

## Soft Computing Technique Based Enhancement of Transmission System Loadability Incorporating Facts

T. Vara Prasad, E. Sujatha

Associate Professor Dept. of Electrical and Electronics Engineering, S.V.P.C.E.T., Puttur.  
PG Scholar Dept. of Electrical and Electronics Engineering, S.V.P.C.E.T., Puttur.

### **Abstract**

Due to the growth of electricity demands and transactions in power markets, existing power networks need to be enhanced in order to increase their loadability. The problem of determining the best locations for network reinforcement can be formulated as a mixed discrete-continuous nonlinear optimization problem (MDCP). The complexity of the problem makes extensive simulations necessary and the computational requirement is high. This paper compares the effectiveness of Evolutionary Programming (EP) and an ordinal optimization (OO) technique is proposed in this paper to solve the MDCP involving two types of flexible ac transmission systems (FACTS) devices, namely static var compensator (SVC) and thyristor controlled series compensator (TCSC), for system loadability enhancement. In this approach, crude models are proposed to cope with the complexity of the problem and speed up the simulations with high alignment confidence. The test and Validation of the proposed algorithm are conducted on IEEE 14-bus system and 22-bus Indian system. Simulation results shows that the proposed models permit the use of OO-based approach for finding good enough solutions with less computational efforts.

**Index Terms**—Flexible ac transmission systems (FACTS), network congestion, Ordinal Optimization, particle swarm optimization, tangent vector, transmission system loadability

### **I. Introduction**

Growing demand for electricity has led to heavy stress on power networks. System maximum loadability can be simulated by increasing the system load until the network or equipment constraints, such as thermal, stability, and voltage security limits, are reached.

Traditionally, new substations and transmission lines are planned and constructed to handle the load growth and relieve network congestion. In some circumstances, due to the difficulty in obtaining right-of-way and the environment issue, some parts of the network have to be reinforced by using temporary measures or advanced technology in order to satisfy the changing requirements. Flexible ac transmission systems (FACTS) devices have been widely utilized to enhance system stability and loadability. They are used for both steady state power flow and dynamic stability controls to exploit the maximum capacity of a transmission network. Thyristor controlled series compensator (TCSC), static var compensator (SVC), and unified power flow controller (UPFC) can be used to balance the transmission line flows and system voltage, resulting in lower system losses and higher loadability. Effective methods for locating these equipments become essential in order to meet the transmission service requests in a competitive power market [1].

Aiming at various objectives, different methods have been proposed to determine optimal locations

and controls of FACTS devices. Continuation Power Flow (CPF) method was used in [2] and [3] to derive the control schemes of FACTS devices to improve system security and system loadability. Tangent vectors- based loss sensitivity analysis was used in [4] to determine which buses should be compensated under a competitive environment. With installed TCSC and UPFC and based on specific generation patterns, a sensitivity-based repetitive linear iterative approach (SRLIA) optimization algorithm was adopted to improve control performance and enhance real-time loadability [5], [6]. A novel method was proposed in [7] to determine the locations, size, and control modes for SVC and TCSC to achieve a bifurcation point-based maximum loadability. When the network voltage magnitude is poor and indicates possible voltage collapse, it was shown that the eigen-vector analysis can be used to point out suitable locations for reactive power compensations.

Two types of FACTS devices, i.e., SVC and TCSC, are considered in this paper for system loadability enhancement. To determine suitable locations for FACTS device installation and their control settings, the problem is formulated as an MDCP [16]–[19]. The computational requirement for this problem is high due to a large size of search space for a practical system. A two-step approach was used by the authors in [20] to solve the problem. The locations suitable for SVC and TCSC installations are first determined by using analytical

approaches, such as eigen-vector, tangent vector, and real power flow performance index (PI) sensitivity factor.

Then, OPF techniques are used to determine the best controls of the installed SVC and TCSC and other controllable devices to achieve maximum system loadability.

In general, computational effort increases in an optimization problem as the size of the problem becomes larger. Ordinal optimization(OO) algorithm was proposed aiming to speed up computation of complicated optimization problems while maintaining solution accuracy. It is one of the probabilistic optimization methods that focus on good enough solutions rather than the best. OO relaxes the cost function calculation such that computational effort is reduced. This is referred to as goal softening[21]. OO technique was used to determine a good enough solution in optimal system operations problems that involve discrete control variables such as switching shunt capacitor banks and transformer taps [16]. It is also an approach suitable for solving the simulation-based multiyear transmission expansion planning problem. Crude models and rough estimates are used to derive a small set of plans for which simulations are necessary and worthwhile to find good enough solutions [17]. An OO-based approach is adopted in this paper to search for good enough solutions for system loadability enhancement with an acceptable alignment probability. Instead of searching the best for sure, the proposed method aims to reduce the number of search samples in the solution space formed by all discrete variables, and seek candidates of good enough solutions in the set of, say top 1%–5%, best solutions for the original problem. A general IEEE-14 bus system is used to illustrate the effectiveness of the proposed method.

