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전압안정도 여유 향상을 위한 무효예비력 기반 상정사고 제약 최적조류계산

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Reactive Reserve Based Contingency Constrained Optimal Power Flow for Enhancement of Voltage Stability Margins

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Abstract - This paper presents a new concept of reactive reserve based contingency constrained optimal power flow (RCCOPF) for voltage stability enhancement. This concept is based on the fact that increase in reactive reserves is effective for enhancement of voltage stability margins of post-contingent states. In this paper, the proposed algorithm is applied to voltage stability margin of interface flow. Interface flow limit, in the open access environment, can be a main drawback. RCCOPF for enhancement of interface flow margin is composed of two modules, modified continuation power flow (MCPF) and optimal power flow (OPF). These modules are recursively performed until satisfying the required margin of interface flow in the given voltage stability criteria.

1. Introduction

In the recent power system operation and planning, voltage stability is one of the main concerns to maintain system security. In the open access environment, diverse power transfers through transmission systems increase degree of vulnerability related to voltage stability because of uncertain system condition. In the literature, considerable researches have been conducted and various tools have been developed for voltage security assessment (VSA). In VSA, there are composed of three parts, i.e. contingency selection, voltage stability evaluation and countermeasure determination. In countermeasure, this paper mainly discusses remedial action, which is required for severe system condition and/or outages in system operation.

Remedial action can be divided into two main categories, preventive and corrective control. Preventive control is for prevention against voltage instability before it occurs, while corrective control is for correction of security violations in unstable systems. This paper focuses on preventive control in the pre-contingent state to maintain post-contingent voltage security. Compared to the literature of preventive and corrective action for one operating point actually, many researchers have concentrated on the topic, there are a few references with preventive action in the normal state considering post-contingent states in terms of voltage stability.

This paper presents a new method named reactive reserve based contingency constrained optimal power flow (RCCOPF) for preventive control in the normal state considering voltage stability margins of post-contingent states. It applies the concept of contingency constrained optimal power flow (CCOPF) [1]. The formulation of RCCOPF contains active power margin constraints of post-contingent states, and it is solved by a decompositionmethod. Using modified continuation power flow (MCPF) [2] module, active power margins of post-contingencies are calculated as sub-problems. To remove active power margin violations of severe contingencies, then, preventive control action as the main problem is performed by optimal power flow (OPF) module with reactive reserve constraints. These reactive reserve constraints act as transformed contingency constraints, and they are not linear constraints but quantity constraints that are constructed to be effective to enhance voltage stability margins with increasing lower limits of the constraints. It should be noted that the number of main iterations to get a solution in RCCOPF can be reduced with adjustment of the lower limits applying sensitivity of active power margin increase with respect to effectivereactive reserve increase.

2. Basic Concept

In this section, the basic concept of RCCOPF is presented. Assume that systems are operated with heavy loads and/or severe interface flows, and that their voltage stability margins corresponding to severe contingencies are insufficient with respect to voltage stability margin criteria. In this situation, system controls for secure operation are required preventively or correctively. Corrective control is considered as economic one in the market environment; nevertheless, preventive control is also needed to reduce system interruption. As stated earlier, the paper concentrates on preventive controls in the normal state to enhance post-contingent margins.

The basic idea of RCCOPF starts from the fact that reactive reserves of dynamic reactive sources have an important effect on post-contingent voltage stability. In the normal operationof a dynamic reactive source, there is some margin from the current reactive generation to the maximum output limit of reactive power. This margin is reactive reserve. When one or more transmission components are tripped, there is increase in reactive power loss resulting from increase in system impedance. Therefore, sufficient reactive reserves are required to supply the additional reactive loss. In the viewpoint of voltage stability, quantitative requirement of reactive reserves increase to keep a certain level of voltage stability margins in post-contingent states. In severe system conditions after outages of equipments, in addition, more reactive reserves are required. Consequently, it is known that reactive reserves in the normal state are closely concerned with voltage stability in post-contingent states.

