An Interior Point Method based Reactive Optimal Power Flow Incorporating Margin Enhancement Constraints

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Abstract - This paper describes a reactive optimal power flow incorporating margin enhancement constraints. Margin sensitivity at a steady-state voltage instability point is calculated using invariant space parametric sensitivity, and it can provide valuable information for selection of effective control parameters. However, the weakest buses in neighboring regions have high margin sensitivities within a certain range. Hence, the control determination using only the sensitivity information might cause violation of operational limits of the base operating point, at which the control is applied to enhance voltage stability margin in the direction of parameter increase. This paper applies an interior point method (IPM) to solve the optimal power flow formulation with the margin enhancement constraints, and shunt capacitances are mainly considered as control variables. In addition, nonlinearity of margin enhancement with respect to control of shunt capacitance is considered for speed-up control determination in the numerical example using the IEEE 118-bus test system.

Keywords: Margin enhancement constraint, reactive optimal power flow, parametric sensitivity, voltage stability

1. Introduction

Voltage stability is one of the main factors limiting the secure region in the operation and planning of today's power systems [1-3]. In the deregulated environment, power systems have been experiencing increase in uncertainty in term of voltage stability resulting from diverse power transactions and benefit based operational schemes, different from the past vertically integrated setting. Therefore, to ensure the firm and reliable operation of power systems, an effective control strategy needs to be established concerning voltage stability.

To select effective control parameters, a margin boundary point, which can be a steady-state voltage instability point or saddle node bifurcation point, must first be detected using either direct or indirect methods. Then, margin sensitivity at the point is calculated with the concept of invariant space parametric sensitivity (ISPS) [4], which is originally proposed in [5]. With margin sensitivity information, in [6], an optimization formulation of linear programming is presented for control determination against voltage collapse. In the experience of sensitivity analysis, however, the weakest buses in a voltage control area usually have high margin sensitivities in a certain range, so in cases of reactive injection-type controls, applying the determined control using only margin sensitivity information to some of the weakest buses might cause violation of operational limits, especially voltage limits, of the base point. Therefore, it should be verified whether the operating point after the control is within the given range of acceptable limits. This paper mainly discusses optimal power flow formulations that can cope with voltage stability margin enhancement as well as the operational constraints involved.

In the literature, there are various formulations of voltage stability constrained optimal power flow (VSCOPF), and they can be classified into two classes. Class I [7-9] is to obtain a control strategy by applying a single state. This can be available for corrective control strategies when the system is in a severe contingent state and hence it does not satisfy the given voltage stability criteria. Class II [10-14] is to determine preventive control strategies in the normal state considering voltage stability of multi-contingencies. This paper focuses on VSCOPF in Class I. Also, Class I is divided in two parts according to whether or not to consider the solution of the base case.

In [7], a direct interior point method is applied to solve both the preventive and corrective control problems of satisfying a certain level of voltage stability margin, but condition at the base solution after applying the controls is not taken into account. In [8], the network equations at the two points (base and maximum) are included in the formulation, and maximization of active load distance

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Received December 17, 2004 ; Accepted March 15, 2005

between the two points is incorporated in the objective function, with minimization of control costs. Thus, the dimension of the problem might be two times that of a conventional optimal power flow (OPF). In [9], instead of using the active power margin index, L-index constraints are placed as voltage stability constraints at the base case point. For real application, the threshold value of L-index for maintaining voltage security of the given system is determined in advance.

This paper presents a methodology to come up with control of reactive power related variables meeting the given voltage stability margin criteria. The algorithm utilizes information of margin sensitivity that can be obtained from voltage stability analysis. In addition, it employs an interior point method (IPM) to solve the reactive optimal power flow problem containing margin enhancement constraints (MEC) constructed using the margin sensitivity. The formulation includes the network equations of only one state and the dimension of the problem to be solved is identical with the conventional OPF. In addition, using IPM makes it possible to apply the method to the maximum point as well as the base point, depending on the aim of the control.

2. Voltage Stability Constraints

This section discusses voltage stability constraints and their incorporation into OPF formulations. Due to the fact that the main equality constraints in OPF are power flow equations, OPF can be used as a tool for maintaining and/or improving system security in a steady-state manner. Also, voltage stability constrained optimal power flow (VSCOPF) can be applied to enhance steady-state voltage stability. Then, first consideration should be given as to how to measure system voltage stability or equivalent proximity to the voltage instability point in the current state. To obtain this proximity information, diverse voltage stability indices have been proposed [15-16].

