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Determination of Reactive Power Compensation Considering Large Disturbances for Power Flow Solvability in the Korean Power System

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Abstract – This paper proposes a methodology using a tool based on the branch-parameter continuation power flow (BCPF) in order to restore the power flow solvability in unsolvable contingencies. A specified contingency from a set of transmission line contingencies is modeled, considering the transient analysis and practice in the Korean power system. This tool traces a solution path that satisfies the power flow equations with respect to the variation of the branch parameter. At a critical point, in which the branch parameter can move on to a maximum value, a sensitivity analysis with a normal vector is performed to identify the most effective compensation. With the sensitivity information, the location of the reactive power compensation is determined and the effectiveness of the sensitivity information is verified to restore the solvability. In the simulation, the proposed framework is then applied to the Korean power system.

Keywords: Reactive power compensation, Power flow solvability, Sensitivity analysis, Transient analysis, Korean power systems

1. Introduction

Recently, Korean power system operating conditions have gradually approached an upper limit because transmission power has been increased, while economic and environmental problems have prevented the transmission system from expanding. Moreover, when a contingency occurs, the power system may have unsolvable cases for which a power flow solution does not exist. These situations mainly occur when the reactive power supplies of the power system do not meet the requirements of the system. Therefore, an adequate plan for either expanding the transmission system or creating reactive power compensation must be established in order for the power system to resolve the undesirable situation.

Security assessments of the power system reflecting the various contingencies must be performed in terms of system operation planning in order to guarantee secure system operations. However, when the system does not have a power flow solution after a contingency, security assessments cannot be performed because the assessments are based on the idea that the power system always has a power flow solution. Hence, a correcting action for the recovery of the power system is required after severe outages in order for the power system to be analyzed in a steady-state condition. In [1] and [2], Overby presented a method for determining system controls in order to restore the power flow based on a damped Newton-Raphson power flow algorithm and a sensitivity analysis [3], [4]. Van Cutsem proposed an approach of corrective control implemented by a fast voltage stability simulator using the minimum unrestored load and sensitivity [5]. Granville et al. adopted the direct interior point method in an optimal power flow in order to calculate the minimum load shedding to restore the power flow [6]. Feng et al. in [7] described a method for determining the minimum load shedding required to find the equilibrium point associated with the post-contingency boundary. An effective direction for load shedding was found with a normal vector.

However, by using load shedding for restoration, the system must experience blackouts even if the area is relatively small. This paper outlines a framework for determining the necessary reactive power compensation, instead of load shedding, to restore the power system. This methodology uses the branch parameter-variation continuation power flow that traces the path of the power flow solutions with respect to the branch parameter. Afterwards, a sensitivity analysis is performed at the nose point to select the proper bus in order to restore the reactive power in several severe contingencies. In [8], Flueck et al. presented a variation to the continuation power flow method applied to the branch admittance to arc-length parameterization. This method can be time consuming in a large-scale power system because the generated matrix used for the calculation may become too complex. We can compensate for this problem by applying a local parameterization for the

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branch-parameter continuation power flow (BCPF). This local parameterization does not require preparation, which reduces the fill-in used for the matrix decomposition that determines the inverse matrix. BCPF can determine the existence or nonexistence of a power flow solution and trace the path of a power flow solution with respect to the branch parameter variation in severe case where the power system does not have a solution. To determine the adequate reactive power compensation strategies used in this paper, the sensitivity between the branch parameter and the injected reactive power is calculated at the nose point of the Y-V curve produced by the BCPF. With this information, the most effective load bus is selected in order to restore the solvability of the contingencies. The selected location is determined with reactive power compensation to solve the problem, such as a switched shunt capacitor. We provide a case study that models the Korean power system at the peak of the summer season in 2005, 2007, and 2010.