Assuming that there is a function that represents voltage stability of a post-contingent state in a closed form, it is easy to incorporate the function into the normal state. OPF formulation in order for preventive control considering post-contingent voltagestability. However, there is no voltage stability index that can be evaluated without a power flow solution of the given state; that is, at least post-contingent power flow equations need to be incorporated into the normal OPF problem to accomplish the objective of the paper. This type of problem is in the category of contingency constrained optimal power flow (CCOPF). To solve the problem, decomposition methods are usuallyused. In these methods, power flow solutions of contingent states and sensitivities of control variables are calculated, and then transformed contingency constraints using the sensitivities are in the constraints of main OPF problem to combine pre- and post-contingent operating points. In this paper, a new decomposition method with reactive reserves is used to solve the OPF problem as shown in (1)

$$\begin{aligned} \min \quad & f(x_0) \\ s.t. \quad & g_0(x_0)=0 \\ & h_{\min,0} \le h_0(x_0) \le h_{\max,0} \\ & g_1(x_1)=0 \end{aligned} \qquad (1)$$

$$
\begin{aligned}
&P_{\min}^{mrg} \le P_1^{mrg}(x_1)\\
&\vdots\\
&g_{nc}(x_{nc}) = 0\\
&P_{\min}^{mrg} \le P_{nc}^{mrg}(x_1)
\end{aligned}
$$

where $f(\cdot)$, $g(\cdot)$, $h(\cdot)$ and $P^{mrg}(\cdot)$ represent the objective function, network equationfunctions, inequality constraint functions of operationallimits in the normal state, and post-contingent margin *constraint functions respectively. In (1), the subscripts 0, 1, 2,* nc denote the normal state and contingent states respectively, $h_{\min}$ *and* $h_{\max}$ *represent lower and upper limits of* $h(\cdot)$, *and* $P_{\min}^{mrg}$ is the lower limit of margin constraints. Assuming that voltage stability margin of the normal state is large enough, the margin constraint of the normal state is excluded in (1)

As mentioned earlier, voltage stability margin function of a state, $P^{mrg}(\cdot)$ in (1), cannot be expressed with a closed-form function, so a decomposition method needs to be applied in order to solve the problem. In this paper, a reactive reserve based decomposition method is used, and reactive reserve acts as a medium to combine the normal and contingent states in term of voltage stability. Thus, the proposed method is named reactive reserve based contingency constrained optimal power flow (RCCOPF). Using MCPF, in RCCOPF, post-contingent voltage stability margins are determined as sub-problems, and preventive control action as the main problem is performed with OPF to remove margin violations in post-contingent states.

The formulation of the main OPF problem in RCCOPF, which contains reactive reserve constraints to combine pre- and post-contingent states, in a compact form is presented in (2). The OPF is performed in the normal state

$$
\begin{aligned}
\min\quad & f(x_0)\\
s.t.\quad & g_0(x_0) = 0\\
& h_{\min,0} \le h_0(x_0) \le h_{\max,0}\\
& R_{\min,1} \le R_{Q1}(x_0)\\
& \vdots\\
& R_{\min,nc} \le R_{Qnc}(x_0) \qquad (2)
\end{aligned}
$$

where $R_{Qc}(\cdot)$ and $R_{min,c}(c{=}1, 2,\cdots, nc)$ are the reactive reserve constraint concerning contingency $c$and the lower limit of the constraint respectively. The formulation considers nc reactive reserve constraints, and nc is the number of severe contingencies to be considered. If each reactive reserve constraint represents voltage stability of the corresponding contingent state well, the formulation can be effective for preventive control with change of the lower limits. Also, the reactive reserve constraints need to be expressed with functions of the control variables in the normal state.