Voltage stability indices can be mainly classified into two types. Type I is the given state based voltage stability index, which is evaluated by comparing a physical parameter of the current point and the theoretically calculated critical value, so it is not necessary to obtain the real critical point. L indicator and Z-index are included in Type I. Type II is the large deviation based index, which can be determined by tracking a certain parameter from the current point to the voltage instability point. Active power and reactive power margins are typical indices in Type II, and they are widely used in voltage stability analysis.

Formulations for VSCOPF apply one of these voltage stability indices, and the applied index can be incorporated implicitly or explicitly in the objective function or constraints [17]. Assuming that the incorporated index can be explicitly represented in the constraints, VSCOPF can be expressed in a compact form as follows:

$$
\begin{aligned}
&\min \ f(x) \\
&s.t. \ \ g(x) = 0 \\
&\ \ h_{\min} \le h(x) \le h_{\max} \\
&\ \ vs_{\min} \le vs(x)
\end{aligned}
\tag{1}
$$

where $f(\cdot)$, $g(\cdot)$, $h(\cdot)$ and $vs(\cdot)$ represent the objective function, network equation functions, inequality constraint functions of operational limits, and voltage stability constraint functions, respectively. In (1), $h_{\min}$ and $h_{\max}$ represent lower and upper limits of $h(\cdot)$, and $vs_{\min}$ is the lower limit of the margin constraints.

If one of the indices in Type I is chosen for voltage stability constraints, it is not that complicated to implement the corresponding VSCOPF. The difficulties in implementation are calculating the monitored parameter at the theoretically critical point and deciding the threshold value of the voltage stability index as the lower limit of the constraints. Thus, before applying this type of VSCOPF to a real system, the threshold value should be adequately decided from the simulation experience.

In the case that one of the Type II indices is employed for VSCOPF implementation, more complicated formations are needed. When active power margin constraints are selected as the constraints, at least the two solutions of the base case and the maximum point should be taken into account as described in [8]. However, incorporation of the network equations at the two points doubles the problem dimension. In addition, we assume that before using VSCOPF to determine control actions for enhancing voltage stability margin, voltage stability analysis is performed in advance. In this paper, we developed a VSCOPF fully utilizing the information from voltage stability analysis. To maintain the problem size equal to that of conventional OPFs, it includes margin enhancement constraints constructed with active power margin sensitivity. This is approximation to direct incorporation of active power margin constraints. Therefore, nonlinearity of margin enhancement needs to be reflected in the process of finding solutions.

3. Formulations and Solution Procedure

This paper uses a simplified voltage stability constraint as mentioned above, and it is not difficult implementing the simplified constraint on the conventional OPF formulations. This section describes the main formulations in the proposed VSCOPF and its solution procedure.

3.1 Objective function

The objective function in this paper is minimization of reactive generation control from the base case as follows.

$$f(x)=\sum_{i\in Su} W_{ui}(u_i^{(k)}-u_i^{(0)})^2 \qquad (2)$$

where S_u represents a set of the selected control variables, W_{ui} represents the weighting factor of control variable u_i, and the superscripts (0) and (k) indicate the base case and iteration in the procedure of the VSCOPF. In this paper, shunt capacitance and tap ratio are regarded as control variables for reactive power dispatch to enhance voltage stability margin. The changing of generator terminal voltages is excluded in control variables because in real application it is usually not accepted.

3.2 Margin enhancement constraint (MEC)

MEC is constructed with margin sensitivity, proposed in [6], which is obtained at the margin boundary. The boundary can be determined with respect to a specified direction of stress, and margin sensitivity is calculated based on the left eigenvector corresponding to the minimum eigenvalue of the power flow Jacobian at the boundary. In the paper, MCPF [14] is applied to analyze voltage stability of the system and to reach the margin boundary. It is important to capture the precise boundary point. During the continuation, MCPF checks whether the nose point has been passed; if so, the solution path is traced back with a small step length; then, this procedure is repeated until the precise boundary point is captured. At the point, the left eigenvector is calculated with application of power method to inverse of the power flow Jacobian.