## II. PROBLEM FORMULATION

An SVC can be installed at a bus to provide reactive power and control local bus voltage, while a TCSC can be used to control the line flows by regulating the branch reactance. Let  $x_{ij,c}$  be a regulated reactance of the TCSC installed on transmission line  $i-j$  and the range is assumed to be  $-0.8x_{ij} \leq x_{ij,c} \leq 0.2x_{ij}$  where  $x_{ij}$  is the reactance of line  $i-j$ . Real and reactive power flows of a compensated line  $i-j$  can be expressed as

$$P_{ij,c} = v_i^2 g'_{ij} - v_i v_j (g'_{ij} \cos \theta_{ij} + b'_{ij} \sin \theta_{ij}) \quad (1)$$

$$Q_{ij,c} = -v_i^2 (b'_{ij} + b_{sh}) - v_i v_j (g'_{ij} \sin \theta_{ij} - b'_{ij} \cos \theta_{ij}) \quad (2)$$

Where  $g'_{ij} = (r_{ij}) / (r^2_{ij} + (x_{ij} + x_{ij,c})^2)$  and  $b'_{ij} = -(x_{ij} - x_{ij,c}) / (r^2_{ij} + (x_{ij} + x_{ij,c})^2)$  are the conductance and susceptance with a TCSC on the line  $i-j$ ;  $\theta_{ij}$  is the phase angle difference between buses  $i$  and  $j$ .

Let  $Q_{ci}$  be a regulated reactive power supplied by an SVC installed at bus  $i$  with a range of  $-Q_c \leq Q_{ci} \leq Q_c$ . In addition, let  $\lambda \geq 0$  be the factor of uniform

increase of system bus load, and then, the real and reactive power balance equations at bus  $i$  can be expressed as,

$$\sum P_{ij,c} - P_{Gi} - P_{Dio} + (1 + \lambda) P_{Dio} = 0 \quad (3)$$

$$\sum Q_{ij,c} - Q_{Gi} - Q_{ci} + (1 + \lambda) Q_{Dio} = 0 \quad (4)$$

Where  $-P_{Gi} + P_{Dio}$  and  $-Q_{Gi} + Q_{Dio}$  are the real and reactive power injections of generator and load at bus  $i$  under base case condition ( $\lambda = 0$ ). Depending on the dispatch generation policy  $P_{Gi}$  and  $Q_{Gi}$  are the real and reactive power generation deviations at bus  $i$  when system load is changed. System operation constraints are expressed as

$$-h \leq h(x, v) \leq h \quad (5)$$

Equation (5) includes bus voltage limits,  $-v_i \leq v_i \leq v_i$ , and generator output limits,  $0 \leq P_{Gi} + P_{Gi} \leq P_{Gi}$  and

$Q_{Gi} \leq Q_{Gi} + Q_{Gi} \leq Q_{Gi}$ , line thermal ratings,  $|S_{ij}| = \sqrt{(P^2_{ij,c} + Q^2_{ij,c})} \leq S_{ij}$ , and the SVC and TCSC operation limits.

The MDCP for determining the locations and control settings of SVC and TCSC for system loadability enhancement is formulated as follows: Max  $\lambda$

$$\begin{aligned} \text{s.t. } & g(x, v) = 0 - h \\ & \leq h(x, v) \leq h \\ & -v_i \leq v_i \leq v_i \end{aligned} \quad (6)$$

Where  $g(x, v) = 0$  represents (3) & (4). After solving the problem, the maximum additional loading of the system,  $\lambda^* \sum P_{Dio}$ , can be obtained.

## III. OO-Based System Loadability Enhancement Study

OO-based method is proposed to solve problem (6) to reduce the computational burden. A summary of the search procedures for obtaining a good enough solution with high probability can be described in the following: 1) using either a uniform selection or a heuristic method to select a representative set (N) for the search space; 2) using an easily computed crude model to roughly evaluate and order the performance of each sample in N and collect the top  $s$  samples to form a selected subset (S), which is the estimated good enough subset. The OO theory would guarantee that S consists of actual good enough solutions with high probability; 3) evaluating the objective value for each sample in S to obtain the good enough solution.

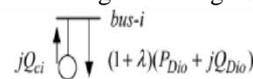


Fig. 1. Bus with an SVC installation.

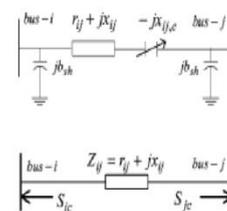


Fig. 2. Equivalent injection model of TCSC.

