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Enhancement of Transmission System Loadability Using Ordinal Optimization Method

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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. 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. Test results based on a practical power system confirm 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, OrdinalOptimization, particle swarm optimization, tangent vector, transmission system loadability.

1. 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 xij,cbe a regulated reactance of the TCSC installed on transmission line i-j and the range is assumed to be $-0.8xij \leq xij,c \leq 0.2xij$ where xij is the reactance of line i-j. Real and reactive power flows of a compensated line i-j can be expressed as

$$Pij,c=vi^2g'ij-vivj(g'ijcos\theta ij+b'ijsin\theta ij) \quad (1)$$
$$Qij,c=-vi^2(b'ij+bsh)-vivj(g'ijsin\theta ij-b'ijcos\theta ij) \quad (2)$$

Where $g'ij=(rij)/(r^2ij+(xij+xij,c)^2$ and $b'ij=(-(xij-xij,c))/(r^2ij+(xij+xij,c)^2)$ are the conductance and susceptance with a TCSC on the line i-j;θij is the phase angle difference between buses i and j.

Let Qci be a regulated reactive power supplied by an SVC installed at bus i with a range of $-Qc \leq Qci \leq Qc$. 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,

$$\sum Pij,c-PGio-PGi+(1+\lambda)PDio =0 \quad (3)$$
$$\sum Qij,c -QGio -QGi -Qci+(1+ \lambda)QDio=0 \quad (4)$$

Where $-PGio+ PDio$ and $-QGio+QDio$ 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 PGi andQGi 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, $-vi\leq vi\leq -vi$, and generator output limits, $0\leq PGio+PGi\leq PGi$ and $-Qgi\leq QGio+QGi\leq QGi$, line thermal ratings,
$|Sij|= \sqrt{(P^2ij,c+Q^2ij,c)}\leq Sij$, 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:

$$\text{Max } \lambda$$
$$\text{s.t.} g(x,v)=0$$
$$-h \leq h(x,v) \leq h$$
$$-vi \leq vi \leq -vi \quad (6)$$

Where $g(x,v)=0$ represents (3)& (4).After solving the problem, the maximum additional loading of the system, $\lambda^*\sum PDio$, 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.

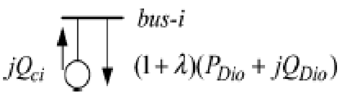

Fig. 1. Bus with an SVC installation.

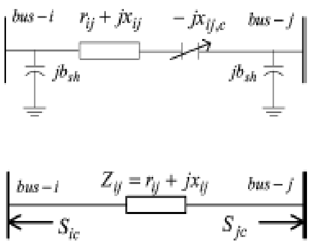

Fig. 2. Equivalent injection model of TCSC.

A. EFFECTS OF SVC AND TCSC ONSYSTEM 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:

$$\mathbf{J}^{-1}\cdot\left(\begin{bmatrix} PG \\ -\lambda PDo \\ -\lambda QDo \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ Qc \end{bmatrix}\right)=\begin{bmatrix} \Delta\theta G \\ \Delta\theta D \\ \Delta VD \end{bmatrix}+\begin{bmatrix} \Delta\theta' G \\ \Delta\theta' D \\ \Delta V' D \end{bmatrix} \quad (7)$$

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

Let $PG=\lambda\Delta\ PG$, where PG is a vector including real power generation deviations associated with a λ. For a scenario with bus injection deviations, (7) can be reformulated as;

$$\begin{bmatrix} \Delta\theta G \\ \Delta\theta D \\ \Delta VD \end{bmatrix}.1/\lambda= \mathbf{J}^{-1}.\begin{bmatrix} PG \\ -\lambda PDo \\ -\lambda QDo \end{bmatrix} \quad (8)$$

and

$$\begin{bmatrix} \Delta\theta' G \\ \Delta\theta' D \\ \Delta V' D \end{bmatrix}=\mathbf{J}^{-1}.\begin{bmatrix} 0 \\ 0 \\ Qc \end{bmatrix} \quad (9)$$

The sensitivities of bus phase angles and voltage magnitudes with respect to λcan be obtained from (8):

$$d\theta/d\lambda \approx \Delta\theta/\lambda \text{ and } dv/d\lambda \approx \Delta v/\lambda \quad (10)$$

and from the equation(2.14) PQ bus voltage magnitudes after the addition of the installed SVC can be expressed as,

$$V'D \approx V'D + \Delta V'D \quad (11)$$

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].

$$Pic \approx Vi^2\Delta gij - ViVj\ (\Delta gijcos\theta ij+\Delta bijsin\theta ij)$$

$$Pjc\approx Vj^2\Delta gij - ViVj\ (\Delta gijcos\theta ij - \Delta bijsin\theta ij) \quad (12)$$

Where,

$$\Delta gij=(xij,crij(x^2ij,c - 2xij))/(x_{ij}^2 + r_{ij}^2)[r_{ij}^2+(x_{ij}-x_{ij,c})^2]$$

$$\Delta bij=-x_{ij,c}(r_{ij}^2- x_{ij}^2+ x_{ij,c}xij)/(x_{ij}^2 + r_{ij}^2)[r_{ij}^2+(x_{ij}-x_{ij,c})^2] \quad (13)$$

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 GCPSO 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 *nv* buses and *ns* 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 λ.