In RCCOPF, the most important thing is how to construct appropriate reactive reserve constraints for improvement of active power margins to remove margin violations of severe contingencies. With the generic concept of reactive reserve, however, it is impossible to differentiate from one contingency to another. Thus, this paper takes the concept of effective reactive reserves with respect to contingencies [3]. In Fig. 1, S-V curves in the normal and a contingent state are shown to illustrate the concept. The letters S and Q represent stress level of system parameter and reactive power generation at each state respectively.

In Fig. 1, superscripts o and $*$ indicate base and critical state respectively, and subscripts n and c correspond to the normal and the contingent state respectively. According to [3], the current effective reactive reserve, R_c^{eff}, corresponding to the contingency c can be described as follows.

$$R_c^{eff} = \sum_{i\in S\varepsilon,c} (Q_{c,i}^{*} - Q_{n,i}^{0}) \qquad (3)$$

where $S_{\varepsilon,c}$ *is the set of generators affecting the margin of stress* level in the corresponding contingent state, $Q_{c,i}^{*}$is the effective maximum reactive generation of generator i it is the same of reactive generation at the maximum point of the contingent state as shown in Fig. 1, and $Q_{n,i}^{o}$is reactive power generation of generator $i$in the normal base point as shown in Fig. 1. Taking the idea of the effective maximum reactive generation makes it possible to differentiate each contingency since an effective maximum reactive generation of a contingency might be different from those of others. Also, an S, affecting generator group, of a severe contingency can be different from those of other contingencies. Although the systems are operated at one operating point in the normal state, effective reactive reserves with respect to contingencies can be different.

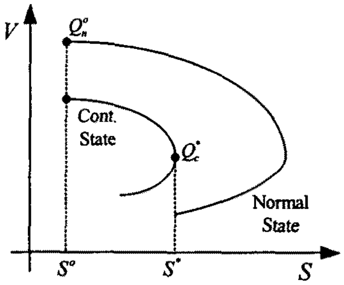

Fig. 1. S-V curves of the normal and a contingent state

Using the effective reactive reserve concept, adequate reactive reserve constraints in the main OPF problem of RCCOPF are constructed, and they are used to force the OPF solution to increase effective reactive reserves of severe contingencies to remove margin violations. In section IV, the simulation result certifies that increases in effective reactive reserves of severe contingencies are available to enhance voltage stability margins of severe contingencies. The reason is also discussed in section IV. The detailed formulation of the reactive reserve constraints is described in the next section.

3. Formulations and Solution Procedure

This section presents the formulations of both OPF and MCPF module and contains the solution procedure of RCCOPF.

A. OPF module

1) *Objective function:* In (2) in the previous section, the compact form of the OPF module is shown, the objective function of which is minimization of reactive generation control from the base case as follows.

$$f(x) = \sum_{i\in SG} W_{Qi}(Q_i^{(k)} - Q_i^{(0)})^2 \qquad (4)$$

where SG corresponds to a set of generators, WQ represents weighting factor of corresponding reactive generation, and the superscript (0) and (k) indicate the base case before execution of RCCOPF and iteration of main loop in RCCOPF respectively. In (4), control variables are reactive power generations at k-th iteration, $Q_i^{(k)}$ s; however, generator terminal voltage settings can be used as control parameters instead.In the OPF module, reactive power is dispatched to minimize reactive generation control and to satisfy the constraints containing the reactive reserve constraints to remove margin violations.

2) *Constraints:* 1) The constraints of the OPF module include the network equations and inequality constraints that contain operating limits, physical limits, and the effective reactive reserve limits. The limits of the inequality constraints are following:

- Upper/lower limits of bus voltages;
- Upper/lower limits of reactive power generations;
- Lower limits of effective reactive reserve constraints.

