Paper

A Study of Transient Stability Constrained Optimal Power Flow with Multi-Contingency

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Transient stability constrained optimal power flow (SCOPF) has been recognized as a potentially mighty tool for secure and optimal operation planning of power systems since its advent, especially in nowadays open transmission access environment. However, although a lot of works have been done regarding this attractive topic, no SCOPF with multi-contingency has been reported until now. In this paper, first, the necessity for multi-contingency SCOPF (MC-SCOPF) is illustrated based on the results of the IEEJ WEST10 model system. Then MC-SCOPF problem is formulated and a solution method is proposed. Computation results on the IEEJ WEST10 model system demonstrate the effectiveness of the presented MC-SCOPF formulation and the efficiency of the proposed calculation approach.

keywords: Optimal Power Flow, Transient Stability, Nonlinear Programming, Interior Point Method

1. Nomenclature

δ_i	rotor angle of *ith* generator
ω_i	rotor speed of *ith* generator
ω_0	rated rotor speed of generators
M_i	moment of inertia of *ith* generator
D_i	damping constant of *ith* generator
P_{mi}	mechanic power input of *ith* generator
P_{ei}	electric power output of *ith* generator
δ_{COI}	position of the inertial center
a_i, b_i, c_i	fuel cost coefficients of thermal plant *i*
P_{gi}, Q_{ri}	active and reactive power injection at bus *i*
P_{li}, Q_{li}	active and reactive power load at bus *i*
$V_i e^{j\theta_i}$	magnitude and phase of voltage $\dot{V}_i$ at bus *i*
$G_{ij} + jB_{ij}$	transfer admittance between buses *i* and *j*
P_{ij}	active power of transmission line (*i,j*)
Δt	integration step-width
$T_{\max}$	maximum integration period
nb	number of buses
ng	number of active power sources
nr	number of reactive power sources
nc	number of contingencies
nt	number of integration time intervals
I	set of buses adjacent to bus *i*
S_G	set of active power sources
S_R	set of reactive power sources
S_N	set of buses
S_{CL}	set of constrained transmission lines
S_T	set of integration steps
S_K	set of contingencies
$\underline{(\cdot)}$	lower limits of variables and quantities
$\overline{(\cdot)}$	upper limits of variables and quantities

2. Introduction

Optimal power flow (OPF) has been in existence since the first OPF paper was presented in the 1960's. The main purpose of an OPF program is to determine the optimal operation state of a power system by optimizing a particular objective while satisfying certain specified physical and operating constraints(1)(2). Because of its capability of integrating the economic and secure aspects of the concerned system into one mathematical formulation, OPF has been attracting many researchers. Nowadays, power system planners and operators often use OPF as a powerful assistant tool both in planning and operating stage.

Transient stability constrained OPF (SCOPF) is a rather new theme. At the IEEE 1995 Winter Power Meeting Panel Session on Challenges to OPF, "how will the future OPF provide local or global control measures to support the impact of critical contingencies, which threaten system voltage and angle stability simulated" was put forward as one of the questions regarding what challenges are before OPF remain to be answered(3). This immediately launched a research campaign on SCOPF which is still going on today.

With regard to SCOPF, several methods have been presented to tackle it(4)~(6). The basic idea of reference (4) and (5) are the same. Transient stability constraints are directly incorporated into conventional OPF. The chief advantage of this kind of method is that well developed transient stability analyzing methodologies can be adopted. Reference (6) proposes another method based on the functional transformation techniques. SCOPF is equivalently converted into an optimization problem with finite dimensions. It possesses the merit that an infinite-dimensional problem is converted into a finite-dimensional problem. However, in spite of all these investments and works to date on SCOPF, no SCOPF with multi-contingency has been reported until now. All the researches are limited to only one contingency.

In fact, in order to get a complete transiently secure optimal operating point for the whole system, multi-contingency SCOPF (MC-SCOPF) is indispensable. In this paper, we first illustrate the necessity for MC-SCOPF through the results of single-contingency SCOPF of the IEEJ WEST10 model system. Then, for the first time, we formulate the MC-SCOPF problem and propose a method to solve it.