Max λ = Min [$1/f_V$, $1/f_S$, $1/f_G$]
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*
$-\alpha P_{Gio} \leq P_{Gi} \leq \beta P_{Gio}$ 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 GCPSO 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.
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 on 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 = λ/(1+pene_v),*and the particles with out a load flow solution *fitness = 10*, where *pene_v*is a penalty that is proportional to the severity and the security constraint violation and *λ* 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 = λ/(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,

$Xi(k+1)=Xi(k+Vi(k+1)$ 15)
$(Vi,j(k+1)= wVi,j(k+1)+c_1r_1,j\ (p_{best}i,j - Xi,j(k)) + c_2r_{2,j}\ (g_{best}i,j - Xi,j(k))$ (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,
$Vi,j(k+1)=wVi,j(k)-Xi,j(k)+p_{besti,j}+\rho(k)r_j$ (17)
Where $r_j$is the random number sampled from U(-1,1) and $\rho(k)$ is the scaling factor determined by,
$\rho(0)=1.0$

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

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.

IV. Test System And Results

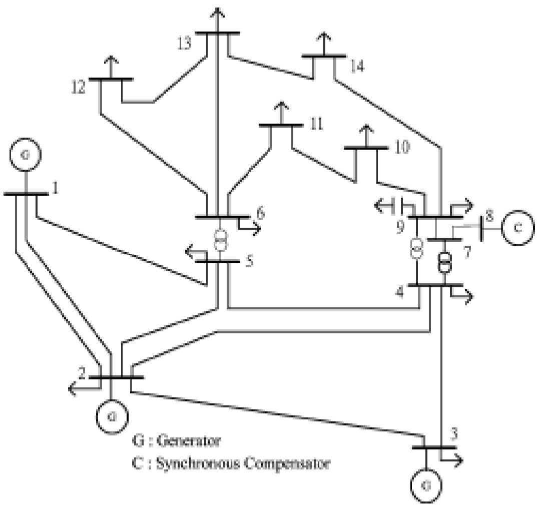

Fig.4 IEEE-14 test bus system

The results for the test system using the Conventional Method is given below,

Table I

Line flow and Losses using Conventional Method

Frm bus	To bus	PMW	QMvar	From bus	To bus	PMW	QMvar	Line loss MW	Line loss 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 losses	14.75	61.44

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	Generation MVar	Load MW	Load 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
Normal 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 (GCPSO) 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,

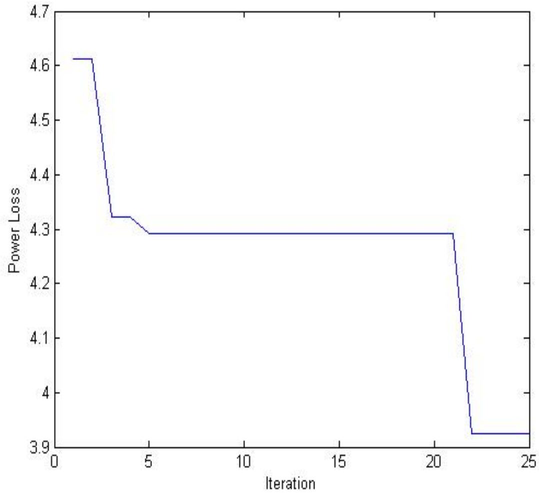

Fig.5 Performance characteristics of iteration and power loss.

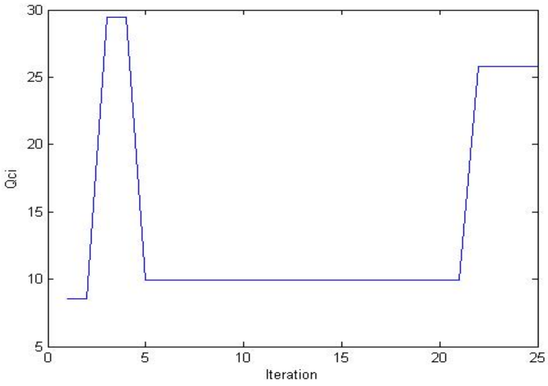

Fig.6 Performance characteristics of iteration and Qci

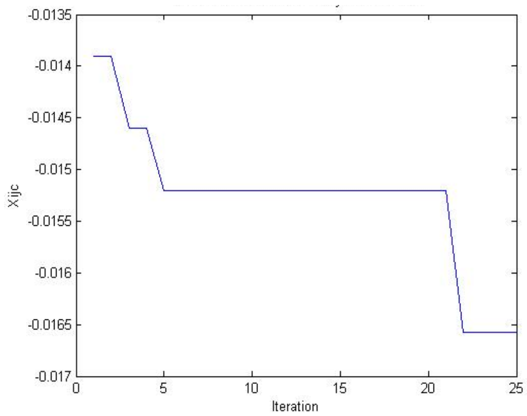

Fig.7 Performance characteristics of iteration and Xij,c

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.

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