MEC of the corresponding state is constructed as follows:

$$\Delta M^{req}\le \sum_{i\in Su} S_{M,ui}(u_i-u_i^o) \qquad (3)$$

where ΔM^{req} denotes the required margin enhancement of the present state, and $S_{M,ui}$ stands for margin sensitivity of control variable u_i and u_i^o is the current value of u_i before execution of the VSCOPF. In the VSCOPF, MECs are placed in the position of voltage stability constraint in (1).

3.3 Modified continuation power flow (MCPF)

MCPF is used to determine the voltage stability margin of active power flow on a set of main transmission lines connecting the study region with other regions. It is also applicable to obtain sensitivity information that is utilized in the construction of MECs. A set of active and reactive power flow equations at bus i of the n-bus system can be expressed as follows:

$$P_{Ti}(\underline{\delta},\underline{V})-P_{Gi}+P_{Li0}=0 \qquad (4.a)$$

$$Q_{Ti}(\underline{\delta},\underline{V})-Q_{Gi}+Q_{Li0}=0 \qquad (4.b)$$

where the vectors $\underline{\delta}$ and $\underline{V}$ denote the bus voltage angle and bus voltage magnitude, respectively, and the subscripts T, G, and L represent injection, generation, and load, respectively. To implement the scenario for increasing flow, the parameter, μ, representing generation shift is incorporated into (5.a). Here, it is assumed that region B is the study region, and that active power is injected from region A to B through the interface lines. The P_{Gi}, active power generation in region A and region B are as follows.

For region A in which generation increases,

$$P_{Gi}=P_{Gio}+k_{GAi}\Delta P_{GB,total} \quad i\in SA \qquad (5.a)$$

For region B in which generation decreases,

$$P_{Gi}=P_{Gio}-\mu k_{GBi}P_{GBo,total} \quad i\in SB \qquad (5.b)$$
$$\Delta P_{GB,total}=\sum_{i\in SB}\mu k_{GBi}P_{GBo,total}$$

where the following notations are made:
P_{Gio} : original active power generation at bus i;
$P_{GBo,total}$: 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.

In order to trace the path of solutions starting from the base case solution with respect to change of the generator shifting parameter, μ, MCPF applies the locally parameterized continuation method, and so it consists of predictor and corrector. The predictor determines the initial guess of the next solution with the tangent vector obtained from the current solution. The corrector calculates the next solution from the initial guess using the Newton-Raphson method.

3.4 Margin sensitivity

For the system with n buses, the power flow equations including the generation shifting parameter, μ, can be expressed compactly as follows:

$$g(x, \mu, p) = 0 \quad (6)$$

where x is the vector containing all the state variables and p is a scalar parameter. At an operating point, the tangent vector $[dx\ d\mu\ dp]^T$ can be determined with the following formula.

$$g_x dx + g_\mu d\mu + g_p dp = 0 \quad (7)$$

When the operating point is on the margin boundary, one eigenvalue of the power flow Jacobian, g_x, is almost zero, so its singularity causes numerical difficulty in power flow calculation both at and near the margin boundary. Let v_o^T be the left eigenvector of the zero eigenvalue, and pre-multiply it to the left and right hand sides of (7). Then the first element can be eliminated due to the definition of the zero left eigenvector. From the remainder, sensitivity of μ with respect to change of an independent parameter p can be obtained as follows:

$$\frac{d\mu}{dp} = -\frac{v_o^T g_p}{v_o^T g_\mu} \quad (8)$$

Finally, margin sensitivity, (which is indeed sensitivity of the generation shifting margin) with respect to p is calculated by multiplying $P_{GBo,total}$ to $d\mu/dp$ as follows:

$$S_{M,p} = -P_{GBo,total} \frac{v_o^T g_p}{v_o^T g_\mu} \quad (9)$$

3.5 Application of interior point method (IPM)

To obtain solution of preventive and corrective OPF, a nonlinear IPM is used. IPM is one of the Newton-type methods to obtain a solution satisfying the KKT (Karush-Kuhn-Tucker) first-order necessary optimality condition. IPM first introduces slack variables (≥ 0) to convert inequality constraints to equality ones; then, it establishes the Lagrangian function including the objective function, the functions corresponding to the total equality constraints, and a scalar log barrier function with the slack variables. Then, Newton method is applied from an initial guess to solve the KKT first-order necessary condition of the Lagrangian function. Because of the log barrier function, the solution is determined inside the inequality constraints, and the starting point should also be within the inequality constraints. The IPM used in this paper is explained in more detail in Appendix [14].

