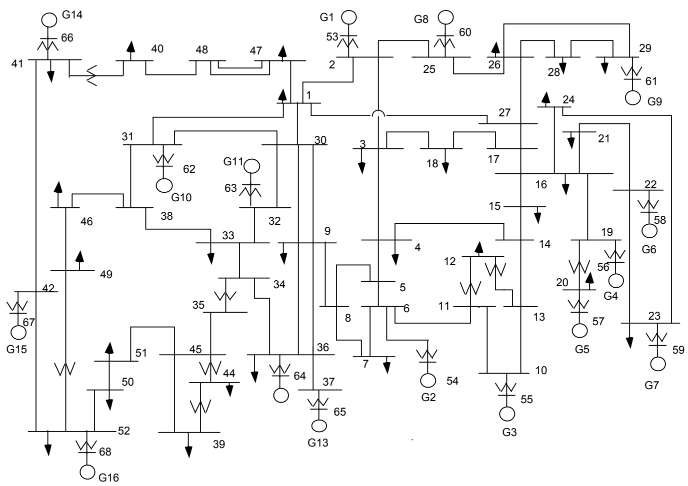

Fig. 1. Single line diagram of a 5-area study system.

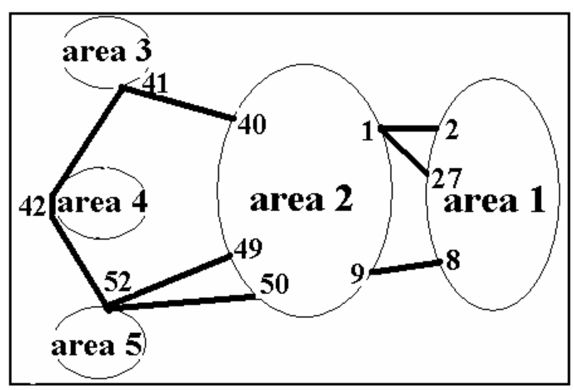

Fig. 2. 5-area of study system.

In the PSO algorithm, n particles for a population are generated randomly where n is selected to be 30. The goal of the optimization is to find the best location of TCSC and SVC, where the optimization is made on two parameters: their location and size. Therefore each particle is a d -dimensional vector in which $d = 2$. The initialization is made on the position randomly for each particle. The number of iteration is considered to be 100, which is the stopping criteria. The parameter in (10) must be tuned. These parameters control the impact of the previous velocities on the current velocity where, in this paper, $c_1 = c_2 = 2.05$ and the weight w is decreasing linearly from 0.95 to 0.2. Also $s_c = f_c$ are equal to 5.

Both versions of PSO find line 52-42 for TCSC placement that its value is a capacitance of $-0.5X_L$,where X_L is the reactance of the line. GCPSO finds bus 40 for SVC with the level of compensation equal to 136.17 MVAr. PSO converge on bus 47 with the level of compensation equal to 213.68 MVAr . To have a better clarity, the convergence characteristics in finding the solutions are given in Figs. 3-6. These figures show that GCPSO has a better feature to find optimal solution.

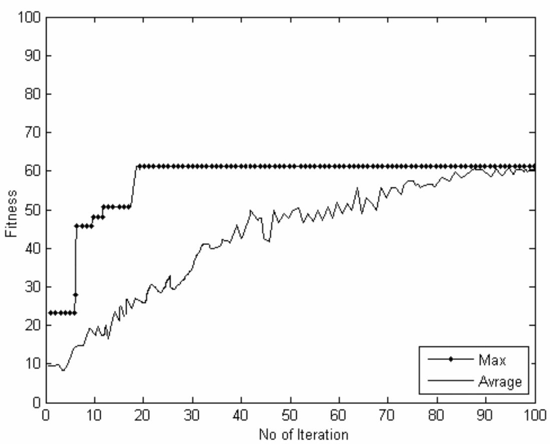

Fig. 3. Convergence characteristics of GCPSO in finding the placement of TCSC.