2. Branch Parameter Continuation Power Flow (BCPF)

This section introduces the concept of BCPF. When a transmission line outage occurs, the branch can gradually move to such outage state by using the parameterizing components of the outage branch. The parameterization of the branch can be depicted as a π-equivalent circuit, as shown in Fig. 1. The branch parameter, named Y, is multiplied by the series and shunt admittance of the branch. If the branch is in service, Y = 0; if it is out of service, Y = 1. Thus, the BCPF can trace the power flow solution in which the state of the branch moves from a pre-contingency to a post-contingency state by changing the Y parameter from zero to one. In Fig. 1, Y_C and Y_{series} represent the shunt and series admittance of the branch, respectively, and $P_{ij} + jQ_{ij}$ and $P_{ji} + jQ_{ji}$ stand for the active and reactive power flow from bus i to bus j and from bus j to bus i, respectively.

The general power flow equation at i_{th} bus is shown as equation (1):

$$\begin{aligned} 0 &= P_{Ti}(\underline{\delta},\underline{V}) - P_{Gi} + P_{Li} \\ 0 &= Q_{Ti}(\underline{\delta},\underline{V}) - Q_{Gi} + Q_{Li} \end{aligned} \tag{1}$$

Where the subscripts T, G, and L indicate the injection, the generation, and the load, respectively, and the vectors **δ** and **V** are the bus voltage angle and the bus voltage magnitude, respectively. As shown in Fig. 1, if the branch of bus i to j is in an outage state, the power flow equation can be reformulated as follows:

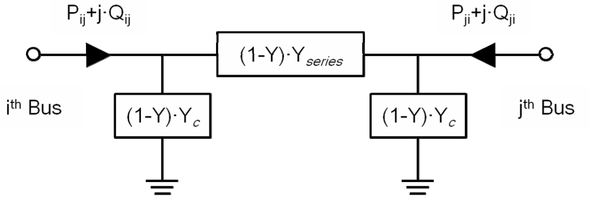

Fig. 1. π-equivalent circuit of the i^{th} to j^{th} branch with branch parameter (Y).

$$\begin{aligned} 0 = {} & |V_i|^2 G_{ii}^{new} \\ & + |V_i| \sum_{\substack{l \in L(i) \\ l \neq j}} |V_l| \left[G_{il}\cos(\theta_{il}) + B_{il}\sin(\theta_{il}) \right] \\ & + |V_i||V_j| \left[G_{ij}^{new}\cos(\theta_{ij}) + B_{ij}^{new}\sin(\theta_{ij}) \right] \\ & + P_{ij}(V_i, V_j, Y) - P_i^{inj} \end{aligned} \tag{2.a}$$

$$\begin{aligned} 0 = {} & -|V_i|^2 B_{ii}^{new} \\ & + |V_i| \sum_{\substack{l \in L(i) \\ l \neq j}} |V_l| \left[G_{il}\sin(\theta_{il}) - B_{il}\cos(\theta_{il}) \right] \\ & + |V_i||V_j| \left[G_{ij}^{new}\sin(\theta_{ij}) - B_{ij}^{new}\cos(\theta_{ij}) \right] \\ & + Q_{ij}(V_i, V_j, Y) - Q_i^{inj} \end{aligned} \tag{2.b}$$

Where L(i) = { l: $|Y_{il}| \neq 0$, l ≠ i } indicates the set of buses that are directly connected to bus i by a branch; $G_{ii}^{new} + B_{ii}^{new}$ and $G_{ij}^{new} + B_{ij}^{new}$ stand for the new i_{th} diagonal terms; and the new (i, j) element is in the admittance matrix of the power system after the branch has been removed. P_i^{inj} and Q_i^{inj} represent P_G-P_L and Q_G-Q_L at i_{th} bus in the previous power flow equation, respectively. θ_{ij} describes the voltage angle difference between the i bus and the j bus. The real and reactive power flow, $P_{ij}(V_i, V_j, Y)$ and $Q_{ij}(V_i, V_j, Y)$, goes from bus i to bus j through the outage branch and is defined as follows:

