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A Study on the Method of the Vulnerable Area Investigation In Severe Contingencies Using Branch Parameter Continuation Power Flow (BCPF)

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Abstract - The most widely used index for the vulnerable area investigation has been the reactive power margin or sensitivity analysis. But we can only obtain the results of these analyses if the results of load flow are convergent in severe contingencies. Otherwise these methods are not adoptable. This paper presents a good index for overcoming severe contingencies, though the power flow equation is unsolvable using the branch parameter continuation power flow. In simulation, the Korea Electric Power Corporation (KEPCO) Systems are applied.

Keywords: Branch parameter, contingencies, continuation power flow, reactive power margin

1. Introduction

Recently, the system operating conditions have reached their limit because the transmission powers have increased and the economic and environmental problems prevent the transmission system from expanding. Therefore, an adequate plan for expansion of the transmission system needs to be established so that the power system can meet this situation from the viewpoint of systems planning. At the same time, when the system is operating close to critical point, a security assessment concerning various contingencies must be performed in terms of system operation planning in order to guarantee secure system operations. In particular, the system operations nearing the critical point can experience severe cases without power flow solutions. As a result, this security assessment is most important. Moreover, the larger and more complex the system becomes, the more severe system collapse problems involving voltage stability and local voltage instability can occur. To ensure stable operation, the system can be maintained by evaluating the system voltage stability and implementing the methods to increase the stability [1-4].

Up to now, feasible countermeasures have been studied to find an operating system solution and to determine the quantitative state of insolvability in the severe contingencies. By the minimum distance between the operating point of the current system and the area with the power flow solution, the state of insolvability has been measured. Also, sensitivity analysis has been used to control the system to minimize the geometric distance in a parameter plane. But this method should repeat calculations to determine the boundary of the power flow solution, and it cannot be ensured that the geometric minimum distance in the load parameter planes is the optimal direction for insuring system operation point [5].

This paper proposes a method of weak bus selection to inject appropriate reactive power by using the branch parameter continuation power flow (BCPF) and the sensitivity analysis in severe contingencies. Previous studies have determined the existence or nonexistence of power flow solution by using BCPF, and in the case of divergence, they determined whether the cause is an initial guessing problem or the nonexistence of a system operation solution. And they have traced the path of the power flow solution with respect to the change of branch parameter in the severe cases without power flow solution.

In this paper, using the proposed BPCF, the path of power flow solutions will be traced. In the severe cases, the bus to inject a reactive power will be selected through the sensitivity analysis using a normal vector and then the compensation of reactive power will be proposed as a method to find the power flow solution of severe contingencies. In the case study, the KEPCO's summer peak system data for 2005, 2007 and 2010 are used.

2. BCPF

The general continuation power flow consists of a predictor and corrector [6-8]. It has an assumption that the continuation power flow calculation has a solution. But if the system does not have a solution, system analysis cannot

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be performed. To solve this problem for the severe contingencies, the system analysis utilizes BCPF, which traces a path of power solutions with respect to the change of the branch parameter impedance [9].

2.1 Reformulation of power flow equation

In order to consider the change of branch parameter impedance when contingencies occur, the power flow equation is reformulated by parameterization of the branch parameter. Figure 1 presents the connection branch between the i-th bus and the j-th bus by π- type equivalent circuit.

As indicated in Figure 1, (1-Y) is multiplied to series and shunt admittances of the studied branches to adjust the value of the branch parameter admittance. When Y equals zero, the state is normal, and when Y equals one, the state has an outage of branches. The power flow equation in which parameter (Y) of the i-th bus is imported can be modified as follows.

$$\begin{aligned} 0 = {} & |V_i|^2 G_{ii}^{new} \\ & + |V_i| \sum_{\substack{l \in L(i) \\ l \neq j}} |V_l| [G_{il} \cos(\theta_{il}) + B_{il} \sin(\theta_{il})] \\ & + |V_i||V_j| [G_{ij}^{new} \cos(\theta_{ij}) + B_{ij}^{new} \sin(\theta_{ij})] \\ & + P_{ij}(V_i, V_j, Y) - P_i^{inj} \end{aligned} \tag{1}$$

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

Where,

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

$$\begin{aligned} Q_{ij}(V_i, V_j, Y) = {} & (1 - Y)\Big\{ - |V_i|^2 B_{ii}^{br} \\ & + |V_i||V_j| [G_{ij}^{br} \sin(\theta_{ij}) - B_{ij}^{br} \cos(\theta_{ij})] \Big\} \end{aligned} \tag{4}$$