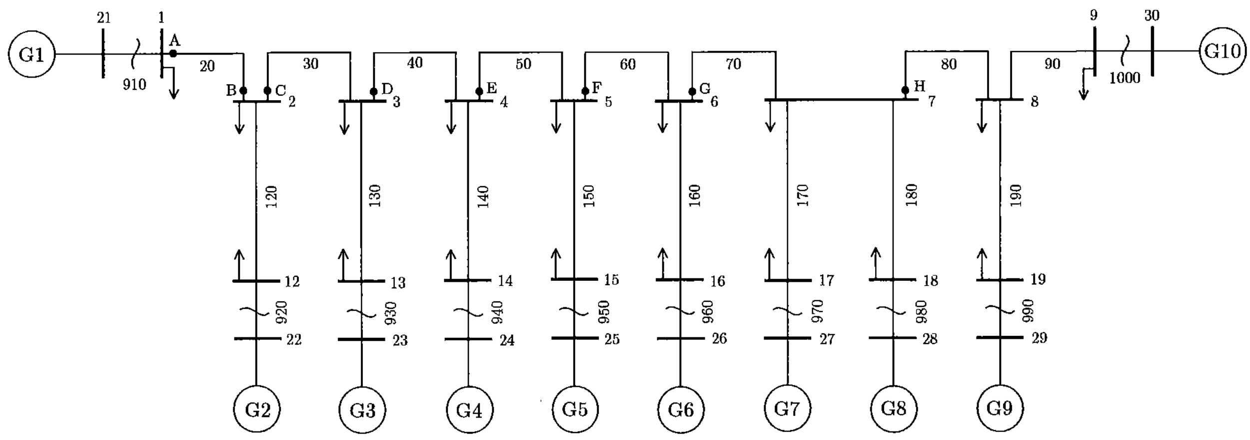

Fig. 1 IEEJ WEST10 model system

Mathematically, SCOPF is a nonlinear optimization problem. Actually, any optimization method applied to the conventional OPF can be adopted. In this study, different from approaches (4)~(6), a methodology based on primal-dual Newton interior point method (IPM) for nonlinear programming (NLP) problems is introduced to solve MC-SCOPF problem. Motivation for this method selection stems from the fact that, as a potentially powerful algorithm, it has been applied with great success to large-scale optimization problems[(7)(8)]. Due to limited space, details of this optimization algorithm[(9)] are not included in this paper.

It is obvious that SCOPF itself contains a large number of variables and constraints. MC-SCOPF is even more high dimensionality. The success of the solution depends on a fast algorithm together with efficiently exploiting sparsity programming technique, which involves extensive code development. We will discuss in detail some issues in implementation of MC-SCOPF program in this paper.

We demonstrate the effectiveness of the presented MC-SCOPF formulation and the efficiency of the proposed solution approach on the IEEJ WEST10 model system. In all cases, dynamic responses obtained by our MC-SCOPF program are verified by widely-used CRIEPI's power system dynamic stability analysis program. Simulation results reveal that the proposed solution approach has good convergence, fast execution time, as well as high accuracy of computation.

3. Necessity for MC-SCOPF

In this section, we illustrate the necessity for MC-SCOPF through the simulation results of the IEEJ WEST10 model system. The IEEJ WEST10 model system is a simplified modeling of the 60Hz power system in Japan[(10)]. It has 10 machines and 27 buses. One-line diagram of the system is shown in Fig.1. All of the transmission lines consist of double circuits. And A~H in this figure indicates fault positions.

Table 1 shows the stable/unstable state of the IEEJ WEST10 model system after given contingency (A~H) under the optimal results obtained by conventional OPF, SCOPF considering one contingency A~H, respectively. In our study, loads are assumed to be 70 percent of the peak condition (daytime condition). The simulation conditions for single-contingency SCOPF is the same as that for multi-contingency SCOPF, which are illustrated in detail in Section 7.

It is obvious from these results that single-contingency SCOPF is capable of shifting the optimal operating point so that the system becomes stable with respect to pre-specified contingency at the expense of increasing total generation cost. Nevertheless, if we consider only one contingency, we cannot obtain an optimal operating point which is stable for all the contingencies. In other words, single-contingency SCOPF is unable to get a complete transiently secure operating point for the whole system. For this reason, MC-SCOPF is an indispensable and very valuable work.

4. Transient stability model used in MC-SCOPF

4.1 Synchronous machine representation

In our study, the classical generator model for transient stability analysis is adopted. It allows the transient electrical performance of the machine to be represented by a simple voltage source of fixed

Table 1. Stable(S)/Unstable(U) state of the IEEJ WEST10 model system after contingency A~H under different operating points

Fault	OPF	Single-contingency SCOPF							
		(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
A	U	S	U	U	U	U	U	U	U
B	U	U	S	S	U	U	U	U	U
C	U	U	U	S	U	U	U	U	U
D	U	U	U	U	S	U	U	U	U
E	S	S	S	S	S	S	S	S	S
F	S	S	S	S	U	S	S	S	S
G	S	S	S	S	S	S	S	S	S
H	U	U	U	U	U	U	U	U	S
Cost	222775	225624	225538	225568	225399	222775	222775	222775	223853
△Cost	+0	+2849	+2763	+2793	+2624	+0	+0	+0	+1078

magnitude E' behind an effective reactance x_d' [11]. This model offers considerable computational simplicity. It is used extensively in transient stability analysis limited to the study of transients for the first swing or for periods on the order of one second, during which the system dynamic response is dependent largely on the stored kinetic energy in the rotating masses.