### A. EFFECTS OF SVC AND TCSC ON SYSTEM STATE AND BRANCH POWER FLOWS

Tangent vector concept used in [4] and [26] is adopted to depict the effects of FACTS devices to the system state. Fig. 1 shows the equivalent injection for a bus with an SVC installation. Including the SVC in the tangent vector of a power flow formulation, we have the following linearized equation:

$$J^{-1} \cdot \begin{bmatrix} PG \\ -\lambda PD_o \\ -\lambda QD_o \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ Q_c \end{bmatrix} = \begin{bmatrix} \Delta\theta G \\ \Delta\theta D \\ \Delta V D \end{bmatrix} + \begin{bmatrix} \Delta\theta' G \\ \Delta\theta' D \\ \Delta V' D \end{bmatrix} \quad (7)$$

Where **J** is the Jacobian matrix under the considered system state for system loadability enhancement vector  $Q_c$  includes the reactive power injected from the installed SVC.

Let  $PG = PG$ , where  $PG$  is a vector including real power generation deviations associated with a  $\lambda$ . For a

scenario with bus injection deviations, (7) can be reformulated as;

$$J^{-1} = J^{-1} \cdot \lambda \Delta \begin{bmatrix} \Delta\theta G \\ \Delta\theta D \\ \Delta V D \end{bmatrix} + \lambda \begin{bmatrix} PG \\ -\lambda PD_o \\ -\lambda QD_o \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} \Delta\theta' G \\ \Delta\theta' D \\ \Delta V' D \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ Q_c \end{bmatrix}$$

The sensitivities of bus phase angles and voltage magnitudes with respect to  $\lambda$  can be obtained from (8):  $d/d\lambda$  and  $d/d\lambda$  (10) and from the equation (2.14) PQ bus voltage magnitudes after the addition of the installed SVC can be expressed as,

$$V'D = V'D + V'D \quad (11)$$

Fig. 2 shows an equivalent injection model for a branch with a TCSC. Equivalent real power injections at terminal buses representing TCSC effects on the system are [22].

$$P_{ic} = V_i^2 g_{ij} - V_i V_j (g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij})$$

$$P_{jc} = V_j^2 g_{ij} - V_i V_j (g_{ij} \cos\theta_{ij} - b_{ij} \sin\theta_{ij})$$

Where,

$$g_{ij} = (x_{ij,c} r_{ij} (x_{ij,c}^2 - 2x_{ij})) / (x_{ij}^2 + r_{ij}^2) [r_{ij}^2 + (x_{ij} - x_{ij,c})^2]$$

$$b_{ij} = -x_{ij,c} (r_{ij}^2 - x_{ij}^2 + x_{ij,c} x_{ij}) / (x_{ij}^2 + r_{ij}^2) [r_{ij}^2 + (x_{ij} - x_{ij,c})^2]$$

(13)

### B. OO- BASED SOLUTION PROCEDURE

The proposed OO solution procedure is shown in Fig. 3. It consists of two stages. First, a large set of candidate solutions are selected randomly, each with different sites for FACTS device installations, and then crude models described above and a GCP SO method are used to quickly determine a subset of

most promising solutions from the candidate solutions. Exact models are then used in the second stage to obtain a good enough solution from the subset.

#### Stage One:

Each candidate has  $n_v$  buses and  $n_s$  transmission lines chosen for SVC and TCSC installations, respectively. With the adjustments of controllable devices in the existing network neglected, for each candidate, the following formulation is used to determine the generation outputs and control settings of SVC and TCSC, and compute  $\lambda$ .

$$\text{Max } \lambda = \text{Min } [1/fV, 1/fS, 1/fG]$$

s.t.  $-Q_c \leq Q_{ci} \leq Q_c$  for all installed SVC  $-0.8X_i \leq X_{ij,c} \leq 0.2X_{ij}$

for all installed TCSC  $-\alpha P_{G_{io}} \leq P_{G_i} \leq \beta P_{G_{io}}$  for all the generators (14)

Once the solution for each candidate is obtained, all candidates are ranked according to the value of  $\lambda^*$  in ascending order. And then, the ranking distribution is compared with the standard ordered performance curve (OPC) described in [17] and [18].

The shape of the OPC determines the nature of the underlying optimization problem. OPC is used to exhibit the performance (fitness) distribution of candidate solutions. Then the GCP SO is performed for the selected subset  $S(\Theta)$  to determine the best solution.

OPC is used to exhibit the performance (fitness) distribution of candidate solutions. In [17], five broad categories of OPC models are described: they are 1) lots of good samples; 2) lots of intermediate but few good and bad samples; 3) equally distributed good, bad, and intermediate samples; 4) lots of good and lots of bad samples but few intermediate ones; and 5) lots of bad samples. A graphical expression for these five OPC models is shown in the Appendix. A formula was derived in [18] to relate the size of the selected subset ( $S$ ) to 1) the shape of the OPC; 2) the size of good enough subset  $G$ ; 3) the alignment level; 4) the alignment probability; and 5) the error bound between the performance value for the crude model and the exact model.