All constraints except the reactive reserve constraints are normally used in optimal reactive power dispatch problems. Assuming that contingency m is in the severe contingent list, the detailed formulation of the reactive reserve constraints concerning contingency m at k-th iteration is described as follows.

$$R^{(k)}_{\min,m} \leq R^{(k)}_{Q,m}(Q^{(k)})$$
$$R^{(k)}_{Q,m}(Q^{(k)} \equiv \sum_{i \in SG} \rho_{m,i}(Q^{*}_{m,i} - Q^{(k)}_{i}) \qquad (5)$$

where $R^{(k)}_{\min,m}$ is the lower limit of the reactive reserve constraint, and $R^{(k)}_{Q,m}(\cdot)$ is the function representing the effective reactive reserve of contingency *m*. In (5), $\rho_{m,i}$ is a binary variable (1 or 0) that determines whether reactive reserve of generator *i* is effective to enhance voltage stability margin of contingency *m*, $Q^{*}_{m,i}$ is the effective maximum reactive generation of generator *i* regarding contingency *m*, and $Q^{(k)}_{i}$, which is a control variable in the objective function (4), is reactive power generation of generator *i* in the normal state. In this paper, it is assumed that $Q^{*}_{m,i}$s in (5) are constant. Actually, they can be changed after preventive control, but constant $Q^{*}_{m,i}$s are used as reference values to increase effective reactive reserves in the OPF module.

To determine the value of *m,i*, in the paper, the following factor is considered.

- Reactive power generation sensitivity [4] of generator *i* at the maximum point of contingency *m* in the corresponding *P-V* curve.

In the process of MCPF, this sensitivity information can be easily obtained. In this paper, relative sensitivities are used, which are calculated by dividing sensitivities by the biggest one. In this paper, affecting generator selection factor, α, is introduced. If relative sensitivity of generator *i* in contingency *m* is greater than α, $\rho_{m,i}$ is 1; otherwise, $\rho_{m,i}$ is 0. Practically, it is recommended to set α between 0.1~0.3.

Change of the lower limit, $R^{k}_{\min,m}$ is the main measure to increase the reactive reserves of the selected generators. Before performing the OPF module, the lower limit is initialized to a certain value, and then the limit is changed for enhancement of the post voltage stability margin. This process is explained in detail in subsection *C*.

2) *Solution method*: To obtain solutions of OPF module, a nonlinear primal-dual interior point method (NPDIPM) is applied, which is described in the Appendix A. This method is not much different from the established methods in the literature [5-7].

B. MCPF module

To obtain active power margin, which is used as a voltage stability index in post-contingent states, RCCOPF applies MCPF. MCPF, an improved version of continuation power flow [8], is available to determine voltage stability limits of interface flows.

1) *Formulation:* The power flow equations at bus i of n-bus system are as follows.

$$P_{Ti}(\underline{\delta}, \underline{V}) - P_{Gi} + P_{Li0} = 0$$
$$Q_{Ti}(\underline{\delta}, \underline{V}) - Q_{Gi} + Q_{Li0} = 0 \qquad (6)$$

where the vectors $\underline{\delta}$ and $\underline{V}$ denote the bus voltage angle and bus voltage magnitude, respectively. To implement the scenario for increasing flow, the continuation parameter representing generation shift is incorporated into the active power equation in (6). The P_{Gi}, active power generation in region A and region B can be as follows.For region A in which generation increases,

For region A in which generation i

$$P_{Gi} = P_{Gi0} + k_{GAi} \Delta P_{GB,\,total} \qquad i \in SA \qquad (7.a)$$

For region B in which generation reduces,

$$P_{Gi} = P_{Gi0} + \mu k_{GBi} P_{GB0,\,total} \qquad i \in SB$$
$$\Delta PGB,\, total = \sum_{i \in SB} \mu k_{GBi} P_{GB0,\,total} \qquad (7.b)$$

where the following notations are made:

P_{Gi0} : original active power generation at bus *i*;
$P_{GB0\,total}$: original total generation in region B;
$\Delta P_{GB\,total}$: total generation decrease in region B;
k_{GAi} : fraction of generation increase at bus *i* in region A;
k_{GBi} : fraction of generation decrease at bus *i* in region B;
SA: set of generators in region A;
SB: set of generators in region B.