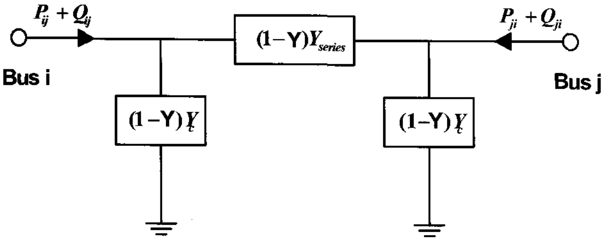

Fig. 1 Branch parameter parameterization of contingencies

2.2 Augmented Jacobian

The case, where the modified power flow equation is applied to the continuation algorithm, uses the augmented Jacobian including the branch parameter (Y) with respect to the state variables. The augmented Jacobian J_A of the n-bus system, which is used in the branch parameter continuation power flow is expressed as follows.

$$J_A = \begin{bmatrix} \partial \underline{P}_T / \partial \underline{\delta} & \partial \underline{P}_T / \partial \underline{V} & \partial \underline{P}_T / \partial Y \\ \partial \underline{Q}_T / \partial \delta & \partial \underline{Q}_T / \partial V & \partial \underline{Q}_T / \partial Y \\ & \underline{e}_k & \end{bmatrix} \tag{5}$$

$$\underline{P}_T \in R^{n-1}, \underline{Q}_T \in R^{n-npv-1}$$

This augmented Jacobian solves singularity at the critical point by adding values in the rows and columns of the existing Jacobian. So, Y-V curves do not have the divergence problem at the critical point. As shown in the augmented Jacobian, local parameterization is applied to the continuation algorithm.

Local parameterization needs no preparation work, which reduces the occurrence of fill-in at the matrix decomposition for finding the inverse matrix: however, arclength parameterization does require preparation work because the last row of the augmented Jacobian does not have a non-zero value.

3. Selection of reactive power injection bus for convergence of power flow

This section presents the selection of weak bus for the convergence of power flow. First, the branch parameter continuation power flow is used to select the severe contingencies, and then the weak bus is selected by performing the sensitivity analysis at the critical point of the branch parameter.

3.1 Selection of severe contingencies

The causes of divergence are ill-condition, bad initial guess and insolvability of cases. However, if a continuation power flow having robust convergence is used, the problem of singularity of Jacobian can be solved. And we can determine whether the cause of the problem is initial guess or unsolvable. Figure 2 presents the Y-V curves for the branch parameter continuation power flow from before contingencies to after contingencies.

As shown in Figure 2, Case 1 has a solution for after contingencies but Case 2 does not. Case 2 is selected by a severe contingency.

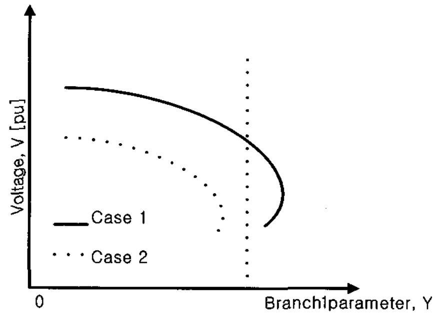

Fig. 2 Selection of contingencies with Y-V curves

3.2 Selection of reactive power injection bus through sensitivity analysis

The weak bus is selected by performing the sensitivity analysis at the critical point of the Y-V curve for selected severe contingencies. In this subsection, the sensitivity analysis is a normal vector of Jacobian matrix.

When the system equation is f, state variables are x and the control parameter is p. The system equation applying the branch parameter is written in Equation (6).

$$\begin{aligned} & f(x,Y,p)=0 \\ & (f \in R^{2n}, Y \in R^{1}, p \in R^{m}) \end{aligned} \tag{6}$$

Equation (7) is obtained by differentiating Equation (6). Then, the sensitivity of the branch parameter with respect to the control parameter can be obtained by multiplying a zero left eigenvector to both sides of Equation (7).

$$\begin{aligned} & -f_{p}dp = f_{Y}dY \\ & (f_{p} \in R^{2n\times m}, dp \in R^{m\times 1}, f_{Y} \in R^{2n\times 1}, dY \in R^{1\times 1}) \end{aligned} \tag{7}$$

Zero right eigenvector represents the change in the direction of vector plane where the initial change of the state variables is at the voltage instability point. Zero left eigenvector represents the normal vector vertical to the boundary plane of the areas with a solution and without, that is, the projection on to the direction of zero right eigenvector just collapse direction. Then, (7) is presented with respect to the i-th control parameter as follows.

$$\begin{aligned} & \frac{\partial Y}{\partial p_{i}} = -Y^{T} f_{pi} / Y^{T} f_{Y} \\ & (\frac{\partial Y}{\partial p_{i}} \in R^{1\times 1}, Y^{T} \in R^{1\times 2n}, f_{pi} \in R^{2n\times 1}) \end{aligned} \tag{8}$$

where the denominator on the right side has the same scalar values with respect to the control parameter of m, and f_{pi} of the numerator is the column vector that has the same constant value at the some control bus. Then, the components of the control bus, i-th bus have all the same values and the other components are zero. So, the sensitivity of the branch parameter with respect to the control parameter is determined by the relative magnitude of the zero left eigenvector of the relevant control para-meters. That is, we can find the relative sensitivity of a bus with respect to parameters by simply comparing the mag-nitude of the zero left eigenvector components. Therefore, the bus that has the biggest normal vector components is the effective bus for changing the critical value of the branch parameter at the Y-V curves.