Randomly select 1000 candidate solutions respectively with $nv$ busses for SVC and $ns$ branches for TCSC installation. The proposed crude model in (B) is then used to evaluate a rough solution for the settings of installed SVC and TCSC for each candidate. Finally, the 1000 candidates are ranked in ascending order according to their rough solutions.
Randomly select 1000 candidate solutions respectively with $nv$ busses for SVC and $ns$ branches for TCSC installation. The proposed crude model in (B) is then used to evaluate a rough solution for the settings of installed SVC and TCSC for each candidate. Finally, the 1000 candidates are ranked in ascending order according to their rough solutions.
Compared to the ordered performance curves (OPCs), determine the size of the selected subset(S) from the 1000 ordered solutions.
For each candidate in S, solve the detailed model in (A) for an exact solution. The good enough solution with 5% best of the whole solution space can then be determined as the solution with the biggest system loadability in S.

Fig.3. OO-based solution algorithm.

**Stage Two:**The selected candidates in S with tentative generation outputs and SVC and TCSC capacity settings at specific installation locations obtained at the first stage is used as the starting point for next stage that uses exact model to determine refined generation outputs PG and capacity settings QC ,for SVC and XC for TCSC at the installation sites. To proceed, in the first few iterations of PSO, 30 particles are initialized randomly with smaller searching ranges around the tentative capacity settings and a load flow computation is executed for each particle. After one load flow solution is obtained in the 30 particles, the constraints are restored to actual bounds to search for the best settings of SVC and TCSC capacities in each candidate.

The steps of the GCPSO algorithm used in this study for evaluating the selected candidates are as follows.

1. Set the GCPSO iteration number.
2. Narrow down the control variable adjustment ranges and generate a swarm with 30(for e.g.)number of iterations.
3. A load flow computation is conducted for each particle with  $Xi(k) = [PG \ QC \ XC]^T$ . If no load flow solution exists in 30 particles, return to step 2. Otherwise set  $p_{best}$  and  $fitness$  for each particle. For a particle with a converged load flow solution,  $fitness = \lambda/(1+pene\_v)$ , and the particles with out a load flow solution  $fitness = 10$ , where  $pene\_vis$  a penalty that is

proportional to the severity and the security constraint violation and  $\lambda$  is the current loading factor. Set  $iter\_num=0$  and go to step 4.

4.  $Iter\_num = iter\_num + 1, g_{best} =$  the  $p_{best}$  of the particle with the maximum fitness. Restore the adjustment variable range to the original problem.
5. Execute load flow for each particle and check the security constraints. Update particle fitness ( $fitness = \lambda/(1+pene\_v)$ ). If the  $iter\_num$  is lower than the maximum iteration number specified, go to step 4 otherwise go to step 6.
6. Record SVC and TCSC record settings, generation outputs, and the loading factor obtained for the selected candidate.

### C. Guaranteed Convergence PSO

The GCPSO was introduced by Van den Bergh to address the issue of premature convergence to solutions that are not guaranteed to be local extrema. A GCPSO algorithm is used to solve the problems in (6) and in (14). In PSO algorithm the position and the velocity of the particle is updated as given below,

$$Xi(k+1) = Xi(k) + Vi(k+1) \quad (15)$$

$$Vi,j(k+1) = wVi,j(k) + c_1r_{1,j}(p_{best,i,j} - Xi,j(k)) + c_2r_{2,j}(g_{best,i,j} - Xi,j(k)) \quad (16)$$

Where  $Xi(k)$  is the position of the particle and  $Vi,(k)$  is the velocity of the particle.

In the early stages of PSO algorithm the stagnation phenomenon is addressed, to avoid the stagnation the velocity of the particle is updated shown below,

$$Vi,j(k+1) = wVi,j(k) - Xi,j(k) + p_{best,i,j} + \rho(k)r_j \quad (17)$$

Where  $r_j$  is the random number sampled from  $U(-1,1)$  and  $\rho(k)$  is the scaling factor determined by,  $\rho(0) = 1.0$

$$\text{and } \rho(k+1) = \begin{cases} 2\rho(k) & \text{if } \#success > sc \\ 0.5\rho(k) & \text{if } \#failure > fc \\ \rho(k) & \text{otherwise} \end{cases} \quad (18)$$

where  $f_c, s_c$  are the threshold values. In this study, in each GCPSO iteration if there is an overall improvement of fitness that is due to the same particle as in the previous iteration, the  $\#success$  index is increased and  $\#failure$  is set to 0. If there is no fitness improvement for  $k$  iterations, then  $\#failure = k$  and  $\#success$  is set to 0. The scaling factor of the particle velocity in (17) is updated according to (18) when  $\#success$  or  $\#failure$  is greater than a specified number. On the other hand, if the improvement of fitness is obtained from different particles, both  $\#success$  and  $\#failure$  are set to 0, and the scaling factor remains the same.