2) Solution method: Applying the locally parameterized continuation method, MCPF is composed of predictor and corrector. In predictor, the initial guess of the next solution is determined using the tangent vector of the known solution. In corrector, the next solution is calculated using the Newton-Raphson method. Details of the solution method are presented in [9].

C. Solution Procedure

In Fig. 2, the flowchart of RCCOPF is shown, which contains the functions of MCPF and OPF module; in addition, the steps in RCCOPF are described as follows.

Step 1) Determine set of contingencies to be applied.
Step 2) Construct active power flow vs. voltage (P-V) curves of all the contingencies sequentially using MCPF.
Step 3) Check active power margin of the current contingency and determine whether it is in severe contingency groups. There are two groups, SC1 and SC2. The contingencies in SC1 don't satisfy the minimum voltage stability margin, $P^{marg}_{\min}$, and those in SC2 satisfy but don't exceed 2 times $P^{marg}_{\min}$.
Step 4) Evaluate effective reactive reserve, R^{eff}, corresponding to each contingency in SC1 and SC2 from its P-V curve.
Step 5) Stop the program if active power margins of all contingencies satisfy the criteria. If not, go to the next step.
Step 6) Construct adequate reactive reserve constraints with respect to contingencies in SC1 and SC2. To remove margin violation, ΔR is added to the reactive reserve lower limit of each contingency in SC1.
Step 7) Perform preventive control with OPF and then go to Step 2.

In Step 3, severe contingencies are selected from the results of *P-V* curves in Step 2. There are two severe contingency groups, SC1 and SC2. The contingencies in SC1 violate the given margin criteria, so their voltage stability margins aren't enough. Those in SC2 don't violate the criteria, but their reactive reserve constraintsare included because through the OPF preventive action, their margins are possible to reduce even to violate the minimum margin. Other contingencies whose margins exceed 2× $P^{marg}_{\min}$ are excluded from this study because they have enough margins.

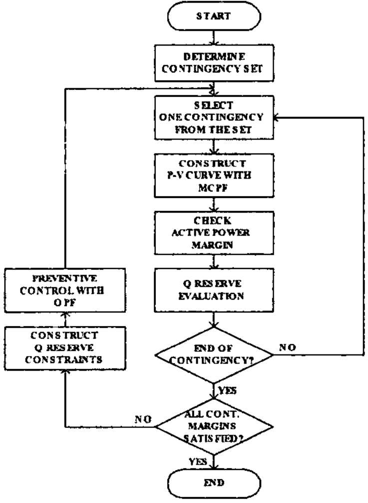

Fig. 2. Flowchart of RCCOPF

To obtain effective reactive reserves of severe contingencies, in Step 4, it is necessary to determine affecting generator groups with relative reactive generation sensitivities. Before the first preventive control with the OPF module, the lower limit of the reactive reserve constraint concerning the corresponding contingency needs to be initialized to R^{eff}, which is obtained in Step 4. The following equation illustrates the lower limit of the reactive reserve constraint regarding contingency *m* before the first preventive control.

$$R^{(0)}_{\min,m} = \sum_{i\in SG}\rho_{m,i}(Q^{*}_{m,i} - Q^{(0)}_{i}) \qquad (8)$$

In Step 6, $R_m$is added to the lower limit of the reactive reserve constraint when voltage stabilitymargin of contingency *m* in SC1 is not acceptable. This can be expressed as follows:

$$R^{(k+1)}_{\min,m} = R^{(k)}_{\min,m} + \Delta R^{(k)}_{m} \qquad (9)$$

If the voltage stability margin contingency *m* is sufficient, the lower limit at k+1-th iteration is fixed to that at k-thiteration. In RCCOPF, a constant value can be used as R_m, but several iterations are needed to get a solution unless it is adequately selected. To reduce the number of main iteration of RCCOPF, in this paper, variable R_m is used applying active power margin increase sensitivity with respect to effective reactive reserve increase obtained in the 1st iteration. Using the sensitivity, R_m in the 2nd iteration is selected as follows:

$$\Delta R^{(2)}_{m} = \kappa\frac{\Delta P^{(1)}_{MRG,m}}{\Delta R^{(1)}_{m}} \qquad (10)$$

where $\Delta P^{(1)}_{MRG,m}$ and $\Delta R^{(1)}_{m}$ are active power margin increase and the additional reactive reserve in the 1st iteration, and κ is correction multiplier for fast convergence. It is recommended to set κ between 1.1~1.3. Excessively large R_m can make the OPF module fail to converge in the 1st preventive control. Thus, R_m in the 1st control needs to be carefully selected. Using variable R_m, RCCOPF converges within the 2nd iteration in most cases in the authors' experience.

In RCCOPF, increase in effective reactive reserves of the affecting generators selected with high reactive generation sensitivities, which is obtained at the maximum points of P-V curves in severe contingent states, physically means relieving reactive power generation of the high sensitive generators. It is used as a measure for mitigating clogging voltage instability in severe contingencies.

4. Case Study

This section provides an example applying the proposed method, RCCOPF, into KEPCO 2003 peak system to verify the method. The objective in this simulation is to increase post-contingent voltage stability margin of active power flow on the set of metropolitan interface. Table I shows the specification of the system.

Table I. Specification of the KEPCO system

Total demand	47783.2 MW
Total generation	48595.5 MW
Metropolitan demand	19897.2 MW
Metropolitan interface flow	8997.7 MW

In simulation, the study region is metropolitan region; thus, a scenario is used to increase active power flow on the interface lines through generation shift from the study region to the external region. Using MCPF, the scenario is performed. Using modified CPF, which traces a path of power flow solution in the given direction of generation dispatch, interface flow vs. voltage (f-V) curves of contingencies are constructed. In this study, 74 contingencies containing outages of 345kV and 765kV routes (double circuit tower outages) are considered. Fig. 3 shows f-V curves of the normal and five severe contingent states. The worst contingency is #18 with 1.7 MW interface flow margin, which measure the difference between interface flow levels of base point and the critical point of the corresponding f-V curve. It is assumed that the required margin of interface flow is 200 MW. Thus, #18 is in SC1 but there is no contingent state in SC2.

After executing MCPF, effective reactive reserve with respect to each contingency is evaluated. To do this, affecting generator groups need to be determined; as stated earlier, the reactive generation sensitivity information is used to find the groups. In Table II, relative Q_G sensitivities of generators and their reactive generations at the maximum points #18 contingency is shown. This information is obtained at the maximum point of *f-V*curves; thus, reactive generation at the maximum point corresponds to the effective maximum reactive output of each generator.

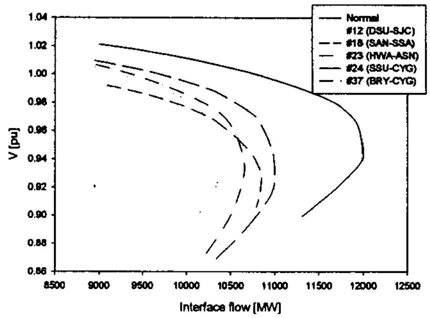

Fig. 3. f-V curves of five severe contingenies

In this simulation, affecting generator selection factor, *α*, sets to 0.2, so the generators whose relative Q_G sensitivities are greater than 0.2 are selected as affecting generators in each contingency. That is, for contingency #18, top ninety generators with high sensitivity are selected. Using (3), effective reactive serve of #18 case is calculated and it is 5247.48 MVAr.