The swing equation set (equations of motion) is:

$$\begin{aligned} &\dot{\delta}_i = \omega_i - \omega_0 \\ &M_i \dot{\omega}_i = \omega_0(-D_i\omega_i + P_{mi} - P_{ei}) \\ &i \in S_G \end{aligned} \tag{1}$$

where

$$P_{ei} = E_i'^2 G_{ii}' + \sum_{\substack{j=1 \\ \neq i}}^{ng} \left[E_i' E_j' B_{ij}' \sin(\delta_i - \delta_j) + E_i' E_j' G_{ij}' \cos(\delta_i - \delta_j) \right]$$

In the above equations, $Y_{ij}' = G_{ij}' + jB_{ij}' (i, j = 1,2,...,ng)$ is the driving point admittance $(i = j)$ and the transfer admittance $(i \neq j)$ converged into generator internal electric potential. Y_{ij}' need to be changed only in the case that there is a change in the configuration of the network because of fault or switch operation.

4.2 Center of inertial (COI)

In describing the transient behavior of the system, it is convenient to use inertial center as a reference frame[12]. The generators' angles with respect to COI are used to indicate whether or not the system is stable. For an ng-generator system with rotor angles δ_i and inertia constant M_i, the position of COI is defined as:

$$\delta_{COI} = \sum_{i=1}^{ng} M_i \delta_i \Big/ \sum_{i=1}^{ng} M_i \tag{2}$$

5. Formulation of MC-SCOPF problem

5.1 Objective function

Minimize total fuel cost:

$$\begin{aligned} &F = \sum_{i \in S_G} f_i(P_{gi}) \\ &f_i(P_{gi}) = a_i + b_i P_{gi} + \frac{c_i}{2} P_{gi}^2 \end{aligned} \tag{3}$$

5.2 Equality constraints

a) Power flow equations H_{pf}:

In our study, the polar coordinate form power flow equations are used:

$$\begin{aligned} &P_{gi} - P_{li} - V_i \sum_{j \in I} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) - V_i^2 G_{ii} = 0 \\ &Q_{ri} - Q_{li} - V_i \sum_{j \in I} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) + V_i^2 B_{ii} = 0 \\ &i \in S_N \end{aligned} \tag{4}$$

b) Swing equations $H_s(k)$:

By the adoption of any implicit integration rule, equations (1) can be discretized at each time step. B.Stott recommended the implicit trapezoidal rule as an excellent method suitable for large-scale short-term simulation[13]. For the k*th* contingency, the differential swing equation set (1) can be converted to the following numerically equivalent algebraic equation set using the trapezoidal rule:

$$\begin{aligned} &\delta_i^t(k) - \delta_i^{t-1}(k) - \frac{\Delta t}{2}[\omega_i^t(k) + \omega_i^{t-1}(k)] = 0 \\ &\omega_i^t(k) - \omega_i^{t-1}(k) - \frac{\Delta t}{2}\left\{ \frac{1}{M_i}[-D_i\omega_i^t(k) + P_{gi} - P_{ei}^t(k)] \right. \\ &\qquad \left. + \frac{1}{M_i}[-D_i\omega_i^{t-1}(k) + P_{gi} - P_{ei}^{t-1}(k)] \right\} = 0 \\ &i \in S_G, t \in S_T, k \in S_K \end{aligned} \tag{5}$$

where

$$\begin{aligned} P_{ei}^t(k) = E_i'^2 G_{ii}''(k) + \sum_{\substack{j=1 \\ \neq i}}^{ng} \{ & E_i' E_j' B_{ij}''(k) \sin[\delta_i^t(k) - \delta_j^t(k)] \\ & + E_i' E_j' G_{ij}''(k) \cos[\delta_i^t(k) - \delta_j^t(k)] \} \end{aligned}$$

c) Initial-value equations H_{iv}:

In order to obtain the initial values of rotor angle δ_i^0 and constant voltage E_i' in the swing equations, the following initial-value equations are introduced:

$$\begin{aligned} &E_i' V_{gi} \sin(\delta_i^0 - \theta_{gi}) - x_{di}' P_{gi} = 0 \\ &V_{gi}^2 - E_i' V_{gi} \cos(\delta_i^0 - \theta_{gi}) + x_{di}' Q_{gi} = 0 \\ &i \in S_G \end{aligned} \tag{6}$$

It should be noted that all of the contingencies have the same values of initial rotor angle δ_i^0 and constant voltage E_i'.