### D. Differential Evolution

In this paper Differential Evolution approach is applied for Transmission loadability and compared Result with OO optimization. The procedure for DE Evolution approach as follows.

Differential Evolution Algorithm is a new floating point encoded evolutionary algorithm developed by Storn and Price in 1996 for global optimization. It is a population based approach having crossover, mutation and selection. In this algorithm it is having a special differential operator used to create anew offspring from parent chromosomes instead of classical crossover. The convergence speed of DE[15] is far better than that of GeneticAlgorithm .The main advantage of DE can able to give the same results consistently for many trials. Due to this best performance DE has been successfully applied in many artificial and real time optimization problems. The operators used in this technique are as follows.

**A.Initialization**

For initialization define the lower and upper boundary limits for each parameter. Initialize the independent variables randomly within their feasible numerical range between 0 and 1. If a variable is discrete or i

**B.Mutation**

Mutation is the process of introducing new parameters into the population. The mutation operation of DE applies the vector differentials between the existing population members for determining both the degree and direction of perturbation applied to the individual subject of the mutation operation. The mutation process at each generation begins by randomly selecting three individuals in the population.

**C.Crossover**

Once the mutation process completed, the crossover process is activated. The perturbed individual vector and the current population member are subjected to crossover operation that finally generates the population of candidates or trial vectors. The trial vector is the combination of mutant vector and target vector.

**D.Selection**

After the mutation and crossover operations, the trial vector and target vector will approach to fitness functions to determine the one to be reserved for the next generation. Compare the fitness of the trial vector and the fitness of the corresponding target vector, and select the one which is having minimum value.

**E. General procedure of Differential Evolution algorithm**

- Step 1 : Initialize vectors in a population.
  - Step 2 : Evaluate the fitness function after Newton Raphson power flow for each vector.
  - Step 3 : Choose a target vector in the population.
  - Step 4 : Calculate the trial vector for the selected target vector using mutation and crossover.
  - Step 5 : Compare the fitness of the target vector and the trial vector.
  - Step 6 : Select the best fitness vector among them.
  - Step 7 : Repeat step 3 to step 5 till the stopping criteria. The stopping criterion is number of iterations.
- integral even then it should be initialized as real value.

**IV. Test System And Results**

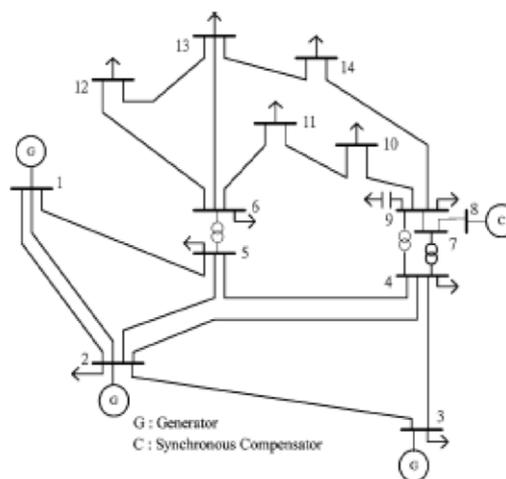


Fig.4 IEEE-14 test bus system

Table I  
 Line flow and Losses using Conventional Method

Frm bus	To bus	PMW	QMvar	From bus	To bus	PMW	QMvar	Line loss	
								MW	Mvar

1	2	157.5	52.41	2	1	-152	-37.8	4.754	14.51
1	5	76.22	22.87	5	1	-73.1	-10.3	3.045	12.57
2	3	73.30	5.655	3	2	-70.7	4.937	2.515	10.59
2	4	55.99	-0.27	4	2	-54.1	5.743	1.804	5.473
2	5	41.78	-0.19	5	2	-40.8	3.200	0.985	3.006
3	4	-23.4	5.186	4	3	23.82	-4.14	0.410	1.045
4	5	-60.3	5.418	5	4	60.83	-3.80	0.512	1.615
4	7	27.32	-14.9	7	4	-27.3	17.02	0.000	2.073
4	9	15.57	-2.13	9	4	-15.5	3.526	0.000	1.392
5	6	45.54	-16.7	6	5	-45.5	22.43	0.000	5.706
6	11	8.802	8.007	11	6	-7.96	-7.76	0.116	0.243
6	12	8.021	3.078	12	6	-7.93	-2.90	0.086	0.178
6	13	18.23	90.55	13	6	-17.9	-9.03	0.264	0.520
7	8	0.000	-22.4	8	7	0.000	23.28	0.000	0.867
7	9	27.32	16.39	9	7	-27.3	-15.3	0.000	1.093
9	10	4.585	-0.04	10	9	-4.57	0.060	0.007	0.018
9	14	8.806	0.895	14	9	-8.70	-0.68	0.101	0.215
10	11	-4.42	-5.86	11	10	4.467	5.965	0.045	0.105
12	13	1.835	1.300	13	12	-1.82	-1.29	0.011	0.010
13	14	6.296	4.526	14	13	-6.19	-4.32	0.101	0.207
Total								14.75	61.44
losses									