4. Case Study

The tested systems were KEPCO's 2005, 2007 and 2010 summer peak systems. First, the severe contingencies were selected by using branch parameter continuation power flow. Then, the weak bus was selected by performing the sensitivity analysis using a normal vector at the critical point of the Y-V curves. Figure 3 depicts the KEPCO system. The thick lines are representative of the 765kV lines.

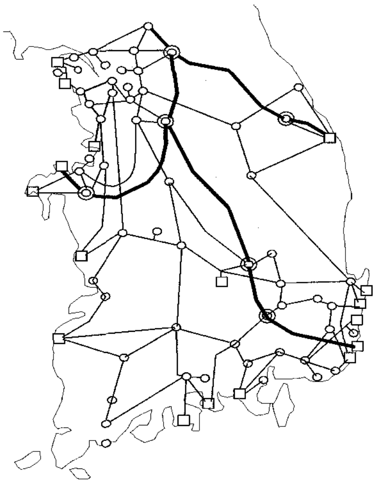

Fig. 3 KEPCO system

4.1 The selection of severe contingencies

The contingencies were selected for 345kV and 765kV metropolitan area lines. Two circuit route contingencies

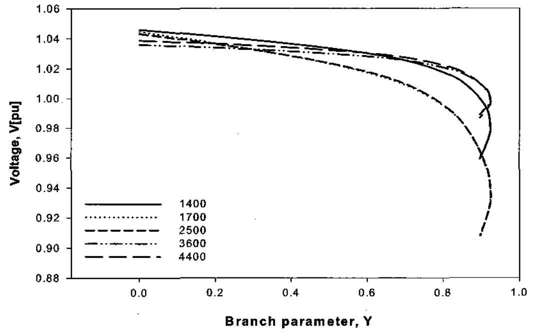

Fig. 4 Y-V curves of 2005' 1020-5010 contingency

were considered. Then, the critical point was confirmed at each case by using Y-V curves. The Y-V curves are presented as follows.

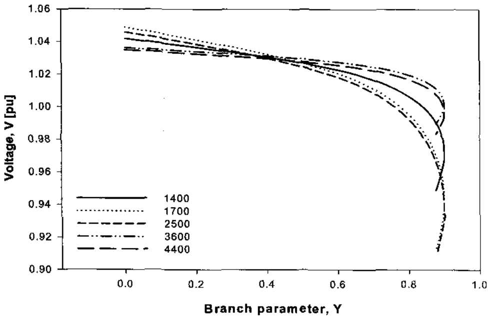

Fig. 5 Y-V curves of 2007' 1020-5010 contingency

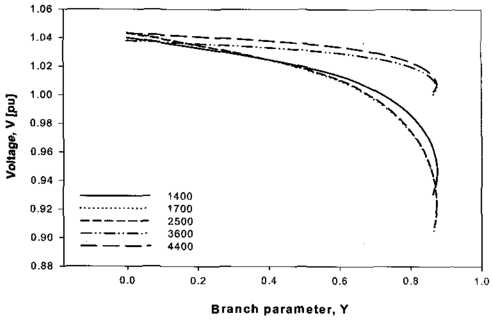

Fig. 6 Y-V curves of 2010' 1020-5010 contingency

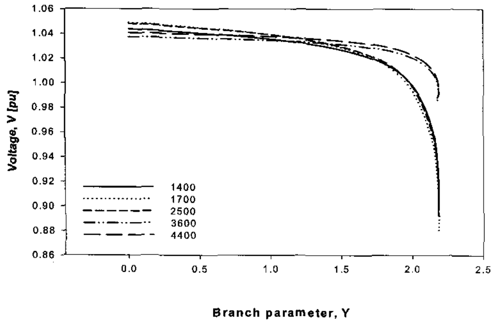

Fig. 7 Y-V curves of 2010' 1200-1500 contingency

From Fig. 4 to Fig. 6, the contingencies are severe with no power flow solution when the branch parameter is one. And Fig. 7 shows a contingency having a power flow solution. Table 1 reveals the selected contingencies.