5.3 Inequality constraints

For the sake of convenience, inequality constraints are divided into two groups G_{uc} and $G_c(k)$. G_{uc} group contains all the inequality constraints as that in conventional OPF, while $G_c(k)$ group consists of the transient stability constraints for all contingencies.

a) Inequality constraints G_{uc}:

$$\begin{aligned} &\underline{P}_{gi} \leq P_{gi} \leq \overline{P}_{gi} && i \in S_G \\ &\underline{Q}_{ri} \leq Q_{ri} \leq \overline{Q}_{ri} && i \in S_R \\ &\underline{V}_i \leq V_i \leq \overline{V}_i && i \in S_N \\ &\underline{P}_{ij} \leq P_{ij} \leq \overline{P}_{ij} && (i,j) \in S_{CL} \end{aligned} \tag{7}$$

b) Stability constraints $G_c(k)$:

As mentioned in Section 4, generators' angles with respect to COI are used to indicate whether or not the system is stable:

$$\begin{aligned} &\underline{\delta} \leq \delta_i^0 - \delta_{COI}^0 \leq \overline{\delta} \\ &\underline{\delta} \leq \delta_i^t(k) - \delta_{COI}^t(k) \leq \overline{\delta} \\ &i \in S_G, t \in S_T, k \in S_K \end{aligned} \tag{8}$$

The above criteria are consistent with industry practice and have been found by utility engineers to be acceptable.

5.4 Formulation of MC-SCOPF

The objective function and all the constraints of the MC-SCOPF problem have been developed. A compact notation is introduced as follows to highlight the character that MC-SCOPF contains multi-contingency.

$$\begin{aligned} &\text{minimize } \ F \\ &\text{subject to } \ H_{pf}=0,\ H_{iv}=0,\ H_s(k)=0 \\ &\qquad \underline{G}_{uc}\le G_{uc}\le \overline{G}_{uc},\ \underline{G}_c\le G_c(k)\le \overline{G}_c \\ &\qquad k\in S_K \end{aligned} \tag{9}$$

6. Computational implementation

MC-SCOPF contains a large number of constraints. For a system with ng-generator, if nc-contingency is considered, and all of the contingencies are assumed to have the same number of integration time intervals nt, the number of inequality constraints imposed by considering transient stability is about $nc\times ng\times nt$, and the number of equality constraints imposed is about twice of this.

Because of the dramatically increasing of the scale of MC-SCOPF problem compared with conventional OPF, it is very challenge to develop efficient implementation approaches. In the following, we discuss in detail some issues in computational implementation.

By examining the framework of the primal-dual Newton IPM algorithm, it is obvious that major computational burden stems from solving the correction equations(9). In considering this problem, we can set out from two ways. One is to reduce the size of the correction equations as far as possible; the other is to make properly arranging of the correction equations so that sparsity programming technique can be exploited.

6.1 How to reduce the size of the correction equations?

First, it is obvious that if we can reduce the number of equality constraints, we can certainly reduce the size of the correction equations. We would like to mention here, in SCOPF study, the key point in the swing equation set (1) is how to express the electric power output of the machine P_{ei}. It greatly influences how to incorporate transient stability constraints into SCOPF formulation. Reference (5) once presented a method which includes both swing equations and network equations. In our study, different from the method in reference (5), we introduce another formulation in Section 4, which only includes swing equations. Our motive for doing this is to reduce the size of the correction equations, as the number of equality constraints decreased considerably if no network equations are needed in SCOPF formulation.

Secondly, if a large integration step-width Δt can be used, the number of equality constraints can also be decreased. However, in numerical transient stability solution, the integration step-width influences the analyzing accuracy. Reference (14) reported that for solving the differential equations with the implicit trapezoidal rule of integration the results are acceptable with a step-width as large as 0.01 second. Because of this, in our study, we exploit a step-width 0.01s.