The above shown table indicates that the power losses of a test system using the conventional method and is compared with the proposed method which is the OO method. The Newton Raphson load flow analysis and the line flow and losses for the proposed method is given below,

Table II

Newton Raphson Load flow Analysis

Bus No:	V (pu)	Angle Degree)	Generation MW MVar		Load MW MVar	
			MW	MVar	MW	MVar
1	1.0600	0.0000	57.450	2.721	0.0000	0.000
2	1.0450	-1.2287	40.000	-19.789	21.700	12.700
3	1.0100	-6.4205	0.000	4.478	94.200	19.000
4	1.0552	-2.5545	82.737	24.055	47.800	-3.900
5	1.0628	-1.6074	82.737	51.632	7.600	1.600
6	1.0700	-6.7127	0.000	-5.182	11.200	7.500
7	1.0690	-5.5356	0.000	0.000	0.000	0.000
8	1.0900	-5.5356	0.000	13.023	0.000	0.000
9	1.0517	-7.1439	-0.000	0.000	29.500	16.600
10	1.0476	-7.3522	0.000	0.000	9.000	5.800
11	1.0552	-7.1598	0.000	0.000	3.500	1.800
12	1.0548	-7.4407	0.000	0.000	6.100	1.600
13	1.0498	-7.0671	0.000	0.000	13.500	5.800
14	1.0329	-8.3501	0.000	0.000	14.900	5.000
Total			262.923	70.938	259.000	73.500

Table III  
 Line Flow and Losses using Ordinal Optimization Method

From bus to bus	P(MW)	Q(MVar)	From bus to bus	P(MW)	Q(MVar)	Line loss MW MVar
1 2	44.330	12.783	2 1	-43.963	-11.662	0.734 1.121
1 5	13.120	-4.331	5 1	-13.028	4.710	0.184 0.379
2 3	50.314	8.720	3 2	-49.192	-3.993	2.244 4.727
2 4	11.034	-9.606	4 2	-11.187	9.961	0.234 0.355
2 5	0.645	-10.921	5 2	-0.583	11.112	0.125 0.191
3 4	-45.008	-7.642	4 3	46.378	11.137	2.738 3.494
4 5	-45.413	-4.383	5 4	45.662	5.171	0.499 0.787
4 7	28.682	-6.348	7 4	-28.682	7.933	0.000 1.585
4 9	16.477	1.338	9 4	-16.477	-0.016	0.000 1.323
5 6	46.085	-1.317	6 5	-43.085	5.181	0.000 3.863
6 11	6.709	4.775	11 6	-6.653	-4.657	0.113 0.118
6 12	7.737	2.673	12 6	-7.665	-2.523	0.144 0.150
6 13	17.439	7.835	13 6	-17.227	-7.419	0.442 0.416
7 8	0.000	-12.117	8 7	0.000	13.023	0.000 0.251
7 9	28.682	17.129	9 7	-28.682	-16.055	0.000 1.075
9 10	5.873	3.008	10 9	-5.860	-2.874	0.025 0 .033
9 14	9.786	2.826	14 9	-9.667	-2.572	0.238 0.254
10 11	-3.140	-2.826	11 10	3.153	2.857	0.027 0.031
12 13	1.565	0.923	13 12	-1.559	-0.917	0.013 0 .006
13 14	5.286	2.537	14 13	-5.223	-2.428	0.107 0.109
Total Loss						7.847
20.26						

Best Connected Bus is: 4 5  
 DE Algorithm Loss: 14.7546  
 Ordinal Optimization Loss : 7.8469

From the above results it is clear that the losses had been reduced to half of the total losses using the Ordinal Optimization method when compared to the Conventional method (Normal losses). Therefore, the transmission system loadability is increased or enhanced by reducing the losses using Ordinal Optimization method which is the combination of Particle Swarm Optimization (PSO) method and Guaranteed Convergence Particle Swarm Optimization (GCP SO) method for the IEEE 14 bus test system.

Some of the performance characteristics for each iteration is given below. The performance characteristics of Iteration to power losses, SVC (Qci) and TCSC (Xij) are shown below,

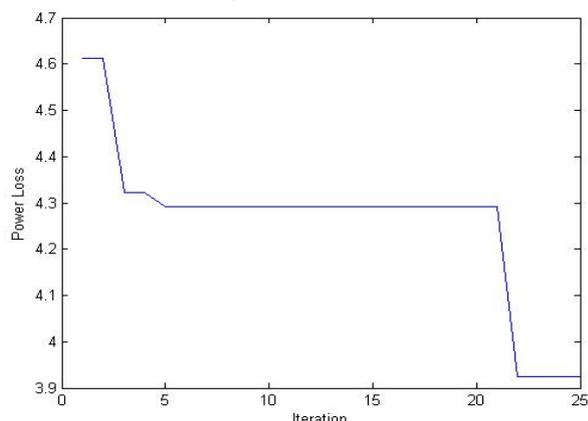


Fig.5 Performance characteristics of iteration and power loss.