$$\begin{aligned} P_{ij}(V_i, V_j, Y) = (1-Y) \Big\{ & |V_i|^2 G_{ii}^{new} + |V_i||V_j| \\ & \left[G_{ij}^{new}\cos(\theta_{ij}) + B_{ij}^{new}\sin(\theta_{ij}) \right] \Big\} \end{aligned} \tag{3.a}$$

$$\begin{aligned} Q_{ij}(V_i, V_j, Y) = (1-Y) \Big\{ & -|V_i|^2 B_{ii}^{new} + |V_i||V_j| \\ & \left[G_{ij}^{new}\sin(\theta_{ij}) - B_{ij}^{new}\cos(\theta_{ij}) \right] \Big\} \end{aligned} \tag{3.b}$$

The reformulated power flow equations still depend on the angle and the magnitude of the bus voltage, and can represent the state of the branch. When Y equals zero, the power flow equation is the original set, whereas when Y equals one, the new power flow equation is used after considering the branch outage.

In order to trace the path of the power flow solution by branch parameter Y, the BCPF uses a locally parameterized continuation method [9]. This method is composed of a predictor, which determines the initial state of the next solution by using the tangent vector of the known solution, and a corrector, which calculates the next solution by the Newton-Raphson method. In the predictor and corrector, the BCPF uses an augmented Jacobian matrix, including the branch parameter (Y). The augmented Jacobian $\mathbf{J_A}$ used in the BCPF can be expressed as follows:

$$J_A = \begin{bmatrix} \partial \underline{P}_T / \partial \underline{\delta} & \partial \underline{P}_T / \partial V & \partial \underline{P}_T / \partial Y \\ \partial \underline{Q}_T / \partial \delta & \partial \underline{Q}_T / \partial V & \partial \underline{Q}_T / \partial Y \\ & \underline{e}_k & \end{bmatrix} \tag{4}$$

$$\underline{P}_T \in R^{N-1}, \underline{Q}_T \in R^{N-NPV-1}$$

Where $\underline{\mathbf{P}}_\mathbf{T}$ and $\underline{\mathbf{Q}}_\mathbf{T}$ represent the injection of the active and reactive power composed by the vectors in equations (1) to (3). Meanwhile, $\mathbf{e_k}$ is a row vector in which all the elements are zero, while the k^{th} element is a unit value. N and NPV indicate the number of buses in the power system and the number of voltage-controlled buses in the generator buses, respectively. In equation (4), $\partial\underline{\mathbf{P}}_\mathbf{T}/\partial\mathbf{Y}$, $\partial\underline{\mathbf{Q}}_\mathbf{T}/\partial\mathbf{Y}$, and $\mathbf{e_k}$ are augmented from the original power flow Jacobian matrix. The $\mathbf{e_k}$ is chosen to remove the ill-conditioned problem from the singularity. This augmented Jacobian solves the singularity at the critical point by adding the values in the rows and columns of the existing Jacobian matrix. Therefore, the branch parameter-voltage (Y-V) curves do not have a divergence problem at the critical point.

The causes of divergence are ill condition, a bad initial guess, and unsolvable cases. However, the problem of the Jacobian singularity can be solved if a CPF with a robust convergence is used. Using these characteristics, the BCPF can determine whether or not the cause of the divergence problem is the initial guess or if the case is unsolvable. When the BCPF deals with unsolvable cases in severe contingencies, Y cannot move from 0 to 1 in the Y-V curve, as shown in case 2 in Fig. 2. In solvable cases, the branch parameter Y of the Y-V curves passes Y = 1, as in case 1 in Fig. 2. It is necessary to consider the case when $0 < Y^* < 1$, where Y^* corresponds to the branch parameter at the nose point. If Y^* is less than 1 during a contingency, there is a certain amount of flow in the branch that cannot be shifted to the other branches. These remaining flows prevent the power flow equations to be solved. Thus, if the remaining flows can be shifted to the other branches by using reactive power compensation, the power system can be restored.