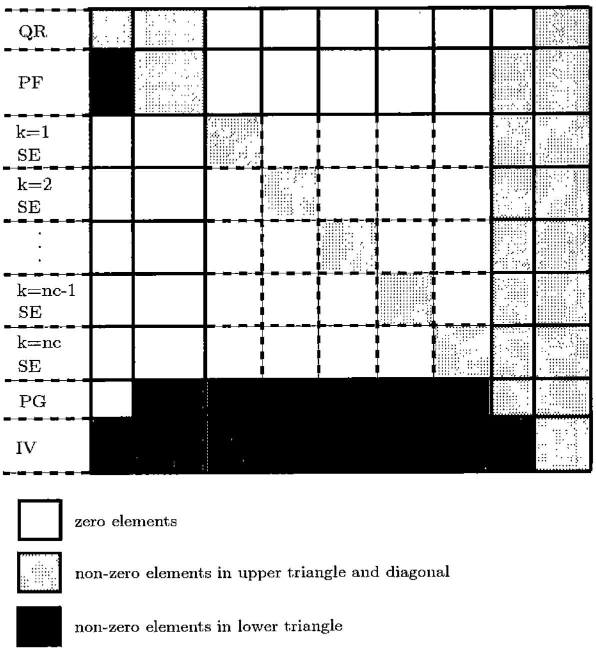

Fig. 2 Matrix frame of correction equations of MC-SCOPF

Table 2. The number of correction equations

	General	IEEJ WEST10 System#
QR	*nr*	10
PF	4*nb*	108
SE(3-contingency)	3*(4*ng***nt*)	24000
PG	*ng*	10
IV	4*ng*	40

$Tmax$=2.0s, Δt=0.01s

6.2 The arrangement of the correction equations

Fig.2 illustrates the matrix frame of correction equations of MC-SCOPF. Where PG and QR indicate control variables $P_{gi}(i\in S_G)$ and $Q_{ri}(i\in S_R)$ respectively; PF, SE and IV indicate the variables corresponding to power flow equations, swing equations and initial-value equations respectively. This matrix is a symmetrical matrix and fairly sparse. In order to reduce both storage and solution time, only the non-zero elements in upper triangle and diagonal need to be saved.

Table 2 shows the number of correction equations for a general MC-SCOPF problem with three contingencies. As an example, the number of correction equations for the IEEJ WEST10 model system is also denoted. Generally, for a ng-generator system, equality constraints imposed by one contingency is $2ng\times nt+2ng$ and inequality constraints imposed by one contingency is $ng\times nt+ng$. For the IEEJ WEST10 model system, each contingency will impose 4020 equality constraints and 2010 inequality constraints if the integration step-width is 0.01s and the integration period is 2.0s.

It is obvious from the above that MC-SCOPF is a large-scale optimization problem. Properly arranging the correction equations, together with efficiently exploiting sparsity programming technique, can realize very fast solution of the correction equations when using IPM for NLP to solve large-scale optimization problems(7)(8). For MC-SCOPF solution, our calculating experiences reveal that a matrix arrangement of the correction equations as that shown in Fig.2 is very effective. Under such arrangement, the number of fill-ins of the SE part is about $(1/nc)\times(2/nt)$ of the total matrix elements of the same part. For the example of the IEEJ WEST10 model system in Table 2, the number of fill-ins of the SE part is 1/300 of the total matrix elements of the same part, which is up to 24000×24000.

7. Test results and discussions

Based upon a well-tested OPF program writing in FORTRAN, we implemented a MC-SCOPF program. The prototype code has been tested on a small system (3-machine 9-bus test system) and a medium system (IEEJ WEST10 model system) respectively. The results of the IEEJ WEST10 model system are presented here with some discussions. We would like to mention here, in order to find an example to verify our MC-SCOPF program, the following simulations about the IEEJ WEST10 model system are based upon optimizations without consideration of line flow constraints although the program can also proceed optimization with line flow constraints.

7.1 Simulation conditions

a) Contingencies: All of the contingencies are three-phase grounding fault (3LG-O). For a certain contingency, it occurs at 0.1s and is removed 70ms later by the opening of one of the double line. This is consistent with the simulation condition of the IEEJ WEST10 model system in IEEJ technical report No.754[10].

b) Stability threshold: For all the machines, we assigned -100 degree and +100 degree as the lower and upper limits of angles with respect to COI respectively. In real-world power system, such thresholds could be determined by operating experience.

c) Integrations: The integration step-width Δt is fixed to be 0.01s because of the reason expressed in Section 6. The maximum integration period T_{max} is set to be 2.0s for the purpose to study first swing transients.

7.2 Cases study

In order to obtain a complete transiently secure optimal operating point for the IEEJ WEST10 model system, MC-SCOPF is used. The results are shown in Table 3. Similar to Table 1, Table 3 illustrates the stable/unstable state of the IEEJ WEST10 model system after given contingency (A~H) under the optimal results obtained by conventional OPF, MC-SCOPF considering one contingency (A), two contingencies (A+D), three contingencies (A+D+F), and three contingencies (A+D+H), respectively.