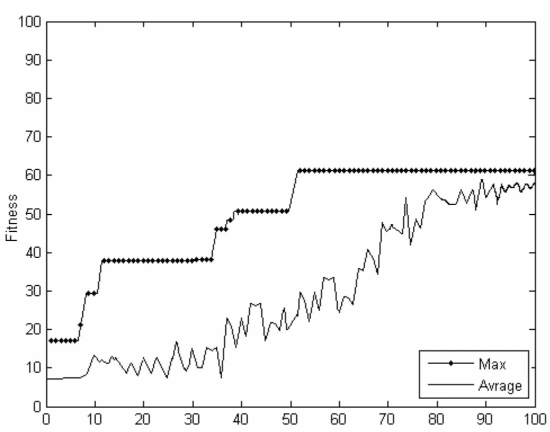

Fig. 4. Convergence characteristics of PSO in finding the placement of TCSC.

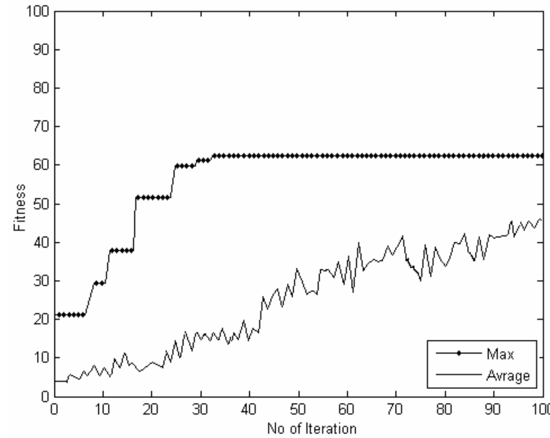

Fig. 5. Convergence characteristics of GCPSO in finding the placement of SVC.

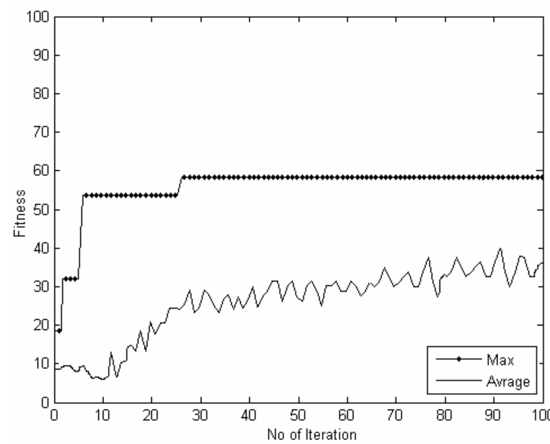

Fig. 6. Convergence characteristics of PSO in finding the placement of SVC.

To validate the results obtained by PSO and GCPSO, GA is applied to solve the problem. Since optimizations are made on two parameters of TCSC and SVC: their location and size, therefore, a configuration is considered with two genes for each. The first gene is related to the location of TCSC or SVC. The second gene is related to the size of them. For each gene 10 bits are considered, and thus the length of the chromosome is 20 bits. The number of chromosomes for a population is set to be 30. In this paper, one point crossover is applied with the crossover probability $p_c = 0.9$ and the mutation probability is selected to be changed linearly from

$p_m = 0.05$ to $p_m = 0.005$. Also, a weighted roulette wheel is used. As in the PSO, the number of iteration is considered to be 100.

GA finds the solution for TCSC and SVC placement as GCPSO. The convergence characteristic of GA to find the solution is shown in Figs. 7-8. These figures show that GA performs similar to GCPSO. In the other word, comparing Figs. 5, 6 and 8 show that PSO converge at the early stage (as explained in Subsection 3.1) and found bus 47 for SVC placement but the curves showing average of fitness in Figs. 5 and 8, illustrate that the algorithms are converging to optimal solution in finding bus 40.