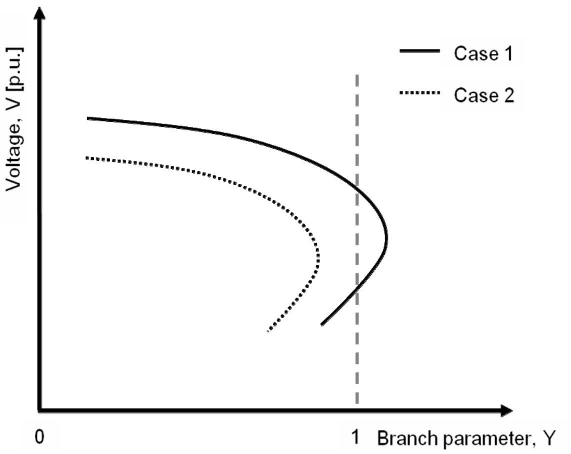

Fig. 2. Selection of contingencies with Y-V curves.

3. A Method of Reactive Power Compensation for the Convergence of Power Flow

This section presents the design of the reactive power compensation method for the restoration of power flow. Fig. 3 shows the procedure for applying the BCPF to obtain a solution. First, a contingency list is prepared to consider what a system operator regards as severe outages from the point of view of the power system operation. In the next stage, the BCPF is applied to select the unsolvable contingencies in the list. If it is unsolvable, a transient analysis is performed. When a power system is not stable in terms of transient stability, a steady-state analysis such as a power flow calculation is not meaningful because the calculation begins from the assumption that the dynamic characteristics of the power system are stable [10]. Therefore, the transient stability of the power system while it is under a large disturbance must be checked. If the contingency is unstable in transient stability terms, a measure is taken to stabilize the power system transient, such as a generator trip. To find effective buses for the reactive power compensation, a sensitivity analysis is then performed at the critical point of the Y-V curve using parametric sensitivity [11], [12]. The formulation for calculating the sensitivity with respect to the reactive power compensation on the ith bus is as follows:

$$\begin{aligned} S_{QSi} &= -\frac{\partial Y^*}{\partial \underline{Q}_i} \\ &= -\left(\begin{bmatrix} v_P^* & v_Q^* \end{bmatrix} \begin{bmatrix} \dfrac{\partial \underline{P}_T}{\partial Q_i} \\ \dfrac{\partial \underline{Q}_T}{\partial Q_i} \end{bmatrix} \Bigg/ \begin{bmatrix} v_P^* & v_Q^* \end{bmatrix} \begin{bmatrix} \dfrac{\partial \underline{P}_T}{\partial Y} \\ \dfrac{\partial \underline{Q}_T}{\partial Y} \end{bmatrix} \right) \end{aligned} \tag{5}$$

Where $\boldsymbol{v}$ (= $[\boldsymbol{v}_\mathbf{P}^*\ \boldsymbol{v}_\mathbf{Q}^*]$) indicates the zero left eigenvector at the nose point and Q_i is a scalar representing the reactive power of bus i. In (5), the vector containing the derivatives $\underline{\mathbf{P}}_\mathbf{T}$ and $\underline{\mathbf{Q}}_\mathbf{T}$ with respect to Y corresponds to the vector in the right-most column in the augmented Jacobian matrix in equation (4). The sensitivity information of the branch parameter with respect to the reactive power control determines the effective bus for moving on to 1, which is the nose point of Y-V curves. The selected buses for controlling the reactive power are compared with the available buses. Using this step, the selected bus compensates the reactive power, for instance by switching the shunt capacitors, and through a power flow calculation, the amount of the injected reactive power is determined. If the power flow equation is solvable, the procedure is stopped; otherwise, the process is repeated. Finally, to verify the effectiveness of the sensitivity information by the BCPF, the order, which is between the effective buses as determined by the sensitivity information and the amount of injected reactive power, is compared.