For the convenience of illustration, we divide the simulations into two cases:

Case-1: (A), (A+D), (A+D+F)

Case-2: (A), (A+D), (A+D+H)

a) Case-1: (A), (A+D), (A+D+F)

From the results of Case-1, it is obvious that MC-SCOPF shifts the operating point produced by the conventional OPF solution so that the system becomes stable with respect to pre-specified contingencies. This demonstrated the effectiveness of the MC-SCOPF.

Another important conclusion can also be made. If the pre-specified contingency is a "binding contingency" (like A and D), the above operations in preventive mode increase the dispatch cost produced by the OPF solution. (A) case has a cost higher than OPF, and (A+D) case is even higher than (A) case. On the other hand, if the pre-specified contingency is a "non-binding contingency" (like F), the dispatch cost does not change even if this contingency is included in MC-SCOPF. (A+D+F) case has the same cost as (A+D) case.

Table 3. Results of MC-SCOPF

Fault	OPF	Multi-contingency SCOPF			
		(A)	(A+D)	(A+D+F)	(A+D+H)
A	U	S	S	S	S
B	U	U	S	S	S
C	U	U	S	S	S
D	U	U	S	S	S
E	S	S	S	S	S
F	S	S	S	S	S
G	S	S	S	S	S
H	U	U	U	U	S
Cost	222775	225624	226392	226392	226515
△Cost	+0	+2849	+3617	+3617	+3740

b) Case-2: (A), (A+D), (A+D+H)

As Case-1 cannot give out a complete transiently secure optimal operating point for the whole system, Case-2 is introduced. Case-2 is different from Case-1 only in that the "non-binding contingency" F is substituted by a "binding contingency" H.

Compared with (A+D) case, (A+D+H) case has a higher dispatch cost. This result is straightforward, as the total generation cost becomes higher if more binding contingencies are placed.

For (A+D+H) case, we would like to mention two additional points of interest. First, under this optimal solution the system is stable after any of the contingencies A~H. We have obtained a complete transiently secure optimal operating point. Secondly, the total generation cost of this case (226515) is higher than that of the conventional OPF without line flow constraints (222775). But much smaller than that of the conventional OPF with line flow constraints (236026), where the line flow constraints were determined by the prior stability simulations. Consequently, from the view point of both secure and economy, this optimal result is very encouraging.

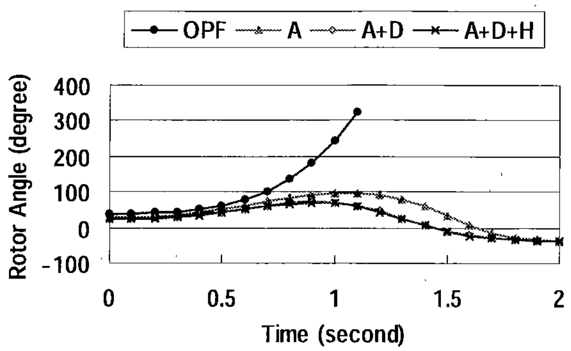

Fig. 3 Dynamic responses of G3 at contingency A

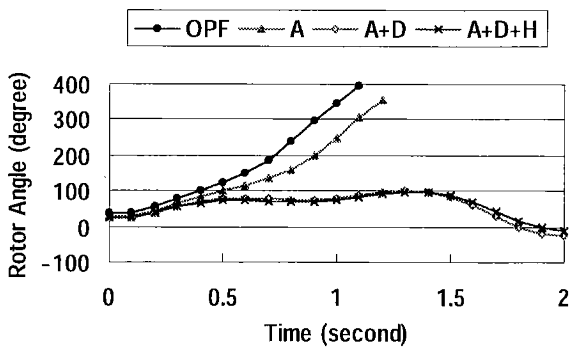

Fig. 4 Dynamic responses of G3 at contingency D

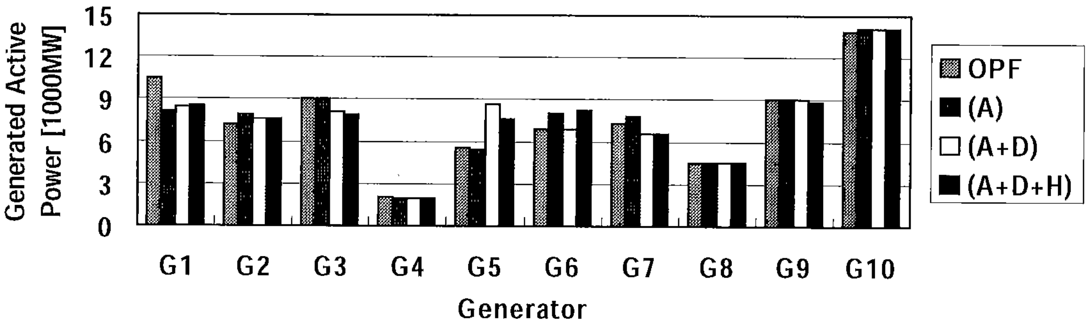

Fig. 5 Optimal generation of the IEEJ WEST10 model system at different operating points