Table 1 Selected contingencies

Year	FROM BUS NUMBER	TO BUS NUMBER	Y_{critical}	Line Capacity
2005	1020 4010	5010 6030	0.92462 0.97428	765 kV
2007	1020 4010	5010 6030	0.90062 0.90062	765 kV
2010	1020 4010	5010 6030	0.87444 0.76414	765 kV

The suggested method is associated with the KEPCO (Korea Electric Power Corporation) system protection scheme. The simulation is performed in detail following the methods in Table 2. Detailed simulation gave the branch parameter of the critical point, as shown in Table 3.

Table 2 Method of detailed simulation

Method	Contents
Method 1	Only contingencies
Method 2	Considering reactor remove
Method 3	Considering generator trip
Method 4	Method 2 + Method 3

Table 3 The critical point of branch parameter at each detailed simulation

CASE	2005	2007	2010
1020-5010 T/L M1	0.92462	0.90062	0.87444
1020-5010 T/L M2	0.95995	0.93514	0.91431
1020-5010 T/L M3	0.97458	0.94447	0.92661
1020-5010 T/L M4	1.00000	0.97167	0.95752
4010-6030 T/L M1	0.97428	0.90062	0.76414
4010-6030 T/L M2	1.00436	0.92180	0.81000
4010-6030 T/L M3	0.98726	0.91574	0.86560
4010-6030 T/L M4	1.01587	0.96034	0.92190

4.2 Selection of reactive power injection bus through sensitivity analysis

In this subsection, the weak buses are selected by using the sensitivity analysis at the critical point of severe contingencies. The result is evaluated by injecting reactive power at the selected weak buses. The significant 20 buses considering the KEPCO system at voltage stability sides are evaluated by the weak buses.

Table 4 The principal monitoring bus

Bus Number	1400	1410	1700	1710
	2500	2510	3600	3610
	4400	4410	4500	4510
	4700	4710	5700	5710
	6950	6960	1200	4100

After setting up a significant number of monitoring buses, sensitivity analysis was performed to select the weak buses. Among the selected weak buses, the top 5 ranked buses are indicated in Table 5 and Table 6.

Table 5 is the list of 1020-5010 T/L contingency and

Table 6 is the list of 4010-6030 T/L contingency. Then reactive power in Table 5 and Table 6 means practically injected reactive power for convergence of the power flow equation at the weak buses. And the symbol (-) represents that the power flow equation cannot be solved by using the injection of reactive power. Also, '0' means that the power flow equation can be solved without any control.

Table 5 The injection buses of reactive power are 1020-5010 T/L contingencies divided by year

YEAR	RANK	1020-5010 T/L							
		M1		M2		M3		M4	
		Bus	MVar	Bus	MVar	Bus	MVar	Bus	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

As indicated in Tables 5 and 6, the result of the sensitivity analysis method is similar to the practically injected reactive power. But, when the value of Y (branch parameter) is very far from 1 (at contingency state), i.e. like as in the cases of M1, M2 and M3, the results of the sensitivity analysis are very different from the practical values. This is simply because the situation of contingencies and the critical point of the Y-V curves have some difference. That is, the power system has a nonlinear property. On the other hand, the sensitivity has the linearity.

However, based on M4 of Tables 5 and 6, it is found that the method of sensitivity analysis through the Y-V curves gave results that were similar to those of the practically injected reactive power. This tendency demonstrates that the sensitivity analysis method is useful. In case of severe contingencies, the previous cannot obtain any information regarding the power system. But, the proposed method can be used as a good guideline for restoring power flow solvability.

Table 6 The injection buses of reactive power are 4010-6030 T/L contingencies divided by year

YEAR	RANK	4010-6030 T/L							
		M1		M2		M3		M4	
		Bus	MVar	Bus	MVar	Bus	MVar	Bus	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

5. Conclusion

In this paper, the method of reactive power injection is introduced to obtain power flow solution for severe contingencies by using the branch parameter continuation power flow. Previous methods are problematic for unsolvable contingencies. To overcome these disadvantages, we suggest a method of the weak bus selection through the sensitivity analysis at the critical point of the Y-V curves. Then, the selected weak buses were practically injected with reactive power. The results between the sensitivity analysis and the practically injected reactive power were similar. The closer the critical point was to 1 (branch parameter) the more similar the results, because it meant the better representation of the situation of system states. The differences are due to the nonlinearity of the system and linearity of the sensitivity. But the proposed method is useful because it provides us with information pertaining to the power system during severe contingencies.

The weak buses should be accurately selected by the voltage stability, and the selection should be more cautious for severe contingencies. The branch parameters below 1 signify severe contingencies. The smaller the parameters are under 1; the worse is the accuracy of the proposed method. So, detailed studies for the case branch parameters far from 1 are expected for future studies.

Acknowledgements

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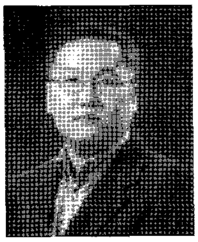

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