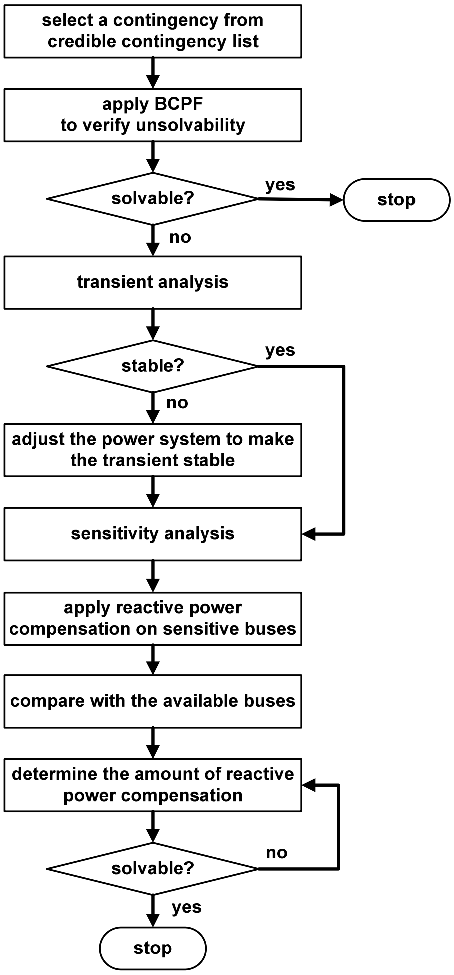

Fig. 3. Reactive power compensation procedures for the convergence of power flow.

4. The Case Study

This section describes the results of modeling the proposed methodology to the Korean power system in 2005, 2007, and 2010. The power system structure is shown in Fig. 4. The total base load demand of the system in 2005, 2007, and 2010 are 5,209, 5,547, and 6,102 MW, respectively. In the simulation, four line contingencies were considered, as follows:

Case 1: Singapyeong – Sintaebaek, two-circuit contingency
Case 2: Sinseosan – Sinansung, two-circuit contingency
Case 3: Asan – Hwasung, two-circuit contingency
Case 4: Seoinchon C/C – Yangju, two-circuit contingency

In case 1, a line contingency with two circuits is considered from Singapyeong to Sintaebaek. Case 2 is also a line outage with two circuits from Sinseosan to Sinansung. Likewise, cases 3 and 4 are line contingencies with two circuits from Asan to Hwasung and from Seoinchon C/C to Yangju, respectively. The voltage level in cases 1 and 2 is 765 kV, while that in cases 3 and 4 is 345 kV.

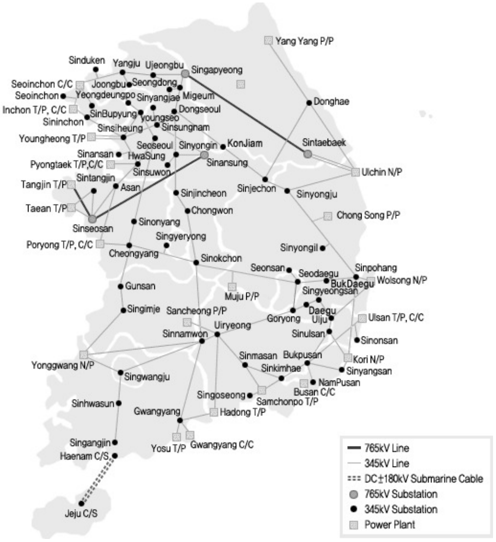

Fig. 4. Transmission diagram of the Korean power system.

First, the BCPF was applied to the contingency list in order to verify the unsolvable cases. The branch parameter values were checked at the nose point of the Y-V curves, as shown in Table 1, where cases 1 and 2 were unsolvable for every year. The worst case was case 2 in 2010 because its Y value is the lowest.

Transient analysis using cases 1 and 2 in each year was then performed before the sensitivity analysis to verify the stability mentioned in the previous section. In case 1, when Uljin #3 was tripped, the power system was stable in terms of transient stability in each year. In case 2, the results are different for every year. The power system using case 2 was stable without a generator trip in 2005. When four generators were tripped in 2007 and two in 2010, the power system was stable in terms of transient stability. The results are described in Table 2.