Incorporating the MEC constraints into the formulation of optimization alters the structure of the Hessian matrix from that in the conventional OPF and makes the solution matrix less sparse. In MEC of (2), there is linkage between the selected control variables. During the calculation of Newton-type optimization, this linkage implicates the existence of the virtual lines connecting the buses of the selected control variables from the viewpoint of generating fill-in elements. When a large number of control variables are linked by MEC, a bus-ordering scheme is necessary to reduce the number of fill-in elements considering the network topology as well as the virtual lines.

3.6 Solution procedure

To obtain the solution, MCPF is first performed for voltage stability analysis of the current state from a set of contingencies. If the margin criteria are not satisfied, margin sensitivity is calculated at the margin boundary point for construction of the margin enhancement constraint. In addition, effective parameters are chosen as the control variables in the VSCOPF, using margin sensitivity with respect to each parameter. Then, the VSCOPF is executed to enhance the margin. When linear MEC is used in the VSCOPF approximately, the effectiveness of the determined control after executing the VSCOPF should be verified with MCPF. Fig. 1 shows the flowchart of the solution procedure.

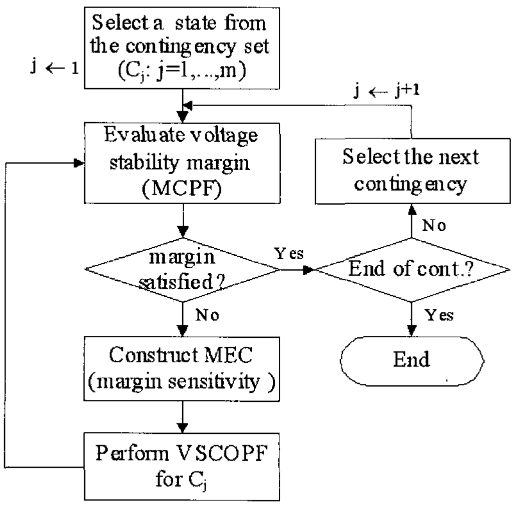

Fig. 1 Flowchart of the solution procedure

4. Numerical Examples

This section provides the numerical results with the IEEE 118-bus test system to illustrate the proposed method in this paper. For clarity of this illustration, the modified system [14] is used in this simulation. Fig. 2 indicates a one-line diagram of the system divided into two regions. In Fig. 2, Region B is the study region, so when applying

MCPF to obtain generation shifting margin or interface flow margin, the generation in Region B is decreased, while that in Region A is increased by the same amount of generation decrease in Region B. This direction of generation shift deteriorates system voltage instability, and there exists limitation of generation shift according to the given state. Table 1 shows the interface lines in the system and their active power flows in the normal state.

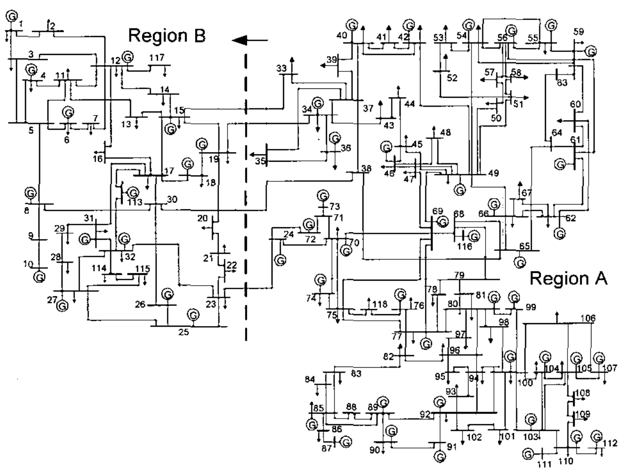

Fig. 2 One-line diagram of IEEE 118-bus system

Table 1 Interface lines in this study and their initial flows

	From (Region A)	To (Region B)	Initial power flow
#1	33	15	13.7 [MW]
#2	34	19	25.1 [MW]
#3	38	30	32.4 [MW]
#4	24	23	28.4 [MW]

This study applies line outages and performs MCPF to identify severe contingencies in terms of interface flow margin, which is by definition active power flow difference from the base point to the maximum point in a f-V curve constructed by MCPF. As indicated in (5), MCPF mainly changes interface flow on a set of the selected lines by generation shift from Region B to A. Table 2 presents the two worst contingencies that have the least interface flow margins and Fig 3. illustrates f-V curves of bus 1 in the normal and two worst cases. Note that other contingencies have almost identical interface flow margins to the normal case.