G3 firstly loses synchronism under the operating point given by OPF. For the convenience of comparison and illustration, rotor angles of G3 under the above four operating points are shown in Fig.3 and 4. Fig.3 is at contingency A, and Fig.4 is at contingency D. Under the operating point given by OPF, G3 is unstable after any of the contingencies A or D. Under the operating point given by (A) case, G3 is stable after contingency A and reaches threshold (stability limit), while it is still unstable after contingency D. Under the operating point given by (A+D) case, G3 is stable after both contingencies A and D. But this time, contingency D reaches stability limit, while contingency A is lower than it.

Fig.5 is a comparison of the optimal generations by OPF, (A) case, (A+D) case, and (A+D+H) case. The shifting of the operating points by the introducing of contingencies can be clearly seen.

7.3 Some issues about simulation

Through the above cases study, we have demonstrated the effectiveness of the formulation of MC-SCOPF. Some issues about simulation are discussed in the following to illustrate that the proposed calculation approach is able to have the solution efficiently and securely.

a) Convergence characteristic

When using primal-dual Newton IPM to solve MC-SCOPF problems, convergence condition is that complementary gap is smaller than a defined tolerance. Thus complementary gap is a very important measure to judge the optimality of solutions and its change reflects the characteristic of the algorithm. Fig.6 shows how it reduced with iterations for (A+D+F) case and (A+D+H) case. We can see it decreases to zero monotonically and rapidly. Fig.7 shows how the objective function changes with iterations for the same cases, in which values are scaled relative to the values of respective optimal solutions:

$$F^i_{Cost} = F^i_{Cost} \Big/ F^{optimal}_{Cost} \times 100\%, \quad i \in Number\ of\ iterations \qquad (10)$$

b) Computational load

As MC-SCOPF problem contains a very large number of constraints, inherently it is time consuming. For the IEEJ WEST10 model system with one contingency, it takes about 3 and a half minutes for our MC-SCOPF program to get the optimal results on a Sun Ultra-10 workstation, which has a 440MHz Ultra™SPARC™-IIi CPU. By examining the framework of the correction equations, we can see that the computation time increases approximately in square ratio with the number of generators. Moreover, according to our calculating experiences, if the number of contingencies considered is *nc*, the computation time is about *nc* times larger than the case of single contingency. On considering that "In perhaps any power system, the number of binding stability constraints is normally very small, say in the order of 5 or less[5]", it seems that the proposed solution can reach a result in acceptable execution time.

c) Calculating accuracy

As pointed out in Section 6, the integration step-width influences the calculating accuracy. In order to check whether an integration step-width as large as 0.01s is suitable, system dynamic responses calculated by our MC-SCOPF program are compared with that by widely-used CRIEPI's power system dynamic stability analysis program, which use the optimal operating points given by MC-SCOPF and set the integration step-width as 0.001s. The results are fairly well identical.

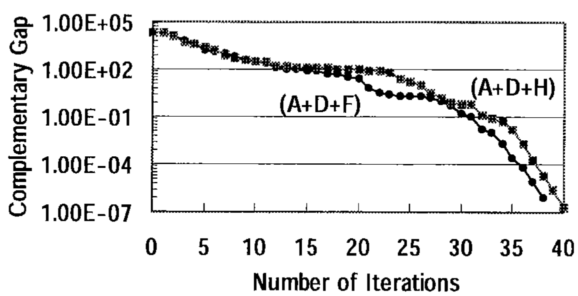

Fig. 6 Complementary gap with iterations

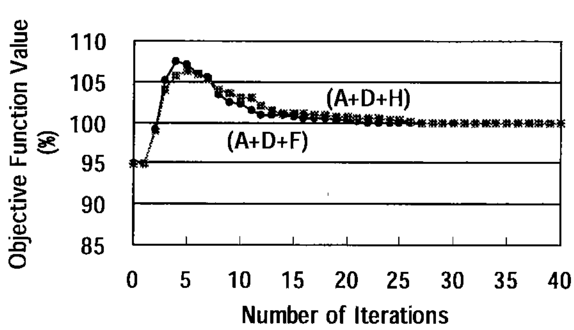

Fig. 7 Objective function with iterations

8. Conclusions and future works

In this paper, we first illustrated the necessity for MC-SCOPF through the results of single-contingency SCOPF of the IEEJ WEST10 model system. Then, for the first time, we formulated the MC-SCOPF problem and proposed a method to solve it. The effectiveness of the MC-SCOPF formulation is demonstrated on the IEEJ WEST10 model system. Also based on the results of the IEEJ WEST10 model system, some phenomena occurred when considering multi-contingency is elaborated.