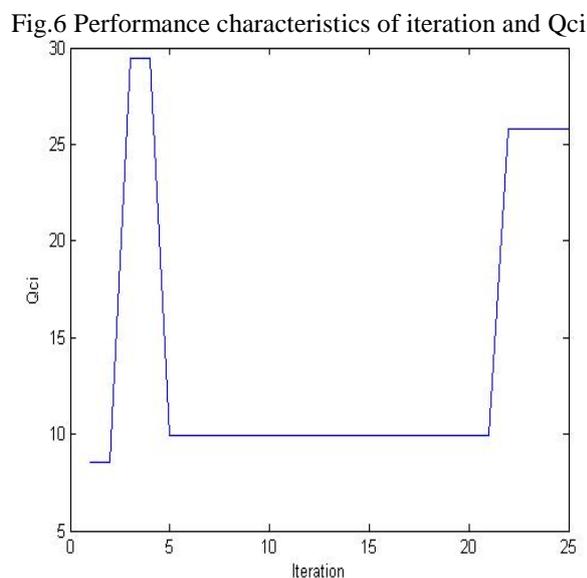


Fig.6 Performance characteristics of iteration and Qci

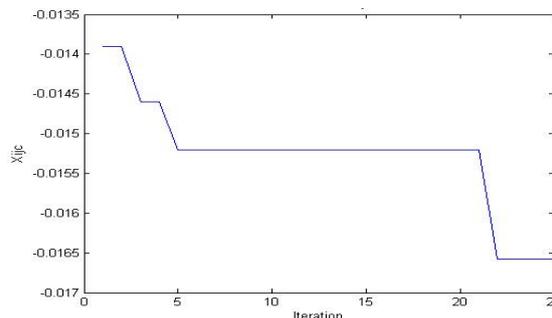


Fig.7 Performance characteristics of iteration and Xij,c

<b>22 bus</b>
Best Connected Bus is :4 6
DE Alogorithm Loss : 539.0466
Ordinal Optimization Loss : 511.4815
<b>30 bus</b>
Best Connected Bus is :29 68
ordinal optimization Loss : 119.9716
DE Algorithm Loss : 215.6633

## V. CONCLUSION

In this paper, the problem of choosing suitable locations and control settings of SVC and TCSC to enhance the system loadability is formulated as an MDCP. To relieve computational burden, a new OO-based loadability study method is proposed to obtain good enough solutions with an acceptable alignment probability. Using appropriate crude models, the number of search samples in the solution space formed by all variables can be reduced to a much smaller set of candidates such that good enough solutions can be ascertained in a short time. Numerical example results from two test systems have confirmed that the proposed crude models could provide reasonably accurate results and permit the use of OO-based approach to accelerate system loadability enhancement study.

From the results it is clear that the losses were reduced to half of the total losses using the Ordinal Optimization method when compared to the DE algorithm losses. Therefore, the transmission system loadability is increased or enhanced by reducing the losses using Ordinal Optimization method which is the combination of Particle Swarm Optimization (PSO) method and Guaranteed Convergence Particle Swarm Optimization (GCP SO) method for the IEEE 14 bus test system, IEEE 30 Bus system and Southern transmission 22 bus system.