Table 2 Interface flow margins of two worst contingencies

Cont.	Outage line	Interface flow margin
#1	8 – 5	206.9 MW
#2	30 – 38	563.7 MW

Assume that in the given voltage criteria interface flow margin in each contingent state should be greater than 300 MW to maintain system voltage security. For contingency #1, then, control strategy should be established. In [14], a preventive control strategy is proposed with dispatch of reactive power generation in the normal state. However, control in the normal state considering multi-contingencies might be limited by operational limits in some cases; in addition, corrective control is usually considered as a more economical measure in system operation. The proposed algorithm with the VSCOPF is designed for determination of control after a severe contingency to enhance the interface flow margin.

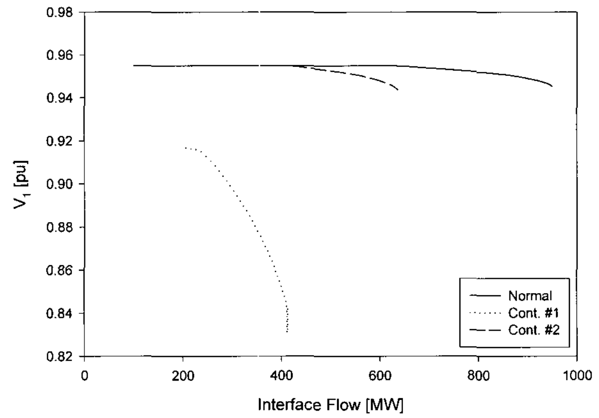

Fig. 3 f-V curves of the normal and two worst contingent cases

After identification of severe contingencies that require corrective control, the solution framework calculates margin sensitivity at the maximum point of each f-V curve. In this study, bus shunt capacitance at each bus is mainly regarded as the control parameter, so margin sensitivity with respect to the parameter is calculated using (9). Table 3 presents the margin sensitivity information at contingency #1. From this table, it can be known that most top 20 sensitive buses are in the upper part of Region B.

Table 3 Margin sensitivity w.r.t. bus shunt capacitance at contingency #1

Rank	Bus #	Sensitivity	Rank	Bus #	Sensitivity
1	16	5.897	11	6	4.753
2	14	5.720	12	5	4.459
3	13	5.711	13	4	4.311
4	117	5.313	14	15	3.533
5	12	5.245	15	19	2.911
6	2	5.220	16	33	2.702
7	11	5.102	17	18	2.517
8	1	5.030	18	20	2.381
9	3	4.935	19	17	2.113
10	7	4.935	20	21	1.968

To improve the interface flow margin at contingency #1, in this study we selected the shunt capacitances of the top 10 sensitive buses as the control variables in the VSCOPF with a MEC constructed as shown in (3). As the required interface flow margin is 300 [MW], the required margin enhancement, ΔM^{req}, needs to be set to 93.1 (=300-206.9). Here, the margin sensitivities in Table 2 are not exactly sensitivities of interface flow margin, but those of generation shift as described in (9). However, the system parameter used to change active power flow on the selected interface lines is the generation shift in MCPF; in addition, if increase in transmission loss can be neglected due to generation shift, sensitivity of generation shift can be applicable for construction of MEC. In the objective function of (2), the weighting factors of all the control variables are set to 1000. For this VSCOPF it causes a reactive power dispatch problem, and only voltage limits need to be incorporated in the formulation of (1). The upper limits are set to 1.05 [pu] and the lower limits 0.90 [pu].

Then, the proposed VSCOPF is executed to determine corrective control strategy of bus shunt capacitances. The MEC in the VSCOPF is a linear constraint using linear sensitivity; thus, after execution of the VSCOPF, real margin enhancement needs to be re-evaluated. Fig. 4 shows the f-V curves of the worst case at each solution step of re-evaluating interface flow margin with MCPF until the required margin is reached. Table 4 presents interface flow margin and total amount of shunt capacitance to be committed at each solution step.