We proposed a solution of MC-SCOPF problem by the primal-dual Newton IPM for NLP problems. And we also discussed in detail some issues in implementing MC-SCOPF program using IPM algorithm. Simulation results reveal that the proposed solution has good convergence, fast execution time, as well as high accuracy of computation.

For future works, we think that the following three topics about MC-SCOPF are valuable and challenging:

The first one is how to pick out "binding contingencies". As can be seen from cases study in this paper, including "non-binding contingency" into MC-SCOPF can only increase computational burden, while contribute nothing to the optimal solution.

The second one is about convergence of the solution. According to our calculating experiences, convergence difficulties may occur when considering more than 5 contingencies for the IEEJ WEST10 model system. Decoupled solution of MC-SCOPF may be a possible alternative methodology to over come this problem.

The third one may be an extension of the formulation of MC-SCOPF to different component modeling to find more practical and robust one.

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Reference

(1) H.W.Dommel, W.F.Tinney: "Optimal Power Flow Solutions", *IEEE Trans. on PAS*, **87**, No.10, 1866-1876(1968)

(2) D.I.Sun, B.Ashley, B.Brewer, A.Hughes, W.F.Tinney: "Optimal Power Flow by Newton Approach", *IEEE Trans. on PAS*, **103**, No.10, 2864-2880(1984)

(3) J.A.Momoh, R.J.Koessler, M.S.Bond, B.Stott, D.Sun, A.Papalexopoulos, P.Ristanovic: "Challenges to Optimal Power Flow", *IEEE Trans. on PWRS*, **12**, No.1, 444-455(1997)

(4) M.L.Scala, M.Trovato, C.Antonelli: "On-line Dynamic Preventive Control: an Algorithm for Transient Security Dispatch", *IEEE Trans. on PWRS*, **13**, No.2, 601-610(1998)

(5) D.Gan, R.J.Thomas, R.D.Zimmerman: "Stability-Constrained Optimal Power Flow", *IEEE Trans. on PWRS*, **15**, No.2, 535-540(2000)

(6) L.Chen, Y.Tada, H.Okamoto, R.Tanabe, A.Ono: "Optimal Operation Solutions of Power Systems with Transient Stability Constraints", *IEEE Trans. on Circuits and Systems I: Fundamental Theory and Applications*, **48**, No.3, 327-339(2001)

(7) H.Wei, H.Sasaki, J.Kubokawa, R.Yokoyama: "An Interior Point Nonlinear Programming for Optimal Power Flow Problems with a Novel Data Structure", *IEEE Trans. on PWRS*, **13**, No.3, 870-877(1998)

(8) H.Wei, H.Sasaki, J.Kubokawa, R.Yokoyama: "Large Scale Hydrothermal Optimal Power Flow Problems Based on Interior Point Nonlinear Programming", *IEEE Trans. on PWRS*, **15**, N0.1, 396-403(2000)

(9) A.S.El-Bakry, R.A.Tapia, T.Tsuchiya, Y Zhang: "On the Formulation and Theory of the Newton Interior-Point Method for Nonlinear Programming", *Journal of Opt. Theory and Applications*, **89**, No.3, 507-541(1996)

(10) IEEJ technical committee: Standard Models of Power Systems, *IEEJ Technical Report*, No.754, November, 1999

(11) P.M.Anderson, A.A.Fouad: Power System Control and Stability, *Iowa State University Press*, 1977

(12) T.Athay, R.Podmore, S.Virmani: "A Practical Method for the Direct Analysis of Transient Stability", *IEEE Trans. on PAS*, **98**, N0.2, 573-584(1979)

(13) B.Stott: "Power System Dynamic Response Calculations", *Proceedings of the IEEE*, **67**, No.2, 219-241(1979)

(14) H.W.Dommel, N.Sato: "Fast Transient Stability Solutions", *IEEE Trans. on PAS*, **91**, N0.4, 1643-1650(1972)

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