The simulation scenarios used to consider the results of the transient analysis are as follows:

Scenario 1: Only a branch outage and does not regard transient stability

Table 1. The branch parameter at the nose point in each case

Years	Cases	Y (at nose point)
2005	Case 1	0.9246
	Case 2	0.9743
	Case 3	1.1508
	Case 4	1.0768
2007	Case 1	0.9006
	Case 2	0.9006
	Case 3	1.1522
	Case 4	1.1375
2010	Case 1	0.8744
	Case 2	0.7641
	Case 3	1.2802
	Case 4	1.0389

Table 1. Results of transient analysis

Cases	2005	2007	2010
Case 1	Unstable	Unstable	Unstable
Minimum number of tripped generators for stability	1	1	1
Case 2	Stable	Unstable	Unstable
Minimum number of tripped generators for stability	0	4	2

Scenario 2: Considers switching off the reactor in which the branch outage occurs (Reactors can generally aggravate the voltage instability when a disturbance happens in its power system)

Scenario 3: Considers generator trips (Generators are selected to make the transient state stable)

Scenario 4: Considers scenarios 2 and 3 together

In scenario 1, only a branch outage is considered, i.e., this is similar with cases 1 and 2. In the Korean power system, the reactor is operated to reduce the voltage at 765 kV substations. However, the reactors can cause the power system to be more severe when the line contingency occurs at 765 kV. Thus, scenario 2 reflects the switching off of the reactors installed at the substations of the outage lines. Scenario 3 considers the results of the transient analysis at cases 1 and 2, as mentioned in section 3. Meanwhile, in scenario 4, scenarios 2 and 3 were considered together.

Table 3 shows the results of which branch parameter at the nose point of Y-V curves is selected in each scenario through the application of BCPF. The branch parameters in scenario 4 were excellent in all years.

The monitored buses are considered for selecting the locations of the reactive power compensation in order to consider a space and geographical location to install the switched shunt devices. Sensitivity analyses using the scenarios were then performed at the nose point of each Y-V curve. The sensitivity indicates that of the reactive power compensation with respect to a branch parameter, and this can be a measure for selecting adequate buses for compensation. Tables 4 and 5 show the five most sensitive buses in each case and the injected amount of reactive power compensation to restore their solvability. The symbol (–) indicates that the power flow equation cannot be solved by injection of reactive power. In addition, '0' means that the power flow equation can be solved without any control. The ranking from the sensitivity analysis is similar to the order derived from the amount of injected reactive power. This indicates that if the reactive power compensation is performed at the bus with a high order of sensitivity, the solvability of the power system can be restored with a minimum amount of effort. However, when the Y* (the branch parameter at the nose point) is very far from 1, i.e., like that in scenarios 1 and 2, the results of the sensitivity analysis are quite different from practical compensation. This is caused by a difference in the state between the contingencies and the nose point of the Y-V curve, that is, the nose point of the Y-V curve in an unsolvable case is different from that during a branch outage. In addition, the power system has a nonlinear property, whereas the sensitivity is linear. As a result, the sensitivity analysis yielded similar results to the reactive power compensation in sce-

Table 3. Branch parameter at the nose point in each detailed simulation

Cases	2005	2007	2010
Case1_Scenario1	0.924617	0.900615	0.874441
Case1_ Scenario2	0.959952	0.935135	0.914306
Case1_ Scenario3	0.974581	0.944466	0.926605
Case1_ Scenario4	1.000001	0.97167	0.957522
Case2_ Scenario1	0.974275	0.900615	0.76414
Case2_ Scenario2	1.004357	0.921798	0.809996
Case2_ Scenario3	0.987264	0.915735	0.865602
Case2_ Scenario4	1.015871	0.960343	0.921895