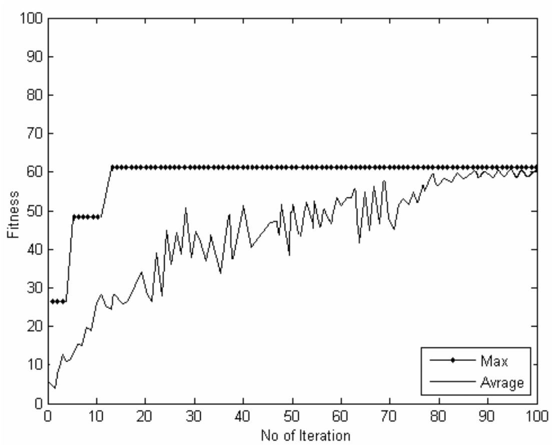

Fig. 7. Convergence characteristics of GA in finding the placement of TCSC.

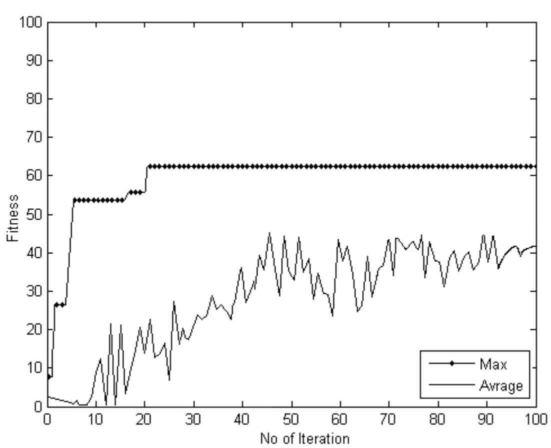

Fig. 8. Convergence characteristics of GA in finding the placement of SVC.

The effects of TCSC and SVC on TTC are given in Tables 1 and 2. These tables show that the TTC has been improved perfectly. For TTC calculation, the system is facing with some limitations that prevent increasing TTC. The limiting conditions of TTC in different areas are listed in Table 3. When the system is stressed, one of the limiting conditions is the voltage stability, where some buses driving the system to the point of collapse.

Table 1. The effects of SVC on TTC

TTC	Without Compensation	With SVC On Bus 40	Percent of increasing TTC with SVC
Area1	30.45%	30.45%	0%
Area3	46.69%	61.35%	14.67%
Area4	34.95%	44.95%	9.99%
Area5	57.85%	57.85%	0%
Total	169.94%	194.6%	24.66%

Table 2. The effects of TCSC on TTC

TTC	Without Compensation	With TCSC On $\text{Line}_{52\text{-}42}$	Percent of increasing TTC with TCSC
Area1	30.45%	30.45%	0%
Area3	46.69%	60.44%	13.75%
Area4	34.95%	46.99%	12.04%
Area5	57.85%	57.85%	0%
Total	169.94%	195.73%	25.79%

Table 3. The Limit Condition of TTC

Limit Condition	Without Compensation	With SVC on bus 40	With TCSC on $\text{Line}_{52\text{-}42}$
In Area1	V_{40} ,V_{48}	$\text{Line}_{1\text{-}30}$	V_{40} ,V_{48}
In Area3	V_{40} ,V_{48}	$\text{Line}_{52\text{-}42}$	V_{40} ,V_{48}
In Area4	$\text{Line}_{52\text{-}42}$ P_{G68}	$\text{Line}_{52\text{-}42}$ P_{G68}	$\text{Line}_{52\text{-}42}$ P_{G68}
In Area5	V_{40} ,V_{48}	Q_{G65}	V_{40} ,V_{48}

5 Conclusion

In this paper, the PSO is applied to determine optimal allocation of TCSC and SVC to maximize TTC between different control areas. TTC is calculated based on voltage level limit, transmission

line thermal limit, generation limit and voltage stability limit. Two different versions of PSO are implemented. Also GA is implemented to verify the validity of the obtained results by PSO. GCPSO and GA algorithms find the same solution for TCSC and SVC placement. Due to having a complex space search, standard PSO fails to converge properly but GCPSO and GA quickly find the high-quality optimal solution with a high convergence rate.
In this paper the effects of SVC and TCSC on TTC improvement are studied separately. The results show that TTC is improved by placing TCSC more than SVC. The effects of the coordinated SVC and TCSC on TTC are the future work of the authors.

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