Table II. Effective Q_G maximum and sensitivity of each generator at #18 case

모선번호	모선이름	Qeff,max	상대감도	모선번호	모선이름	Qeff,max	상대감도
831	울진3G	316.22	1	754	신인G12	68.41	0.28205
832	울진4G	320.78	0.99963	847	소양2G	36.5	0.28199
829	울진1G	289.4	0.99477	846	소양1G	36.86	0.28198
830	울진2G	289.4	0.99477	758	신인G14	68.31	0.28162
873	보령4G	229.01	0.78523	752	신인G10	67.34	0.27663
874	보령5G	229.01	0.78523	751	신인G9	67.22	0.27596
907	영광1G	301.17	0.76831	765	서인G3	42.4	0.24851
910	영광4G	289.14	0.75125	770	서인G8	42.14	0.24629
909	영광3G	288.74	0.7512	855	동해2G	73.75	0.24607
869	태안6G	225.19	0.70552	854	동해1G	73.75	0.24607
864	태안1G	225.19	0.70552	764	서인G2	41.92	0.24516
865	태안2G	225.19	0.70552	766	서인G4	41.77	0.24419
866	태안3G	225.19	0.70552	768	서인G6	41.66	0.24294
867	태안4G	225.19	0.70552	769	서인G7	41.57	0.24242
868	태안5G	225.19	0.70552	767	서인G5	41.45	0.24166
871	보령2G	210.19	0.69706	763	서인G1	41.31	0.24095
911	영광5G	324.88	0.64429	921	하동5G	144.56	0.24051
912	영광6G	324.88	0.64429	922	하동6G	144.56	0.24051
781	인천3G	132.24	0.59752	920	하동4G	144.56	0.24051
782	인천4G	132.07	0.58969	918	하동2G	144.56	0.24051
931	월성4G	268.75	0.58015	919	하동3G	144.56	0.24051
741	서울TP4	76.19	0.53548	917	하동1G	144.56	0.24051
890	당진3G	180.18	0.49216	882	보령S1	70.47	0.23615
891	당진4G	180.18	0.49216	876	보령G1	70.3	0.23535
747	일산ST1	80.69	0.44423	966	산청1P	-1.55	0.23379
936	고리4G	281.24	0.42759	967	산청2P	-1.55	0.23379
935	고리3G	281.01	0.42757	880	보령G5	69.49	0.23205
930	월성3G	209.7	0.41595	877	보령G2	69.07	0.2303
929	월성2G	209.6	0.41595	881	보령G6	68.65	0.22856
928	월성1G	244.17	0.41218	883	보령S2	68.42	0.22774
960	삼천포3G	167.68	0.35035	745	일산GT3	41.71	0.22507
853	영동2G	117.16	0.32038	746	일산GT4	41.71	0.22507
761	신인S11	72.07	0.30065	743	일산GT1	41.71	0.22507
762	신인S12	71.6	0.29805	744	일산GT2	41.71	0.22507
878	보령G3	86.27	0.29418	817	분당S1	66.66	0.21827
755	신인S9	70.68	0.29363	961	삼천포4G	161.23	0.21533
879	보령G4	85.25	0.28994	958	삼천포1G	161.77	0.21521
756	신인S10	69.86	0.28912	959	삼천포2G	161.77	0.21521
888	당진1G	187.54	0.28784	962	삼천포5G	154.63	0.21505
889	당진2G	187.54	0.28784	963	삼천포6G	154.63	0.21505
802	부천S	53.65	0.28671	899	현대G1	43.7	0.20424
759	신인G15	69	0.28524	852	영동1G	63	0.20299
757	신인G13	68.93	0.28506	750	일산ST2	39.35	0.20296
753	신인G11	68.83	0.28438	748	일산GT5	39.36	0.20296
760	신인G16	68.58	0.28294	749	일산GT6	39.36	0.20296

Using (5), (8) and (9), then, reactive reserve constraint are constructed to enhance interface flow margin of #18 in SC1, and the reactive reserve constraint of #18 is incorporated in the OPF formulation. In this simulation, weighting factors, W_{Gi}s, of the generators of effective generator group are set to 1000.