Table 2. Order of sensitivities and the injected reactive power about case 1 by years

Year	Ranking	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
		# Bus	Q [MVar]	# Bus	Q [MVar]	# Bus	Q [MVar]	# Bus	Q [MVar]
2005	1	5710	1110	5710	746	1710	170	1710	0
	2	5700	1150	1710	1000	2510	240	2510	0
	3	1710	1580	5700	770	1700	260	4710	0
	4	2510	1530	2510	950	4510	260	4510	0
	5	1200	1850	1200	1120	2500	260	2500	0
2007	1	5710	1440	5710	1150	2510	560	2510	200
	2	1710	2240	5700	1230	1710	600	1710	210
	3	2510	2060	2510	1610	4710	600	4710	220
	4	5700	1530	1710	1940	5710	540	2500	220
	5	1700	2580	2500	1850	2500	650	1700	230
2010	1	1710	-	2510	1670	1710	830	1710	450
	2	2510	2100	1710	1750	2510	800	4710	480
	3	1700	2530	1700	2000	4710	810	2510	450
	4	2500	2480	2500	1940	1700	890	1700	490
	5	4710	2240	4710	1780	2500	930	2500	480

Table 4. Order of sensitivities and the injected reactive power about case 2 by years

Year	Ranking	Scenario1		Scenario 2		Scenario 3		Scenario 4	
		# Bus	Q [MVar]	# Bus	Q [MVar]	# Bus	Q [MVar]	# Bus	Q [MVar]
2005	1	4710	270	4510	0	4510	90	4510	0
	2	4510	1150	4710	0	2510	100	4710	0
	3	4700	290	4510	0	4500	90	4510	0
	4	4100	290	4100	0	1710	100	4100	0
	5	4500	290	4700	0	4100	290	4700	0
2007	1	5710	-	5710	-	4710	900	4710	410
	2	1710	-	5700	-	2510	1000	4510	440
	3	2510	-	2510	-	4510	920	2510	410
	4	5700	-	1710	-	1710	1070	1710	490
	5	1700	-	2500	-	4700	980	4700	440
2010	1	1710	2020	1710	1220	1710	770	1710	460
	2	2510	1970	4710	1060	2510	740	4710	400
	3	4710	-	2510	1200	4710	720	2510	460
	4	4700	2120	4700	1200	1700	780	4700	480
	5	1700	2300	1700	1350	4700	760	1700	460

nario 4, and the amount of compensation was the smallest among all the scenarios. This verifies the effectiveness of the proposed strategy, in which transient analysis should be performed before the sensitivity analysis.

Furthermore, the conventional power flow method cannot obtain any information about the power system in severe contingencies; however, the proposed method can be used as a good guideline and control for restoring power flow solvability in terms of reactive power compensation.

5. Conclusion

This paper introduced a reactive power compensation strategy using the BCPF algorithm for obtaining a power flow solution in the event of severe contingencies. Based on the BCPF, which traces a path of power flow solutions with respect to variations of branch parameters, this paper suggested an algorithm that includes the selection of adequate locations by using sensitivity analysis at the nose point of Y-V curves. In a case study, reactive power compensations were modeled on the Korean power systems, thus restoring the solvability in severe contingencies. The results from the scenarios were similar; the closer the critical point is to 1 (branch parameter) before compensation, the more similar the results are. This is related to the nonlinearity of reactive power compensation by the proposed method becomes profound as the parameters are farther from 1 before compensation. Thus, although there exists a certain limitation in the sensitivity analysis used in severe contingencies, it can provide information on how severe a given contingency is in the corresponding system state. System operators can provide information through monitoring a given contingency list using the proposed method on online operation. For adequate compensation strategies, weak buses used as compensation locations must be carefully chosen in terms of voltage stability, especially in the more severe contingencies.

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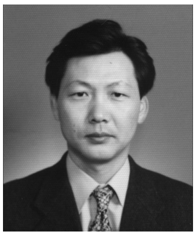

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