## References

- [1] M. Santiago-Luna and J. R. Cedeno-Maldonado, "Optimal placement of FACTS controllers in power systems via evolution strategies," in *Proc. IEEE/PES Transmission and Distribution Conf. Expo.: Latin America (TDC'06)*, Aug. 15–18, 2006, pp. 1–6.
- [2] R. Rajaraman et al., "Determination of location and amount of series compensation to increase power transfer capability," *IEEE Trans Power Syst.*, vol. 13, no. 2, pp. 294–299, May 1998.
- [3] A. R. Messina, M. A. Per`ez, and E. Hernan`dez, "Coordinated application of FACTS devices to enhance steady-state voltage stability," *Int. J. Elect. Power Energy Syst.*, vol. 19, no. 2, pp. 259–267, 2003.
- [4] A. C. Z. de Souza, L. M. Hon`orio, G. L. Torres, and G. Lambert-Torres, "Increasing the loadability of power systems through optimal-localcontrol actions," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 188–204, Feb. 2004.
- [5] G. Li, M. Zhou, and Y. Gao, "Determination of total transfer capability incorporating FACTS devices in power markets," in *Proc. Int. Conf. Power Electronics and Drives Systems (PEDS)*, 2005, pp. 1327–1332.
- [6] K. Audomvongseeree and A. Yokoyama, "Consideration of an appropriate TTC by probabilistic approach," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 375–383, Feb. 2004.
- [7] A. Kazemi and B. Badrdeh, "Modeling and simulation of SVC and TCSC to study their limits on maximum loadability point," *Int. J. Elect Power Energy Syst.*, vol. 26, no. 5, pp. 381–388, Jun. 2004.
- [8] W. Shao and V. Vijay, "LP-based OPF for exact model FACTS control to relieve overloads and voltage violations," *IEEE Trans. Power Syst.*, vol. 21, no. 4, pp. 1832–1839, Nov. 2006.
- [9] A. Kumar, S. Chanana, and S. Parida, "Combined optimal location of FACTS controllers and loadability enhancement in competitive electric markets," in *Proc. IEEE PES Summer Meeting*, San Francisco, CA, Jun. 12–16, 2005.
- [10] H. Farahmand, M. Rashidi-Nejad, and M. Fotuhi-Firoozabad, "Implementation of FACTS devices for ATC enhancement using RPF technique," in *Proc. Large Engineering Systems Conf. Power Engineering*, Jul. 28–30, 2004, pp. 30–35.
- [11] T. T. Ma, "Enhancement of power transmission systems by using multiple UPFC on evolutionary programming," in *Proc. IEEE Bologna Power Tech Conf.*, Jun. 2003, vol. 4.
- [12] S. Gerbex, R. Cherkaoui, and A. J. Germond, "Optimal location of multi-type FACTS devices in a power system by means of genetic algorithm," *IEEE Trans. Power Syst.*, vol. 16, no. 3, pp. 537–544, Aug. 2001.
- [13] P. Bhasaputra and W. Ongsakul, "Optimal power flow with multi-type of FACTS devices by hybrid TS/SA approach," in *Proc. IEEE Int. Conf. Industrial Technology*, Dec. 2002, vol. 1, pp. 285–290.
- [14] M. Saravanan, S. M. R. Slochanal, P. Venkatesh, and J. P. S. Abraham, "Application of PSO technique for optimal location of FACTS devices considering system loadability and cost of installation," in *Proc. 7<sup>th</sup> Int. Power Engineering Conf (IPEC)*, Dec. 2005, vol. 2, pp. 716–721.
- [15] K. Y. Lee, M. Farsangi, and H. Nezamabadi-Pour, "Hybrid of analytical and heuristic techniques for FACTS devices in transmission systems," in *Proc. IEEE PES General Meeting*, Jun. 24–28, 2007, pp. 1–8.
- [16] S. Y. Lin, Y. C. Ho, and C. H. Lin, "An ordinal optimization theory based algorithm for solving the optimal power flow problem with discrete control variables," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 276–286, Feb. 2004.
- [17] M. Xie, J. Zhong, and F. F. Wu, "Multiyear transmission expansion planning using ordinal optimization," *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1420–1428, Nov. 2007.
- [18] T. W. E. Lau and Y. C. Ho, "Universal alignment probabilities and subset selection for ordinal optimization," *J. Optim. Theory Appl.*, vol. 93, no. 3, pp. 445–489, Jun. 1997.
- [19] *Power Syst.*, vol. 3, no. 2, pp. 676–682, May 1988.
- [20] Y. C. Chang and R. F. Chang, "Utilization performance based FACTS devices installation strategy for transmission loadability enhancement," in *Proc. 4th IEEE Conf. Industrial Electronics and Applications (ICIEA 2009)*, May 25– 27, 2009, pp. 2661–2666.
- [21] F. Li, "Application of ordinal optimization for distribution system reconfiguration," in *Proc. IEEE/PES Power Systems Conf. Expo.*, 2009.

- [22] S. N. Singh and A. K. David, "Congestion management by optimizing FACTS device location," in *Proc. Int. Conf. Electric Utility Deregulation and Restructuring and Power Technologies*, Apr. 4–7, 2000, pp. 23–28.
- [23] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation and Control*. New York: Wiley, 1996.
- [24] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proc.1995 IEEE Int. Conf. Neural Networks (ICNN'95)*, vol. IV, pp.1942–1948.
- [25] F. Van den Bergh and A. P. Engelbrecht, "A new locally convergentparticle swarm optimiser," in *Proc. IEEE Conf. Systems, Man and Cybernetics*, Hammamet, Tunisia, Oct. 2002, vol. 3, pp. 6–9.
- [26] A. C. Zambroni de Souza, C. A. Canizares, and V. H. Quintana, "Newtechniques to speed up voltage collapse computations using tangent vectors," *IEEE Trans. Power Syst.*, vol. 12, no. 3, pp. 1380–1387, Aug. 1997.