A. Application with constant ΔR (100 MVAr)

In this subsection, the result applying constant ΔR is shown. In this simulation, the additional reactive reserve ΔR is 100 MVAr; in the 1st preventive OPF, therefore, the lower limit of #18 reactive reserve constraint is increased to 5347.48 MVAr. With the reactive reserve constraint, OPF for preventive control is performed, and then interface flow margin of the worst case is obtained again. After the first preventive control, the margin of #1 contingency is 51.6 MW. Since the margin doesn't satisfy the 200 MW-criterion, preventive control needs to be executed again, with the lower limit of #1 constraint 5447.48 MVAr. After the 2nd preventive control, the margin of #1 case is 90.5

MW, which doesn't satisfy the criterion. Thus, RCCOPF is performed by 5th control until the margin is more than 200 MW. In Fig. 4, f-V curves at before and after preventive control are shown; in addition, in Table III and Fig. 5, interface flow margins before and after controls are shown.

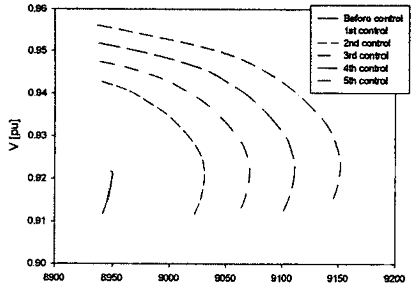

Fig. 4. f-V curves of #18 case before and after control

Table III. Interface flow margins before and after control (Constant ΔR)

	Initial	1st	2nd	3rd	4th	5th
Margin	1.7 MW	51.6 MW	90.5 MW	130.6 MW	170.5 MW	211 4 MW

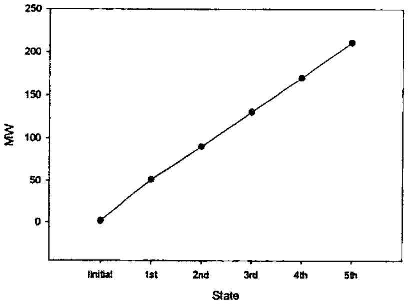

Fig. 5. Interface flow margins before and after control (Constant ΔR)

B. Application with variable ΔR

In the authors'experience, the function of active power margin increase with respect to effective reactive reserve increase is a non-decreasing function as shown in Fig. 5. Thus, it is possible to use variable ΔR, which is determined by (10), to reduce the number of the main iteration in RCCOPF. In this simulation, the 1stcontrol is executed with the same R (100MVAr), which is arbitrary selected in the previous simulation, but the 2nd control is performed with another R, which is determined using the sensitivity obtained in the 1st control. As shown in Table VI, active power margin sensitivity with respect to reactive reserve increase in the 1st control is 0.499 [MW/MVAr]. In this simulation, is set to 1.3, so $\Delta R_{\#1}^{(2)}$, the reactive reserve increase of #1 case in the 2nd control, is 486.6 MVAr and the lower limit of #1 reactive reserve constraint is 5734.08 MVAr. As shown in Table IV, the active power margin of #1 case after 2nd control satisfies the margin criterion. Using variable *R*, the number of the main iteration can be reduced in RCCOPF

Table IV. Interface flow margins before and after control (Variable ΔR)

	Initial	1st	2nd
Margin	1.7 MW	51.6 MW	208.7 MW

5. Conclusions

This paper introduces a concept of reactive reserve based contingency constrained optimal power flow (RCCOPF), which solves preventive control in the normal state concerning voltage stabilitymargins of post-contingent states. To solve the problem, in this paper, a decomposition method is used, which is based on effective reactive reserve. As sub-problems, active power margins of post-contingent states are determined with MCPF, and as the main problem, OPF for preventive control is performed to remove margin violations of severe contingencies. To combine the main and sub-problems, in RCCOPF, reactive reserve constraints are used as transformed contingency constraints, and the reactive reserve constraints are effectively constructed to enhance margins of severe contingencies. From the simulation results, it is known that post-contingent voltage stability margins can be enhanced with increase in effective reactive reserve of the corresponding contingency in RCCOPF, and that using variable ΔR, applying sensitivity of margin increase with respect to reactive reserve increase, can reduce the number of main iteration in RCCOPF

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