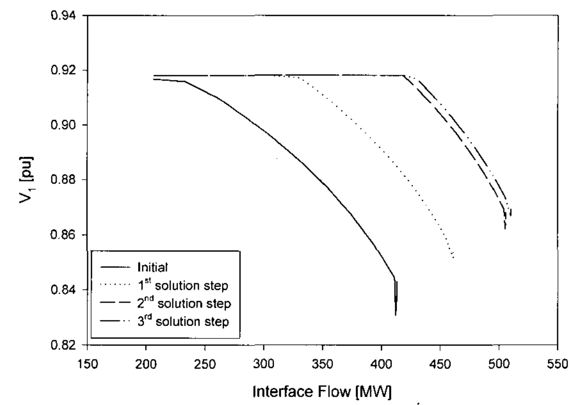

Fig. 4 f-V curves before and after VSCOPF execution

Table 4 Interface flow margin and total shunt capacitance to be committed at each solution step

	Solution Step			
	Initial	1st	2nd	3rd
Interface flow margin	206.9 MW	253.7 MW	299.3 MW	303.7 MW
Total shunt capacitance	0	17.46 MVAr	34.75 MVAr	36.46 MVAr

After the 1st execution of VSCOPF with ΔM^{req} of 93.1 as the lower limit of the MEC, the real margin enhancement is increased by 46.8 [MW]. Thus, in the 2nd solution step, $\Delta M^{req(2)}$ is set to 185.2 with the ratio of the real margin enhancement to $\Delta M^{req(1)}$, where the superscripts (1) and (2) correspond to the 1st and 2nd solution step, respectively. After the 2nd execution of VSCOPF, interface flow margin is 299.3 [MW], which is very close to the margin requirement. In the 3rd solution step, ΔM^{req} is set to 194.4 using the following formula:

$$\Delta M^{req(3)} = \kappa\left(\Delta M^{req(2)} - \Delta M^{req(1)}\right) + \Delta M^{req(1)} \quad (10)$$

where κ is the margin enhancement correction multiplier, and in the 3rd solution step, it is set to 1.1.

In the formulation of the MEC, margin sensitivity obtained at the initial condition in Table 2 is applied in order that a reference for selection of ΔM^{req} is needed. In this simulation, significant change in ranking of sensitive buses is not experienced. Table 5 indicates margin sensitivities of the top 10 buses at each solution step. In Table 5, there is a minor ranking change between bus 3 and bus 7. However, as total amount of reactive compensation increases, margin sensitivities of the 10 buses tend to decrease. This indicates that effectiveness of control with shunt capacitance is reduced with a certain shape of a saturated function. In some severe cases, the margin is rather decreased even though shunt capacitance is more greatly applied within a certain range. Therefore, using too large a value for κ in (10), when control variables are shunt capacitances, should be carefully taken into account. It is recommended to set κ between 1.1~1.3.

Table 5 Margin sensitivities of top 10 buses at each solution step

Bus #	Margin Sensitivity			
	Initial	1st	2nd	3rd
16	5.897	4.469	4.108	4.074
14	5.720	4.335	3.983	3.950
13	5.711	4.328	3.976	3.943
117	5.313	4.034	3.709	3.679
12	5.245	3.976	3.652	3.621
2	5.220	3.958	3.635	3.604
11	5.102	3.869	3.554	3.524
1	5.030	3.815	3.505	3.476
3	4.935	3.744	3.439	3.411
7	4.935	3.745	3.440	3.411

5. Conclusions

This paper presents a reactive optimal power flow incorporating margin enhancement constraints as voltage stability constraints. Using the margin enhancement constraints constructed with margin sensitivity enables selective control, which is desirable for corrective control determination and is effective to reduce the number of linkage among control variables that cause fill-in elements during factorization for Newton-type optimal power flow. Taking into account nonlinearity in margin enhancement with respect to shunt capacitance, practical adaptation of the lower limit change is explained. For further research, discrete control in the formulation of VSCOPF will be incorporated.

Acknowledgement

This work was financially supported by MOCIE through the EIRC program with APSRC at Korea University.

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